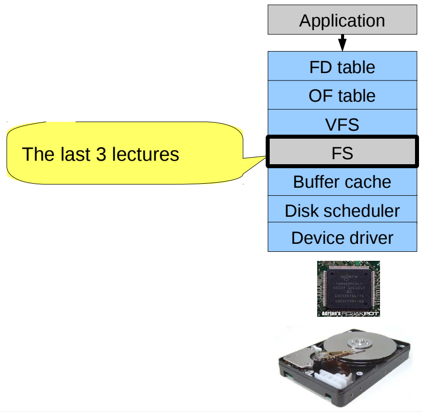
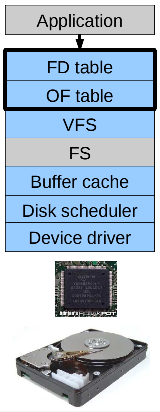
UNIX File Management (continued)

OS storage stack (recap)



File Descriptor & Open File Tables



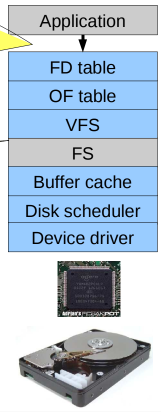
Motivation

System call interface:

```
fd = open("file",…);
read(fd,…);write(fd,…);lseek(fd,…);
close(fd);
```

FS interface:

```
inode = open("file",…);
read(inode,offset);
write(inode,offset);
close(inode);
```



File Descriptors

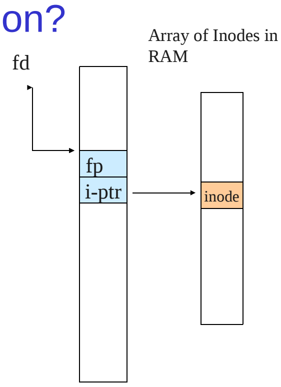
- File descriptors
  - Each open file has a file descriptor
  - Read/Write/lseek/…. use them to specify which file to operate on.
- State associated with a file fescriptor
  - File pointer
    - Determines where in the file the next read or write is performed
  - Mode
    - Was the file opened read-only, etc….

An Option?

- Use inode numbers as file descriptors and add a file pointer to the inode
- Problems
  - What happens when we concurrently open the same file twice?
    - We should get two separate file descriptors and file pointers….

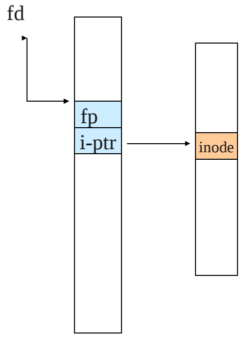
An Option?

- Single global open file array
  - *fd* is an index into the array
  - Entries contain file pointer and pointer to an inode



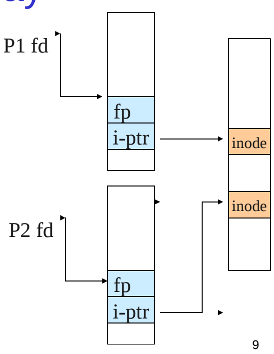
Issues

- File descriptor 1 is stdout
  - Stdout is
    - console for some processes
    - A file for others
- Entry 1 needs to be different per process!



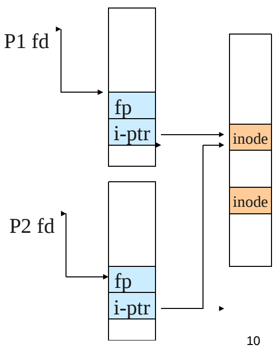
Per-process File Descriptor Array

- Each process has its own open file array
  - Contains fp, i-ptr etc.
  - *Fd* 1 can be any inode for each process (console, log file).



