CS162
Operating Systems and Systems Programming
Lecture 9

Sockets, Networking (Con't)
Scheduling

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Prof. John Kubiatowicz

http://cs162.eecs.Berkeley.edu

Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Recall: POSIX I/O: Everything (looks like) a "File"

- Identical interface for:
  - Devices (terminals, printers, etc.)
  - Regular files on disk
  - Networking (sockets)
  - Local interprocess communication (pipes, sockets)
- Based on open(), read(), write(), and close()
- Allows simple composition of programs
  - » `find | grep | wc …`
- HOWEVER: Not every thing actually IS a file!
  - Pipes are only buffered in memory!
  - Network sockets only buffered in memory/network!

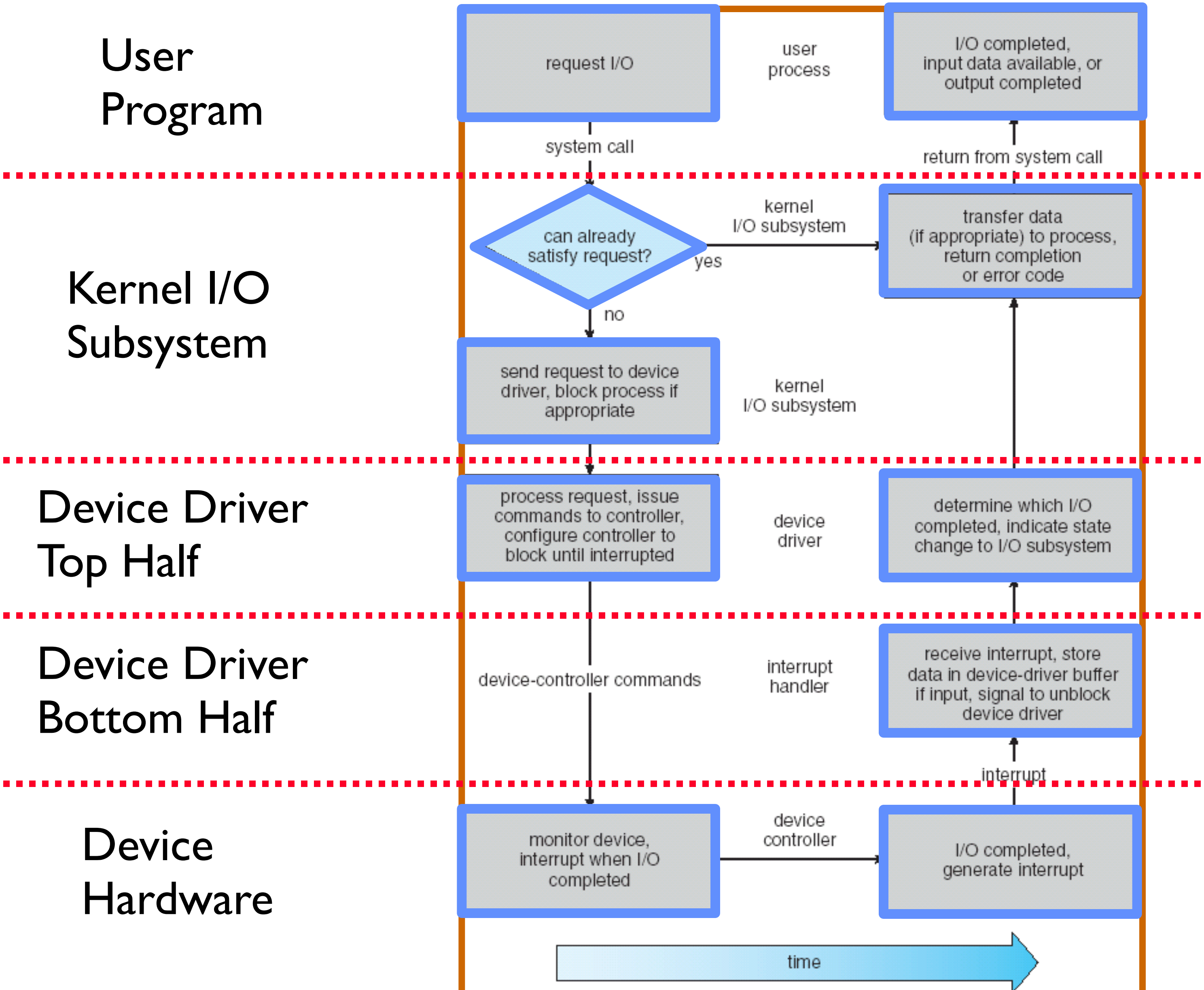
Recall: POSIX I/O Design Patterns

- Open before use
  - Access control check, setup happens here
- Byte-oriented
  - Least common denominator
  - OS responsible for hiding the fact that real devices may not work this way (e.g. hard drive stores data in blocks)
- Explicit close
- Reads are buffered
  - Part of making everything byte-oriented
  - Process is blocked while waiting for device
  - Let other processes run while gathering result
- Writes are buffered
  - Complete in background (more later on)
  - Return to user when data is "handed off" to kernel
- Errors relayed to user in a variety of ways!
  - Make sure to check them!

Recall: 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

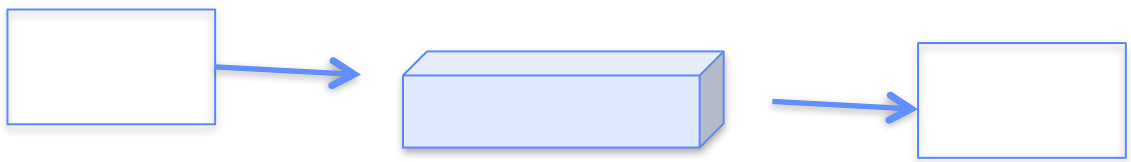
Recall: Life Cycle of An I/O Request



Communication between processes

- Can we view files as communication channels?

```
write(wfd, wbuf, wlen);
```

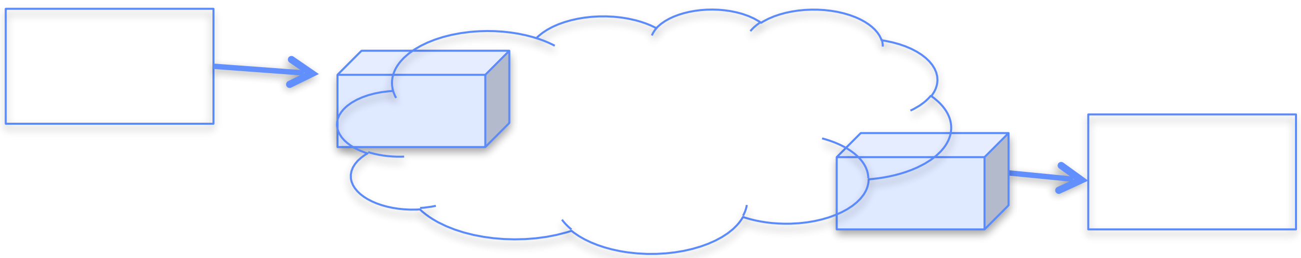


```
n = read(rfd,rbuf,rmax);
```

- Producer and Consumer of a file may be distinct processes
  – May be separated in time (or not)
- However, what if data written once and consumed once?
  – Don't we want something more like a queue?
  – Can still look like File I/O!

Communication Across the world looks like file IO

```
write(wfd, wbuf, wlen);
```



```
n = read(rfd,rbuf,rmax);
```

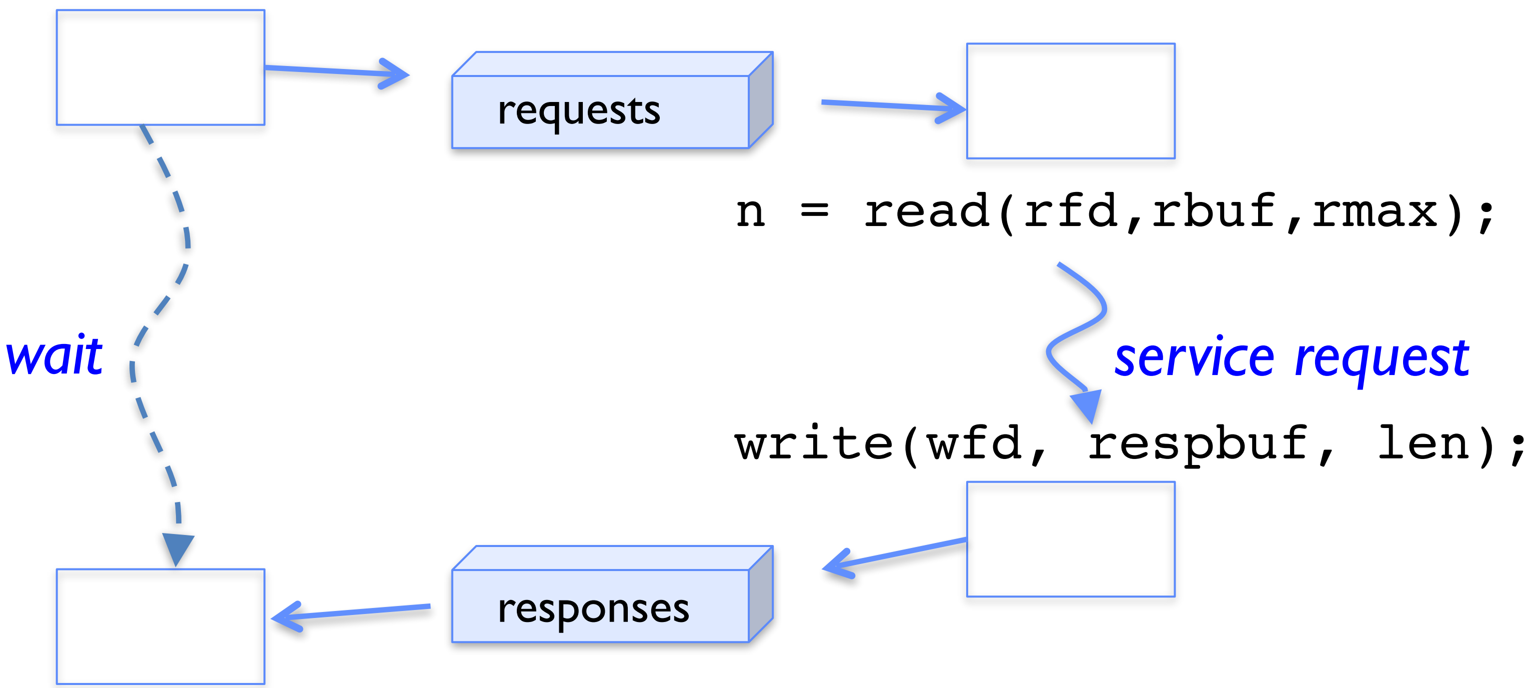
- Connected queues over the Internet
  - But what's the analog of open?
  - What is the namespace?
  - How are they connected in time?

