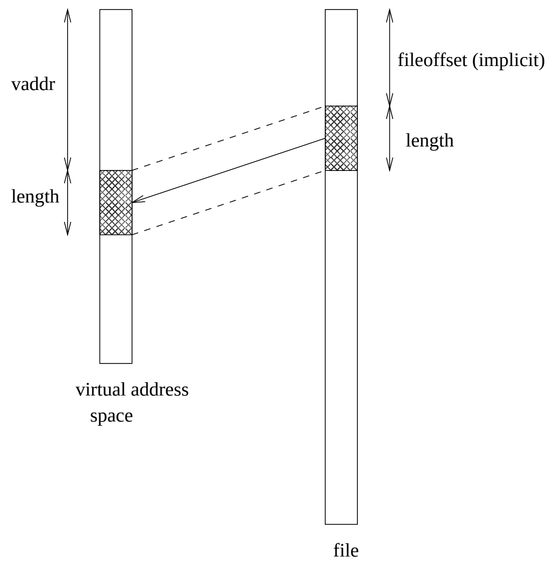
Files and File Systems

- files: persistent, named data objects
  - data consists of a sequence of numbered bytes
  - alternatively, a file may have some internal structure, e.g., a data may consist of sequence of numbered records
  - file may change size over time
  - file has associated meta-data (attributes), in addition to the file name
    - examples: owner, access controls, file type, creation and access timestamps
- file system: a collection of files which share a common name space
  - allows files to be created, destroyed, renamed, . . .

File Interface

- open, close
  - open returns a file identifier (or handle or descriptor), which is used in subsequent operations to identify the file. (Why is this done?)
- read, write
  - must specify which file to read, which part of the file to read, and where to put the data that has been read (similar for write).
  - often, file position is implicit (why?)
- seek
- get/set file attributes, e.g., Unix `fstat, chmod`

File Read



`read(fileID, vaddr, length)`

File Position

- may be associated with the file, with a process, or with a file descriptor (Unix style)
- read and write operations
  - start from the current file position
  - update the current file position
- this makes sequental file I/O easy for an application to request
- for non-sequental (random) file I/O, use:
  - `seek`, to adjust file position before reading or writing
  - a positioned read or write operation, e.g., Unix `pread, pwrite`: `pread(fileId,vaddr,length,filePosition)`

Sequential File Reading Example (Unix)

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
for(i=0;i<100;i++) {
  read(f,(void *)buf,512);
}
close(f);
```

Read the first $100 * 512$ bytes of a file, 512 bytes at a time.

File Reading Example Using Seek (Unix)

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
lseek(f,99*512,SEEK_SET);
for(i=0;i<100;i++) {
  read(f,(void *)buf,512);
  lseek(f,-1024,SEEK_CUR);
}
close(f);
```

Read the first $100 * 512$ bytes of a file, 512 bytes at a time, in reverse order.