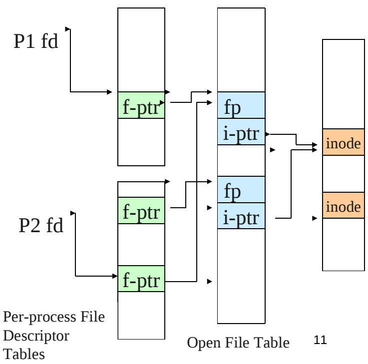
Issue

- Fork
  - Fork defines that the child shares the file pointer with the parent
- Dup2
  - Also defines the file descriptors share the file pointer
- With per-process table, we can only have independent file pointers
  - Even when accessing the same file



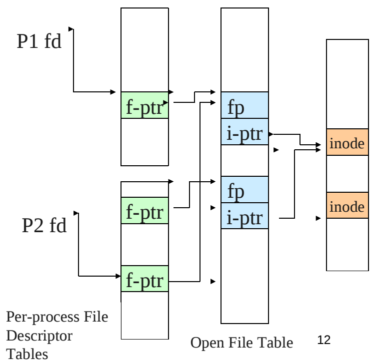
Per-Process *fd* table with global open file table

- Per-process file descriptor array
  - Contains pointers to *open file table entry*
- Open file table array
  - Contain entries with a fp and pointer to an inode.
- Provides
  - Shared file pointers if required
  - Independent file pointers if required
- Example:
  - All three *fds* refer to the same file, two share a file pointer, one has an independent file pointer

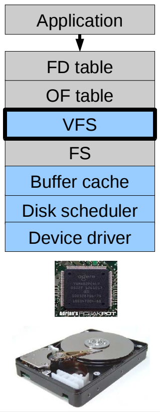


Per-Process *fd* table with global open file table

- Used by Linux and most other Unix operating systems



Virtual File System (VFS)



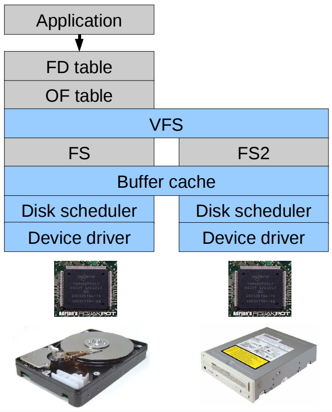
Older Systems only had a single file system

- They had file system specific open, close, read, write, … calls.
- The open file table pointed to an in-memory representation of the inode
  - inode format was specific to the file system used (s5fs, Berkley FFS, etc)
- However, modern systems need to support many file system types
  - ISO9660 (CDROM), MSDOS (floppy), ext2fs, tmpfs

Supporting Multiple File Systems

- Alternatives
  - Change the file system code to understand different file system types
    - Prone to code bloat, complex, non-solution
  - Provide a framework that separates file system independent and file system dependent code.
    - Allows different file systems to be "plugged in"
    - File descriptor, open file table and other parts of the kernel can be independent of underlying file system

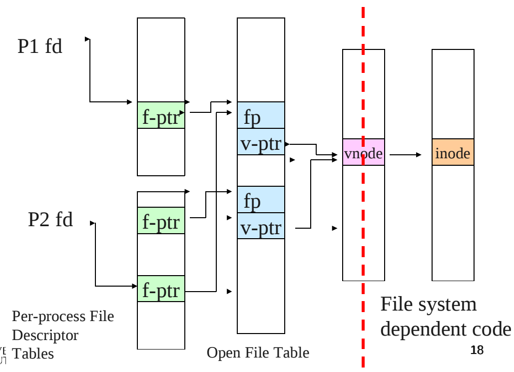
Virtual File System (VFS)



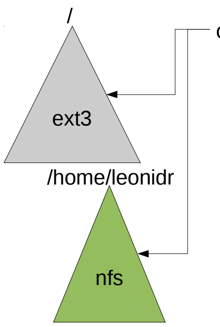
Virtual File System (VFS)

