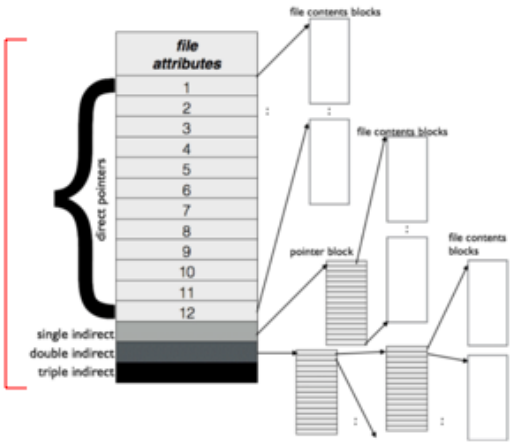
1. a) 1) 4 - inode blocks. 1 for the file `c`, and 3 for the directdories `/`, `a`, `b`
   2) 3 - directory blocks - one for root `/`, one for `a`, the other for `b`
   3) 1 - single indirect block as far as we know. The file definitely has more than 12 blocks (# of data blocks pointed by direct pounters),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

2. (a) 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

(b) 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

(c)
- **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
```

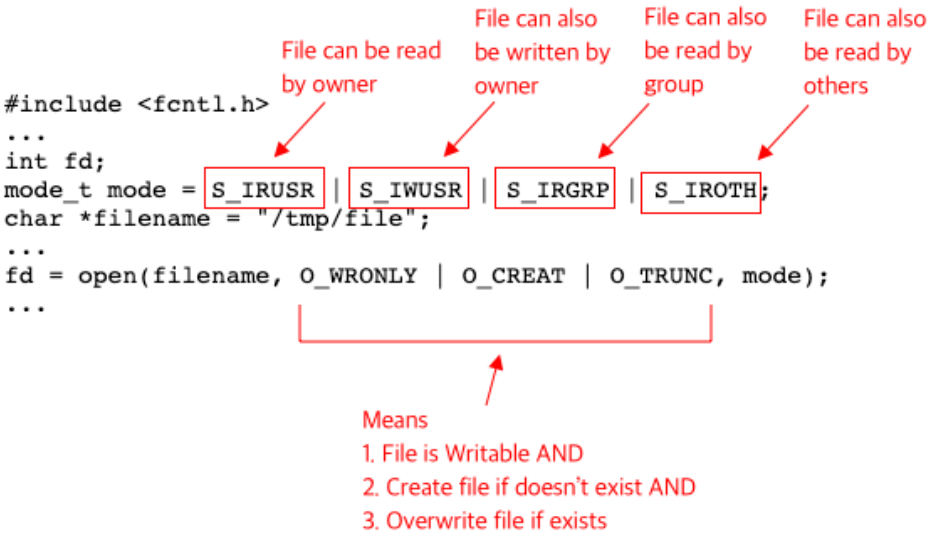
Notes

- 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:**

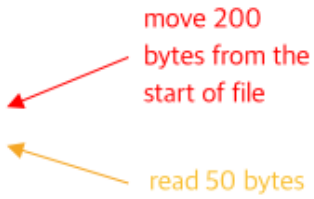
    ```
    off_t lseek (int fd, off_t offset, int whence)
    ```

