## 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 file 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, . . .

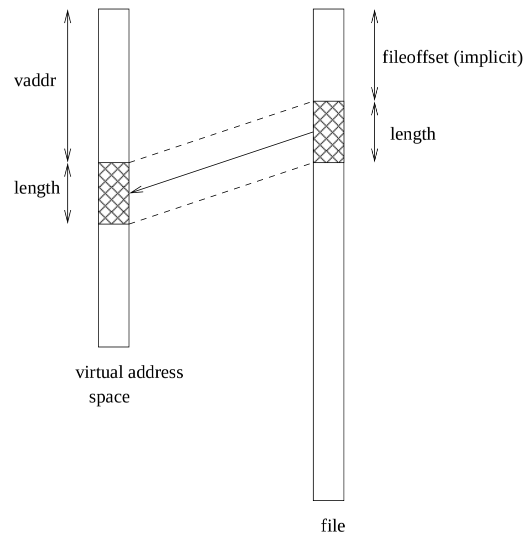




## File Interface

- 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 sequential file I/O easy for an application to request
- for non-sequential (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);
for(i=1; i<=100; i++) {
  lseek(f,(100-i)*512,SEEK_SET);
  read(f,(void *)buf,512);
}
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<100; i+=2) {
  pread(f,(void *)buf,512,i*512);
}
close(f);
```

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





## Memory-Mapped Files

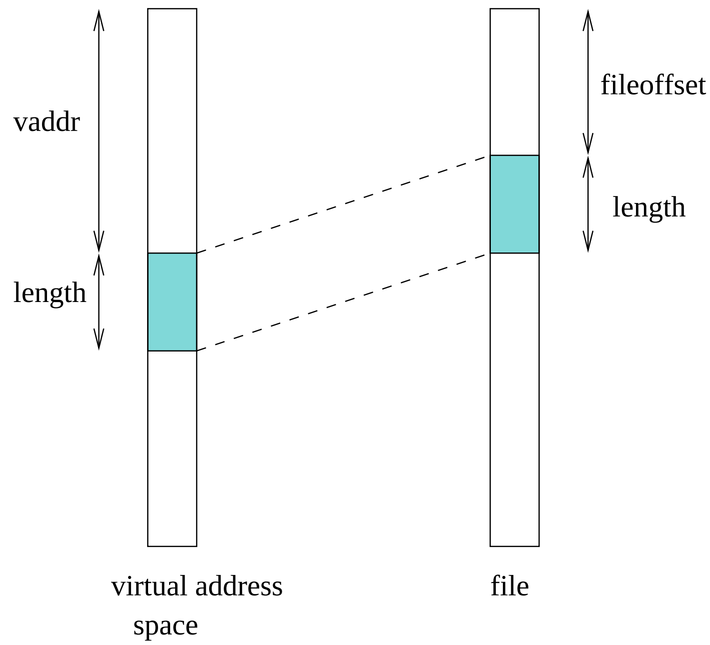
- generic interface:

  `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



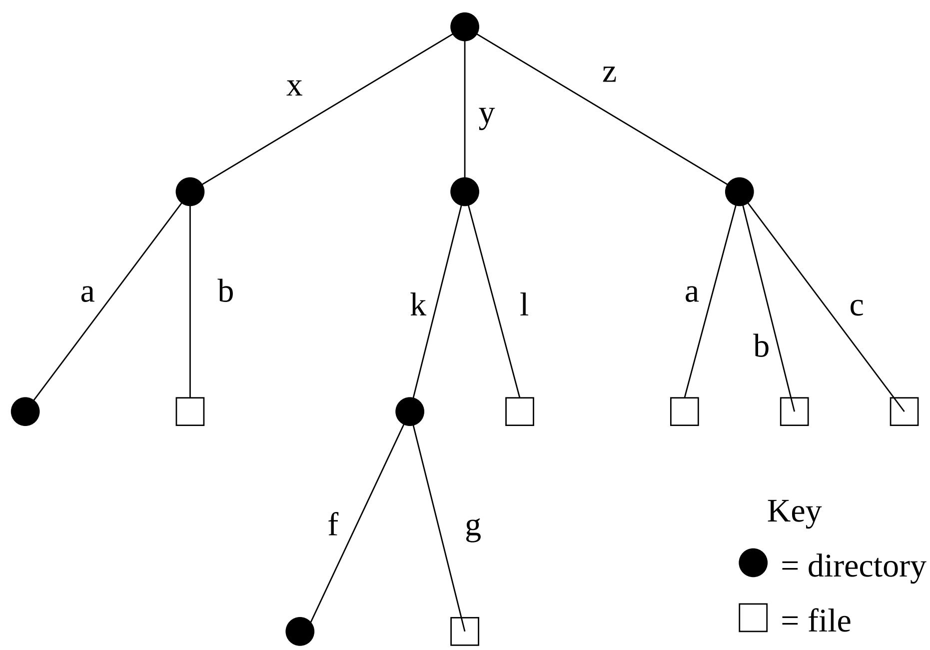


## File Names

- application-visible objects (e.g., files, directories) are given names
- the file system is responsible for associating names with objects
- the namespace is typically structured, often as a tree or a DAG
- namespace structure provides a way for users and applications to organize and manage information
- in a structured namespace, objects may be identified by *pathnames*, which describe a path from a root object to the object being identified, e.g.:

  `/home/kmsalem/courses/cs350/notes/filesys.ps`

## Hierarchical Namespace Example





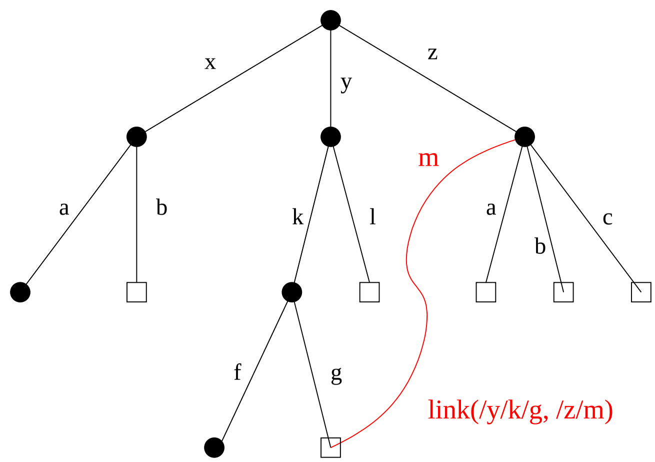



## Hard Links

- a *hard link* is an association between a name and an underlying file (or directory)
- typically, when a file is created, a single link is created to the file as well (else the file would be difficult to use!)
  - POSIX example: `creat(pathname,mode)` creates both a new empty file object and a link to that object (using `pathname`)
- some file systems allow additional hard links to be made to existing files. This allows more than one name from the file system's namespace to refer the *same underlying object*.
  - POSIX example: `link(oldpath,newpath)` creates a new hard link, using `newpath`, to the underlying object identified by `oldpath`

File systems ensure *referential integrity* for hard links. A hard link refers to the object it was created for until the link is explicitly destroyed. (What are the implications of this?)

## Hard Link Illustration

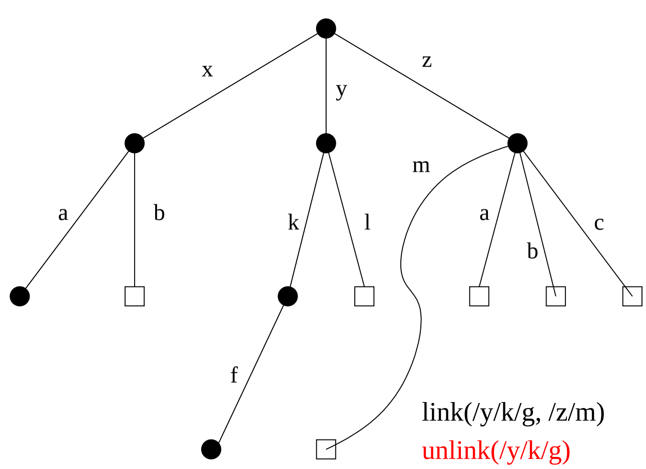



Hard links are a way to create *non-hierarchical structure* in the namespace. Hard link creation may be restricted to restrict the kinds of structure that applications can create. Example: no hard links to directories.





