Files and Filesystems

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Filesystems (FS)

- A disk (CD-ROM, flash-drive etc.) is a linear sequence of fixed-size blocks and supporting reading and writing of blocks.
- The user/application views the disk in terms of directories and files.
  - How do you implement a file?
  - How do you implement a directory?
  - How do you find information?
  - How do you keep one user from reading another's data?
  - How do you know which blocks are free?

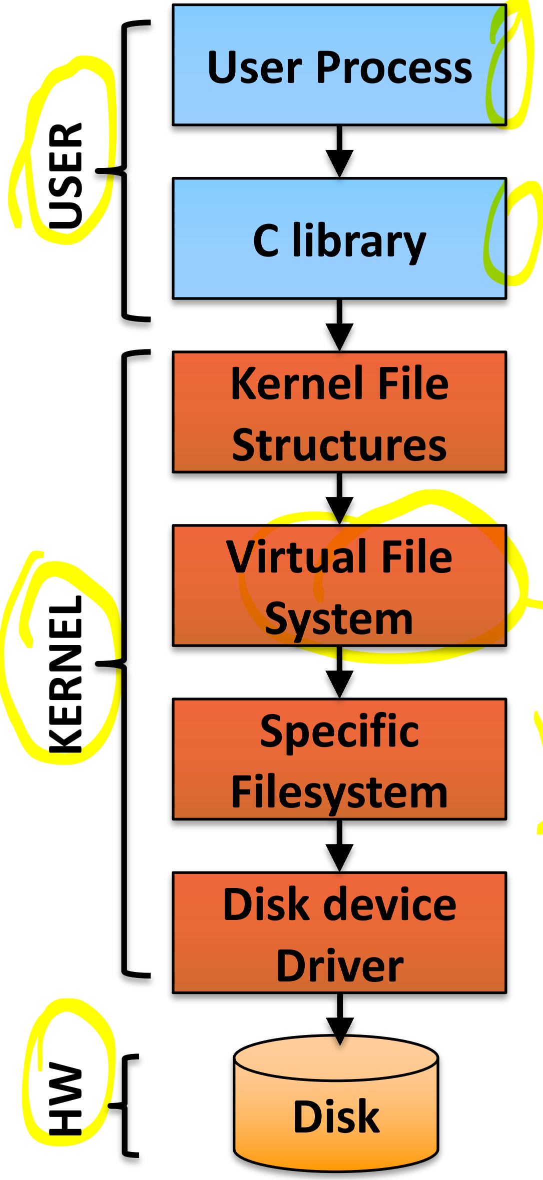
Filesystem as a structure

- A filesystem is
  - essentially a data structure designed for secondary storage.
  - that keeps allocation information in same storage, as well as
  - extra information about files;
  - such as security, access right, timestamps, etc.
- Moreover;
  - support storage of large amount of data
  - Data should persist after termination
  - Concurrently accessible, keeping integrity of data

Filesystem as abstraction

- Provide an abstraction over block based raw data access on storage devices. A filesystem is essentially built around
  - The concept of a file
  - The concept of directory - essentially a specific type of file
  -
- Mask the details of low-level sector-based I/O operations
  - Actual I/O: fragmented, distributed blocks on different areas of storage.
- Caches recently-accessed data in memory

Filesystem abstraction levels



Library calls: `fopen()`, `fseek()`, `fread()`

System calls: `open()`, `lseek()`, `read()`

`struct file`, `struct inode`, `struct vnode`

FS specific calls: `fat_lookup`, `fat_open`, `fat_read`

Device driver calls: `dev_open`, `dev_read`

Low level I/O instructions (e.g. SCSI protocol)

File operations - 1

- Standard operations:
  - Write, Read – often via position pointer
  - Seek – adjust position pointer for next access
  - Truncate - Trim some data from end of file (common case: all data)
  - Append – write at the end of file
- Directory based:
  - Create – locate space, enter into directory
  - Delete – remove from directory, release space
  - Rename - Change name of file inside a directory
  - Move a file between two directories

File operations - 2

- Change attributes:
  - Change owner,
  - permissions,
  - type,
  - timestamps
- Extra operations:
  - Lock file/regions,
  - map to memory

Filesystem Design - Issues and constraints

- **Design issues:**
  - **File to block mapping**
  - **Metadata representation (attributes)**
  - **Directory organization**
  - **Free block management**
- **Design constraints:**
  - **Storage media constraints: read-only, once writable, block size. (DVD, Flash disk, Hard disk, RAM disk)**
  - **Size constraints: 1.4MB vs Petabytes**
  - **Storage organization: single disk, multiple disks, cluster of disks, network accessed storage**

A FS should also support..

- Integrity of data (after a reboot, or power-off)
- Efficient file operations that minimize overhead and delays.
- Minimize fragmentation
- Maximize the maximum size for files on a disk.
- Recovery, repair facilities.
- Dynamic grow/shrink/change of storage.
- Snapshots and versioning.
  - Some filesystems, such as MacOS time machine, Solaris zfs, support rollback to a past state
- Accounting and quota support
- Indexing and search
- Encryption
- Automatic compression of infrequently used files

