CS24: Introduction to Computing Systems

Spring 2015

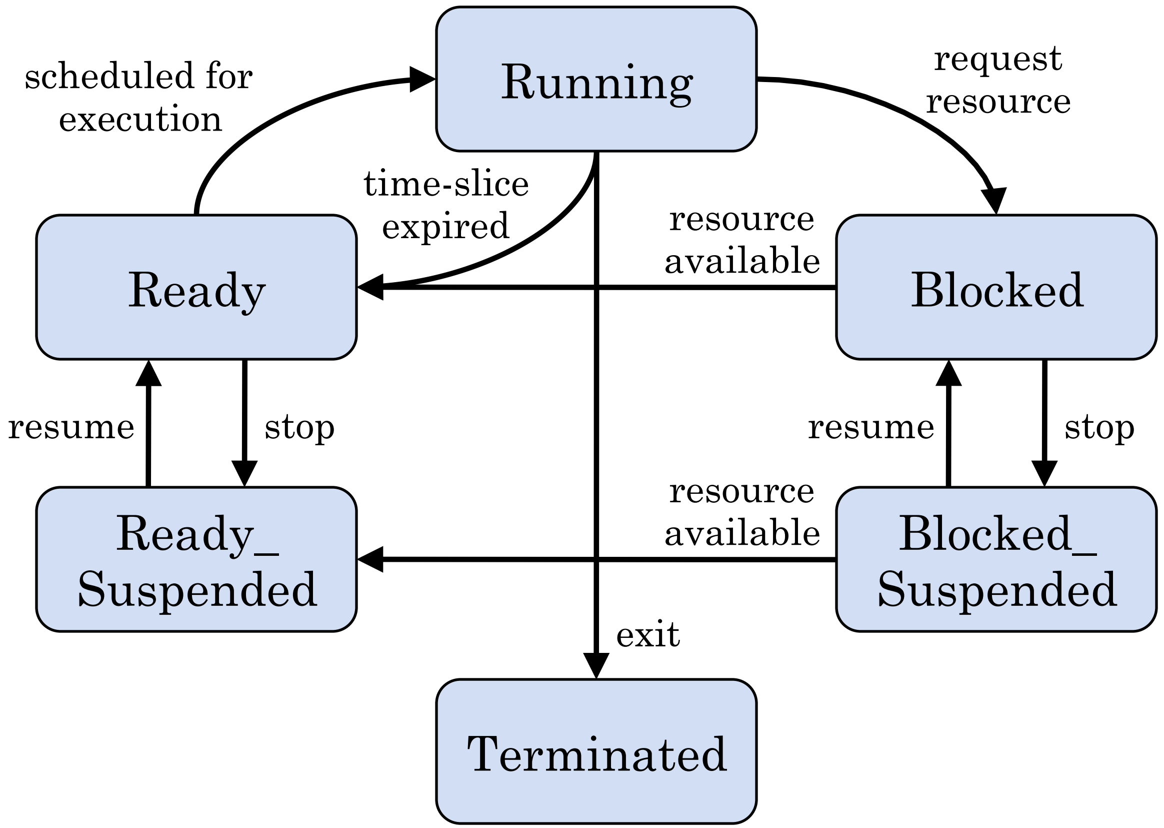
Lecture 21

Last Time: UNIX Process Model

- Began to explore the implementation of the UNIX process model
  - The user API is very simple:
    - **`fork()`** creates a new process
    - **`exit()`** terminates a running process
    - **`wait()`**, **`waitpid()`** reap terminated ("zombie") child processes
    - **`execve()`** loads and runs a program in a process
    - **`kill()`** sends a signal to another process
  - The implementation is *much* more involved
- Implementation of process model can vary widely
  - We will cover the major themes

Last Time: UNIX Process States

- Only one process can be Running per CPU (core)
  - Processes waiting for the CPU are Ready
  - Processes waiting for slow resources are Blocked
  - Can also stop (Suspend) and resume processes



