

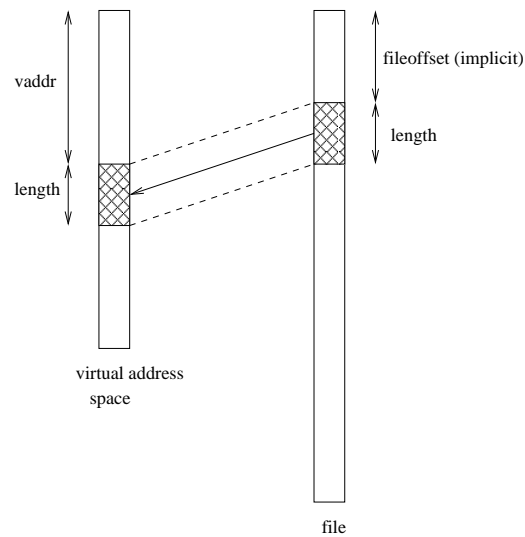
## Files and File Systems

- 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);
```

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

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### 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);
```

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

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### 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);
```

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

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### 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

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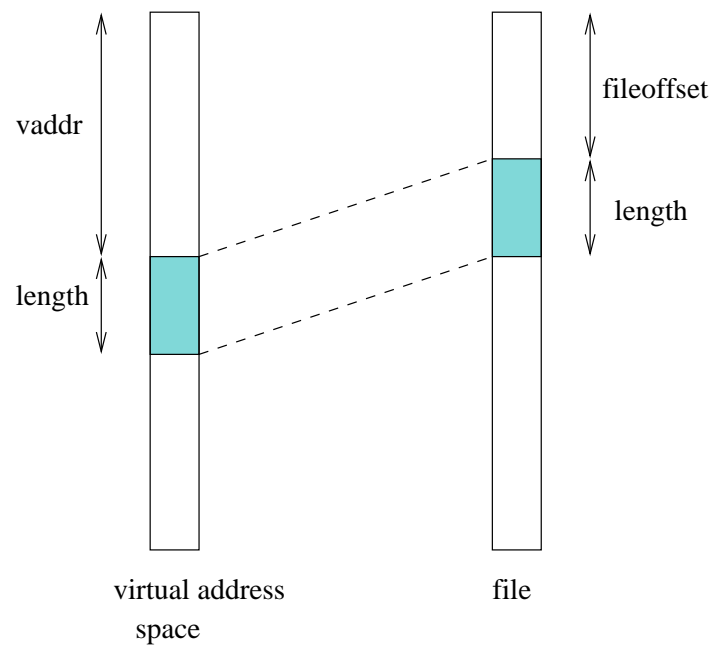
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Memory-mapping is an alternative to the read/write file interface.

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### 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

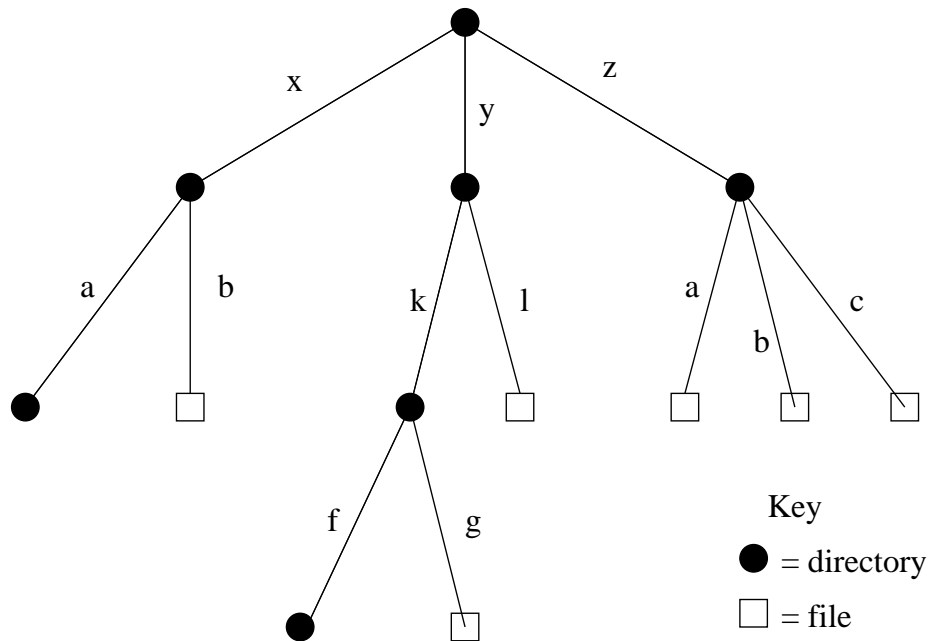
- what should happen if a memory mapped file is updated?
  - by a process that has mmapped the same file
  - by a process that is updating the file using a `write()` system call
- options are similar to those on the previous slide. Typically:
  - propagate lazily: processes that have mapped the file *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/user/courses/cs350/notes/filesys.pdf
```

### 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`

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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?)