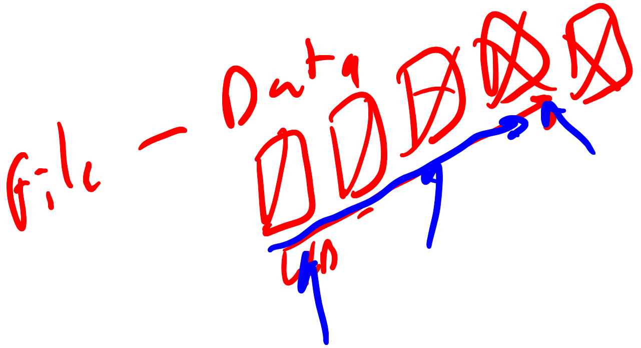
File Concept

File → Data
→ Attributes – Name
Perm
Loc

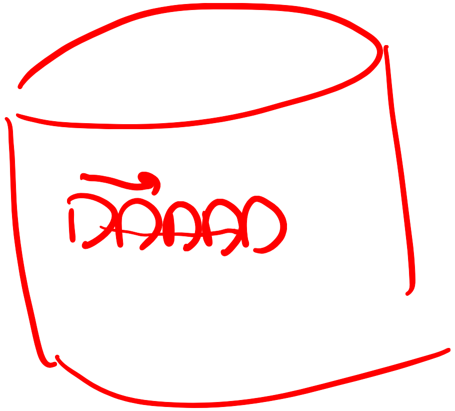
- From the user point of view, file is the only unit through which data can be written onto storage devices.
- File is a logical storage unit abstraction.
  - Hide details of storage devices
    - sector addressing/ SCSI vs. IDE
  - Hide details of allocation/location on a storage device
- The information in a file as well as the attributes of the file is determined by its creator.
  - Data: Numeric/character/binary
  - Program

When a file is created, it becomes independent of the process, the user and even the system that created it.

File Block Management



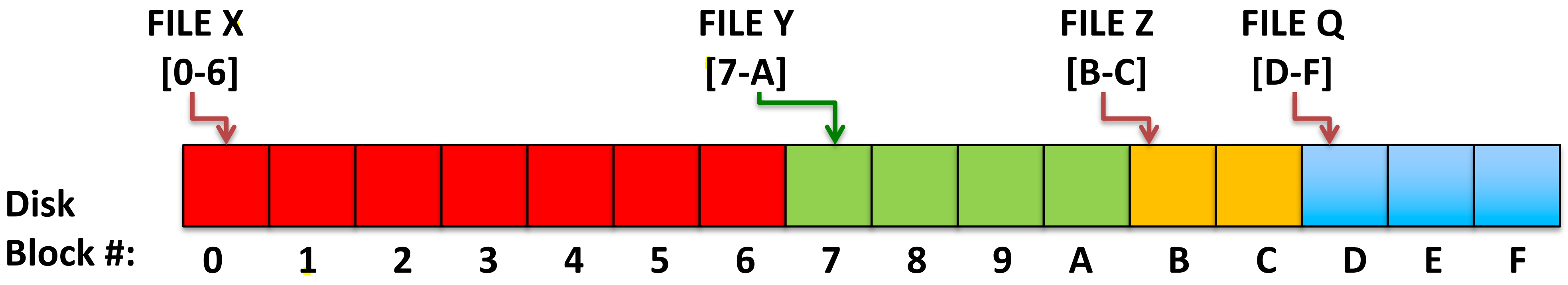
- Files are “logically continuous” storage regions.
  - However, actual data blocks may or may not be distributed in different regions of disk.
  - They can grow, shrink, or be deleted.
- File blocks can be accessed
  - sequentially (text files) or
  - randomly (indexed files)
- File -> Block Allocation
  - Contiguous allocation
  - Linked-list allocation
  - File Allocation table
  - Indexed allocation



Note that spatial locality of files, keeping blocks of the file consecutive on disk, has advantages in some storage types, such as hard disks.