- Provides single system call interface for many file systems
  - E.g., UFS, Ext2, XFS, DOS, ISO9660,…
- Transparent handling of network file systems
  - E.g., NFS, AFS, CODA
- File-based interface to arbitrary device drivers (`/dev`)
- File-based interface to kernel data structures (`/proc`)
- Provides an indirection layer for system calls
  - File operation table set up at file open time
  - Points to actual handling code for particular type
  - Further file operations redirected to those functions

The file system independent code deals with vfs and vnodes



Virtual file system (VFS)



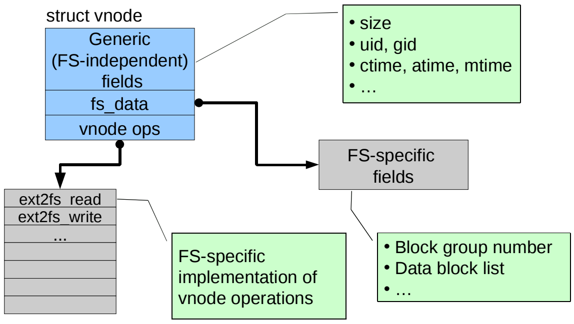
open("/home/leonidr/file", …);

Traversing the directory hierarchy may require VFS to issue requests to several underlying file systems

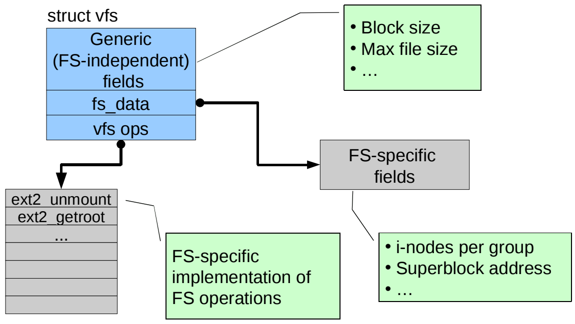
VFS Interface

- Reference
  - S.R. Kleiman., "Vnodes: An Architecture for Multiple File System Types in Sun Unix," USENIX Association: Summer Conference Proceedings, Atlanta, 1986
  - Linux and OS/161 differ slightly, but the principles are the same
- Two major data types
  - vfs
    - Represents all file system types
    - Contains pointers to functions to manipulate each file system as a whole (e.g. mount, unmount)
      - Form a standard interface to the file system
  - vnode
    - Represents a file (inode) in the underlying filesystem
    - Points to the real inode
    - Contains pointers to functions to manipulate files/inodes (e.g. open, close, read, write,…)

Vfs and Vnode Structures



Vfs and Vnode Structures



A look at OS/161's VFS

The OS161's file system type
Represents interface to a mounted filesystem

```
struct fs {
   int          (*fs_sync)(struct fs *);
   const char  *(*fs_getvolname)(struct fs *);
   struct vnode *(*fs_getroot)(struct fs *);
   int          (*fs_unmount)(struct fs *);

   void *fs_data;
};
```

Force the filesystem to flush its content to disk

Retrieve the volume name

Retrieve the vnode associated with the root of the filesystem

Unmount the filesystem
Note: mount called via function ptr passed to **vfs_mount**

Private file system specific data

Vnode

```
struct vnode {
  int vn_refcount;
  int vn_opencount;
  struct lock *vn_countlock;
  struct fs *vn_fs;
  void *vn_data;

  const struct vnode_ops *vn_ops;
};
```

Count the number of "references" to this vnode

Number of times vnode is currently open

Lock for mutual exclusive access to counts

Pointer to FS containing the vnode

Pointer to FS specific vnode data (e.g. inode)

