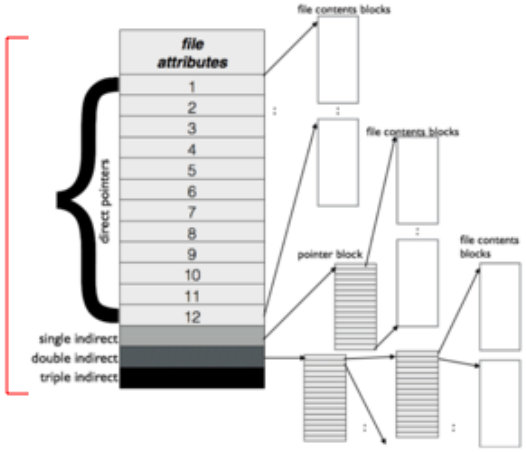
1. a) 1) 4 - inode blocks. 1 for the file `c`, and 3 for the directdories `/`, `a`, `b`
   2) 3 - directory blocks - one for root `/`, one for `a`, the other for `b`
   3) 1 - single indirect block as far as we know. The file definitely has more than 12 blocks (# of data blocks pointed by direct pounters), but less than 1036 (# of data blocks pointed by direct pointers and single indirect pointers). We are reading block 1034.
   4) 1 - data block for file `c`

   b) All of the above

Notes

- **Inode**

```
owner       : remzi
permissions : read-write
size        : 1
pointer     : 4
pointer     : null
pointer     : null
pointer     : null
```



  - Is short form of **index node**
  - Describes a file system object such as file or data
  - Contains all information about a file/directory, including
    * File Type,
    * Size
    * Number of blocks allocated to it
    * Protection information
    * Time information (e.g time created, time modified)
    * Location of data blocks residing on disk

References

1) Wikipedia, Inode, link
2) Machanick, Philip. (2016). Teaching Operating Systems: Just Enough Abstraction. 642. 10.1007/978-3-319-47680-3_10., link

c) Size, the location of data blocks that reside on disk

Notes

- I wonder what information about blocks inode has. Is it total number of blocks both inode and data, or just data?
- I struggled a bit on this one. I should find an easier way to remember which information inode has

d)
- **Inode Bitmap and Data Block Bitmap**

  ```
  (b) - Data Leak
  (c) - Inode Leak
  ```
- **New Directory Inode**

  ```
  (a) - No inconsistency
  ```
- **Inode Bitmap**, **Data Block Bitmap**, **Existing Directory Data**, **New Directory Inode**, and **New Directory Data**

  ```
  (e) - Inconsistent inode data
  ```
- **Inode Bitmap**, and **New Directory Inode**

  ```
  (c) - Inode leak
  (d) - Multiple file paths may point to same inode
  ```
- **New Directory Inode**, **Existing Directory Inode**, **Existing Directory Data**

  ```
  (e) - Inconsistent inode data
  (f) - Something points to garbage
  ```

Correct Solution

- **Inode Bitmap and Data Block Bitmap**

  ```
  (b) - Data Leak
  (c) - Inode Leak
  ```
- **New Directory Inode**

  ```
  (a) - No inconsistency
  ```
- **Inode Bitmap**, **Data Block Bitmap**, **Existing Directory Data**, **New Directory Inode**, and **New Directory Data**

  ```
  (e) - Inconsistent inode data
  ```
- **Inode Bitmap**, and **New Directory Inode**

  ```
  (c) - Inode leak
  ```
- **New Directory Inode**, **Existing Directory Inode**, **Existing Directory Data**

```
(d) - Multiple file paths may point to same inode
(f) - Something points to garbage
```

