Concurrent Programming
In this lecture...

- Study concurrent programming with an emphasis on correctness
  - Parallel programs have the same correctness issues

- Start with a simpler and easier machine/programming model
  - Use Java as a language
  - Use an Abstract Shared Memory Machine Model

- Next Lecture...
  - Use C/C++ primitives (MPI)
  - Study parallel programming with an emphasis on performance
  - Using a distributed memory machine
What is concurrency?

- What is a sequential program?
  - A single thread of control that executes one instruction and when it is finished execute the next logical instruction

- What is a concurrent program?
  - A collection of autonomous sequential threads, executing (logically) in parallel

- The implementation (i.e. execution) of a collection of threads can be:
  - Multiprogramming
    - Threads multiplex their executions on a single processor.
  - Multiprocessing
    - Threads multiplex their executions on a multiprocessor or a multicore system
  - Distributed Processing
    - Processes multiplex their executions on several different machines
Concurrency and Parallelism

- Concurrency is not (only) parallelism

- Interleaved Concurrency
  - Logically simultaneous processing
  - Interleaved execution on a single processor

- Parallelism
  - Physically simultaneous processing
  - Requires a multiprocessors or a multicore system
Account and Bank

import java.util.*;

public class Account {
    String id;
    String password;
    int balance;

    Account(String id, String password, String balance) {
        this.id = id;
        this.password = password;
        this.balance = balance;
    }

    boolean is_password(String password) {
        return password == this.password;
    }

    int getbal() {
        return balance;
    }

    void post(int v) {
        balance = balance + v;
    }
}

import java.util.*;

public class Bank {
    HashMap<String, Account> accounts;
    static Bank theBank = null;

    private Bank() {
        accounts = new HashMap<String, Account>();
    }

    public static Bank getbank() {
        if (theBank == null)
            theBank = new Bank();
        return theBank;
    }

    public Account get(String ID) {
        return accounts.get(ID);
    }
    ...

public class ATM {
    static Bank bnk;
    PrintStream out;
    BufferedReader in;

    ATM(PrintStream out, BufferedReader in) {
        this.out = out;
        this.in = in;
    }

    public static void main(String[] args) {
        bnk = Bank.getBank();
        BufferedReader stdin = new BufferedReader(new InputStreamReader(System.in));
        ATM atm = new ATM(System.out, stdin);
        atm.run();
    }

    public void run() {
        while(true) {
            try {
                try {
                    out.print("Account ID > ");
                    String id = in.readLine();
                    String acc = bnk.get(id);
                    if (acc == null) throw new Exception();
                    out.print("Password > ");
                    String pass = in.readLine();
                    if (!acc.is_password(pass))
                        throw new Exception();
                    out.print("your balance is "+ acc.getBal());
                    out.print("Deposit or withdraw amount > ");
                    int val = in.read();
                    if (acc.getBal() + val > 0)
                        acc.post(val);
                    else
                        throw new Exception();
                    out.print("your balance is "+ acc.getBal());
                } catch(Exception e) {
                    out.println("Invalid input, restart");
                }
            } catch(Exception e) {
                out.println("Invalid input, restart");
            }
        }
    }
}
Activity trace

ATM

Time
import java.util.*;
import java.io.*;

public class ATM {
    static Bank bnk;
    PrintStream out;
    BufferedReader in;

    ATM(PrintStream out, BufferedReader in) {
        this.out = out;
        this.in = in;
    }

    public static void main(String[] args) {
        bnk = Bank.getbank();
        BufferedReader stdin = new BufferedReader(new InputStreamReader(System.in));

