# 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
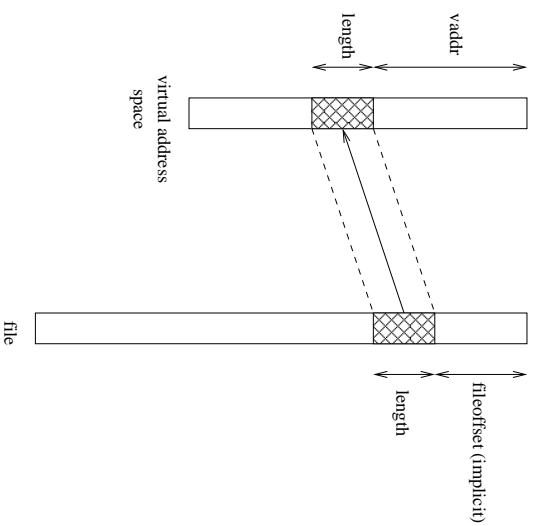
```
read(fileID, vaddr, length)
```

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

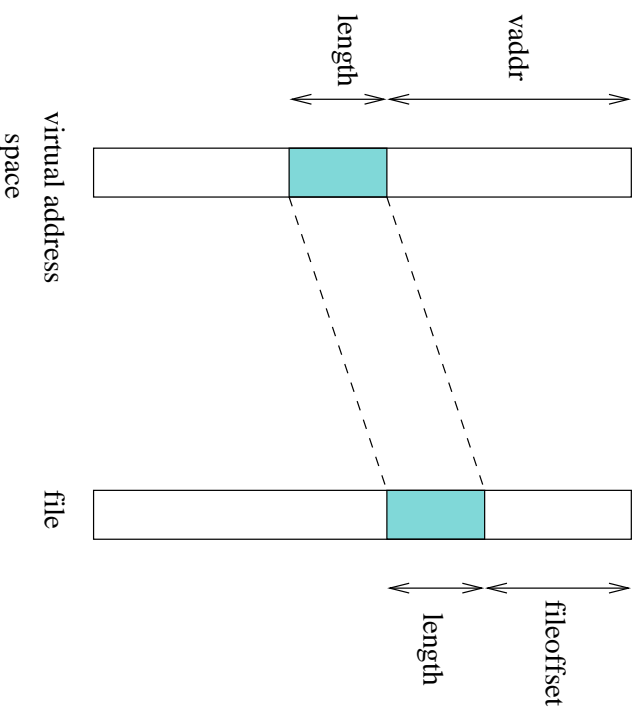- munmap call unmaps mapped files within the specified virtual address range

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

a b x y z f k g l a b c

Key
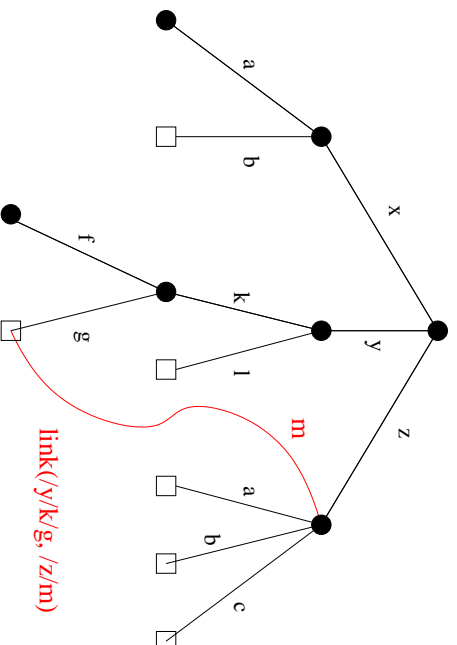● = directory
□ = file
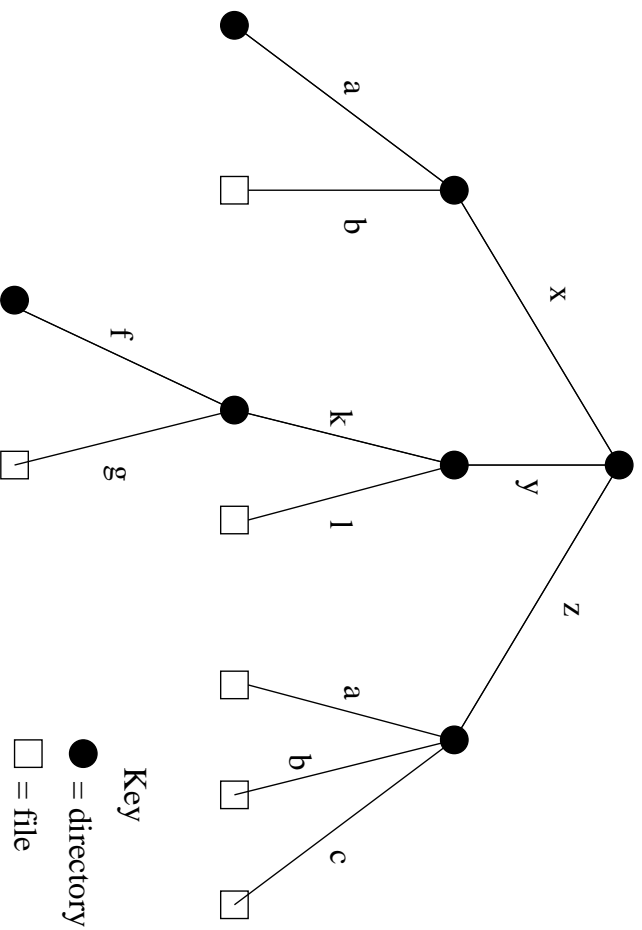
Hard Links

