CHAPTER III
SCHEDULING

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Chapter overview

- ***The problem***
- ***Non-preemptive policies:***
  - FCFS, SJF
- ***Preemptive policies:***
  - Round robin, multilevel queues with feedback, guaranteed scheduling
  - Examples: UNIX, Linux, Windows NT and after

The scheduler

- Part of the OS that decides ***how to allocate the processor cores and the main memory*** to processes
- Will focus here on the ***CPU scheduler***
  - Decides which ready process should get a processor core
  - Also called short-term scheduler

Objectives

- A good scheduler should
  - Minimize ***user response times*** of all interactive processes
    - ***Major objective today***
  - Maximize ***system throughput***
  - Be ***fair***
  - Avoid ***starvation***

What is starvation?

- Starvation happens whenever some ready processes never get core time
  - Typical of schedulers using priorities
    - Lowest-priority processes keep getting set aside
- Remedy is to ***increase*** the priorities of processes that have waited ***too long***

Fairness

- Ensuring fairness is more difficult than avoiding starvation
  - *If I give freshly-baked cookies to half of my nephews and stale bread to the others, I am not fair but I still ensure that nobody starves*

Non-preemptive Schedulers

- A ***non-preemptive*** CPU scheduler will never remove a core from a running process
- Will wait until the process releases the core because
  - It issues a system call
  - It terminates
- Now ***obsolete***

How SJF works

- Five students wait for their instructor at the beginning of her office hours
    - Ann needs 20 minutes of her time
    - Bob needs 30 minutes
    - Carol needs 10 minutes
    - Dean needs 5 minutes
    - Emily needs 5 minutes

Examples (I)

- ***First-Come First-Served (FCFS):***
  - Simplest and easiest to implement
    - Uses a FIFO queue
  - Seems a good idea but
    - Processes requiring a few ms of core time have to wait behind processes that make much bigger demands
    - ***Inacceptable***

Examples (II)

- ***Shortest Job First (SJF):***
  - Gives a core to the process requesting the least amount of core time
    - Will reduce average wait
    - Must know ahead of time how much core time each process needs
      - ***Not possible***
    - Still lets processes monopolize a core

FCFS schedule

Student	Time	Wait
Ann	20	0
Bob	30	20
Carol	10	50
Dean	5	60
Emily	5	65

The outcome

- Average wait time:
  - (0 + 20 + 50 + 60 + 65)/5 = 39 minutes

SJF schedule

Student	Time	Wait
Dean	5	0
Emily	5	5
Carol	10	10
Ann	20	20
Bob	30	40

The outcome

- Average wait time:
  - (0 + 5 + 10 + 20 + 40)/5 = 15 minutes

- Less than half the wait time of the FCFS schedule
  - The data were rigged

Preemptive Schedulers

- A ***preemptive*** scheduler can return a running process to the ready queue whenever another process requires that core in a more urgent fashion
  - Has been for too long in the ready queue
  - Has higher priority
- ***Sole acceptable solution***
  - Prevents processes from “hogging” a core