## Unlink Example




Removing the *last* link to a file causes the file itself to be deleted. Deleting a file that has a link would destroy the referential integrity of the link.

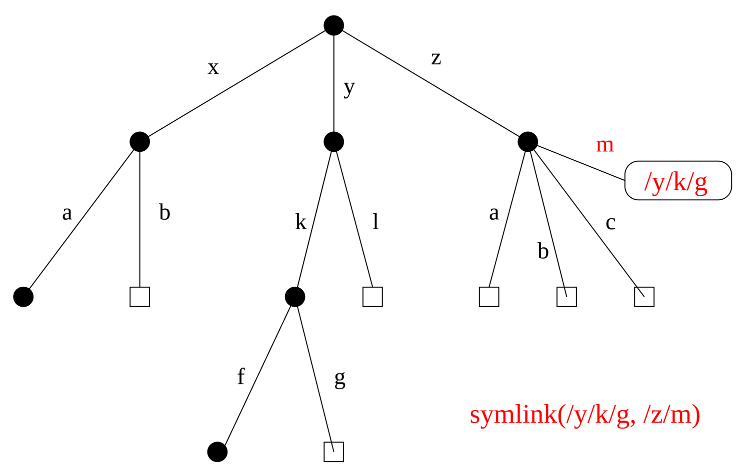
## Symbolic Links

- a *Symbolic link*, or *soft link*, is an association between two names in the file namespace. Think of it is a way of defining a synonym for a filename.
  - `symlink(oldpath,newpath)` creates a symbolic link from `newpath` to `oldpath`, i.e., `newpath` becomes a synonym for `oldpath`.
- symbolic links relate filenames to filenames, while hard links relate filenames to underlying file objects!
- referential integrity is *not* preserved for symbolic links, e.g., the system call above can succeed even if there is no object named `oldpath`



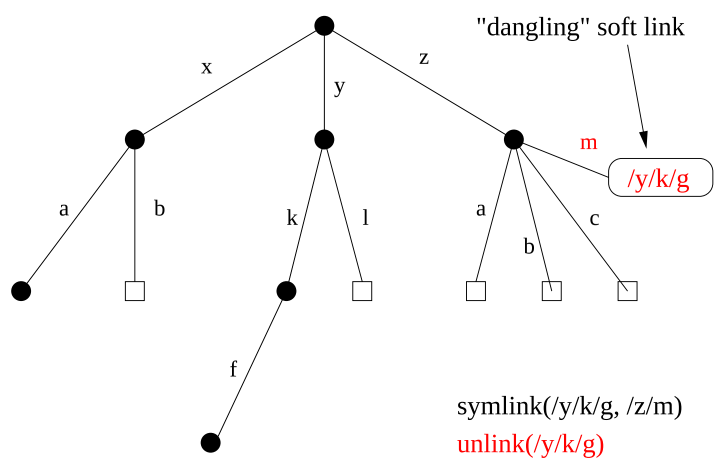


## Soft Link Example




`/y/k/g` still has only one hard link after the `symlink` call. A new symlink object records the association between `/z/m` and `/y/k/g`. `open(/z/m)` will now have the same effect as `open(/y/k/g)`.

## Soft Link Example with Unlink




A file is deleted by this `unlink` call. An attempt to `open(/z/m)` after the `unlink` will result in an error. If a *new* file called `/y/k/g` is created, a subsequent `open(/z/m)` will open the new file.