        ATM atm = new ATM(System.out, stdin);
        atm.run();
    }
}

public void run() {
    while(true) {
        try {
            String id = in.readLine();
            String acc = bnk.get(id);
            if (acc == null) throw new Exception();
            String pass = in.readLine();
            if (!acc.is_password(pass)) throw new Exception();

            out.print("Account ID >");
            out.print("Password >");
            int val = in.read();
            if (acc.getbal() + val > 0)
                acc.post(val);
            else
                throw new Exception();

            acc = bnk.get(id);
            if (acc == null) throw new Exception();
            String pass = in.readLine();
            if (!acc.is_password(pass)) throw new Exception();

            out.print("your balance is ");
            out.print(acc.getbal());
            out.print("Deposit or withdraw amount >");

            int val = in.read();
            if (acc.getbal() + val > 0)
                acc.post(val);
            else
                throw new Exception();

            acc = bnk.get(id);
            if (acc == null) throw new Exception();

            out.print("your balance is ");
            out.print(acc.getbal());
        }
        catch(Exception e) {
            out.println("Invalid input, restart");
        }
    }
}

I need to run multiple ATM machines from my program, how do I do that?

Prof. Saman Amarasinghe, MIT.

6.189 IAP 2007 MIT
Concurrent in Java

- Java has a predefined class `java.lang.Thread` which provides the mechanism by which threads are created

```java
public class MyThread extends Thread {
    public void run() {
    }
}
```

- However to avoid all threads having to be subtypes of `Thread`, Java also provides a standard interface

```java
public interface Runnable {
    public void run();
}
```

- Hence, any class which wishes to express concurrent execution must implement this interface and provide the `run` method

- Threads do not begin their execution until the `start` method in the `Thread` class is called
Why use Concurrent Programming?

- Natural Application Structure
  - The world is not sequential! Easier to program multiple independent and concurrent activities.

- Increased application throughput and responsiveness
  - Not blocking the entire application due to blocking IO

- Performance from multiprocessor/multicore hardware
  - Parallel execution

- Distributed systems
  - Single application on multiple machines
  - Client/server type or peer-to-peer systems
import java.util.*;
import java.io.*;

public class ATM {
    static Bank bnk;
    PrintStream out;
    BufferedReader in;

    ATM(PrintStream out, BufferedReader in) {
        this.out = out;
        this.in = in;
    }

    public void run() {
        while(true) {
            try {
                out.print("Account ID > ");
                String id = in.readLine();
                String acc = bnk.get(id);
                if (acc == null) throw new Exception();
                out.print("Password > ");
                String pass = in.readLine();
                if (!acc.is_password(pass))
                    throw new Exception();
                out.print("your balance is " + acc.getbal());
                out.print("Deposit or withdraw amount > ");
                int val = in.read();
                if (acc.getbal() + val > 0)
                    acc.post(val);
                else
                    throw new Exception();
                out.print("your balance is " + acc.getbal());
            } catch(Exception e) {
                out.println("Invalid input, restart");
            }
        }
    }

    public static void main(String[] args) {
        bnk = Bank.getbank();
        BufferedReader stdin = new BufferedReader(new InputStreamReader(System.in));
        ATM atm = new ATM(System.out, stdin);
        atm.run();
    }
}

I need to run multiple ATM machines from my program, how do I do that?
import java.util.*;
import java.io.*;

public class ATMs extends Thread {
    static final int numATMs = 4;
    static Bank bnk;
    PrintStream out;
    BufferedReader in;
    int atmnum;

    ATMs(int num, PrintStream out, BufferedReader in) {
        this.out = out;
        this.in = in;
        this.atmnum = num;
    }

    public static void main(String[] args) {
        bnk = Bank.getbank();
        ATMs atm[] = new ATMs[numATMs];
        for(int i=0; i<numATMs; i++) {
            atm[i] = new ATMs(i, outdevice(i), indevice(i));
            atm[i].start();
        }
    }

    public void run() {
        while(true) {
            try {
                out.print("Account ID > ");
                String id = in.readLine();
                String acc = bnk.get(id);
                if (acc == null) throw new Exception();
                out.print("Password > ");
                String pass = in.readLine();
                if (!acc.is_password(pass))
                    throw new Exception();
                out.print("your balance is "+ acc.getbal());
                int val = in.read();
                if (acc.getbal() + val > 0)
                    acc.post(val);
                else
                    throw new Exception();
            } catch(Exception e) {
                out.println("Invalid input, restart");
            }
        }
    }
}

