CS162
Operating Systems and Systems Programming
Lecture 10

Scheduling 1: Concepts and Classic Policies

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Recall: Monitors and Condition Variables

- Monitor: a lock and zero or more condition variables for managing concurrent access to shared data
  - Use of Monitors is a programming paradigm
  - Some languages like Java provide monitors in the language
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section
- Operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!

Recall: Structure of *Mesa* Monitor Program

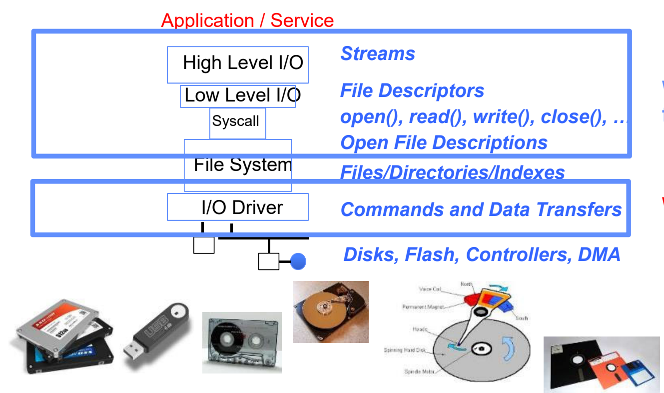
- Monitors represent the synchronization logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of mesa monitor-based program:

```
lock
while (need to wait) {
   condvar.wait();
}
unlock

do something so no need to wait

lock

condvar.signal();

unlock
```

Check and/or update state variables
Wait if necessary

Check and/or update state variables

Recall: I/O and Storage Layers



What we've covered so far…

What we'll peek at next

Layers of I/O…

User App:

```
length = read(input_fd, buffer, BUFFER_SIZE);
```

User library:

```
ssize_t read(int, void *, size_t) {
  marshal args into registers
  issue syscall
  register result of syscall to rtn value
};
```

Application / Service

High Level I/O

Low Level I/O

Syscall

File System

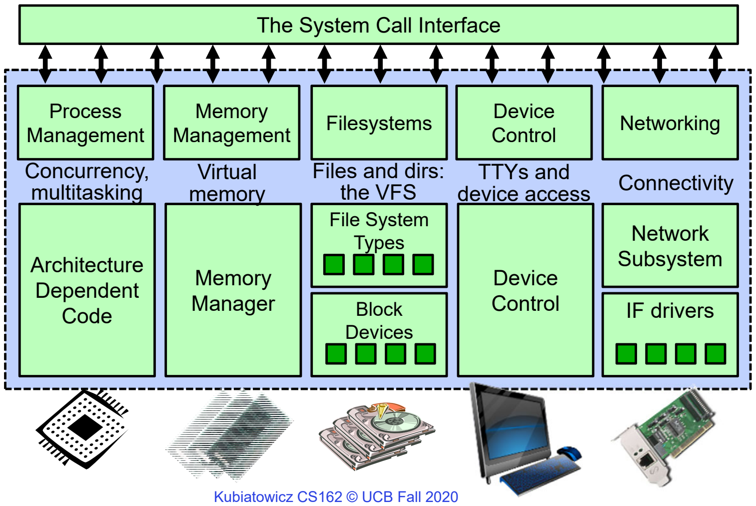
I/O Driver

```
Exception U→K, interrupt processing
void syscall_handler (struct intr_frame *f) {
   unmarshall call#, args from regs
   dispatch : handlers[call#](args)
   marshal results fo syscall ret
}
```

```
ssize_t vfs_read(struct file *file, char __user *buf,
                 size_t count, loff_t *pos) {
  User Process/File System relationship
  call device driver to do the work
}
```