    - `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

System Calls	Return Code	Current Offset
`fd = open("file", O_RDONLY);`	3	0
`lseek(fd, 200, SEEK_SET);`	200	200
`read(fd, buffer, 50);`	50	250
`close(fd);`	0	–



- `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

```
int fd = open("foo.txt.tmp", O_WRONLY|O_CREAT|O_TRUNC,
              S_IRUSR|S_IWUSR);
write(fd, buffer, size); // write out new version of file
fsync(fd);
close(fd);
rename("foo.txt.tmp", "foo.txt");
```

e.g. "hello\n"

- `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`

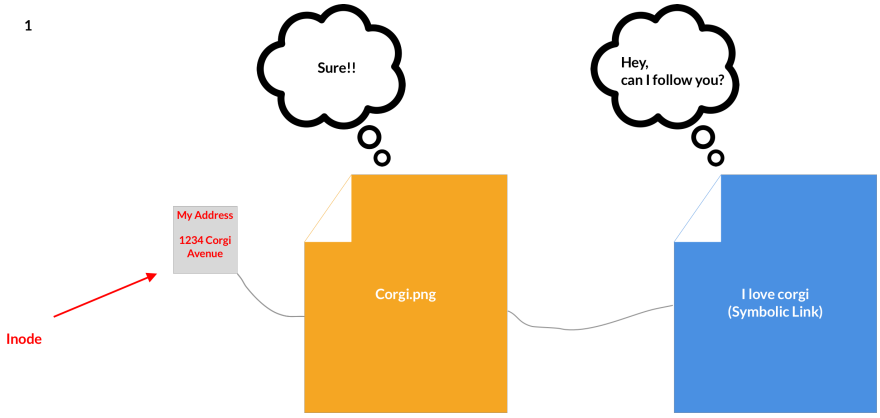
Example

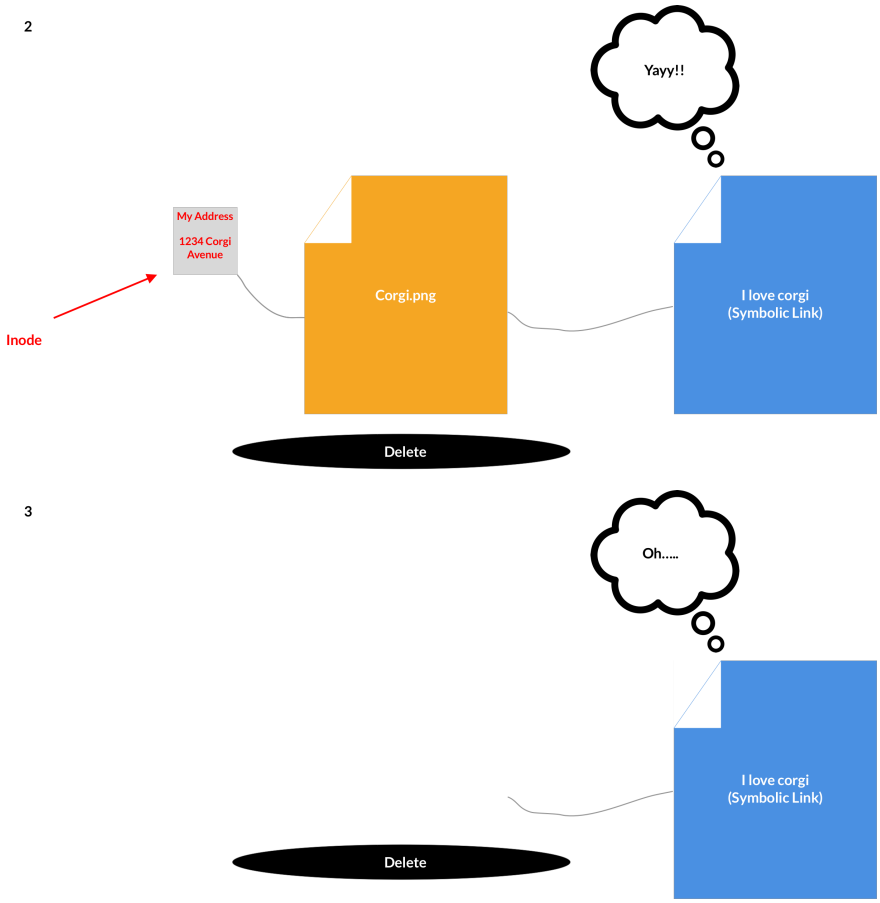
```
#include <unistd.h>

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

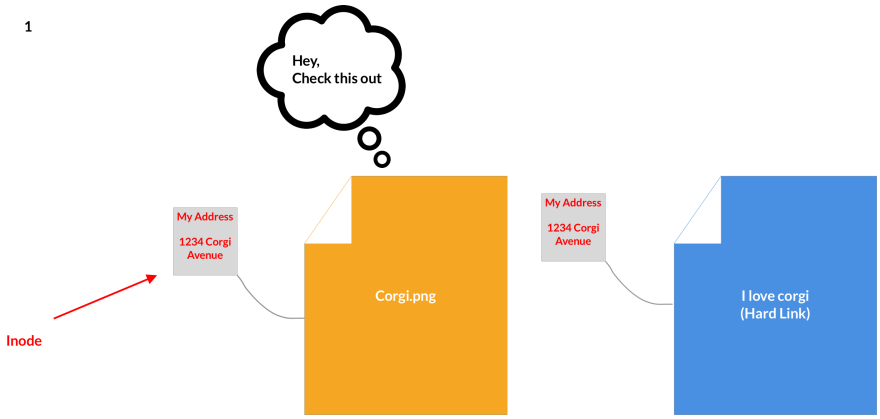
```
prompt> echo hello > file
prompt> stat file
... Inode: 67158084    Links: 1 ...