I need to run multiple ATM machines from my program, how do I do that?
Activity trace

<table>
<thead>
<tr>
<th>ATM 1</th>
<th>ATM 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time

Prof. Saman Amarasinghe, MIT.
Activity trace II

ATM 1

ATM 2

100 - 90 - 90 = 10!!!
ATM 1

```
out.print("your balance is " + acc.getbal());
Your account balance is 100

out.print("Deposit or withdraw amount > ");
Deposit or Withdraw amount >

-90
int val = in.read();

if (acc.getbal() + val > 0)
    acc.post(val);

out.print("your balance is " + acc.getbal());
Your account balance is 10
```

ATM 2

```
out.print("your balance is " + acc.getbal());
Your account balance is 100

out.print("Deposit or withdraw amount > ");
Deposit or Withdraw amount >

-90
int val = in.read();

if (acc.getbal() + val > 0)
    acc.post(val);

out.print("your balance is " + acc.getbal());
Your account balance is 10
```
Activity trace II

ATM 1

**Balance**: 100

void post(int v) {

    v = 100;

    balance = 100 + 10;

    balance = 100 + 10;

    balance = 100 + 10;

}

ATM 2

**Balance**: 100

void post(int v) {

    v = -90;

    balance = 100 + 10;

    balance = 100 + 10;

    balance = 100 + 10;

}

Prof. Saman Amarasinghe, MIT. 16 6.189 IAP 2007 MIT
Synchronization

● All the interleavings of the threads are NOT acceptable correct programs.

● Java provides synchronization mechanism to restrict the interleavings

● Synchronization serves two purposes:
  ■ Ensure safety for shared updates
    – Avoid race conditions
  ■ Coordinate actions of threads
    – Parallel computation
    – Event notification
Safety

- Multiple threads access shared resource simultaneously

- **Safe** only if:
  - All accesses have no effect on resource,
    - e.g., reading a variable,
  
or
  - All accesses *idempotent*
    - E.g., \( y = \text{sign}(a), a = a*2; \)
  
or
  - Only one access at a time: *mutual exclusion*
Safety: Example

- “The too much milk problem”

<table>
<thead>
<tr>
<th>time</th>
<th>You</th>
<th>Your Roommate</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:00</td>
<td>Arrive home</td>
<td>Arrive home</td>
</tr>
<tr>
<td>3:05</td>
<td>Look in fridge, no milk</td>
<td>Look in fridge, no milk</td>
</tr>
<tr>
<td>3:10</td>
<td>Leave for grocery</td>
<td>Leave for grocery</td>
</tr>
<tr>
<td>3:15</td>
<td>Arrive at grocery</td>
<td></td>
</tr>
<tr>
<td>3:20</td>
<td></td>
<td>Buy Milk</td>
</tr>
<tr>
<td>3:25</td>
<td>Buy milk</td>
<td></td>
</tr>
<tr>
<td>3:35</td>
<td>Arrive home, put milk in fridge</td>
<td></td>
</tr>
<tr>
<td>3:50</td>
<td></td>
<td>Buy Milk</td>
</tr>
<tr>
<td>3:50</td>
<td></td>
<td>Arrive home, put up milk</td>
</tr>
</tbody>
</table>

- Model of need to **synchronize** activities
Why You Need Locks

thread A

if (no milk && no note)
leave note
buy milk
remove note

thread B

if (no milk && no note)
leave note
buy milk
remove note

● Does this work?