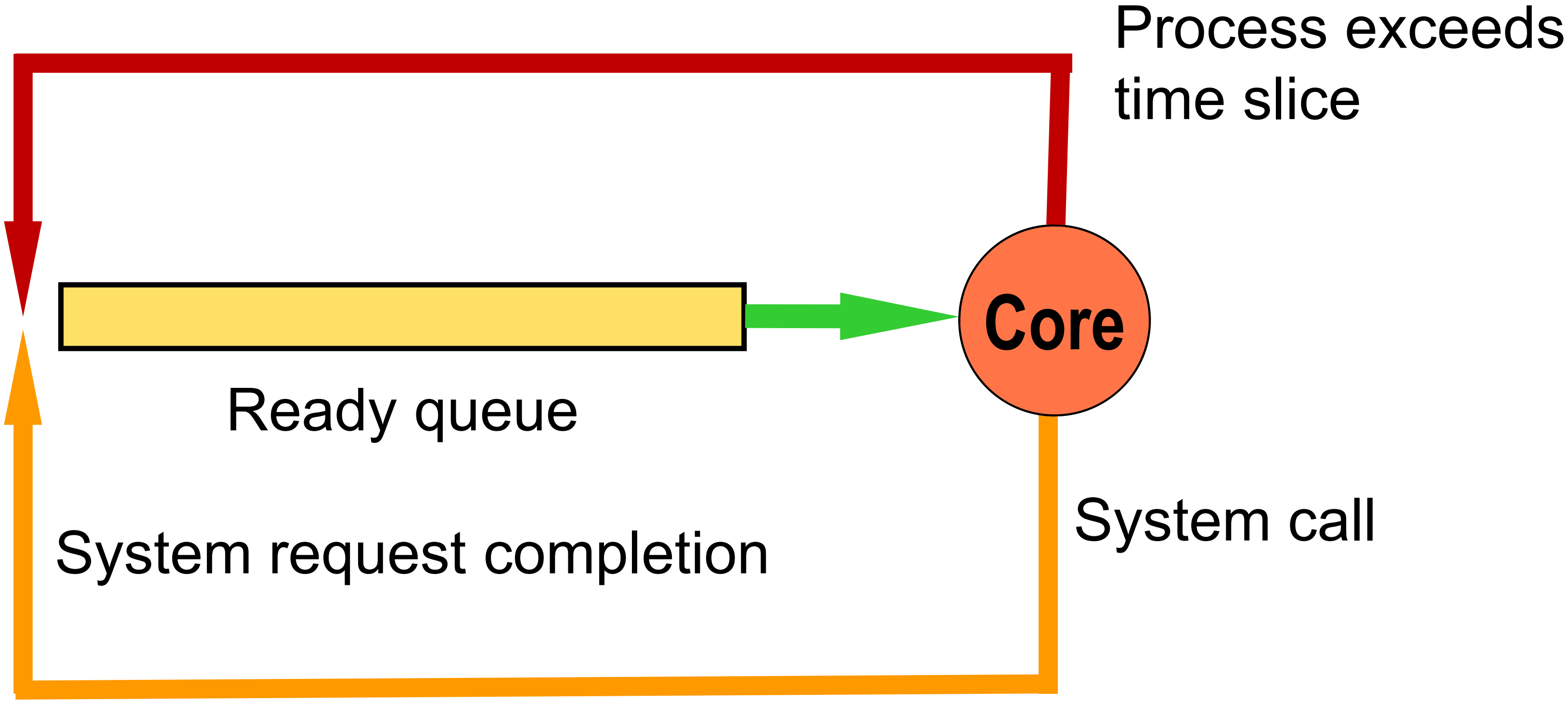
Types of preemptive schedulers

- ***Preemptive schedulers w/o priorities:***
  - All processes have the same priority
  - Ready queue is FIFO
- ***Preemptive schedulers with priorities:***
  - Use multiple queues
  - Differ in the way they adjust process priorities

Round robin (I)

- Assumes all processes have ***same priority***
  - Guaranteed to be starvation-free
- Similar to FCFS but processes only get the a core for ***up to*** T_{CPU} time units
  - ***Time slice*** or ***time quantum***
- Processes that exceed their time slice return to the end of the ready queue

Round robin (II)



How RR works

- Assume
  - Single core
  - Time slice is 100ms (reasonable choice)
  - Ready queue contains processes A, B and C
- A gets core at *t* = 0ms
- A releases the core at *t* = 24ms to do an I/O
- B gets core at *t* = 24ms
- A returns to ready queue at *t* = 32ms
- B forced to release the core at *t* = 124ms

Finding the right time slice (I)

- A small time slice means a good response time
  - No process will ever have to wait more than

$$(\boldsymbol{n}_{\boldsymbol{readyQueue}} + 1)\boldsymbol{T}_{\boldsymbol{CPU}} \text{ time units}$$

where $\boldsymbol{n}_{\boldsymbol{readyQueue}}$ is the number of processes already in the ready queue

- A large time slice means a better throughput
  - Fewer context switches

Finding the right time slice (II)

Ideal CPU schedule

True CPU schedule

The problem

- Want to adjust the time slice to guarantee a maximum waiting time in the ready queue

$$T_{CPU} = T_{max} / (n_{ready\_queue} + 1)$$

  - Works well as long as system is lightly loaded
  - Produces very small time slices when system is loaded
    - Too much context switch overhead!

