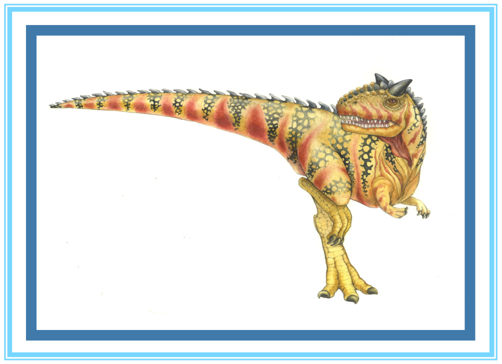
Chapter 5: Process Synchronization



Chapter 5: Process Synchronization

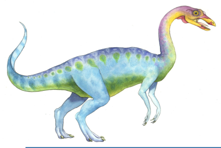
- Background
- The Critical-Section Problem
- Peterson’ s Solution
- Synchronization Hardware
- Mutex Locks
- Semaphores
- Classic Problems of Synchronization
- Monitors
- Synchronization Examples
- Alternative Approaches

Objectives

- To introduce the critical-section problem, whose solutions can be used to ensure the consistency of shared data
- To present both software and hardware solutions of the critical-section problem
- To examine several classical process-synchronization problems
- To explore several tools that are used to solve process synchronization problems

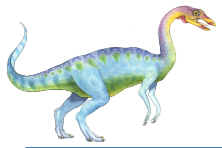
Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes
- Illustration of the problem:
  Suppose that we wanted to provide a solution to the consumer-producer problem that fills ***all*** the buffers. We can do so by having an integer **`counter`** that keeps track of the number of full buffers. Initially, **`counter`** is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.



Producer

```
while (true) {
     /* produce an item in next produced */

     while (counter == BUFFER SIZE) ;
          /* do nothing */
     buffer[in] = next produced;
     in = (in + 1) % BUFFER SIZE;
     counter++;
}
```



Consumer

```
while (true) {
     while (counter == 0)
          ; /* do nothing */
     next consumed = buffer[out];
     out = (out + 1) % BUFFER SIZE;
     counter--;
     /* consume the item in next consumed */
}
```

Race Condition

- `counter++` could be implemented as

```
register1 = counter
register1 = register1 + 1
counter = register1
```

- `counter--` could be implemented as

```
register2 = counter
register2 = register2 - 1
counter = register2
```

- Consider this execution interleaving with “count = 5” initially:

```
S0: producer  executes register1 = counter           {register1 = 5}
S1: producer  executes register1 = register1 + 1     {register1 = 6}
S2: consumer executes register2 = counter            {register2 = 5}
S3: consumer executes register2 = register2 – 1      {register2 = 4}
S4: producer  executes counter = register1           {counter = 6}
S5: consumer executes counter = register2            {counter = 4}
```

Critical Section Problem

- Consider system of ***n*** processes { P_0, P_1, …, P_{n-1} }
- Each process has a **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc.
  - When one process is in its critical section, no other may be executing in its critical section
- ***Critical-section problem*** is to design a protocol to solve this
- Each process must ask permission to enter its critical section in **entry section**, may follow critical section with **exit section**, the remaining code is in its **remainder section**

Critical Section

- General structure of process ***P**_i_* is

```
do {
     entry section
          critical section
     exit section
          remainder section
} while (true);
```

Solution to Critical-Section Problem

1. **Mutual Exclusion** - If process $\boldsymbol{P_i}$ is executing in its critical section, then no other processes can be executing in their critical sections

2. **Progress** - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then only the processes not in their remainder section can participate in the selection of the process that will enter its critical section next; the selection cannot be postponed indefinitely

3. **Bounded Waiting** - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
   - Assume that each process executes at a nonzero speed
   - No assumption concerning **relative speed** of the ***n*** processes

Solution to Critical-Section Problem

- Two approaches for handling critical sections in OSes, depending on if kernel is preemptive or non-preemptive
  - **Preemptive** – allows preemption of process when running in kernel mode
    - Specially difficult in multiprocessor architectures, but it makes the system more responsive
  - **Non-preemptive** – runs until exits kernel mode, blocks, or voluntarily yields CPU
    - Essentially free of race conditions on kernel data structures in kernel mode, since only one active process in the kernel at a time

