Operating Systems

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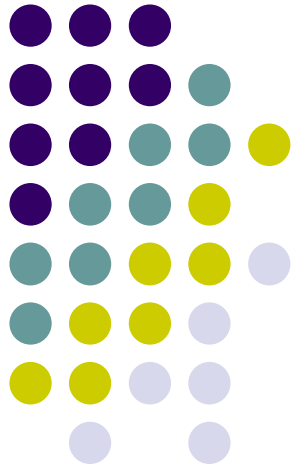
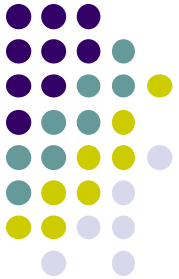
U of T

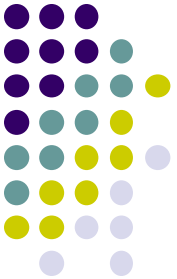


Today …



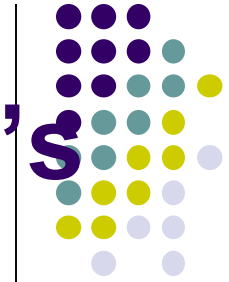
- Another Synchronization example
- Scheduling

Another Synchronization Example



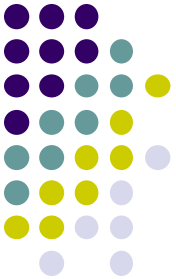
- Dining philosophers

Higher-level Abstractions for CS's



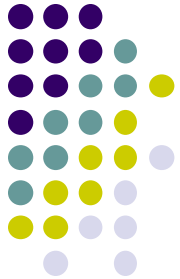
- Locks
  - Very primitive, minimal semantics
  - Operations: acquire(lock), release(lock)
- Semaphores
  - Basic, easy to understand, hard to program with
- Monitors
  - High-level, ideally has language support (Java)
- Messages
  - Simple model for communication & synchronization
  - Direct application to distributed systems

Semaphores



- Semaphores are abstract data types that provide synchronization. They include:
  - An integer variable, accessed only through 2 atomic operations
  - The atomic operation *wait* (also called *P* or *decrement*) - decrement the variable and block until semaphore is free
  - The atomic operation *signal* (also called *V* or *increment*) - increment the variable, unblock a waiting a thread if there are any
  - A queue of waiting threads

Types of Semaphores



- Mutex (or Binary) Semaphore
  - Represents single access to a resource
  - Guarantees mutual exclusion to a critical section
- Counting semaphore
  - Represents a resource with many units available, or a resource that allows certain kinds of unsynchronized concurrent access (e.g., reading)
  - Multiple threads can pass the semaphore
  - Max number of threads is determined by semaphore's initial value, *count*
    - Mutex has *count* = *1,* counting has *count* = *N*

Semaphores

- Integer variable `count` with two **atomic** operations
  - Operation *wait* (also called *P* or *decrement*)
    - block until `count` > 0 then decrement variable

```
wait(semaphore *s) {
        while (s->count == 0) ;
        s->count -= 1;
}
```

  - Operation *signal* (also called *V* or *increment*)
    - increment `count`, unblock a waiting thread if any

```
signal(semaphore *s) {
        s->count += 1;
        ……                    //unblock one waiter
}
```

  - A queue of waiting threads

Using Binary Semaphores

- Use is similar to locks, but semantics are different

Have semaphore, S, associated with acct

```
typedef struct account {
    double balance;
    semaphore S;
} account_t;

Withdraw(account_t *acct, amt){
    double bal;
    wait(acct->S);
    bal = acct->balance;
    bal = bal - amt;
    acct->balance = bal;
    signal(acct->S);
    return bal;
}
```

Three threads execute Withdraw()

```
wait(S);
bal = acct->balance;
bal = bal - amt;
```

```
wait(acct->S);
```

```
wait(acct->S);
```

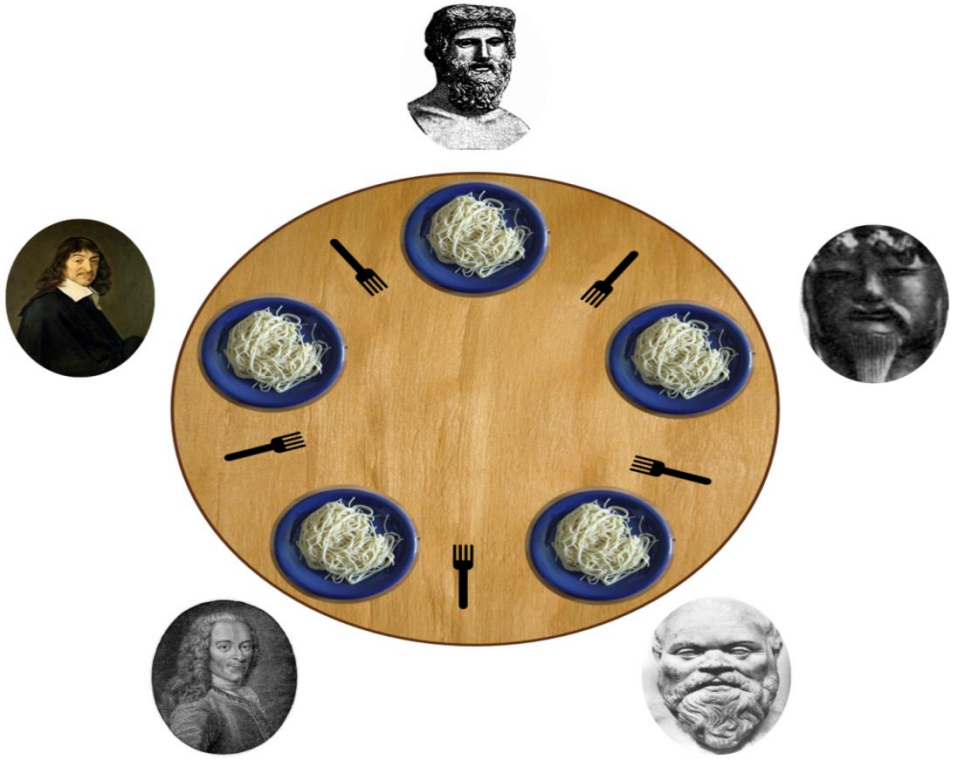
```
acct->balance = bal;
signal(acct->S);
```

```
...
signal(acct->S);
```

```
...
signal(acct->S);
```