prompt> ln file file2
prompt> stat file
... Inode: 67158084    Links: 2 ...
prompt> stat file2
... Inode: 67158084    Links: 2 ...
prompt> ln file2 file3
prompt> stat file
... Inode: 67158084    Links: 3 ...
prompt> rm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

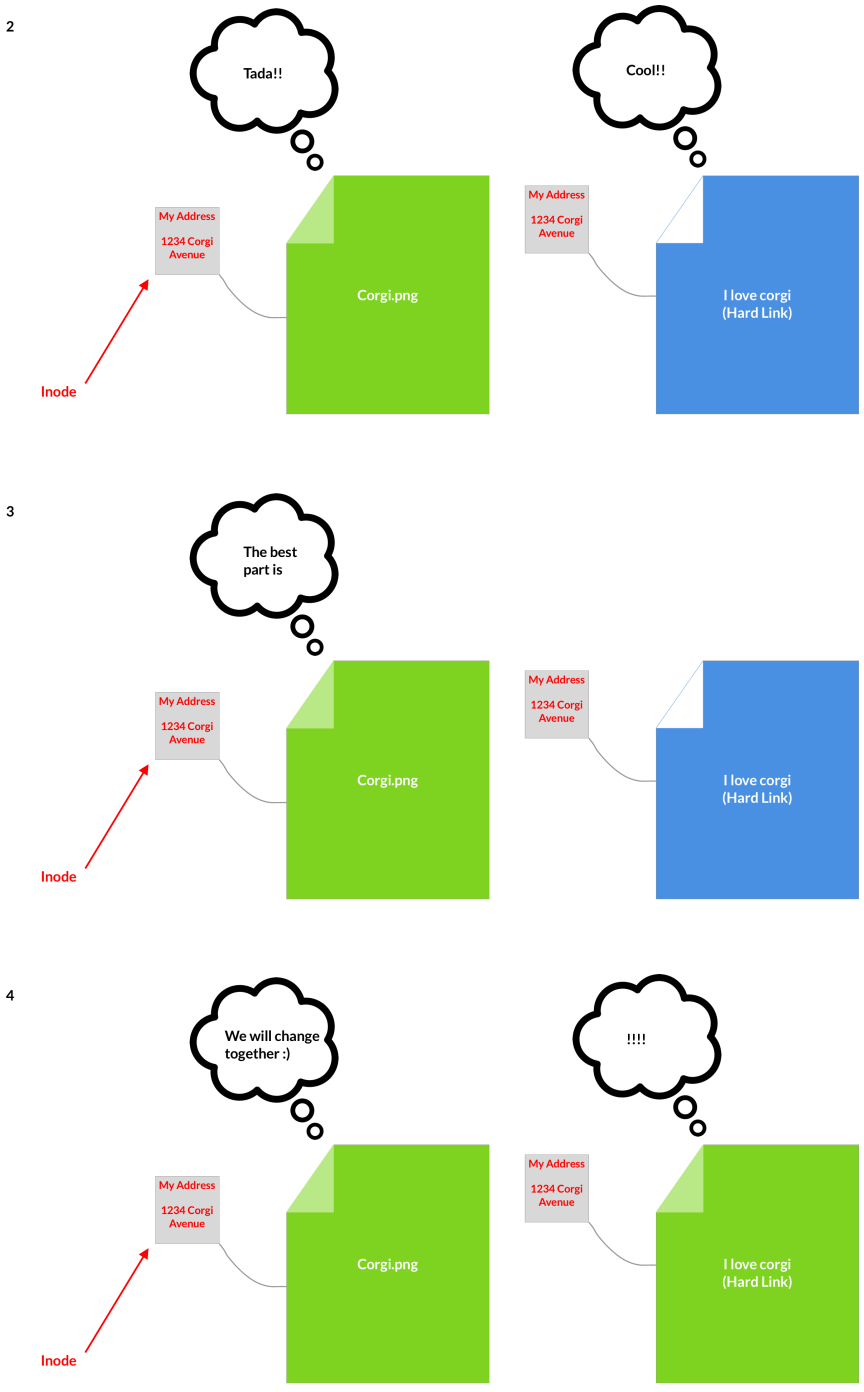
- **Symbolic Link:**
  - Is directory entry containing "true" path to the file
  - Is a shortcut that reference to a file instead of inode value [2]



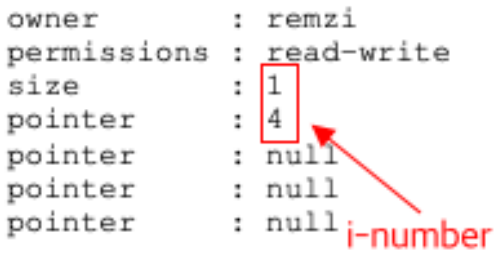


- **Hard Link:**
  - Is a direct reference to a file via its inode [2]
  - Is second directory entry identical to first

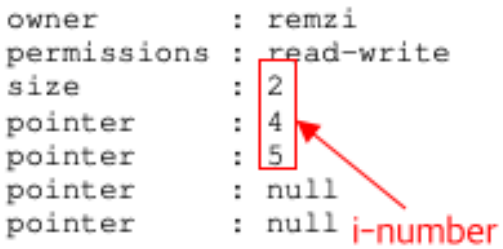




- **Crash Consistency**
  - Inode before update



– Inode after update



References

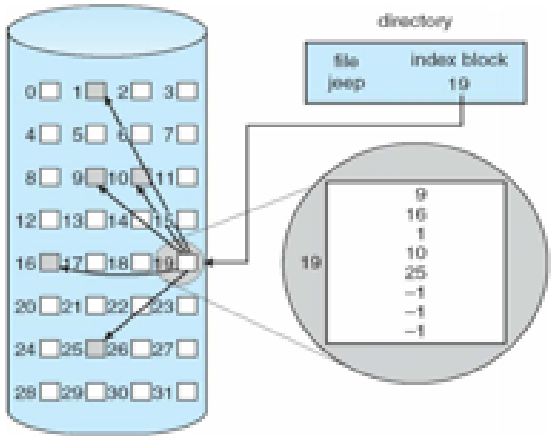
1) codewiki, stat, link
2) The Open Group Base Specification, unlink, link

3. a) Indexed-based file system uses inode number and pointers to find data blocks, and data blocks can be set and anywhere, so external fragmentation isn't a problem

