Module 4 – CPU Scheduling

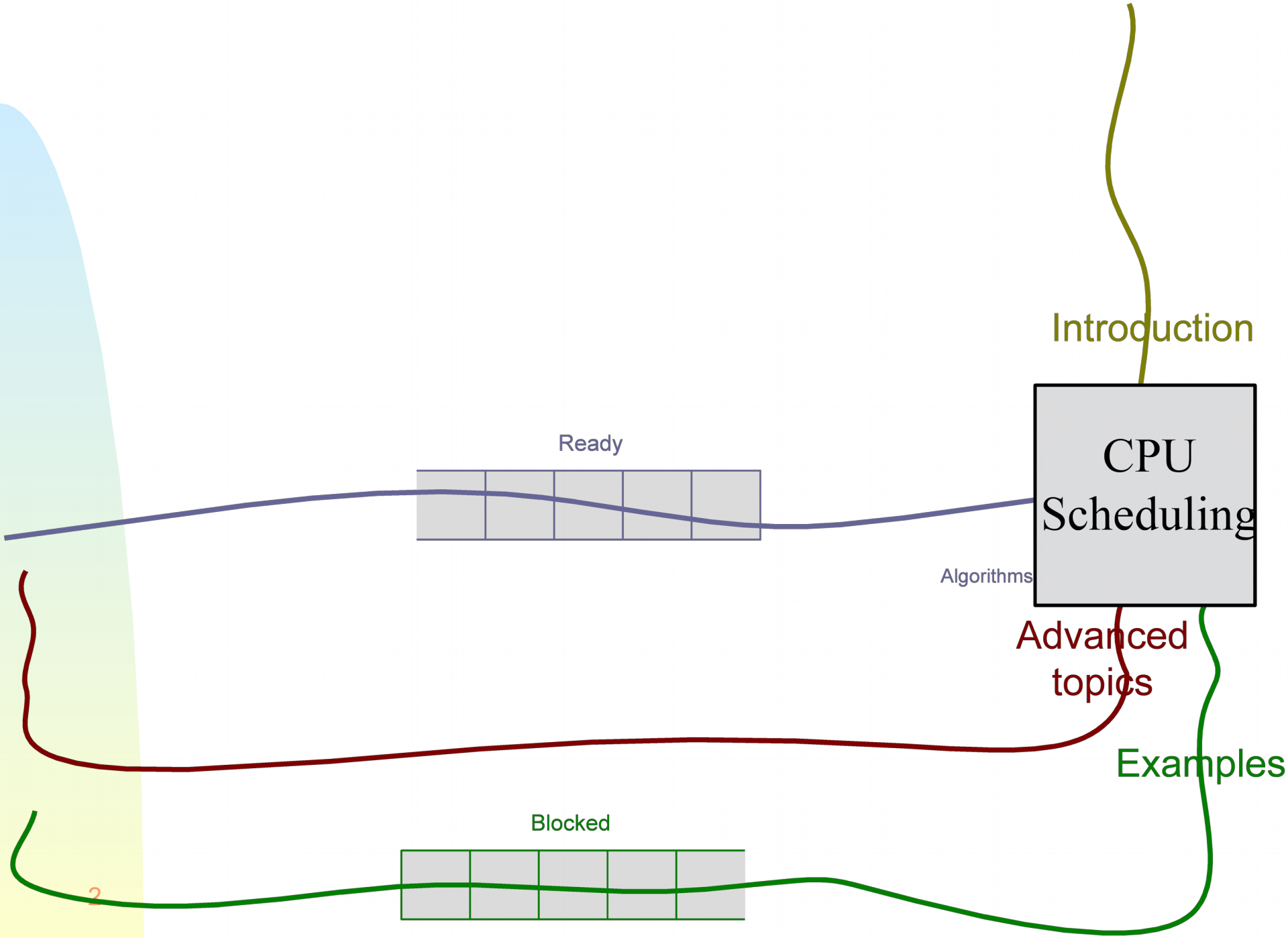
Reading: Chapter 5

Providing some motivation and scheduling criteria.

Shall study a number of different algorithms used by CPU (short-term) schedulers.

Overview some advance topics such as multiprocessor scheduling and evaluating algorithms.

Examine how scheduling is done in some real systems.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CPU Scheduling
Ready
Algorithms
Advanced topics
Examples
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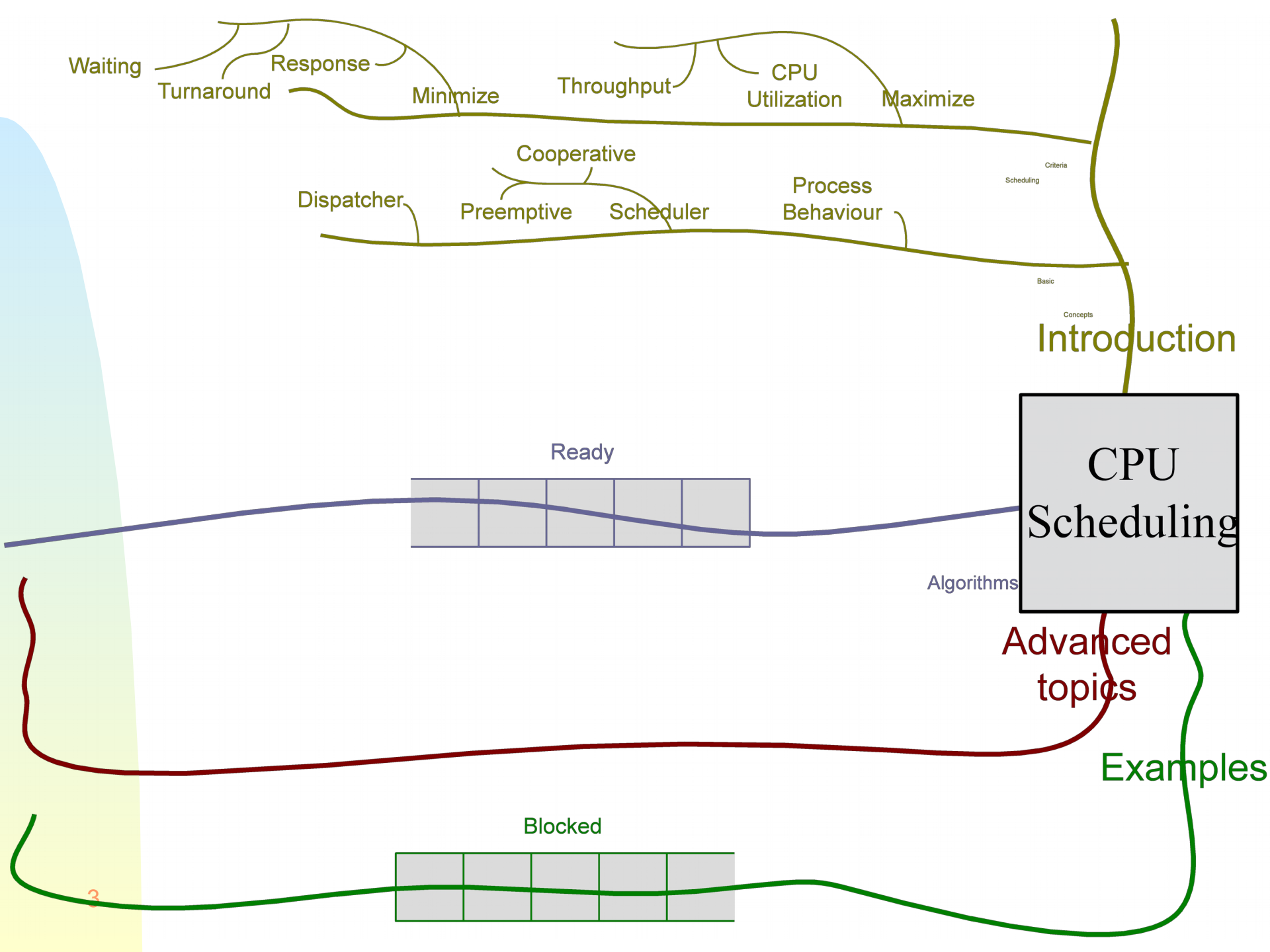
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Basic Concepts

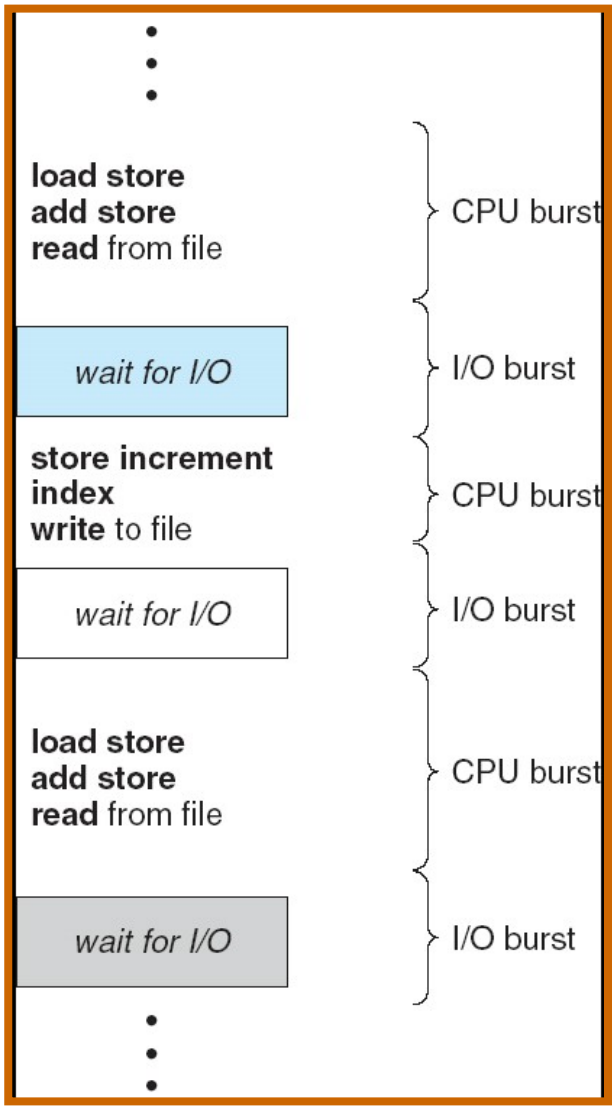
Why do we want multiprogramming?

- **To efficiently use the computer resources (CPU, I/O devices)**
- **I.e. when one process blocks, assign the CPU to another process**
- **That means we need to decide which process to execute, and then give the control to it**
- If we want efficient resource utilization, we need CPU scheduling
  - CPU scheduling principles can be applied to scheduling of other resources (I/O devices, etc.)