It is **undefined** which thread runs after a **signal**

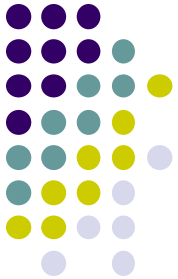
Dining Philosophers



philosopher -> processes
fork -> shared resources

- A philosopher needs two forks to eat.
- Idea for protocol:
  - When philosopher gets hungry grab left fork, then grab right fork.
- Is this a good solution?

Dining Philosophers Problem (1)



```
#define N 5                                     /* number of philosophers */

void philosopher(int i)                         /* i: philosopher number, from 0 to 4 */
{
        while (TRUE) {
                think( );                       /* philosopher is thinking */
                take_fork(i);                   /* take left fork */
                take_fork((i+1) % N);           /* take right fork; % is modulo operator */
                eat( );                         /* yum-yum, spaghetti */
                put_fork(i);                    /* put left fork back on the table */
                put_fork((i+1) % N);            /* put right fork back on the table */
        }
}
```

A nonsolution to the dining philosophers problem.

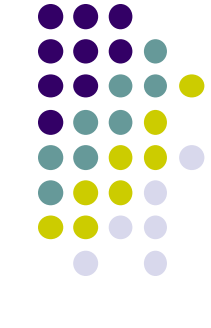
Dining Philosophers Problem (2)

```
#define N           5                       /* number of philosophers */
#define LEFT        (i+N–1)%N               /* number of i's left neighbor */
#define RIGHT       (i+1)%N                 /* number of i's right neighbor */
#define THINKING    0                       /* philosopher is thinking */
#define HUNGRY      1                       /* philosopher is trying to get forks */
#define EATING      2                       /* philosopher is eating */
typedef int semaphore;                      /* semaphores are a special kind of int */
int state[N];                               /* array to keep track of everyone's state */
semaphore mutex = 1;                        /* mutual exclusion for critical regions */
semaphore s[N];                             /* one semaphore per philosopher */
void philosopher(int i)                     /* i: philosopher number, from 0 to N–1 */
{
    while (TRUE) {                          /* repeat forever */
        think( );                           /* philosopher is thinking */
        take_forks(i);                      /* acquire two forks or block */
        eat( );                             /* yum-yum, spaghetti */
        put_forks(i);                       /* put both forks back on table */
    }
}. . .
```

semphamore s for each philosopher instead of each fork.

A solution to the dining philosophers problem.

Dining Philosophers Problem (3)



require mutex semaphore state is synchronized, this is because adjacent philosophers, in addition to the philosopher himself, are able to change this philosopher's state

```
. . .

void take_forks(int i)                    /* i: philosopher number, from 0 to N–1 */
{
    down(&mutex);                         /* enter critical region */
    state[i] = HUNGRY;                    /* record fact that philosopher i is hungry */
    test(i);                              /* try to acquire 2 forks */
    up(&mutex);                           /* exit critical region */
    down(&s[i]);                          /* block if forks were not acquired */
}

. . .
```

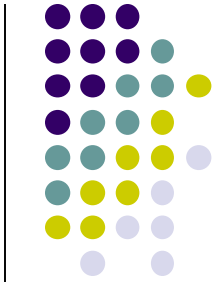
mutex ensure exclusive access to state!

declare interest

if test i is successful, s[i] = 1, available, starts eating
otherwise test fails, either left or right philosopher is eating, so blocked here when left and right philosopher exists, where it signals i-th current philosopher

A solution to the dining philosophers problem.

Dining Philosophers Problem (4)



. . .

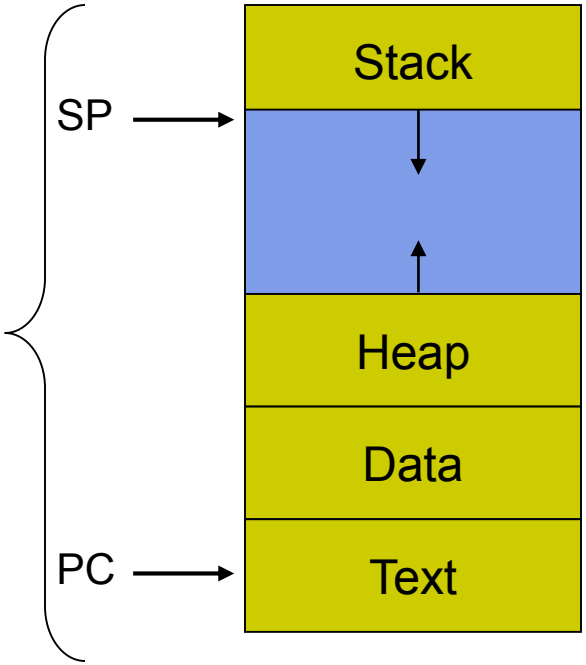
```
void put_forks(i)                          /* i: philosopher number, from 0 to N–1 */
{                                          thinking and testing -> returning the forks
    down(&mutex);                          /* enter critical region */
    state[i] = THINKING;                   /* philosopher has finished eating */
    test(LEFT);   act as signal to adjacent philosophers
                                           /* see if left neighbor can now eat */
    test(RIGHT);                           /* see if right neighbor can now eat */
    up(&mutex);                            /* exit critical region */
}       signal adjacent philosophers to give
        them semaphore if they are ready to eat

void test(i) /* i: philosopher number, from 0 to N–1 */
{
    if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;                 -> fork at left and right is available
        up(&s[i]);
    }   increment s[i] so that take_forks() can exit properly, i.e. starts eating..
}
```

A solution to the dining philosophers problem.