too much milk
Mutual Exclusion

- Prevent more than one thread from accessing *critical section* at a given time
  - Once a thread is in the critical section, no other thread can enter that critical section until the first thread has left the critical section.
  - No interleavings of threads within the critical section
  - **Serializes** access to section

```java
synchronized int getbal() {
    return balance;
}

synchronized void post(int v) {
    balance = balance + v;
}
```
### Activity trace II zoomed-in

<table>
<thead>
<tr>
<th>balance</th>
<th>ATM 1</th>
<th>ATM 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>int val = in.read();</td>
<td>int val = in.read();</td>
</tr>
<tr>
<td>100</td>
<td>if (acc.getbal() + val &gt; 0)</td>
<td>if (acc.getbal() + val &gt; 0)</td>
</tr>
<tr>
<td>100</td>
<td>acc.post(val);</td>
<td>acc.post(val);</td>
</tr>
<tr>
<td>10</td>
<td>out.print(&quot;your balance is &quot; + acc.getbal());</td>
<td>out.print(&quot;your balance is &quot; + acc.getbal());</td>
</tr>
<tr>
<td>-80</td>
<td>Your account balance is -80</td>
<td>Your account balance is -80</td>
</tr>
</tbody>
</table>

---

Negative Bank Balance!
**Atomicity**

- Synchronized methods execute the body as an atomic unit.
- May need to execute a code region as the atomic unit.
- Block Synchronization is a mechanism where a region of code can be labeled as synchronized.
- The `synchronized` keyword takes as a parameter an object whose lock the system needs to obtain before it can continue.
- Example:
  ```java
  synchronized (acc) {
      if (acc.getbal() + val > 0)
          acc.post(val);
      else
          throw new Exception();
      out.print("your balance is " + acc.getbal());
  }
  ```
public class ATMs extends Thread {
    static final int numATMs = 1;
    static Bank bnk;
    PrintStream out;
    BufferedReader in;
    int atmnum;

    ATMs(int num, PrintStream out, BufferedReader in) {
        this.out = out;
        this.in = in;
        this.atmnum = num;
    }

    public static void main(String[] args) {
        bnk = Bank.getbank();
        ATMs atm[] = new ATMs[numATMs];
        for(int i=0; i<numATMs; i++){
            atm[i] = new ATMs(i, outdevice(i), indevice(i));
            atm[i].start();
        }
    }

    public void run() {
        while(true) {
            try {
                out.print("Account ID > ");
                String id = in.readLine();
                String acc = bnk.get(id);
                if (acc == null) throw new Exception();
                out.print("Password > ");
                String pass = in.readLine();
                if (!acc.is_password(pass))
                    throw new Exception();
                synchronized (acc) {
                    String accID = id;
                    if (acc.getbal() + val > 0)
                        acc.post(val);
                    else
                        throw new Exception();
                }
                out.print("your balance is "+ acc.getbal());
            } catch(Exception e) {
                out.println("Invalid input, restart");
            }
        }
    }
}
### Activity trace II

<table>
<thead>
<tr>
<th>balance</th>
<th>ATM 1</th>
<th>ATM 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
<td>out.print(&quot;your balance is &quot; + acc.getbal());</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>Your account balance is 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>out.print(&quot;Deposit or withdraw amount &gt; &quot;);</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deposit or Withdraw amount &gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>int val = in.read();</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>synchronized(acc)</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>if (acc.getbal() + val &gt; 0)</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>acc.post(val);</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>out.print(&quot;your balance is &quot; + acc.getbal());</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>Your account balance is 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>synchronized(acc)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>if (acc.getbal() + val &gt; 0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>throw new Exception()</td>
</tr>
</tbody>
</table>

Balance shows 100, but couldn’t withdraw!
import java.util.*;
import java.io.*;

public class ATMs extends Thread {
    static final int numATMs = 1;
    static Bank bnk;
    PrintStream out;
    BufferedReader in;
    int atmnum;