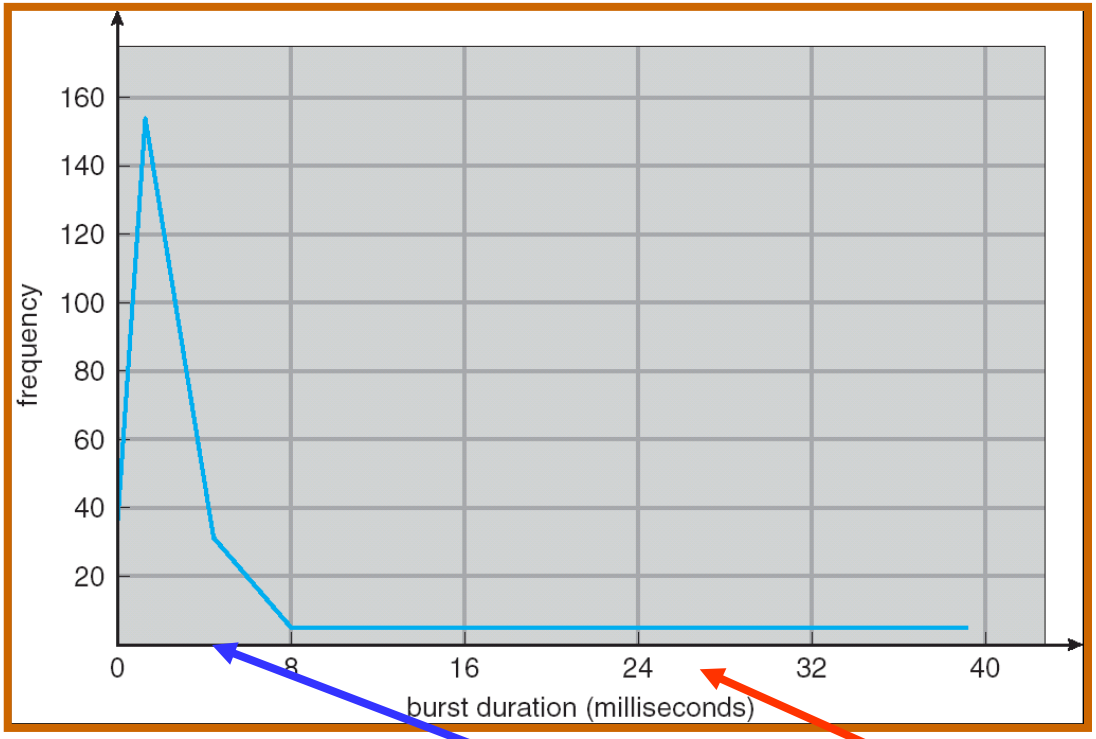
Process behaviour

- **Different processes might have different needs of resources**
- **Process execution can be seen as alternating bursts of CPU execution and I/O wait**
- If we want intelligent scheduling decisions, we need to understand process behaviour

Closer look at process behaviour



Histogram of CPU-burst Times



- Experimental observation:
  - In a typical system, we normally see a large number of short CPU bursts, and a small number of long CPU bursts
- CPU bound processes are normally composed of a few long CPU bursts.
- I/O bound processes are normally composed of many short CPU bursts

CPU (Short term) Scheduler

- Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them
- When may (should) the CPU scheduling decisions take place?
  1. A process switches from running to waiting state
     - made an I/O request
  2. A process terminates
  3. A process switches from running to ready state
     - used up its allotted time slice
  4. A process switches from waiting to ready
     - I/O operation completed
- Preemptive scheduling
  - The CPU is taken from the currently running process before the process voluntarily relinquishes it
  - Which of the above cases involve preemptive scheduling?

Dispatcher

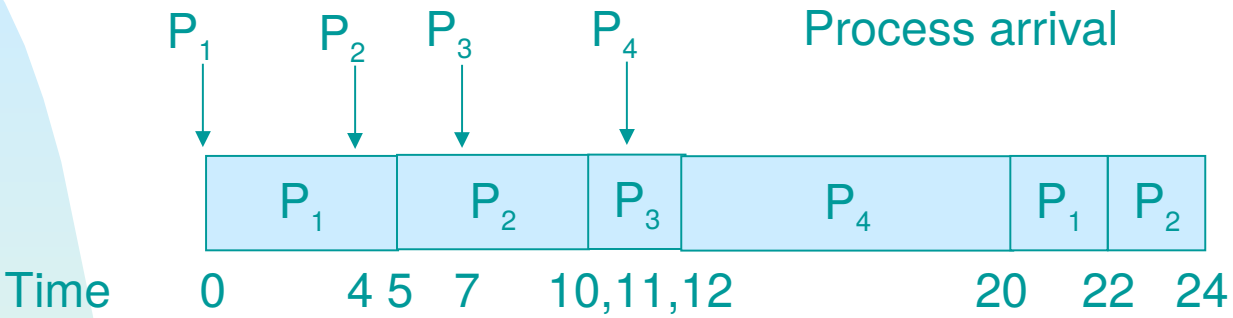
- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
  - switching context
  - switching to user mode
  - jumping to the proper location in the user program to restart that program
- *Dispatch latency* – time it takes for the dispatcher to stop one process and start another running
  - we want this to be really low

Scheduling Criteria

What kind of criteria we might want the scheduler to optimize?

- **Main reason for multiprogramming?**
  - **resource utilization – keep the CPU and I/O as busy as possible**
- **On time-shared systems?**
  - **Response time – amount of time it takes from when a request was submitted until the first response is produced (starts to output)**
- **On servers?**
  - **Throughput – # of processes that complete their execution per time unit**
- **On batch systems?**
  - **Turnaround time – amount of time from job submission to its completion**
- **On heavily loaded systems**
  - **Fairness/Waiting time – amount of time a process has been waiting in the ready queue**
- Averages are often considered

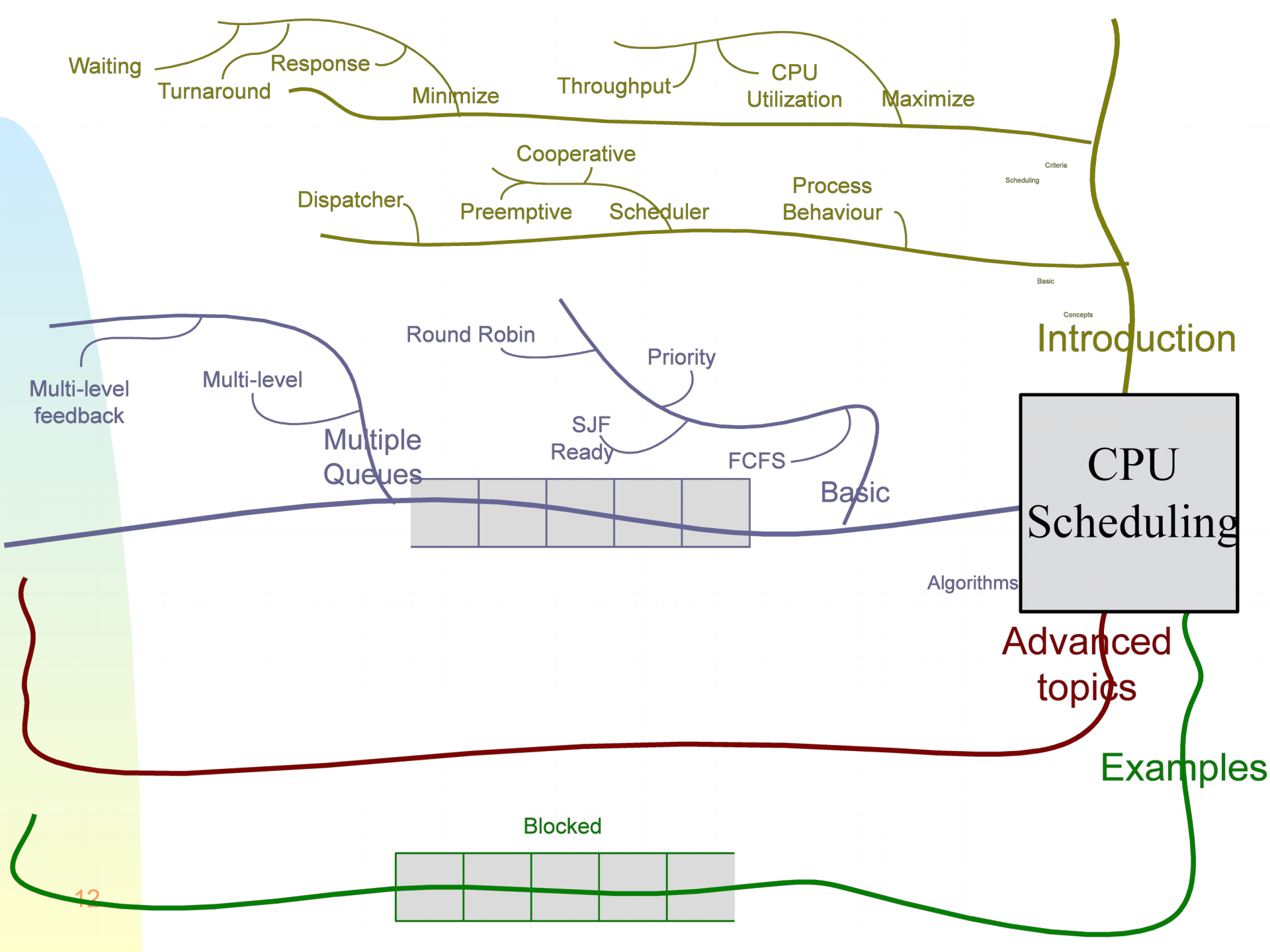
Scheduling Criteria Example



- **CPU utilization:**
  - **100%**
- **Throughput :**
  - **4/24**
- **Turnaround time (P_3, P_2):**
  - **P_3: 5**
  - **P_2: 20**
- **Waiting time (P_2):**
  - **P_2: 13**
- **Response time (P_3, P_2):**
  - **P_3: 3**
  - **P_2: 1**

Optimization Criteria

- Maximize
  - CPU utilization
  - throughput
- Minimize
  - turnaround time
  - waiting time
  - response time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Now, let's see some algorithms!

What is the simplest scheduling algorithm you can imagine?

- **First-Come, First-Serve**

How does FCFS work?

- **When a process arrives, it is put at the end of the ready queue**
- **The running process runs until its CPU burst is finished**

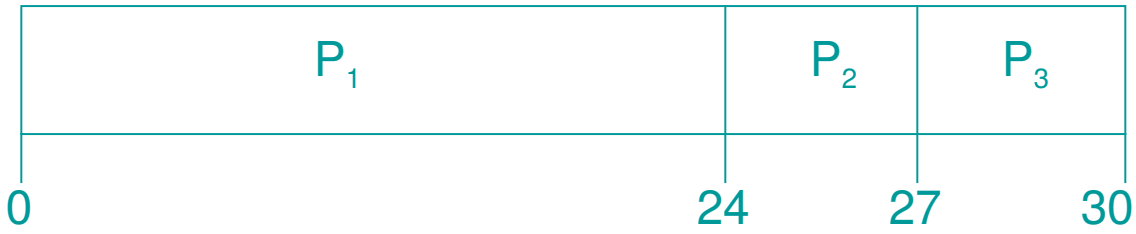
Is it preemptive?

- **No**

Let's see an example:

First-Come, First-Served (FCFS) Scheduling

Process	Burst Length	Arrival Time
P_1	24	0 (first)
P_2	3	0 (second)
P_3	3	0 (third)



Waiting time for P_1 = 0; P_2 = 24; P_3 = 27

Average waiting time: (0 + 24 + 27)/3 = 17

FCFS Scheduling (Cont.)

Suppose that the processes arrive in the order

$$P_2 , P_3 , P_1$$

The schedule now looks this way:

Waiting time for *P1* = 6*; P2* = 0*; P3* = 3
Average waiting time: (6 + 0 + 3)/3 = 3
Much better than the previous case

Convoy Effect with the FCFS

- Consider a single CPU bound process and many I/O bound processes (fairly normal situation).
- The I/O bound processes wait for the CPU: I/O under utilized (*).
- The CPU bound process requests I/O: the other processes rapidly complete CPU bursts and go back to I/O: CPU under utilized.
- CPU bound process finishes I/O, and so do the other processes: back to *
- Solutions?

FCFS Scheduling Discussion

Is it simple and easy to program?

- **Yes!**

Can we find other benefits?

- **It costs little time to make scheduling decision**

Does it provide low waiting time?

- **Not at all, can be quite awful**

Does it provide good CPU utilization?

- **No – the convoy effect**

OK, forget about it.