Review: The Process Concept

- Process = job / unit of work
- Process = a program in execution
- A process contains all state of program in execution
  - An address space
  - Set of OS resources
    - Open files network connections …
  - Set of general-purpose registers with current values
  - Accounting info

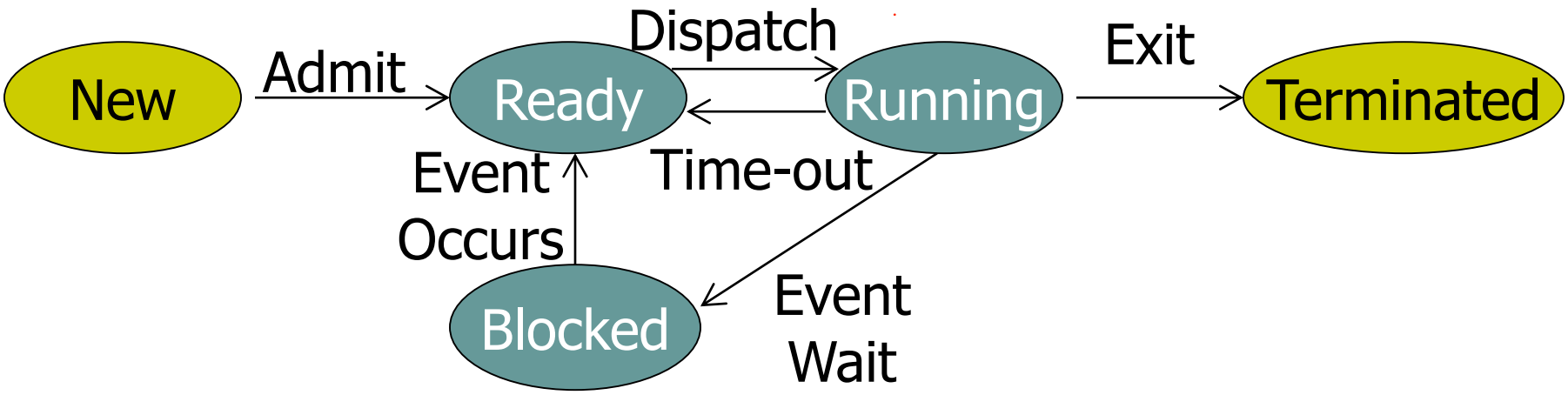


- A process is named by its process ID (PID)

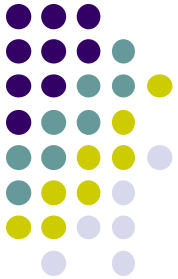
Process states

- The OS manages processes by keeping track of their *state* BLOCKED, RUNNING, WAITING
  - Different *events* cause changes to a process state, which the OS must record/implement

scheduler is for dispatching processes



State Queues



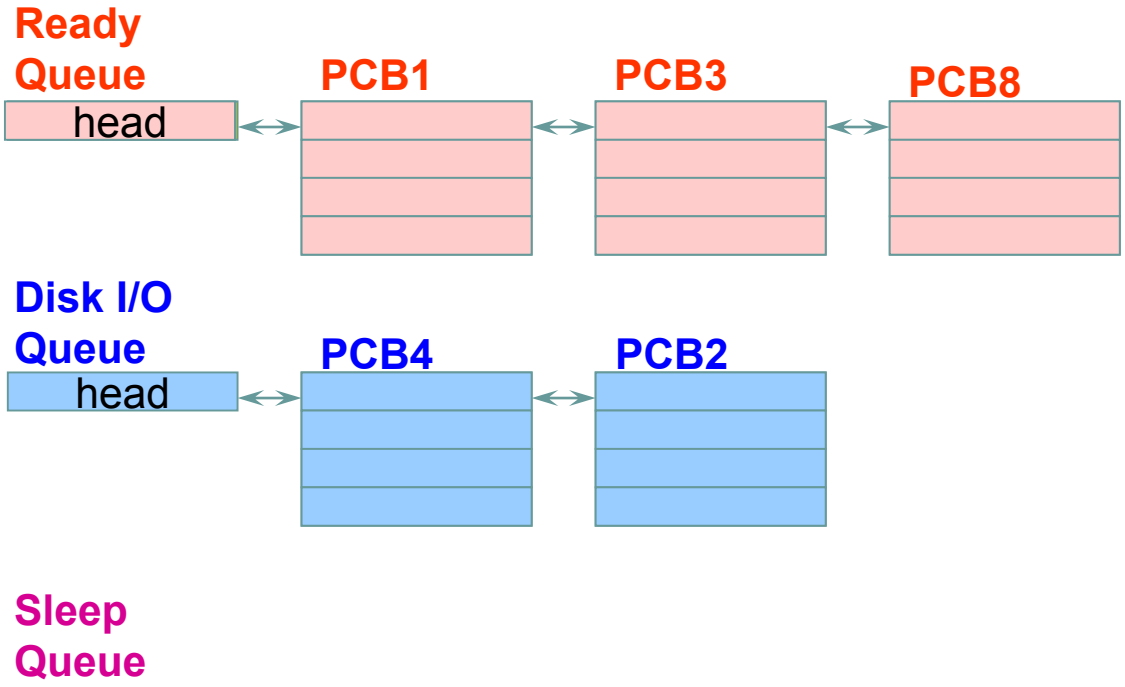
How does the OS keep track of processes?