Array of pointers to functions operating on vnodes

Vnode Ops

```
struct vnode_ops {
    unsigned long vop_magic;       /* should always be VOP_MAGIC */

    int (*vop_open)(struct vnode *object, int flags_from_open);
    int (*vop_close)(struct vnode *object);
    int (*vop_reclaim)(struct vnode *vnode);


    int (*vop_read)(struct vnode *file, struct uio *uio);
    int (*vop_readlink)(struct vnode *link, struct uio *uio);
    int (*vop_getdirentry)(struct vnode *dir, struct uio *uio);
    int (*vop_write)(struct vnode *file, struct uio *uio);
    int (*vop_ioctl)(struct vnode *object, int op, userptr_t data);
    int (*vop_stat)(struct vnode *object, struct stat *statbuf);
    int (*vop_gettype)(struct vnode *object, int *result);
    int (*vop_tryseek)(struct vnode *object, off_t pos);
    int (*vop_fsync)(struct vnode *object);
    int (*vop_mmap)(struct vnode *file /* add stuff */);
    int (*vop_truncate)(struct vnode *file, off_t len);
    int (*vop_namefile)(struct vnode *file, struct uio *uio);
```


Vnode Ops

```
    int (*vop_creat)(struct vnode *dir,
     const char *name, int excl,
     struct vnode **result);
    int (*vop_symlink)(struct vnode *dir,
       const char *contents, const char *name);
    int (*vop_mkdir)(struct vnode *parentdir,
     const char *name);
    int (*vop_link)(struct vnode *dir,
    const char *name, struct vnode *file);
    int (*vop_remove)(struct vnode *dir,
      const char *name);
    int (*vop_rmdir)(struct vnode *dir,
     const char *name);

    int (*vop_rename)(struct vnode *vn1, const char *name1,
      struct vnode *vn2, const char *name2);


    int (*vop_lookup)(struct vnode *dir,
      char *pathname, struct vnode **result);
    int (*vop_lookparent)(struct vnode *dir,
          char *pathname, struct vnode **result,
          char *buf, size_t len);
};
```


Vnode Ops

- Note that most operation are on vnodes. How do we operate on file names?
  - Higher level API on names that uses the internal VOP_* functions

```
int vfs_open(char *path, int openflags, struct vnode **ret);
void vfs_close(struct vnode *vn);
int vfs_readlink(char *path, struct uio *data);
int vfs_symlink(const char *contents, char *path);
int vfs_mkdir(char *path);
int vfs_link(char *oldpath, char *newpath);
int vfs_remove(char *path);
int vfs_rmdir(char *path);
int vfs_rename(char *oldpath, char *newpath);

int vfs_chdir(char *path);
int vfs_getcwd(struct uio *buf);
```


Example: OS/161 emufs vnode ops

```
/*
 * Function table for emufs
   files.
 */
static const struct vnode_ops
   emufs_fileops = {
   VOP_MAGIC,   /* mark this a
   valid vnode ops table */

   emufs_open,
   emufs_close,
   emufs_reclaim,

   emufs_read,
   NOTDIR,   /* readlink */
   NOTDIR,   /* getdirentry */
   emufs_write,
   emufs_ioctl,
   emufs_stat,
   emufs_file_gettype,
   emufs_tryseek,
   emufs_fsync,
   UNIMP,    /* mmap */
   emufs_truncate,
   NOTDIR,   /* namefile */

   NOTDIR,   /* creat */
   NOTDIR,   /* symlink */
   NOTDIR,   /* mkdir */
   NOTDIR,   /* link */
   NOTDIR,   /* remove */
   NOTDIR,   /* rmdir */
   NOTDIR,   /* rename */

   NOTDIR,   /* lookup */
   NOTDIR,   /* lookparent */
};
```

Buffer Cache

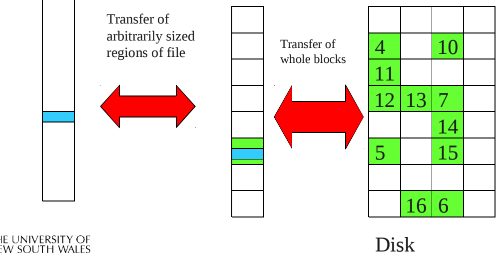
- Application
- FD table
- OF table
- VFS
- FS
- **Buffer cache**
- Disk scheduler
- Device driver

