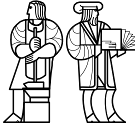
6.170 Lecture 22
Concurrency and Parallelism



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including material form Emery Berger @ UMASS and David Cairns @ University of Stirling, UK

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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);
    }
    ...
}
```

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ATM

```
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 {
                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");
            }
        }
    }
}
```

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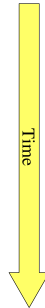
Activity trace

ATM



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ATM

```
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 {
                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");
            }
        }
    }
}
```

I need to run multiple ATM machines from my program, how do I do that? 5

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

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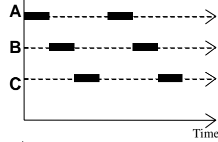
Concurrency and Parallelism

Concurrency is not (only) parallelism

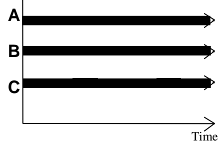
Interleaved Concurrency

- Logically simultaneous processing
- Interleaved execution on a single processor



Parallelism

- Physically simultaneous processing
- Requires a multiprocessors or a multicore system



Concurrency in Java

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

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

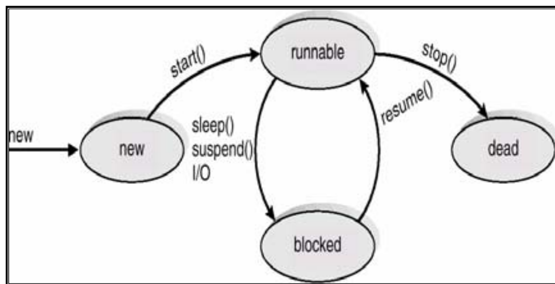
However to avoid all threads having to be subtypes of `Thread`, Java also provides a standard interface

```
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

Java Thread States



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

Multiple ATMs

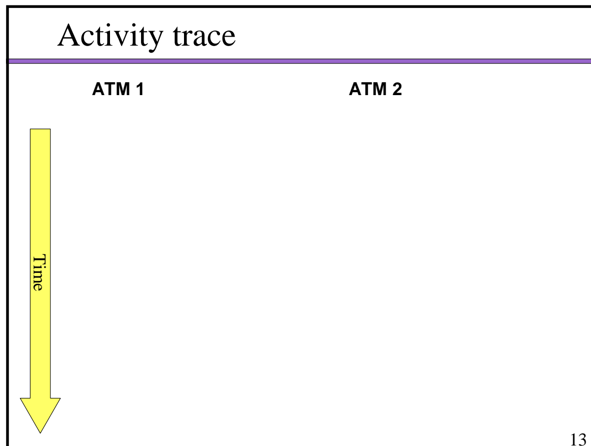
```
import java.util.*;
import java.io.*;

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 {
          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");
        }
      }
    }
}
```

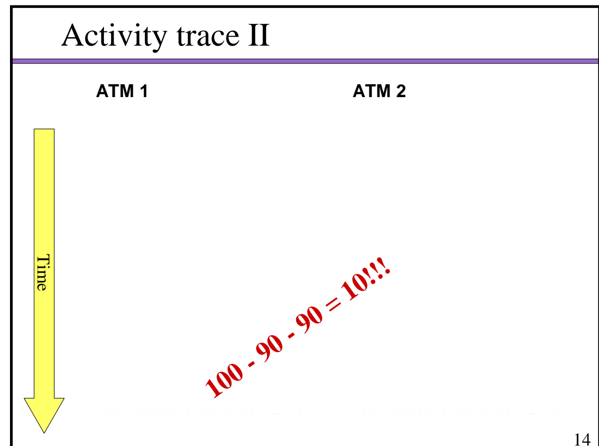
I need to run multiple ATM machines from my program, how do I do that?