- The OS maintains a collection of queues that represent the state of all processes in the system
- Typically, the OS has one queue for each state
  - Ready, waiting, etc.

so something like 3 queues

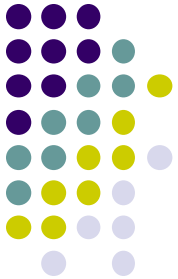
- Each PCB is queued on a state queue according to its current state
- As a process changes state, its PCB is unlinked from one queue and linked into another

State Queues



- There may be many wait queues, one for each type of wait (disk, console, timer, network, etc.)

Process Scheduling



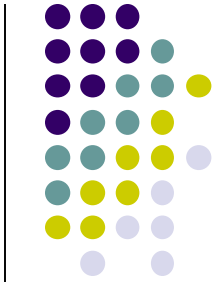
- Only one process can run at a time on a CPU
- Scheduler decides which process to run
- Goal of CPU scheduling:
  - Give illusion that processes are running concurrently
  - Maximize CPU utilization

reduce idle time

- Will talk about CPU scheduling in more detail …

process life cycle
+ process repeatedly alternate between computation and I/O
+ called CPU bursts and and I/O bursts
+ last CPU bursts ends with a call to terminate process (_exit())
    + CPU-bound: very long CPU bursts, infrequent I/O
    + IO bound: short CPU bursts, frequent I/O bursts
+ so should not wait for I/O bursts since CPU gets idled

Scheduling Goals



- All systems
  - **Fairness** - each process receives fair share of CPU
  - Avoid starvation
  - Policy enforcement - usage policies should be met
  - Balance - all parts of the system should be busy
- Batch systems
  - **Throughput** - maximize jobs completed per hour
  - **Turnaround time** - minimize time between submission and completion
  - CPU utilization - keep the CPU busy all the time

say some processes should be running on same corse as other processes

i.e. both CPU and disk should be busy

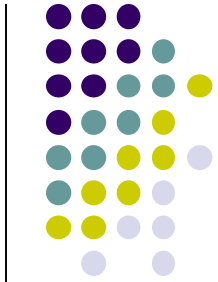
Interactive system
+ response time - minimize time between receiving request and starting to produce output
+ proportionality - simple tasks complete quickly
real time system
+ predictability

Types of Scheduling

- Non-preemptive scheduling
  - once the CPU has been allocated to a process, it keeps the CPU until it terminates
  - Suitable for batch scheduling
- Preemptive scheduling personal computer is preemptive
  - CPU can be taken from a running process and allocated to another
  - Needed in interactive or real-time systems

for system with both CPU bound and IO bound tasks

Scheduling Algorithms: FCFS

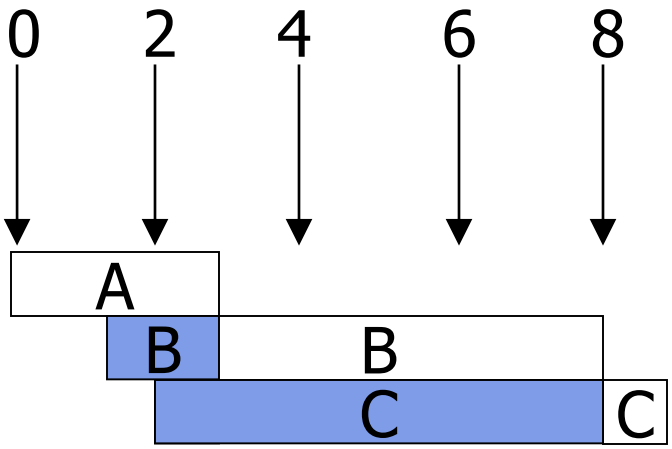


- "First come, first served"
- Non-preemptive
- Choose the process at the head of the FIFO queue of ready processes

new process appended to end of FIFO

FCFS Example

Process	Arrival Time	Service Time
A	0	3
B	1	5
C	2	1



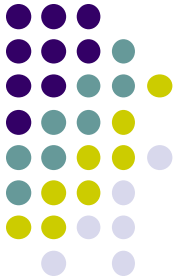
- Note *C* waits six times as long as it runs!
  - Total wait time is 8, avg. wait is 8/3=2.66

Problem with FCFS

- Average waiting time often quite long
  - Convoy effect: all other processes wait for the one big process to release the CPU

What can we do to minimize wait times?