File Reading Example Using Positioned Read

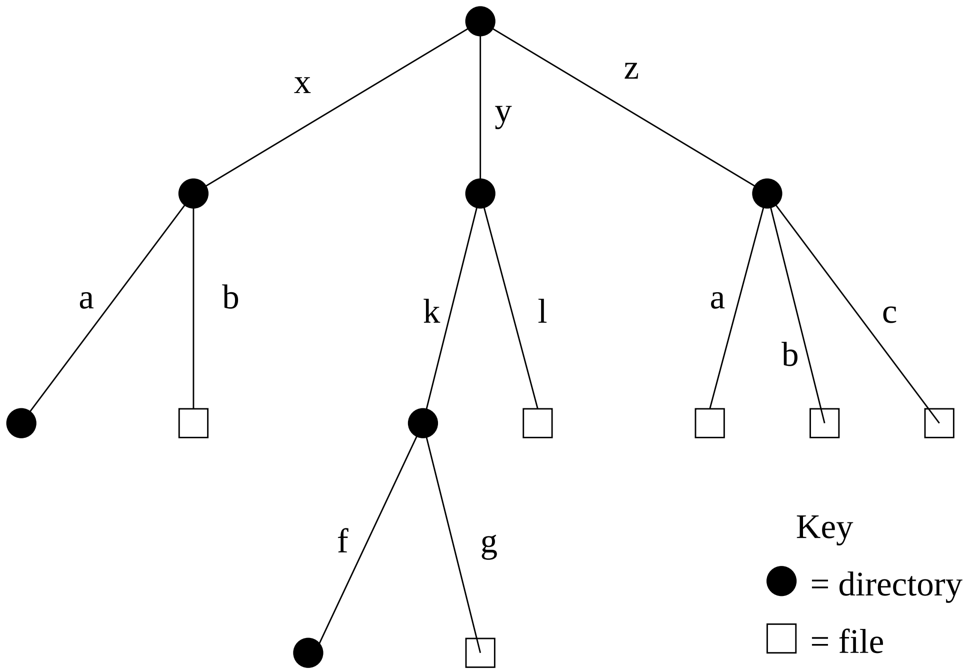
```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
for(i=0;i<50;i+=1) {
  pread(f,(void *)buf,512,i*512);
}
close(f);
```

Read every second 512 byte chunk of a file, until 50 have been read.

File Names

- flat namespace
  - file names are simple strings
- hierarchical namespace
  - directories (folders) can be used to organize files and/or other directories
  - directory inclusion graph is a tree
  - pathname: file or directory is identified by a *path* in the tree
    Unix: `/home/kmsalem/courses/cs350/notes/filesys.ps`
    Windows: `c:\kmsalem\cs350\schedule.txt`

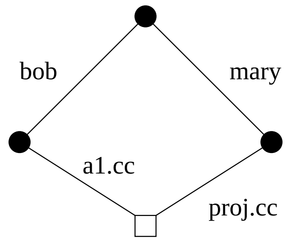
Hierarchical Namespace Example



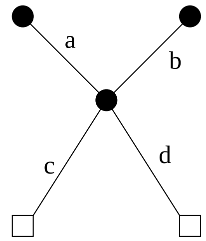
Acyclic File Namespaces

- directory inclusion graph can be a (rooted) DAG
- allows files/directories to have more than one pathname
  - increased flexibility for file sharing and file organization
  - file removal and some other file system operations are more complicated
- examples:

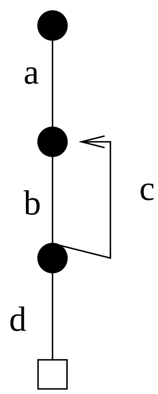
Rooted Acyclic Namespace



An Unrooted DAG



General File Namespaces

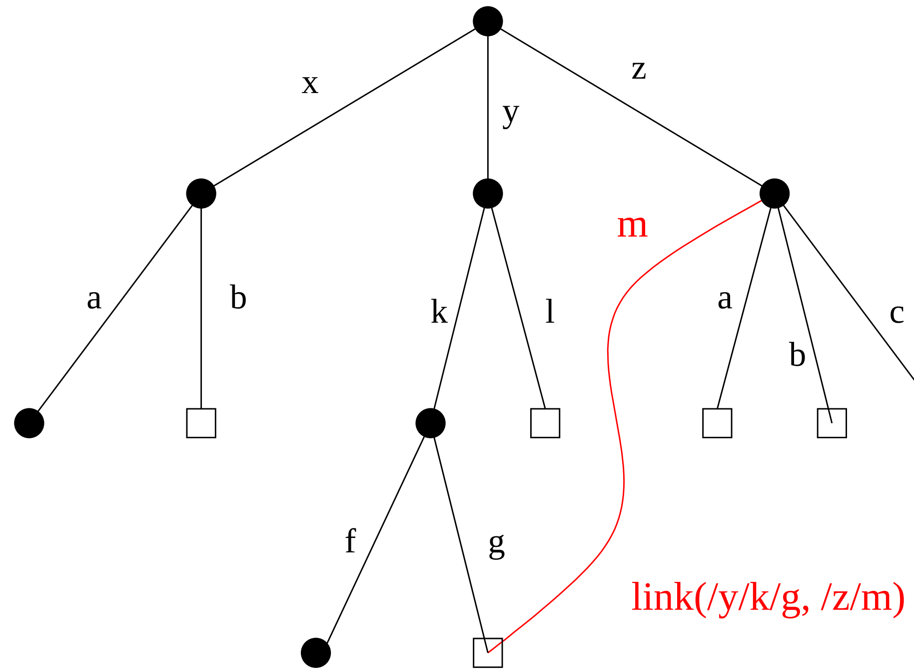


- no restriction on inclusion graph (except perhaps that it should have a designated root node)
- maximum flexibility
- additional complications, e.g.:
  - reference counts are no longer sufficient for implementing file deletion
  - pathnames can have an infinite number of components

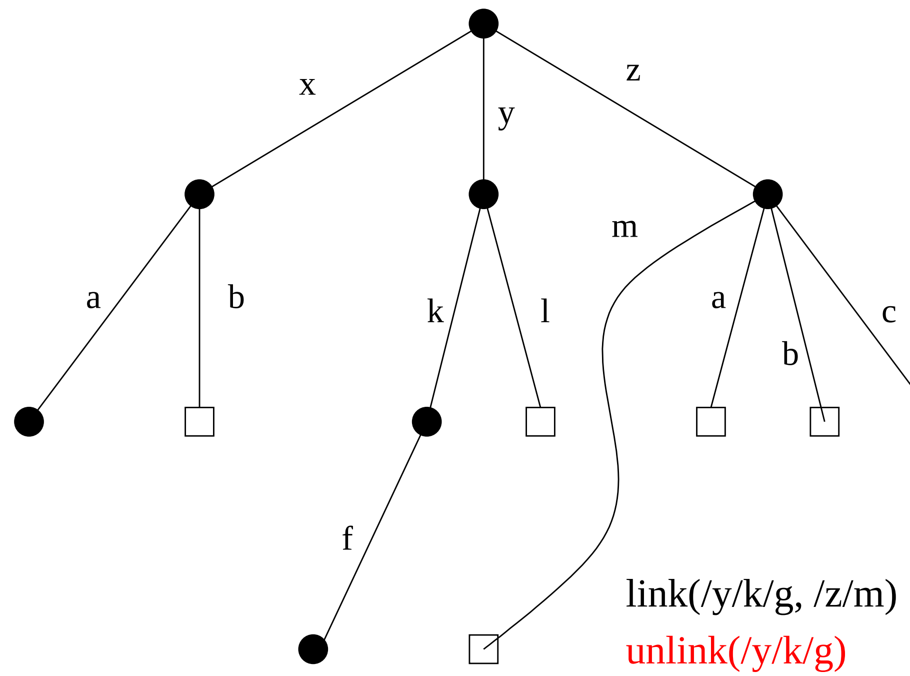
File Links

- typically, a new file or directory is linked to a single "parent" directory when it is created. This gives a hierarchical namespace.
- another mechanism can then be used to create additional links to existing files or directories, introducing non-hierarchical structure in the namespace.
- hard links
  - "first class" links, like the original link to a file
  - *referential integrity* is maintained (no "dangling" hard links)
  - scope usually restricted to a single file system
  - Unix: hard links can be made to files, but not to directories. This restriction is sufficient to avoid cycles. (Why?)
- soft links (a.k.a. "symbolic links", "shortcuts")
  - referential integrity is *not* maintained
  - flexible: may be allowed to span file systems, may link to directories and (possibly) create cycles