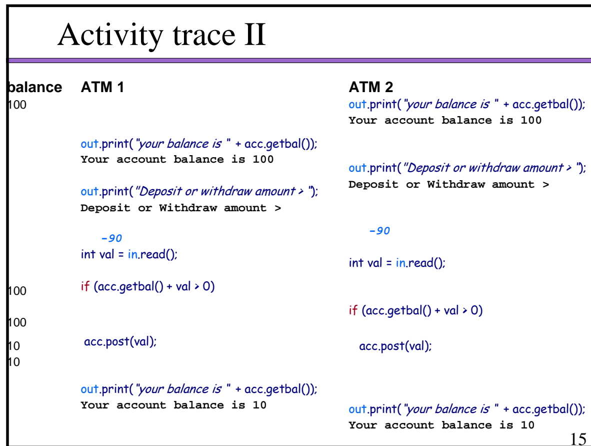
Multiple ATMs

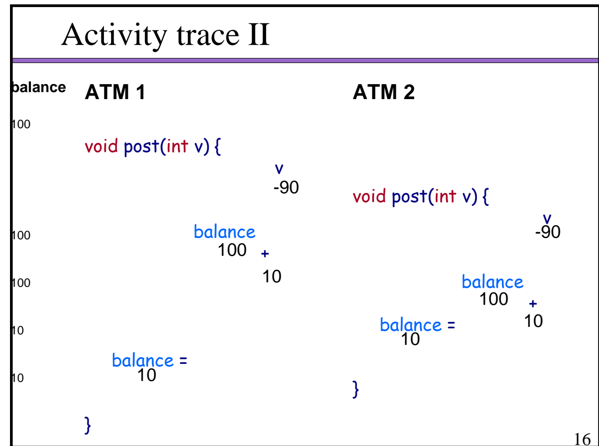
```
import java.util.*;
import java.io.*;

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());
          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");
        }
      }
    }
}
```

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









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

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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 = sign(a)`, `a = a*2;`
  - or
  - Only one access at a time: *mutual exclusion*

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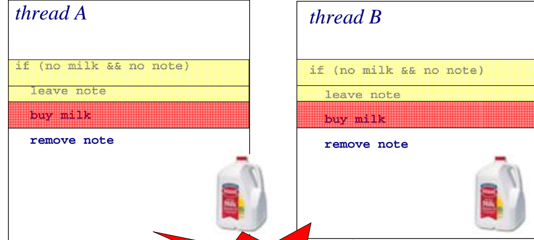
Safety: Example

"The *too much milk* problem"

time	You	Your Roommate
3:00	Arrive home	
3:05	Look in fridge, no milk	
3:10	Leave for grocery	
3:15		Arrive home
3:20	Arrive at grocery	Look in fridge, no milk
3:25	Buy milk	Leave for grocery
3:35	Arrive home, put milk in fridge	
3:45		Buy Milk
3:50		Arrive home, put up milk
3:50		Oh no!

Model of need to **synchronize** activities

Why You Need Locks



Does this w

too much milk

Mutual Exclusion

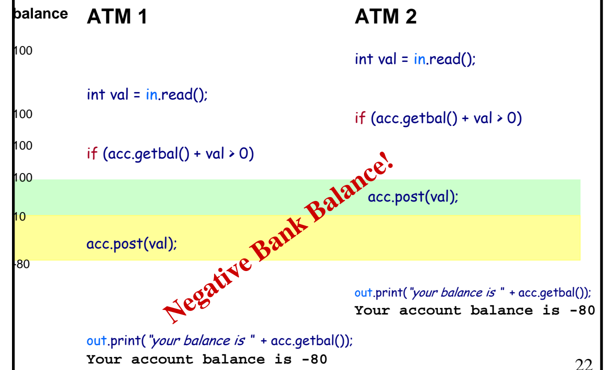
Prevent more than one thread from accessing *critical section* at a given time

- 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

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

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


Activity trace II zoomed-in



out.print("your balance is " + acc.getbal());
Your account balance is -80

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:

```
synchronized (acc) {
    if (acc.getbal() + val > 0)
        acc.post(val);
    else
        throw new Exception();
    out.print("your balance is " + acc.getbal());
}
```


Synchronizing a block

```
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();
            out.print("your balance is " + acc.getbal());
            out.print("Deposit or withdraw amount > ");
            int val = in.read();
            synchronized (acc) {
                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

balance	ATM 1	ATM 2
		out.print("your balance is " + acc.getbal());
		Your account balance is 100
100		
	out.print("your balance is " + acc.getbal());	
100	Your account balance is 100	
		out.print("Deposit or withdraw amount > ");
		Deposit or Withdraw amount >
	out.print("Deposit or withdraw amount > ");	
	Deposit or Withdraw amount >	
		-90
	-90	
		int val = in.read();
	int val = in.read();	
100	synchronized(acc)	
100	if (acc.getbal() + val > 0)	synchronized(acc)
10	acc.post(val);	
	out.print("your balance is " + acc.getbal());	
10	Your account balance is 10	
10		if (acc.getbal() + val > 0) throw new Exception()

Balance shows 100, but couldn't withdraw!

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Synchronizing a block