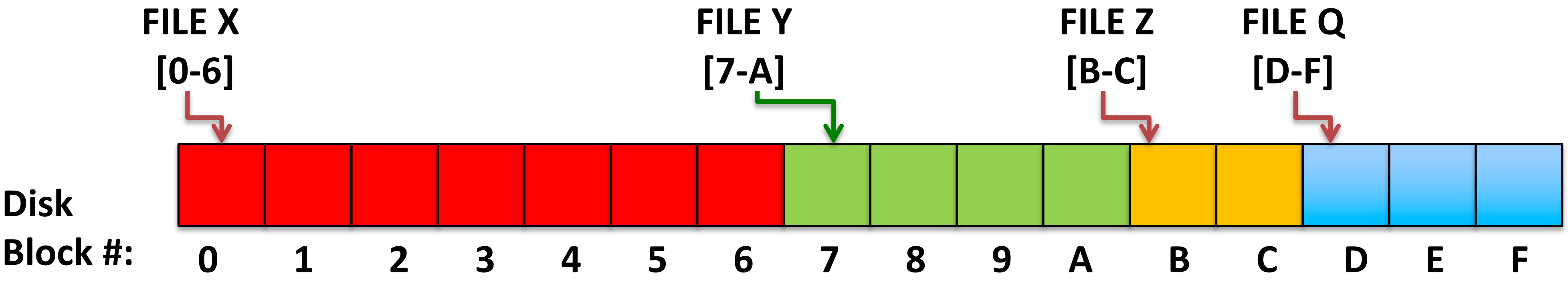
File->Block: Contiguous Allocation

- File data is stored in contiguous blocks on the disk



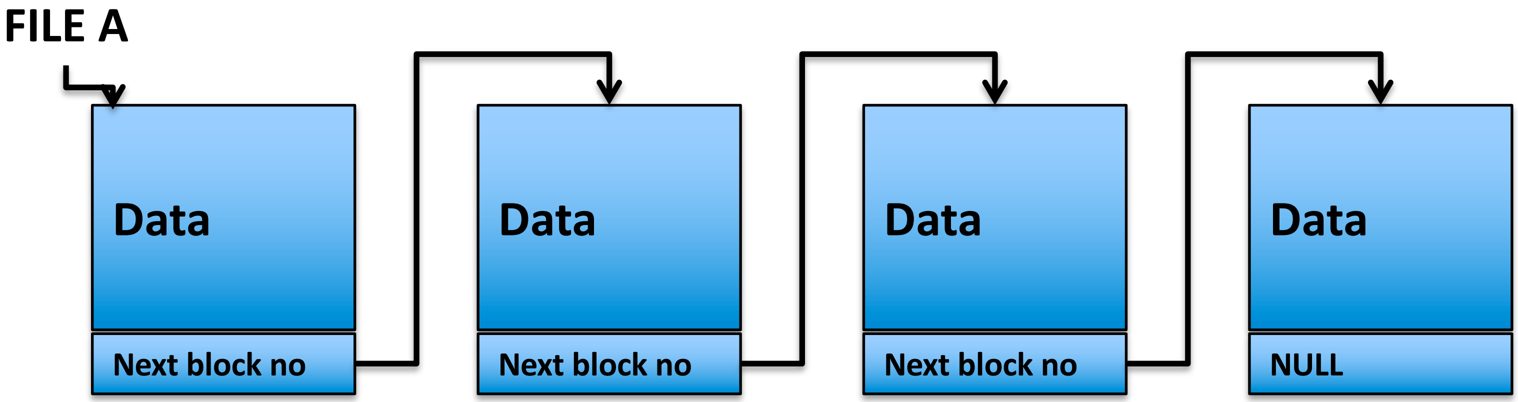
File->Block: Contiguous Allocation

- Harder to manage. Avoiding external fragmentation is a challenge.
- For main memory: buddy system, free lists of various sizes are used.
- Harder problem for slower devices like disks.
- File growth is harder to control.
  - Size is not known in advance.
  - File grows in increments of blocks, not like memory (first allocate and fill later).
- Fixed size allocation, easier to implement.
- Fast sequential access



File->Block: Linked list allocation

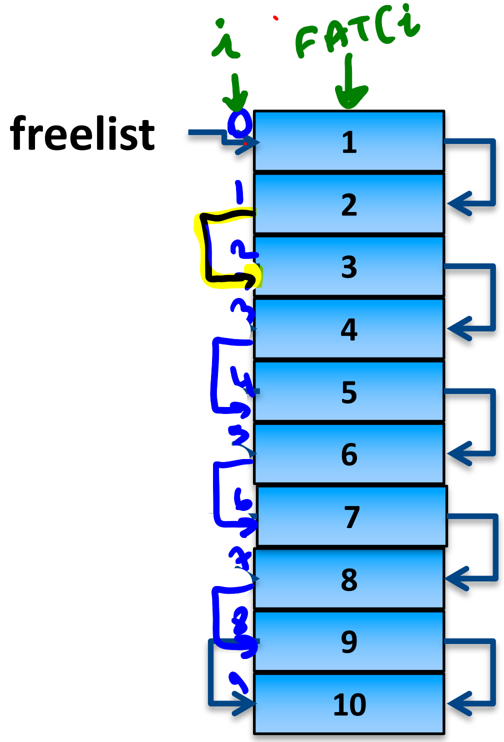
Link information part of data block:



- 4096 byte block 4092 bytes data, 4 bytes next. 4092 as block size?
- Traversing link chain requires full read/write block.
- Cache does not help much since data blocks are large in total.

File->Block: File Allocation Table (FAT)

- Free list and file chain is separated.
- FAT, a table of next page pointers.
- FAT[i] corresponds to data block i.

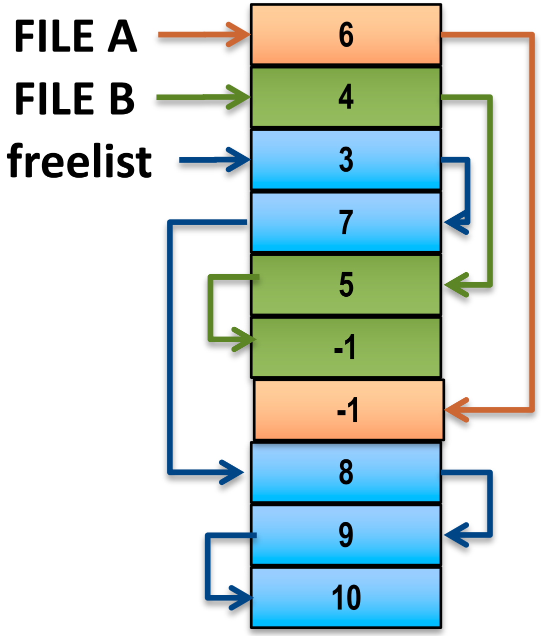


Initial condition:

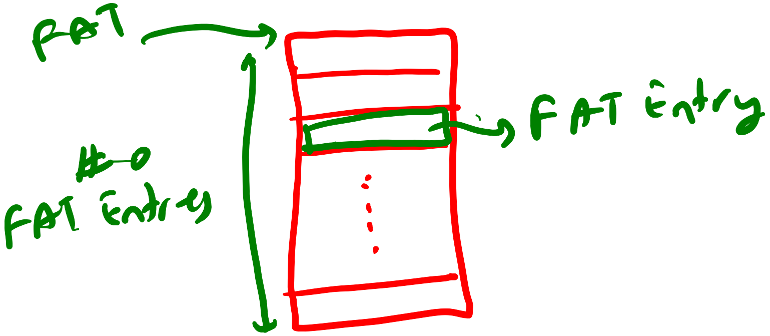
- all pages are free, free list starts at 0.