Now, let's try to reduce the average waiting time

Idea: **It is better to execute ready processes with short CPU bursts**

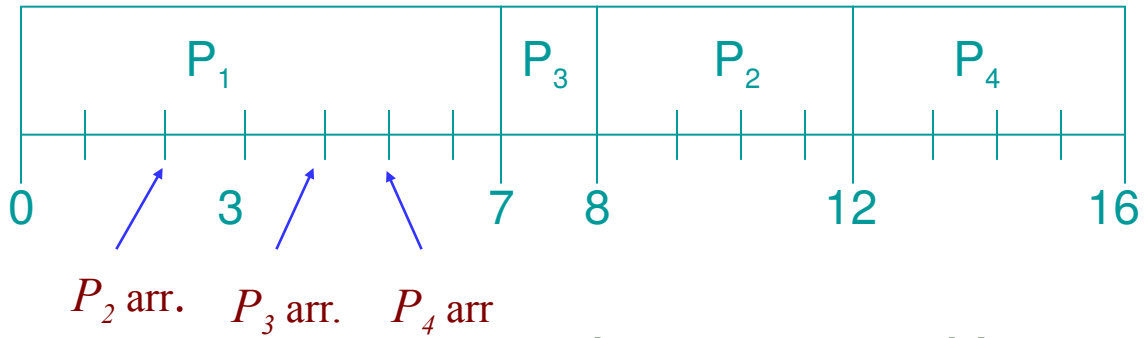
Shortest-Job-First (SJR) Scheduling

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time
- Two schemes:
  - nonpreemptive – once CPU given to the process it cannot be preempted until completes its CPU burst
  - preemptive – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. This scheme is also know as the Shortest-Remaining-Time-First (SRTF)
    - *Just call it preemptive SJF*
- Preemptive SJF is optimal – gives minimum average waiting time for a given set of processes
  - Moving a process with short CPU burst in front of a process with longer CPU burst reduces average waiting time

Example of Non-Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (non-preemptive)

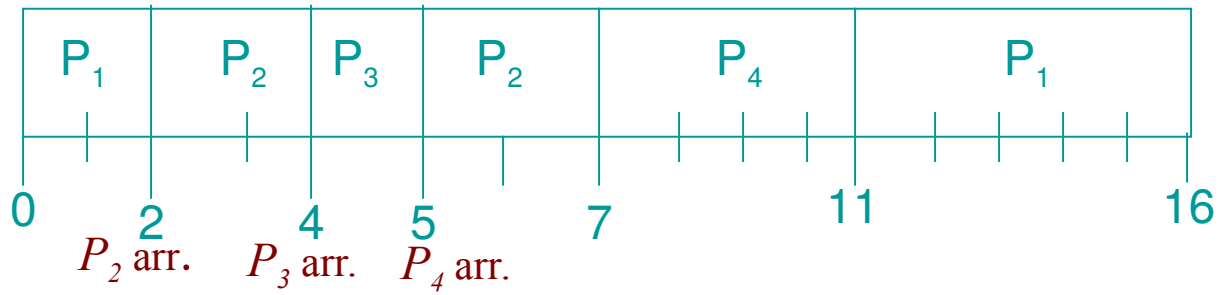


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

Example of Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (preemptive)



- Average waiting time = (9 + 1 + 0 +2)/4 = 3

Small technical detail with SJF

How do we know the length of the next CPU burst?

- **If you know that, you probably know also tomorrow's stock market prices…**
  - **You will be rich and won't need to waste time in CSI3131 class**
- **So, we can only estimate it**

Any idea how to estimate the length of the next CPU burst?

- **Probably similar as the previous bursts from this process**
- **Makes sense to give more weight to the more recent bursts, not just straightforward averaging**
  - **Use exponential averaging**

Exponential averaging with SJF

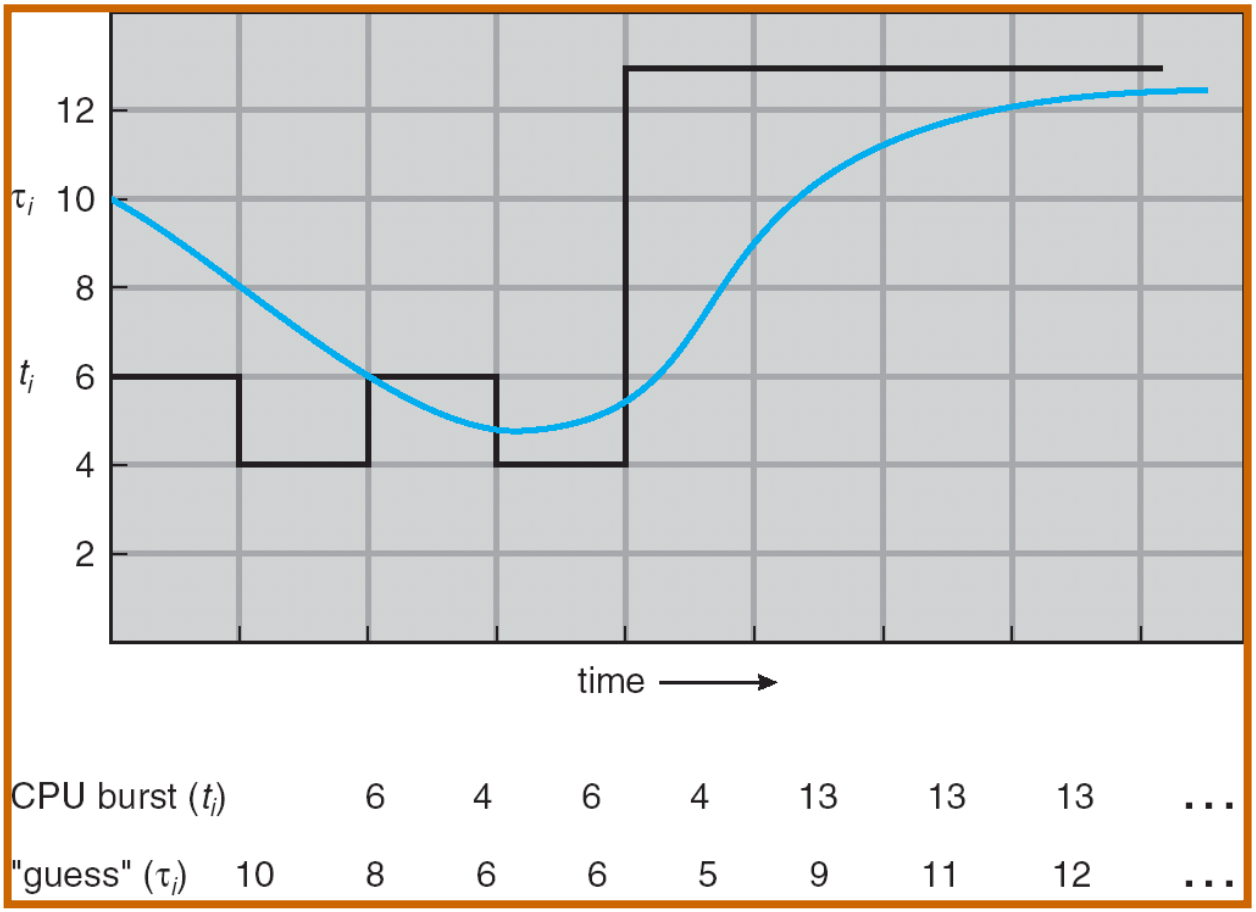
1. t_n = actual length of n^{th} CPU burst
2. τ_{n+1} = predicted value for the next CPU burst
3. $\alpha, 0 \le \alpha \le 1$ = relative weight of recent vs past history
4. Define:

$$\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$$

$$\tau_{n+1} = \alpha t_n + (1 - \alpha)\alpha t_{n-1} + (1 - \alpha)^2 \alpha t_{n-2} + \ldots$$

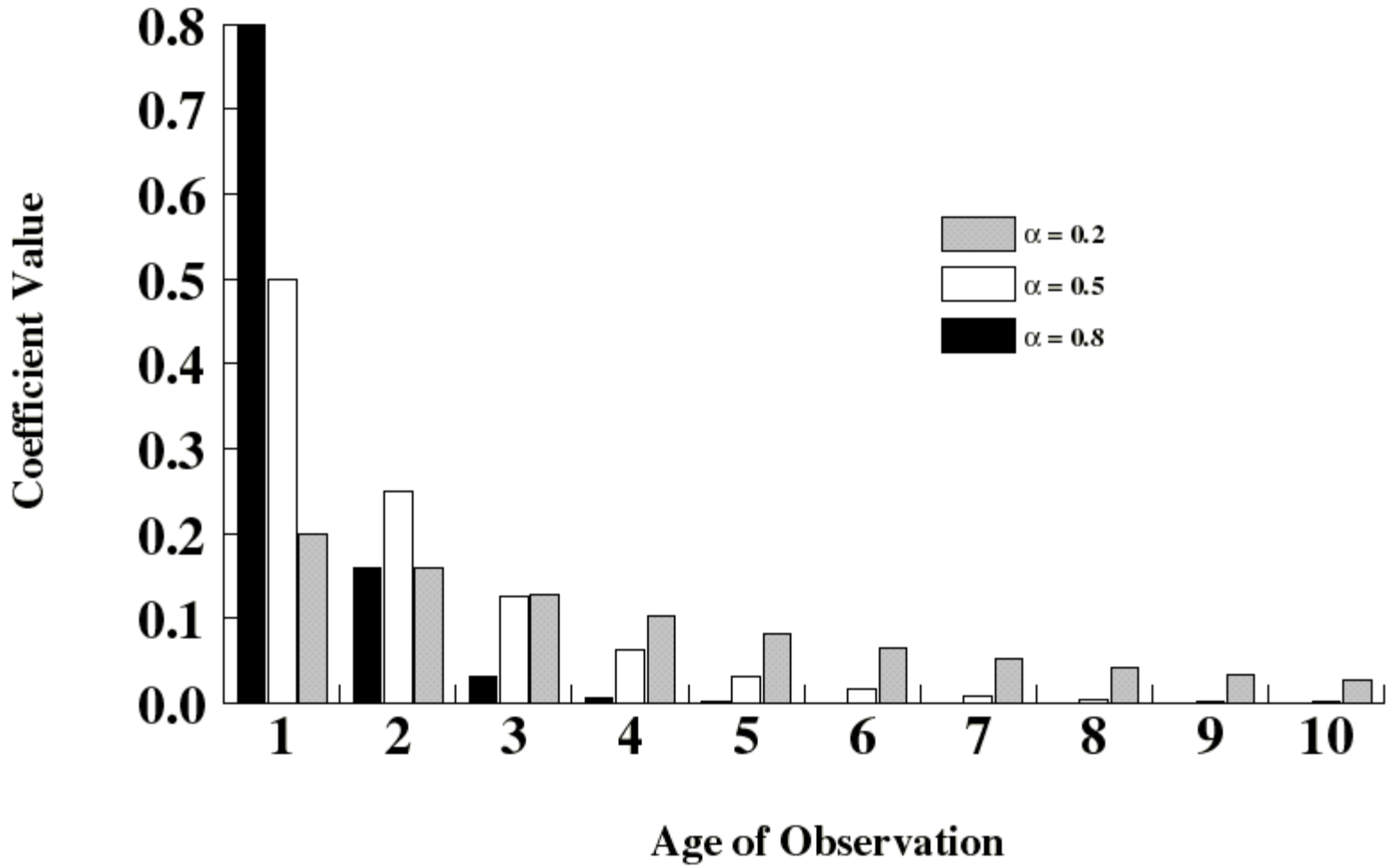
$$+ (1 - \alpha)^i \alpha t_{n-i} + \ldots + (1 - \alpha)^n t_1$$