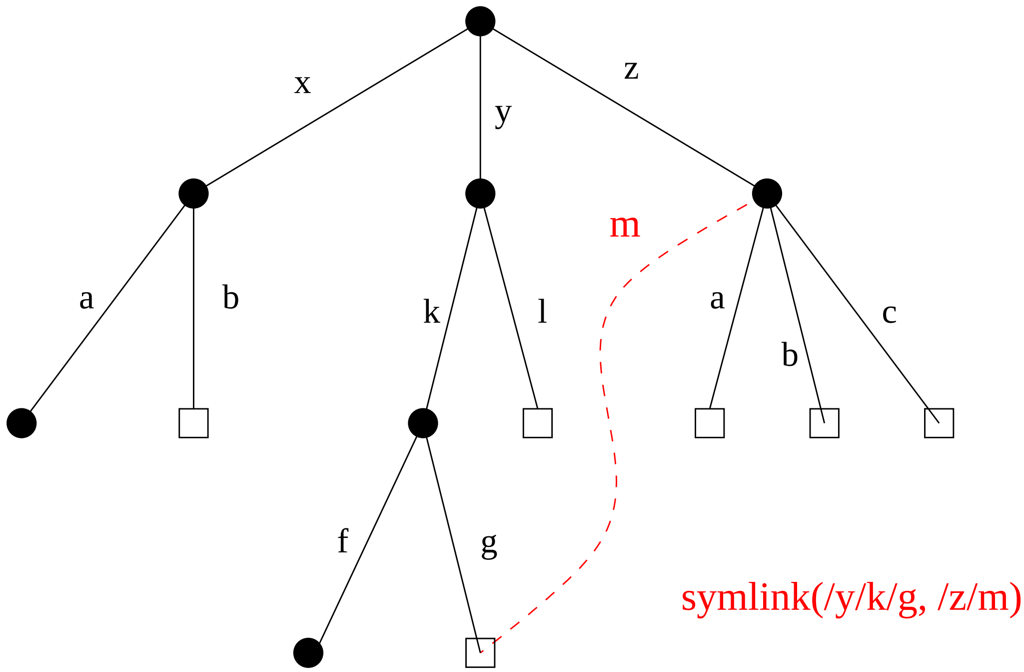
Hard Link Example (Part 1)



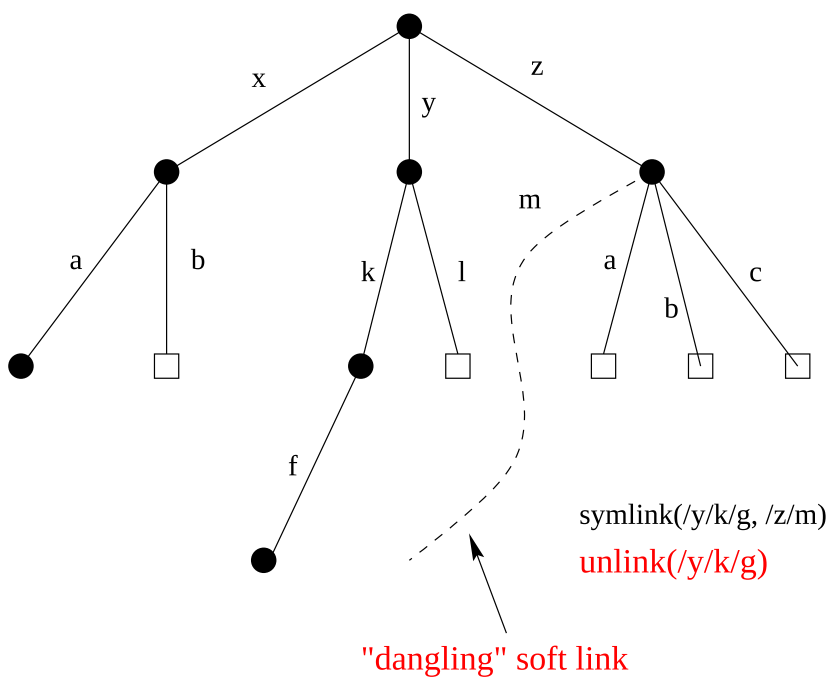
Hard Link Example (Part 2)



Soft Link Example (Part 1)