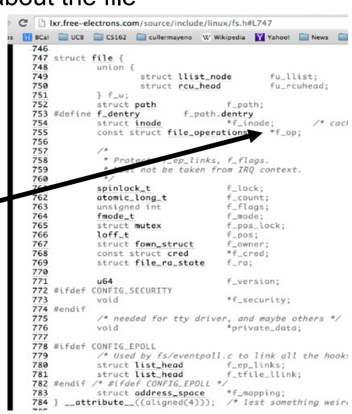
Device Driver

Many different types of I/O



Recall: Internal OS File Description

- Internal Data Structure describing everything about the file
  – Where it resides
  – Its status
  – How to access it
- Pointer: `struct file *file`
  – Everything accessed with file descriptor has one of these
- `Struct file_operations *f_op`: Describes how this particular device implements its operations
  – For disks: points to file operations
  – For pipes: points to pipe operations
  – For sockets: points to socket operations



lxr.free-electrons.com/source/include/linux/fs.h#L747

```
struct file {
        union {
                struct llist_node       fu_llist;
                struct rcu_head         fu_rcuhead;
        } f_u;
        struct path             f_path;
#define f_dentry        f_path.dentry
        struct inode            *f_inode;       /* cac
        const struct file_operations    *f_op;

        /*
         * Protects f_ep_links, f_flags.
         * Must not be taken from IRQ context.
         */
        spinlock_t              f_lock;
        atomic_long_t           f_count;
        unsigned int            f_flags;
        fmode_t                 f_mode;
        struct mutex            f_pos_lock;
        loff_t                  f_pos;
        struct fown_struct      f_owner;
        const struct cred       *f_cred;
        struct file_ra_state    f_ra;

        u64                     f_version;
#ifdef CONFIG_SECURITY
        void                    *f_security;
#endif
        /* needed for tty driver, and maybe others */
        void                    *private_data;

#ifdef CONFIG_EPOLL
        /* Used by fs/eventpoll.c to link all the hook
        struct list_head        f_ep_links;
        struct list_head        f_tfile_llink;
#endif /* #ifdef CONFIG_EPOLL */
        struct address_space    *f_mapping;
} __attribute__((aligned(4)));  /* lest something weir
```


File_operations: Why everything can look like a file

- Associated with particular hardware device or environment (i.e. file system)
- Registers / Unregisters itself with the kernel
- Handler functions for each of the file operations

```
struct file_operations {
    struct module *owner;
    loff_t (*llseek) (struct file *, loff_t, int);
    ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
    ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
    ssize_t (*aio_read) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
    ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
    int (*readdir) (struct file *, void *, filldir_t);
    unsigned int (*poll) (struct file *, struct poll_table_struct *);
    int (*ioctl) (struct inode *, struct file *, unsigned int, unsigned long);
    int (*mmap) (struct file *, struct vm_area_struct *);
    int (*open) (struct inode *, struct file *);
    int (*flush) (struct file *, fl_owner_t id);
    int (*release) (struct inode *, struct file *);
    int (*fsync) (struct file *, struct dentry *, int datasync);
    int (*fasync) (int, struct file *, int);
    int (*flock) (struct file *, int, struct file_lock *);
    [...]
};
```

File System: From Syscall to Driver

```c
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return
  if (!file->f_op || (!file->f_op->read &&
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

- Read up to “count” bytes from “file” starting from “pos” into “buf”.
- Return error or number of bytes read.

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```c
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) retur
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Make sure we are allowed to read this file

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```c
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Check if file has read methods

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```c
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, cour
    else
      ret = do_sync_read(file, buf, count, p
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

- Check whether we can write to buf (e.g., buf is in the user space range)
- unlikely(): hint to branch prediction this condition is unlikely

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos)
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Check whether we read from a valid range in the file.

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

If driver provide a read function (f_op->read) use it; otherwise use do_sync_read()

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(f
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Notify the parent of this file that the file was read (see http://www.fieldses.org/~bfields/kernel/vfs.txt)

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Update the number of bytes read by “current” task (for scheduling purposes)

Linux: `fs/read_write.c`

File System: From Syscall to Driver

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

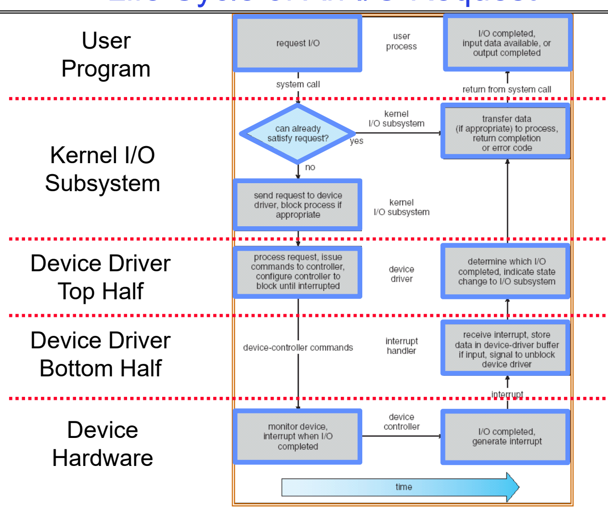
Update the number of read syscalls by "current" task (for scheduling purposes)

Linux: `fs/read_write.c`

Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the `ioctl()` system call
- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - » implements a set of standard, cross-device calls like `open()`, `close()`, `read()`, `write()`, `ioctl()`, `strategy()`
    - » This is the kernel's interface to the device driver
    - » Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - » Gets input or transfers next block of output
    - » May wake sleeping threads if I/O now complete

Life Cycle of An I/O Request

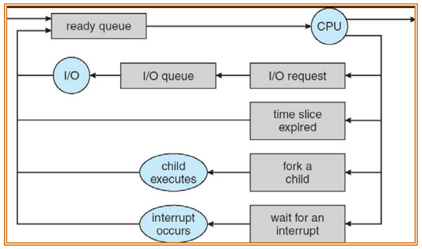


Goal for Today