Prediction of the Length of the Next CPU Burst

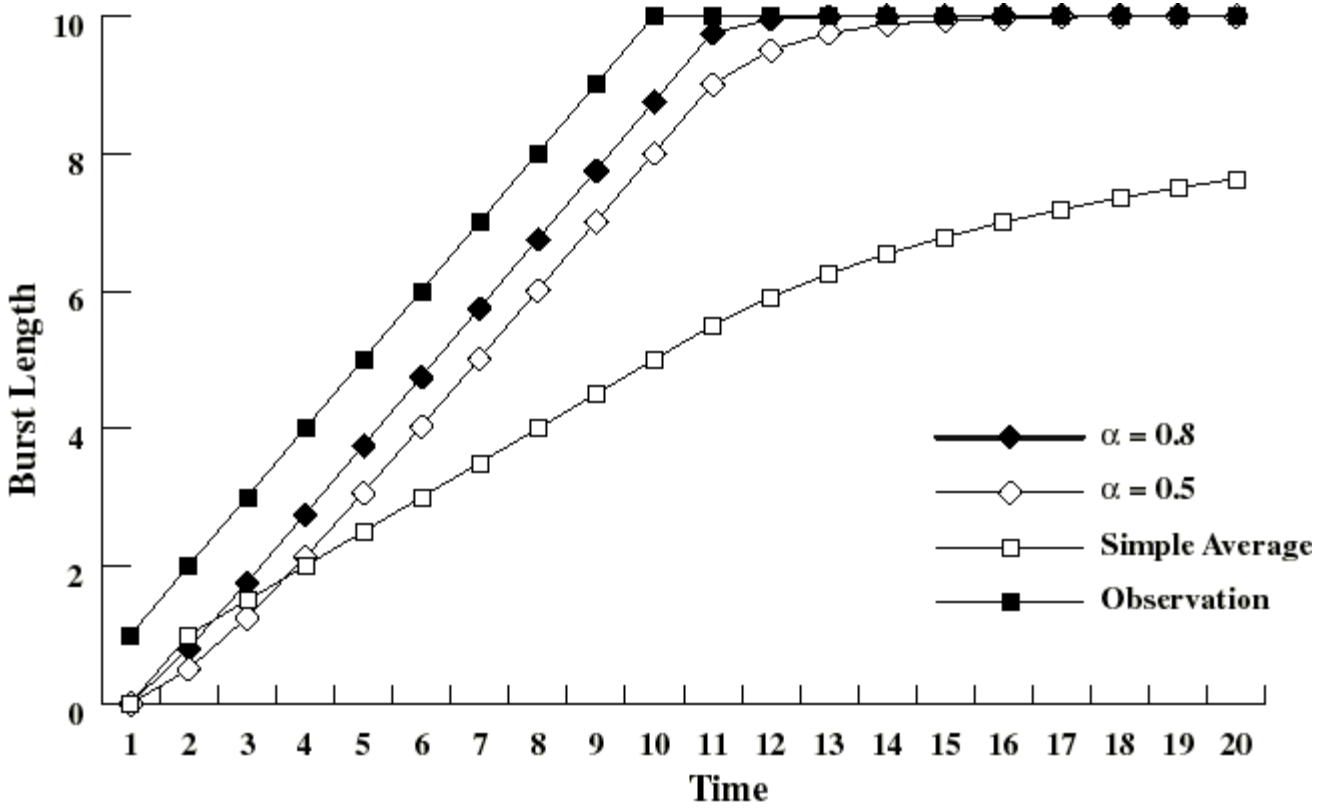


CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Exponential decrease of coefficients [Stallings]

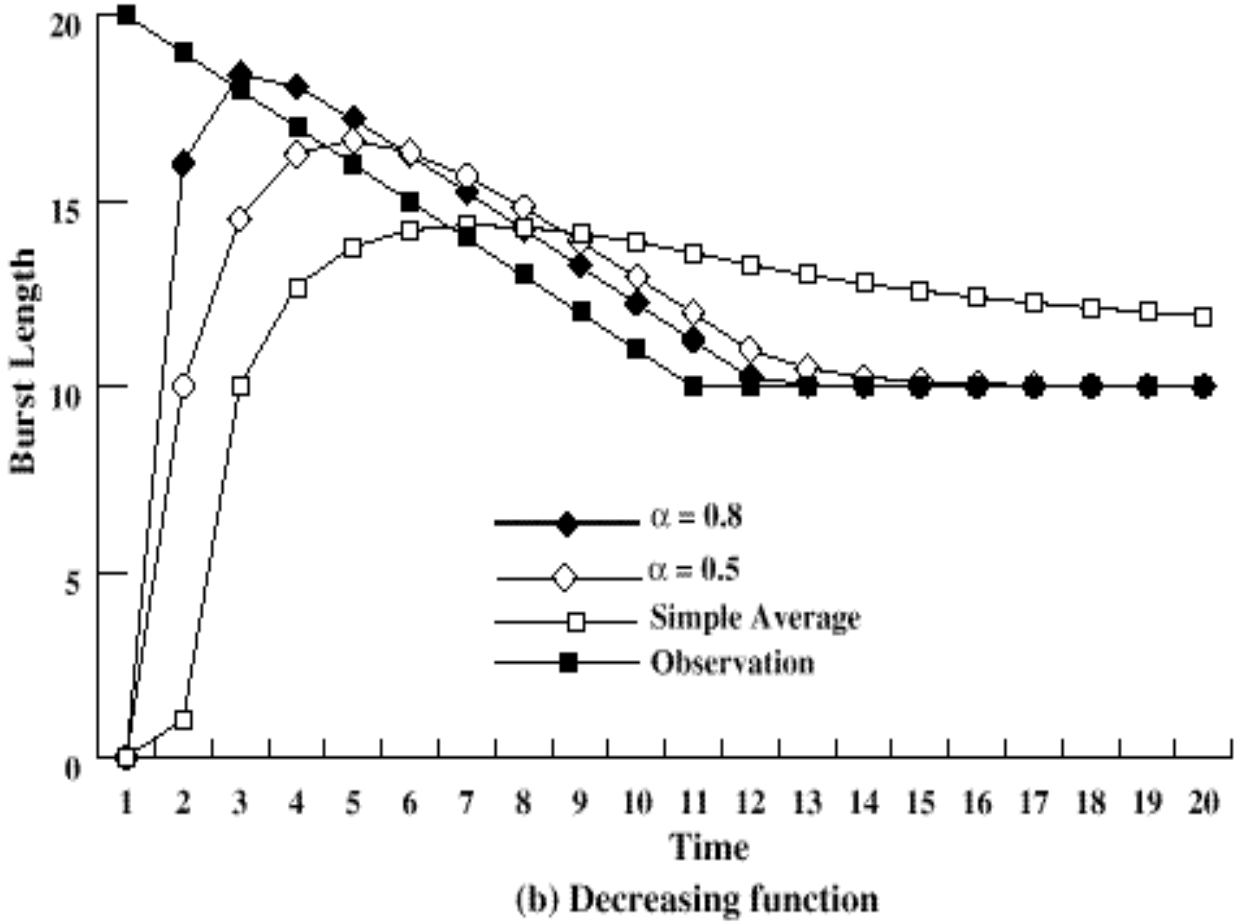


Exponential decrease of coefficients [Stallings]



- $t_1 = 0$ (priority is given to new processes)
- A larger coefficient leads to estimates that react more rapidly to changes in the process behaviour

A second example [Stallings]



(b) Decreasing function

How to choose the coefficient α

- A small coefficient is advantageous when a process can have anomalies in behaviour, after which it returns to previous behaviour (must ignore recent behaviour).
  - Limit case: $\alpha = 0$, use only the initial estimate
- A large coefficient is advantageous when a process is susceptible to changing rapidly from one type of activity to another.
  - Limit case: $\alpha = 1$, $\tau_{n+1} = t_n$
  - The last burst is the only one used for estimating the next one.

SJF Discussion

Does it ensure low average waiting time?

- **Yes, it was designed that way**
  - **As long as our burst-length predictions more-or-less work**

Does it provide low response time?

- **Not necessarily, if there is a steady stream of short CPU bursts, the longer bursts will not be scheduled**
- **This is called** starvation
  - **A process is blocked forever, always overtaken by other processes (well, or at least while the system is busy)**

Let's see Priority Scheduling.

Priority Scheduling

- A priority number (usually integer) is associated with each process
  - On some systems (Windows), the higher number has higher priority
  - On others (Unix) , the smaller number has higher priority
- The CPU is allocated to the process with the highest priority
  - Can be preemptive or non-preemptive
  - but usually you want to preempt low-priority process when a high priority process becomes ready
- Priority can be explicit
  - Assigned by the sysadmin/programmer, often for political reasons
    - Professor jobs are of higher priority
  - But also for technical reasons
    - This device has to be serviced really fast, otherwise the vital data will be lost (real-time processing)
- Priority can also be implicit (computed by the OS)
  - SJF can be seen as priority scheduling where priority is the predicted next CPU burst time

Priority Scheduling Discussion

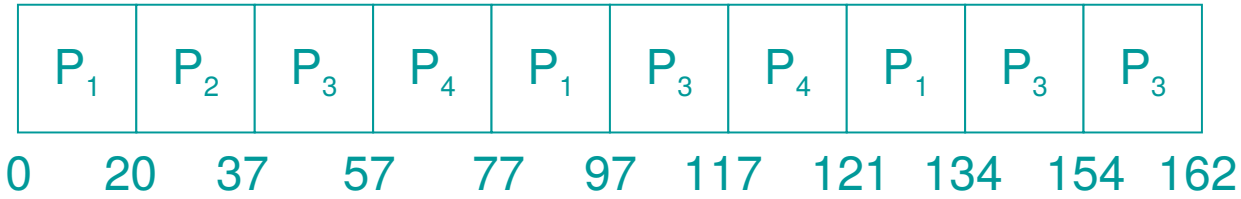
- Good properties
  - Professor jobs will be scheduled before student jobs
  - Allows support of real-time processing
- Bad properties
  - Professor jobs will be scheduled before student jobs
    - OK, give me something else
  - starvation – low priority processes may never execute
- How to resolve the starvation problem?
  - aging – keep increasing the priority of a process that has not been scheduled for a long time
- What to do with the processes of the same priority level?
  - FCFS
  - Might as well add preemption = Round Robin

Round Robin (RR)

- Each process gets a small unit of CPU time (*time quantum, time slice*), usually 10-100 milliseconds.
  - After this time has elapsed, the process is preempted and added to the end of the ready queue.
  - The CPU is then given to the process at the head of the queue.
- If there are *n* processes in the ready queue and the time quantum is *q*, then each process gets 1/*n* of the CPU time in chunks of at most *q* time units at once.
  - No process waits more than (*n*-1)*q* time units.
- Performance
  - *q* large ⇒ FCFS
  - *q* small ⇒ too much context switching overhead
    - *q* must be large with respect to context switch time