Request Response Protocol

Client (issues requests)

Server (performs operations)

```
write(rqfd, rqbuf, buflen);
```



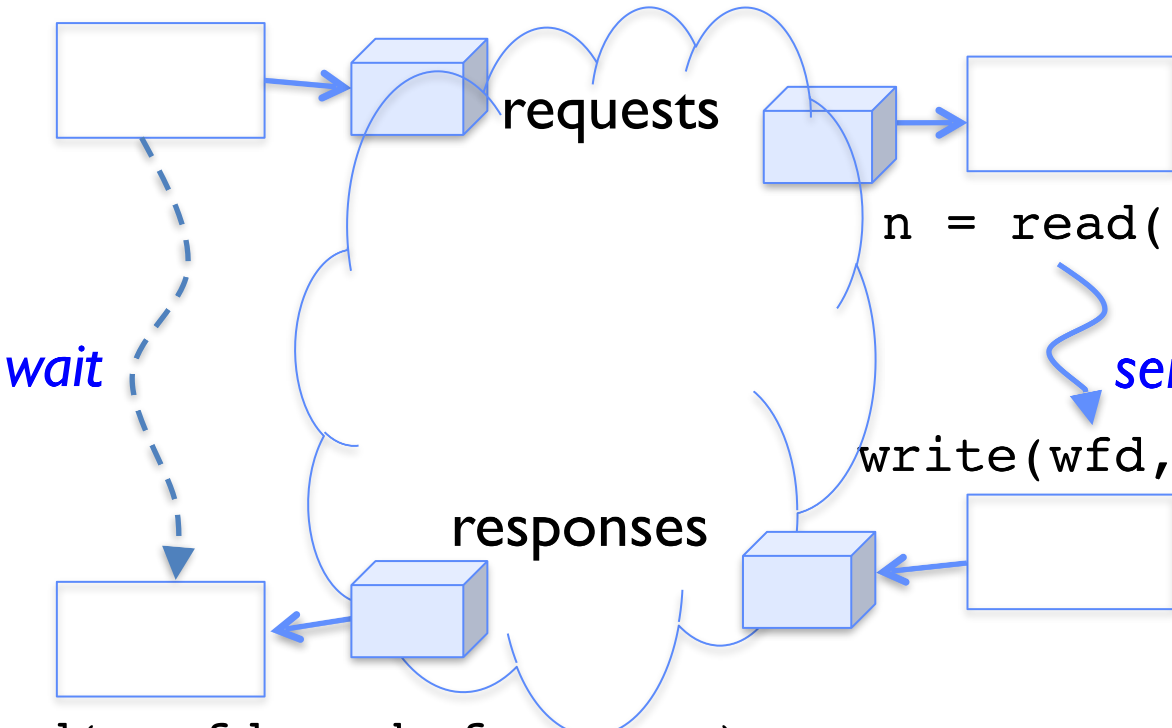

```
n = read(resfd,resbuf,resmax);
```

Request Response Protocol

Client (issues requests)

Server (performs operations)

`write(rqfd, rqbuf, buflen);`

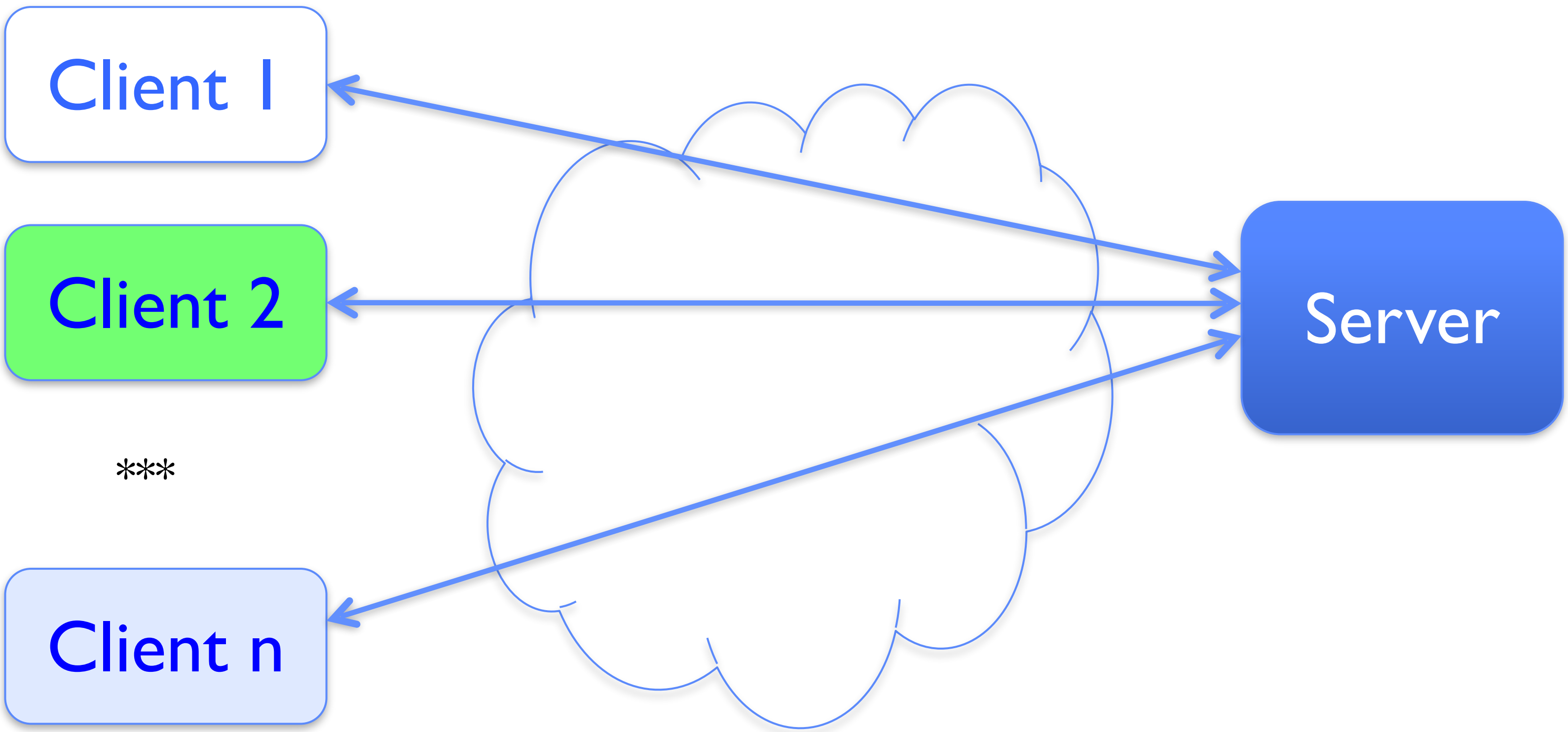


`n = read(rfd,rbuf,rmax);`

`write(wfd, respbuf, len);`

`n = read(resfd,resbuf,resmax);`

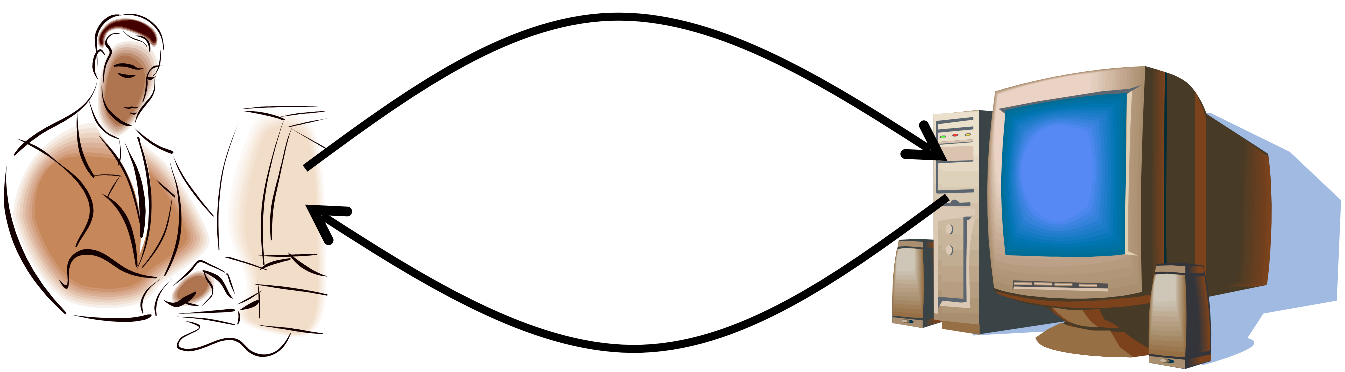
Client-Server Models



- File servers, web, FTP, Databases, …
- Many clients accessing a common server

Client-Server Communication

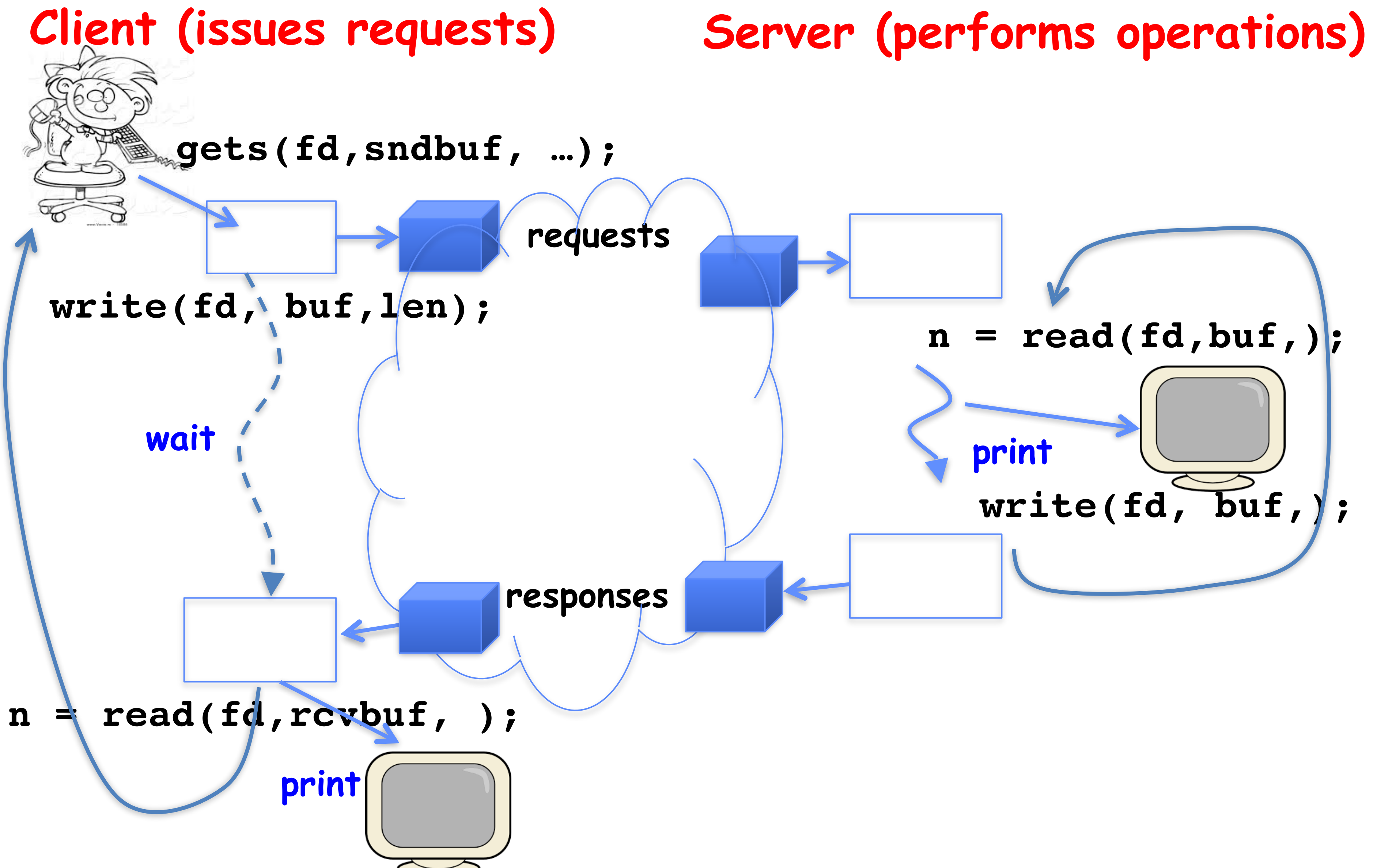
- Client "sometimes on"
  - Initiates a request to the server when interested
  - E.g., Web browser on your laptop or cell phone
  - Doesn't communicate directly with other clients
  - Needs to know the server's address
- Server is "always on"
  - Services requests from many client hosts
  - E.g., Web server for the *www.cnn.com* Web site
  - Doesn't initiate contact with the clients
  - Needs a fixed, well-known address