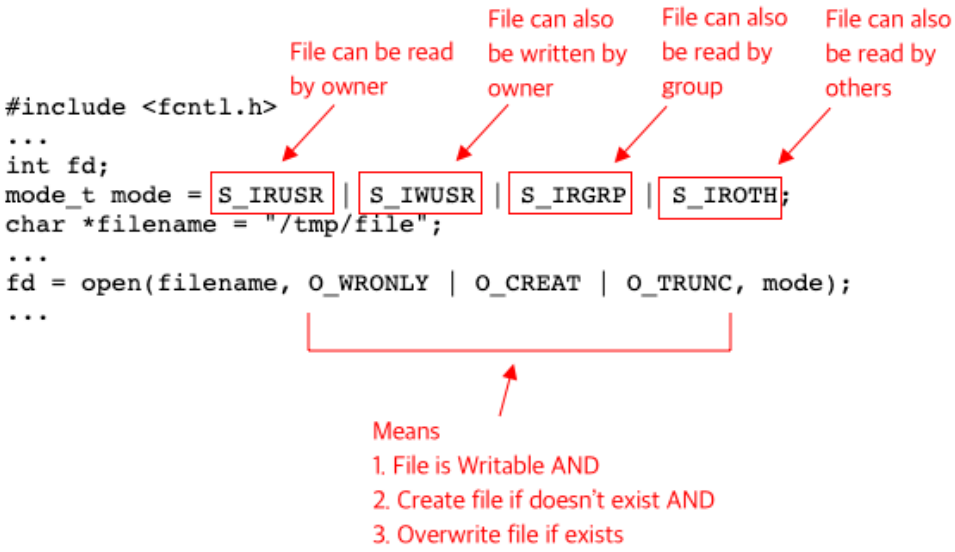
Notes

- I wonder how system call for reading file/directory works in UNIX. Does it check for bitmap?
- I wonder how system call for deleting file/directory works in UNIX
- I wonder how system call for creatubg file/directory works in UNIX
- Learned that
  - Missing Inode Bitmap - multiple file paths may point to same inode
- **File API**
  - `open` (create/access file)
    - Is a system call
    - Reads target inode into memory (when loading)
    - Does three things on creation
      1) make structure (inode) that racks all relevant information about file
      2) link human readible name to the file, and put that link to a directory
      3) increment **reference count** in inode
    - **Syntax:**

      ```
      int fd = open("foo". O_CREAT|O_WRONLY|O_TRUNC, S_IRUSR|S_IWUSR)
      ```

      - `O_CREAT` - Creates file "foo" if does not exist
      - `O_WRONLY` - Open file for writing only (default)
      - `O_TRUNC` - Overwrites existing file Need example/Clarification
      - Can have multiple flags
    - Returns **file descriptor** or `fd` for short
      - Is an integer
      - Is used to access a file
      - Is private per process
      - Can be used to `read()` and `write()` files

      Example



  - Amount of I/O generated by `open()` is proportional to length of pathname (wait. How is I/O involved in open()?)

- (read) (read file)
  - Is a system call
  - **Syntax:**

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

    - `fd` - file descriptor (from `open()`)
    - `buf` - container for the read data
    - `count` - number of bytes to read
  - Returns number of bytes read, if successful
  - Returns 0 if is at, or past the end of file

  Example

```
char buf[4096];
int fd = open("/a/b/c", 0); // open in read-only mode
lseek(fd, 1034*4096, 0);    // seek to position (1034*4096) from start of file
read(fd, buf, 4096);        // read 4k of data from file
```

System Calls	Return Code	Current Offset	
`fd = open("file", O_RDONLY);`	3	0	
`read(fd, buffer, 100);`	100	100	read continues for each call
`read(fd, buffer, 100);`	100	200	
`read(fd, buffer, 100);`	100	300	
`read(fd, buffer, 100);`	0	300	returns 0 if at end
`close(fd);`	0	–	

- `write` (write file)
  - Is a system call
  - Writes data out of a buffer
  - **Syntax:**

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

    - `fd` - file descriptor
    - `buf` - A pointer to a buffer to write to file
    - `nbytes` - number of bytes to write. If smaller than buffer, the output is truncated

  Example

```c
#include <unistd.h>
#include <fcntl.h>

int main(void)
{
    int filedesc = open("testfile.txt", O_WRONLY | O_APPEND);

    if (filedesc < 0) {
        return -1;
    }

    if (write(filedesc, "This will be output to testfile.txt\n", 36) != 36) {
        write(2, "There was an error writing to testfile.txt\n", 43);
        return -1;
    }

    return 0;
}
```

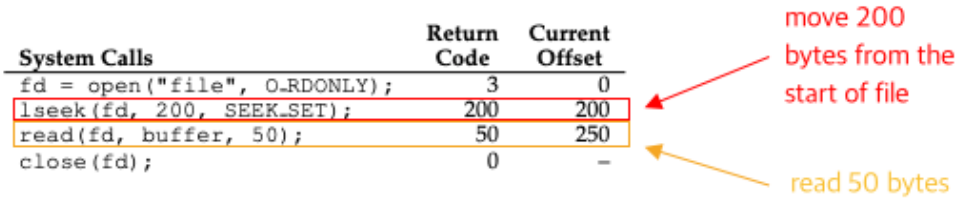
- `lseek`
  - Reads or write to a specific offset within a file
  - **Syntax:**

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

    - `fd` - file descriptor
    - `offset` - the offset of pointer within file (in bytes)
    - `whence` - the method of offset

