

CS370 Operating Systems

Colorado State University

Yashwant K Malaiya

Fall 2024 L12

Synchronization (Chap 6, 7)



Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

Project

Options

- A. Research
- B. Development

Deliverable *D1 Team composition and idea proposal* specified separately in the document [Fall 2024 Term Project](#) .
Similarly, D2, D3, D4 and D5 are specified.

You have to do some research for both of them.

Research: Search Databases

Specific sources: database indexes

- Google Scholar
 - Forward links: [Paper X Cited by](#)
 - Backward Links: [Paper X cites](#)
- Researcher sites
 - Personal/Group Website
 - DBLP
 - Google Scholar: [researcher](#)
- CSU Library etc.

General (*accessible through CSU Library*)

- ACM Digital Library
- IEEEExplore Digital Library
- ScienceDirect etc

Research: Source types

- Journals: published several times a year
 - Rigorously reviewed, long publication delay
 - Journal, Transactions, ...
- Conferences: held once a year, proceedings published
 - Conference, Symposium, ...
- Research groups
 - Industry, academic, consultants: web site
- News, Industry publications
 - Magazines, blogs, white papers, product website
- Books: often well-known stuff

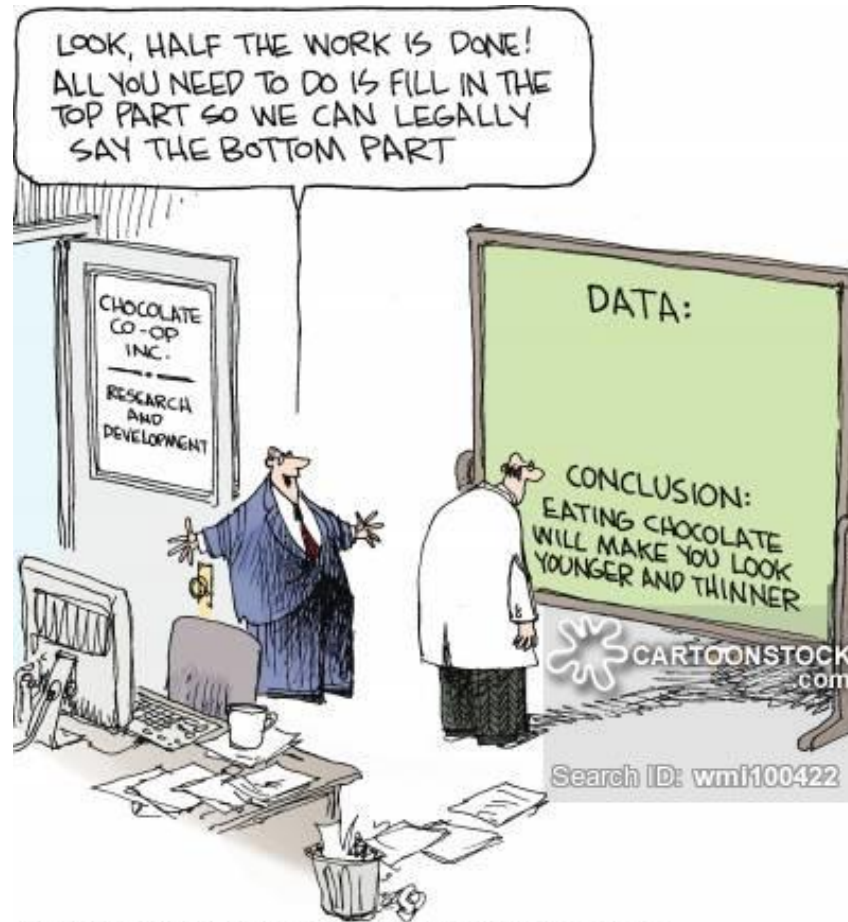
Research: How to Read a Paper: THE THREE-PASS

APPROACH

- The first pass: Read
 - the title, abstract, and introduction
 - section and sub-section headings, but ignore everything else
 - the conclusions
- The second pass: Read
 - figures, diagrams and other illustrations
 - mark relevant unread references for further reading
 - Do you need to read it in detail?
- The third pass: Read critically
 - identify and challenge assumption and views
 - Loop up references needed

Keshav, S., How to Read a Paper, ACM SIGCOMM,
<http://ccr.sigcomm.org/online/files/p83-keshavA.pdf>

