Concurrency: Threads, Processes, Race Conditions, Mutual Exclusion

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Programming Language Concepts

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Concurrent programming

- Multiprocessing
  - Single processor executes several computations "in parallel"
  - Time-slicing to share access

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- Logically parallel actions within a single application
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  - User-interface is running in parallel with network access

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  - Communicate via "shared memory"
  - Context switches are easier

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  - Time-slicing involves saving the state of one process and loading the suspended state of another
- Threads
  - Operated on same local variables
  - Communicate via "shared memory"
  - Context switches are easier
- Henceforth, we use process and thread interchangeably

Shared variables

- Browser example: download thread and user-interface thread run in parallel
  - Shared boolean variable `terminate` indicates whether download should be interrupted
  - `terminate` is initially false
  - Clicking `Stop` sets it to true
  - Download thread checks the value of this variable periodically and aborts if it is set to true

Shared variables

- Browser example: download thread and user-interface thread run in parallel
  - Shared boolean variable `terminate` indicates whether download should be interrupted
  - `terminate` is initially false
  - Clicking `Stop` sets it to true
  - Download thread checks the value of this variable periodically and aborts if it is set to true
- Watch out for race conditions
  - Shared variables must be updated consistently

Creating threads in Java

- Have a class extend `Thread`

```
public class Parallel extends Thread{
  private int id;

  public Parallel(int i){ id = i; }
}
```

Creating threads in Java

- Have a class extend `Thread`
- Define a function `run()` where execution can begin in parallel

```
public class Parallel extends Thread{
  private int id;
  public Parallel(int i){ id = i; }
  public void run(){
    for (int j = 0; j < 100; j++){
      System.out.println("My id is "+id);
      try{
        sleep(1000);        // Sleep for 1000 ms
      }
      catch(InterruptedException e){}
    }
  }
}
```

Creating threads in Java

- Have a class extend `Thread`
- Define a function `run()` where execution can begin in parallel
- Invoking `p[i].start()` initiates `p[i].run()` in a separate thread

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  }
}

public class TestParallel {
  public static void main(String[] args){
    Parallel p[] = new Parallel[5];
    for (int i = 0; i < 5; i++){
      p[i] = new Parallel(i);
      p[i].start();   // Start p[i].run()
    }                 // in concurrent thread
  }
}
```

Creating threads in Java

- Have a class extend Thread
- Define a function run() where execution can begin in parallel
- Invoking p[i].start() initiates p[i].run() in a separate thread
  - Directly calling p[i].run() does not execute in separate thread!

```
public class Parallel extends Thread{
  private int id;
  public Parallel(int i){ id = i; }
  public void run(){
    for (int j = 0; j < 100; j++){
      System.out.println("My id is "+id);
      try{
        sleep(1000);        // Sleep for 1000 ms
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      catch(InterruptedException e){}
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- Invoking `p[i].start()` initiates `p[i].run()` in a separate thread
  - Directly calling `p[i].run()` does not execute in separate thread!
- `sleep(t)` suspends thread for `t` milliseconds
  - Static function — use `Thread.sleep()` if current class does not extend `Thread`
  - Throws `InterruptedException` — later

```
public class Parallel extends Thread{
  private int id;
  public Parallel(int i){ id = i; }
  public void run(){
    for (int j = 0; j < 100; j++){
      System.out.println("My id is "+id);
      try{
        sleep(1000);        // Sleep for 1000 ms
      }
      catch(InterruptedException e){}
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  }
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}
```

Creating threads in Java

- Have a class extend `Thread`
- Define a function `run()` where execution can begin in parallel
- Invoking `p[i].start()` initiates `p[i].run()` in a separate thread
  - Directly calling `p[i].run()` does not execute in separate thread!
- `sleep(t)` suspends thread for `t` milliseconds
  - Static function — use `Thread.sleep()` if current class does not extend `Thread`
  - Throws `InterruptedException` — later

Typical output

```
My id is 0
My id is 3
My id is 2
My id is 1
My id is 4
My id is 0
My id is 2
My id is 3
My id is 4
My id is 1
My id is 0
My id is 3
My id is 1
My id is 2
My id is 4
My id is 0
...
```

Java threads ...

- Cannot always extend `Thread`
  - Single inheritance

Java threads . . .

- Cannot always extend Thread
  - Single inheritance
- Instead, implement Runnable

```
public class Parallel implements Runnable{
  // only the line above has changed
  private int id;
  public Parallel(int i){ ... } // Constructor
  public void run(){ ... }

}
```

Java threads . . .