```
if ( readyThreads(TCBs) ) {
        nextTCB = selectThread(TCBs);
        run( nextTCB );
} else {
        run_idle_thread();
}
```

- Discussion of Scheduling:
  - Which thread should run on the CPU next?
- Scheduling goals, policies
- Look at a number of different schedulers

Recall: Scheduling



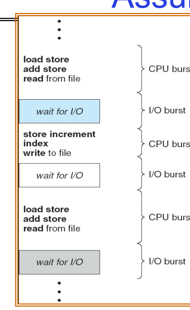
- Question: How is the OS to decide which of several tasks to take off a queue?
- Scheduling: deciding which threads are given access to resources from moment to moment
  – Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access

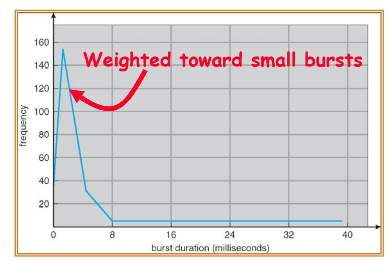
Scheduling: All About Queues

Scheduling Assumptions

- CPU scheduling big area of research in early 70's
- Many implicit assumptions for CPU scheduling:
  – One program per user
  – One thread per program
  – Programs are independent
- Clearly, these are unrealistic but they simplify the problem so it can be solved
  – For instance: is "fair" about fairness among users or programs?
    » If I run one compilation job and you run five, you get five times as much CPU on many operating systems
- The high-level goal: Dole out CPU time to optimize some desired parameters of system

Assumption: CPU Bursts





- Execution model: programs alternate between bursts of CPU and I/O
  – Program typically uses the CPU for some period of time, then does I/O, then uses CPU again
  – Each scheduling decision is about which job to give to the CPU for use by its next CPU burst
  – With timeslicing, thread may be forced to give up CPU before finishing current CPU burst

Scheduling Policy Goals/Criteria

- Minimize Response Time
  - Minimize elapsed time to do an operation (or job)
  - Response time is what the user sees:
    - » Time to echo a keystroke in editor
    - » Time to compile a program
    - » Real-time Tasks: Must meet deadlines imposed by World
- Maximize Throughput
  - Maximize operations (or jobs) per second
  - Throughput related to response time, but not identical:
    - » Minimizing response time will lead to more context switching than if you only maximized throughput
  - Two parts to maximizing throughput
    - » Minimize overhead (for example, context-switching)
    - » Efficient use of resources (CPU, disk, memory, etc)
- Fairness
  - Share CPU among users in some equitable way
  - Fairness is not minimizing average response time:
    - » Better *average* response time by making system *less* fair

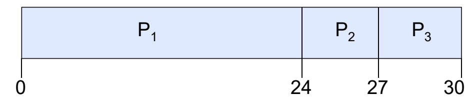
First-Come, First-Served (FCFS) Scheduling

- First-Come, First-Served (FCFS)
  - Also “First In, First Out” (FIFO) or “Run until done”
    - » In early systems, FCFS meant one program scheduled until done (including I/O)
    - » Now, means keep CPU until thread blocks

- Example:

Process	Burst Time
P_1	24
P_2	3
P_3	3

  - Suppose processes arrive in the order: P_1 , P_2 , P_3 The Gantt Chart for the schedule is:



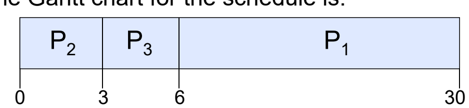
  - Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
  - Average waiting time: (0 + 24 + 27)/3 = 17
  - Average Completion time: (24 + 27 + 30)/3 = 27
- *Convoy effect:* short process stuck behind long process

Convoy effect

- With FCFS non-preemptive scheduling, convoys of small tasks tend to build up when a large one is running.

FCFS Scheduling (Cont.)

- Example continued:
  - Suppose that processes arrive in order: P2 , P3 , P1 Now, the Gantt chart for the schedule is:



  - Waiting time for P1 = 6; P2 = 0; P3 = 3