Sockets

- Socket: an abstraction of a network I/O queue
  – Mechanism for inter-process communication
  – Embodies one side of a communication channel
    » Same interface regardless of location of other end
    » Could be local machine (called "UNIX socket") or remote machine (called "network socket")
  – First introduced in 4.2 BSD UNIX: big innovation at time
    » Now most operating systems provide some notion of socket
- Data transfer like files
  – Read / Write against a descriptor
- Over ANY kind of network
  – Local to a machine
  – Over the internet (TCP/IP, UDP/IP)
  – OSI, Appletalk, SNA, IPX, SIP, NS, …

Silly Echo Server – running example



Echo client-server example

```
void client(int sockfd) {
  int n;
  char sndbuf[MAXIN]; char rcvbuf[MAXOUT];
  getreq(sndbuf, MAXIN);        /* prompt */
  while (strlen(sndbuf) > 0) {
    write(sockfd, sndbuf, strlen(sndbuf)); /* send */
    memset(rcvbuf,0,MAXOUT);               /* clear */
    n=read(sockfd, rcvbuf, MAXOUT-1);      /* receive */
    write(STDOUT_FILENO, rcvbuf, n);     /* echo */
    getreq(sndbuf, MAXIN);                 /* prompt */
  }
}
```

```
void server(int consockfd) {
  char reqbuf[MAXREQ];
  int n;
  while (1) {
    memset(reqbuf,0, MAXREQ);
    n = read(consockfd,reqbuf,MAXREQ-1); /* Recv */
    if (n <= 0) return;
    n = write(STDOUT_FILENO, reqbuf, strlen(reqbuf));
    n = write(consockfd, reqbuf, strlen(reqbuf)) /*
echo*/
  }
}
```

What assumptions are we making?

- Reliable
  - Write to a file => Read it back. Nothing is lost.
  - Write to a (TCP) socket => Read from the other side, same.
  - Like pipes
- In order (sequential stream)
  - Write X then write Y => read gets X then read gets Y
- When ready?
  - File read gets whatever is there at the time. Assumes writing already took place.
  - Like pipes!

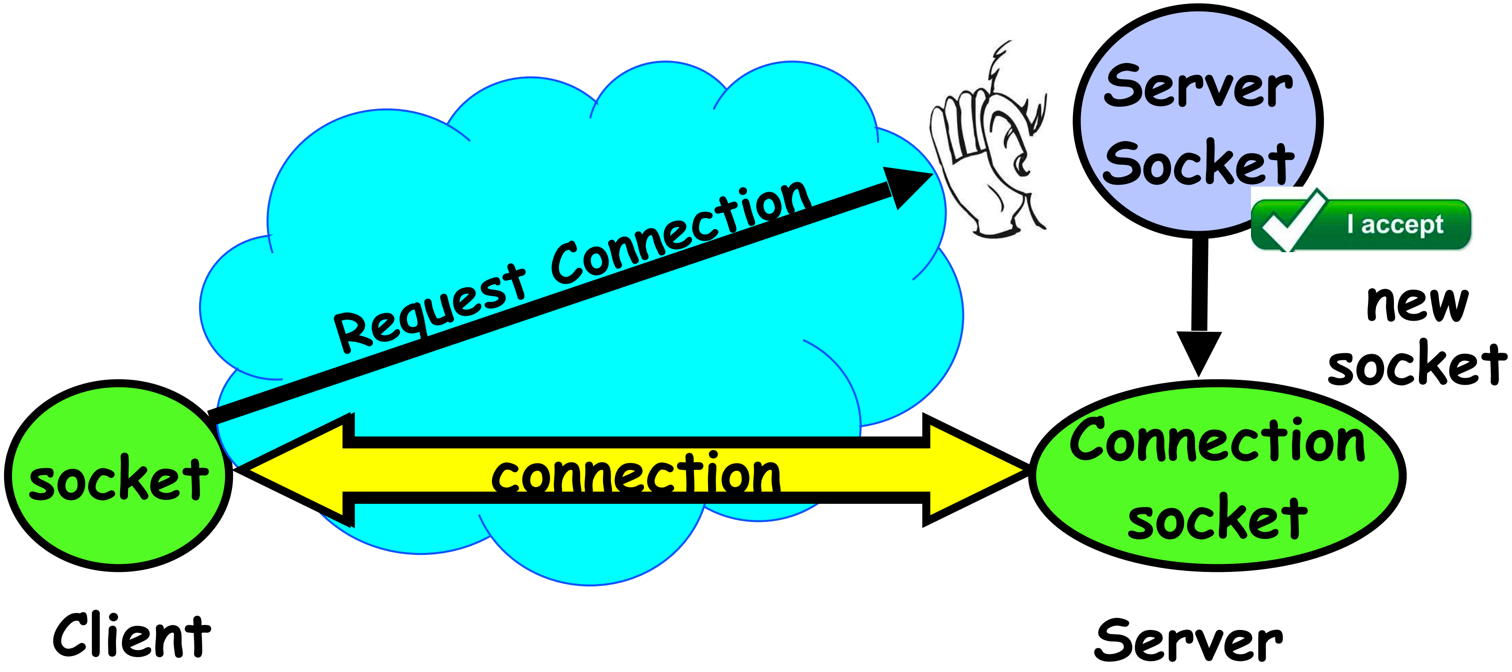
Socket creation and connection

- File systems provide a collection of permanent objects in structured name space
  - Processes open, read/write/close them
  - Files exist independent of the processes
- Sockets provide a means for processes to communicate (transfer data) to other processes.
- Creation and connection is more complex
- Form 2-way pipes between processes
  - Possibly worlds away
- How do we name them?
- How do these completely independent programs know that the other wants to "talk" to them?

Namespaces for communication over IP

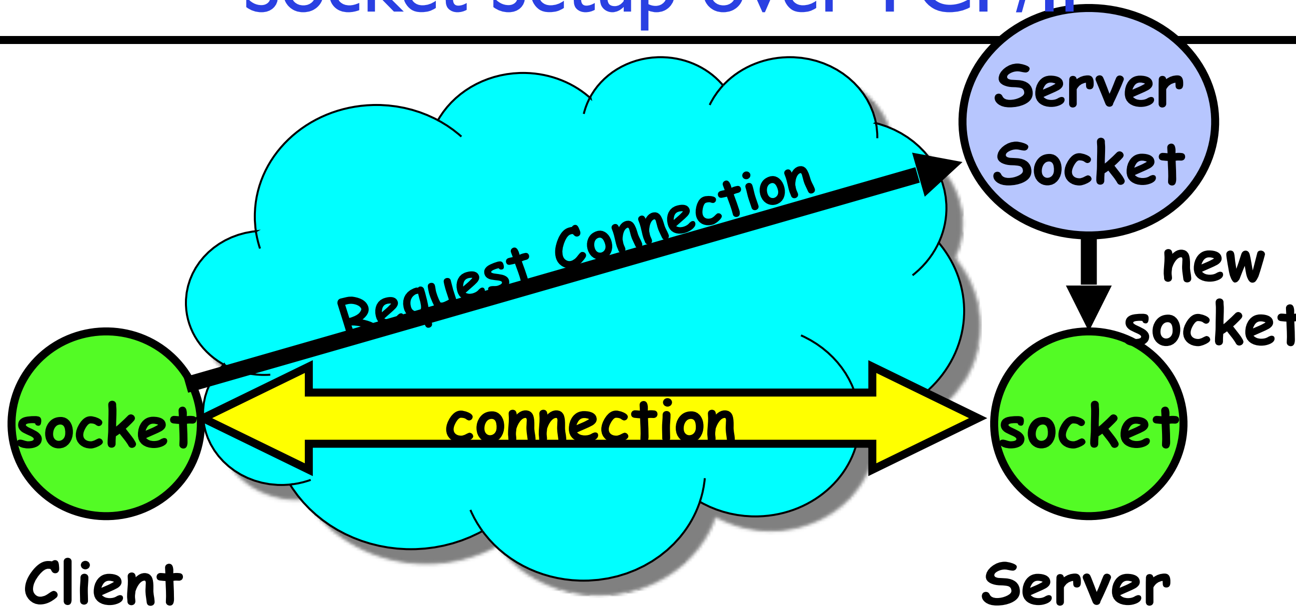
- Hostname
  – www.eecs.berkeley.edu
- IP address
  – 128.32.244.172 (ipv6?)
- Port Number
  – 0-1023 are "well known" or "system" ports
    » Superuser privileges to bind to one
  – 1024 – 49151 are "registered" ports (registry)
    » Assigned by IANA for specific services
  – 49152–65535 ($2^{15}+2^{14}$ to $2^{16}-1$) are "dynamic" or "private"
    » Automatically allocated as "ephemeral Ports"