States and Processes

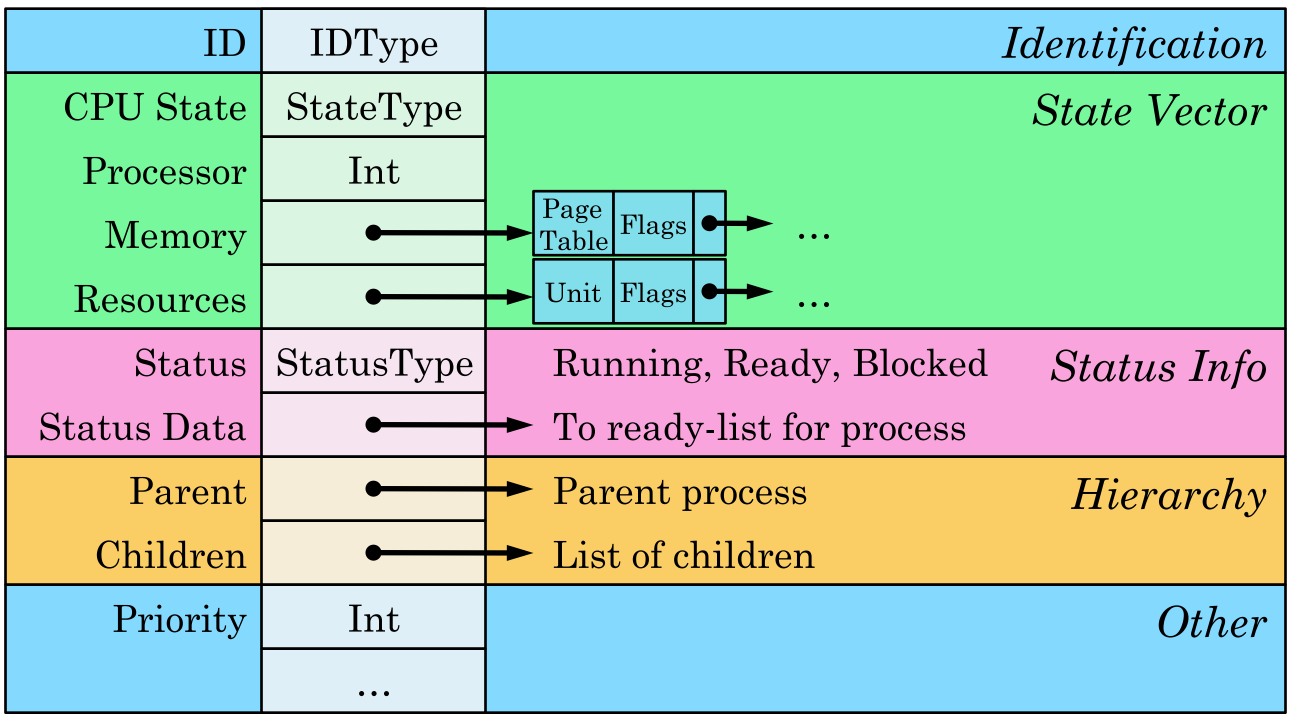
- At application level, UNIX processes are either Running, Stopped, or Terminated…
- At implementation level, only one process may be in Running state for each CPU in the computer
  - e.g. 4 cores = 4 processes in Running state
- <u>Many</u> processes can be in the other states!
- Kernel needs to manage collections of processes in each state
  - Different strategies for managing these processes, so different kinds of collections are employed

Process Control Block

- Each process has a Process Control Block (PCB) associated with it
  - Contains all information necessary for managing the process, and for performing context-switches
- The PCB can contain a lot of information:
  - Process ID, parent and child process IDs
  - When not running, register and memory state of process
  - Information about resources the process is using
  - Pending resource-requests that need to be filled
  - Scheduling information
  - *etc.*
- All necessary to allow kernel to coordinate processes using different resources on a single physical system

Process Control Block (2)

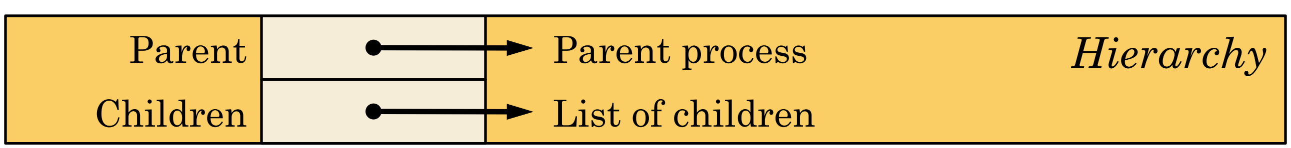
- Each process control block in the system contains information like this:



Process Identification, Hierarchy

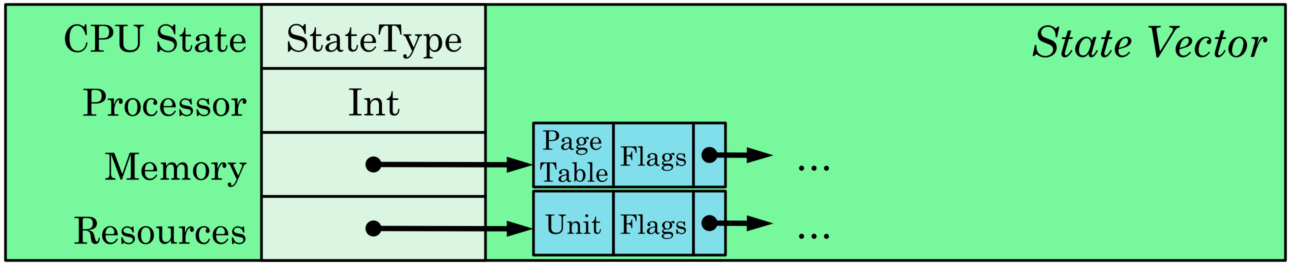
- The kernel manages a mapping of Process IDs to Process Control Blocks
  - Identification information uniquely identifies the process

- Several options for mapping PIDs to PCBs
  - Linux uses a hashtable, with bins containing linked-lists of PCBs
  - Rationale:
    - More space-efficient than a table where PIDs are indexes
    - Expect that process-count will typically be *much* smaller than the system limits
- UNIX process model also includes parent and child processes



Process State Vector

- State vector specifies all process context information



- CPU state:
  - Process capabilities and protection info
  - When suspended, also includes PC and register contents
  - Depends on processor architecture
- Processor:
  - Set to CPU number when running; otherwise undefined
- Memory:
  - Contents of process' code, data, stack, etc.
  - (Heavily leverages virtual memory system)
- Resources:
  - All allocated resources (files, network sockets, etc.)
  - Resource class + unit descriptions

PROCESS STATUS INFORMATION

- Process control block also includes current status

Status	StatusType	Running, Ready, Blocked	*Status Info*
Status Data	→	To ready-list for process	

- Running:
  - Process is currently running on a CPU
- Ready:
  - Process is ready to run, but waiting for a CPU
- Blocked:
  - Process cannot proceed until it receives a resource or a message
- Also includes other states, e.g. Suspended, etc.
- Status data can be used for:
  - Specifying pending resource-requests for this process
  - Specifying other processes in the same state and priority

Process Management

- Must provide several operations to support this model
  - **Create()**: create and initialize a new process
  - **Destroy(p)**: remove a process from the system
  - **Suspend(p)**: change process state to Suspended
  - **Resume(p)**: change process state to Ready
- Another important question:
  - *If we destroy or suspend a process, which process in the Ready state should actually run next?*
- A <u>scheduler</u> decides which process should run next
  - Given information about process behaviors and priorities, scheduler picks a process to resume, and then resumes it
  - When we need a new process to run, invoke the scheduler: it will choose a process, and then resume it
  - *(Will talk about how the scheduler makes this decision momentarily…)*

Create Operation

- Steps for the **Create()** operation:
  - Allocate a new Process Control Block
  - Assign a Process ID to this PCB
  - Initialize p->CPU_State
    - Set initial register values
    - Set Program Counter to the starting address of the process
    - UNIX: **`fork()`** creates a process, so use Program Counter from invoker as initial Program Counter for new process
      - **`fork()`** is called once but returns twice
  - Initialize all resources
    - UNIX: child process inherits all resources of parent process
  - Initialize other process accounting
    - e.g. p->Priority = Normal, etc.
  - Set process status to Ready; add to Ready collection!