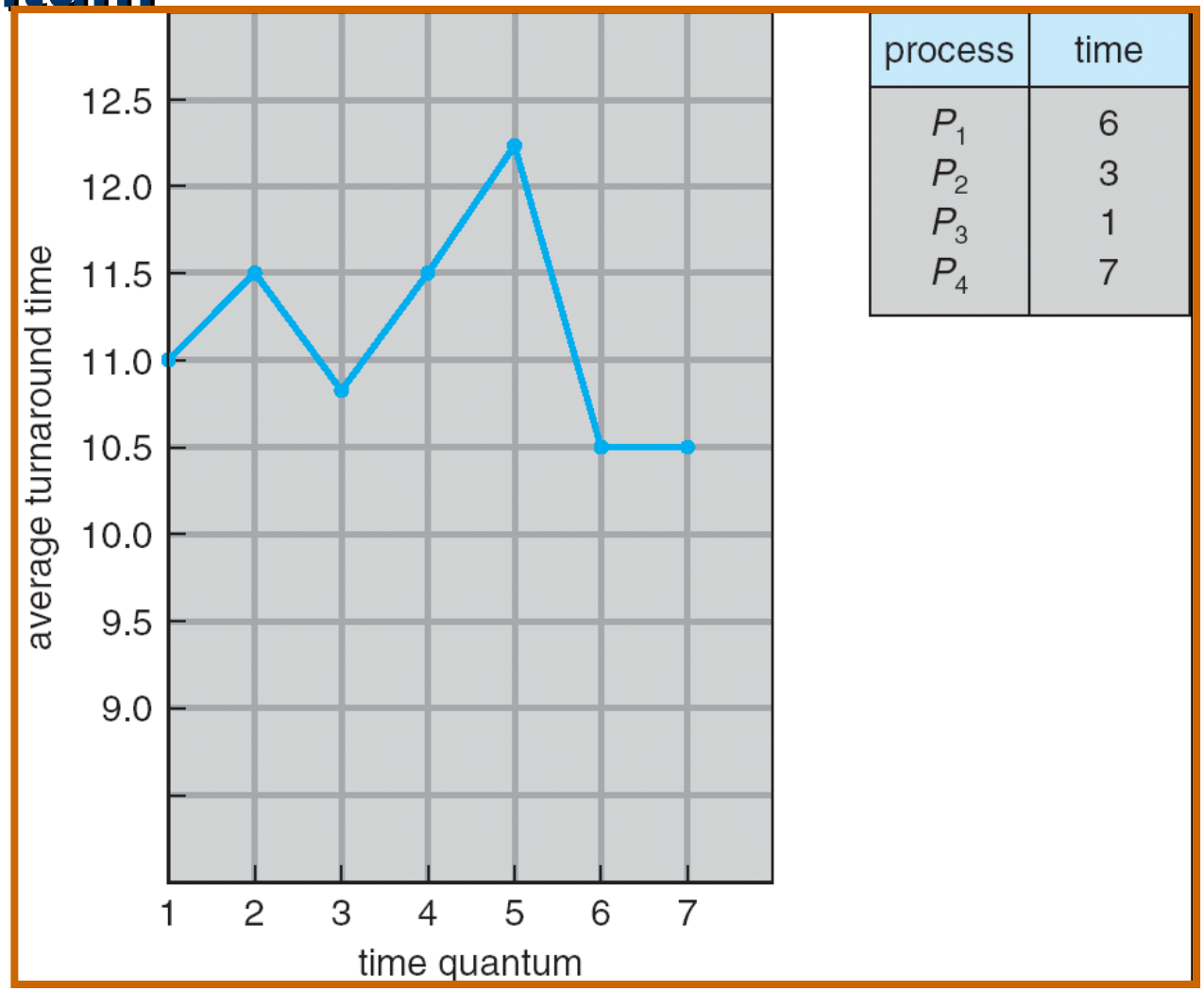
Example of RR with Time Quantum = 20

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24



- Typically, higher average turnaround than SJF, but better *response*

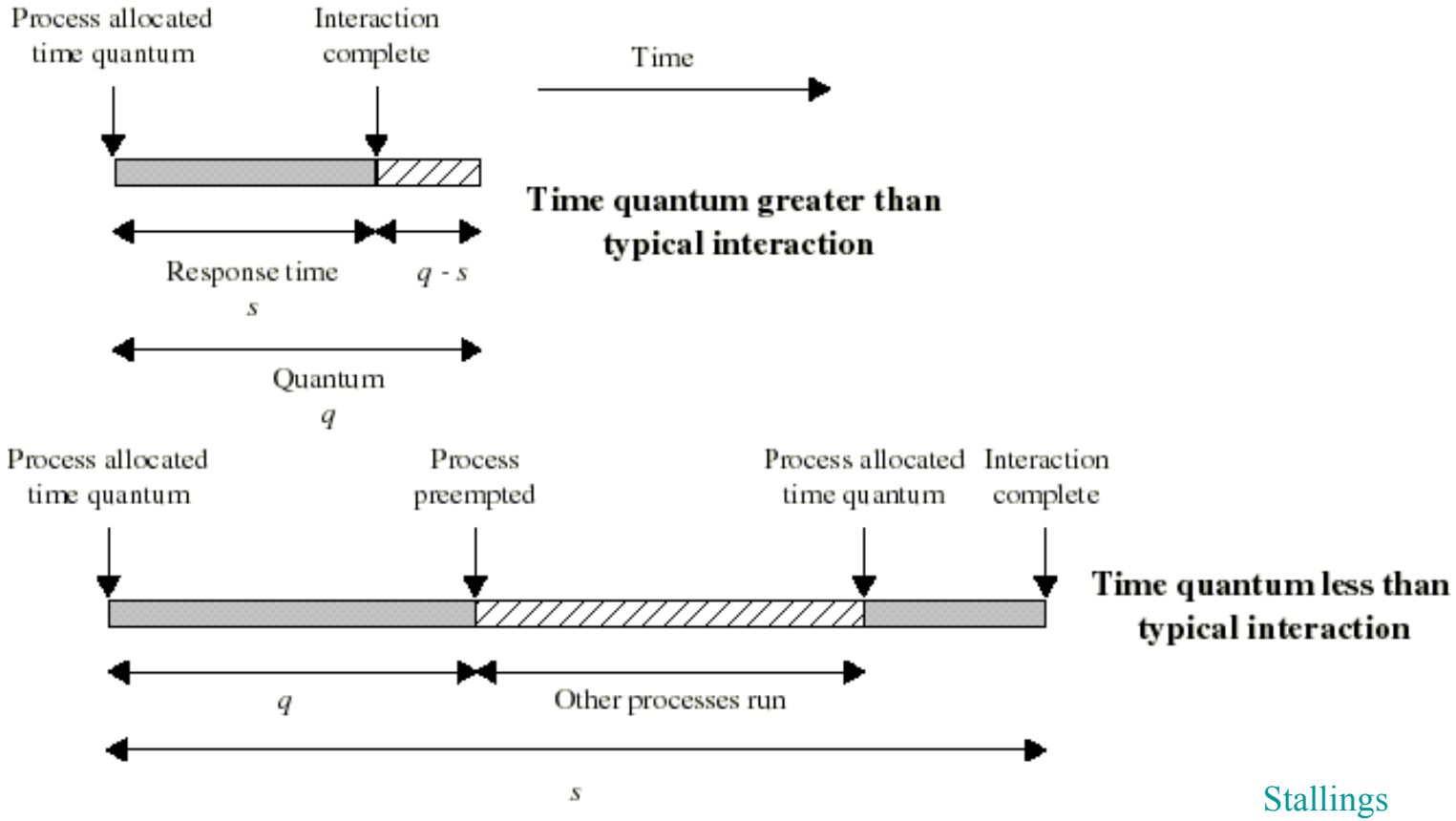
Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

Selecting quantum for Round Robin [Stallings]

- Must be much larger than time for executing context switching
- Must be larger that the typical CPU burst length (to give time for most processes to complete their burst, but not so long to penalize the processes with short bursts).



Algorithms we have seen so far

- First Come First Serve
  - simple, little overhead, but poor properties
- Shortest Job First
  - needs to know CPU burst times
  - exponential averaging of the past
- Priority Scheduling
  - This is actually a class of algorithms
- Round Robin
  - FCFS with preemption

Let's see how they work – Tutorial Exercise

Consider three processes P1, P2, P3

- Burst times for P1: 14,12,17
- Burst times for P2: 2,2,2,3,2,2,2,3,2,2,2,3,2,2,2,3
- Burst times for P3: 6,3,8,2,1,3,4,1,2,9,7
- All three arrive at time 0, in order P1, P2, P3
- Each CPU burst is followed by an I/O operation taking 6 time units
- Let's simulate the scheduling algorithms
  - FCFS
  - Round Robin (quantum=5)
  - Non-preemptive SJF or Preemptive SJF (your choice)
  - Round robin (quantum=5) with Priority scheduling, priorities are P2=P3>P1

Multilevel Queue

Idea: **Partition the ready queue into several queues, and handle each queue separately.**

Example:

- **foreground queue (interactive processes)**
- **background (batch processes)**

Each queue might have its own scheduling algorithm

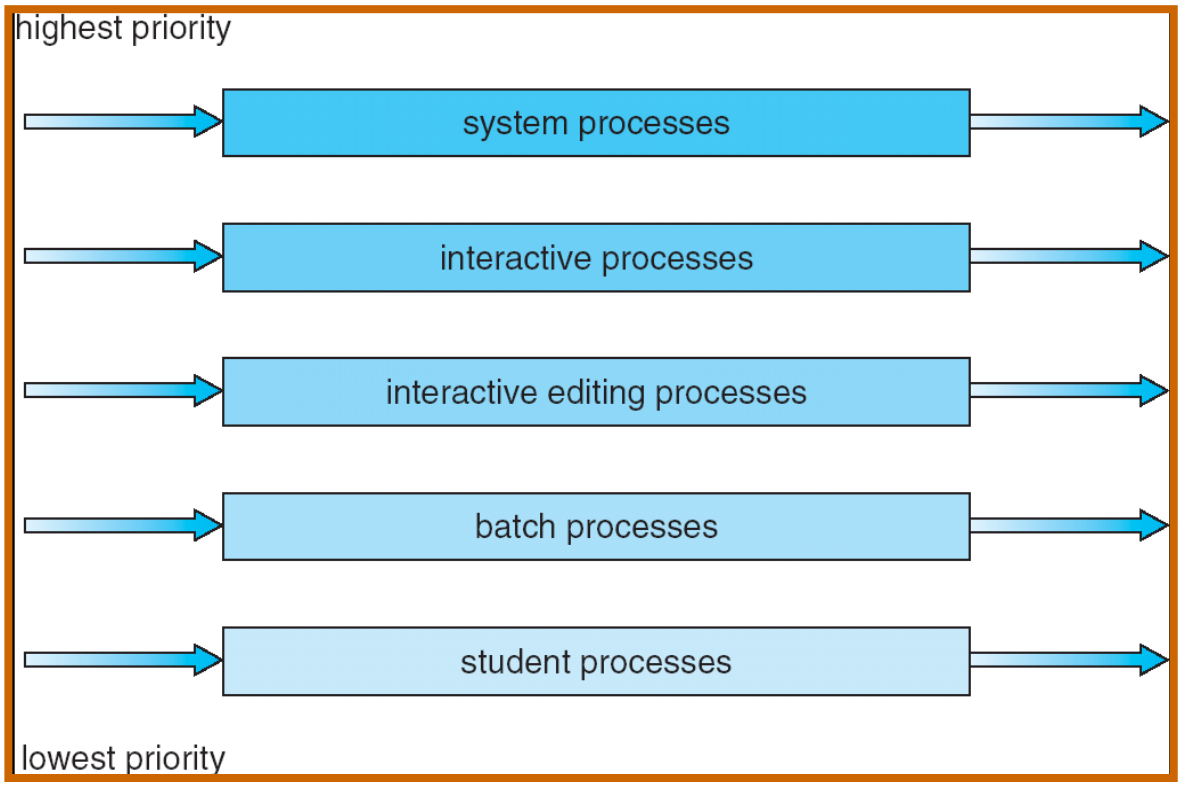
- **foreground – RR (for low response time)**
- **background – FCFS (for simplicity and low context-switch overhead)**

Multilevel Queue

How to schedule from among the queues?