Buffer

- Buffer:
  - Temporary storage used when transferring data between two entities
    - Especially when the entities work at different rates
    - Or when the unit of transfer is incompatible
    - Example: between application program and disk

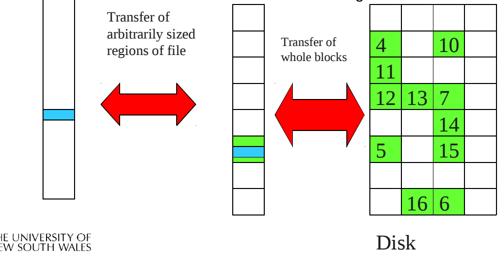
Buffering Disk Blocks

- Allow applications to work with arbitrarily sized region of a file
  - However, apps can still optimise for a particular block size



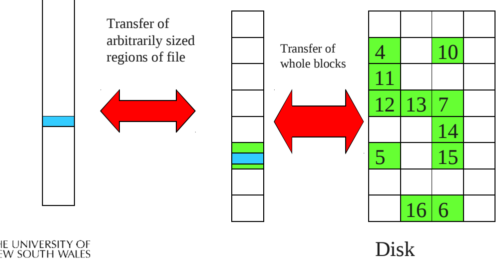
Buffering Disk Blocks

- Writes can return immediately after copying to kernel buffer
  - Avoids waiting until write to disk is complete
  - Write is scheduled in the background



Buffering Disk Blocks

- Can implement read-ahead by pre-loading next block on disk into kernel buffer
  - Avoids having to wait until next read is issued

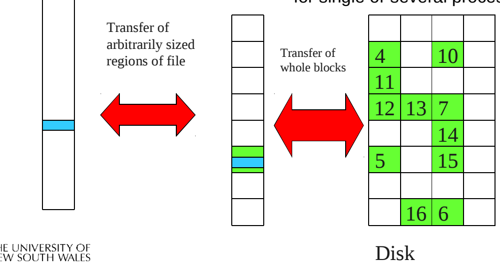


Cache

- Cache:
  - Fast storage used to temporarily hold data to speed up repeated access to the data
    - Example: Main memory can cache disk blocks

Caching Disk Blocks

- On access
  - Before loading block from disk, check if it is in cache first
    - Avoids disk accesses
- Can optimise for repeated access for single or several processes



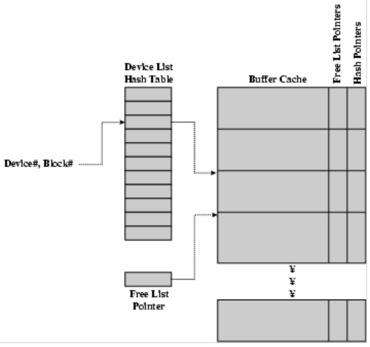
Buffering and caching are related

- Data is read into buffer; extra cache copy would be wasteful
- After use, block should be put in a cache
- Future access may hit cached copy
- Cache utilises unused kernel memory space; may have to shrink

Unix Buffer Cache

On read

- Hash the device#, block#
- Check if match in buffer cache
- Yes, simply use in-memory copy
- No, follow the collision chain
- If not found, we load block from disk into cache



Replacement

- What happens when the buffer cache is full and we need to read another block into memory?
  - We must choose an existing entry to replace
    - Need a policy to choose a victim
      - Can use First-in First-out
      - Least Recently Used, or others.
    - Timestamps required for LRU implementation
    - However, is strict LRU what we want?

File System Consistency

- File data is expected to survive
- Strict LRU could keep critical data in memory forever if it is frequently used.