An observation

- The throughput of a system using a RR scheduler actually decreases when its workload exceeds some threshold
  - ☐ ***Rare*** among ***physical systems***
  - ☐ ***Frequent*** among systems experiencing ***congestion***
    - Freeway throughput actually decreases when its load exceeds some threshold

The solution (I)

- Add ***priorities***
- Distinguish among
  - ***Interactive processes***
  - ***I/O-bound processes***
    - Require small amounts of core time
  - ***CPU-bound processe***s
    - Require large amounts of core time (*number crunching*)

The solution (II)

- Assign
  - ***High priorities*** to interactive processes
  - ***Medium priorities*** to I/O-bound processes
  - ***Low priorities*** to CPU-bound processes

The solution (III)

- Assign
  - ***Smallest time slices*** to interactive processes
  - ***Medium time slices*** to I/O-bound processes
  - ***Biggest time slices*** to CPU-bound processes
- Allow higher priority processes to ***steal cores*** from lower priority processes

The outcome

- Interactive processes will get good response times
- CPU-bound processes will get the CPU
  - Less frequently than with RR
  - For longer periods of time
  - Less context switch overhead

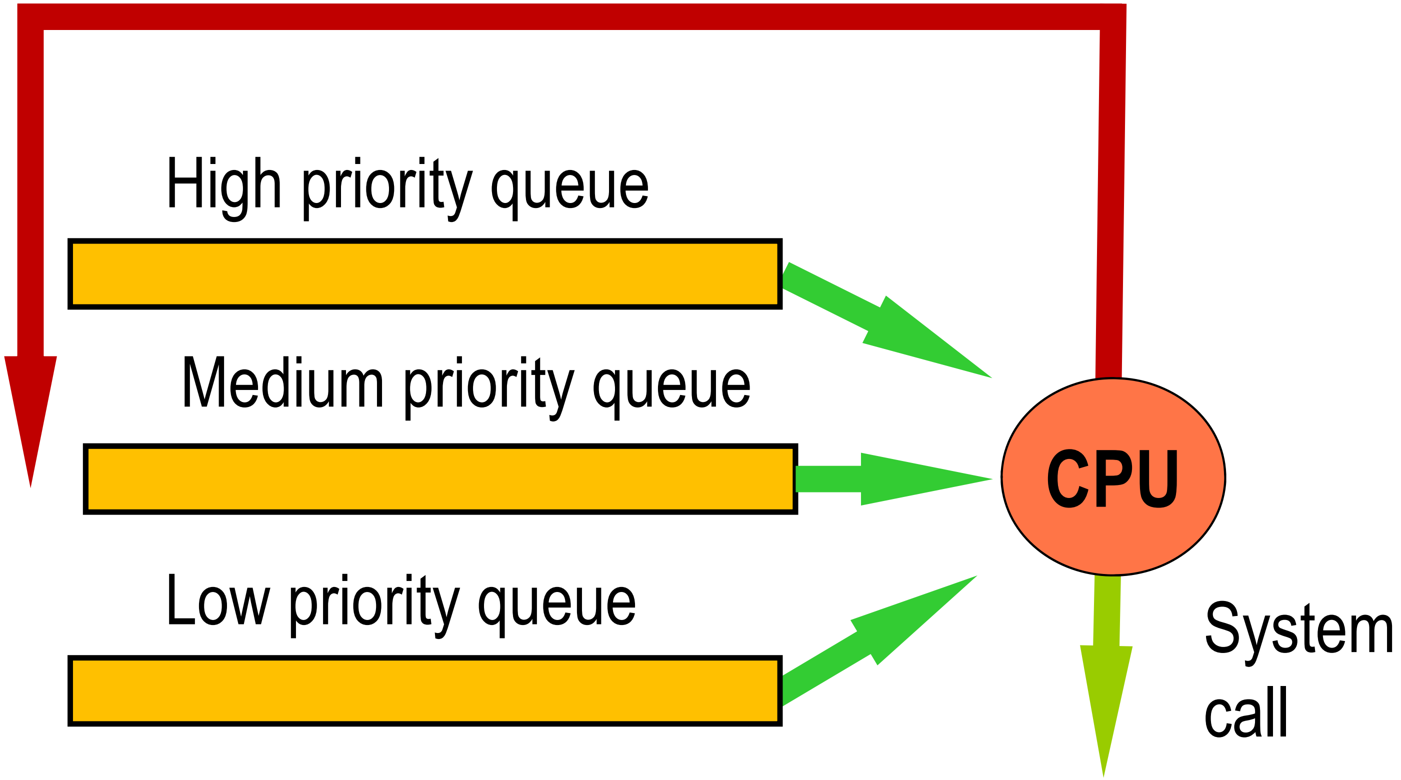
Two problems

- ***How to assign priorities to processes?***
  - Process behaviors may change during their execution
    - *Should adjust process priorities*
- ***How to avoid starvation?***
    - *Adjust process priorities*