Socket Setup over TCP/IP



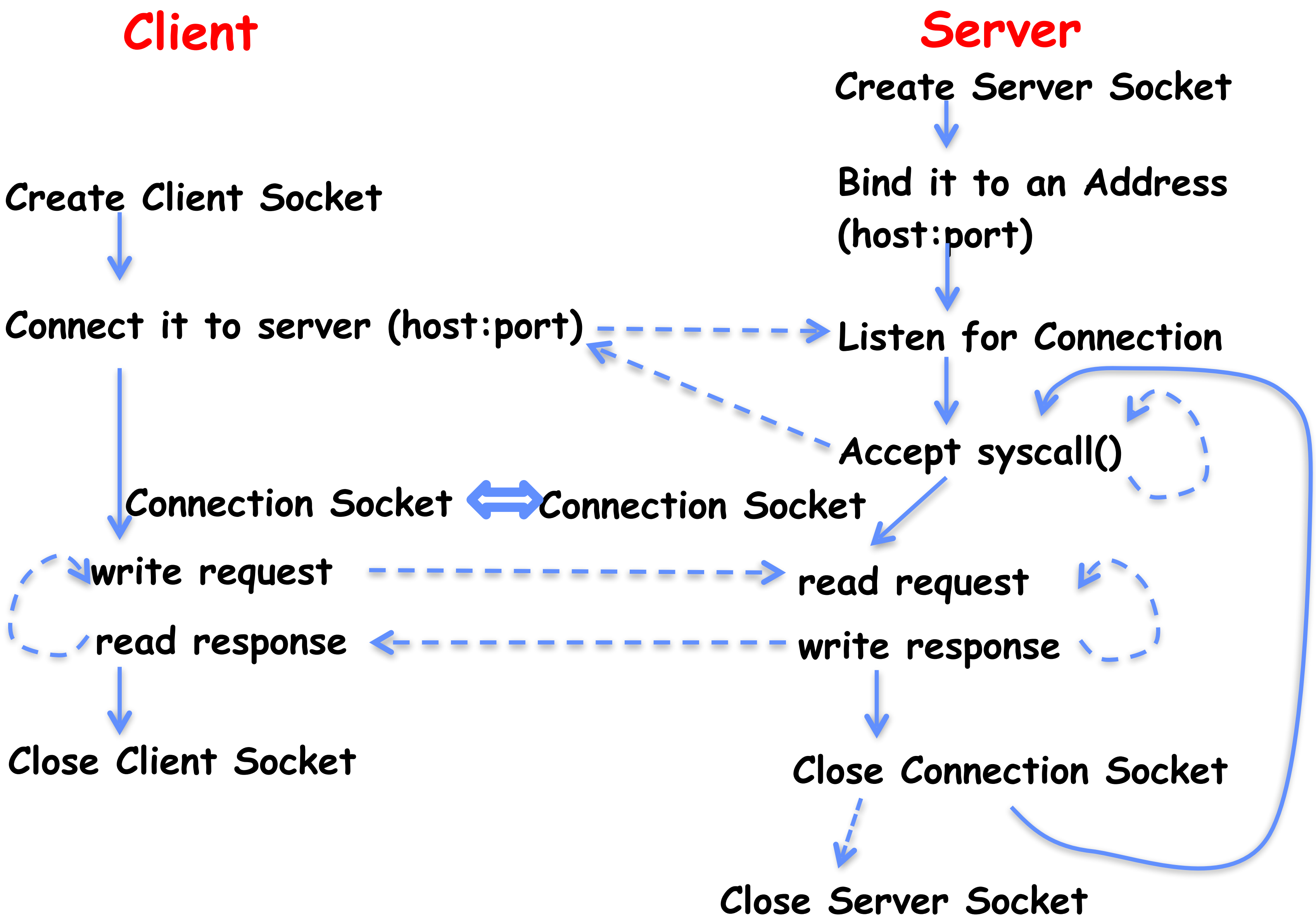
- Special kind of socket: server socket
  - Has file descriptor
  - Can't read or write
- Two operations:
  1. **`listen()`**: Start allowing clients to connect
  2. **`accept()`**: Create a *new socket* for a *particular* client connection

Socket Setup over TCP/IP



- Server Socket: Listens for new connections
  - Produces new sockets for each unique connection
  - 3-way handshake to establish new connection!
- Things to remember:
  - Connection involves 5 values:
    [Client Addr, Client Port, Server Addr, Server Port, Protocol]
  - Often, Client Port "randomly" assigned
    - » Done by OS during client socket setup
  - Server Port often "well known"
    - » 80 (web), 443 (secure web), 25 (sendmail), etc
    - » Well-known ports from 0—1023

Web Server using Sockets (in concept)



Client-Side of Protocol

```
char *host_name, port_name;

// Create a socket
struct addrinfo *server = lookup_host(host_name, port_name);
int sock_fd = socket(server->ai_family, server->ai_socktype,
                     server->ai_protocol);

// Connect to specified host and port
connect(sock_fd, server->ai_addr, server->ai_addrlen);

// Carry out Client-Server protocol
run_client(sock_fd);

/* Clean up on termination */
close(sock_fd);
```

Client: getting the server address (as addrinfo)

```
struct addrinfo *lookup_host(char *host_name, char *port) {
  struct addrinfo *server;
  struct addrinfo hints;

  // Constraints on returned address
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;    // Either IPv4 or IPv6
  hints.ai_socktype = SOCK_STREAM;// Reliable stream (i.e. TCP)

  // Lookup host:port, constrained by hints, return ptr in
server
  int rv = getaddrinfo(host_name, port_name, &hints, &server);
  if (rv != 0) {
    printf("getaddrinfo failed: %s\n", gai_strerror(rv));
    return NULL;
  }
  return server;
}
```

Server Protocol (v1)

```
// Create socket to listen for client connections
char *port_name;
struct addrinfo *server = setup_address(port_name);
int server_socket = socket(server->ai_family, server-
                       >ai_socktype,server->ai_protocol);

// Bind socket to specific port
bind(server_socket, server->ai_addr, server->ai_addrlen);

// Start listening for new client connections
listen(server_socket, MAX_QUEUE);

while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  serve_client(conn_socket);
  close(conn_socket);
}

close(server_socket);
```

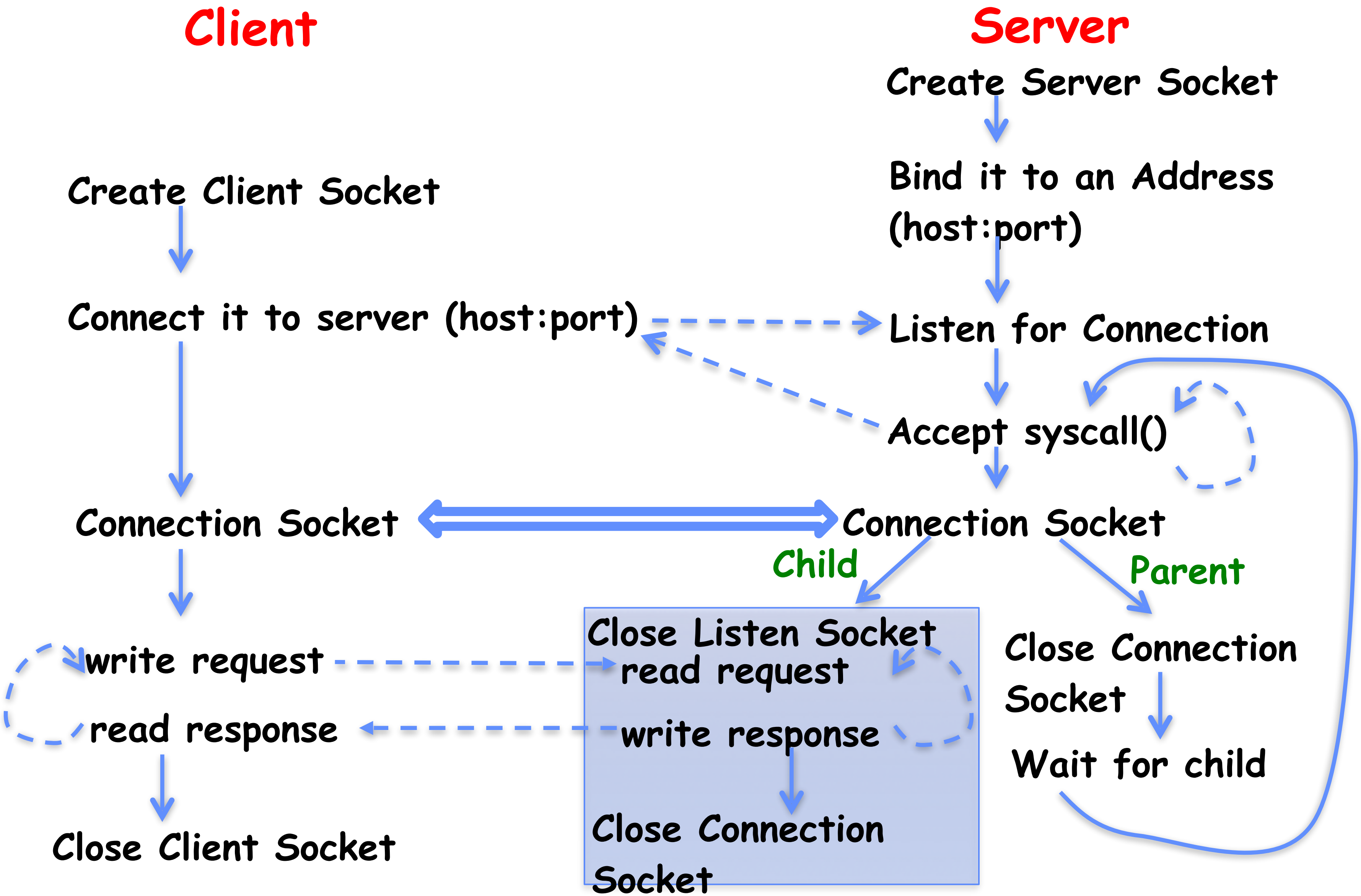
Server: getting server addrinfo – for itself

```
struct addrinfo *setup_address(char *port) {
  struct addrinfo *server;
  struct addrinfo hints;

  // Constraints on returned address
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;    // IPv4 or IPv6
  hints.ai_socktype = SOCK_STREAM;// Reliable stream (i.e. TCP)
  hints.ai_flags = AI_PASSIVE;    // Address for listening

  // Match any local address:port, constrained by hints, return
ptr
  int rv = getaddrinfo(NULL, port, &hints, &server);
  if (rv != 0) {
    printf("getaddrinfo failed: %s\n", gai_strerror(rv));
    return NULL;
  }
  return server;
}
```

How does the server protect itself?