  - Average waiting time: (6 + 0 + 3)/3 = 3
  - Average Completion time: (3 + 6 + 30)/3 = 13
- In second case:
  - Average waiting time is much better (before it was 17)
  - Average completion time is better (before it was 27)
- FIFO Pros and Cons:
  - Simple (+)
  - Short jobs get stuck behind long ones (-)
    - » Safeway: Getting milk, always stuck behind cart full of items! Upside: get to read about Space Aliens!

Round Robin (RR) Scheduling

- FCFS Scheme: Potentially bad for short jobs!
  - Depends on submit order
  - If you are first in line at supermarket with milk, you don't care who is behind you, on the other hand…
- Round Robin Scheme: Preemption!
  - Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds
  - After quantum expires, the process is preempted and added to the end of the ready queue.
  - n processes in ready queue and time quantum is $q \Rightarrow$
    - » Each process gets $1/n$ of the CPU time
    - » In chunks of at most q time units
    - » No process waits more than $(n-1)q$ time units

RR Scheduling (Cont.)

- Performance
  - q large $\Rightarrow$ FCFS
  - q small $\Rightarrow$ Interleaved (really small $\Rightarrow$ hyperthreading?)
  - q must be large with respect to context switch, otherwise overhead is too high (all overhead)

Example of RR with Time Quantum = 20

- Example:

Process	Burst Time
P_1	53
P_2	8
P_3	68
P_4	24

- The Gantt chart is:

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

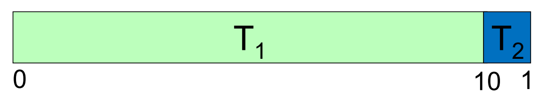
0 20 28 48 68 88 108 112 125 145 153

- Waiting time for $P_1=(68-20)+(112-88)=72$
  $P_2=(20-0)=20$
  $P_3=(28-0)+(88-48)+(125-108)=85$
  $P_4=(48-0)+(108-68)=88$
- Average waiting time = (72+20+85+88)/4=66¼
- Average completion time = (125+28+153+112)/4 = 104½

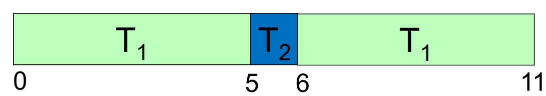
- Thus, Round-Robin Pros and Cons:
  - Better for short jobs, Fair (+)
  - Context-switching time adds up for long jobs (-)

Decrease Response Time

- T_1: Burst Length 10
- T_2: Burst Length 1
- $Q = 10$



  - Average Response Time = (10 + 11)/2 = 10.5
- $Q = 5$

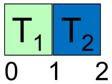


  - Average Response Time = (6 + 11)/2 = 8.5

Same Response Time

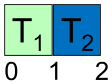
- T_1: Burst Length 1
- T_2: Burst Length 1

- $Q = 10$



  – Average Response Time = (1 + 2)/2 = 1.5

- $Q = 1$

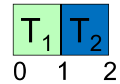


  – Average Response Time = (1 + 2)/2 = 1.5

Increase Response Time

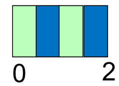
- T_1: Burst Length 1
- T_2: Burst Length 1

- $Q = 1$



  – Average Response Time = (1 + 2)/2 = 1.5

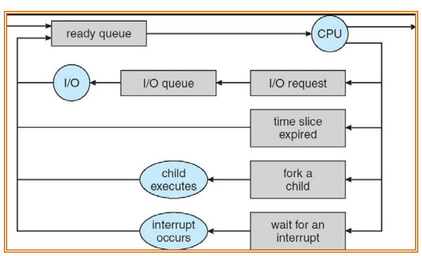
- $Q = 0.5$



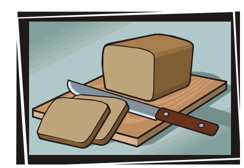
  – Average Response Time = (1.5 + 2)/2 = 1.75

How to Implement RR in the Kernel?

- FIFO Queue, as in FCFS
- But preempt job after quantum expires, and send it to the back of the queue
  – How? Timer interrupt!
  – And, of course, careful synchronization



Round-Robin Discussion



- How do you choose time slice?
  – What if too big?
    » Response time suffers
  – What if infinite (∞)?
    » Get back FIFO
  – What if time slice too small?
    » Throughput suffers!
- Actual choices of timeslice:
  – Initially, UNIX timeslice one second:
    » Worked ok when UNIX was used by one or two people.
    » What if three compilations going on? 3 seconds to echo each keystroke!
  – Need to balance short-job performance and long-job throughput:
    » Typical time slice today is between 10ms – 100ms
    » Typical context-switching overhead is 0.1ms – 1ms