After a while:

- Free list starts at 2. 2, 3, 7, 8, 9, 10,… are free
- File A is at data blocks 0 and 6
- File B is at data blocks 1, 4 and 5
- -1 denotes termination.



FAT



Block size: 4KB $= 2^{12}$ bytes

Disk size $= 4$TB $= 2^{42}$ bytes

$\Rightarrow$ # of blocks $= 2^{42}/2^{12} = 2^{30}$

$\Rightarrow$ Block id $= 30$ bits $\Rightarrow$ 4 bytes

FAT Entry size = 4 bytes

# of FAT Entries $= 2^{30}$

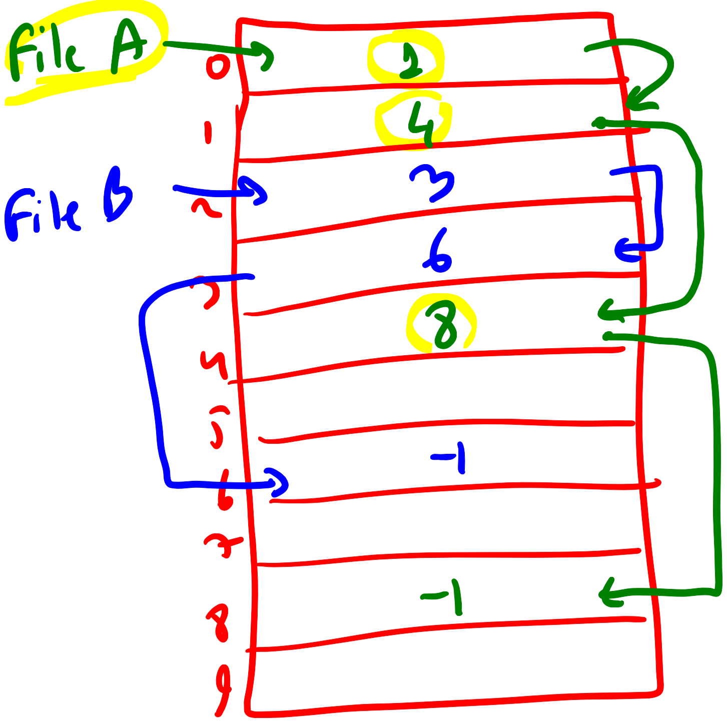
FAT size $= 2^{30} \cdot 4 = 2^{32} = 4$ GByte

- **FAT requires a pointer for each data block:**
- **Size/Block size * Pointer size**
- **i.e. 4TB disk with 4K blocks:**
- **4TB/4K*4 bytes = 4GBytes**
- **Large but also keeps file to data mapping. Increase block size to make it smaller → internal fragmentation.**
- **Typical operations:**
  - Finding a free page: Just use the first page in free list. Constant time
  - Marking a page free or allocated: Add or remove from the chain. A number update.
  - Contiguous allocation is difficult, List may contain block size too however block id to FAT entry mapping is lost.
- **Relies on caching as well. Only efficient when FAT blocks are cached.**

FAT: File to Block Mapping

- Each file is a sub-list in FAT.
- Sequential access = link list sequential traversal
- Direct access to nth block? Linear scan of list n times.
- Only feasible when FAT is in main memory

