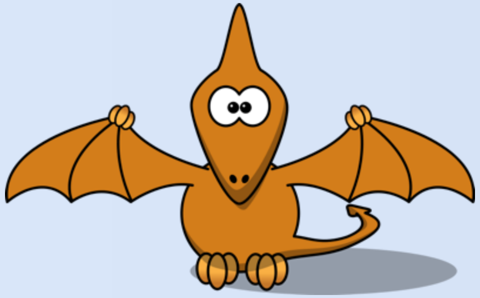
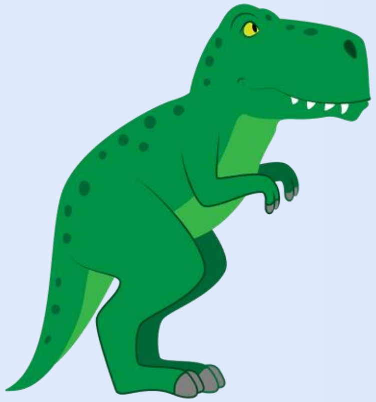


Chapter 7.

Synchronization Examples



Operating System Concepts (10th Ed.)

7.1 Classic Problems of Synchronization

- Examples of a large class of *Concurrency-Control* Problems:
  - The ***Bounded-Buffer*** Problem
    - The Producer-Consumer Problem
  - The ***Readers-Writers*** Problem
  - The ***Dining-Philosophers*** Problem

7.1 Classic Problems of Synchronization

- The Bounded-Buffer Problem:
  - Recall the Producer-Consumer Problem
    - with a pool consisting of *n* buffers, each capable of *holding one* item.
  - The producer *produces full buffers* for the consumer
    - The consumer *produces empty buffers* for the producer.

7.1 Classic Problems of Synchronization

- Shared Data Structures:
  - A *binary semaphore* **mutex**
    - provides *mutual exclusion* for accesses to the buffer pool
    - and is *initialized* to the value 1.
  - Two *counting semaphores* **empty** and **full**
    - are used to *count* the number of *empty* and *full* buffers.
    - empty is initialized to the value n, full is to the value 0.

```
int n;
semaphore mutex = 1;
semaphore empty = n;
semaphore full = 0
```

7.1 Classic Problems of Synchronization

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

Figure 7.1 *The structure of the producer process.*

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

Figure 7.2 *The structure of the consumer process.*

- The Readers-Writers Problem:
  - What if the *processes* running *concurrently*
    - are either the ***readers*** or the ***writers*** to the *shared* data?
    - e.g., a *database* shared among several concurrent processes.
  - The readers may want *only to read* the database,
    - whereas the writers to *update* (that is, *read and write*) the database.
  - Note that, obviously, *no adverse effects* will result,
    - if *two or more readers* access the shared data simultaneously.
  - However, *chaos* may ensue,
    - if a *writer* and some other process (either a *reader* or a *writer*)
    - access the database simultaneously.

7.1 Classic Problems of Synchronization

- Some Variations of the Readers-Writers Problem:
  - ***Priorities*** are involved with all the variations.
  - The ***first*** readers-writers problem:
    - *No reader* should *wait* for other readers to finish
    - simply because a *writer* is *waiting*.
  - The ***second*** readers-writers problem:
    - If a *writer* is waiting to access the object,
    - *no new readers* may start *reading*.
  - Note that *starvation* may occur in these two cases.

7.1 Classic Problems of Synchronization

- Solution to the ***first*** readers-writers problem:
  - The reader processes share the following data structures:

```
semaphore rw_mutex = 1;
semaphore mutex = 1;
int read_count = 0;
```

  - **rw_mutex** is *common* to both readers and writers.
  - **mutex** is used to ensure *mutual exclusion*
    - when the variable **read_count** is updated.
  - **read_count** keeps track of
    - how many processes are currently reading the object.

7.1 Classic Problems of Synchronization

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

Figure 7.3 *The structure of a writer process.*

```
while (true) {
   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);
}
```

Figure 7.4 *The structure of a reader process.*

- Solution to the Readers-Writers Problem:
  - Note that, if *a writer* is in the *critical section*, and n readers are waiting,
    - then *one reader* is queued on **rw_mutex**,
    - and $n - 1$ *readers* are queued on **mutex**.
  - Also observe that, when a writer executes **`signal(rw_mutex)`**,
    - we may resume the execution of
    - either the *waiting readers* or *a single waiting writer*.
    - The selection is made by the *scheduler*.