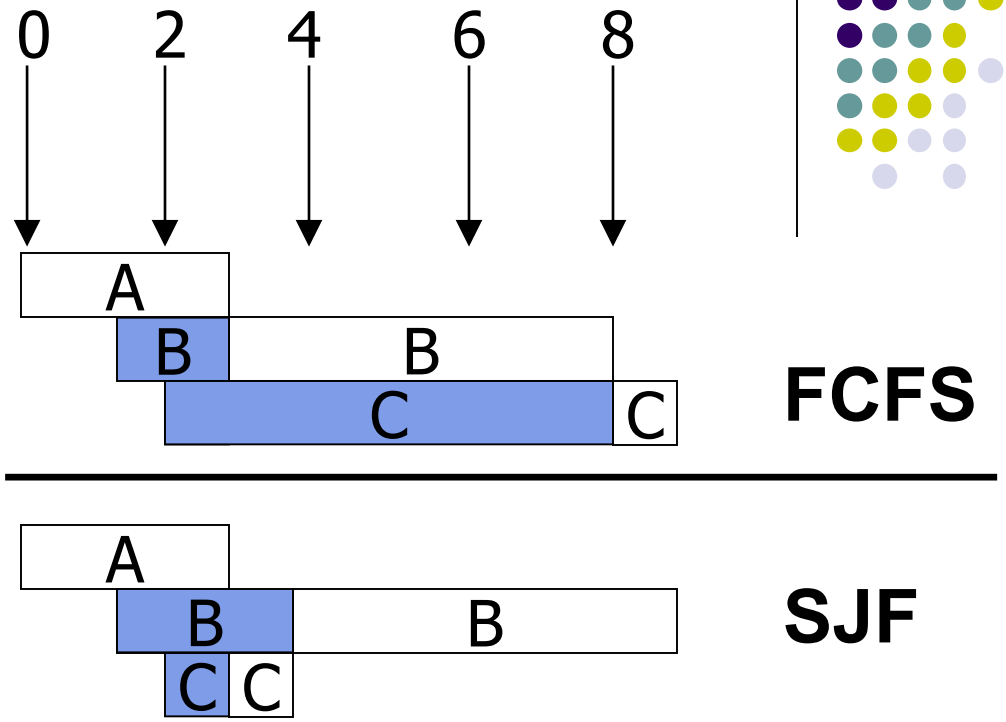
Algorithm: Shortest-Job-First



- Choose the process with the shortest processing time

SJF Example

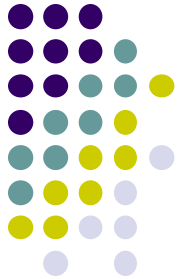
Process	Arrival Time	Service Time
A	0	3
B	1	5
C	2	1



- FCFS:Total wait time is 8, avg. wait is 8/3=2.66
- SJF: Total wait time is 4, avg. wait is 4/3=1.33

We cut wait time in half just by scheduling!

Algorithm: Shortest-Job-First

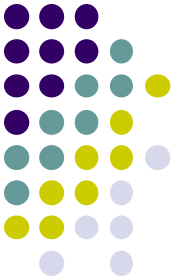


- Choose the process with the shortest processing time
- Provably optimal average wait time
- Problems with SJF?
  - Need to know processing time in advance
    - Programmer estimate
    - History statistics
  - Starvation + fairness?

which has to be estimated….

long running processes may experience starvation, unfair amongst a queue of lots of small jobs

So far …



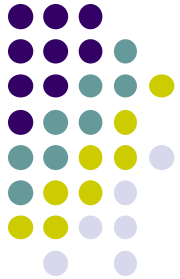
- SJF has **short wait times**, but is **unfair**
- FCFS is **fair**, but can lead to **long wait times**
  - Short jobs can get stuck behind long jobs

How can we be fair, but avoid the "short jobs getting stuck behind long jobs" problem?

IDEA: Allow preemption

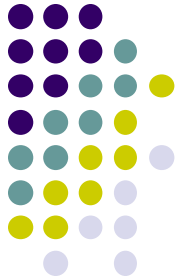
- Don't always run jobs to completion
- Preempt a job that's running too long

Algorithm: Round Robin



- Designed for time-sharing systems
- Pre-emptive
- Ready queue is circular
  - Each process is allowed to run for time quantum q before being preempted and put back on queue
- Choice of quantum (aka time slice) is critical
  - as $q \rightarrow \infty$, RR $\rightarrow$ FCFS; no job ever preempted
  - as $q \rightarrow 0$, RR $\rightarrow$ processor sharing (PS) too many costly context switches
  - we want q to be large w.r.t. the context switch time

Priority Scheduling

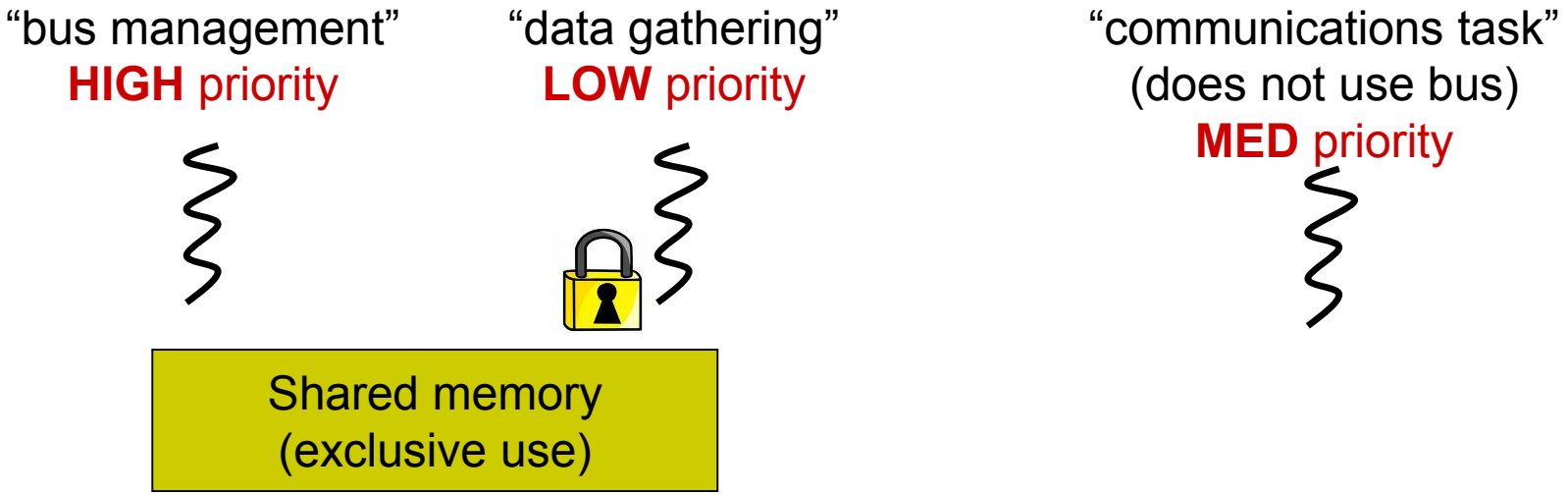


- A priority, *p*, is associated with each process
- Highest priority job is selected from Ready queue
  maybe different queue for different priorities
  - Can be pre-emptive or non-preemptive
- Enforcing this policy is tricky
  processes may have shared resources…
  - A low priority task may never get to run (*starvation*)
  - A low priority task may prevent a high priority task from making progress by holding a resource (*priority inversion*)