	first disk block
File A	0
File B	2

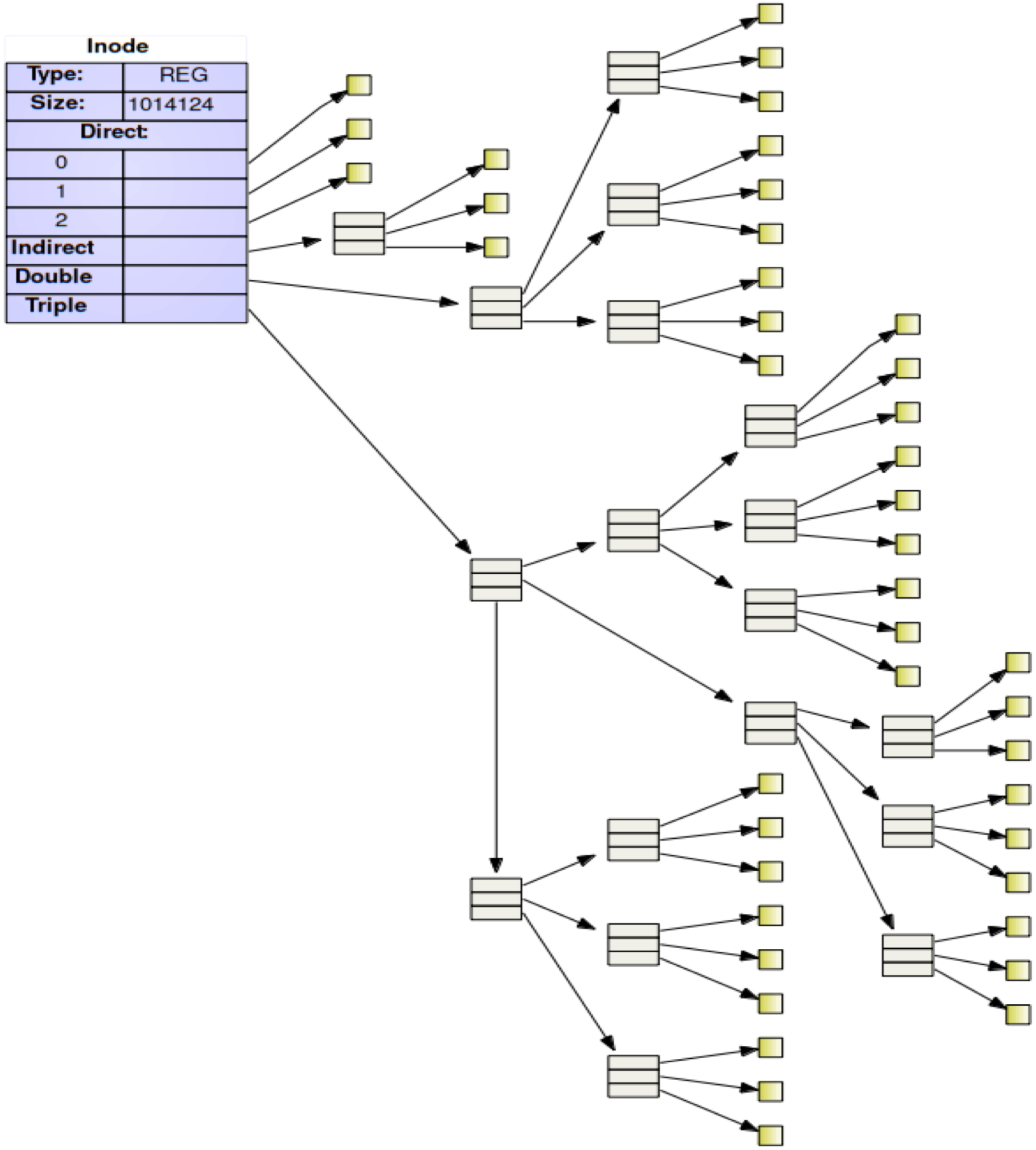


File->Block: Indexed Mapping

- Keep an index of data blocks per file.
- Unix/Linux: keep a tree of block pointers in i-node (index block)
- NTFS: kept in a database area together with other file attributes.
- Random access requires given file and offset return data address quick.
- XFS, reiserfs uses a B+ tree for file,offset to data block mapping.

File->Block: Indexed Mapping

- For small data, direct blocks are used
- An indirect block contains an array of data block pointers
- If file is larger, double indirect block contains array of pointers to indirect blocks
- For larger files, triple indirect pointers contains pointers to double indirect pointers

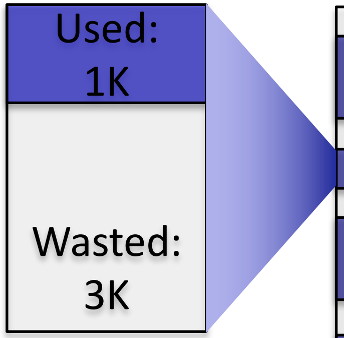


Fragmentation

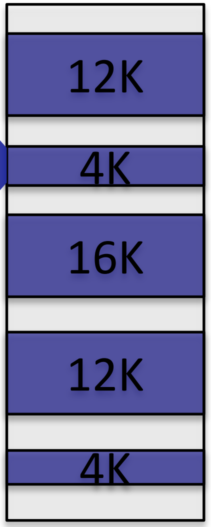
- Unused and useless areas on disk causing bad utilization.
- Internal Fragmentation: Unused space within allocated blocks. Small unused areas when required area is smaller than the block size.
- External Fragmentation: Unused space between allocated blocks. No useful contiguous area left on disk whereas the total amount of free area is large.

Internal fragmentation

%75 of the block wasted

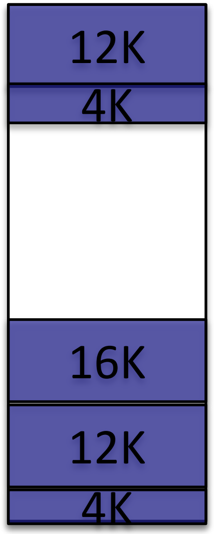


Block size: 4K



Physical Memory

External fragmentation
24K free but no contiguous free area larger than 8K.



Physical Memory

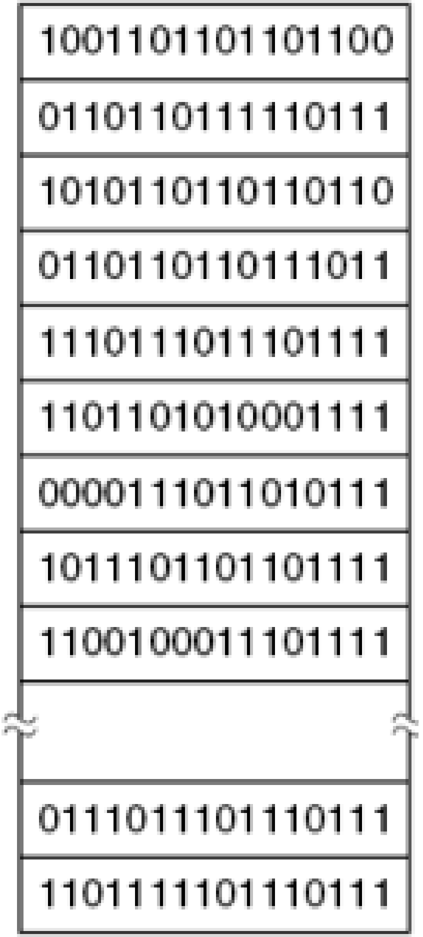
No External fragmentation,
A large contiguous area is free.

Block/Cluster Size

- **Block size affects and is affected by:**
  - Storage device native block size. (no smaller read, smaller writes require, read, update in mem, write)
  - VM page size (caching)
- **Filesystems may choose a cluster of blocks as unit to support larger disks and file sizes.**
  - **Large cluster size → Internal fragmentation**
  - **Small cluster size bad → locality.**

Free Block Management: Bitmaps

- Free block bitmaps
- Each block needs a single bit of information 0 for free, 1 for in use.
- Very compact. TotSize/BlockSize/8 bytes
- For 4TBytes with 4K blocks → 128MBytes
- Typical operations:
  - Finding a free page: May require a full scan of the bitmap in the worst case
  - Marking a page free or allocated: A complete block needs to be read and written.
  - Contiguous allocation requires full scan of bitmaps in the worst case.