Soft Link Example (Part 2)



Multiple File Systems

- it is not uncommon for a system to have multiple file systems
- some kind of global file namespace is required
- two examples:

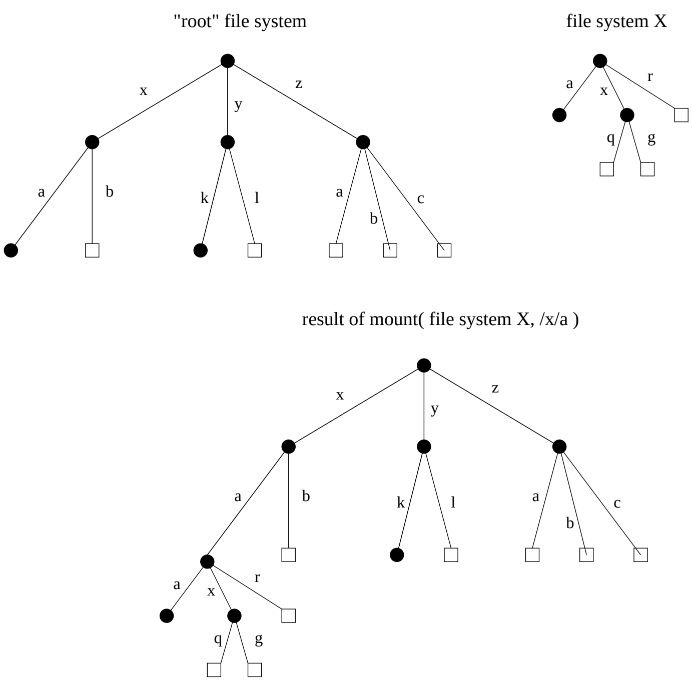
DOS: use two-part file names: file system name,pathname

– example: `C:\kmsalem\cs350\schedule.txt`

Unix: merge file graphs into a single graph

– Unix `mount` system call does this

Unix `mount` Example



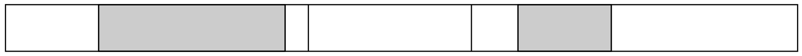
File System Implementation

- space management
- file indexing (how to locate file data and meta-data)
- directories
- links
- buffering, in-memory data structures
- persistence

Space Allocation

- space may be allocated in fixed-size chunks, or in chuncks of varying size
- fixed-size chunks
  - simple space management
  - internal fragmentation
- variable-size chunks
  - external fragmentation

fixed-size allocation



variable-size allocation

Space Allocation (continued)

- differences between primary and secondary memory
  - larger transfers are cheaper (per byte) than smaller transfers
  - sequential I/O is faster than random I/O
- both of these suggest that space should be allocated to files in large chunks, sometimes called *extents*

File Indexing

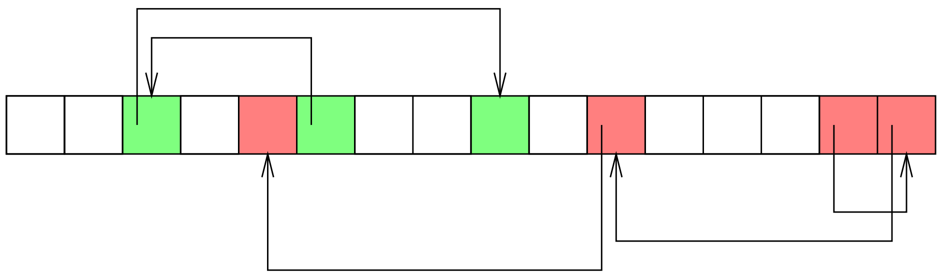
- in general, a file will require more than one chunk of allocated space (extent)
- this is especially true because files can grow
- how to find all of a file's data?

  chaining:
  - each chunk includes a pointer to the next chunk
  - OK for sequential access, poor for random access