Peterson’s Solution

- Good algorithmic description of solving the problem (but no guarantees for modern architectures)
- Solution restricted to two processes in alternate execution (critical section and remainder section)
- Assume that the **`load`** and **`store`** instructions are atomic; i.e., cannot be interrupted
- The two processes share two variables:
  - **`int turn`**
  - **`boolean flag[2]`**
- The variable **`turn`** indicates whose turn it is to enter its critical section
- The **`flag`** array is used to indicate if a process is ready to enter its critical section
  `flag[i] == true` implies that process P_i is ready to enter its critical section

Algorithm for Process P_i

```
do {
   flag[i] = true;
   turn = j;
   while (flag[j] && turn == j);
          critical section
   flag[i] = false;
          remainder section
} while (true);
```

- Provable that

1. Mutual exclusion is preserved
2. Progress requirement is satisfied
3. Bounded-waiting requirement is met

Synchronization Hardware

- Many systems provide hardware support for critical section code
- All solutions below based on idea of **locking**
  - Protecting critical regions via locks
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- Modern machines provide special atomic hardware instructions
    - **Atomic** = non-interruptible
  - Either test memory word and set value
  - Or swap contents of two memory words

Solution to Critical-Section Problem Using Locks

```
do {
   acquire lock
        critical section
   release lock
        remainder section
} while (TRUE);
```

Solution using test_and_set()

- Two `test_and_set()` cannot be executed simultaneously
- Shared boolean variable `lock`, initialized to FALSE
- Solution:

```
boolean test_and_set(boolean *target)
{
   boolean rv = *target;
   *target = TRUE;
   return rv:
}
```

```
do {
   while (test_and_set(&lock))
      ; /* do nothing */
   /* critical section */
   lock = false;
   /* remainder section */
} while (true);
```

compare_and_swap Instruction

- Definition:

```
int compare_and_swap(int *value, int expected, int new_value) {
   int temp = *value;
   if (*value == expected)
      *value = new_value;
   return temp;
}
```

Solution using compare_and_swap

- Shared boolean variable **`lock`** initialized to FALSE
- Each process has a local boolean variable **`key`**
- Solution:

```
do {
   while (compare_and_swap(&lock, 0, 1) != 0)  //value,expected,new
      ; /* do nothing */
      /* critical section */
   lock = 0;
      /* remainder section */
} while (true);
```

Bounded-waiting Mutual Exclusion with test_and_set

```
do {
   waiting[i] = true;
   key = true;
   while (waiting[i] && key)
      key = test_and_set(&lock);  //only first lock==false will set key=false
   waiting[i] = false;
   /* critical section */
   j = (i + 1) % n;    //look for the next P[j] waiting: bound-waiting req.
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = false;
   else
      waiting[j] = false; //wakeup only one process P[j] without releasing lock
   /* remainder section */
} while (true);
```

Mutex Locks

- Previous solutions are complicated and generally inaccessible to application programmers
- OS designers build software tools to solve critical section problem
- Simplest synchronization is done with mutex lock
- Protect critical regions by first **`acquire()`** a lock (then all other processes attempting to get the lock are blocked), and then **`release()`** it
  - Boolean variable indicating if lock is available or not

```
acquire() {
   while (!available)
      ; /* busy wait */
   available = false;
}
release() {
   available = true;
}
```

```
do {
   acquire lock
      critical section
   release lock
      remainder section
} while (true);
```

Mutex Locks

- Calls to **`acquire()`** and **`release()`** must be atomic
  - Usually implemented via hardware atomic instructions
- But this solution requires **busy waiting**
  - All other processes trying to get the lock must continuously loop
  - This lock is therefore called a **spinlock**
  - Very wasteful of CPU cycles
  - Might still be more efficient than (costly) context switches for shorter wait times

Semaphore

- Synchronization tool that does not require busy waiting
- Semaphore ***S*** – integer variable
- Two standard operations modify ***S***: **`wait()`** and **`signal()`**
- Less complicated
- Can only be accessed via two indivisible (atomic) operations

```
wait (S) {
    while (S <= 0)
       ; // busy wait
    S--;
}
signal (S) {
    S++;
}
```

Semaphore Usage

- **Counting semaphore** – integer value can range over an unrestricted domain
- **Binary semaphore** – integer value can range only between 0 and 1
  - Then equivalent to a **mutex lock**
- Can solve various synchronization problems
- Consider P_1 and P_2 that require S_1 to happen before S_2

```
P1:
   S1;
   signal(synch);   //sync++ has added one resource
P2:
   wait(synch);     //executed only when synch is > 0
   S2;
```