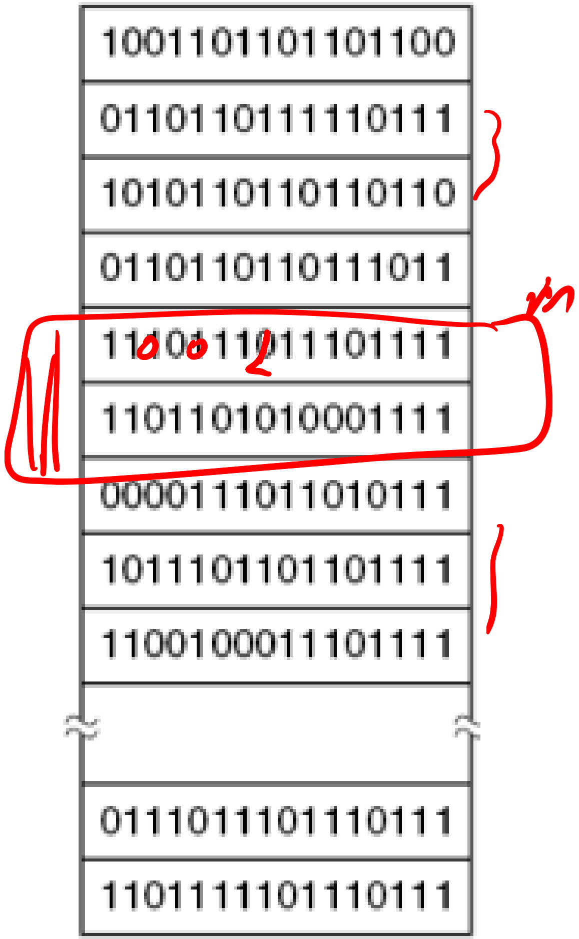


```
1001101101101100
0110110111110111
1010110110110110
0110110110111011
1110111011101111
1101101010001111
0000111011010111
1011101101101111
1100100011101111

0111011101110111
1101111101110111
```

Free Block Management: Bitmaps

- Relies on caching. Most operations are carried in main memory and written afterwards.
- Fixed size structure
  - The size of the bitmap is the same for a free disk as the bitmap for a full disk.
- Integrity alert!!!!
  - Improper shutdown and some bitmap changes are lost!!

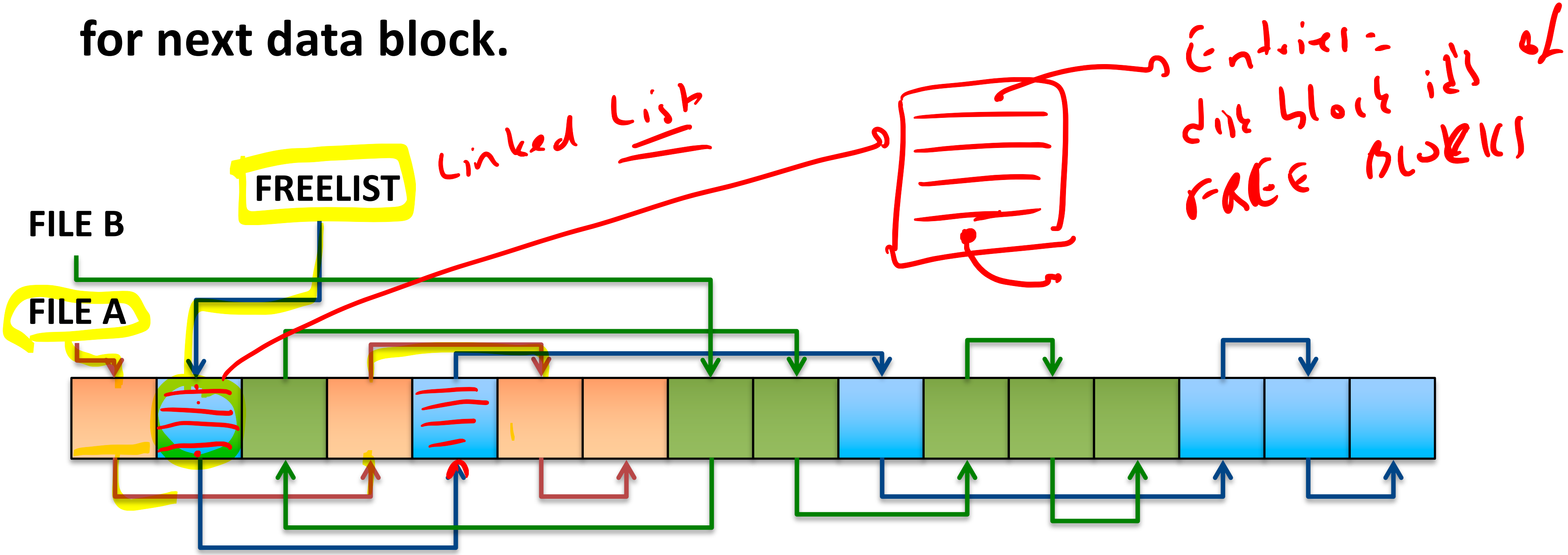


1001101101101100
0110110111110111
1010110110110110
0110110110111011
1110111011101111
1101101010001111
0000111011010111
1011101101101111
1100100011101111

0111011101110111
1101111101110111

Free Block Management: Free Lists

- Free blocks are kept as a linked list.
- Pointers on disk: number of the target block
- For allocated blocks, same list can be used as the file block to data block mapping .i.e. next file block follows the link for next data block.