- Fixed priority scheduling
  - i.e. the processes from foreground queue get the CPU, the background processes get the CPU only if the foreground queue is empty
  - Possibility of starvation.
- Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes
  - i.e., 80% to foreground queue, 20% to background queue
  - not necessarily optimal

Multilevel Queue Scheduling



Multilevel Feedback Queue

Idea:

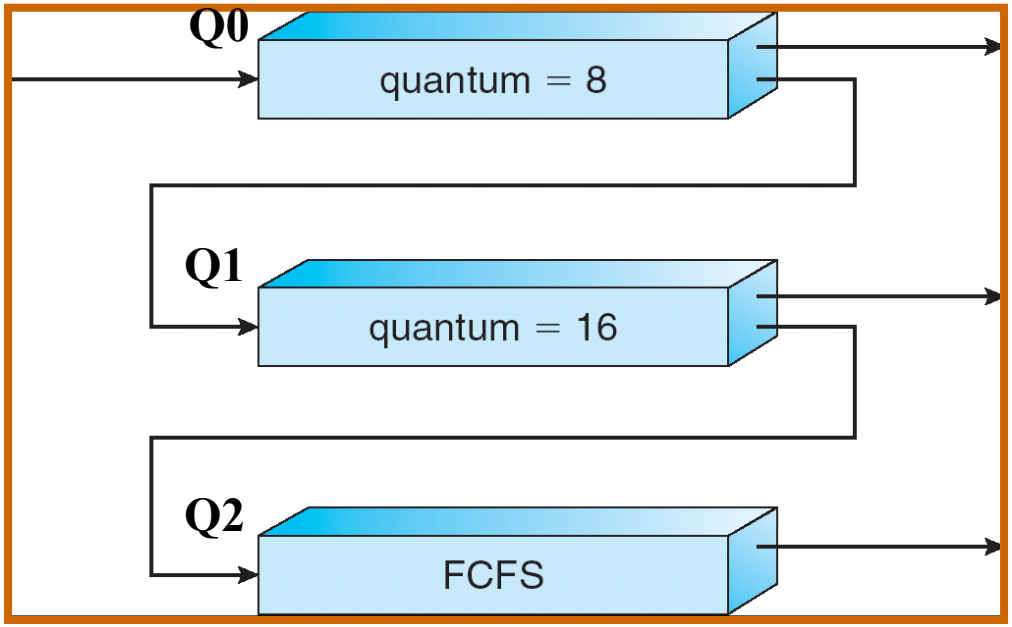
- **Use multilevel queues**
- **A process can move up and down queue hierarchy**
  - **Why would a process move to a lower priority queue?**
    - **It is using too much CPU time**
  - **Why would a process move to a higher priority queue?**
    - **Has been starved of CPU for long time**
    - **A way to implement aging**

Multilevel Feedback Queue

- Multilevel-feedback-queue scheduler defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method used to determine when to upgrade a process
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when that process needs service
- This algorithm is the most general one
  - It can be adapted to specific systems
  - But it is also the most complex algorithm

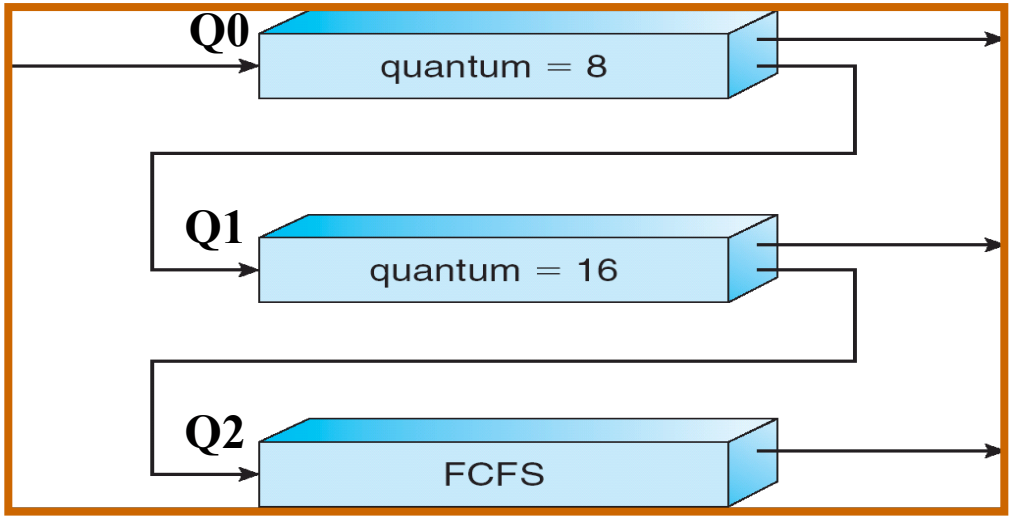
Example of Multilevel Feedback Queue

- Scheduler selects processes in Q0 first (highest priority)
  - If Q0 is empty, the processes from Q1 are selected.
  - If both Q0 and Q1 are empty, processes from Q2 are selected
- If a process arrives in a higher priority queue when another from a lower priority queue is running, the running process will be preempted, to allow the arriving process to run.
- When a process exhausts its quantum in either Q0 or Q1, it is preempted and moved to the lower priority queue.



Example of Multilevel Feedback Queue

- Scheduling example
  - A new job enters queue Q_0 which is served FCFS. When it gains CPU, job receives 8 milliseconds.
  - If it does not finish in 8 milliseconds, job is preempted and moved to queue Q_1 and served again FCFS to receive another 16 additional milliseconds.
  - If it still does not complete, it is preempted and moved to queue Q_2.



Multilevel Feedback Queue Discussion

Exact properties depend on the parameters

Flexible enough to accommodate most requirements

The convoy example:

- One process with long CPU burst time
- Several I/O bound processes with short CPU burst time
- Even if the all processes start at the same level, the CPU-intensive process will be soon demoted to a low priority queue
- The I/O bound processes will remain at high priority and will be swiftly serviced, keeping the I/O devices busy

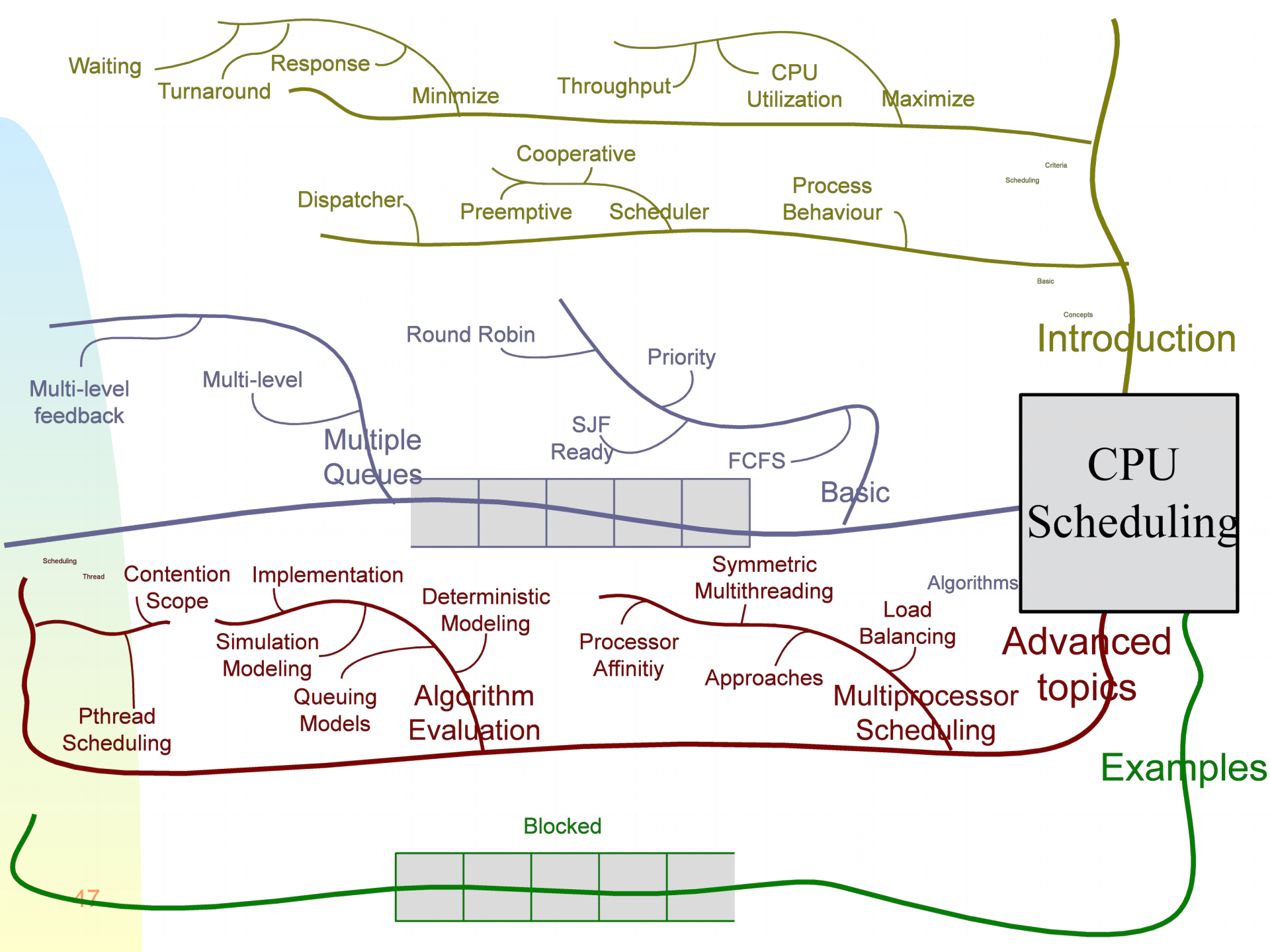
Let's simulate the multi-level feedback queue – Tutorial Exercise

Consider three processes P1, P2, P3

- Burst times for P1: 14,12,17
- Burst times for P2: 2,2,2,3,2,2,2,3,2,2,2,3,2,2,2,3
- Burst times for P3: 6,3,8,2,1,3,4,1,2,9,7
- All three arrive at time 0, in order P1, P2, P3
- Each CPU burst is followed by an I/O operation taking 6 time units
- Parameters:
  - Queue 0 – quantum of 2 time units
  - Queue 1 – quantum of 4 time units
  - Queue 2 – FCFS

The scheduling algorithms we have seen

- First Come First Serve
  - simple, little overhead, but poor properties
- Shortest Job First
  - needs to know CPU burst times
  - exponential averaging of the past
- Priority Scheduling
  - This is actually a class of algorithms
- Round Robin
  - FCFS with preemption
- Multilevel Queues
  - Different scheduling algorithms possible in each queue
- Multilevel Feedback Queues
  - combines many ideas and techniques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Multiple-Processor Scheduling

Good news:

- **With multiple CPUs, we can share the load**
- **We can also share the OS overhead**

Bad news:

- **We are expected to efficiently share the load**
- **Managing the OS structures gets more complicated**
- **The scheduling gets more complex**

Multiple-Processor Scheduling - Approaches

- We assume *homogeneous processors*
  - i.e. all processors have the same functionality
- Still, the scheduler (and possibly the whole OS) might be run on a single CPU
  - *Asymmetric multiprocessing* – only one CPU accesses the system data structures and makes scheduling decisions
    - alleviates the need for data sharing
    - but might become bottleneck
  - *Symmetric multiprocessing (SMP)* – each CPU is self-scheduling
    - Either from a common ready queue, or from a private ready queue
    - Care must be taken when CPUs access common data structures
    - Virtually all modern operating systems support SMP including Windows XP, Solaris, Linux, Mac OS X.