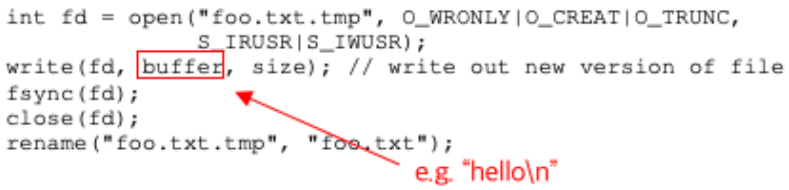
      `SEEK_SET` - offset from the start of file (absolute)
      `SEEK_CUR` - offset from current location + offset bytes (relative)
      `SEEK_END` - offset from the end of file
  - Returns offset amount (in bytes) from the beginning of file
  - Returns -1 if error

Example



- `rename` (update file name)
  - Is a system call
  - Changes the name of file
  - Is **atomic** (after crash, it will be either old or new, but not in-between)
  - **Syntax:** `int rename(const char *old, const char *new)`
    - `old` - name of old file
    - `new` - name of new file
  - Returns 0 if successful
  - Returns -1 if error

Example



- `stat` (get file info)
  - displays metadata of a certain file stored in **inode**
  - **Syntax:** `int stat(const char *path, struct stat *buf)`
    - `path` - file descriptor of file that's being inquired
    - `buf` - A `stat` structure where data about the file will be stored (see below)

```
struct stat {
  dev_t     st_dev;     // ID of device containing file
  ino_t     st_ino;     // inode number
  mode_t    st_mode;    // protection
  nlink_t   st_nlink;   // number of hard links
  uid_t     st_uid;     // user ID of owner
  gid_t     st_gid;     // group ID of owner
  dev_t     st_rdev;    // device ID (if special file)
  off_t     st_size;    // total size, in bytes
  blksize_t st_blksize; // blocksize for filesystem I/O
  blkcnt_t  st_blocks;  // number of blocks allocated
  time_t    st_atime;   // time of last access
  time_t    st_mtime;   // time of last modification
  time_t    st_ctime;   // time of last status change
};
```

Figure 39.5: **The `stat` structure.**

Example

```c
#include <unistd.h>
#include <stdio.h>
#include <sys/stat.h>
#include <sys/types.h>

int main(int argc, char **argv)
{
    if(argc != 2)
        return 1;

    struct stat fileStat;
    if(stat(argv[1],&fileStat) < 0)
        return 1;

    printf("Information for %s\n",argv[1]);
    printf("---------------------------\n");
    printf("File Size: \t\t%d bytes\n",fileStat.st_size);
    printf("Number of Links: \t%d\n",fileStat.st_nlink);
    printf("File inode: \t\t%d\n",fileStat.st_ino);

    printf("File Permissions: \t");
    printf( (S_ISDIR(fileStat.st_mode)) ? "d" : "-");
    printf( (fileStat.st_mode & S_IRUSR) ? "r" : "-");
    printf( (fileStat.st_mode & S_IWUSR) ? "w" : "-");
    printf( (fileStat.st_mode & S_IXUSR) ? "x" : "-");
    printf( (fileStat.st_mode & S_IRGRP) ? "r" : "-");
    printf( (fileStat.st_mode & S_IWGRP) ? "w" : "-");
    printf( (fileStat.st_mode & S_IXGRP) ? "x" : "-");
    printf( (fileStat.st_mode & S_IROTH) ? "r" : "-");
    printf( (fileStat.st_mode & S_IWOTH) ? "w" : "-");
    printf( (fileStat.st_mode & S_IXOTH) ? "x" : "-");
    printf("\n\n");

    printf("The file %s a symbolic link\n", (S_ISLNK(fileStat.st_mode)) ? "is" : "is not");

    return 0;
}
```

The result of above is:

```
$ ./testProgram testfile.sh

Information for testfile.sh
---------------------------
File Size:              36 bytes
Number of Links:        1
File inode:             180055
File Permissions:       -rwxr-xr-x

The file is not a symbolic link
```

- `unlink` (removing file)
  - Is a system call
  - Removes a file (including symbolic link) from the system
  - **Syntax:** `int unlink(const char *pathname)`
    - `pathname` - path to file
  - Returns 0 if successful
  - Returns -1 if error

Example

```
#include <unistd.h>


char *path = "/modules/pass1";
int   status;
...
status = unlink(path);
```

- `mkdir` (creating directory)
  - Is a system call
  - **Syntax:** `int mkdir(const char *path, mode_t mode)`
    - `path` - path of directory (including name)
    - `mode` - permission group
  - Returns 0 if successful
  - Returns -1 if error
  - directories can never be written directly
    - directory is in format called **File System Metadata**
    - directory can only be updated directly
  - creates two directories on creation `.` (current) and `..` (parent)

Example

```
#include <sys/types.h>
#include <sys/stat.h>


int status;
...
status = mkdir("/home/cnd/mod1", S_IRWXU | S_IRWXG | S_IROTH | S_IXOTH);
```