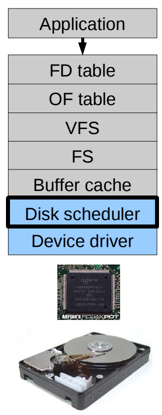
File System Consistency

- Generally, cached disk blocks are prioritised in terms of how critical they are to file system consistency
  - Directory blocks, inode blocks if lost can corrupt entire filesystem
    - E.g. imagine losing the root directory
    - These blocks are usually scheduled for immediate write to disk
  - Data blocks if lost corrupt only the file that they are associated with
    - These block are only scheduled for write back to disk periodically
    - In UNIX, flushd (*flush daemon*) flushes all modified blocks to disk every 30 seconds

File System Consistency

- Alternatively, use a write-through cache
  - All modified blocks are written immediately to disk
  - Generates much more disk traffic
    - Temporary files written back
    - Multiple updates not combined
  - Used by DOS
    - Gave okay consistency when
      - Floppies were removed from drives
      - Users were constantly resetting (or crashing) their machines
  - Still used, e.g. USB storage devices

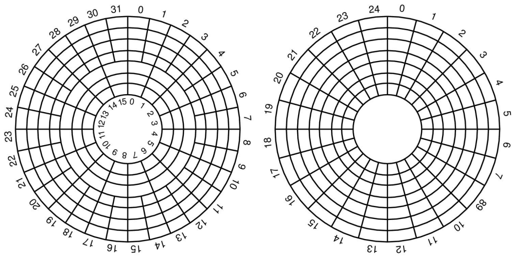
Disk scheduler



Disk Management

- Management and ordering of disk access requests is important:
  - Huge speed gap between memory and disk
  - Disk throughput is extremely sensitive to
    - Request order $\Rightarrow$ Disk Scheduling
    - Placement of data on the disk $\Rightarrow$ file system design
  - Disk scheduler must be aware of *disk geometry*

Disk Geometry



- Physical geometry of a disk with two zones
  - Outer tracks can store more sectors than inner without exceed max information density
- A possible virtual geometry for this disk

Evolution of Disk Hardware

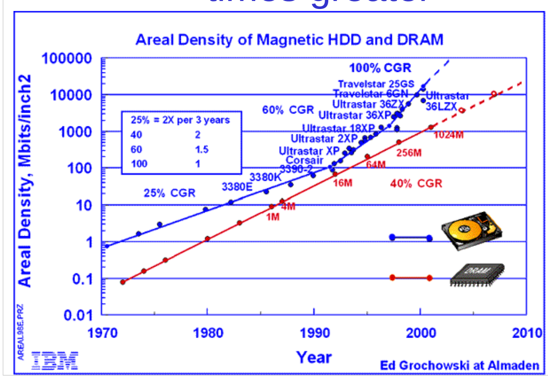
Parameter	IBM 360-KB floppy disk	WD 18300 hard disk
Number of cylinders	40	10601
Tracks per cylinder	2	12
Sectors per track	9	281 (avg)
Sectors per disk	720	35742000
Bytes per sector	512	512
Disk capacity	360 KB	18.3 GB
Seek time (adjacent cylinders)	6 msec	0.8 msec
Seek time (average case)	77 msec	6.9 msec
Rotation time	200 msec	8.33 msec
Motor stop/start time	250 msec	20 sec
Time to transfer 1 sector	22 msec	17 µsec

Disk parameters for the original IBM PC floppy disk and a Western Digital WD 18300 hard disk

Things to Note

- Average seek time is approx 12 times better
- Rotation time is 24 times faster
- Transfer time is 1300 times faster
  - Most of this gain is due to increase in density
- Represents a gradual engineering improvement

Storage Capacity is 50000 times greater



Estimating Access Time

- *Seek time* T_s: Moving the head to the required track
  - not linear in the number of tracks to traverse:
    - ➜ startup time
    - ➜ settling time
  - Typical average seek time: a few milliseconds
- *Rotational delay:*
  - rotational speed, r, of 5,000 to 10,000rpm
  - At 10,000rpm, one revolution per 6ms $\Rightarrow$ average delay 3ms
- *Transfer time:*

  to transfer b bytes, with N bytes per track: $T = \frac{b}{rN}$

Total average access time: $T_a = T_s + \frac{1}{2r} + \frac{b}{rN}$

A Timing Comparison

- $T_s = 2$ ms, $r = 10,000$ rpm, 512B sect, 320 sect/track
- Read a file with 2560 sectors (= 1.3MB)
- File stored compactly (8 adjacent tracks):