Research: Avoid Prior Bias



© Wiley Ink, inc./Distributed by Universal Uclick via Cartoonstock

Evaluating research

- These are the attributes generally evaluated
- Novelty/interest/Applicability
- Technical: Extent of research/contribution
 - Key sources? Recent developments?
 - citations
- Presentation
 - Visuals: Non-text: diagrams, charts, algorithms
 - Systematic/quantitative: tables, numbers
 - Readability, coherence
- Overall

Course Notes

- The Midterm and the Final will use the Respondus Lockdown Browser with camera recording.
 - You must use a laptop with the Respondus Lockdown Browser installed and tested. A test quiz will be provided.
- The Sec 001 students will bring the fully charged and tested laptop to the designated room.
 - The 1 hour 15 min Midterm will be on Tues Oct 8 during the regular class time.
- The Sec 801 students will take their Midterm on Oct 9 any time from 12:10 AM (early morning) to 11:50 PM.
- Anyone with a significant conflict should contact me directly.

Process Synchronization: Outline

- Critical-section problem to ensure the consistency of shared data
- Software and hardware solutions of the critical-section problem
 - Peterson's solution
 - Atomic instructions
 - Mutex locks and semaphores
- Classical process-synchronization problems
 - Bounded buffer,
 - Readers Writers,
 - Dining Philosophers
- Another approach: Monitors

Semaphores: Implementation with no Busy waiting

```
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);
    }
}
```

If value < 0
abs(value) is the number
of waiting processes

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

Bounded-Buffer Problem

- n buffers, each can hold one item
- Binary semaphore (**mutex**)
 - Provides mutual exclusion for accesses to buffer pool
 - Initialized to 1
- Counting semaphores
 - **empty**: Number of empty slots available
 - Initialized to n
 - **full**: Number of filled slots available n
 - Initialized to 0

3 semaphores needed,
1 binary, 2 counting

Bounded-Buffer : Note

- Producer and consumer must be ready before they attempt to enter critical section
- Producer readiness?
 - When a slot is available to add produced item
 - wait(empty)
 - empty is initialized to n
- Consumer readiness?
 - When a producer has added new item to the
 - wait(full)
 - full initialized to 0

empty: Number of empty slots available
wait(empty) wait until at least 1 empty

full: Number of filled slots available
wait(full) wait until at least 1 full

Bounded Buffer Problem (Cont.)

The structure of the producer process

empty: initialized to n
full: initialized to 0

```
do {  
    ...  
    /* produce an item in next_produced */  
    ...  
    wait(empty);           wait till slot available  
    wait(mutex);         Allow producer OR consumer to (re)enter critical section  
    ...  
    /* add next produced to the buffer */  
    ...  
    signal(mutex);      Allow producer OR consumer to (re)enter critical section  
    signal(full);       signal consumer that a slot is available  
} while (true);
```

Bounded Buffer Problem (Cont.)

The structure of the consumer process

empty: initialized to n
full: initialized to 0

```
Do {  
    wait(full); wait till slot available for consumption  
    wait(mutex); Only producer OR consumer can be in critical section  
    ...  
    /* remove an item from buffer to next_consumed */  
    ...  
    signal(mutex); Allow producer OR consumer to (re)enter critical section  
    signal(empty); signal producer that a slot is available to add  
    ...  
    /* consume the item in next consumed */  
    ...  
} while (true);
```

Classical Problems of Synchronization

Classical problems

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem
- **Bounded buffer Review**
 - n buffers, each can hold one item
 - A binary semaphore: mutex
 - Provides mutual exclusion for accesses to buffer pool
 - Initialized to 1
 - Two counting semaphores
 - empty: Number of empty slots available, Initialized to n
 - full: Number of filled slots available n, Initialized to 0

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 one single writer can access the shared data at the same time. No readers permitted when writer is accessing the data.
- Several variations of how readers and writers are considered – all involve some form of priorities

Readers-Writers Problem

- Shared Data
 - Data set
 - Semaphore **rw_mutex** initialized to 1 (mutual exclusion for writer)
 - Semaphore **mutex** initialized to 1 (mutual exclusion for read_count)
 - Integer **read_count** initialized to 0 (how many readers?)

Readers-Writers Problem (Cont.)

- The structure of a writer process

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

Readers-Writers Problem (Cont.)