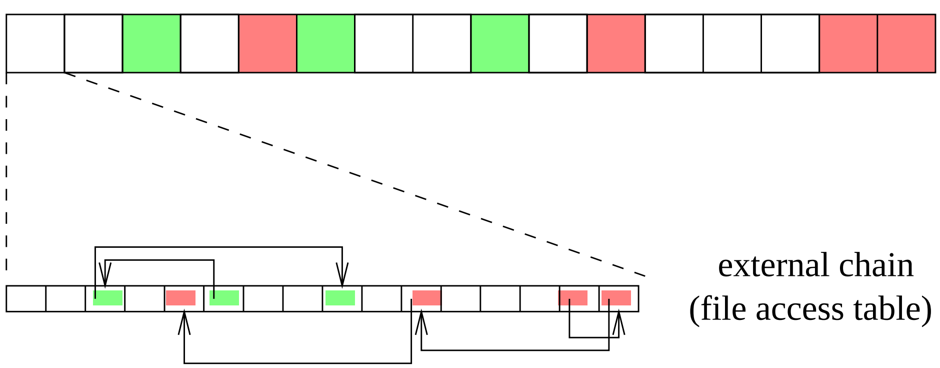
  external chaining: DOS file allocation table (FAT), for example
  - like chaining, but the chain is kept in an external structure

  per-file index: Unix i-node and NachOS FileHeader, for example
  - for each file, maintain a table of pointers to the file's blocks or extents

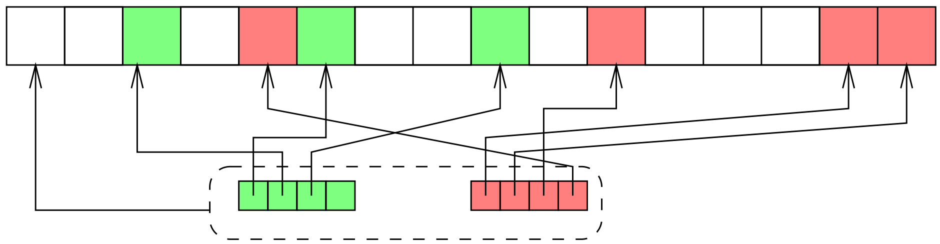
Chaining



External Chaining (File Access Table)



Per-File Indexing



File Meta-Data and Other Information

- where to store file meta-data?
  - immediately preceding the file data
  - with the file index (if per-file indexing is being used)
  - with the directory entry for the file
    - ∗ this is a problem if a file can have multiple names, and thus multiple directory entries

Unix i-nodes

- an i-node is a particular implementation of a per-file index
- each i-node is uniquely identified by an i-number, which determines its physical location on the disk
- an i-node is a fixed size record containing:

  file attribute values
  - file type
  - file owner and group
  - access controls
  - creation, reference and update timestamps
  - file size

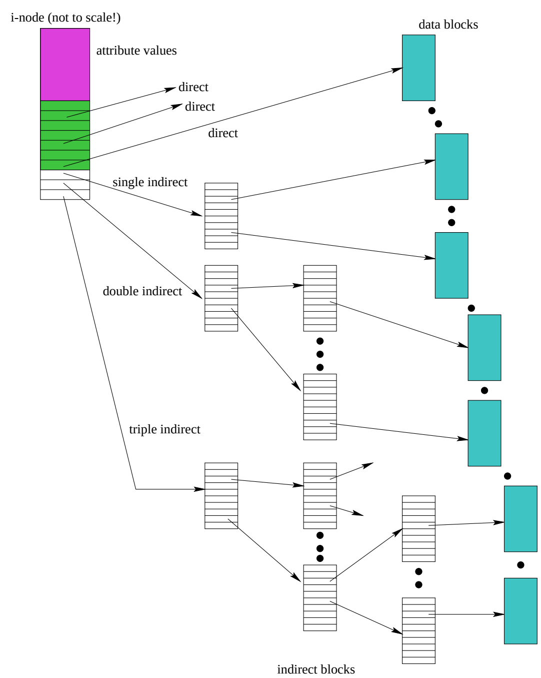
  direct block pointers: approximately 10 of these

  single indirect block pointer

  double indirect block pointer

  triple indirect block pointer

i-node Diagram



NachOS FileHeader

```
#define NumDirect ((SectorSize-2*sizeof(int))/sizeof(int))
class FileHeader {
  public:
  // methods here
  private:
    int numBytes;    // file size in bytes
    int numSectors;  // file size in sectors
    int dataSectors[NumDirect]; // direct pointers
}
```