- Isolate the handling of each connection
- By forking it off as another process

Sockets With Protection



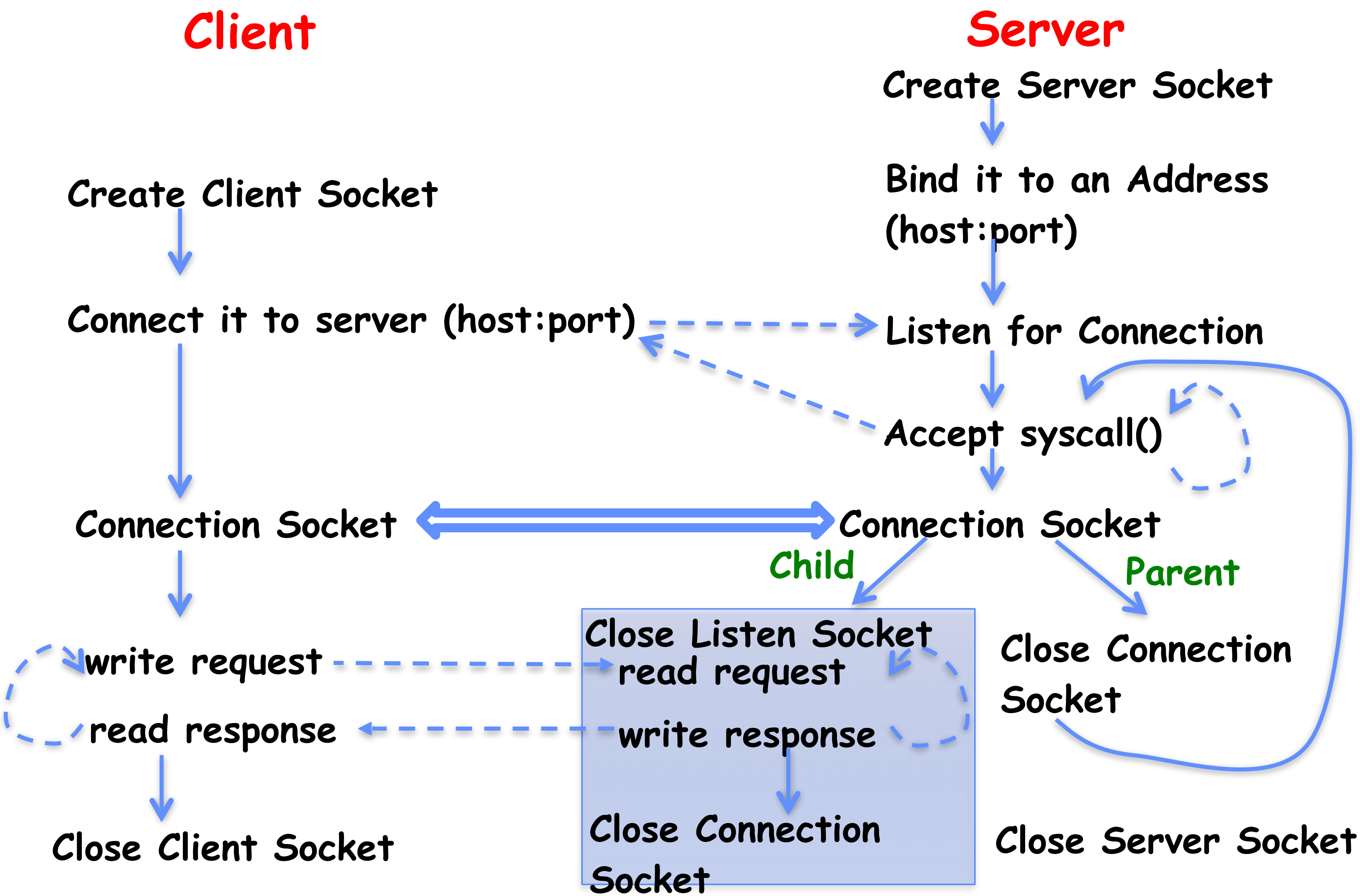
Server Protocol (v2)

```
// Start listening for new client connections
listen(server_socket, MAX_QUEUE);

while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);

  pid_t pid = fork();                // New process for connection
  if (pid == 0) {                    // Child process
    close(server_socket);            // Doesn't need server_socket
    serve_client(conn_socket);       // Serve up content to client
    close(conn_socket);              // Done with client!
    exit(EXIT_SUCCESS);
  } else {                           // Parent process
    close(conn_socket);              // Don't need client socket
    wait(NULL);                      // Wait for our (one) child
  }
}
close(server_socket);
```

Concurrent Server

- Listen will queue requests
- Buffering present elsewhere
- But server waits for each connection to terminate before initiating the next

Sockets With Protection and Parallelism



Server Protocol (v3)

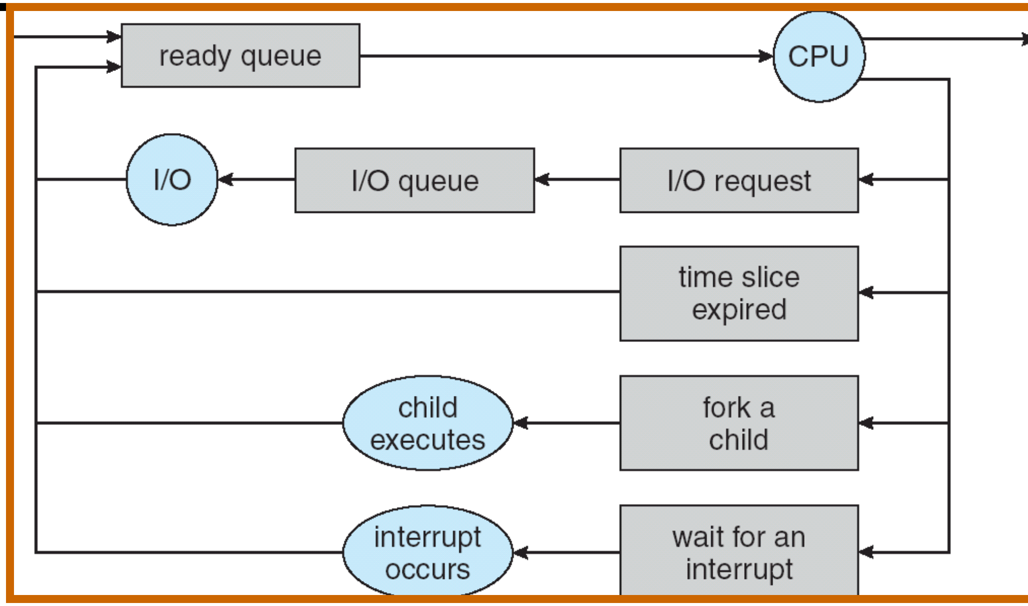
```
// Start listening for new client connections
listen(server_socket, MAX_QUEUE);
signal(SIGCHLD,SIG_IGN);              // Prevent zombie children
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);

  pid_t pid = fork();                 // New process for connection
  if (pid == 0) {                     // Child process
    close(server_socket);             // Doesn't need server_socket
    serve_client(conn_socket);        // Serve up content to client
    close(conn_socket);               // Done with client!
    exit(EXIT_SUCCESS);
  } else {                            // Parent process
    close(conn_socket);               // Don't need client socket
    // wait(NULL);                    // Don't wait (SIGCHLD
                                     //   ignored, above)
  }
}
close(server_socket);
```

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



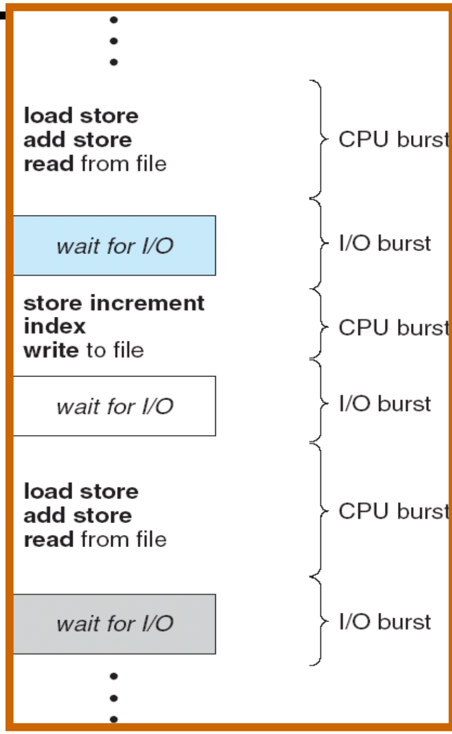
- Question: How is the OS to decide which of several tasks to take off a queue?
- Scheduling: deciding which threads are given access to resources from moment to moment
  - Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access

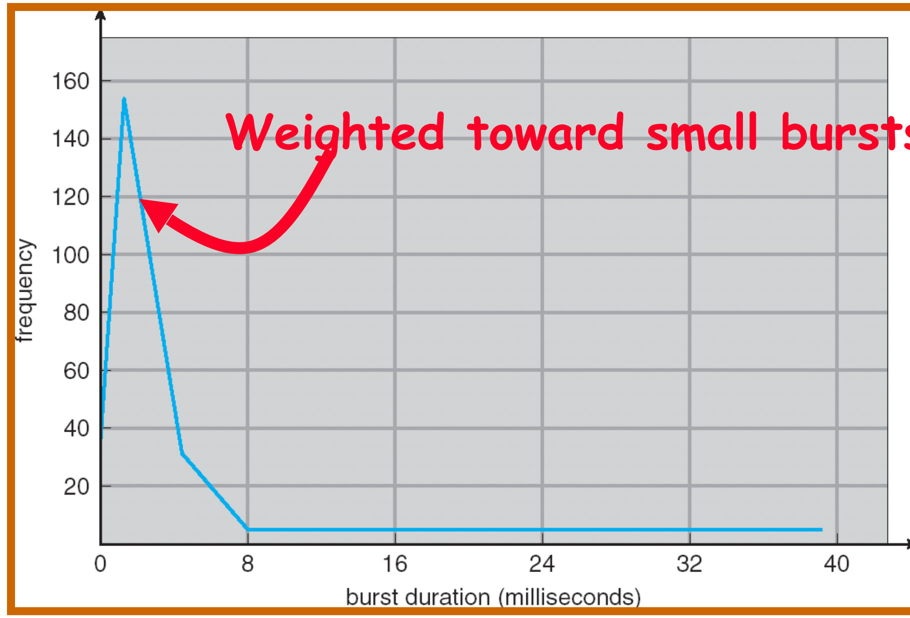
Scheduling: All About Queues

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

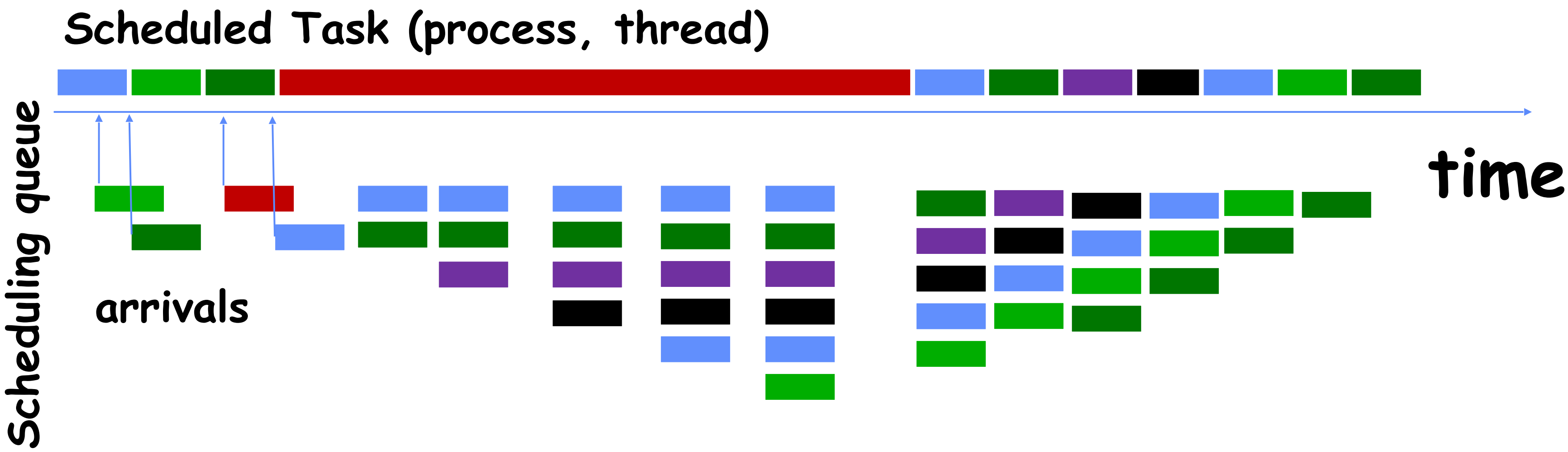
- First-Come, First-Served (FCFS)
  - Also "First In, First Out" (FIFO) or "Run until done"
    - » In early systems, FCFS meant one program scheduled until done (including I/O)
    - » Now, means keep CPU until thread blocks
- Example:

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 (-)
    » Getting milk, always stuck behind cart full of items!