- 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?)
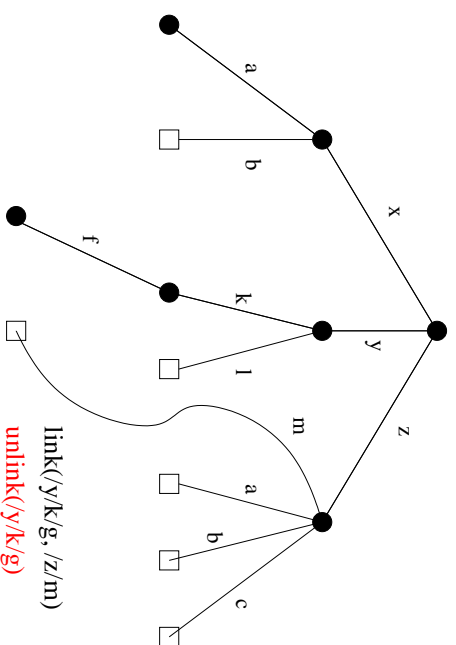
Hard Link Illustration

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.

link(/y/k/g, /z/m)

Unlink Example

link(/y/k/g, /z/m)
unlink(/y/k/g)

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`
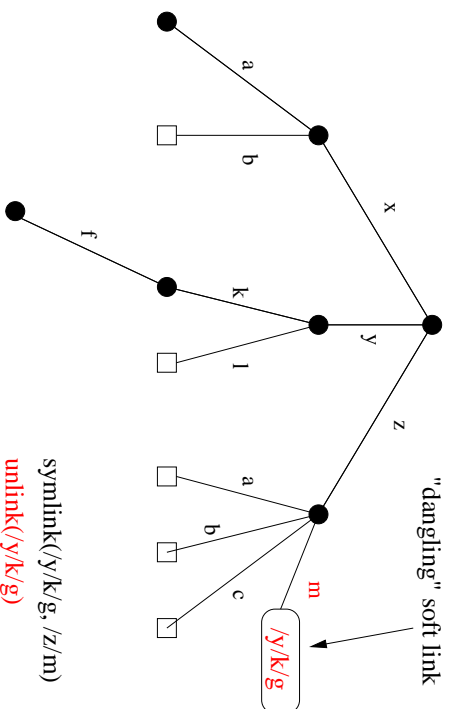

Soft Link Example

symlink(/y/k/g,/z/m)