Semaphore Implementation

- Must guarantee that no two processes can execute **`wait()`** and **`signal()`** on the same semaphore at the same time
- Thus, implementation *becomes the critical section problem*, where the **`wait`** and **`signal`** codes are placed in the critical section
  - Could now have **busy waiting** in critical section implementation
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied
- Note that applications may spend lots of time in critical sections and therefore this is not a good solution

Semaphore Implementation with no Busy Waiting

- With each semaphore there is an associated waiting queue
- Each entry in a waiting queue has two data items:
  - value (of type integer)
  - pointer to next record in the list

```
typedef struct {
   int value;
   struct process *list;
} semaphore;
```

- Two operations:
  - **block** – place the process invoking the operation in the appropriate waiting queue
  - **wakeup** – remove one of the processes in the waiting queue and place it in the ready queue

```
wait(semaphore *S) {
   S->value--;
   if (S->value < 0) {
      add this process to S->list;
      block();
   }
}
```

```
signal(semaphore *S) {
   S->value++;
   if (S->value <= 0) {
      remove a process P from S->list;
      wakeup(P);
   }
}
```

Deadlock and Starvation

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let *S* and *Q* be two semaphores initialized to 1

```
         P0                              P1
 wait(S); //exec 1st         wait(Q);  //exec 2nd
 wait(Q); //exec 3rd         wait(S);  //exec 4th
     ...                             ...
signal(S);                  signal(Q);
signal(Q);                  signal(S);
```

- **Starvation** – **indefinite blocking**
  - A process may never be removed from the semaphore queue in which it is suspended

Priority Inversion

- Scheduling problem when lower-priority process holds a lock needed by higher-priority process
- Scenario :
  - Processes with priorities **L** < **M** < **H** request resource *r*
  - **L** first locks on *r* ; then **H** requests *r*, but must wait until **L** ends
  - In the meantime, **M** requests *r* and preempts **L**
  - **H** is waiting longer for lower-priority processes
- Not a problem with only two levels of priorities, but two levels are insufficient for most OSes
- Solved via **priority-inheritance protocol**
  - All lower-priority processes with a resource requested by a higher-priority process, inherits the higher-priority level until it releases the resource

Classical Problems of Synchronization

- Classical problems used to test newly-proposed synchronization schemes
  - Bounded-Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem

Bounded-Buffer Problem

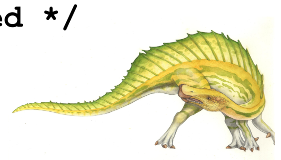
- Shared data structures:
  - ***n*** buffers, each can hold one item
  - Semaphore **`mutex`** initialized to the value 1
  - Semaphore **`full`** initialized to the value 0
  - Semaphore **`empty`** initialized to the value *n*

- The structure of the producer process

```
do {
      ...
   /* produce an item in next_produced */
      ...
   wait(empty);
   wait(mutex);
      ...
   /* add next_produced to the buffer */
      ...
   signal(mutex);
   signal(full);
} while (true);
```

- The structure of the consumer process

```
do {
   wait(full);
   wait(mutex);
      ...
   /* remove an item from buffer to next_consumed */
      ...
   signal(mutex);
   signal(empty);
      ...
   /* consume the item in next_consumed */
      ...
} while (true);
```



Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do ***not*** perform any updates
  - Writers – can both read and write
- Problem
  - Allow multiple readers to read at the same time
  - Only a ***single*** writer can access the shared data at the same time
- Several variations of how readers and writers are treated – all involve priorities
- Variations to the problem:
  - *First* variation – no reader kept waiting, unless writer has permission to use shared object
  - *Second* variation – once writer is ready, it performs a write as soon as possible
  - Both may have starvation, leading to even more variations
    - first: readers keep coming in while writers are never treated
    - second: writers keep coming in while readers are never treated
  - Problem is solved on some systems by kernel providing **reader-writer locks**

Readers-Writers Problem

- Shared data
  - Data set
  - Semaphore **`rw_mutex`** initialized to 1
  - Semaphore **`mutex`** initialized to 1
  - Integer **`read_count`** initialized to 0