Multi-Level with Feedback Queues

- Use ***dynamic priorities***
- ***Reward***
  - Processes that issue system calls
  - Processes that interact with user
  - Processes that have been a long time in the ready queue
- ***Penalize***
  - Processes that exceed their time slice

Implementation (I)



Implementation (II)

- Time slice increase when priority decreases, say
    - T for high priority processes
    - 2T for medium priority processes
    - 4T for low priority processes

The priority game

- Different systems have different conventions for priorities
  - ***0 is highest***
    - Most UNIX systems, Linux
  - ***0 is lowest***
    - UNIX System V Release 4 (V.4)
    - Windows NT and after

System V.4 scheduler

- Three process classes:
    - Real-time
    - Time-sharing
    - System (for kernel processes)
- Each process class has its own priority levels
    - Real-time processes have highest priority
    - Time-sharing lowest

Real-time processes

- Have ***fixed priorities***
  - *As in Windows scheduler*
- System administrator can define
  - A different *quantum size* (**`rt_quantum`**) for each priority level

Timesharing processes (I)

- Have ***variable priorities***
- System administrator can specify the parameters of each priority level
  - Maximum flexibility
  - Maximum risk of making a bad choice

Leaving too many tuning options for the system administrator increases the chances that the some options will be poorly selected

Timesharing processes (II)

- Parameters include
  - Quantum size (`ts_quantum`)
  - New priority for processes that use their whole CPU quantum (`ts_tqexp`)
  - New priority for processes returning from blocking state (`ts_slpret`)

Timesharing processes (III)

- Maximum amount of time a process can remain in the ready queue without having its priority recomputed (**`ts_maxwait`**)
- New priority for processes that have been in the ready queue for **`ts_maxwait`** (**`ts_lwait`**)

Example

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000         0         1        50000        1      #  0
    500         0         2        20000        2      #  1
    200         1         3        10000        3      #  2
    100         2         3        10000        3      #  3
```

- System has four priority levels
  - 0 is lowest
  - 3 is highest
- Anything after a pound sign is a comment

How to read it

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000        0        1        50000       1     #  0
    500        0        2        20000       2     #  1
    200        1        3        10000       3     #  2
    100        2        3        10000       3     #  3
```

- New priorities can be
  - Rewarding a “good” behavior: `ts_slpret` and `ts_lwait`
  - Penalizing CPU “hogs”: `ts_tqexp`

How?

- We ***increase*** the priority of processes that
  - Have completed a system call
    - They might become less CPU-bound
  - Have waited a long time in the ready queue
    - To prevent starvation
- We ***decrease*** the priority of processes that
  - Have exhausted their time quantum
    - They might be more CPU-bound

Second example (I)

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000        0        1       50000        1     #  0
    500        X        2       20000        2     #  1
    200        1        3       10000        3     #  2
    100        2        Y       10000        4     #  3
    100        3        4       10000        Z     #  4
```

- Table now defines five priority levels
- What are the ***correct values*** for X, Y and Z?

Second example (II)

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000         0         1        50000        1     #  0
    500         X         2        20000        2     #  1
    200         1         3        10000        3     #  2
    100         2         Y        10000        4     #  3
    100         3         4        10000        Z     #  4
```

- X is the new priority for processes at level 1 that exceed their time quantum
  - Must be lower than current priority
    - **X=0**

Second example(III)

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000        0         1       50000        1     #  0
    500        0         2       20000        2     #  1
    200        1         3       10000        3     #  2
    100        2         Y       10000        4     #  3
    100        3         4       10000        Z     #  4
```

- Y is a the new priority for processes at level 3 that exceed their time quantum
  - Must be higher than current priority
    - **Y=4**

Second example (IV)

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000        0        1        50000       1     #  0
    500        0        2        20000       2     #  1
    200        1        3        10000       3     #  2
    100        2        4        10000       4     #  3
    100        3        4        10000       Z     #  4
```

- Z is a the new priority for processes at level 4 that have waited too long in the ready queue
  - ☐ Should be higher than current priority
  - ☐ Level 4 already is the highest priority
    - **Z = 4**

Second example (V)

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000        0         1       50000        1     #  0
    500        0         2       20000        2     #  1
    200        1         3       10000        3     #  2
    100        2         Y       10000        4     #  3
    100        3         4       10000        Z     #  4
```

- Recall that
  - **`ts_slpret`** and **`ts_lwait`** reward “good” behaviors
  - **`ts_tqexp`** penalizes a “bad” one

An exercise

- Fill the missing values

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000        X        1         50000       1      #  0
    500        Y        2         20000       2      #  1
    200        1        3         10000       3      #  2
    100        2        Z         10000       V      #  3
    100        3        U         10000       W      #  4
```