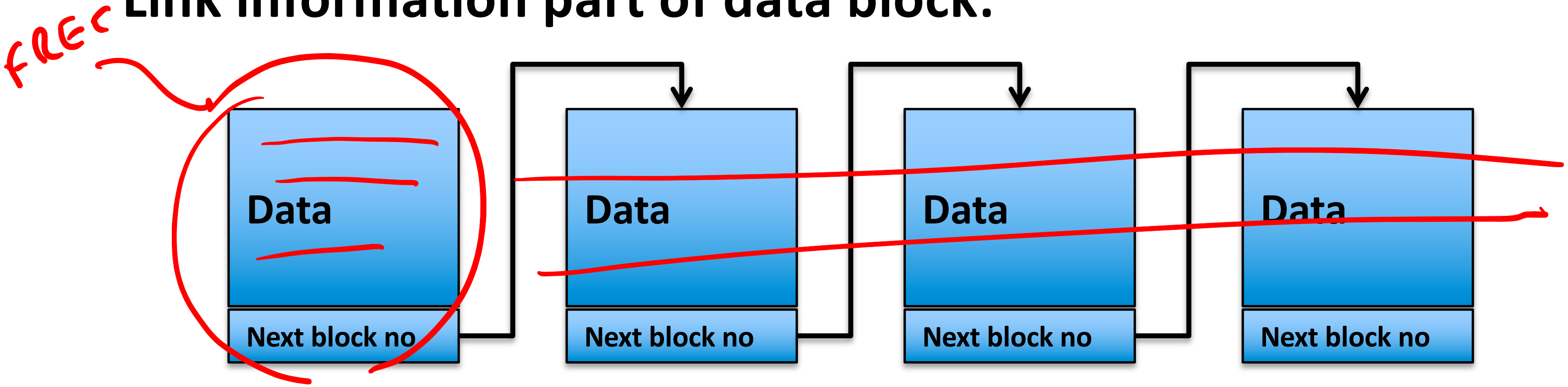


Free List

Disk Empty => FREE LIST LARGE

Disk Full => FREE LIST is SMALL

Link information part of data block:



- 4096 byte block 4092 bytes data, 4 bytes next. 4092 as block size?
- Traversing link chain requires full read/write block.
- Cache does not help much since data blocks are large in total.

File → Data
↳ Attributes

File Attributes

- Name – only information kept in human-readable form
- Identifier – unique tag (number) identifies file within file system
- Type – needed for systems that support different types
- Location – pointer to file location on device
- Size – current file size
- Credentials: who owns the file? User/group
- Permissions: which type of accesses granted for different groups.
- Timestamps: Last access, modification and attribute change times of the file

File attributes are kept separately from its data on the disk

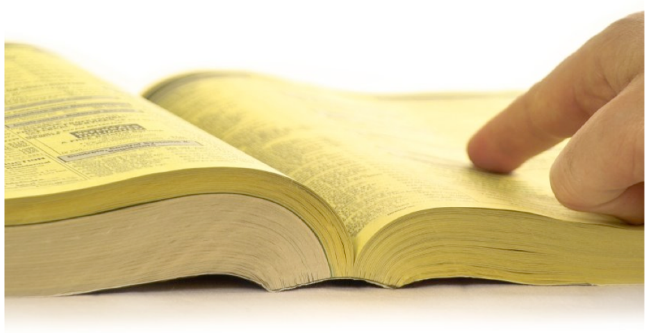
File Type/Extension

- File type provides information on what can be done with that file to the OS.
- Windows uses a three letter code following a dot as extension to determine file type.
  - *.exe are executable, *.c are C source files
- Unix like systems do not rely on extension, but look at first group of bytes to determine the file type (ELF binary vs. a script)
  - See “man file”, “man magic”
  - Mac OS TEXT/APPL is used for all files.
    - Creator application is stored as an attribute.

File Attributes - Where do we keep them?

- FAT: keep in directory structure. A directory entry also contains files attributes along with its entry point in FAT.
- Unix/Linux: i-node, a block containing all attributes of a file. An i-node per file is maintained. Inode also contains pointers for data block tree.
- NTFS: Master File Table database contains file attribute mapping.

Directories



- A directory is
  - A means of organizing files
    - Typically in a tree structure
  - A special file that links filenames to their filesystem internal identifiers.

human-readable

TC kimlik No

- Arbitrary changes on directory files are not allowed
  - Integrity of directory tree has to be preserved.
- Special set of system calls for accessing/updating directories only:
  - mkdir, chdir, rmdir, opendir, readdir, file lookup (internal), …

Operations Performed on Directory

- Search for a file
  - Given a name or a pattern of names, we should be able to find all the files that use it.
- Create a file

  -
    ```
    touch assignment3.c
    ```
- Delete a file

  -
    ```
    rm assignment3.c
    ```
- List a directory

  -
    ```
    ls
    ```
- Rename a file