- Cannot always extend `Thread`
  - Single inheritance
- Instead, implement `Runnable`
- To use `Runnable` class, explicitly create a `Thread` and `start()` it

```
public class Parallel implements Runnable{
  // only the line above has changed
  private int id;
  public Parallel(int i){ ... } // Constructor
  public void run(){ ... }

}

public class TestParallel {
  public static void main(String[] args){
    Parallel p[] = new Parallel[5];
    Thread t[]   = new Thread[5];

    for (int i = 0; i < 5; i++){
       p[i] = new Parallel(i);
       t[i] = new Thread(p[i]);
             // Make a thread t[i] from p[i]
       t[i].start();   // Start off p[i].run()
                       // Note: t[i].start(),
    }                  //   not p[i].start()
  }
}
```

Runnable

Maintaining data consistency

- `double accounts[100]` describes 100 bank accounts

Maintaining data consistency

- `double accounts[100]` describes 100 bank accounts
- Two functions that operate on `accounts`: `transfer()` and `audit()`

```
boolean transfer (double amount,
                  int source,
                  int target){
  if (accounts[source] < amount){
    return false;
  }
  accounts[source] -= amount;
  accounts[target] += amount;
  return true;
}

double audit(){
  // total balance across all accounts
  double balance = 0.00;
  for (int i = 0; i < 100; i++){
    balance += accounts[i];
  }
  return balance;
}
```

Maintaining data consistency

- `double accounts[100]` describes 100 bank accounts
- Two functions that operate on `accounts`: `transfer()` and `audit()`
- What are the possibilities when we execute the following?

Thread 1	Thread 2
`...`	`...`
`status =`	`System.out.`
`  transfer(500.00,7,8);`	` print(audit());`
`...`	`...`

```
boolean transfer (double amount,
                  int source,
                  int target){
  if (accounts[source] < amount){
    return false;
  }
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Maintaining data consistency ...

- What are the possibilities when we execute the following?

```
Thread 1                    Thread 2
...                         ...
status =                    System.out.
  transfer(500.00,7,8);      print(audit());
...                         ...
```

- audit() can report an overall total that is 500 more or less than the actual assets

```
boolean transfer (double amount,
                  int source,
                  int target){
  if (accounts[source] < amount){
    return false;
  }
  accounts[source] -= amount;   ← debit
  accounts[target] += amount;   ← credit
  return true;
}

double audit(){
  // total balance across all accounts
  double balance = 0.00;
  for (int i = 0; i < 100; i++){
    balance += accounts[i];
  }
  return balance;
}
```

Maintaining data consistency . . .

- What are the possibilities when we execute the following?

```
Thread 1                  Thread 2
...                       ...
status =                  System.out.
  transfer(500.00,7,8);    print(audit());
...                       ...
```

- `audit()` can report an overall total that is 500 more or less than the actual assets
  - Depends on how actions of `transfer` are interleaved with actions of `audit`

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Maintaining data consistency . . .

- What are the possibilities when we execute the following?

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Thread 1                    Thread 2
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status =                    System.out.
  transfer(500.00,7,8);      print(audit());
...                         ...
```

- audit() can report an overall total that is 500 more or less than the actual assets
  - Depends on how actions of transfer are interleaved with actions of audit
  - Can even report an error if transfer happens atomically

```
boolean transfer (double amount,
                  int source,
                  int target){
  if (accounts[source] < amount){
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  }
  accounts[source] -= amount;
  accounts[target] += amount;
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}

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    balance += accounts[i];
  }
  return balance;
}
```

Atomicity of updates

- Two threads increment a shared variable `n`

Thread 1	Thread 2
...	...
`m = n;`	`k = n;`
`m++;`	`k++;`
`n = m;`	`n = k;`
...	...

Atomicity of updates

- Two threads increment a shared variable `n`

```
Thread 1        Thread 2
...             ...
m = n;          k = n;
m++;            k++;
n = m;          n = k;
...             ...
```

- Expect `n` to increase by 2 . . .

Atomicity of updates

- Two threads increment a shared variable `n`

```
Thread 1            Thread 2
...                 ...
m = n;              k = n;
m++;                k++;
n = m;              n = k;
...                 ...
```

Wait

- Expect `n` to increase by 2 . . .
- . . . but, time-slicing may order execution as follows

```
Thread 1: m = n;
Thread 1: m++;
Thread 2: k = n;    // k gets the original value of n
Thread 2: k++;
Thread 1: n = m;
Thread 2: n = k;    // Same value as that set by Thread 1
```

Lost update

Race conditions and mutual exclusion

- Race condition — concurrent update of shared variables, unpredictable outcome
  - Executing `transfer()` and `audit()` concurrently can cause `audit()` to report more or less than the actual assets

```
boolean transfer (double amount,
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Race conditions and mutual exclusion

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- Avoid this by insisting that `transfer()` and `audit()` do not interleave

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  - Executing `transfer()` and `audit()` concurrently can cause `audit()` to report more or less than the actual assets
- Avoid this by insisting that `transfer()` and `audit()` do not interleave
- Never simultaneously have current control point of one thread within `transfer()` and another thread within `audit()`

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                  int source,
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  if (accounts[source] < amount){
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double audit(){
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    balance += accounts[i];
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- Race condition — concurrent update of shared variables, unpredictable outcome
  - Executing `transfer()` and `audit()` concurrently can cause `audit()` to report more or less than the actual assets
- Avoid this by insisting that `transfer()` and `audit()` do not interleave
- Never simultaneously have current control point of one thread within `transfer()` and another thread within `audit()`
- Mutually exclusive access to critical regions of code

