Programming Language Support for Concurrency

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Programming Language Concepts

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Race conditions

- Concurrent update of a shared variable can lead to data inconsistenccy
  - Race condition
- Control behaviour of threads to regulate concurrent updates
  - Critical sections — sections of code where shared variables are updated
  - Mutual exclusion — at most one thread at a time can be in a critical section
- 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

Test and set

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- If more than one thread does this in parallel, updates may overlap and get lost
- Need to combine test and set into an atomic, indivisible step
- Cannot be guaranteed without adding this as a language primitive

Compare And Swap [CAS]

Semaphores

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  - Integer variable with atomic test-and-set operation

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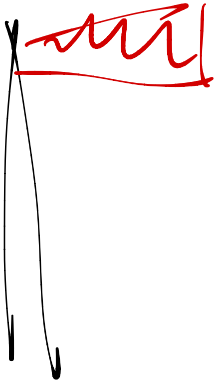
- A semaphore `S` supports two atomic operations
  - `P(s)` — from Dutch passeren, to pass
  - `V(s)` — from Dutch vrygeven, to release



Semaphores

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- Dijkstra's semaphores
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```
if (S > 0)
  decrement S;
else
  wait for S to become positive;
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if (S > 0)
  decrement S;
else
  wait for S to become positive;
```

- `V(S)` atomically executes the following

```
if (there are threads waiting
    for S to become positive)
  wake one of them up;
    //choice is nondeterministic
else
  increment S;
```

Using semaphores

- Mutual exclusion using semaphores

```
Thread 1
...
P(S);
// Enter critical section
   ...
// Leave critical section
V(S);
...
```

```
Thread 2
...
P(S);
// Enter critical section
   ...
// Leave critical section
V(S);
...
```

Using semaphores

- Mutual exclusion using semaphores

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Thread 1
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P(S);
// Enter critical section
   ...
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V(S);
...
```

```
Thread 2
...
P(S);
// Enter critical section
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```

- Semaphores guarantee
  - Mutual exclusion
  - Freedom from starvation
  - Freedom from deadlock

Problems with semaphores

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Problems with semaphores

- Too low level
- No clear relationship between a semaphore and the critical region that it protects
- All threads must cooperate to correctly reset semaphore
- Cannot enforce that each `P(S)` has a matching `V(S)`
- Can even execute `V(S)` without having done `P(S)`

Monitors

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- Monitors — Per Brinch Hansen and CAR Hoare
- Monitor is like a class in an OO language
  - Data definition — to which access is restricted across threads
  - Collections of functions operating on this data — all are implicitly mutually exclusive

```
monitor bank_account{
  double accounts[100];

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

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

Monitors

- Attach synchronization control to the data that is being protected
- Monitors — Per Brinch Hansen and CAR Hoare
- Monitor is like a class in an OO language
  - Data definition — to which access is restricted across threads
  - Collections of functions operating on this data — all are implicitly mutually exclusive
- Monitor guarantees mutual exclusion — if one function is active, any other function will have to wait for it to finish

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Monitors: external queue

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Monitors: external queue

- Monitor ensures `transfer` and `audit` are mutually exclusive
- If `Thread 1` is executing `transfer` and `Thread 2` invokes `audit`, it must wait
- Implicit queue associated with each monitor
  - Contains all processes waiting for access
  - In practice, this may be just a set, not a queue

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monitor bank_account{
  double accounts[100];

  boolean transfer (double amount,
                    int source,
                    int target){
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Making monitors more flexible

- Our definition of monitors may be too restrictive

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transfer(500.00,i,j);
transfer(400.00,j,k);
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- If these calls are reordered and `accounts[j] < 400` initially, this will fail

Making monitors more flexible

- Our definition of monitors may be too restrictive

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transfer(500.00,i,j);
transfer(400.00,j,k);
```

- This should always succeed if `accounts[i] > 500`
- If these calls are reordered and `accounts[j] < 400` initially, this will fail
- A possible fix — let an account wait for pending inflows

```
boolean transfer (double amount, int source, int target){
  if (accounts[source] < amount){
    // wait for another transaction to transfer money
    // into accounts[source]
  }
  accounts[source] -= amount;
  accounts[target] += amount;
  return true;
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Monitors — wait()

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- All other processes are blocked out while this process waits!

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- Need a mechanism for a thread to suspend itself and give up the monitor

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- Have a separate internal queue, as opposed to external queue where initially blocked threads wait

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- Need a mechanism for a thread to suspend itself and give up the monitor
- A suspended process is waiting for monitor to change its state
- Have a separate internal queue, as opposed to external queue where initially blocked threads wait
- Dual operation to notify and wake up suspended processes

Monitors — notify()

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

Monitors — notify()

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- Signal and exit — notifying process immediately exits the monitor
  - `notify()` must be the last instruction

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  - `notify()` must be the last instruction
- Signal and wait — notifying process swaps roles and goes into the internal queue of the monitor
- Signal and continue — notifying process keeps control till it completes and then one of the notified processes steps in

Monitors — `wait()` and `notify()`

- Should check the `wait()` condition again on wake up
  - Change of state may not be sufficient to continue — e.g., not enough inflow into the account to allow transfer