- `opendir, readdir, closedir` (reading directory)
  - Are system calls
  - Are under <`dirent.h`> library
  - Requires `struct dirent` data structure

```
struct dirent {
  char           d_name[256]; // filename
  ino_t          d_ino;       // inode number
  off_t          d_off;       // offset to the next dirent
  unsigned short d_reclen;    // length of this record
  unsigned char  d_type;      // type of file
};
```

  - **Syntax (opendir):** `DIR *opendir(const char *dirname)`
    - `dirname` - directory path
    - Returns a pointer to the directory stream
    - The stream is positioned at the first entry in the directory.
  - **Syntax (readdir):** `struct dirent *readdir(DIR *dirp);`
    - `dirp` - directory stream
    - Returns a pointer to a dirent structure representing the next directory entry in the directory stream
    - Returns NULL on reaching the end of the directory stream
  - **Syntax (closedir):** `int closedir(DIR *dirp));`
    - `dirp` - directory stream
    - Returns 0 if successful
    - Returns -1 otherwise

  Example

```
int main(int argc, char *argv[]) {
    DIR *dp = opendir(".");
    assert(dp != NULL);
    struct dirent *d;
    while ((d = readdir(dp)) != NULL) {
        printf("%lu %s\n", (unsigned long) d->d_ino,
                d->d_name);
    }
    closedir(dp);
    return 0;
}
```

- rmdir (Deleting Directories)
  - Removes a directory whose name is given by path
  - Is performed only when directory is empty
  - Is included in `<unistd.h>` library
  - Fails if is symbolic link
  - **Syntax:** `int rmdir(const char *path)`
    - `path` - path of directory
  - Returns 0 if successful
  - Returns -1 if error

Example

```
#include <unistd.h>

int status;
...
status = rmdir("/home/cnd/mod1");
```

- `unlink` (Remove file)
  - Remove a link to a file
  - Is called **unlink** because it decrements **reference count** in inode
    - Deletes file completely when reference count within the inode number is 0
  - **Syntax:**

    ```
    #include <unistd.h>

    int unlink(const char *pathname);
    ```

    - `pathname` - pathname to file
  - Returns 0 if successful
  - Returns -1 if error
  - Is used by linux command `rm`