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 ⇒ FCFS
  - q small ⇒ Interleaved (really small ⇒ 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 $P_1=(68-20)+(112-88)=72$

$P_2=(20-0)=20$

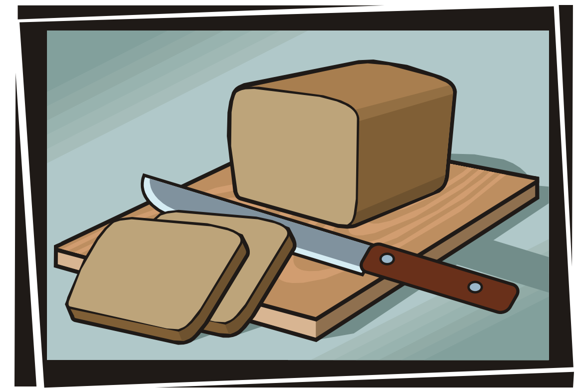
$P_3=(28-0)+(88-48)+(125-108)=85$

$P_4=(48-0)+(108-68)=88$

  – 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 (-)

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!

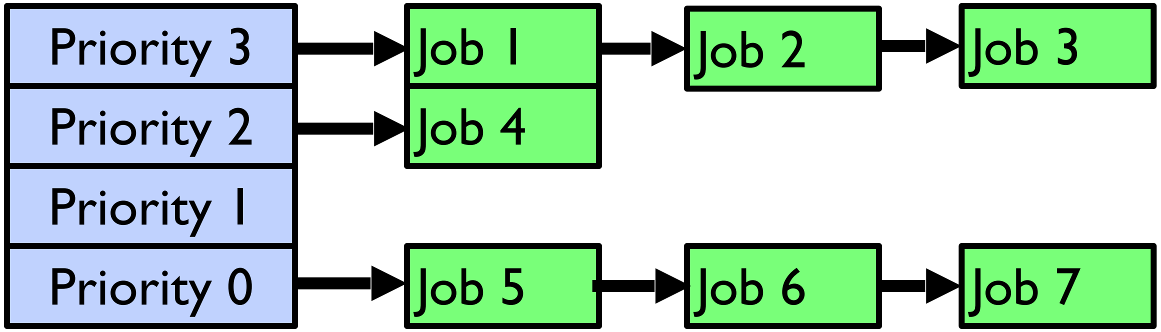
Earlier Example with Different Time Quantum

Best FCFS:

P_2 [8]	P_4 [24]	P_1 [53]	P_3 [68]
0 – 8	8 – 32	32 – 85	85 – 153

	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
    - » Not strictly a problem with priority scheduling, but happens when low priority task has lock needed by high-priority task
    - » Usually involves third, intermediate priority task that keeps running even though high-priority task should be 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

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.)

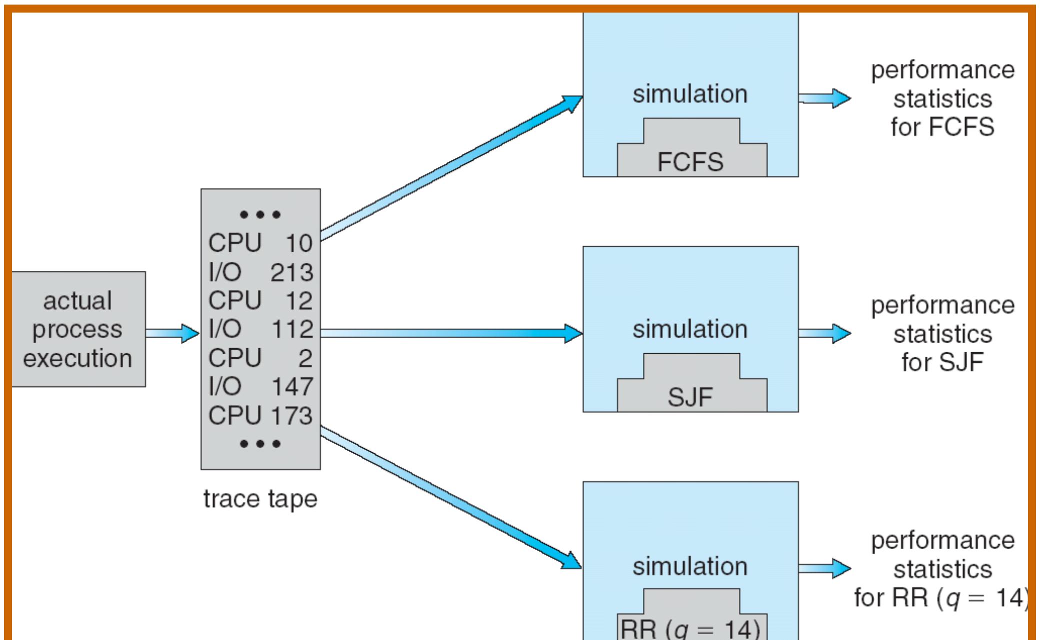
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# 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%

  – W
  re
    » 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 ⇒ Interactivity ⇒ 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)

What if we Knew the Future?

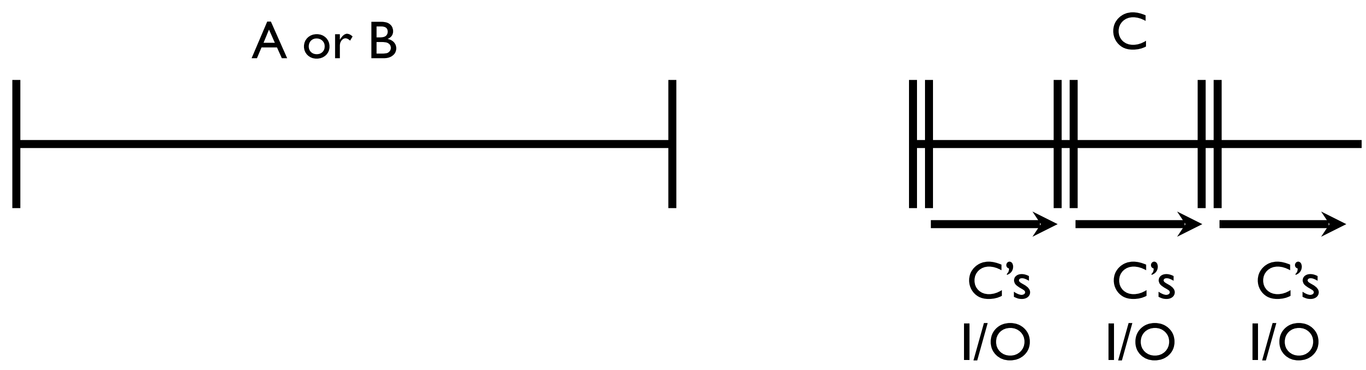
- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  - Run whatever job has least amount of computation to do
  - Sometimes called "Shortest Time to Completion First" (STCF)
- Shortest Remaining Time First (SRTF):
  - Preemptive version of SJF: if job arrives and has a shorter time to completion 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

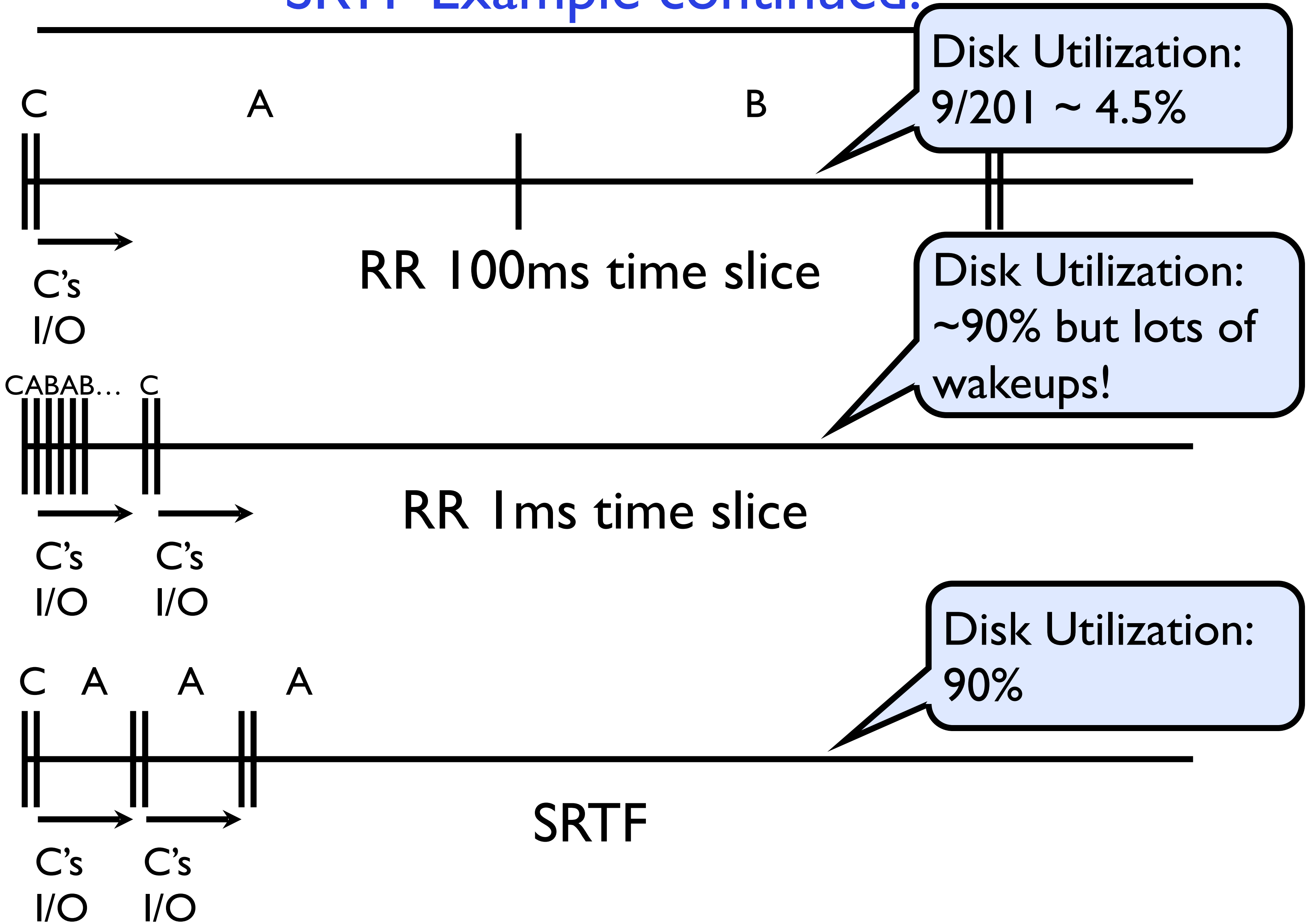
- Comparison of SRTF with FCFS
  - What if all jobs the same length?
    - » SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
  - What if jobs have varying length?
    - » SRTF: short jobs not stuck behind long ones