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## Symbolic Links

- a *Symbolic link*, or *soft link*, is an association between two names in the file namespace. Think of it as 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`

## UNIX/Linux Link Example (1 of 3)

```
% cat > file1
This is file1.
<ctrl-d>
% ls -li
685844 -rw----- 1 user group 15 2008-08-20 file1
% ln file1 link1
% ln -s file1 sym1
% ln not-here link2
ln: not-here: No such file or directory
% ln -s not-here sym2
```

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Files, hard links, and soft/symbolic links.

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**UNIX/Linux Link Example (2 of 3)**

```
% ls -li
685844 -rw----- 2 user group 15 2008-08-20 file1
685844 -rw----- 2 user group 15 2008-08-20 link1
685845 lrwxrwxrwx 1 user group  5 2008-08-20 sym1 -> file1
685846 lrwxrwxrwx 1 user group  8 2008-08-20 sym2 -> not-here
% cat file1
This is file1.
% cat link1
This is file1.
% cat sym1
This is file1.
% cat sym2
cat: sym2: No such file or directory
% /bin/rm file1
```

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Accessing and manipulating files, hard links, and soft/symbolic links.

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**UNIX/Linux Link Example (3 of 3)**

```
% ls -li
685844 -rw----- 1 user group 15 2008-08-20 link1
685845 lrwxrwxrwx 1 user group  5 2008-08-20 sym1 -> file1
685846 lrwxrwxrwx 1 user group  8 2008-08-20 sym2 -> not-here
% cat link1
This is file1.
% cat sym1
cat: sym1: No such file or directory
% cat > file1
This is a brand new file1.
<ctrl-d>
% ls -li
685847 -rw----- 1 user group 27 2008-08-20 file1
685844 -rw----- 1 user group 15 2008-08-20 link1
685845 lrwxrwxrwx 1 user group  5 2008-08-20 sym1 -> file1
685846 lrwxrwxrwx 1 user group  8 2008-08-20 sym2 -> not-here
% cat link1
This is file1.
% cat sym1
This is a brand new file1.
```

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Different behaviour for hard links and soft/symbolic links.

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## 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:

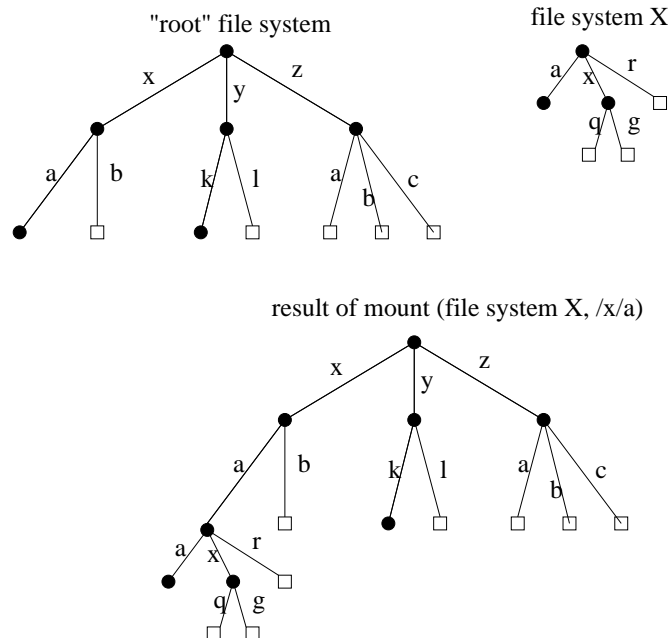
**DOS/Windows:** use two-part file names: file system name, pathname

– example: `C:\user\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
- fault tolerance

## 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

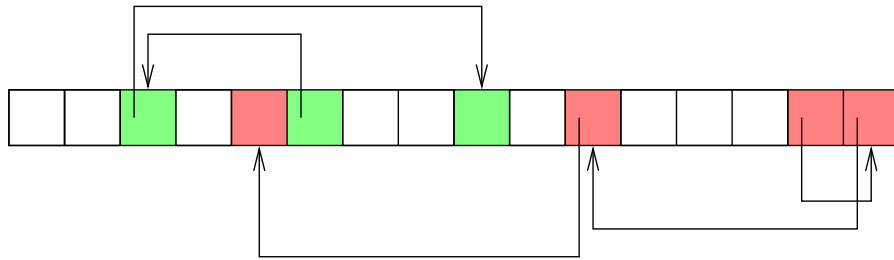
### external chaining: DOS file allocation table (FAT), for example