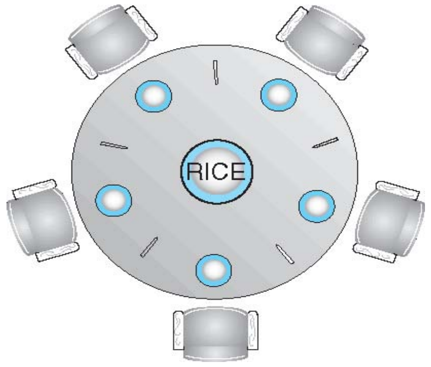
- The structure of a writer process

```
do {
       wait(rw_mutex);
       ...
        /* writing is performed */
       ...
       signal(rw_mutex);
} while (true);
```

- The structure of a reader process

```
do {
    wait(mutex);
    read_count++;
    if (read_count == 1)
       wait(rw_mutex);
    signal(mutex);
     ...
    /* reading is performed */
     ...
    wait(mutex);
    read_count--;
    if (read_count == 0)
       signal(rw_mutex);
    signal(mutex);
} while (true);
```

Dining-Philosophers Problem



- Philosophers spend their lives thinking and eating
- They do not interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time, on either side) to eat from bowl
  - Need both chopsticks to eat
  - Put back in their place both chopsticks when done eating
- Shared data for 5 philosophers
  - Bowl of rice (data set)
  - Semaphore `chopstick[5]` initialized to 1

- The structure of Philosopher *i* :

```
do  {
    wait(chopstick[i]);
    wait(chopstick[(i+1)%5]);
    //  eat
    signal(chopstick[i]);
    signal(chopstick[(i+1)%5]);
    //  think
} while (TRUE);
```

- What is the problem with this algorithm?

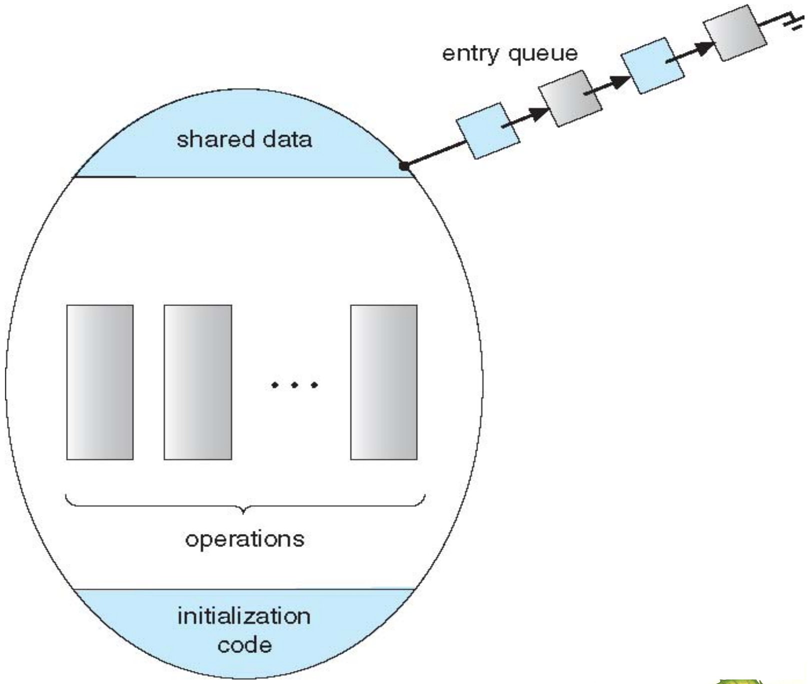
Problems with Semaphores

- Incorrect use of semaphore operations can be difficult to detect, e.g. :
  - Inversed order: `signal(mutex)   ...   wait(mutex)`
  - Repeated calls: `wait(mutex)   ...   wait(mutex)`
  - Omitted calls: `wait(mutex)` or `signal(mutex)` (or both)
- Results in deadlock and/or starvation