- 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);
```

Cannot read
if writer is
writing

First reader needs to wait for the writer to finish.
If other readers are already reading, a new reader
Process just goes in.

mutex for mutual
exclusion to read_count

When:
writer in critical section
and if n readers waiting
1 is queued on rw_mutex
(n-1) queued on mutex

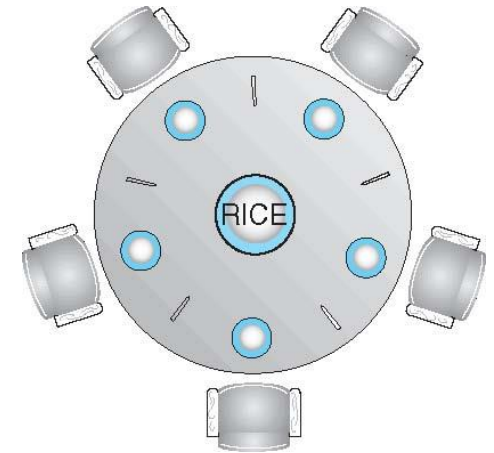
When the last reader leaves, a writer can go in.

Readers-Writers Problem Variations

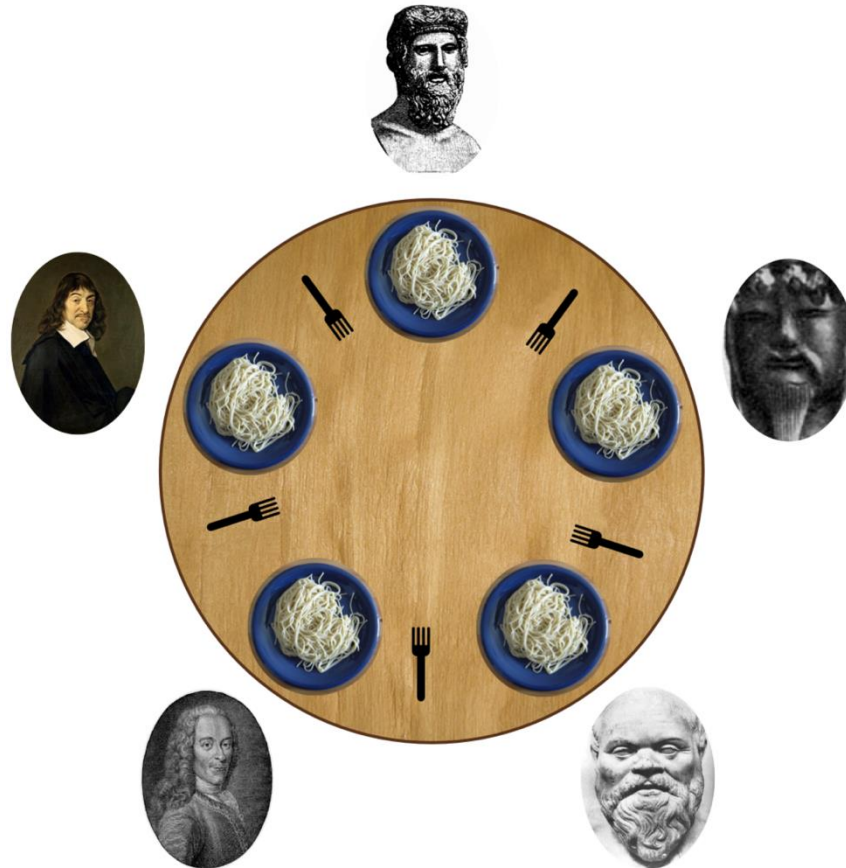
- **First** variation – no reader kept waiting unless writer has already obtained permission to use shared object
- **Second** variation – once writer is ready, it performs the write ASAP, i.e. if a writer is waiting, no new readers may start.
- Both may have starvation leading to even more variations
- Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem

- Philosophers spend their lives alternating thinking and eating
- Don't interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
 - Need both to eat,
 - then release both when done
- Each chopstick is a semaphore
 - Grab by executing wait ()
 - Release by executing signal ()
- Shared data
 - Bowl of rice (data set)
 - Semaphore **chopstick [5]** initialized to 1



Dining-Philosophers Problem



Plato, Confucius, Socrates, Voltaire and Descartes

Dining-Philosophers Problem Algorithm: Simple solution?