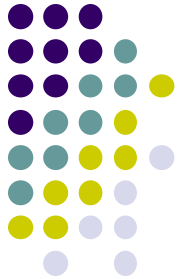
Priority Inversion Example

- Mars Rover *Pathfinder* bug
  - In the press:
    - "software glitches",
    - "computer was doing too many things at once"

+ low priority task gets a lock, preempted by high priority task,
+ high priority task is blocked since lock unavailable
+ medium priority arrives, executed before low priority task (since higher priority)
and executed before high priority task (priority inversion)

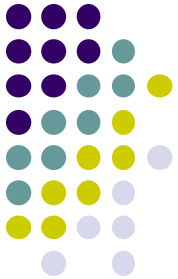


Priority Inversion Example



- Mars Rover *Pathfinder* bug
  - Shared "information bus" – essentially shared memory area
  - Mutual exclusion provided by lock on info bus
  - High priority "bus management" task moves data in/out of information bus
  - Low priority "data gathering" task writes data to the information bus
  - Medium priority, compute-bound "communications" task that does not use the information bus
  - See the problem?
    - Data gathering task locks bus and is preempted by higher priority bus management task, which blocks on the lock. If communications task becomes runnable, data gathering task can't complete and release the lock so high priority task stays blocked.

What do real systems do?

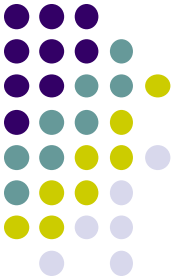


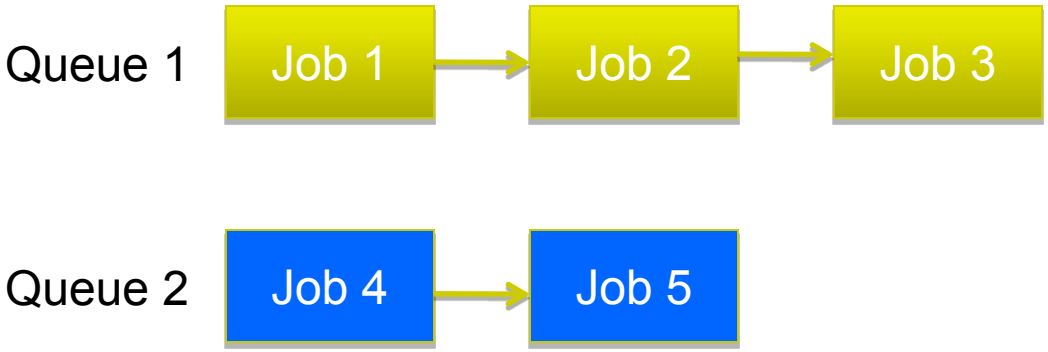
- Combination of
  - Multi-level queue scheduling
    - Typically with RR and priorities
  - Feedback scheduling

multiple queue, each queue with different types (priority, interactive?) of tasks, as well as different scheduling algorithms (different quntum q different algo)

- What does that mean …

Multi-Level Queue Scheduling

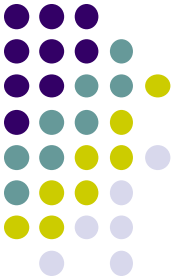




- Have two scheduling policies
  - First decides which queue to serve
    - E.g. based on queue priorities
  - Seconds decides which job within a queue to choose
    - E.g. FCFS or RR

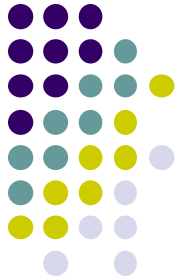
what queue to pick next and what job in that queue to pick from (algo)

Multiple Queues with Priority Scheduling



- Highest priority gets one quantum, second highest gets 2…..
  - If highest finishes during quantum, great. Otherwise bump it to second highest priority and so on into the night
- Consequently, shortest (high priority) jobs get out of town first
- They announce themselves-no previous knowledge assumed!

Feedback Scheduling



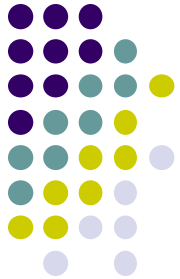
- Motivation:
  - Want to give priority to shorter jobs
  - Want to give priority to IO bound jobs
  - Want to give priority to interactive jobs
  - Want to …

  - But don't know beforehand whether a job is short or long and whether it's IO bound or CPU bound …

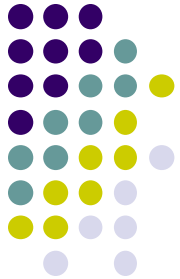
Feedback Scheduling

change priority based on observation

- Adjust criteria for choosing a particular process based on past history
  - Combine with MLQ
  - Can prefer processes that do not use full quantum
  - Can change priority of processes based on age
  - Can change priority of processes based on CPU consumed so far
  - Can boost priority following a user-input event
- Move processes between queues