    » Roughly 1% overhead due to context-switching

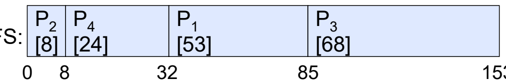
Comparisons between FCFS and Round Robin

- Assuming zero-cost context-switching time, is RR always better than FCFS?
- Simple example: 10 jobs, each take 100s of CPU time
  RR scheduler quantum of 1s
  All jobs start at the same time
- Completion Times:

Job #	FIFO	RR
1	100	991
2	200	992
…	…	…
9	900	999
10	1000	1000

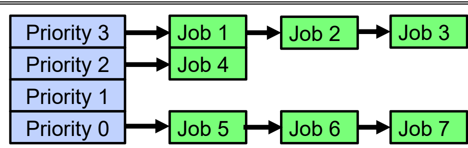
  – Both RR and FCFS finish at the same time
  – Average response time is much worse under RR!
    » Bad when all jobs same length
- Also: Cache state must be shared between all jobs with RR but can be devoted to each job with FIFO
  – Total time for RR longer even for zero-cost switch!

Earlier Example with Different Time Quantum

Best FCFS:


	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	61¼
	Q = 8	80	8	85	56	57¼
	Q = 10	82	10	85	68	61¼
	Q = 20	72	20	85	88	66¼
	Worst FCFS	68	145	0	121	83½
Completion Time	Best FCFS	85	8	153	32	69½
	Q = 1	137	30	153	81	100½
	Q = 5	135	28	153	82	99½
	Q = 8	133	16	153	80	95½
	Q = 10	135	18	153	92	99½
	Q = 20	125	28	153	112	104½
	Worst FCFS	121	153	68	145	121¾

Handling Differences in Importance: Strict Priority Scheduling



- Execution Plan
  – Always execute highest-priority runable jobs to completion
  – Each queue can be processed in RR with some time-quantum
- Problems:
  – Starvation:
    » Lower priority jobs don't get to run because higher priority jobs
  – Deadlock: Priority Inversion
    » Happens when low priority task has lock needed by high-priority task
    » Usually involves third, intermediate priority task preventing high-priority task from running
- How to fix problems?
  – Dynamic priorities – adjust base-level priority up or down based on heuristics about interactivity, locking, burst behavior, etc…

Scheduling Fairness

- What about fairness?
  – Strict fixed-priority scheduling between queues is unfair (run highest, then next, etc):
    » long running jobs may never get CPU
    » Urban legend: In Multics, shut down machine, found 10-year-old job ⇒ Ok, probably not…
  – Must give long-running jobs a fraction of the CPU even when there are shorter jobs to run
  – Tradeoff: fairness gained by hurting avg response time!

Scheduling Fairness

- How to implement fairness?
  - Could give each queue some fraction of the CPU
    - » What if one long-running job and 100 short-running ones?
    - » Like express lanes in a supermarket—sometimes express lanes get so long, get better service by going into one of the other lines
  - Could increase priority of jobs that don't get service
    - » What is done in some variants of UNIX
    - » This is ad hoc—what rate should you increase priorities?
    - » And, as system gets overloaded, no job gets CPU time, so everyone increases in priority⇒Interactive jobs suffer

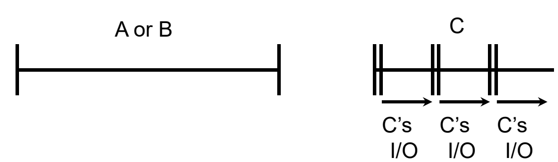
What if we Knew the Future?

- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  - Run whatever job has least amount of computation to do
  - Sometimes called "Shortest Time to Completion First" (STCF)
- Shortest Remaining Time First (SRTF):
  - Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
  - Sometimes called "Shortest Remaining Time to Completion First" (SRTCF)
- These can be applied to whole program or current CPU burst
  - Idea is to get short jobs out of the system
  - Big effect on short jobs, only small effect on long ones
  - Result is better average response time