The solution

```
#ts_quantum ts_tqexp ts_slpret ts_maxwait ts_lwait LEVEL
   1000        X=0      1        50000        1      #  0
    500        Y=0      2        20000        2      #  1
    200        1        3        10000        3      #  2
    100        2        Z=4      10000        V=4    #  3
    100        3        U=4      10000        W=4    #  4
```

- Recall that the only valid priorities are 0 to 4!

MacOS X Scheduler (I)

- Mac OS X uses a multilevel feedback queue
  - Manages threads, not processes
  - Four priority bands for threads
    - Normal
    - System high priority
    - Kernel mode only
    - Real-time

MacOS Scheduler (II)

- Thread priorities will vary
  - Must remain within their bands
  - Real-time threads tell the scheduler the number A of clock cycles they will need out of the next B clock cycles
    - Say 4000 out of the next 9000 clock cycles

Windows Scheduler

- An update of the old VMS scheduler
- Scheduler manages ***threads*** rather than processes.
- Has 32 priority levels:
  - 16 to 31 for ***real-time threads***
  - 0 to 15 for ***other threads***
- ***Priority zero reserved*** for the system thread zeroing free pages

Priority classes

- Apply to processes
- Five classes of process priorities
  - **IDLE_PRIORITY_CLASS**
  - **BELOW_NORMAL_PRIORITY_CLASS**
  - **NORMAL_PRIORITY_CLASS**
  - **ABOVE_NORMAL_PRIORITY_CLASS**
  - **HIGH_PRIORITY_CLASS**
  - **REALTIME_PRIORITY_CLASS**

Base priorities

- Apply to threads
- Defined within each process class
  - **THREAD_PRIORITY_IDLE**
  - **THREAD_PRIORITY_LOWEST**
  - **THREAD_PRIORITY_BELOW_NORMAL**
  - **THREAD_PRIORITY_NORMAL**
  - **THREAD_PRIORITY_ABOVE_NORMAL**
  - **THREAD_PRIORITY_HIGHEST**
  - **THREAD_PRIORITY_TIME_CRITICAL**

Real-time threads

- Real-time processes belong to **REALTIME_PRIORITY_CLASS**
- Threads at ***fixed priorities*** between 16 and 31
  - Specified by their ***base priority***
- Scheduling is ***round-robin*** within each priority level

Other threads (I)

- Run at ***variable priorities*** between 1 and 15
- Each thread has a ***base priority***
  - Value depends on process class and thread priority level within class
    - 1 for all threads with **THREAD_PRIORITY_IDLE**
    - 15 for all threads with **THREAD_PRIORITY_TIME_CRITICAL**

Other threads (II)

- Thread priorities ***never go below*** their base priority
- These priorities are
  - ***"Boosted"*** whenever they return from the blocked state
  - ***Decremented*** when they exhaust their time slice

Thread affinity

- ***Thread affinity*** specifies the set of processors on which the thread can run.
    - "Setting thread affinity should generally be avoided because it can interfere with the scheduler's ability to schedule threads effectively across processors."
        - **https://msdn.microsoft.com/en-us/library/windows/desktop/ms684251(v=vs.85).aspx**

Thread ideal processor

- Instructs the scheduler to run the thread on that processor whenever possible
  - Does ***not*** guarantee that processor will always be chosen

Note

- Do not be confused by the two different usages of "suspended"
  - Suspending a process is the same as swapping it out
  - Suspending a thread in this context means moving it to the blocked state

Guaranteed scheduling

- Class of scheduling algorithms that want to ensure that its process has its ***fair share*** of CPU time
- Penalize processes that have used a large amount of CPU
- Most versions of UNIX, Windows NT and after, Linux

Old UNIX Scheduler (I)

DO NOT MEMORIZE THIS

- Priorities take into account ***past CPU usage***

  `p_usrpri = PUSER+p_cpu/2+p_nice`

  where
  - **`PUSER`** is the user's base priority
  - **`p_cpu`** its current CPU usage
  - **`p_nice`** a user-settable parameter

Old UNIX Scheduler (II)

DO NOT
MEMORIZE
THIS

- **`p_cpu`** is updated every second according to a decay function

```
decay(p_cpu) = p_cpu/2
```