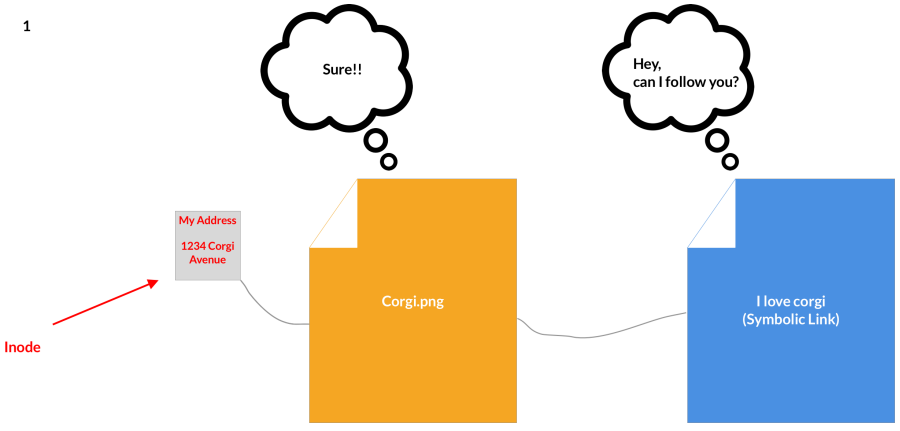
Example

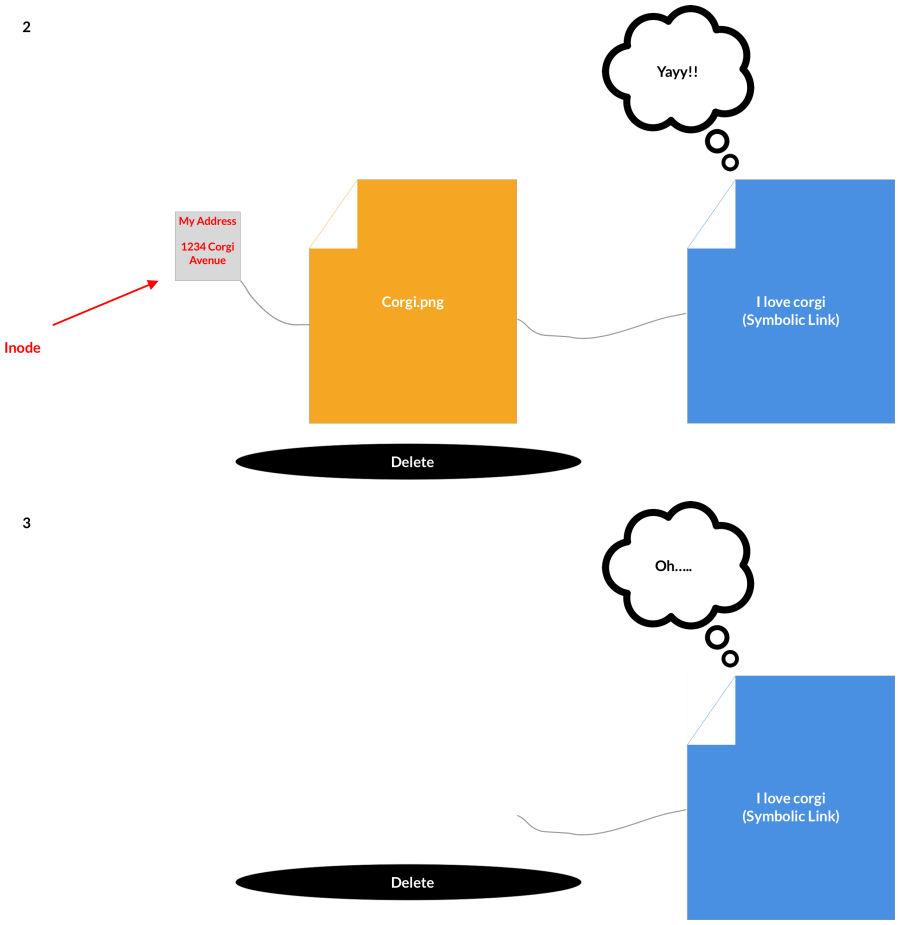
```
#include <unistd.h>


char *path = "/modules/pass1";
int   status;
...
status = unlink(path);
```

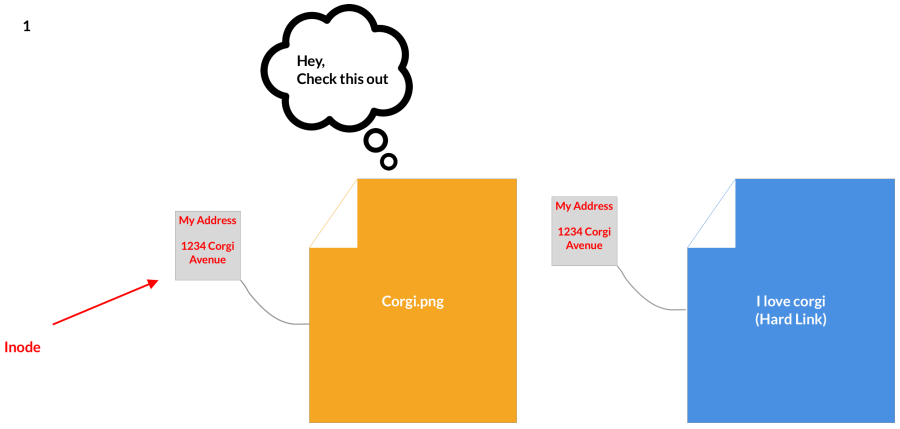
```
prompt> echo hello > file
prompt> stat file
... Inode: 67158084    Links: 1 ...
prompt> ln file file2
prompt> stat file
... Inode: 67158084    Links: 2 ...
prompt> stat file2
... Inode: 67158084    Links: 2 ...
prompt> ln file2 file3
prompt> stat file
... Inode: 67158084    Links: 3 ...
prompt> rm file
prompt> stat file2
... Inode: 67158084    Links: 2 ...
prompt> rm file2
prompt> stat file3
... Inode: 67158084    Links: 1 ...
prompt> rm file3
```