## Linux Link Example (1 of 2)

```
% cat > file1
This is file1.
% ls -li
685844 -rw------- 1 kmsalem kmsalem 15 2008-08-20 file1
% ln file1 link1
% ln -s file1 sym1
% ls -li
685844 -rw------- 2 kmsalem kmsalem 15 2008-08-20 file1
685844 -rw------- 2 kmsalem kmsalem 15 2008-08-20 link1
685845 lrwxrwxrwx 1 kmsalem kmsalem  5 2008-08-20 sym1 -> file1
% cat file1
This is file1.
% cat link1
This is file1.
% cat sym1
This is file1.
```

A file, a hard link, a soft link.

## Linux Link Example (2 of 2)

```
% /bin/rm file1
% ls -li
685844 -rw------- 1 kmsalem kmsalem 15 2008-08-20 link1
685845 lrwxrwxrwx 1 kmsalem kmsalem  5 2008-08-20 sym1 -> file1
% cat link1
This is file1.
% cat sym1
cat: sym1: No such file or directory
% cat > file1
This is a brand new file1.
% ls -li
685846 -rw------- 1 kmsalem kmsalem 27 2008-08-20 file1
685844 -rw------- 1 kmsalem kmsalem 15 2008-08-20 link1
685845 lrwxrwxrwx 1 kmsalem kmsalem  5 2008-08-20 sym1 -> file1
% cat link1
This is file1.
% cat sym1
This is a brand new file1.
```

Different behaviour for hard links and soft links.





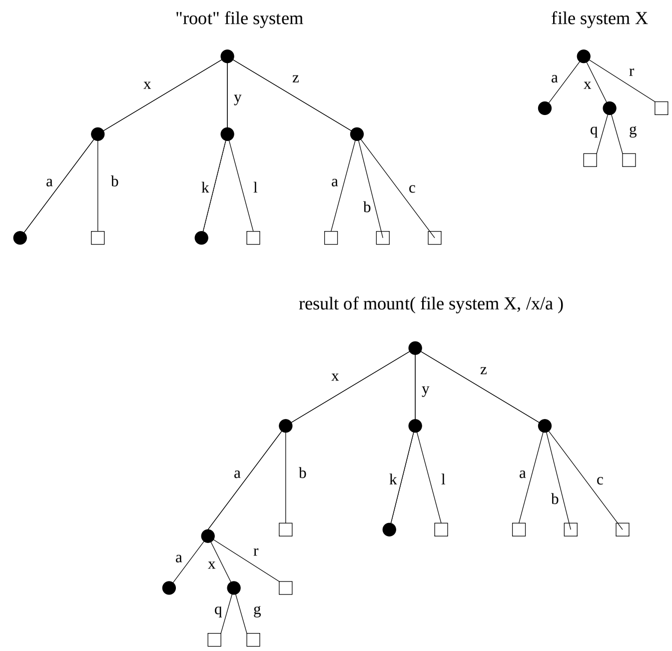
## Multiple File Systems

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

  **DOS/Windows:** 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








## Links and Multiple File Systems

- a hard link associates a name in the file system namespace with a file in that file system
- typically, hard links cannot cross file system boundaries
- for example, even after the mount operation illustrated on the previous slide, `link(/x/a/x/g,/z/d)` would result in an error, because the new link, which is in the root file system refers to an object in file system X
- soft links do not have this limitation
- for example, after the mount operation illustrated on the previous slide:
  - `symlink(/x/a/x/g,/z/d)` would succeed
  - `open(/z/d)` would succeed, with the effect of opening `/z/a/x/g`.