Read first track	
Average seek	2ms
Rot. delay	3ms
Read 320 sectors	6ms
	11ms

$\Rightarrow$ All sectors: $11 + 7 * 8 = 67\ ms$

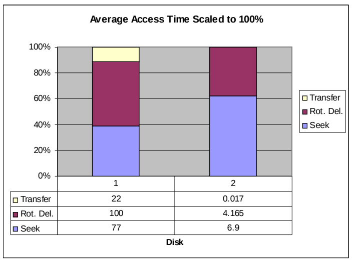
- Sectors distributed randomly over the disk:

Read any sector	
Average seek	2ms
Rot. delay	3ms
Read 1 sector	0.01875ms
	5.01875ms

$\Rightarrow$ All: $2560 * 5.01875 = 20,328ms$

Disk Performance is Entirely Dominated by Seek and Rotational Delays

- Will only get worse as capacity increases much faster than increase in seek time and rotation speed
  - Note it has been easier to spin the disk faster than improve seek time
- Operating System should minimise mechanical delays as much as possible



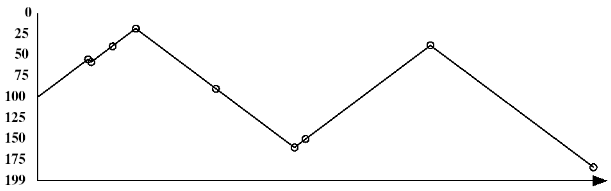
Disk Arm Scheduling Algorithms

- Time required to read or write a disk block determined by 3 factors
  1. Seek time
  2. Rotational delay
  3. Actual transfer time
- Seek time dominates
- For a single disk, there will be a number of I/O requests
  - Processing them in random order leads to worst possible performance

First-in, First-out (FIFO)

- Process requests as they come
- Fair (no starvation)
- Good for a few processes with clustered requests
- Deteriorates to random if there are many processes

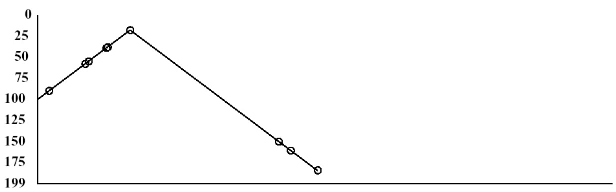
Request tracks: 55, 58, 39, 18, 90, 160, 150, 38, 184



Shortest Seek Time First

- Select request that minimises the seek time
- Generally performs much better than FIFO
- May lead to starvation

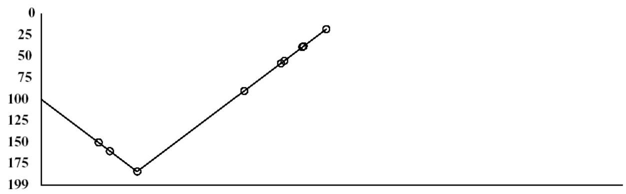
Request tracks: 55, 58, 39, 18, 90, 160, 150, 38, 184



Elevator Algorithm (SCAN)

- **Move head in one direction**
  - Services requests in track order until it reaches the last track, then reverses direction
- **Better than FIFO, usually worse than SSTF**
- **Avoids starvation**
- **Makes poor use of sequential reads (on down-scan)**
- **Less Locality**

Request tracks: 55, 58, 39, 18, 90, 160, 150, 38, 184



Modified Elevator (Circular SCAN, C-SCAN)

- Like elevator, but reads sectors in only one direction
  - When reaching last track, go back to first track non-stop
- Better locality on sequential reads
- Better use of read ahead cache on controller
- Reduces max delay to read a particular sector

Request tracks: 55, 58, 39, 18, 90, 160, 150, 38, 184