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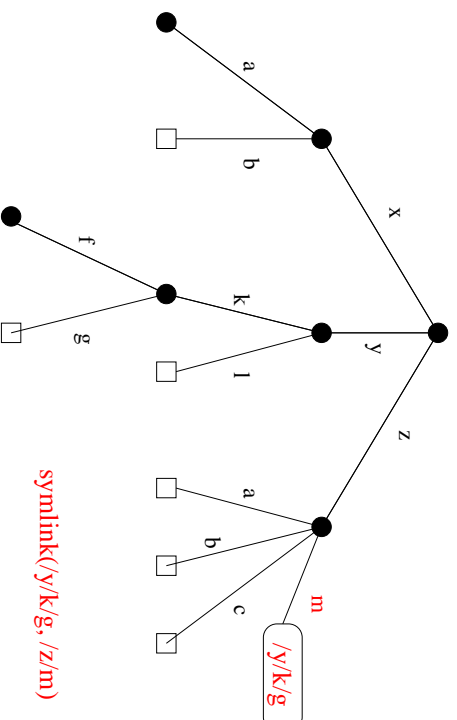
`/y/k/g` still has only one hard link after the `symlink` call. A new symlink object records the association between `/z/m` and `/y/k/g`. `open(/z/m)` will now have the same effect as `open(/y/k/g)`.

Soft Link Example with Unlink

"dangling" soft link

symlink(/y/k/g, /z/m)
unlink(/y/k/g)

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
% 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

"root" file system

result of mount(file system X, /x/a)
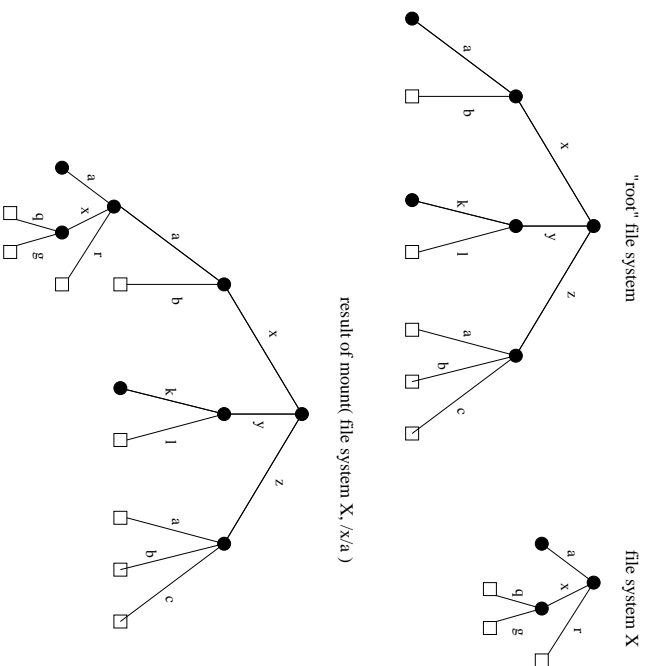
file system X

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
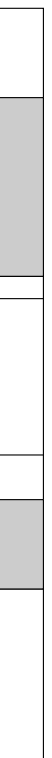
variable−size allocation

- *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

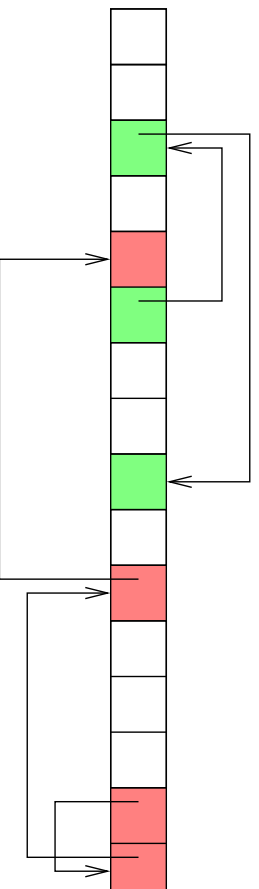– OK for sequential access, poor for random access

external chaining: DOS file allocation table (FAT), for example

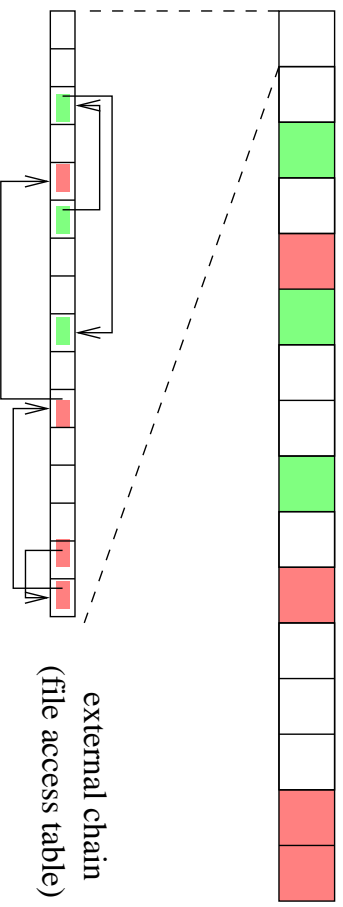– like chaining, but the chain is kept in an external structure