    ATMs(int num, PrintStream out, BufferedReader in) {
        this.out = out;
        this.in = in;
        this.atmnum = num;
    }

    public static void main(String[] args) {
        bnk = Bank.getbank();
        ATMs atm[] = new ATMs[numATMs];
        for(int i=0; i<numATMs; i++){
            atm[i] = new ATMs(i, outdevice(i), indevice(i));
            atm[i].start();
        }
    }

    public void run() {
        while(true) {
            try {
                out.print("Account ID > ");
                String id = in.readLine();
                String acc = bnk.get(id);
                if (acc == null) throw new Exception();
                out.print("Password > ");
                String pass = in.readLine();
                if (!acc.is_password(pass))
                    throw new Exception();
                synchronized (acc) {
                    out.print("your balance is "+ acc.getbal());
                    out.print("Deposit or withdraw amount > ");
                    int val = in.read();
                    if (acc.getbal() + val > 0)
                        acc.post(val);
                    else
                        throw new Exception();
                    out.print("your balance is "+ acc.getbal());
                }
            } catch(Exception e) {
                out.println("Invalid input, restart");
            }
        }
    }
}

Synchronizing a block
Activity trace II

ATM 1

Account ID >

\textit{ben}

Password >

\textit{6189cell}

\texttt{synchronized(acc)}

\texttt{out.print("your balance is" + acc.getbal());}

Your account balance is 100

\texttt{out.print("Deposit or withdraw amount > ");}

Deposit or Withdraw amount >

\texttt{synchronized(acc)}

- 90

ATM 2

Account ID >

\textit{ben}

Password >

\textit{6189cell}

Image removed due to copyright restrictions.

Image by MIT OpenCourseWare.
public boolean transfer(Account from, Account to, int val) {
    synchronized(from) {
        if (from.getbal() > val)
            from.post(-val);
        else
            throw new Exception();
    }
    synchronized(to) {
        to.post(val);
    }
}
Account Transfers

Allyssa wants to transfer $10 to Ben’s account
While Ben wants to also transfer $20 to Allyssa’s account

Allyssa → Ben

synchronized(from)
if (from.getbal() > val)
from.post(-val);

synchronized(to)
Waiting for Ben’s account to be released to perform

Ben → Allysa

synchronized(from)
if (from.getbal() > val)
from.post(-val);

synchronized(to)
Waiting for Allyssa’s account to be released to perform

DEADLOCKED!
Avoiding Deadlock

● Cycle in locking graph = deadlock

● Standard solution: canonical order for locks
  ■ Acquire in increasing order
  ■ Release in decreasing order

● Ensures deadlock-freedom, but not always easy to do
public class Account {
    String id;
    String password;
    int balance;
    static int count;

    Account(String id,
            String password,
            String balance) {
        this.id = id;
        this.password = password;
        this.balance = balance;
    }

    public boolean transfer(Account from,
                             Account to,
                             int val) {
        synchronized(from) {
            synchronized(to) {
                if (from.getbal() > val)
                    from.post(-val);
                else
                    throw new Exception();
                to.post(val);
            }
        }
    }
}
public class Account {
    String id;
    String password;
    int balance;
    static int count;
    public int rank;

    Account(String id,
            String password,
            String balance) {
        this.id = id;
        this.password = password;
        this.balance = balance;
        rank = count++;
    }

    ...
Races

Race conditions – insidious bugs

- Non-deterministic, timing dependent
- Cause data corruption, crashes
- Difficult to detect, reproduce, eliminate

- Many programs contain races
  - Inadvertent programming errors
  - Failure to observe locking discipline
Data Races

- **A data race** happens when two threads access a variable simultaneously, and one access is a *write*

```c
int t1;  
t1 = hits;  
hits = t1 + 1;
```

```c
int t2;  
t2 = hits;  
hits = t2 + 1;
```
A **data race** happens when two threads access a variable simultaneously, and one access is a *write*.
Data Races