```
boolean transfer (double amount,
                  int source,
                  int target){
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    return false;
  }
  accounts[source] -= amount;
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  return true;
}

double audit(){
  // total balance across all accounts
  double balance = 0.00;
  for (int i = 0; i < 100; i++){
    balance += accounts[i];
  }
  return balance;
}
```

Mutual exclusion for two processes

- First attempt

turn = 1 or 2

```
Thread 1

...
while (turn != 1){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 2;
...
```

```
Thread 2

...
while (turn != 2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 1;
...
```

Mutual exclusion for two processes

- First attempt

```
Thread 1
...
while (turn != 1){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 2;
...
```

```
Thread 2
...
while (turn != 2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 1;
...
```

- Shared variable `turn` — no assumption about initial value, atomic update

Mutual exclusion for two processes

- First attempt

Thread 1

```
...
while (turn != 1){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 2;
...
```

Thread 2

```
...
while (turn != 2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 1;
...
```

- Shared variable `turn` — no assumption about initial value, atomic update
- Mutually exclusive access is guaranteed ...

Mutual exclusion for two processes

- First attempt

```
Thread 1
...
while (turn != 1){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 2;
...
```

```
Thread 2
...
while (turn != 2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
turn = 1;
...
```

- Shared variable `turn` — no assumption about initial value, atomic update
- Mutually exclusive access is guaranteed . . .
- . . . but one thread is locked out permanently if other thread shuts down
  - Starvation!

Mutual exclusion for two processes . . .

- Second attempt

Thread 1

```
...
request_1 = true;
while (request_2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_1 = false;
...
```

Thread 2

```
...
request_2 = true;
while (request_1)
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_2 = false;
...
```

Mutual exclusion for two processes . . .

- Second attempt

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Thread 1
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// Leave critical section
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```

```
Thread 2
...
request_2 = true;
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}
// Enter critical section
   ...
// Leave critical section
request_2 = false;
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```

- Mutually exclusive access is guaranteed . . .

Mutual exclusion for two processes . . .

- Second attempt

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Thread 1
...
request_1 = true;
while (request_2){
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```

```
Thread 2
...
request_2 = true;
while (request_1)
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_2 = false;
...
```

- Mutually exclusive access is guaranteed . . .
- . . . but if both threads try simultaneously, they block each other
  - Deadlock!

Peterson's algorithm

```
Thread 1
...
request_1 = true;
turn = 2;
while (request_2 &&
       turn != 1){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_1 = false;
...
```

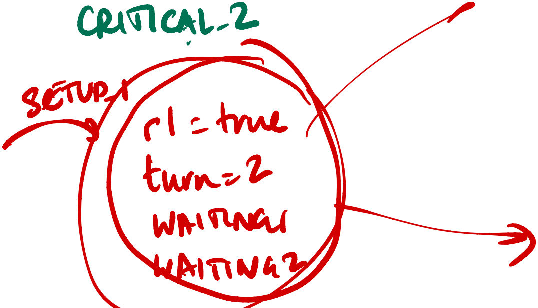
```
Thread 2
...
request_2 = true;
turn = 1;
while (request_1 &&
       turn != 2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_2 = false;
...
```

- Combines the previous two approaches

Proof?

Build a graph
"Control point" of each process
+ Values of r_0, r_1, turn

SETUP_1	SETUP_2
WAITING_1	WAITING_2
CRITICAL_1	CRITICAL_2



Prove that a state with
CRITICAL_1
CRITICAL_2
is not reachable

Peterson's algorithm

Thread 1

```
...
request_1 = true;
turn = 2;
while (request_2 &&
       turn != 1){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_1 = false;
...
```

Thread 2

```
...
request_2 = true;
turn = 1;
while (request_1 &&
       turn != 2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_2 = false;
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- Combines the previous two approaches
- If both try simultaneously, `turn` decides who goes through

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```

```
Thread 2
...
request_2 = true;
turn = 1;
while (request_1 &&
       turn != 2){
  // "Busy" wait
}
// Enter critical section
   ...
// Leave critical section
request_2 = false;
...
```

- Combines the previous two approaches
- If both try simultaneously, `turn` decides who goes through
- If only one is alive, `request` for that process is stuck at false and `turn` is irrelevant

Beyond two processes

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- For n process mutual exclusion other solutions exist
- Lamport's Bakery Algorithm
  - Each new process picks up a token (increments a counter) that is larger than all waiting processes
  - Lowest token number gets served next
  - Still need to break ties — token counter is not atomic

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  - Each new process picks up a token (increments a counter) that is larger than all waiting processes
  - Lowest token number gets served next
  - Still need to break ties — token counter is not atomic
- Need specific clever solutions for different situations
- Need to argue correctness in each case
- Instead, provide higher level support in programming language for synchronization

Summary

- We can construct protocols that guarantee mutual exclusion to critical sections
  - Watch out for starvation and deadlock
- These protocols cleverly use regular variables
  - No assumptions about initial values, atomicity of updates
- Difficult to generalize such protocols to arbitrary situations
- Look to programming language for features that control synchronization