- 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?
 - If all of them pick up the the left chopstick first -
Deadlock

- Deadlock handling
 - Allow at most 4 philosophers to be sitting simultaneously at the table (with the same 5 forks).
 - Allow a philosopher to pick up the forks only if both are available (picking must be done in a critical section).
 - Use an asymmetric solution -- an odd-numbered philosopher picks up first the left chopstick and then the right chopstick. Even-numbered philosopher picks up first the right chopstick and then the left chopstick.

Problems with Semaphores

- Incorrect use of semaphore operations:
 - Omitting of wait (mutex)
 - Violation of mutual exclusion
 - or signal (mutex)
 - Deadlock!
- Solution:
 - Monitors: a higher-level implementation of synchronization

Monitors

Monitors

Monitor: 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
 - Automatically provide mutual exclusion
 - Implement waiting for conditions
- Queues:
 - for entry
 - for each condition
- Originally proposed for Concurrent Pascal 1975
- Directly supported by Java (see self exercise) but not C

Monitors

- Only one process may be actively under execution in the monitor.
- A generic monitor construct is used here. Implementation varies by language.

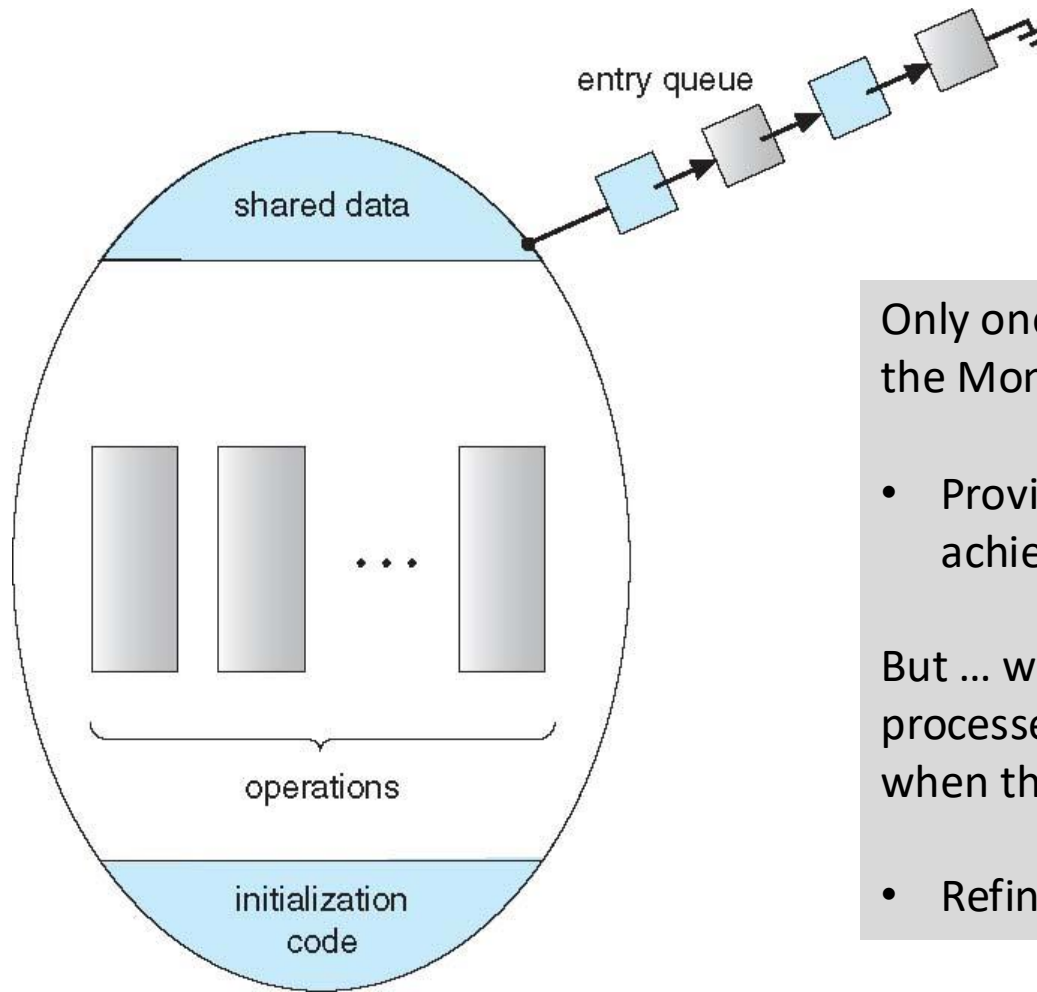
```
monitor monitor-name
{
  // shared variable declarations