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:

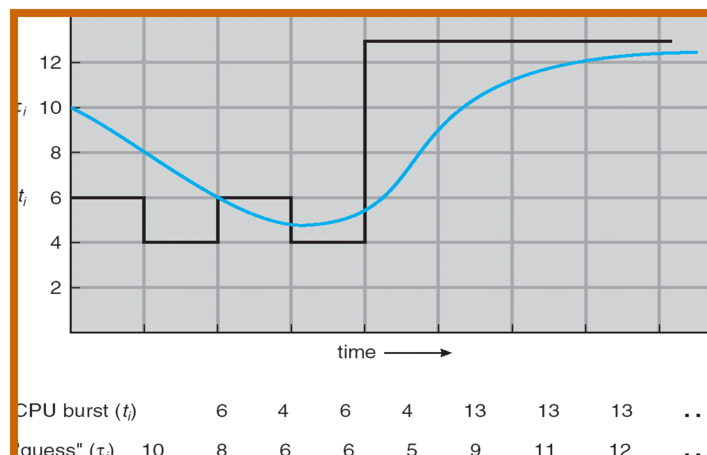


SRTF Further discussion

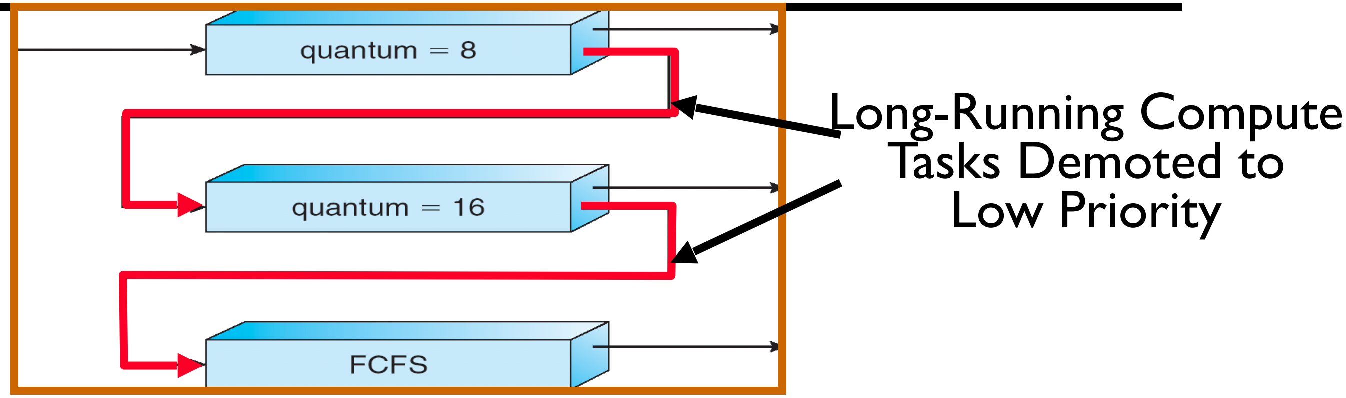
- Starvation
  - SRTF can lead to starvation if many small jobs!
  - Large jobs never get to run
- Somehow need to predict future
  - How can we do this?
  - Some systems ask the user
    - » When you submit a job, have to say how long it will take
    - » To stop cheating, system kills job if takes 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 $\tau n = f(tn\text{-}1, tn\text{-}2, tn\text{-}3, \ldots)$
  - Function f could be one of many different time series estimation schemes (Kalman filters, etc)
  - For instance,
    exponential averaging
    $\tau n = \alpha tn\text{-}1 + (1\text{-}\alpha)\tau n\text{-}1$
    with $(0<\alpha\leq 1)$

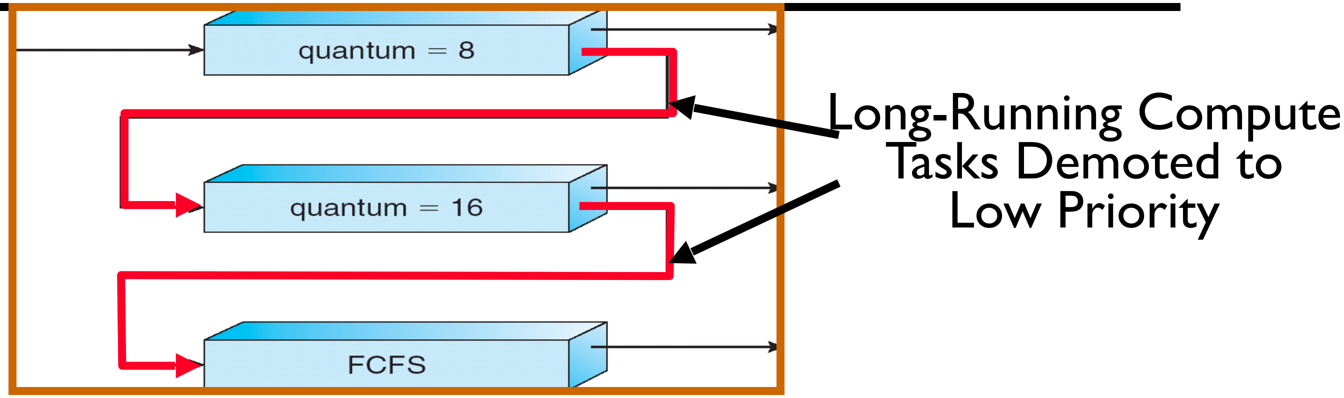


Multi-Level Feedback Scheduling



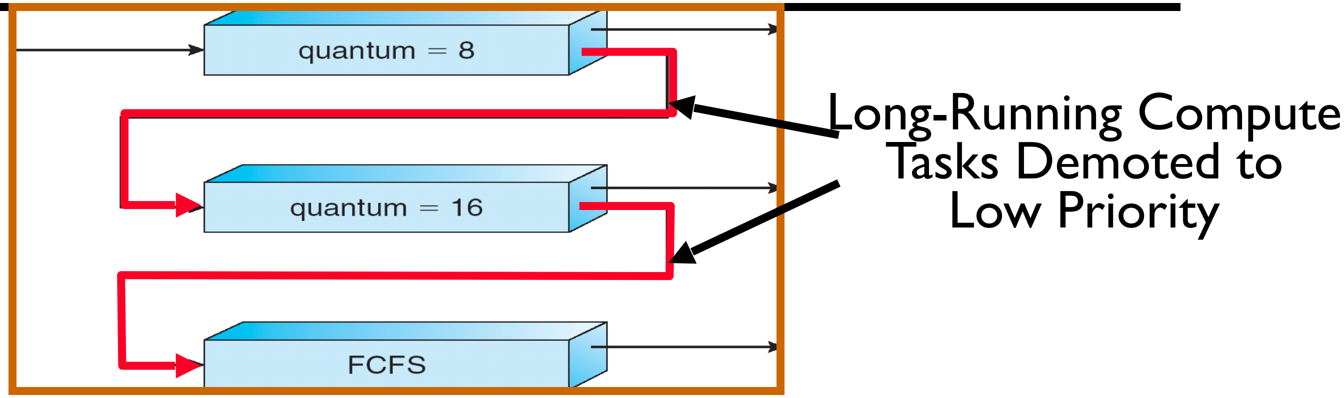
- Another method for exploiting past behavior (first use in CTSS)
  - Multiple queues, each with different priority
    - » Higher priority queues often considered "foreground" tasks
  - Each queue has its own scheduling algorithm
    - » e.g. foreground – RR, background – FCFS
    - » Sometimes multiple 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!

Case Study: Linux O(1) Scheduler

- Priority-based scheduler: 140 priorities
  - 40 for "user tasks" (set by "nice"), 100 for "Realtime/Kernel"
  - Lower priority value ⇒ higher priority (for nice values)
  - Highest priority value ⇒ Lower priority (for realtime values)
  - All algorithms O(1)
    - » Timeslices/priorities/interactivity credits all computed when job finishes time slice
    - » 140-bit bit mask indicates presence or absence of job at given priority level
- Two separate priority queues: "active" and "expired"
  - All tasks in the active queue use up their timeslices and get placed on the expired queue, after which queues swapped
- Timeslice depends on priority – linearly mapped onto timeslice range
  - Like a multi-level queue (one queue per priority) with different timeslice at each level
  - Execution split into "Timeslice Granularity" chunks – round robin through priority

O(1) Scheduler Continued

- Heuristics
  - User-task priority adjusted ±5 based on heuristics
    - » p->sleep_avg = sleep_time – run_time
    - » Higher sleep_avg ⇒ more I/O bound the task, more reward (and vice versa)
  - Interactive Credit
    - » Earned when a task sleeps for a "long" time
    - » Spend when a task runs for a "long" time
    - » IC is used to provide hysteresis to avoid changing interactivity for temporary changes in behavior
  - However, "interactive tasks" get special dispensation
    - » To try to maintain interactivity
    - » Placed back into active queue, unless some other task has been starved for too long…
- Real-Time Tasks
  - Always preempt non-RT tasks
  - No dynamic adjustment of priorities
  - Scheduling schemes:
    - » SCHED_FIFO: preempts other tasks, no timeslice limit
    - » SCHED_RR: preempts normal tasks, RR scheduling amongst tasks of same priority

Linux Completely Fair Scheduler (CFS)