- even if the `symlink` operation were to occur *before* the `mount` command, it would succeed

## File System Implementation

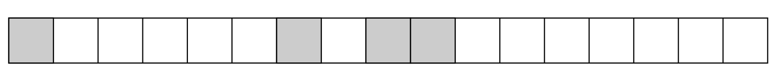
- space management
- file indexing (how to locate file data and meta-data)
- directories
- links
- buffering, in-memory data structures
- persistence



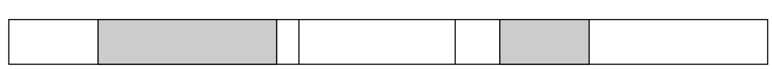


## Space Allocation and Layout

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



fixed−size allocation



variable−size allocation

- *layout* matters! Try to lay a file out sequentially, or in large sequential extents that can be read and written efficiently.

# File Indexing

- in general, a file will require more than one chunk of allocated space
- 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

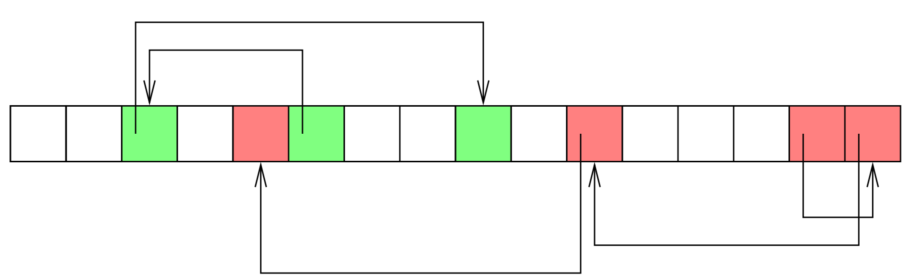
  **external chaining:** DOS file allocation table (FAT), for example
  - like chaining, but the chain is kept in an external structure

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

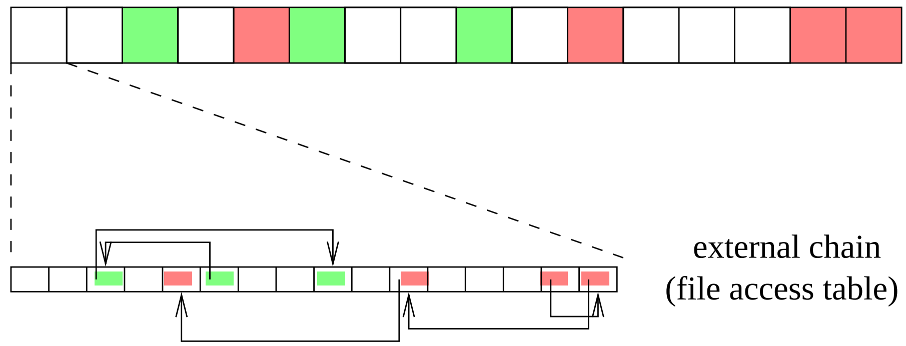




# Chaining



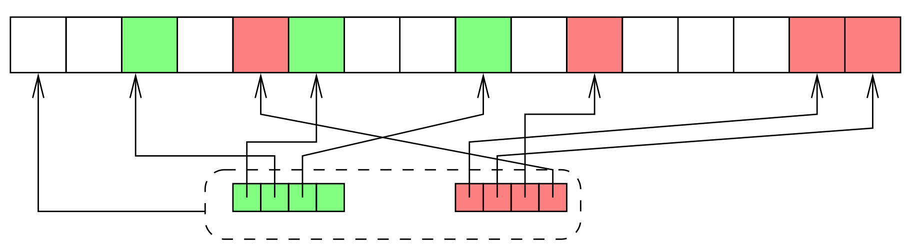
## External Chaining (File Access Table)








## Per-File Indexing



## Internal File Identifiers

- typically, a file system will assign a unique internal identifier to each file, directory or other object
- given an identifer, the file system can *directly* locate a record containing key information about the file, such as:
  - the per-file index to the file data (if per-file indexing is used), or the location of the file's first data block (if chaining is used)