  procedure P1 (...) { ... }

  procedure Pn (...) {.....}

  Initialization code (...) { ... }
}
}
```

Preliminary Schematic view of a Monitor



Only one process/thread in the Monitor

- Provides an easy way to achieve mutual exclusion

But ... we also need a way for processes to **block** when they cannot proceed.

- Refinement next ...

Shows 4 processes waiting in the queue.

Condition Variables

Some actions need some conditions to go ahead.

The **condition** construct

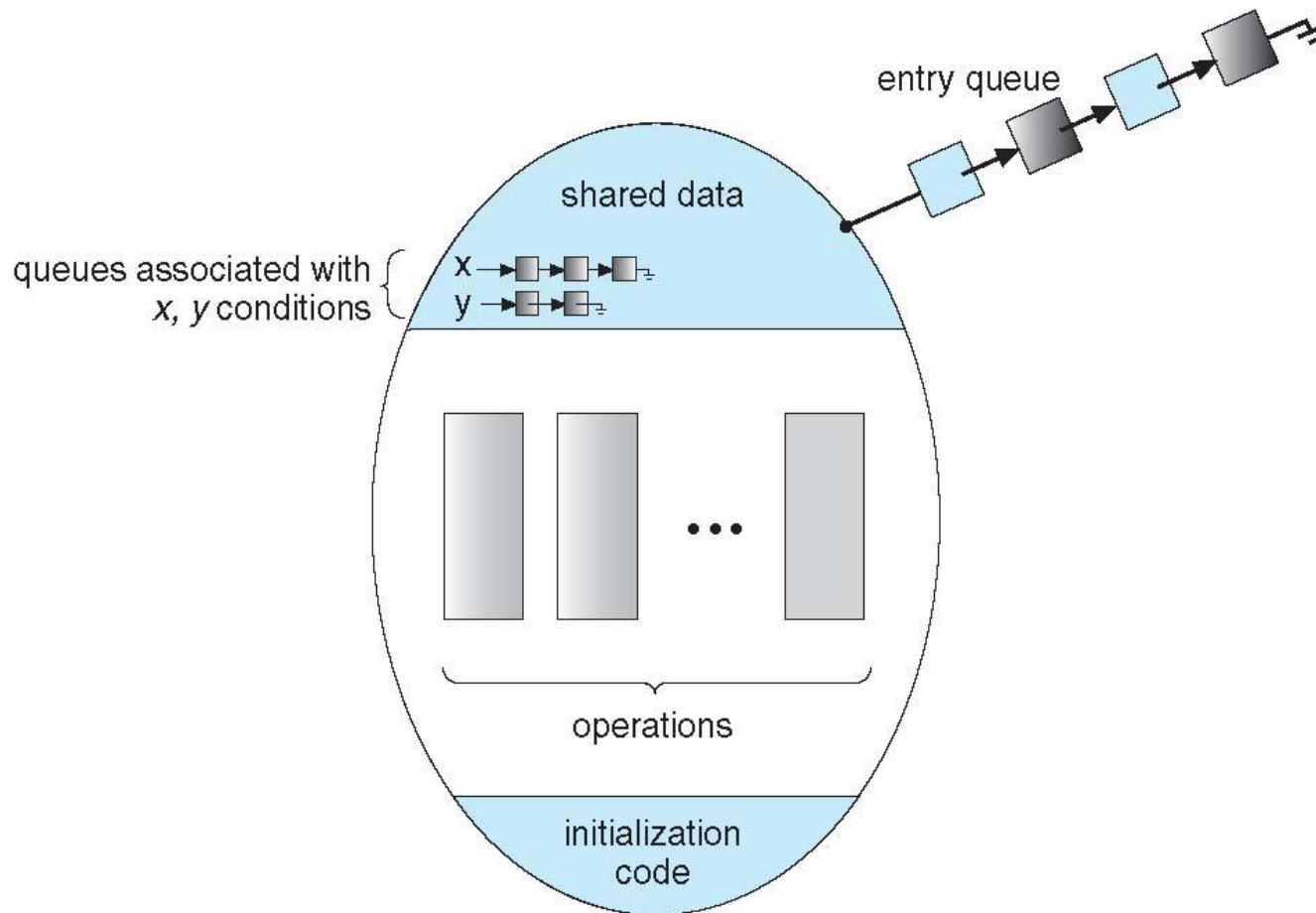
- **condition** **x**, **y**;
- Two operations are allowed on a condition variable:
 - **x.wait()** – a process that invokes the operation is suspended until **x.signal()**
 - **x.signal()** – resumes one of processes (if any) that invoked **x.wait()**
 - If no **x.wait()** on the condition variable, then it has no effect on the variable. *Signal is lost.*

Compare with semaphore.
Here no integer value is associated.

Difference between the signal() in semaphores and monitors

- Condition variables in Monitors: Not persistent
 - If a signal is performed and no waiting threads?
 - Signal is simply ignored
 - During subsequent wait operations
 - Thread (or process) blocks
- Compare with semaphores
 - Signal increments semaphore value even if there are no waiting threads
 - Future wait operations would immediately succeed!

Monitor **with** Condition Variables



Condition Variables Choices

- If process P invokes `x.signal()`, and process Q is suspended in `x.wait()`, what should happen next?
 - Both Q and P cannot execute in parallel. If Q is resumed, then P must wait
- Options include
 - **Signal and wait** – P waits until Q either leaves the monitor or it waits for another condition
 - **Signal and continue** – Q waits until P either leaves the monitor or it waits for another condition
 - Both have pros and cons – language implementer can decide
 - Monitors implemented in [Concurrent Pascal \('75\)](#) compromise
 - P executing signal immediately leaves the monitor, Q is resumed
 - Implemented in other languages including C#, Java

Monitor Solution to Dining Philosophers: Deadlock-free