```java
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");
         }
      }
   }
}
```

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Activity trace II

ATM 1	ATM 2
	Account ID >
Account ID >	
ben	
Password >	
	ben
	Password >
6.170isthebest	
	6.170isthebest
synchronized(acc)	
out.print("your balance is " + acc.getbal());	
Your account balance is 100	
	synchronized(acc)
out.print("Deposit or withdraw amount > ");	
Deposit or Withdraw amount >	
-90	

NO RESPONSE!!

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Account transfers

```java
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);
        }
    }
}
```

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Account Transfers

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

Allyssa→Ben	Ben→Allysa
synchronized(from)	
if (from.getbal() > val)	synchronized(from)
from.post(-val);	if (from.getbal() > val)
	from.post(-val);
synchronized(to) **Waiting for Ben's account to be released to perform**	synchronized(to) **Waiting for Allyssa's account to be released to perform**

DEADLOCKED!

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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

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Account and Bank

```
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);
      }
    }
}
...
```


Account and Bank

```
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++;
    }

    ...
}
```

```
...
public boolean transfer(Account from,
                        Account to,
                        int val) {

    Account first = (from.rank > to.rank)?from:to;
    Account second = (from.rank > to.rank)?to:from;
    synchronized(first) {
      synchronized(second) {
        if (from.getbal() > val)
          from.post(-val);
        else
          throw new Exception();
        to.post(val);
      }
    }
}
...
```


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**

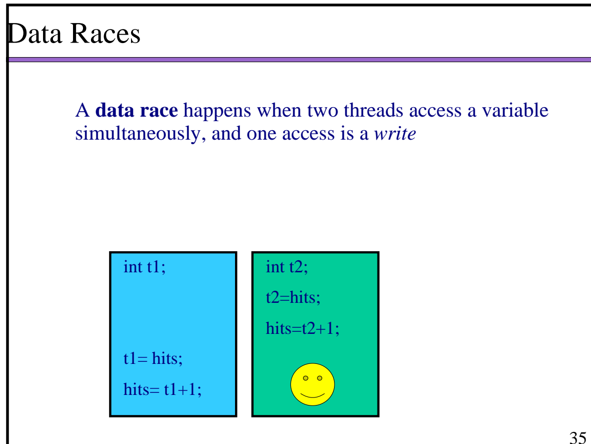
Data Races

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

Thread 1	Thread 2
int t1;	int t2;
t1= hits;	t2=hits;
hits= t1+1;	hits=t2+1;

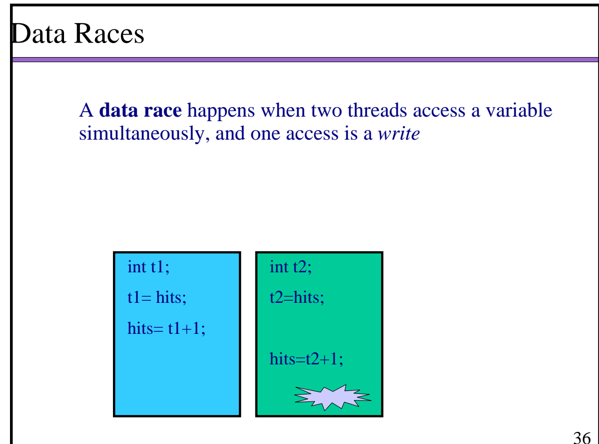
Data Races

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*



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.

Dining Philosophers Problem Setup

```
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();
      }
    }

    ...
}
```


Dining Philosophers Problem: Take I

```
public void run() {
    try {
        while(true) {
1           synchronized(left) {
2               synchronized(right) {
3                   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) {
1           synchronized(table) {
2               synchronized(left) {
3                   synchronized(right) {
4                       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 III

```
public void run() {
    try {
        Chopstick first = (position%2 == 0)?left:right;
        Chopstick second = (position%2 == 0)?right:left;
        while(true) {
1           synchronized(first) {
2               synchronized(second) {
3                   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

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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.

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Issues with Parallelism

- Amdhal's Law
  - Any computation can be analyzed in terms of a portion that must be executed sequentially, Ts, and a portion that can be executed in parallel, Tp. Then for n processors:
  - $T(n) = Ts + Tp/n$
  - $T(\infty) = Ts$, thus maximum speedup $(Ts + Tp) / Ts$
- Load Balancing
  - The work is distributed among processors so that ***all*** processors are kept busy ***all*** of the time.
- Granularity
  - The size of the parallel regions between synchronizations or the ratio of computation (useful work) to communication (overhead).

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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

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