Directories

- A directory consists of a set of entries, where each entry is a record that includes:
  - a file name (component of a path name)
  - a file "locator"
    - location of the first block of the file, if chaining or external chaining is used
    - location of the file index, if per-file indexing is being used
- A directory can be implemented like any other file, except:
  - interface should allow reading of records (can be provided by a special system call or an library)
  - file should not be writable directly by application programs
  - directory records are updated by the kernel as files are created and destroyed

Implementing Hard Links (Unix)

- hard links are simply directory entries
- for example, consider:

  `link(/y/k/g,/z/m)`
- to implement this:
  - create a new entry in directory `/z`
    - file name in new entry is `m`
    - file locator (i-number) in the new entry is the same as the i-number for entry `g` in directory `/y/k`

Implementing Soft Links (Unix)

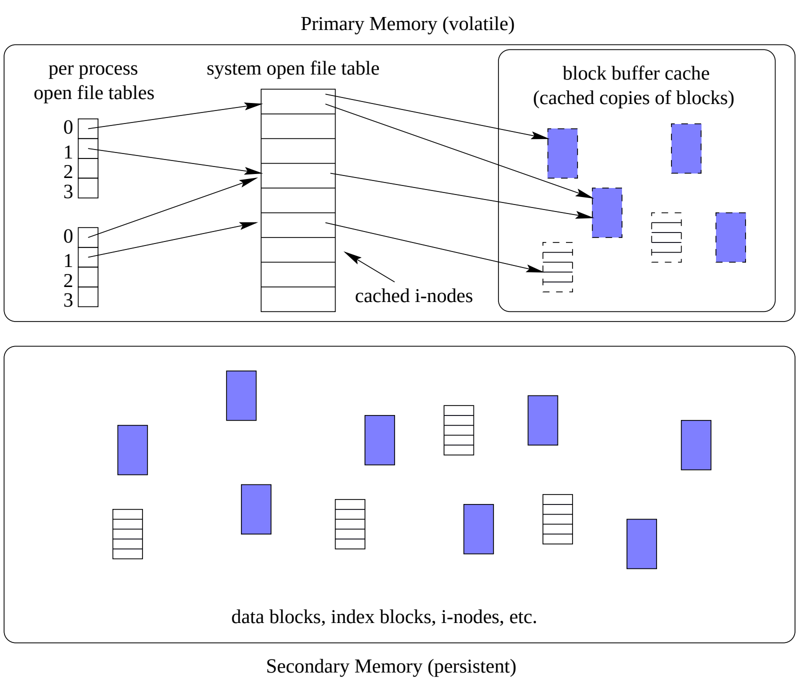
- soft links are implemented as a special type of file
- for example, consider:

  `symlink(/y/k/g,/z/m)`
- to implement this:
  - create a new *symlink* file
  - add a new entry in directory `/z`
    - file name in new entry is `m`
    - i-number in the new entry is the i-number of the new symlink file
  - store the pathname string "/y/k/g" as the contents of the new symlink file
- change the behaviour of the `open` system call so that when the symlink file is encountered during `open(/z/m)`, the file `/y/k/g` will be opened instead.

File System Meta-Data

- file system must record:
  - location of file indexes or file allocation table
  - location of free list(s) or free space index
  - file system parameters, e.g., block size
  - file system identifier and other attributes
- example: Unix *superblock*
  - located at fixed, predefined location(s) on the disk
- example: NachOS free space bitmap and directory files
  - headers for these files are located in disk sectors 0 and 1

Main Memory Data Structures



A Simple Exercise

- Walk through the steps that the file system must take to implement `Open`.
  - which data structures (from the previous slide) are updated?
  - how much disk I/O is involved?