Suspend Operation

- Overview of Suspend operation:
  - If the process is currently running, need to stop it
    - Record the process' context into its Process Control Block
  - Change the process status to Suspended
    - Specifically, Ready_Suspended or Blocked_Suspended
- Pseudocode for **Suspend(p)**:

```
if (p->Status == Running) {  /* Process was running on a CPU. */
    Stop(p);                 /* Record context of p into its PCB. */
    p->Status = Ready_Suspended;
    schedule();              /* Choose a Ready process to run. */
}
else if (p->Status == Ready) {          /* Process wasn't actually */
    p->Status = Ready_Suspended;        /* running, so no need to  */
} else if (p->Status == Blocked) {      /* stop it, or to invoke the */
    p->Status = Blocked_Suspended;      /* scheduler.              */
}
```

Stopping a Process

- **Stop(p)** operation is generally simple
  - Records entire process context into p->CPU_State
- Make it a separate operation to handle multi-processor systems more easily
  - Also, other operations can use Stop()
- If computer has multiple processors:
  - Kernel process may be executing on one CPU, while process p is running on another CPU
  - Cause an interrupt on the CPU running p, so that the process can be interrupted and suspended
- If the computer has a single processor:
  - The kernel code is already running! ☺
  - Don’t need to interrupt p; simply record its context

Resuming Suspended Processes

- Suspended processes are not scheduled for execution, until they are resumed
  - Only processes in the Ready state may be scheduled for execution
- Overview of the Resume operation:
  - Process is in either the Ready_Suspended state, or the Blocked_Suspended state
  - If in Ready_Suspended state, change to Ready, then invoke scheduler to start running the process
  - If in Blocked_Suspended state, change to Blocked
    - Can't schedule this process, so don't invoke the scheduler

Resume Operation

- Pseudocode for **Resume(p)**:

```
if (p->Status == Ready_Suspended) {
    p->Status = Ready;
    schedule();
}
else {  /* Process is Blocked_Suspended */
    p->Status = Blocked;
}
```

Destroy Operation

- Destroy may be called on a running process
  - e.g. process calls **`exit()`**, or receives a signal that terminates the process
  - In this case, a new process needs to be scheduled for the CPU
- If Destroy is given a suspended process, not necessary to schedule a new process
- Process also holds a number of resources when it is terminated
  - Destroy operation needs to release these resources

Destroy Operation (2)

- Pseudocode for **Destroy(p)**:

```
bool sched = false;
if (p->Status == Running) {
    Stop(p);
    sched = true;
}
...  /* Properly handle child processes. */
for each resource r the process holds:
    release_resource(r);
free(p);
if (sched)            /* A CPU is available, so        */
    schedule();       /* schedule another process. */
```

Other Operations

- This is a very high-level overview!
  - Many details left out of the description
  - e.g. moving a process from Blocked_Suspended to Ready_Suspended
    - Updating state is easy; managing hardware resources, requests, and interrupts is definitely not!
- The other important issue:
  - How to manage processes that are Ready to execute?
  - How to choose the process to execute next?
- The scheduler is responsible for this task
  - Given a set of Ready processes, choose a specific process to start running on the CPU

Scheduling Example

- You are running:
  - **`emacs`** to implement your **`sthreads`** package
  - **`gcc`** to compile your **`sthreads`** package
  - VLC to watch a video on your computer
  - A program searching for the next Mersenne Prime

- Process scheduling considerations?
  - When you type on **`emacs`**, it should respond quickly
  - **`gcc`** and Mersenne Prime program shouldn't mess up your video player
  - Prime number program will run much longer than **`gcc`**, so it shouldn't impede **`gcc`** progress

Scheduling Considerations

- Processes vary <u>widely</u> in their behavior! ☹
- Compute-intensive processes:
  - Execute for long periods of time
  - Use the CPU heavily; typically not blocked on IO
  - e.g. compilers, database servers
- Interactive processes:
  - Constantly waiting for user input (i.e. blocked on IO)
  - Usually not running on the CPU…
  - …but when input comes, need to respond quickly!
  - e.g. text editors, web browsers
- Real-time processes:
  - Require relatively small, but <u>very</u> regular, time on the CPU
  - Typically deadline-driven scheduling requirements
  - e.g. audio/video players

Scheduling Considerations (2)

- The scheduler should also be <u>fair</u>
  - All processes should eventually receive time on CPU
  - (Actual time given to each process may vary…)
- The scheduler should also be <u>fast</u>
  - Time spent in scheduler takes away from running processes…
  - Need to come up with a good answer, and quickly
  - Context-switches take approx. 5-10μs
    (roughly time of several thousand instructions)

What Do We Know?