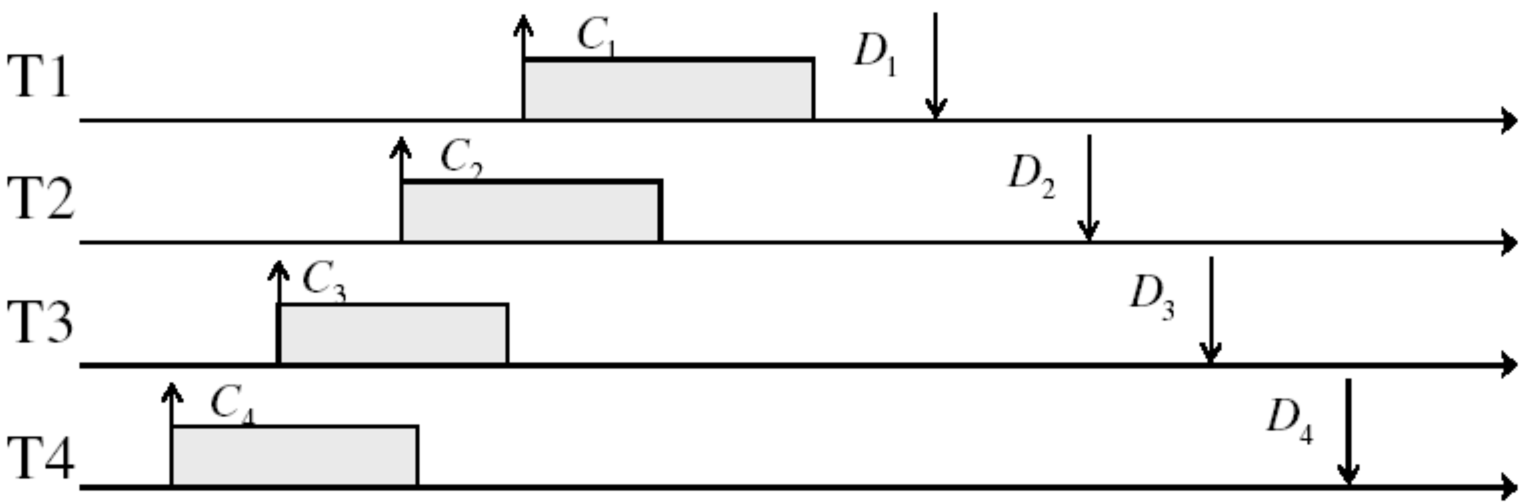
- First appeared in 2.6.23, modified in 2.6.24
- "CFS doesn't track sleeping time and doesn't use heuristics to identify interactive tasks—it just makes sure every process gets a fair share of CPU within a set amount of time given the number of runnable processes on the CPU."
- Inspired by Networking "Fair Queueing"
  - Each process given their fair share of resources
  - Models an "ideal multitasking processor" in which N processes execute simultaneously as if they truly got 1/N of the processor
    - Tries to give each process an equal fraction of the processor
  - Priorities reflected by weights such that increasing a task's priority by 1 always gives the same fractional increase in CPU time – regardless of current priority

Real-Time Scheduling (RTS)

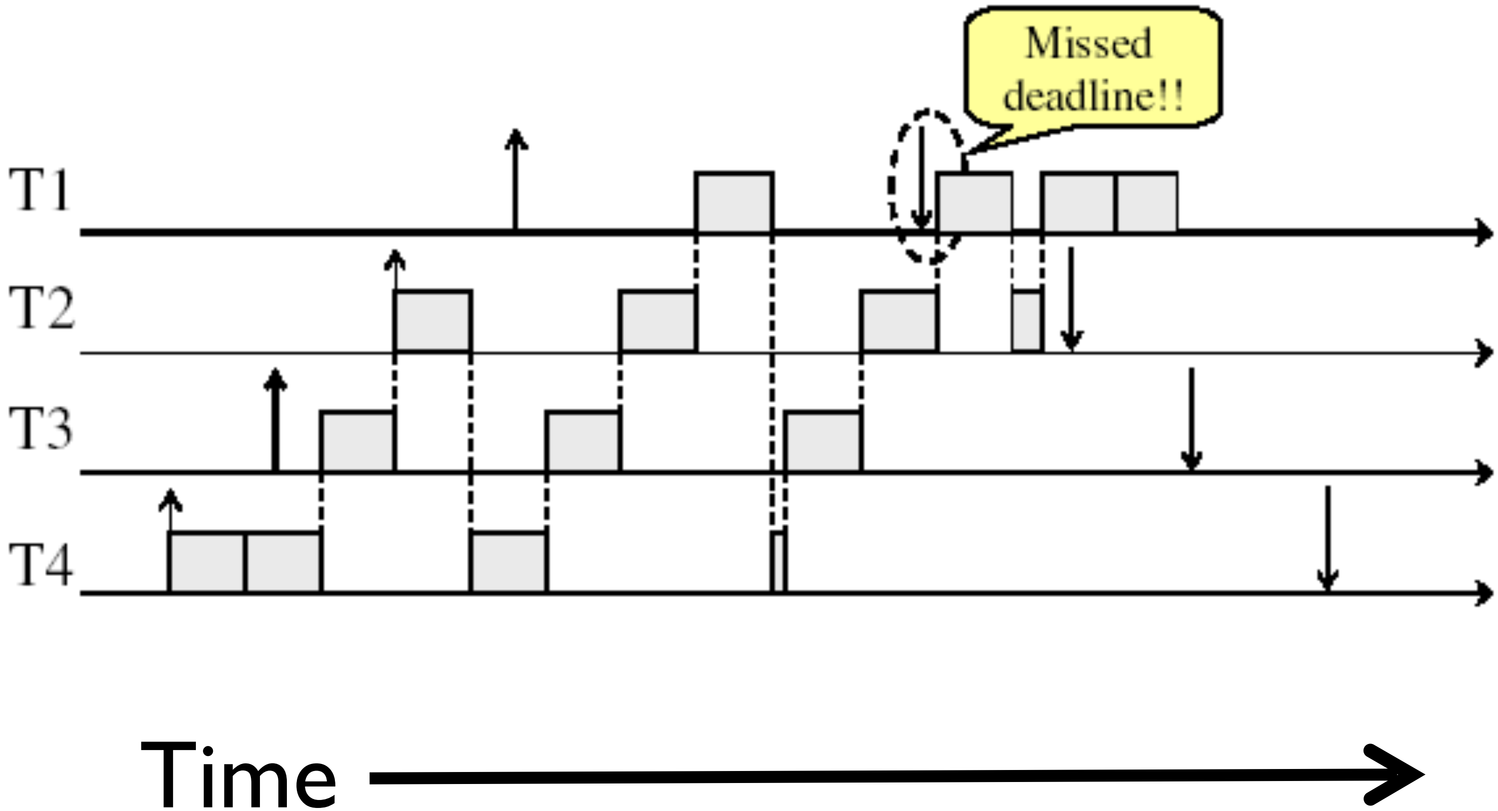
- Efficiency is important but predictability is essential:
  - We need to predict with confidence worst case response times for systems
  - In RTS, performance guarantees are:
    - » Task- and/or class centric and often ensured a priori
  - In conventional systems, performance is:
    - » System/throughput oriented with post-processing (… wait and see …)
  - Real-time is about enforcing predictability, and does not equal fast computing!!!
- Hard Real-Time
  - *Attempt to meet all deadlines*
  - EDF (Earliest Deadline First), LLF (Least Laxity First), RMS (Rate-Monotonic Scheduling), DM (Deadline Monotonic Scheduling)
- Soft Real-Time
  - *Attempt to meet deadlines with high probability*
  - Minimize miss ratio / maximize completion ratio (firm real-time)
  - Important for multimedia applications
  - CBS (Constant Bandwidth Server)

Example: Workload Characteristics

- Tasks are preemptable, independent with arbitrary arrival (=release) times
- Tasks have deadlines (D) and known computation times (C)
- Example Setup:

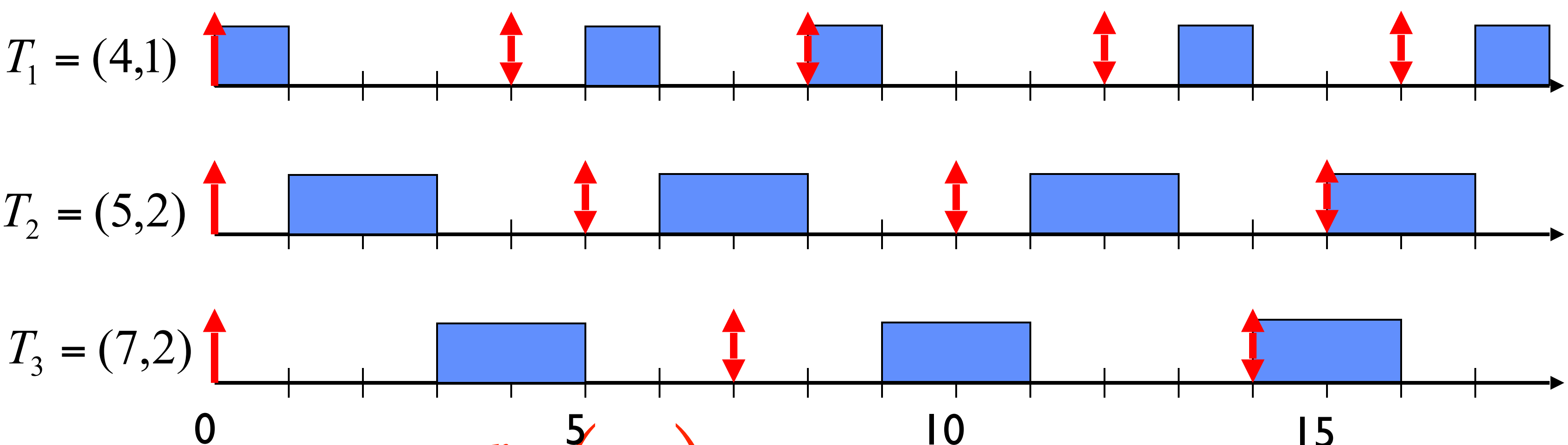


Example: Round-Robin Scheduling Doesn't Work



Earliest Deadline First (EDF)

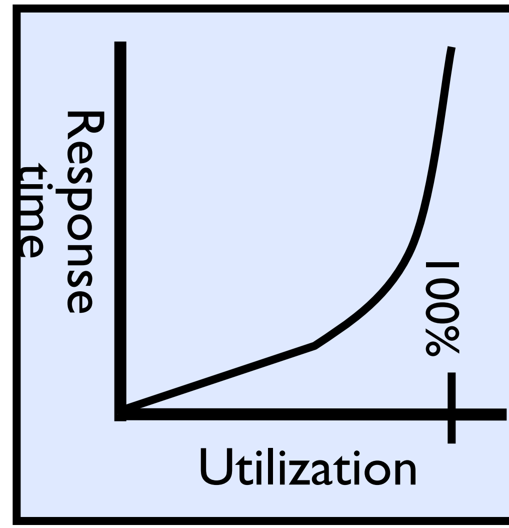
- Tasks periodic with period P and computation C in each period: (P_i, C_i) for each task i
- Preemptive priority-based dynamic scheduling:
  - Each task is assigned a (current) priority based on how close the absolute deadline is (i.e. $D_i^{t+1} = D_i^t + P_i$ for each task!)
  - The scheduler always schedules the active task with the closest absolute deadline



- Schedulable when $\sum_{i=1}^{n}\left(\frac{C_i}{P_i}\right) \leq 1$

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

Summary (1 of 2)

- 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

Summary (2 of 2)

- Lottery Scheduling:
  – Give each thread a priority-dependent number of tokens (short tasks⇒more tokens)
- Linux CFS Scheduler: Fair fraction of CPU
  – Approximates a "ideal" multitasking processor
- Realtime Schedulers such as EDF
  – Guaranteed behavior by meeting deadlines
  – Realtime tasks defined by tuple of compute time and period
  – Schedulability test: is it possible to meet deadlines with proposed set of processes?