per-file index: Unix i-node, for example

– for each file, maintain a table of pointers to the file's blocks or extents
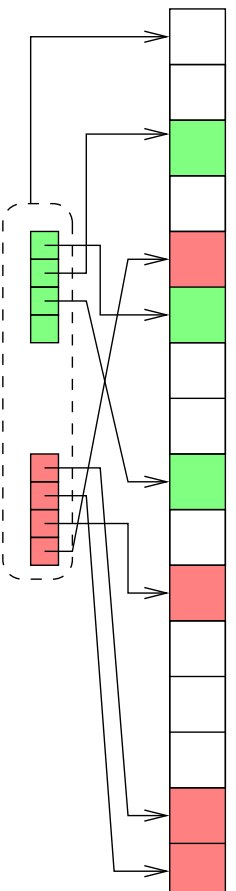

Chaining

External Chaining (File Access Table)

external chain
(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 identifier, 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

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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
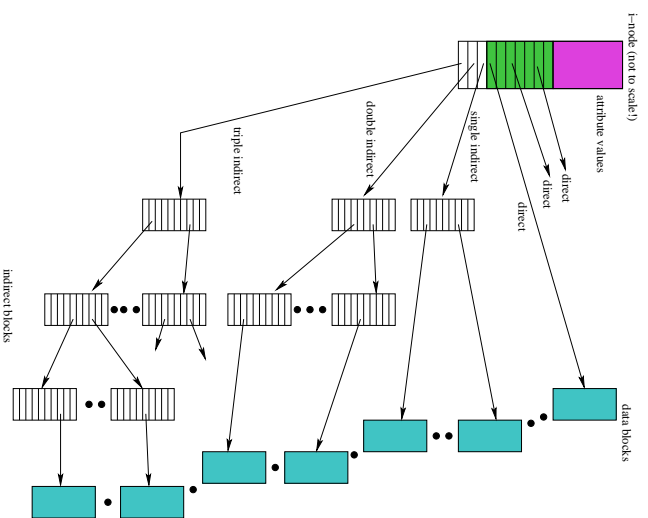
  single indirect block pointer

  double indirect block pointer

  triple indirect block pointer

i-node Diagram

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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
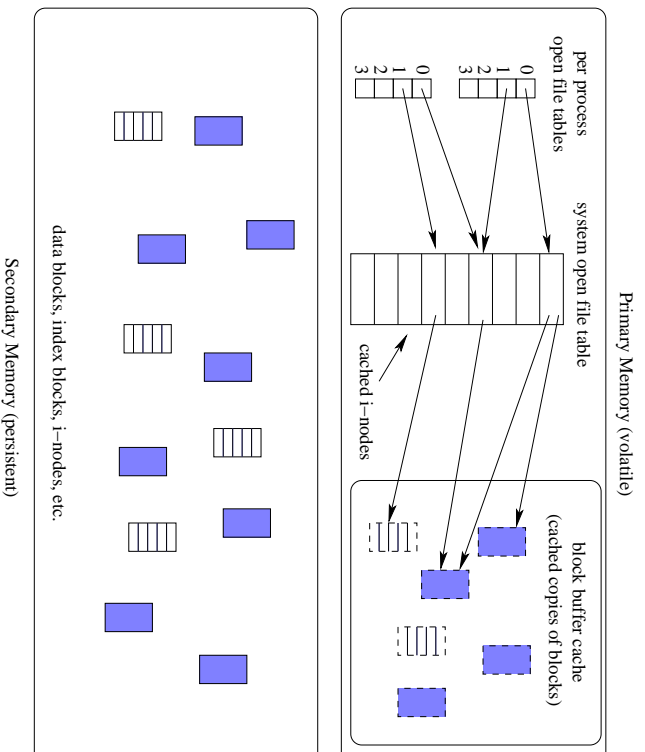
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Implementing Hard Links

- 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

Primary Memory (volatile)

per process
open file tables

system open file table

block buffer cache
(cached copies of blocks)

cached i-nodes

Secondary Memory (persistent)

data blocks, index blocks, i-nodes, etc.

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 of 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