- How can scheduler know what a process needs?
  - How often will the process block on IO operations?
  - How quickly will IO requests be satisfied?
    - e.g. BitTorrent download vs. you writing your hum paper
  - Does a process have real-time requirements?
  - Does the user expect that some programs will run for a long time?
- We cannot know with certainty:
  - How long before a program blocks on IO
  - How long a program will take to complete
  - How long a human being will take to respond to the program!

What Can We Guess?

- The scheduler can observe some aspects of process behavior
  - Does a process block regularly?
  - Does a process get preempted regularly by the kernel, because it does a lot of computation but no IO?
- Assumption: the future will be like the past
  - A process that regularly blocks on input, will continue to do so
  - A process that blocks on IO but regularly receives data, will continue to do so
  - A process that regularly consumes large amounts of CPU cycles without blocking, will continue to do so
- Scheduler uses a simple model to track behavior
  - Must be inexpensive to update and to use

What Must We Be Told?

- If a process has real-time constraints, the only real solution is to inform the kernel
  - e.g. Linux **`sched_setscheduler()`** function allows a process to control how it is scheduled by the kernel

- Similarly, if a user doesn't expect a program to finish quickly, they can alter its priority
  - Programs can use **`getpriority()`**, **`setpriority()`** to adjust the relative priority of a process
  - The **`nice`** utility uses these functions to run a process at a lower priority
  - e.g. don't want Mersenne Prime program to slow down **`gcc`** compilation!

Round-Robin Scheduling

- A simple scheduling approach:
  - Choose a fixed length time-slice, e.g. 100ms
  - Scheduler cycles through all processes, giving each one a turn to execute
  - If a process blocks or terminates, scheduler immediately goes on to next process
- Benefits:
  - Very simple scheduling algorithm
  - Completely fair – no process is starved

Round-Robin Scheduling (2)

- Compute-intensive tasks:
  - Benefit greatly from this approach! Large, regular time-slices with infrequent context-switches.
- Interactive tasks:
  - When a process blocks on IO, it is removed from the ready queue
    - When it becomes ready again, it is added to end of queue
  - If a process blocks on IO regularly, it will be forced to wait for long-running processes to use their full time-slice
- Can vary size of time-slice given to each process
  - Simple way to implement priorities

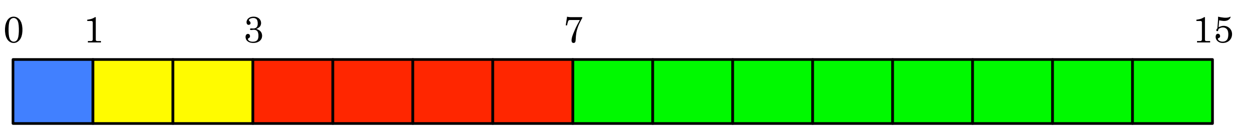
Interactive Tasks

- With round-robin, interactive tasks are delayed by long-running processes
  - Text editor or web browser becomes sluggish and unresponsive

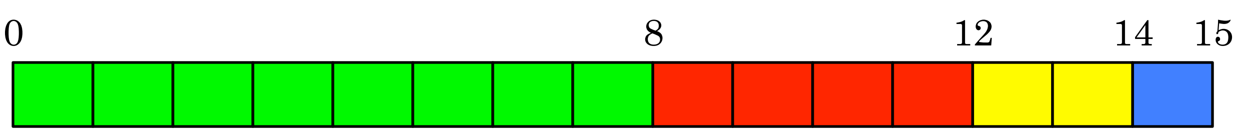
- Another approach:
  - Use past behavior of each process to estimate the run-time until it blocks
- Scheduler runs shortest jobs first
  - Higher priority than long-running tasks
  - Interactive processes are no longer delayed by long-running tasks