7.1 Classic Problems of Synchronization

- The Reader-Writer Locks
  - The readers-writers problem and its solutions
    - have been *generalized* to provide *reader-writer locks*.
  - Acquiring a reader-writer lock
    - requires specifying the mode of the lock: either *read* or *write*.
  - Note that
    - *multiple processes* may acquire *a reader-writer lock* in read mode,
    - but *only one process* may acquire the *lock for writing*,
    - as exclusive access is required for writers.

▪ PThread solution to the Bounded-Buffer Problem:

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <pthread.h>
#include <semaphore.h>

#define true 1
#define BUFFER_SIZE 5

int buffer[BUFFER_SIZE];

pthread_mutex_t mutex;
sem_t empty, full;

int in = 0, out = 0;
```

```
int main(int argc, char *argv[]) {
    int i, numOfProducers = 1, numOfConsumers = 1;
    pthread_t tid;

    pthread_mutex_init(&mutex, NULL);
    sem_init(&empty, 0, BUFFER_SIZE);
    sem_init(&full, 0, 0);
    srand(time(0));
    // Create the producers
    for (i = 0; i < numOfProducers; i++)
        pthread_create(&tid, NULL, producer, NULL);
    // Create the consumers
    for (i = 0; i < numOfConsumers; i++)
        pthread_create(&tid, NULL, consumer, NULL);

    sleep(10);
    return 0;
}
```

7.1 Classic Problems of Synchronization

```
void *producer(void *param) {
    int item;
    while (true) {
        usleep((1 + rand() % 5) * 100000);
        item = 1000 + rand() % 1000;
        insert_item(item); // critical section
    }
}
```

```
void *consumer(void *param) {
    int item;
    while (true) {
        usleep((1 + rand() % 5) * 100000);
        remove_item(&item); // critical section
    }
}
```

```c
void insert_item(int item) {
    sem_wait(&empty);
    pthread_mutex_lock(&mutex);

    buffer[in] = item;
    in = (in + 1) % BUFFER_SIZE;
    printf("Producer: inserted $%d\n", item);

    pthread_mutex_unlock(&mutex);
    sem_post(&full);
}
```

```c
void remove_item(int *item) {
    sem_wait(&full);
    pthread_mutex_lock(&mutex);

    *item = buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    printf("Consumer: removed $%d\n", *item);

    pthread_mutex_unlock(&mutex);
    sem_post(&empty);
}
```

7.1 Classic Problems of Synchronization

- Java solution to the Bounded-Buffer Problem:

```
public class BoundedBuffer {

    public static void main(String[] args) {
        CashBox cashBox = new CashBox(1);
        Thread[] producers = new Thread[1];
        Thread[] consumers = new Thread[1];
        // Create threads of producers
        for (int i = 0; i < producers.length; i++) {
            producers[i] = new Thread(new ProdRunner(cashBox));
            producers[i].start();
        }
        // Create threads of consumers
        for (int i = 0; i < consumers.length; i++) {
            consumers[i] = new Thread(new ConsRunner(cashBox));
            consumers[i].start();
        }
    }
}
```

```
class ProdRunner implements Runnable {
    CashBox cashBox;
    public ProdRunner(CashBox cashBox) {
        this.cashBox = cashBox;
    }
    @Override
    public void run() {
        try {
            while (true) {
                Thread.sleep((long)(Math.random()*500));
                int money = ((int)(1 + Math.random()*9))*10000;
                cashBox.give(money);
            }
        } catch (InterruptedException e) {}
    }
}
```

7.1 Classic Problems of Synchronization

```java
class ConsRunner implements Runnable {
    CashBox cashBox;
    public ConsRunner(CashBox cashBox) {
        this.cashBox = cashBox;
    }
    @Override
    public void run() {
        try {
            while (true) {
                Thread.sleep((long)(Math.random()*500));
                int money = cashBox.take();
            }
        } catch (InterruptedException e) {}
    }
}
```

7.1 Classic Problems of Synchronization

```
class CashBox {

    private int[] buffer;

    private int count, in, out;

    public CashBox(int bufferSize) {
        buffer = new int[bufferSize];
        count = in = out = 0;
    }

    synchronized public void give(int money) throws InterruptedException {
        // critical section
    }

    synchronized public int take() throws InterruptedException {
        // critical section
    }
}
```