```
enum {THINKING, HUNGRY, EATING} state[5];
```

- `state[i] = EATING` only if
 - `state[(i+4)%5] != EATING && state[(i+1)%5] != EATING`
- `condition self[5]`
 - Delay self when **HUNGRY but unable** to get chopsticks

Sequence of actions

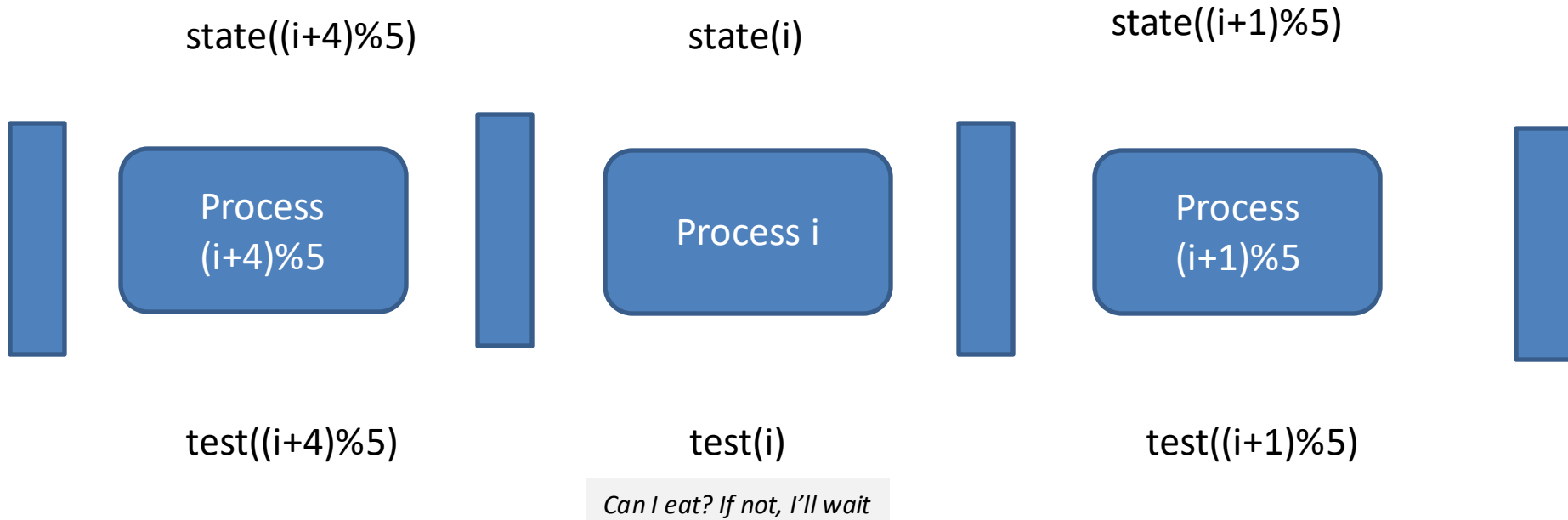
- Before eating, must invoke `pickup()`
 - May result in suspension of philosopher process
 - After completion of operation, philosopher may eat