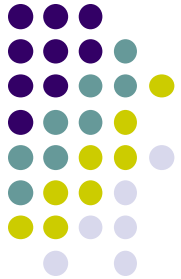
Linux 2.6 CPU scheduling



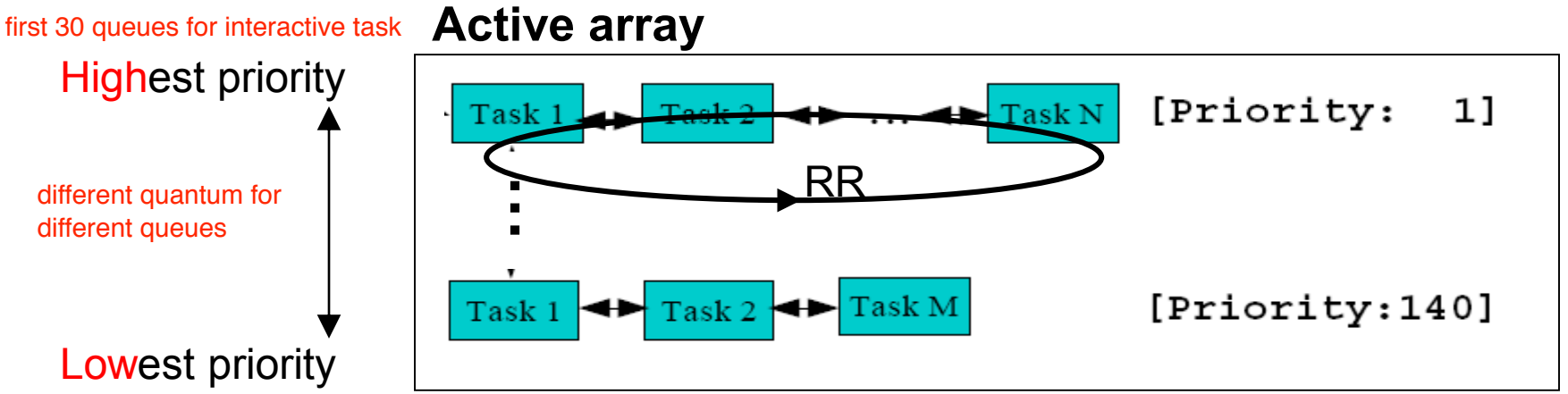
- Combination of
  - Multilevel queues
    - With priorities and RR
  - Feedback scheduling
- Distinguishes 3 classes
  - Realtime FIFO processes
  - Realtime RR processes
  - Timesharing processes
- Our discussion focuses on timesharing processes

talking about 3 classes of threads here

Linux 2.6 CPU scheduling



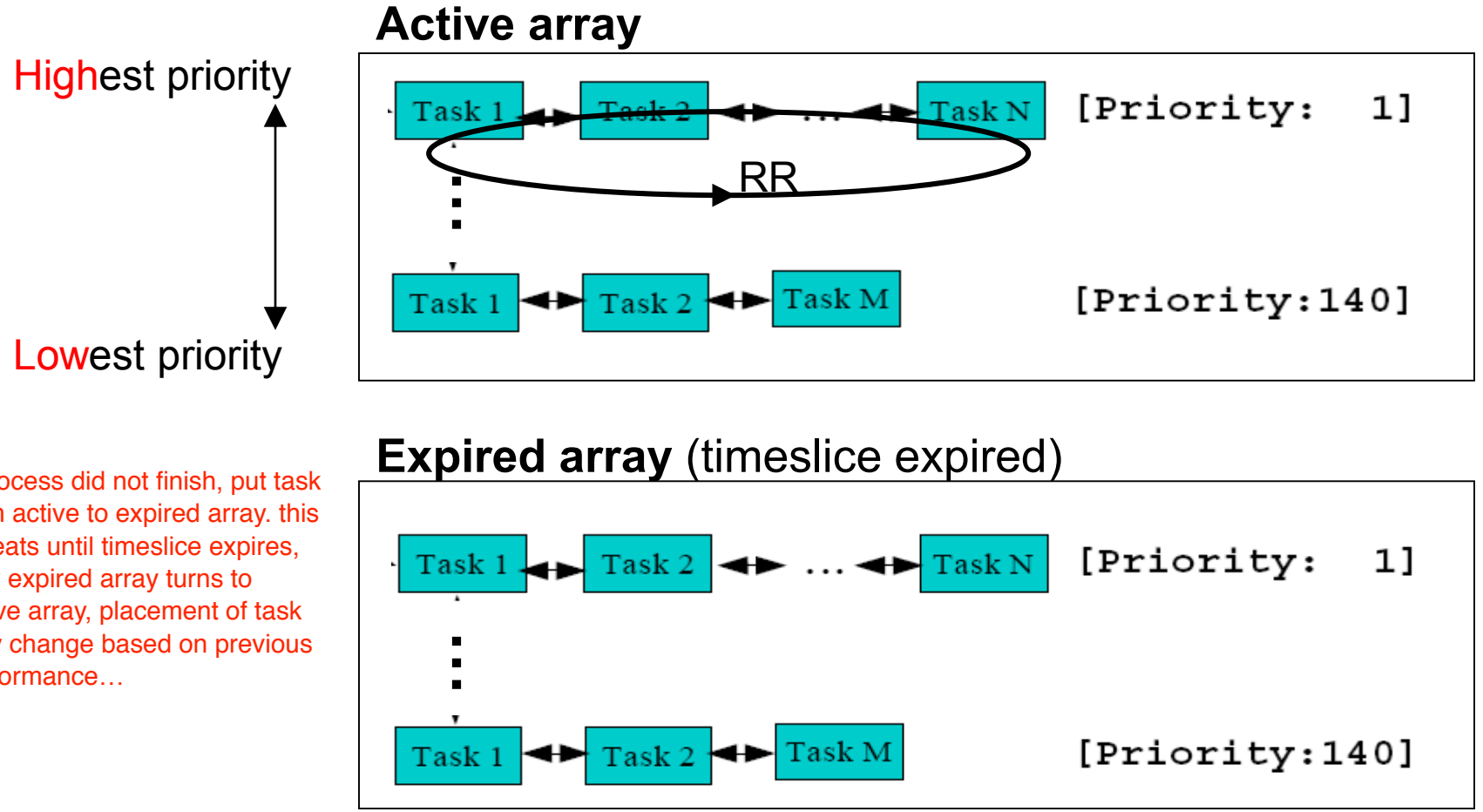
- Always run the task in active array with highest priority
- If there are procs with same priority, do RR between them
  - Switch after **`granularity`** time units



How do you avoid starvation of low priority processes?