Monitors

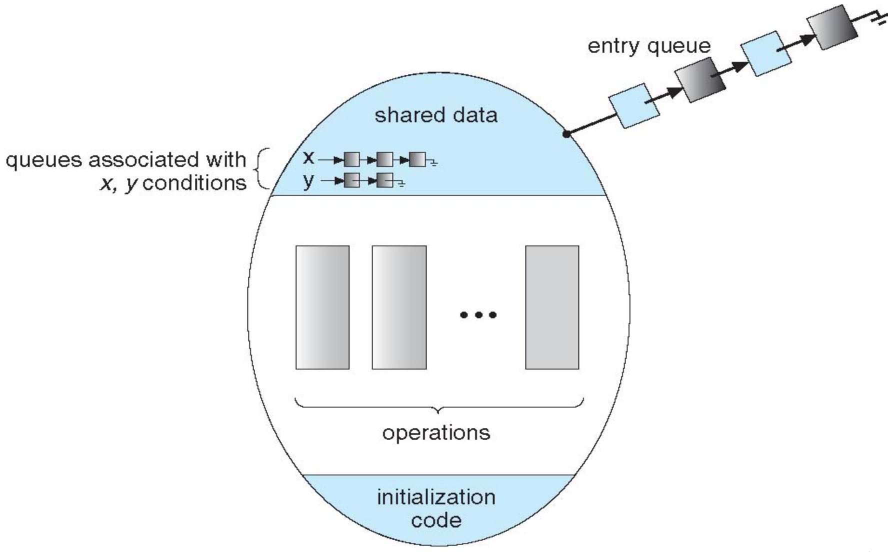
- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- *Abstract data type*, internal variables only accessible by code within the procedure
- Only ***one*** process may be active within the monitor at a time
- But not powerful enough to model some synchronization schemes

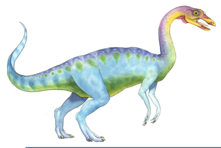
```
monitor monitor-name
{
   // shared variable declarations
   function P1(...) { ... }
   ...
   function Pn(...) { ... }

  initialization_code (...) { ... }
}
```



Condition Variables

- Synchronization mechanism for monitors declared as variables:
  - **`condition x, y;`**
- Only two operations can be invoked on a condition variable:
  - **`x.wait()`** – a process that invokes the operation is suspended until **`x.signal()`**
  - **`x.signal()`** – resumes one of processes (if any) that invoked **`x.wait()`**
    - If no **`x.wait()`** on the condition variable, then it has no effect on the variable





Condition Variables Choices

- If process P invokes `x.signal()`, with Q in `x.wait()` state, what should happen next?
  - If Q is resumed, then P must wait, otherwise two processes would be active in the monitor
- Options include
  - **Signal and wait** – P waits until Q leaves monitor or waits for another condition
  - **Signal and continue** – Q waits until P leaves the monitor or waits for another condition
  - Both have pros and cons – language implementer can decide
  - Monitors implemented in Concurrent Pascal compromise
    - P executing signal immediately leaves the monitor, Q is resumed
  - Implemented in other languages including Mesa, C#, Java

Solution to Dining Philosophers

```
monitor DiningPhilosophers
{
    enum { THINKING; HUNGRY, EATING) state[5];
    condition self[5];

    void pickup(int i) {
      state[i] = HUNGRY;
      test(i);
      if (state[i] != EATING)
        self[i].wait();
    }

    void putdown(int i) {
      state[i] = THINKING;
      // test left and right neighbors
      test((i+4)%5);
      test((i+1)%5);
    }

    void test(int i) {
      if ((state[(i+4)%5] != EATING) &&
          (state[i] == HUNGRY) &&
          (state[(i+1)%5] != EATING) ) {
             state[i] = EATING;
             self[i].signal();
      }
    }

    initialization_code() {
      for (int i = 0; i < 5; i++)
        state[i] = THINKING;
    }
}
```

Solution to Dining Philosophers (cont.)

- Each philosopher *i* invokes the operations **`pickup()`** and **`putdown()`** in the following sequence:

```
DiningPhilosophers.pickup(i);
...
EAT
...
DiningPhilosophers.putdown(i);
```

- No deadlocks, but starvation is possible

Monitor Implementation Using Semaphores

- Variables

```
semaphore mutex;  // (initially  = 1)
semaphore next;   // (initially  = 0)
int next_count = 0;
```

- Each external function ***F*** will be replaced by

```
wait(mutex);
...
body of F;
...
if (next_count > 0)
    signal(next);
else
    signal(mutex);
```

- Mutual exclusion within a monitor is ensured

Monitor Implementation – Condition Variables

- For each condition variable ***x***, we have:

```
semaphore x_sem;   // (initially  = 0)
int x_count = 0;
```