```java
synchronized public void give(int money) {
    while (count == buffer.length) {
        try {
            wait();
        }
        catch (InterruptedException e) {}
    }

    buffer[in] = money;
    in = (in + 1) % buffer.length;
    count++;
    System.out.printf("여기있다, 용돈: %d원\n", money);

    notify();
}
```

7.1 Classic Problems of Synchronization

```
    synchronized public int take() throws InterruptedException {
        while (count == 0) {
            try {
                wait();
            }
            catch (InterruptedException e) {}
        }

        int money = buffer[out];
        out = (out + 1) % buffer.length;
        count--;
        System.out.printf("고마워유, 용돈: %d원\n", money);

        notify();
        return money;
    }
}
```

- Java solution to the first Readers-Writers Problem:

```
class SharedDB {

    private int readerCount = 0;
    private boolean isWriting = false;

    public void read() {
        // read from the database here.
    }

    public void write() {
        // write into the database here.
    }

    // ……
}
```

```
sharedDB.acquireReadLock();
sharedDB.read();
sharedDB.releaseReadLock();
```

```
sharedDB.acquireWriteLock();
sharedDB.write();
sharedDB.releaseWriteLock();
```

```
synchronized public void acquireReadLock() {
    while (isWriting == true) {
        try {
            wait();
        } catch (InterruptedException e) {}
    }
    readerCount++;
}

synchronized public void releaseReadLock() {
    readerCount--;
    if (readerCount == 0)
        notify();
}
```

```
synchronized public void acquireWriteLock() {
    while (readerCount > 0 || isWriting == true) {
        try {
            wait();
        } catch (InterruptedException e) {}
    }
    isWriting = true;
}

synchronized public void releaseWriteLock() {
    isWriting = true;
    notifyAll();
}
```

- The Dining-Philosophers Problem:
    - Consider ***five*** *philosophers* who spend their lives *thinking* and *eating*.
        - sharing ***five*** *single chopsticks*.
    - Sometimes, a philosopher gets hungry
        - and tries to pick up ***two chopsticks*** that are closest to her.
    - When a hungry philosopher has *both her chopsticks* at the same time,
        - she eats *without releasing* the chopsticks.

7.1 Classic Problems of Synchronization

- The Dining-Philosophers Problem:
  - need to allocate *several resources* among *several processes*
    - in a ***deadlock-free*** and ***starvation-free*** manner.

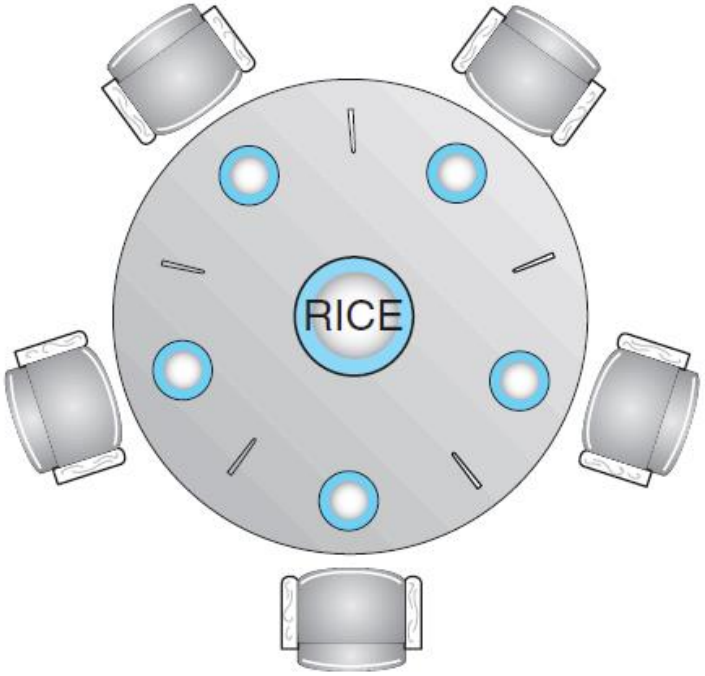


Figure 7.5 *The situation of the dining philosophers.*

Semaphore Solution:

- One simple solution is to represent each chopstick with a semaphore.
  - A philosopher *acquires* a chopstick by executing a *wait*() operation.
  - She *releases* her chopsticks by executing a *signal*() operation.