  -
    ```
    mv assignment3.c odev3.c
    ```
- Traverse the file system

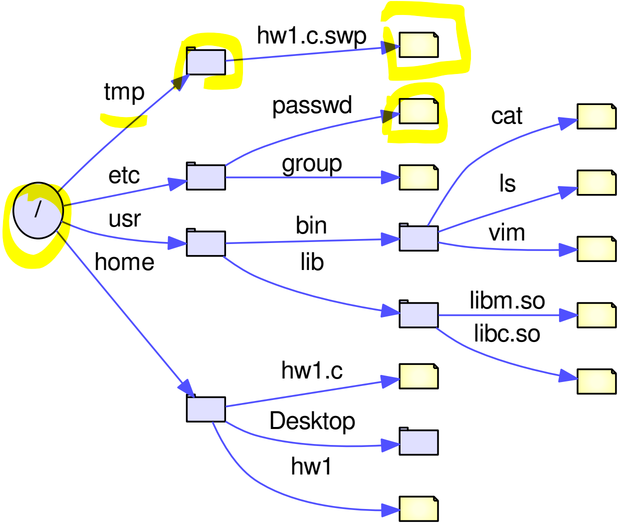
  -
    ```
    cd include
    ```

Directory requirements

- Efficiency – locating a file quickly
- Naming – convenient to users
  - Two users can have same name for different files
  - The same file can have several different names
- Grouping – logical grouping of files by properties, (e.g., all Java programs, all games, …)

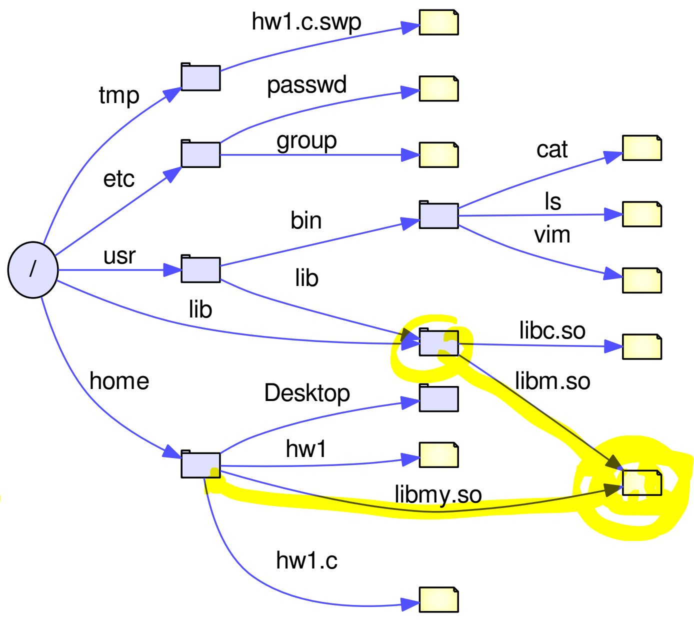
Directory Organization

- Early mainframes used a flat structure
  - no nesting but "Cylinders", virtual containers for files
- Modern systems use N-ary tree in directories as intermediate nodes, and any other file type on leaves.



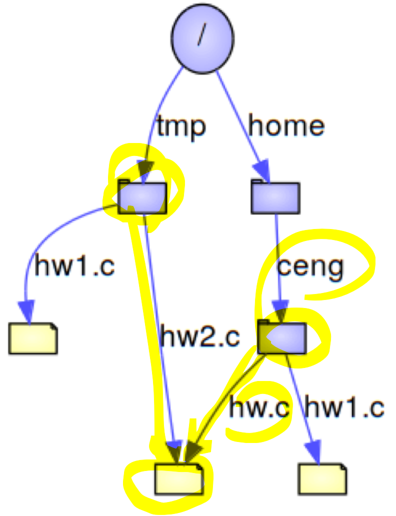
Links

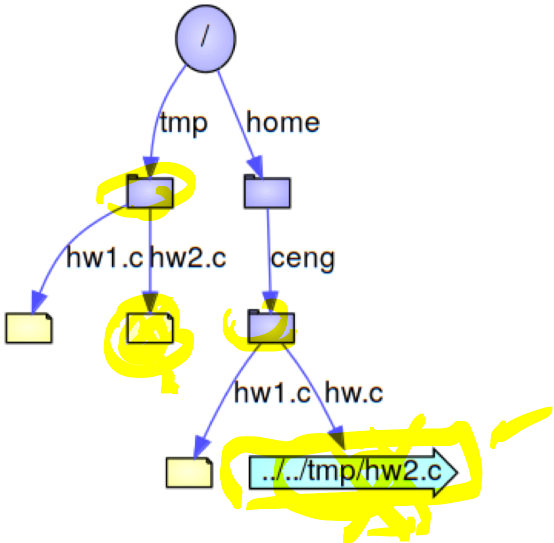
- Links: Two or more paths accessing same node.
- Transforms the tree structure into DAG (Directed Acyclic Graph) structure
- Pros:
  - Provides a more natural categorization
    - /Photos/Places/METU/ceng334.jpg
    - /Photos/Years/2020/ceng334.jpg
- Cons:
  - Caution needed during file removal
  - Caution needed during backups not to create unintentional duplicates



Links

- Hard links:
  - Completely transparent, directory entry points to same file position.
  - No distinction between original and the link
  - `ln ../../tmp/hw2.c  hw.c`
- Soft links (shortcuts in Windows, or symbolic links):
  - Special file implemented as a redirection.
  - OS opens, expands and follows its content. Still transparent but link and the original file differs.
  - `ln –s ../../tmp/hw2.c hw.c`





Links - discussion

- Hard links:
  - more efficient,
  - cannot span multiple filesystems,
  - cannot link directories.
- Soft links:
  - can span multiple filesystems,
  - can link directories, but may dangle (link may exist without its target), when relative (i.e. ../../dir/file.txt) it can be moved with the original file.
- Directory linking may cause cycles.
  - Cycles causes no problems for the OS but programs accessing filesystem recursively may end up in infinite loops.
- OS's can break cycles of soft links by limiting total number of link expansions in a path.