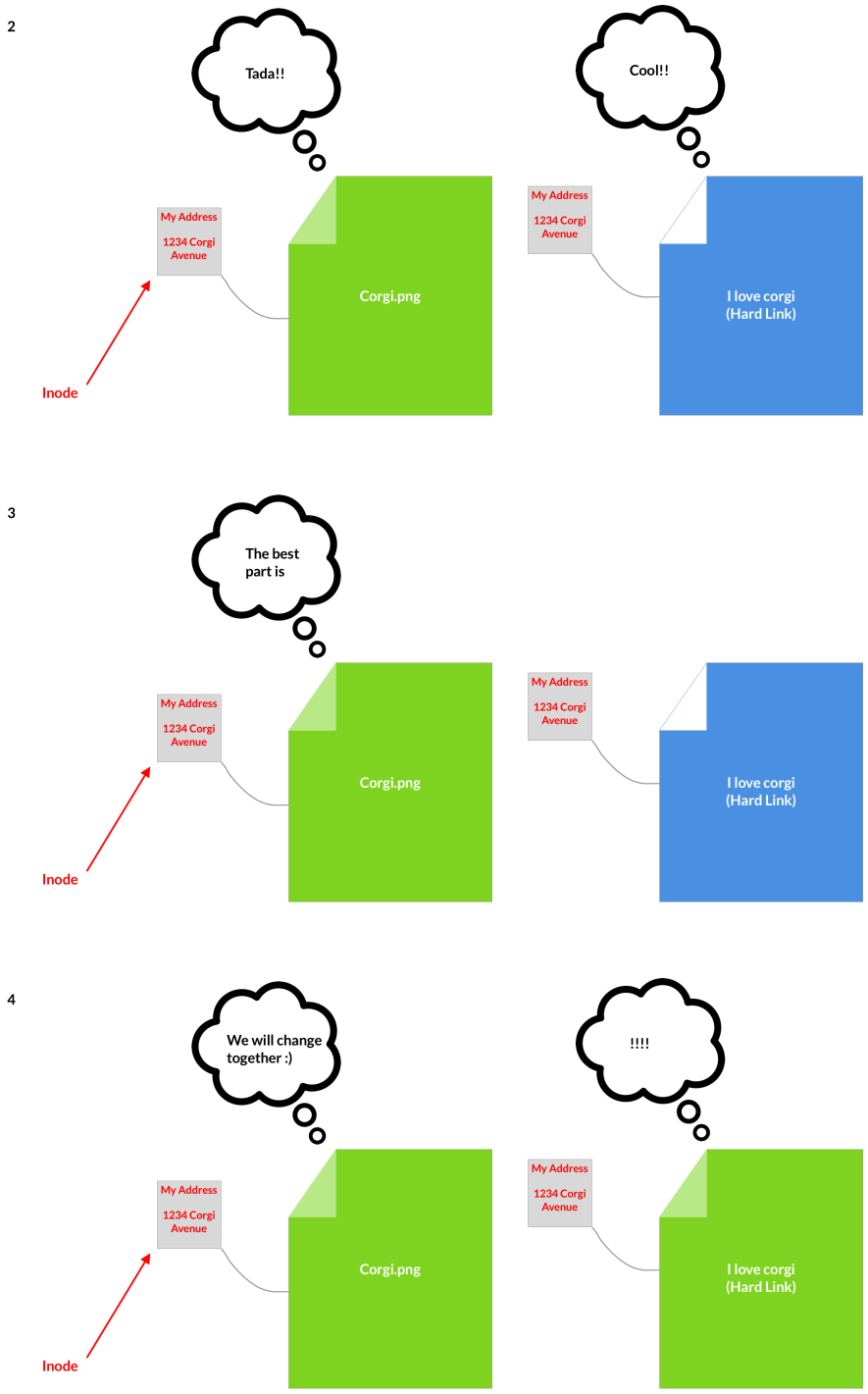
- **Symbolic Link:**
  - Is directory entry containing "true" path to the file
  - Is a shortcut that reference to a file instead of inode value [2]



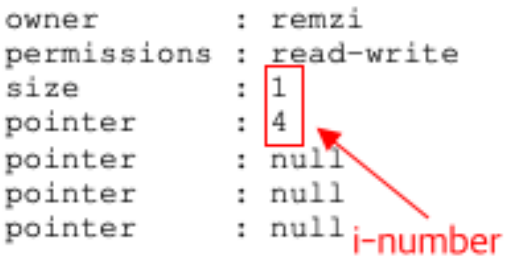


- **Hard Link:**
  - Is a direct reference to a file via its inode [2]
  - Is second directory entry identical to first

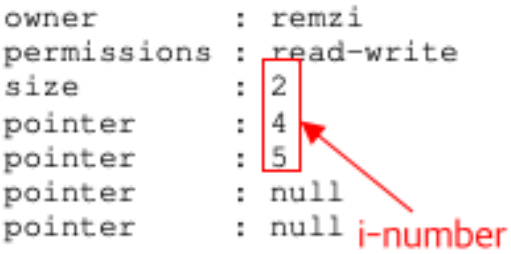




- **Crash Consistency**
  - Inode before update



– Inode after update



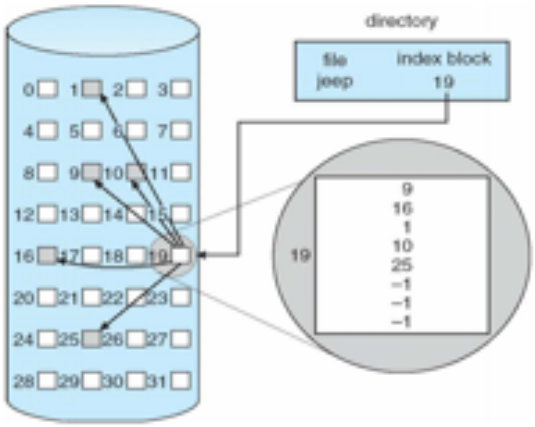
References

1) codewiki, stat, link
2) The Open Group Base Specification, unlink, link

e) a)