SMP Scheduling Issues

- **Processor Affinity**
  - When process runs on a physical CPU, cache memory is updated with content of the process
  - If the process is moved to another CPU, benefits of caching is lost.
  - SMP systems try to keep processes running on the same physical CPU – know as processor affinity
- **Load Balancing**
  - Required when each CPU has its own Ready Queue
  - Push migration: a task is run periodically to redistribute load among CPUs (their ready queue)
  - Pull migration: An idle CPU (i.e. with an empty ready queue), will pull processes from other CPUs
  - Linux supports both techniques
  - Can counteract the benefits of processor affinity, since it moves processes from one CPU to another

Multi-Core and Multithreading

- Feature provided in hardware
- A single physical processor contains several logical CPUs
  - Achieved by replicating some resources such as the program counter (instruction pointer)
  - Big advantage is that many resources can be shared (such as arithmetic and logic units).
- Each logical processor can be assigned different threads (one or more) to execute
- To benefit from such hardware
  - Applications should be SMT aware
  - OS's should differentiate between logical and physical processors (e.g. schedule on different physical CPUs first
- Dual-core processors are examples of such processors

Thread Scheduling

Contention Scope

- **Process contention scope (PCS)**
  - The threads within a process compete for the LWPs, i.e. to attain the running state
  - Managed by the threads library when many-to-one or many-to-many model is used

- **Global contention scope (SCS)**
  - All kernel threads compete for the CPU
  - Managed by the kernel – kernel decides which thread to schedule
  - Implied when one-to-one model is used

PThread Scheduling

- The POSIX Pthread standard provides the means to specify either PCS or SCS scopes
  - See next slide for coding example.
- On systems that support a many-to-many threading model
  - PTHREAD_SCOPE_PROCESS policy schedules user-level threads onto available LWPs
  - PTHREAD_SCOPE_SYSTEM policy creates and binds an LWP to each user-level thread
- On some systems, only one scope is supported
  - E.g. Linux and Mac OS X only support PTHREAD_SCOPE_SYSTEM – why?

Pthread Scheduling API

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5
int main(int argc, char *argv[])
{
    int i;
   pthread_t tid[NUM_THREADS];
   pthread_attr_t attr;
   /* get the default attributes */
   pthread_attr_init(&attr);
   /* set the scheduling algorithm to PROCESS or SYSTEM */
   pthread_attr_setscope(&attr, PTHREAD_SCOPE_SYSTEM);
   /* set the scheduling policy - FIFO, RT, or OTHER */
   pthread_attr_setschedpolicy(&attr, SCHED_OTHER);
   /* create the threads */
   . . .
```

Algorithm Evaluation

- Deterministic modeling
  - takes a particular predetermined workload
  - compute the performance of each algorithm for that workload
  - we did that in class for very small examples
  - was limited applicability
    - how to get representative workloads?
- Queuing models
  - Computer system is described as a network of servers, each with its own queue
  - Knowing arrival rates and service rates, we can compute utilizations, average queue lengths, average wait time…

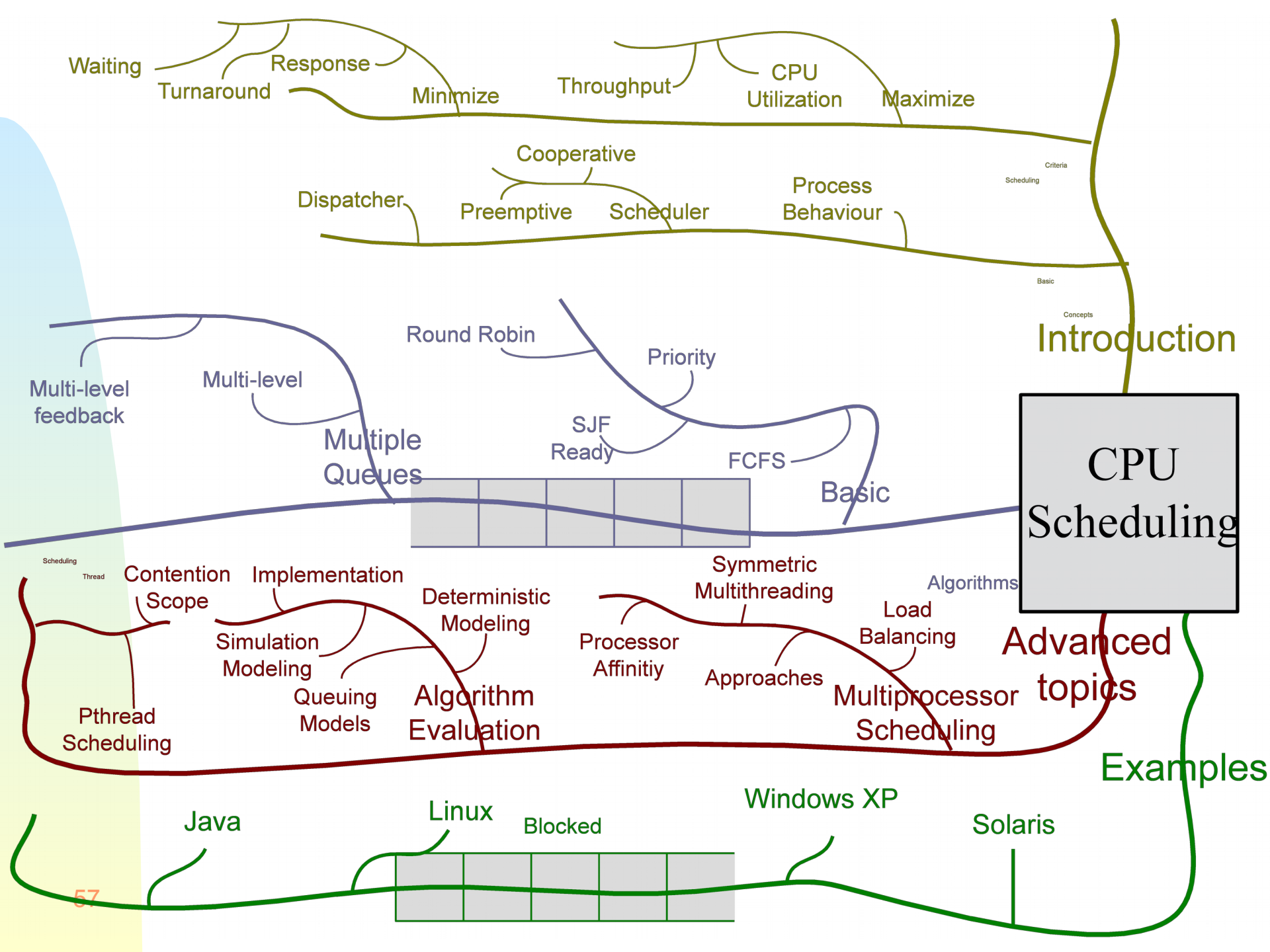
Algorithm Evaluation

Simulation

- Create simulator, run different scheduling algorithms and evaluate results
- How to feed it the data about CPU and I/O bursts?
  - Generate randomly based on some empirically observed distribution
  - Feed it data from a real system – trace tapes
- Still, the results are not always representative

Implement & test in real life

- High cost
- Still, the use of the system might change over time, and with it also the requirements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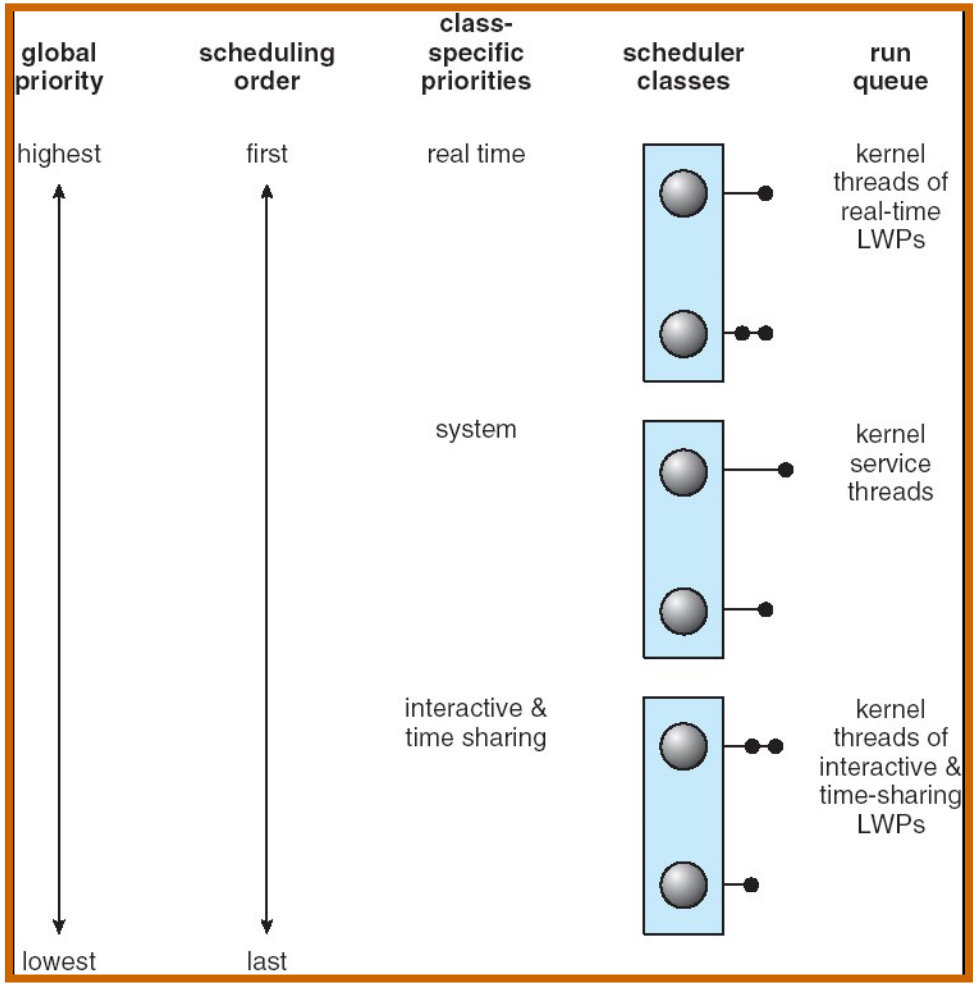
Solaris

Solaris Scheduling

- Four classes of scheduling
  - Real time
  - System
  - Time sharing
  - Interactive
- Default class
  - time sharing
- Algorithm:
  - multi-level feedback queue



Solaris Scheduling Table (interactive/time-sharing classes)

Gives high priority for processes returning from sleep, to keep interactive and I/O bound processes busy

Note that high priority processes have short time quanta.

Priorities are lowered when time quantum expires

Low

High

priority	time quantum	time quantum expired	return from sleep
0	200	0	50
5	200	0	50
10	160	0	51
15	160	5	51
20	120	10	52
25	120	15	52
30	80	20	53
35	80	25	54
40	40	30	55
45	40	35	56
50	40	40	58
55	40	45	58
59	20	49	59

Windows XP Priorities

Preemptive, priority based.

Has priority classes, and within each priority class has relative priorities.

Except for the real-time class, the priorities are variable.

- Expired time quantum lowers relative priority, returning from sleep-I/O rises it

	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

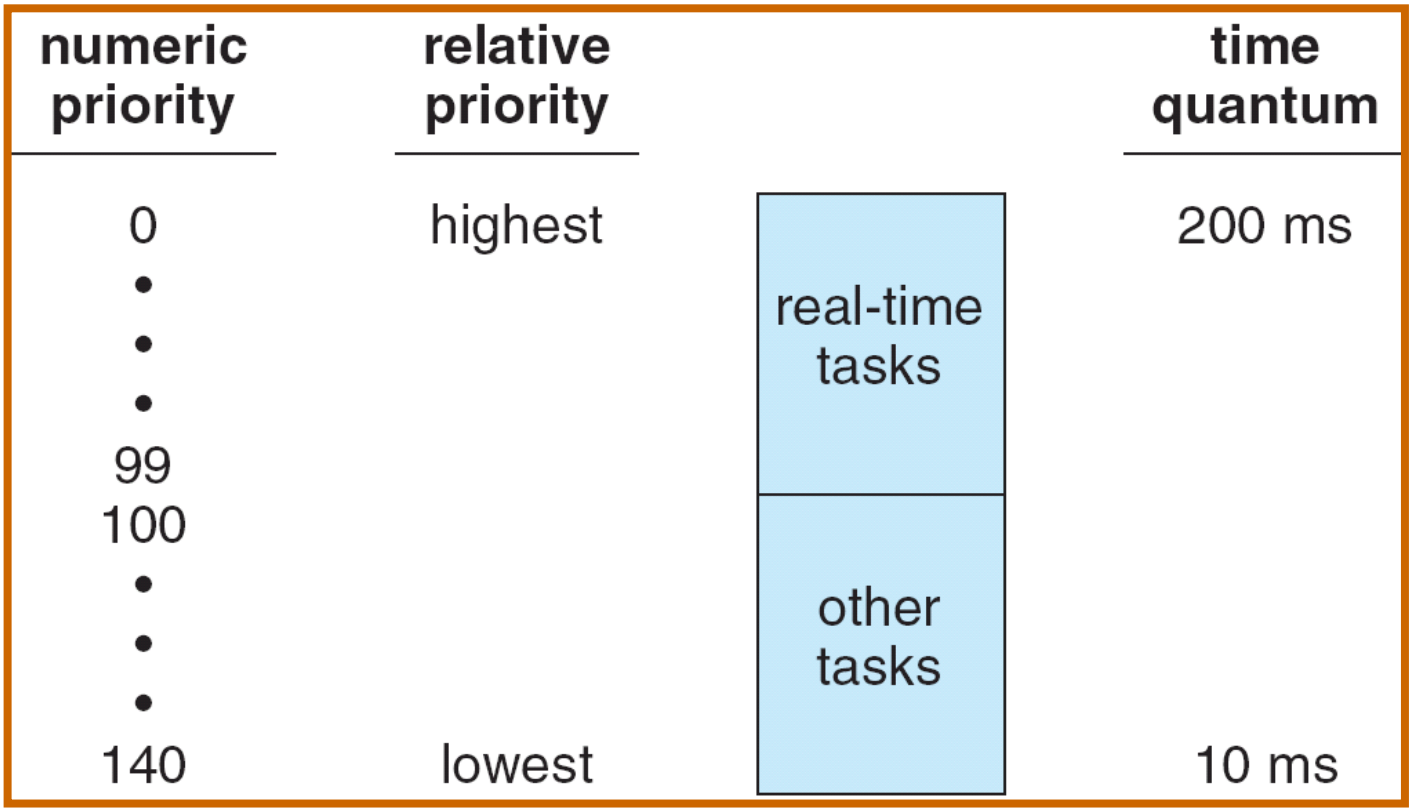
Linux Scheduling

- Preemptive, priority-based
- Two priority ranges: time-sharing and real-time
- Time-sharing
  - Task with highest priority in active array is selected.
  - Task remains in active array as long as time remains in its time slice.
  - When task exhaust time-slice, new priority/timeslice is computed and task is moved to expired array.
    - Priority also affected by interactivity (increases when I/O is long)
  - When active array is empty, expired array becomes active and vice versa
- Real-time
  - Soft real-time
  - Posix.1b compliant – two classes
    - FCFS and RR
    - Highest priority process always runs first

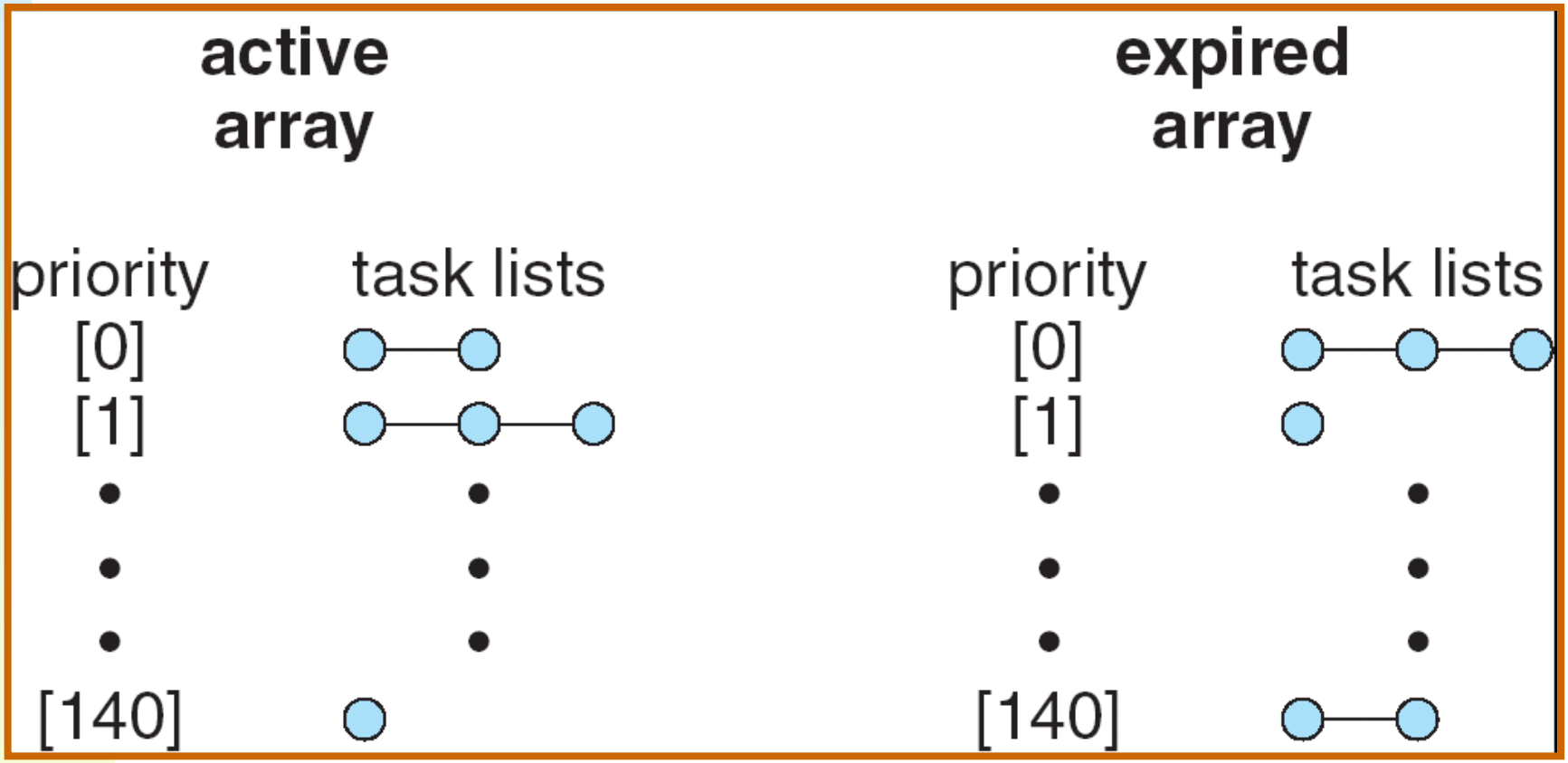
Linux Scheduling

Note that the time quanta/priority relationship is opposite, compared to Solaris.

Note also that low numbers indicate high priority.



Linux Scheduling Lists



Java Thread Scheduling

- JVM Uses a preemptive, fixed-priority scheduling algorithm
  - If higher priority thread enters ready state, the currently running lower priority thread is preempted
- FCFS is used within the same priority level
- Note that JVM does not specify whether the threads are time-sliced or not.

Time-Slicing

Since the JVM Doesn't Ensure Time-Slicing, the yield() Method May Be Used:

```
while (true) {
        // perform CPU-intensive task
        . . .
        Thread.yield();
}
```

This Yields Control to Another Thread of Equal Priority

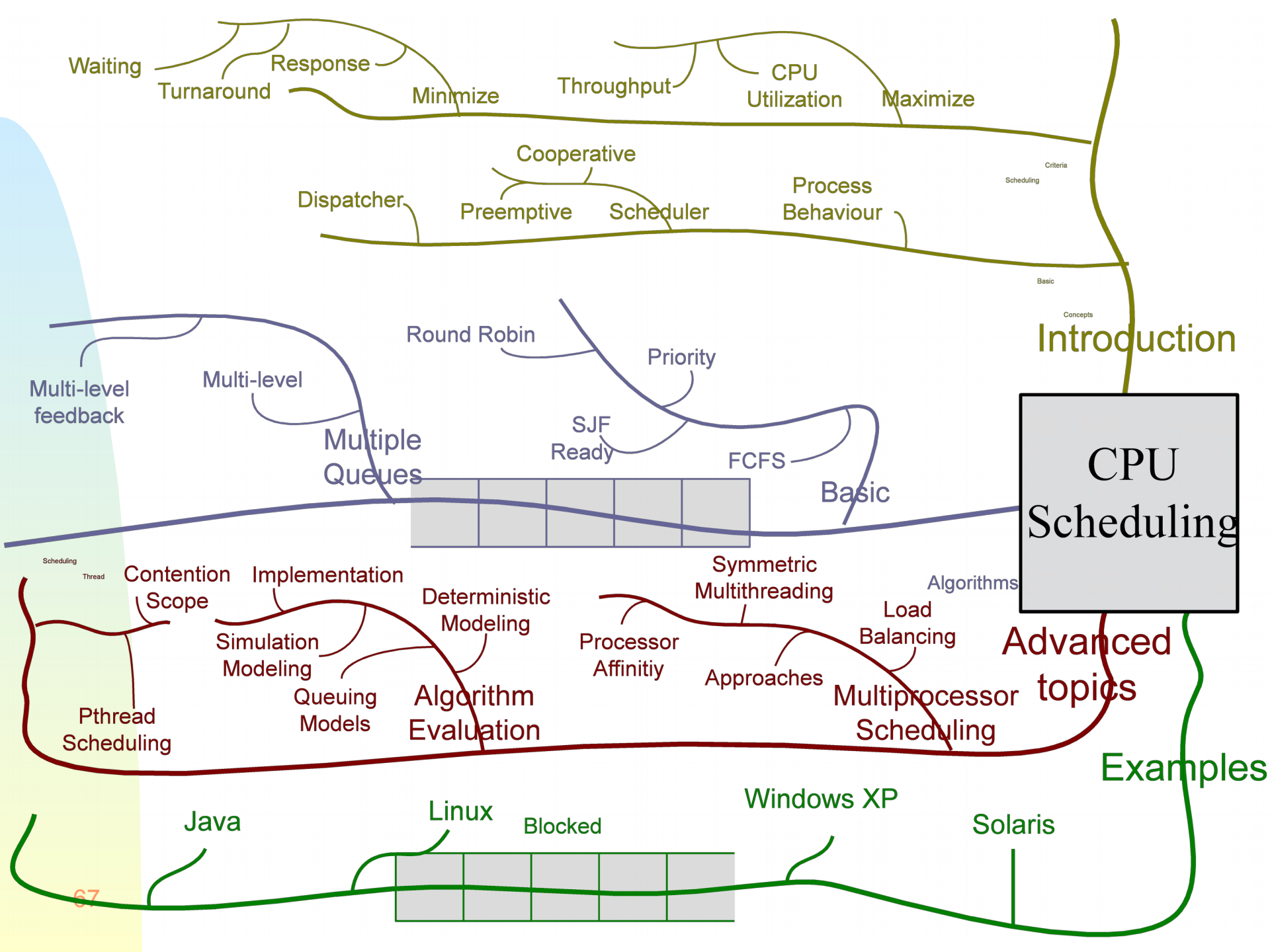
Setting Thread Priorities from Java

Priority	Comment
Thread.MIN_PRIORITY	Minimum Thread Priority(1)
Thread.MAX_PRIORITY	Maximum Thread Priority (10)
Thread.NORM_PRIORITY	Default Thread Priority (5)

A newly created thread inherits its priority from the thread that created it.

Priorities may be set using setPriority() method:

```
setPriority(Thread.NORM_PRIORITY + 2);
```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