- A **data race** happens when two threads access a variable simultaneously, and one access is a *write*

```plaintext
int t1;
t1 = hits;
hits = t1 + 1;

int t2;
t2 = hits;
hits = t2 + 1;
```
Data Races

- Problem with data races: **non-determinism**
  - Depends on interleaving of threads

- Usual way to avoid data races: **mutual exclusion**
  - Ensures **serialized** access of all the shared objects
Dining Philosophers Problem

- There are 5 philosophers sitting at a round table.
- Between each adjacent pair of philosophers is a chopstick.
- Each philosopher does two things: think and eat.
  - The philosopher thinks for a while.
  - When the philosopher becomes hungry, she stops thinking and...
    - Picks up left and right chopstick
    - He cannot eat until he has both chopsticks, has to wait until both chopsticks are available
    - When the philosopher gets the two chopsticks she eats
  - When the philosopher is done eating he puts down the chopsticks and begins thinking again.
import java.io.*;
import java.util.*;

public class Philosopher extends Thread {
    static final int count = 5;
    Chopstick left;
    Chopstick right;
    int position;

    Philosopher(int position,
                Chopstick left,
                Chopstick right) {
        this.position = position;
        this.left = left;
        this.right = right;
    }

    public static void main(String[] args) {
        Philosopher phil[] = new Philosopher[count];
        Chopstick last = new Chopstick();
        Chopstick left = last;
        for(int i=0; i<count; i++){
            Chopstick right = (i==count-1)?last :
                                new Chopstick();
            phil[i] = new Philosopher(i, left, right);
            left = right;
        }

        for(int i=0; i<count; i++){
            phil[i].start();
        }
    }
}
public void run() {
    try {
        while(true) {
            synchronized(left) {
                synchronized(right) {
                    System.out.println(times + " : Philosopher " + position + " is done eating");
                }
            }
        }
    } catch (Exception e) {
        System.out.println("Philosopher " + position + ", s meal got disturbed");
    }
}
Dining Philosophers Problem: Take II

static Object table;
public void run() {
    try {
        while(true) {
            synchronized(table) {
                synchronized(left) {
                    synchronized(right) {
                        System.out.println(times + " : Philosopher " + position + " is done eating");
                    }
                }
            }
        }
    } catch (Exception e) {
        System.out.println("Philosopher " + position + "," + position + "'s meal got disturbed");
    }
}
Dining Philosophers Problem: Take III

```java
public void run() {
    try {
        Chopstick first = (position%2 == 0)?left:right;
        Chopstick second = (position%2 == 0)?right:left;
        while(true) {
            synchronized(first) {
                synchronized(second) {
                    System.out.println(times + "\: Philosopher " + position + " is done eating";
                }
            }
        }
    } catch (Exception e) {
        System.out.println("Philosopher " + position + ",\'s meal got disturbed");
    }
}
```
Other types of Synchronization

- There are a lot of ways to use Concurrency in Java
  - Semaphores
  - Blocking & non-blocking queues
  - Concurrent hash maps
  - Copy-on-write arrays
  - Exchangers
  - Barriers
  - Futures
  - Thread pool support
Potential Concurrency Problems

- **Deadlock**
  - Two or more threads stop and wait for each other

- **Livelock**
  - Two or more threads continue to execute, but make no progress toward the ultimate goal.

- **Starvation**
  - Some thread gets deferred forever.

- **Lack of fairness**
  - Each thread gets a turn to make progress.

- **Race Condition**
  - Some possible interleaving of threads results in an undesired computation result.
Conclusion

● Concurrency and Parallelism are important concepts in Computer Science
● Concurrency can simplify programming
   ■ However it can be very hard to understand and debug concurrent programs
● Parallelism is critical for high performance
   ■ From Supercomputers in national labs to Multicores and GPUs on your desktop
● Concurrency is the basis for writing parallel programs
● Next Lecture: How to write a Parallel Program