```
semaphore chopstick[5];
```

```
while (true) {
   wait(chopstick[i]);
   wait(chopstick[(i+1) % 5]);
      . . .
   /* eat for a while */
      . . .
   signal(chopstick[i]);
   signal(chopstick[(i+1) % 5]);
      . . .
   /* think for awhile */
      . . .
}
```

Figure 7.6 *The structure of philosopher i.*

7.1 Classic Problems of Synchronization

- The problem of *deadlock* and *starvation*:
  - Simple semaphore solution guarantees *mutual exclusion*.
  - However, how about deadlock or starvation?
    - Suppose that all five philosophers become hungry at the same time
    - and each grabs her left chopstick, trying to grab her right chopstick.
    - Here comes a deadlock situation.

7.1 Classic Problems of Synchronization

- Possible *remedies* to the deadlock problem:
  - Allow *at most four philosophers* to be sitting simultaneously at the table.
  - Allow a philosopher to pick up her chopsticks
    - only if *both chopsticks* are available.
  - Use an *asymmetric* solution:
    - an *odd-numbered* philosopher picks up first her *left chopstick* and then her *right chopstick*,
    - whereas an *even-numbered* philosopher picks up her *right chopstick* and the her *left chopstick*.
  - Note that a deadlock-free solution
    - does not necessarily eliminate the possibility of ***starvation***.

7.1 Classic Problems of Synchronization

- Monitor Solution:
  - Let a philosopher to pick up her chopsticks
    - only if *both* of them are *available*.
  - We need to distinguish among *three states* of the philosophers:
    - *thinking*, *hungry*, and *eating*.
  - A philosopher can *set* her state to be *eating*,
    - only if her *two neighbors* are *not in* the state of *eating*.
  - We also need a *condition variable* which
    - allows a philosopher to *delay* herself when she is *hungry*
    - but is *unable to obtain* the chopsticks she needs.

- Solution to the Dining-Philosophers Problem:
  - The distribution of the chopsticks
    - is controlled by the monitor, ***DiningPhilosopher***.
  - Each philosopher must to invoke the operation *pickup*(),
    - before starting to eat, suspending the philosopher process.
  - After the successful completion of pickup(),
    - the philosopher may eat, and invokes the operation *putdown*().

  - Note that
    - *mutual exclusion* is guaranteed and *no deadlocks* will occur,
    - however, *starvation* is still *possible*.

7.1 Classic Problems of Synchronization

```
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((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;
   }
}
```

Figure 7.7 *A monitor solution to the dining-philosopher problem.*

- Pthread solution to the Dining-Philosophers Problem:

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <pthread.h>

#define true 1
#define NUM_PHILS 5

enum {THINKING, HUNGRY, EATING} state[NUM_PHILS];

pthread_mutex_t mutex_lock;
pthread_cond_t cond_vars[NUM_PHILS];
```

```c
int main() {
    int i;
    pthread_t tid;
    init();
    for (i = 0; i < NUM_PHILS; i++)
        pthread_create(&tid, NULL, philosopher, (void *)&i);
    for (i = 0; i < NUM_PHILS; i++)
        pthread_join(tid, NULL);
    return 0;
}
```

7.1 Classic Problems of Synchronization

```
void init() {
    int i;
    for (i = 0; i < NUM_PHILS; i++) {
        state[i] = THINKING;
        pthread_cond_init(&cond_vars[i], NULL);
    }
    pthread_mutex_init(&mutex_lock, NULL);
    srand(time(0));
}
```

```
int leftOf(int i) {
    return (i + NUM_PHILS - 1) % NUM_PHILS;
}

int rightOf(int i) {
    return (i + 1) % NUM_PHILS;
}
```