```
think  
DiningPhilosophers.pickup(i);  
eat  
DiningPhilosophers.putdown(i);  
think
```



Monitor Solution to Dining Philosophers: Deadlock-free

```
enum {THINKING, HUNGRY, EATING} state[5];
```



The pickup() and putdown() operations

monitor DiningPhilosophers

```
{
  enum { THINKING, HUNGRY, EATING} state [5] ;
  condition self [5];

  void pickup (int i) {
    state[i] = HUNGRY;
    test(i);    //below
    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);
  }
}
```

Suspend self if
unable to acquire
chopstick

Eat only if HUNGRY
and Person on Left
AND Right
are not eating

Check to see if person
on left or right can use
the chopstick

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

Signal a process that
was suspended while
trying to eat

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

Possibility of starvation

- Philosopher i can starve if eating periods of philosophers on left and right overlap
- Possible solution
 - Introduce new state: STARVING
 - Chopsticks can be picked up if no neighbor is starving
 - Effectively wait for neighbor's neighbor to stop eating
 - REDUCES concurrency!

Monitor Implementation of Mutual Exclusion

For each monitor

- Semaphore mutex initialized to 1
- Process must execute
 - wait(mutex) : Before entering the monitor
 - signal(mutex): Before leaving the monitor

Resuming Processes within a Monitor

- If several processes queued on condition x , and $x.\text{signal}()$ is executed, which should be resumed?
- FCFS frequently not adequate
- **conditional-wait** construct of the form $x.\text{wait}(c)$
 - Where c is **priority number**
 - Process with lowest number (highest priority) is scheduled next

Single Resource allocation

- Allocate a single resource among competing processes using priority numbers that specify the maximum time a process plans to use the resource

```
R.acquire(t);  
    ...  
access the resource;  
    ...  
R.release;
```

- Where R is an instance of type **ResourceAllocator**
- **A monitor based solution next.**

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
```

```
{
```

```
    boolean busy;
```

```
    condition x;
```

```
    void acquire(int time) {
```

```
        if (busy)
```

```
            x.wait(time);
```

```
        busy = TRUE;
```

```
    }
```

```
    void release() {
```

```
        busy = FALSE;
```

```
        x.signal();
```

```
    }
```

```
    initialization code() {
```

```
        busy = FALSE;
```

```
    }
```

```
}
```

Sleep, Time used
to prioritize
waiting
processes

Wakes up
one of the
processes

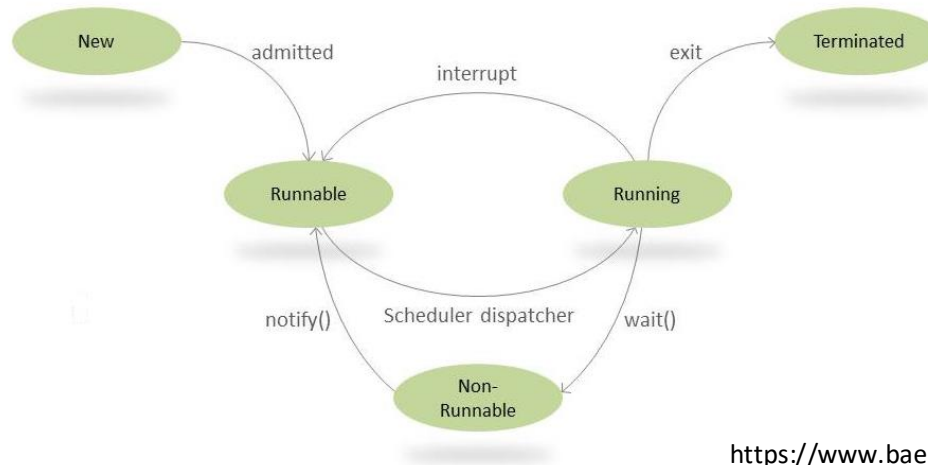
Java Synchronization

- For simple synchronization, Java provides the `synchronized` keyword
 - synchronizing methods

```
public synchronized void increment( ) { c++; }
```
 - synchronizing blocks

```
synchronized(this) {  
    lastName = name;  
    nameCount++;  
}
```
- `wait()` and `notify()` allows a thread to wait for an event. A call to `notifyAll()` allows all threads that are on `wait()` with the same lock to be notified.
- `notify()` notifies one thread from a pool of identical threads, `notifyAll()` when threads have different purposes
- For more sophisticated locking mechanisms, starting from Java 5, the package `java.concurrent.locks` provides additional capabilities.