Notes

- What is a sector? What is a sector address?
- How can I get to specific inode from block (e.g inode # 32 on block 2)?
- **Index Based File System**

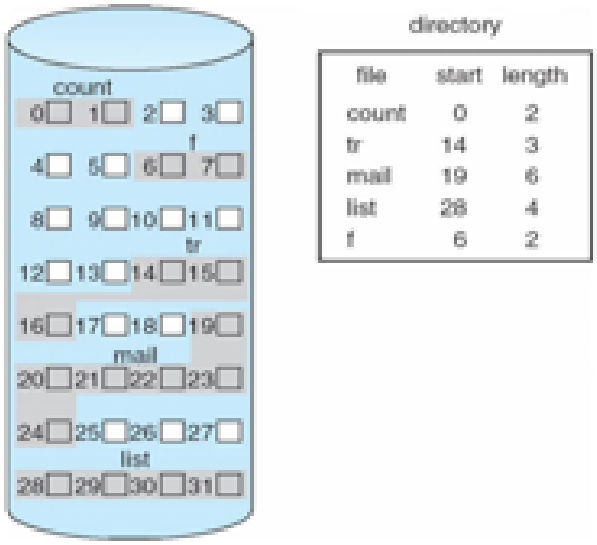


- Has 15 blocks of pointers that points to either inode, indirect pointers, or data block
- No external fragmentation
- Files can be easily grown

Example

Linux's ext2, ext3

- **Extent Based File System**



- Requires only a disk pointer + length (in blocks)
- Is also called **contiguous allocation**
- Is simple
- Is less flexible but more compact
- Works well when there is enough free space on the disk and files can be laid out contiguously

Example

Linux's ext 4

- **inode**
  - Inode block computation

$$\texttt{block number} = (\texttt{inode \# * sizeof(inode)})/\texttt{block size} \quad (1)$$

Example

Target: inode #32
Inode Size: 256 bytes
Block Size: 4096 bytes

$$\begin{aligned} \texttt{block number} &= (\texttt{inode \# * sizeof(inode)})/\texttt{block size} && (2)\\ &= \frac{32 * 256}{4096} && (3)\\ &= 2 && (4) \end{aligned}$$

- **superblock**
  - Contains information about the following
    - The number of inodes and data blocks in a particular file system
    - The magic number of some knd to identify the file system type
    - Where the inode table begins
  - Is read first on mount before attaching to file system
- **inode/data bitmap**
  - Accessed only when allocation/deallocation is needed
    - `Read()` $\rightarrow$ no bitmap required
  - Uses bit to indicate whether the corres object/block is free
    - 0 means free
    - 1 means in use
- **Reading a File from Disk**
  Example