7.1 Classic Problems of Synchronization

```c
void *philosopher(void *param) {
    int id = *((int *)param);
    while (true) {
        think(id);
        pickup(id);
        eat(id);
        putdown(id);
    }
}
```

```c
void think(int id) {
    printf("%d: Now, I'm thiking...\n", id);
    usleep((1 + rand() % 50) * 10000);
}

void eat(int id) {
    printf("%d: Now, I'm eating...\n", id);
    usleep((1 + rand() % 50) * 10000);
}
```

```c
void test(int i) {
    // If I'm hungry and my neighbors are not eating,
    // then let me eat.
    if (state[i] == HUNGRY &&
        state[leftOf(i)] != EATING && state[rightOf(i)] != EATING)
    {
        state[i] = EATING;
        pthread_cond_signal(&cond_vars[i]);
    }
}
```

```
void pickup(int i) {
    pthread_mutex_lock(&mutex_lock);

    state[i] = HUNGRY;
    test(i);
    while (state[i] != EATING) {
        pthread_cond_wait(&cond_vars[i], &mutex_lock);
    }

    pthread_mutex_unlock(&mutex_lock);
}
```

```
void putdown(int i) {
    pthread_mutex_lock(&mutex_lock);

    state[i] = THINKING;
    test(leftOf(i));
    test(rightOf(i));

    pthread_mutex_unlock(&mutex_lock);
}
```

- Java solution to the Dining-Philosophers Problem:

```
import java.util.concurrent.locks.Condition;
import java.util.concurrent.locks.Lock;
import java.util.concurrent.locks.ReentrantLock;

enum State {
    THINKING, HUNGRY, EATING
}

public class DiningPhilosophers {

    public static void main(String[] args) throws Exception {
        int numOfPhils = 5;
        Philosopher[] philosophers = new Philosopher[numOfPhils];
        DiningPhilosopherMonitor monitor = new DiningPhilosopherMonitor(numOfPhils);
        for (int i = 0; i < philosophers.length; i++)
            new Thread(new Philosopher(i, monitor)).start();
    }
}
```

7.1 Classic Problems of Synchronization

```java
class Philosopher implements Runnable {

    private int id;
    private DiningPhilosopherMonitor monitor;

    public Philosopher(int id, DiningPhilosopherMonitor monitor) {
        this.id = id;
        this.monitor = monitor;
    }


    @Override
    public void run() {
        while (true) {
            think();
            monitor.pickup(id);
            eat();
            monitor.putdown(id);
        }
    }
```

```
    private void think() {
        try {
            System.out.println(id + ": Now I'm thinking.");
            Thread.sleep((long)(Math.random()*500));
        } catch (InterruptedException e) { }
    }

    private void eat() {
        try {
            System.out.println(id + ": Now I'm eating.");
            Thread.sleep((long)(Math.random()*50));
        } catch (InterruptedException e) { }
    }
}
```

7.1 Classic Problems of Synchronization

```
class DiningPhilosopherMonitor {

    private int numOfPhils;
    private State[] state;
    private Condition[] self;
    private Lock lock;

    public DiningPhilosopherMonitor(int num) {
        numOfPhils = num;
        state = new State[num];
        self = new Condition[num];
        lock = new ReentrantLock();
        for (int i = 0; i < num; i++) {
            state[i] = State.THINKING;
            self[i] = lock.newCondition();
        }
    }

    //......
}
```

```
private int leftOf(int i) {
    return (i + numOfPhils - 1) % numOfPhils;
}

private int rightOf(int i) {
    return (i + 1) % numOfPhils;
}

private void test(int i) {
    if (state[i] == State.HUNGRY &&
            state[leftOf(i)] != State.EATING &&
            state[rightOf(i)] != State.EATING)
    {
        state[i] = State.EATING;
        self[i].signal();
    }
}
```

7.1 Classic Problems of Synchronization

```
public void pickup(int id) {
    lock.lock();
    try {
        state[id] = State.HUNGRY;
        test(id);
        if (state[id] != State.EATING)
            self[id].await();
    }
    catch (InterruptedException e) {
    }
    finally {
        lock.unlock();
    }
}
```

```
public void putdown(int id) {
    lock.lock();
    try {
        state[id] = State.THINKING;
        test(leftOf(id)); // left neighbor
        test(rightOf(id)); // right neighbor
    }
    finally {
        lock.unlock();
    }
}
```

7.5 Alternative Approaches

- Thread-Safe Concurrent Applications:
  - *Concurrent applications* have good performance on multicore systems,
    - using techniques such as *mutex locks*, *semaphores*, and *monitors*.
  - However, they present an increased risk of
    - ***race conditions*** and ***liveness hazards*** such as *deadlock*.
  - There are alternative approaches
    - for the design of ***thread-safe** concurrent* applications.

1. **Transactional Memory**:
2. **OpenMP**
3. **Functional Programming Language**

Any Questions?