Shortest Jobs First Scheduling

- With interactive processes, we care about <u>response time</u>
  - Time between data IO (e.g. key-press) and first response from the process
- Example:
  - Four jobs, with estimated length 1, 2, 4, 8
- Scheduling shortest jobs first:



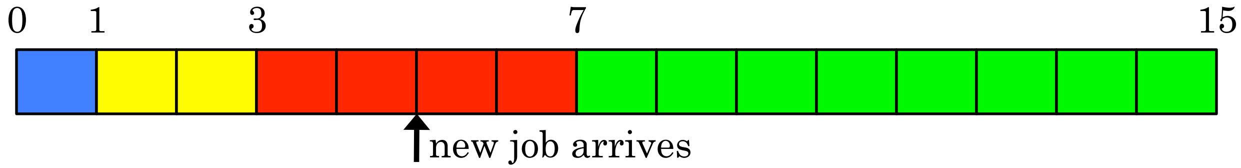
  - Response times are 0, 1, 3, 7. Avg = 2.75, max = 7.
- Conversely, scheduling longest jobs first:



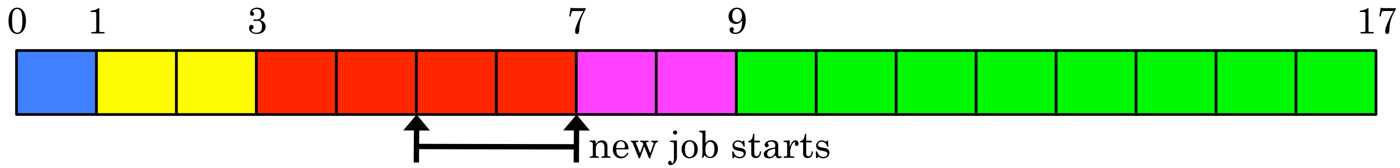
  - Response times are 0, 8, 12, 14. Avg = 8.5, max = 14.

Shortest Jobs First Scheduling (2)

- What if new jobs show up while current jobs are executing?
- From previous example:
  - Four jobs, with estimated length 1, 2, 4, 8



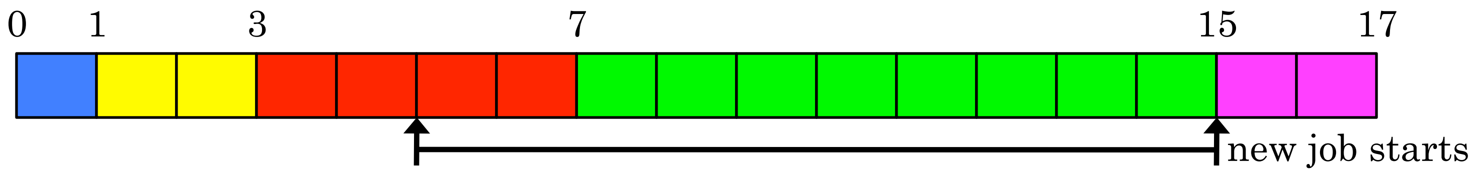
  - At timestep 5, a new job of length 2 shows up…
- Can schedule the new shortest job next



  - Wait times = 0, 1, 3, 2, 9. Avg = 3, max = 9.
- Problems?
  - If new short jobs keep arriving, long jobs will be starved! This approach is not fair!

Shortest Jobs First Scheduling (3)

- Can also defer the new shortest job until after previous jobs have all completed



  - Wait times = 0, 1, 3, 7, 10. Avg = 4.2, max = 10.
- Average and maximum response times get worse, but at least it's fair

Next Time

- Round-robin scheduling is good for compute-intensive tasks, but bad for interactive tasks
- Shortest jobs first scheduling good for interactive tasks, but bad for compute-intensive tasks
- Next time:
  - How do we schedule for real-time tasks?
  - How do we build a generic scheduler that can properly handle various process behaviors?