- The operation **`x.wait()`** can be implemented as:

```
x_count++;
if (next_count > 0)
    signal(next);
else
    signal(mutex);
wait(x_sem);
x_count--;
```

- The operation **`x.signal()`** can be implemented as:

```
if (x_count > 0) {
    next_count++;
    signal(x_sem);
    wait(next);
    next_count--;
}
```

Resuming Processes within a Monitor

- If several processes queued on condition **`x`**, and **`x.signal()`** executed, which one should be resumed?
- First-come, first-served (FCFS) frequently not adequate
- **conditional-wait** construct of the form **`x.wait(c)`**
  - where **`c`** is **priority number**
  - Process with lowest number (highest priority) is scheduled next
  - Example of ResourceAllocator, next

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
{
    boolean busy;
    condition x;

    void acquire(int time) {
        if (busy)
            x.wait(time); //time: maximum time it will keep resource
        busy = TRUE;
    }

    void release() {
        busy = FALSE;
        x.signal();
    }

    initialization_code() {
        busy = FALSE;
    }
}
```

Synchronization Examples

- Windows XP
- Solaris
- Linux
- Pthreads

Windows XP Synchronization

- Uses interrupt masks to protect access to global resources on uniprocessor systems
- Uses **spinlocks** on multiprocessor systems
  - Spinlocking-thread will never be preempted
- Also provides **dispatcher objects** user-land (outside the kernel) which may act as mutex locks, semaphores, events, and timers
  - **Event** acts much like a condition variable (notify thread(s) when condition occurs)
  - **Timer** notifies one or more threads when specified amount of time has expired
  - Dispatcher objects either **signaled-state** (object available) or **non-signaled state** (thread will block)

Solaris Synchronization

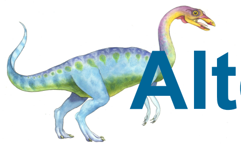
- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing
- Uses **adaptive mutex locks** for efficiency when protecting data from short code segments
  - Starts as a standard semaphore spin-lock
  - If lock is held, and by a thread running on another CPU, spins
  - If lock is held by non-run-state thread, block and sleep, waiting for signal of lock being released
- Uses **condition variables**
- Uses **readers-writers** locks when longer sections of code need access to data
- Uses **turnstiles** to order the list of threads waiting to acquire either an adaptive mutex or reader-writer lock
  - Turnstiles are per-lock-holding-thread, not per-object
- Priority-inheritance per-turnstile gives the running thread the highest of the priorities of the threads in its turnstile

Linux Synchronization

- Linux:
  - Prior to kernel Version 2.6, disables interrupts to implement short critical sections
  - Version 2.6 and later, fully preemptive
- Linux provides:
  - semaphores
  - spinlocks
  - reader-writer versions of both
- On single-cpu system, spinlocks replaced by enabling and disabling kernel preemption

Pthreads Synchronization

- Pthreads API is OS-independent
- It provides:
  - mutex locks
  - condition variables
- Non-portable extensions include:
  - read-write locks
  - spinlocks



Alternatives to Thread-safe Concurrent Applications

- Transactional memory
- OpenMP
- Functional programming languages

Transactional Memory

- Assures that operations happen as a single logical unit of work, in its entirety, or not at all
- Related to the field of database systems
- Challenge is assuring atomicity, despite computer system failures
- Transaction - collection of instructions or operations that performs single logical function
  - Here we are concerned with changes to stable storage – disk
  - Transaction is series of read and write operations
  - Terminated by commit (transaction successful) or abort (transaction failed) operation
  - Aborted transaction must be rolled back to undo any changes it performed
- In software, compiler is responsible to identify the concurrent sections of the code and to augment them with proper lock mechanisms
- In hardware, implemented as cache hierarchies, and cache coherency mechanisms
- Transactional memory is not widespread yet, but…

OpenMP

- Indicates where in the code only one thread may be active at a time
  - similar to a mutex lock
- Special compiler instruction
  - `#pragma omp critical`
- Programmer must still handle race conditions and deadlocks

Functional Languages

- E.g.: Erlang, Scala
- Functional languages do not maintain state
  - Once a variable is assigned a value, it cannot change anymore
- No such problems as race conditions and deadlocks
- Therefore suitable for concurrent/parallel programming on multicores

End of Chapter 5