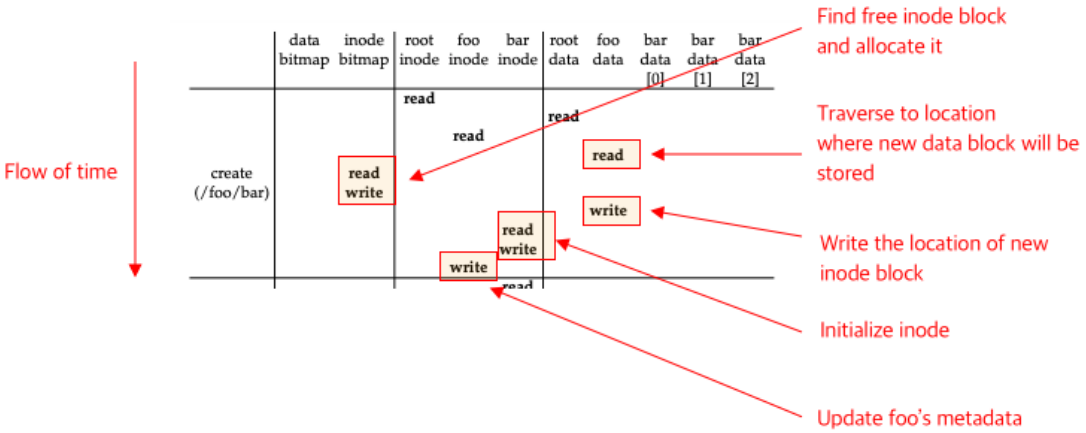
  When

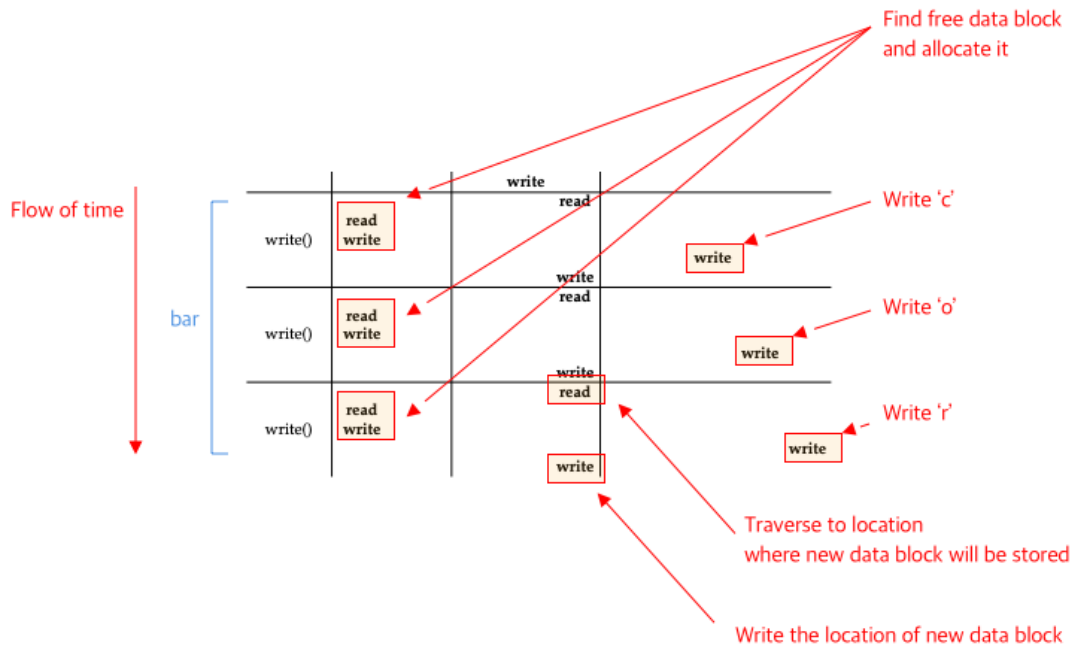
  ```
  open("/foo/bar", O_READONLY)
  ```

  is called

- the goal is to find the inode of the file `bar` to read its basic information (i.e. includes permission, information, file size etc)
- done by traversing the pathname and locate the desired inode
- Steps
  1. Find **inode** of the root directory by looking for **i-number** (or **inode number**)
     * Root directory has no parent directory
     * Root directory's **inode number** is 2 (for UNIX file systems)
  2. Read the **inode** of root directory
  3. Once its **inode** is read, read through its directory data (pointers to **data blocks**) until the inode number of `foo` is found (e.g 42)
  4. Recursively traverse the pathname until the desired inode is found (more specifically, the **inode number** of bar)
  5. Issue a `open()` to read `bar`'s inode to memory
  6. Issue a `read()` system call to read from file `bar`
     * without `lseek()`, reads file from the first file data block (e.g. `bar data[0]`)
     * `lseek(..., offset_amt * size_of_file_block)` is used to offset/move to desired block in `bar`
  7. Trasnfer data to `buf` data block
  8. Read until `read()` returns 0, or desired data block has been read
  9. Close `fd`. No I/O is read.

- **Writing to Disk**





Given a call

`create(...)` (Note: `open` to be exact)

- 5 I/Os are generated per write
  - Read inode (to traverse to the location of new data block)
  - Reading data bitmap
  - Writing data bitmap
  - Write data block
  - Write inode (to update data block's location in inode)
- 10 I/Os are generated per file creation:
  - Read inode bitmap (to find free inode)
  - Write inode bitmap (to mark it allocated)
  - Create one new inode (to initialize it)
  - Write the location of new inode block in `foo` (by linking high-level name of file `bar` to its inode number and storing in data block)
  - Perform one read and write to the directory inode and update it

- **Static Partitioning**
  - Divides resources into fixed proportion
  - Advantages
    - Ensures each user receives some share of the resource
    - Delivers more predictable performance (usually)

    * Easier to implement
- **Dynamic Partitioning**
  - Gives out different amounts of resources over time
  - Lets resource-hungry users consume idle resources
  - Advantages
    * Flexible
    * Can achieve better utilization than **static partitioning**
  - Disadvantages
    * More complex to implement
    * Could lead to worse performance
      · e.g idle resource got consumed by others and take long time to reclaim it when needed (the perodic frozen feeling when loading screen)

References

1) Columbia University, Operating Systems, link