Problems Caused by Failures

- a single logical file system operation may require several disk I/O operations
- example: deleting a file
  - remove entry from directory
  - remove file index (i-node) from i-node table
  - mark file's data blocks free in free space index
- what if, because a failure, some but not all of these changes are reflected on the disk?

Fault Tolerance

- special-purpose consistency checkers (e.g., Unix `fsck` in Berkeley FFS, Linux ext2)
  - runs after a crash, before normal operations resume
  - find and attempt to repair inconsistent file system data structures, e.g.:
    * file with no directory entry
    * free space that is not marked as free
- journaling (e.g., Veritas, NTFS, Linux ext3)
  - record file system meta-data changes in a journal (log), so that sequences of changes can be written to disk in a single operation
  - *after* changes have been journaled, update the disk data structures (*write-ahead logging*)
  - after a failure, redo journaled updates in case they were not done before the failure

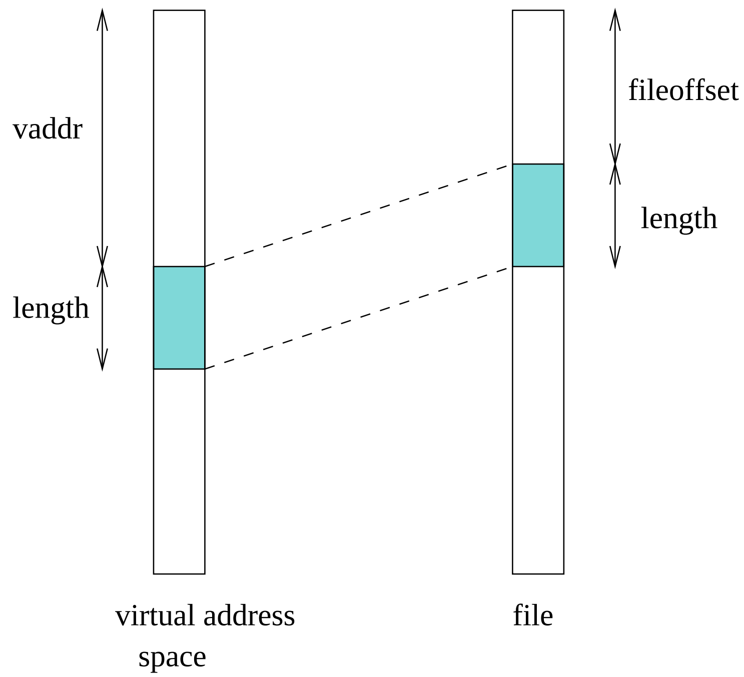
Memory-Mapped Files

- generic interface:

  `vaddr ← mmap(file descriptor,fileoffset,length)`
  `munmap(vaddr,length)`
- `mmap` call returns the virtual address to which the file is mapped
- `munmap` call unmaps mapped files within the specified virtual address range

Memory-mapping is an alternative to the read/write file interface.

Memory Mapping Illustration



Memory Mapping Update Semantics

- what should happen if the virtual memory to which a file has been mapped is updated?
- some options:
  - prohibit updates (read-only mapping)
  - eager propagation of the update to the file (too slow!)
  - lazy propagation of the update to the file
    - user may be able to request propagation (e.g., Posix `msync()`
    - propagation may be guaranteed by `munmap()`
  - allow updates, but do not propagate them to the file

Memory Mapping Concurrency Semantics

- what should happen if a memory mapped file is updated?
  - by a process that has mmapped the same file
  - by a process that is updating the file using a `write()` system call
- options are similar to those on the previous slide. Typically:
  - propagate lazily: processes that have mapped the file *may* eventually see the changes
  - propagate eagerly: other processes will see the changes
    - typically implemented by invalidating other process's page table entries