- After k seconds, penalty is decreased by a factor $1/2^k$

BSD scheduler (I)

DO NOT MEMORIZE THIS

- The time quantum is 100 ms

`p_usrpri = PUSER + p_cpu/4 + 2×p_nice`

- **`p_cpu`** is updated every second according to:

`p_cpu = (2×ld)/(2×ld+1)×p_cpu + p_nice`

- where **`ld`** is a sampled average of the length of the run queue over the last minute

BSD scheduler (II)

- Unlike the old UNIX scheduler, the BSD scheduler takes into account the system load
  - Through length of ready queue
    - “Load average”
  - Forgives old CPU usage ***more slowly*** when system load is ***high***

Linux 2.4 scheduler (I)

- Partitions the CPU time into ***epochs***.
- At the beginning of each epoch, each process is assigned a ***time quantum***
  - Specifies the maximum CPU time the process can have during that epoch.
- Processes that exhaust their time quantum cannot get CPU time until the next epoch starts

Linux 2.4 scheduler (II)

- Processes that release the CPU before their time quantum is exhausted can get more CPU time during the same epoch.
- Epoch ends when all ready processes have exhausted their time quanta.
- Priority of a process is the sum of its base priority plus the amount of CPU time left to the process before its quantum expires.

Stride scheduling (I)

NOT COVERED THIS SEMESTER

- Deterministic fair-share scheduler
- Start by allocating tickets to processes/threads
  - More tickets mean more core time
- Each thread has a ***stride***
    - ***Inversely*** proportional to the number *n* of tickets it has
    - If thread A has 10 tickets, thread B has 5 tickets and thread C has 20 tickets
      - Stride of A is 10, stride of B is 20 and stride of C is 5

Stride scheduling (II)

NOT COVERED THIS SEMESTER

- Each process has a ***pass*** value
  - Initially set to process stride
- Each time a process releases the CPU
  - Scheduler selects process with ***lowest pass***
  - Gives it the CPU for a ***fixed time slide***
- Each time a process gets the CPU
  - Scheduler ***adds*** the process stride to its pass value

NOT COVERED THIS SEMESTER

The key idea

- Use epochs
- Have a thread priority ("pass")
  - Initially set to "stride"
    - Inversely proportional to the number of tickets allocated to
- Always schedule thread with lowest pass
- Penalize differently past core usage

Stride scheduling (II)

NOT COVERED THIS SEMESTER

- Scheme is ***starvation free***
  - Processes that do not get any CPU time keep their original pass values
  - Other processes will see their pass values increase

NOT COVERED THIS SEMESTER

Example

Round	**Pass values**			**Scheduler will pick thread**
	Thread A 10 tickets stride is 10	**Thread B** 5 tickets stride is 20	**Thread C** 25 tickets stride is 4	
1	10	20	**4**	**C**
2	10	20	**8**	**C**
3	**10**	20	12	**A**
4	20	20	**12**	**C**
5	20	20	**16**	**C**

Explanations

- Process C gets first slot
  - Lowest pass value (4)
- Process C gets second slot
  - Lowest pass value (8)
- Process A gets third slot
  - Lowest pass value (10)
- Process C gets fourth slot
  - Lowest pass value (12)

Note

NOT COVERED THIS SEMESTER

- Whenever two threads have the same pass value, the scheduler will pick the thread with the ***lowest stride***

FreeBSD 5.0 ULE scheduler

- Designed for threads running on multicore architectures
  - For more details **http://www.informit.com/articles/article.aspx?p=2249436&seqNum=4**
- Two parts
  - Low-level scheduler
    - Run every time a core is released
  - High-level scheduler
    - Run every second

Low-level scheduler

- Kernel maintains a set of ***run queues*** for each CPU
    - With different priorities
- Low-level scheduler selects first thread on highest-level non-empty run queue

High-level scheduler

- Reevaluates thread priorities
  - Real-time threads have fixed priorities
  - Scheduler detects interactive threads on the base of their ***interactivity score:***
    - $Scaling\ factor \times \frac{Sleep\ time}{Run\ time}$
- Also assigns threads to CPUs
  - Complex process

Observations

- Low-level scheduler is kept simple
  - Quick decisions
- High-level scheduler uses a very clever method to detect interactive processes

$$\frac{(Voluntary)Sleep\ time}{Run\ time}$$

- Must still pick length of observation period
  - Short term v. long term behavior