  - file meta-data (or a reference to the meta-data), such as
    - file owner
    - file access permissions
    - file acesss timestamps
    - file type
- for example, a file identifier might be a number which indexes an on-disk array of file records





## Example: Unix i-nodes

- an i-node is a record describing a file
- 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

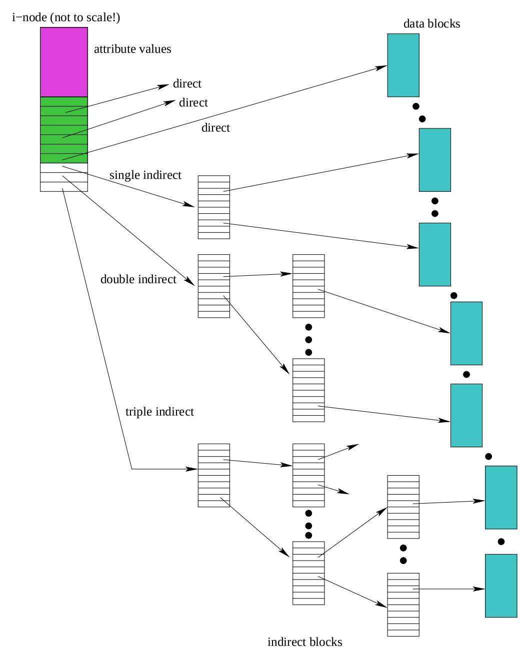
  **direct block pointers:** approximately 10 of these

  **single indirect block pointer**

  **double indirect block pointer**

  **triple indirect block pointer**

## i-node Diagram








## 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)
  - the internal file identifier (e.g., i-number) of the file
- A directory can be implemented as a special type of file. The directory entries are the contents of the file.
- The file system should not allow directory files to be directly written by application programs. Instead, the directory is updated by the file system as files are created and destroyed

## Implementing Hard Links

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

  `link(/y/k/g,/z/m)`
- to implement this:
  1. find out the internal file identifier for `/y/k/g`
  2. create a new entry in directory `/z`
     - file name in new entry is `m`
     - file identifier (i-number) in the new entry is the one discovered in step 1



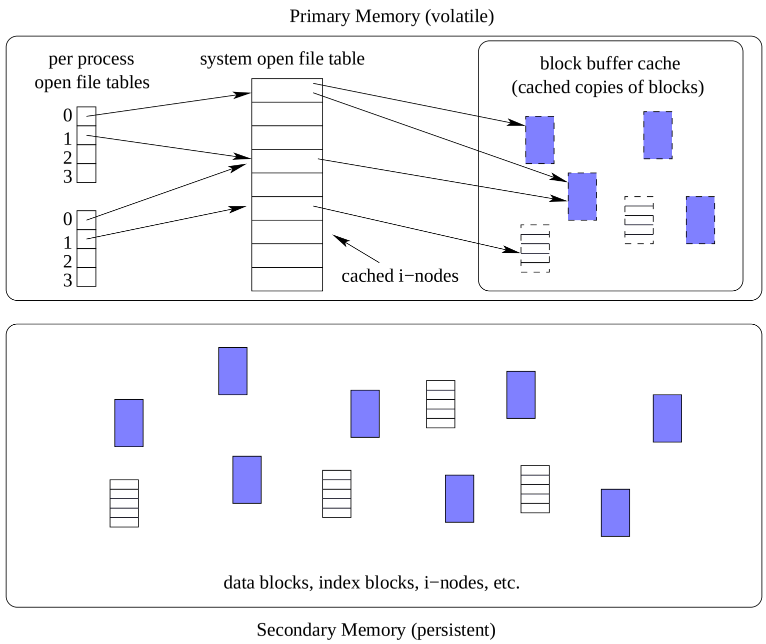


## Implementing Soft Links

- soft links can be 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.

## Main Memory Data Structures








## 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