Discussion

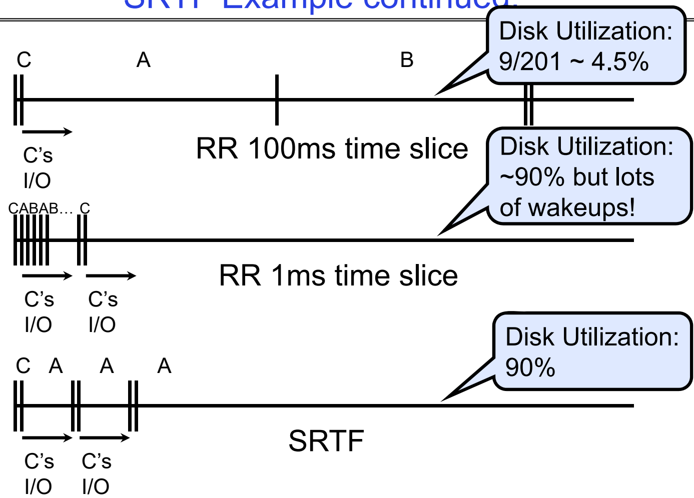
- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - Since SRTF is always at least as good as SJF, focus on SRTF
- Comparison of SRTF with FCFS
  - What if all jobs the same length?
    - » SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
  - What if jobs have varying length?
    - » SRTF: short jobs not stuck behind long ones

Example to illustrate benefits of SRTF



- Three jobs:
  - A, B: both CPU bound, run for week
    C: I/O bound, loop 1ms CPU, 9ms disk I/O
  - If only one at a time, C uses 90% of the disk, A or B could use 100% of the CPU
- With FCFS:
  - Once A or B get in, keep CPU for two weeks
- What about RR or SRTF?
  - Easier to see with a timeline

SRTF Example continued:

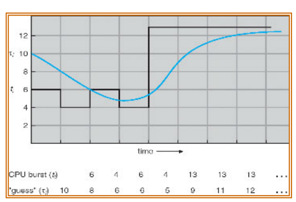


SRTF Further discussion

- Starvation
  - SRTF can lead to starvation if many small jobs!
  - Large jobs never get to run
- Somehow need to predict future
  - How can we do this?
  - Some systems ask the user
    - » When you submit a job, have to say how long it will take
    - » To stop cheating, system kills job if takes too long
  - But: hard to predict job's runtime even for non-malicious users
- Bottom line, can't really know how long job will take
  - However, can use SRTF as a yardstick for measuring other policies
  - Optimal, so can't do any better
- SRTF Pros & Cons
  - Optimal (average response time) (+)
  - Hard to predict future (-)
  - Unfair (-)

Predicting the Length of the Next CPU Burst

- Adaptive: Changing policy based on past behavior
  - CPU scheduling, in virtual memory, in file systems, etc
  - Works because programs have predictable behavior
    - » If program was I/O bound in past, likely in future
    - » If computer behavior were random, wouldn't help
- Example: SRTF with estimated burst length
  - Use an estimator function on previous bursts:
    Let tn-1, tn-2, tn-3, etc. be previous CPU burst lengths.
    Estimate next burst τn = f(tn-1, tn-2, tn-3, …)
  - Function f could be one of many different time series estimation schemes (Kalman filters, etc)
  - For instance, exponential averaging
    $\tau n = \alpha tn\text{-}1+(1-\alpha)\tau n\text{-}1$
    with $(0<\alpha\leq 1)$



Lottery Scheduling

- Yet another alternative: Lottery Scheduling
  - Give each job some number of lottery tickets
  - On each time slice, randomly pick a winning ticket
  - On average, CPU time is proportional to number of tickets given to each job
- How to assign tickets?
  - To approximate SRTF, short running jobs get more, long running jobs get fewer
  - To avoid starvation, every job gets at least one ticket (everyone makes progress)
- Advantage over strict priority scheduling: behaves gracefully as load changes
  - Adding or deleting a job affects all jobs proportionally, independent of how many tickets each job possesses

Lottery Scheduling Example (Cont.)

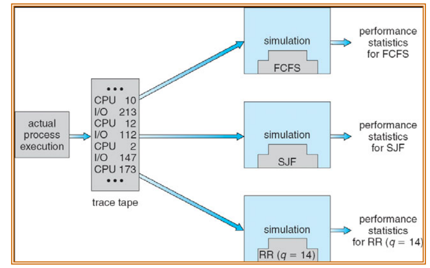
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# short jobs/ # long jobs	% of CPU each short jobs gets	% of CPU each long jobs gets
1/1	91%	9%
0/2	N/A	50%
2/0	50%	N/A
10/1	9.9%	0.99%
1/10	50%	5%

  - What if too many short jobs to give reasonable response time?
    - » If load average is 100, hard to make progress
    - » One approach: log some user out

How to Evaluate a Scheduling algorithm?

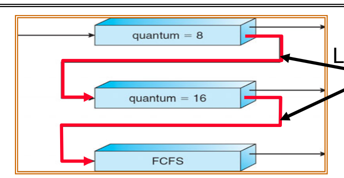
- Deterministic modeling
  - takes a predetermined workload and compute the performance of each algorithm for that workload