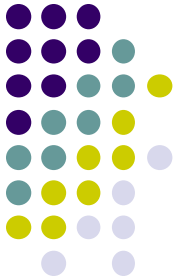
Linux 2.6 CPU scheduling

- Always run the task in active array with highest priority
- If there are procs with same priority, do RR between them
  - Switch after **`granularity`** time units
- If **`timeslice`** expires move to “Expired array”



if process did not finish, put task from active to expired array. this repeats until timeslice expires, now expired array turns to active array, placement of task may change based on previous performance…

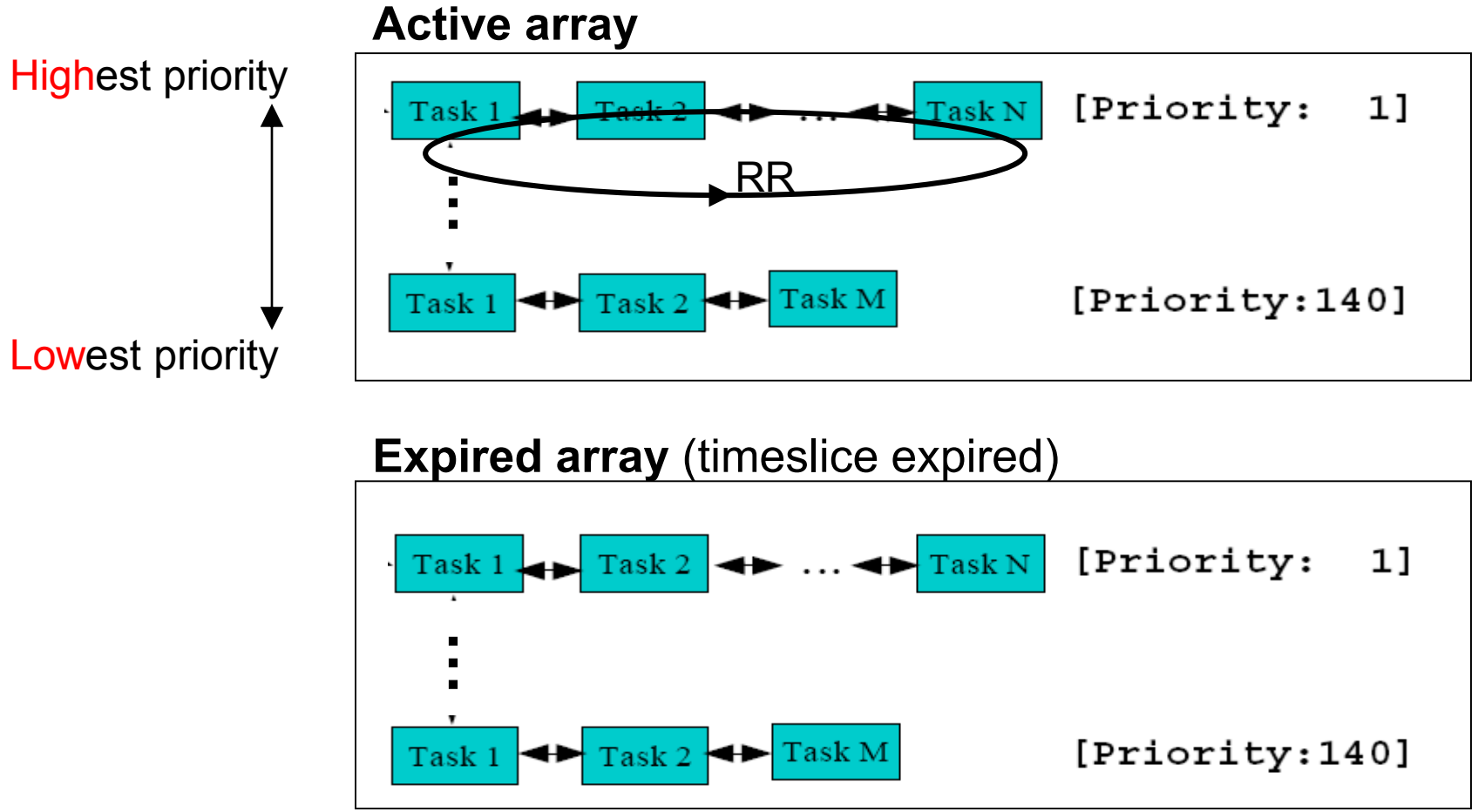
Linux 2.6 CPU scheduling



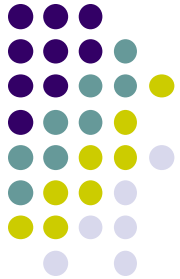
- How to determine priority of process?
  - Some processes are more important than others
    - Assign **static priorities** [-20, 19] (user-determined)
    - Done through **`nice`** system call
  - Interactive & IO bound processes should be favored
    - Give bonus/penalty on top of static priority
  - **`priority = static_priority + bonus`** (bonus: dynamically determined)
- How to identify interactive / IO bound processes?
  - Maintain **`sleep_avg`** (time process is sleeping vs CPU time)

Linux 2.6 CPU scheduling

- Always run the task in active array with highest priority
- If there are procs with same priority, do RR between them
  - Switch after **`granularity`** time units
- If **`timeslice`** expires move to “Expired array”



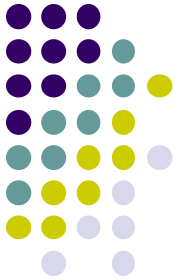
Linux 2.6 CPU scheduling



- How to set **`timeslice`** and **`granularity`**?
  - **`Timeslice`** depends on **static** priority
    - Between 5ms and 800ms
  - **`Granularity`** depends on **dynamic** priority

- Many of the details keep changing …

New topic next week:



- Memory management!