Java Synchronization



Each object automatically has a monitor (mutex) associated with it

- When a method is synchronized, the runtime must obtain the lock on the object's monitor before execution of that method begins (and must release the lock before control returns to the calling code)

`wait()` and `notify()` allows a thread to wait for an event.

- `wait()`: Causes the current thread to wait until another thread invokes the `notify()` method or the `notifyAll()` method for this object.
- `notify()`: Wakes up a single thread that is waiting on this object's monitor. If any threads are waiting on this object, one of them is chosen to be awakened.
- A call to `notifyall()` allows all threads that are on `wait()` with the same lock to be released, they will run in sequence according to priority.

Java Synchronization: Dining Philosophers

```
public synchronized void pickup(int i)
    throws InterruptedException {
    setState(i, State.HUNGRY);
    test(i);
    while (state[i] != State.EATING) {
        this.wait();
        // Recheck condition in loop,
        // since we might have been notified
        // when we were still hungry
    }
}
```

```
public synchronized void putdown(int i) {
    setState(i, State.THINKING);
    test(right(i));
    test(left(i));
}
```

```
private synchronized void test(int i) {
    if (state[left(i)] != State.EATING &&
        state[right(i)] != State.EATING &&
        state[i] == State.HUNGRY)
    {
        setState(i, State.EATING);
        // Wake up all waiting threads
        this.notifyAll();
    }
}
```

Synchronization Examples

- Solaris
- Windows
- Linux
- Pthreads

Solaris Synchronization

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing
- Uses **adaptive mutexes** for efficiency when protecting data from short code segments
 - Starts as a standard semaphore spin-lock
 - If lock held, and by a thread running on another CPU, spins
 - If lock 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

Windows 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 which may act mutexes, semaphores, events, and timers
 - **Events**
 - An event acts much like a condition variable
 - Timers notify one or more thread when time expired
 - Dispatcher objects either **signaled-state** (object available) or **non-signaled state** (thread will block)

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
 - atomic operations on integers
 - 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 variable
- Non-portable extensions include:
 - read-write locks
 - spinlocks

Alternative Approaches

- Transactional Memory
- OpenMP
- Functional Programming Languages

Transactional Memory

- A **memory transaction** is a sequence of read-write operations to memory that are performed atomically without the use of locks.

```
void update() {  
    atomic{  
        /* modify shared data*/  
    }  
}
```

May be implemented by hardware or software.

OpenMP

- OpenMP is a set of compiler directives and API that support parallel programming.

```
void update(int value)
{
    #pragma omp critical
    {
        count += value
    }
}
```

The code contained within the `#pragma omp critical` directive is treated as a critical section and performed atomically.

CS370 Operating Systems

Colorado State University

Yashwant K Malaiya

Spring 2020



Deadlock

Slides based on

- Text by Silberschatz, Galvin, Gagne
- Various sources

Chapter 8: Deadlocks

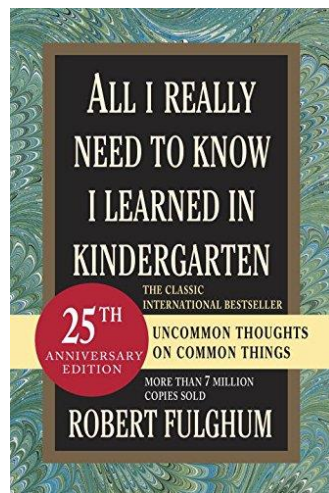
- System Model
- Deadlock Characterization
- Methods for Handling Deadlocks
 - Deadlock Prevention
 - Deadlock Avoidance resource-allocation
 - Deadlock Detection
 - Recovery from Deadlock

Deadlock

- Can you give a real life example of a deadlock?

A Kansas Law

- Early 20th century Kansas Law
 - “When *two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone*”
- [Story of the two silly goats](#): Aesop 6th cent BCE?



A contemporary example