   b) Extent based file system only requires a pointer to first data block of file, and the rest is read by traveling contiguously, and this requires less disk block access than index-based file system of which has to go to inode block, indirect pointers and data blocks to go to a particular byte in file.

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)?
- I should record differences between linked-list-based FS, Extent-based FS, and indexed FS
- **Index Based File System**

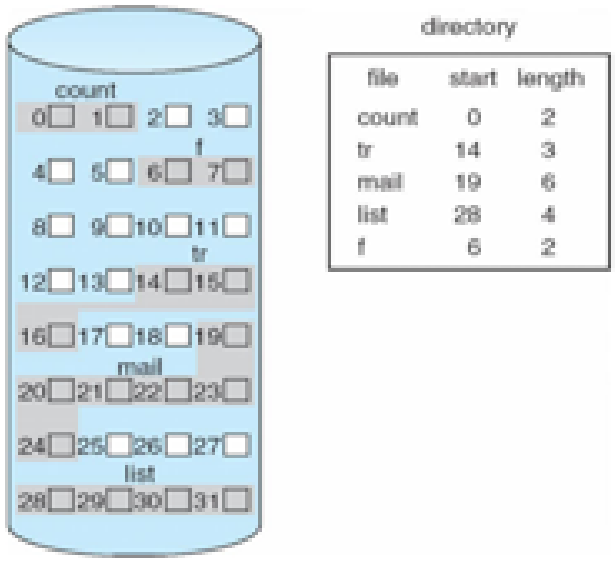


- Has 15 blocks of pointers that points to either inode, indirect pointers, or data block
- No external fragmentation
- Files can be easily grown

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

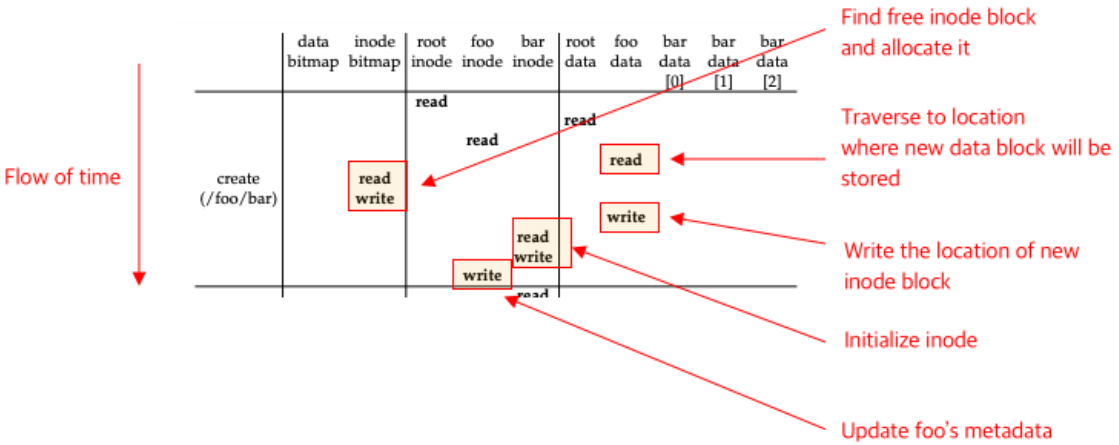
  When

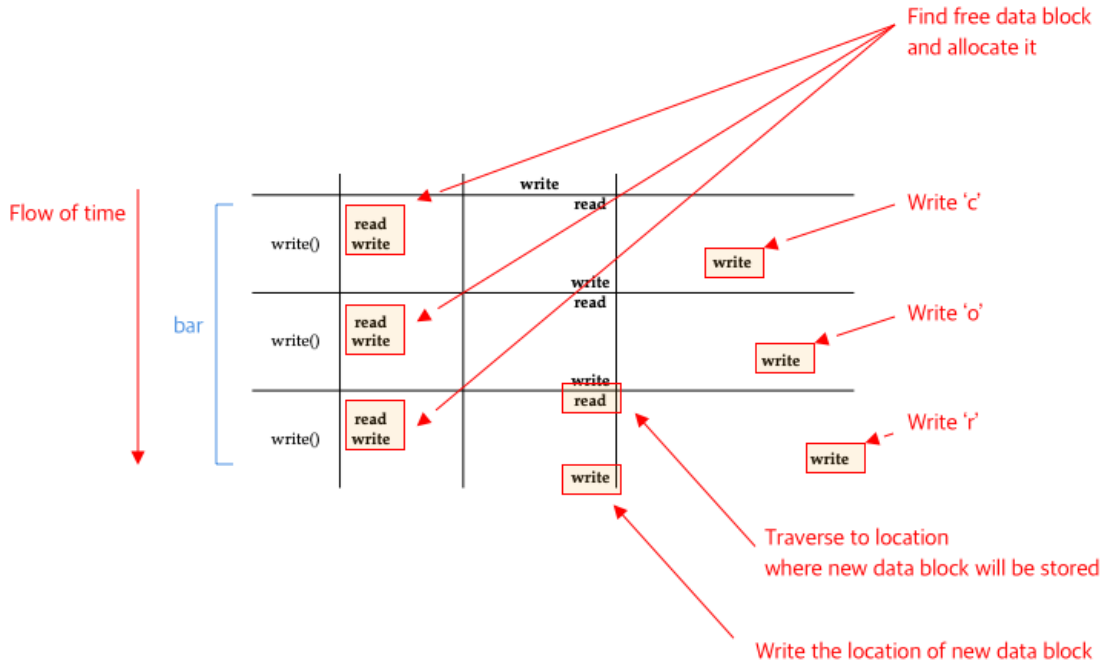
`open("/foo/bar", O_READONLY)`

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 <u>once</u>
    - e.g. two possible users of memory → give fraction of memory to one user and rest to the other

  - Advantages
    * Ensures each user receives some share of the resource
    * Delivers more predictable performance (usually)
    * Easier to implement
  - Disadvantages
    * Is wasteful
    *

- **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

4. 1) i) all of the above

   ii) To minimize damage, it should be updated in order of
   `Data Region-Inode Table-`
   1. Data Region
   2. Inode Table
   3. Data Bitmap
   4. Inode Bitmap

   The reason is that when data block and/or inode block are set and crash happens, the file system treats as if nothing had happened.

   And the reason is that before data/inode block is allocated, it first checks the inode and data bitmap, which contains information about whether the block is occupied or not.

   Once they are allocated, we risk data/inode leak, and if done improperly, the data/inode block would not be available until actions are taken.