- Queueing models
  - Mathematical approach for handling stochastic workloads
- Implementation/Simulation:
  - Build system which allows actual algorithms to be run against actual data
  - Most flexible/general



How to Handle Simultaneous Mix of Diff Types of Apps?

- Consider mix of interactive and high throughput apps:
  - How to best schedule them?
  - How to recognize one from the other?
    - » Do you trust app to say that it is “interactive”?
  - Should you schedule the set of apps identically on servers, workstations, pads, and cellphones?
- For instance, is Burst Time (observed) useful to decide which application gets CPU time?
  - Short Bursts $\Rightarrow$ Interactivity $\Rightarrow$ High Priority?
- Assumptions encoded into many schedulers:
  - Apps that sleep a lot and have short bursts must be interactive apps – they should get high priority
  - Apps that compute a lot should get low(er?) priority, since they won’t notice intermittent bursts from interactive apps
- Hard to characterize apps:
  - What about apps that sleep for a long time, but then compute for a long time?
  - Or, what about apps that must run under all circumstances (say periodically)

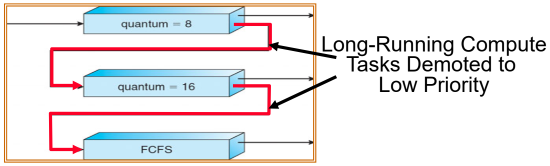
Multi-Level Feedback Scheduling



Long-Running Compute Tasks Demoted to Low Priority

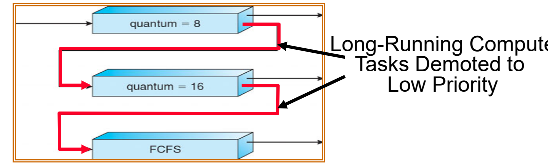
- Another method for exploiting past behavior (first use in CTSS)
  - Multiple queues, each with different priority
    - » Higher priority queues often considered “foreground” tasks
  - Each queue has its own scheduling algorithm
    - » e.g. foreground – RR, background – FCFS
    - » Sometimes multiple RR priorities with quantum increasing exponentially (highest:1ms, next: 2ms, next: 4ms, etc)
- Adjust each job’s priority as follows (details vary)
  - Job starts in highest priority queue
  - If timeout expires, drop one level
  - If timeout doesn’t expire, push up one level (or to top)

Scheduling Details



- Result approximates SRTF:
  - CPU bound jobs drop like a rock
  - Short-running I/O bound jobs stay near top
- Scheduling must be done between the queues
  - Fixed priority scheduling:
    - » serve all from highest priority, then next priority, etc.
  - Time slice:
    - » each queue gets a certain amount of CPU time
    - » e.g., 70% to highest, 20% next, 10% lowest

Scheduling Details



- Countermeasure: user action that can foil intent of the OS designers
  - For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
  - Of course, if everyone did this, wouldn't work!
- Example of Othello program:
  - Playing against competitor, so key was to do computing at higher priority the competitors.
    - » Put in printf's, ran much faster!

So, Does the OS Schedule Processes or Threads?

- Many textbooks use the "old model"—one thread per process
- Usually it's really: **threads** (e.g., in Linux)
- One point to notice: switching threads vs. switching processes incurs different costs:
  - Switch threads: Save/restore registers
  - Switch processes: Change active address space too!
    - » Expensive
    - » Disrupts caching

Multi-Core Scheduling

- Algorithmically, not a huge difference from single-core scheduling
- Implementation-wise, helpful to have *per-core* scheduling data structures
  - Cache coherence
- *Affinity scheduling*: once a thread is scheduled on a CPU, OS tries to reschedule it on the same CPU
  - Cache reuse

Recall: *Spinlock*

- Spinlock implementation:

```
int value = 0; // Free
Acquire() {
  while (test&set(value)) {}; // spin while busy
}
Release() {
  value = 0;               // atomic store
}
```

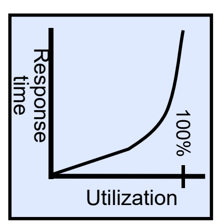
- Spinlock doesn't put the calling thread to sleep—it just busy waits
  – When might this be preferable?
- For multiprocessor cache coherence: every test&set() is a write, which makes value ping-pong around in cache (using lots of memory BW)

Gang Scheduling and Parallel Applications

- When multiple threads work together on a multi-core system, try to schedule them together
  – Makes spin-waiting more efficient (inefficient to spin-wait for a thread that's suspended)
- Alternative: OS informs a parallel program how many processors its threads are scheduled on (*Scheduler Activations*)
  – Application adapts to number of cores that it has scheduled
  – "Space sharing" with other parallel programs can be more efficient, because parallel speedup is often sublinear with the number of cores

A Final Word On Scheduling

- When do the details of the scheduling policy and fairness really matter?
  – When there aren't enough resources to go around
- When should you simply buy a faster computer?
  – (Or network link, or expanded highway, or …)
  – One approach: Buy it when it will pay for itself in improved response time
    » Perhaps you're paying for worse response time in reduced productivity, customer angst, etc…
    » Might think that you should buy a faster X when X is utilized 100%, but usually, response time goes to infinity as utilization⇒100%
- An interesting implication of this curve:
  – Most scheduling algorithms work fine in the "linear" portion of the load curve, fail otherwise
  – Argues for buying a faster X when hit "knee" of curve



Conclusion

- Round-Robin Scheduling:
  – Give each thread a small amount of CPU time when it executes; cycle between all ready threads
  – Pros: Better for short jobs
- Shortest Job First (SJF)/Shortest Remaining Time First (SRTF):
  – Run whatever job has the least amount of computation to do/least remaining amount of computation to do
  – Pros: Optimal (average response time)
  – Cons: Hard to predict future, Unfair
- Multi-Level Feedback Scheduling:
  – Multiple queues of different priorities and scheduling algorithms
  – Automatic promotion/demotion of process priority in order to approximate SJF/SRTF
- Lottery Scheduling:
  – Give each thread a priority-dependent number of tokens (short tasks⇒more tokens)