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  - At wake-up, the state was fine, but it has changed again due to some other concurrent action
- wait() should be in a while, not in an if

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  accounts[source] -= amount;
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- Makes sense to have more than one internal queue
- Monitor can have condition variables to describe internal queues

```
monitor bank_account{
  double accounts[100];
  queue q[100]; // one internal queue
                // for each account
  boolean transfer (double amount,
                    int source,
                    int target){
    while (accounts[source] < amount){
      q[source].wait();  // wait in the queue
                         // associated with source
    }
    accounts[source] -= amount;
    accounts[target] += amount;
    q[target].notify();  // notify the queue
                         // associated with target
    return true;
  }

  // compute the balance across all accounts
  double audit(){ ...}
}
```

Monitors in Java

- Monitors incorporated within existing class definitions

```
public class bank_account{
 double accounts[100];

 public synchronized boolean
   transfer(double amount, int source, int target){
  while (accounts[source] < amount){ wait(); }
  accounts[source] -= amount;
  accounts[target] += amount;
  notifyAll();
  return true;
 }

 public synchronized double audit(){
  double balance = 0.0;
  for (int i = 0; i < 100; i++)
    balance += accounts[i];
  return balance;
 }

 public double current_balance(int i){
  return accounts[i];   // not synchronized!
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}
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- Function declared synchronized is to be executed atomically

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- Each object has a lock
  - To execute a synchronized method, thread must acquire lock
  - Thread gives up lock when the method exits
  - Only one thread can have the lock at any time

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- Each object has a lock
  - To execute a synchronized method, thread must acquire lock
  - Thread gives up lock when the method exits
  - Only one thread can have the lock at any time
- Wait for lock in external queue

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Monitors in Java

- `wait()` and `notify()` to suspend and resume

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Monitors in Java

- wait() and notify() to suspend and resume
- Wait — single internal queue

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 double accounts[100];

 public synchronized boolean
   transfer(double amount, int source, int target){
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```

Monitors in Java

- wait() and notify() to suspend and resume
- Wait — single internal queue
- Notify
  - notify() signals one (arbitrary) waiting process
  - notifyAll() signals all waiting processes ALWAYS USE THIS!
  - Java uses signal and continue

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Object locks . . .

- Use object locks to synchronize arbitrary blocks of code

```
public class XYZ{
  Object o = new Object();

  public int f(){
    ...
    synchronized(o){ ... }
  }

  public double g(){
    ...
    synchronized(o){ ... }
    }
  }
}
```

CRITICAL SECTIONS

Object locks . . .

- Use object locks to synchronize arbitrary blocks of code
- `f()` and `g()` can start in parallel
- Only one of the threads can grab the lock for `o`

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- Use object locks to synchronize arbitrary blocks of code
- `f()` and `g()` can start in parallel
- Only one of the threads can grab the lock for `o`
- Each object has its own internal queue

```
Object o = new Object();

public int f(){
  ..
  synchronized(o){
     ...
     o.wait();   // Wait in queue attached to "o"
     ...
  }
}

public double g(){
  ..
  synchronized(o){
     ...
     o.notifyAll();   // Wake up queue attached to
     ...
  }
}
```

external queue for o

internal for o

Object locks . . .

- Use object locks to synchronize arbitrary blocks of code
- `f()` and `g()` can start in parallel
- Only one of the threads can grab the lock for `o`
- Each object has its own internal queue
- Can convert methods from "externally" synchronized to "internally" synchronized

```
public double h(){
  synchronized(this){
    ...
  }
}
```

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- `f()` and `g()` can start in parallel
- Only one of the threads can grab the lock for `o`
- Each object has its own internal queue
- Can convert methods from "externally" synchronized to "internally" synchronized
- "Anonymous" `wait()`, `notify()`, `notifyAll()` abbreviate `this.wait()`, `this.notify()`, `this.notifyAll()`

```
public double h(){
  synchronized(this){
    ...
  }
}
```

Object locks ...

- Actually, `wait()` can be “interrupted” by an `InterruptedException`

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- Should write

```
try{
  wait();
}
catch (InterruptedException e) {
  ...
};
```

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- Should write

```
try{
  wait();
}
catch (InterruptedException e) {
  ...
};
```

- Error to use `wait()`, `notify()`, `notifyAll()` outside synchronized method
  - `IllegalMonitorStateException`
- Likewise, use `o.wait()`, `o.notify()`, `o.notifyAll()` only in block synchronized on `o`

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

```
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){}
    }
  }
}

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
  }
}
```

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- 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
- 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()
  }
}
```

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- Raises `InterruptedException` within `wait()`, `sleep()`
- No exception raised if thread is running!
  - `interrupt()` sets a status flag
  - `interrupted()` checks interrupt status and clears the flag
- Detecting an interrupt while running or waiting

```
public void run(){
  try{
    j = 0;
    while(!interrupted() && j < 100){
      System.out.println("My id is "+id);
      sleep(1000);    // Sleep for 1000 ms
      j++;
    }
  }
  catch(InterruptedException e){}
}
```

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- Waiting for other threads
  - `t.join()` waits for `t` to terminate