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

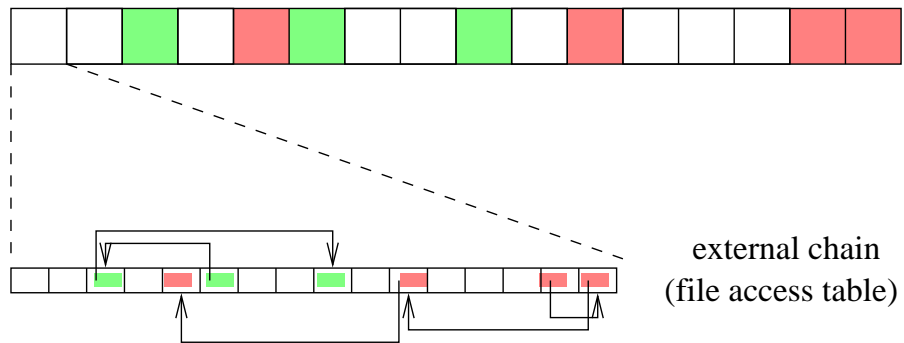
### per-file index: Unix i-node, for example

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

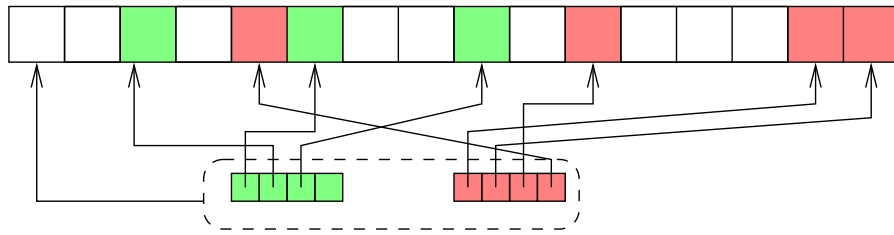
### Chaining



### 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 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 access 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

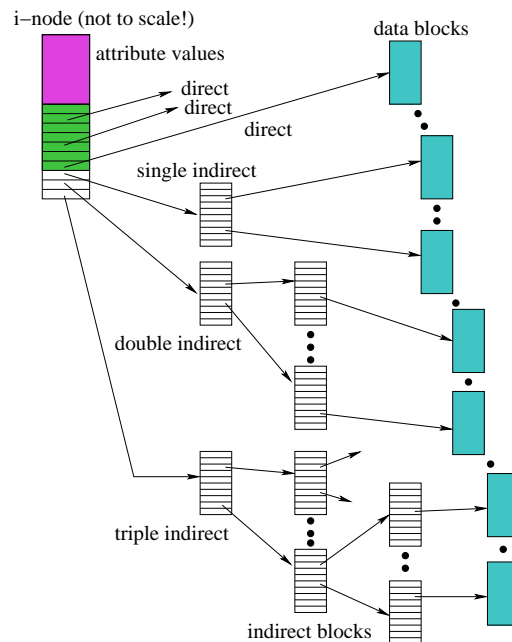
**direct block pointers:** approximately 10 of these

**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

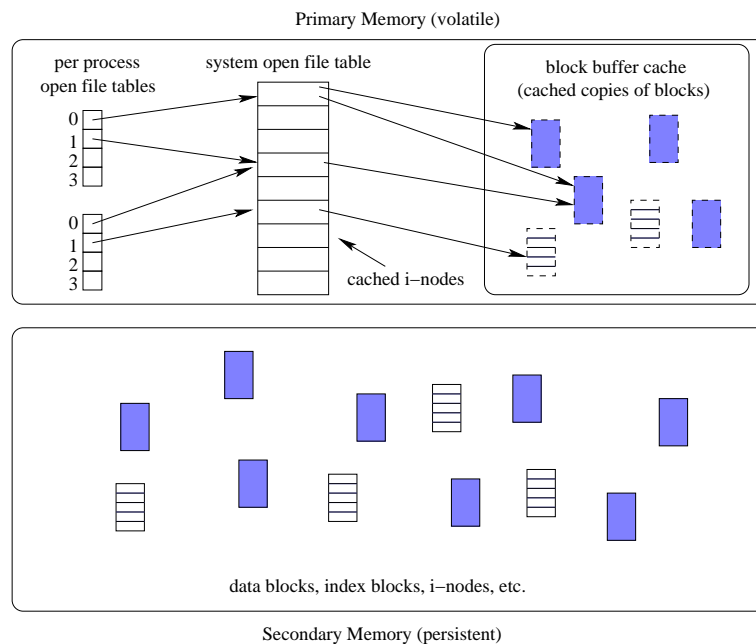
- hard links are simply directory entries
- for example, consider:  
`link(/y/k/g, /z/m)`
- to implement this:
  1. find out the internal file identifier for `/y/k/g`
  2. create a new entry in directory `/z`
    - file name in new entry is `m`
    - file identifier (i-number) in the new entry is the 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 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