Concurrent Programming: Threads

CS 18000
Sunil Prabhakar
Department of Computer Science
Purdue University

Objectives

- This week we will get introduced to concurrent programming
  - Creating a new thread of execution
  - Waiting for threads to terminate
  - Thread states and scheduling
  - sleep() and yield()
  - Simple synchronization among threads

One-track mind?

- Often, in real life we perform multiple tasks at the same time
  - Doing the laundry
  - Making a pot of coffee
- This is more efficient.
- Our programs thus far have had a single track (thread) of execution
  - at any point in time, there is only one statement being executed
  - not always efficient -- can stall (e.g., user input)

Multiple Concurrent Threads

- There are many instances in computing where we can benefit from multiple concurrent threads of execution.
- For example:
  - GUI responsiveness. The GUI should not freeze while performing time-consuming operations.
  - Liveness in games: display shouldn't "lock up"
  - Exploiting available processing: speeding up processing by using all computing cores

Motivation: Gaming

- Consider a game program that has to repeatedly
  - redraw the scene
  - play the game, record scores, ask the user if they want to play again.
- We don't want to stop redrawing the scene while waiting for the user input.
- *Solution: perform both tasks at the same time (concurrently)*

Motivation: GUIs

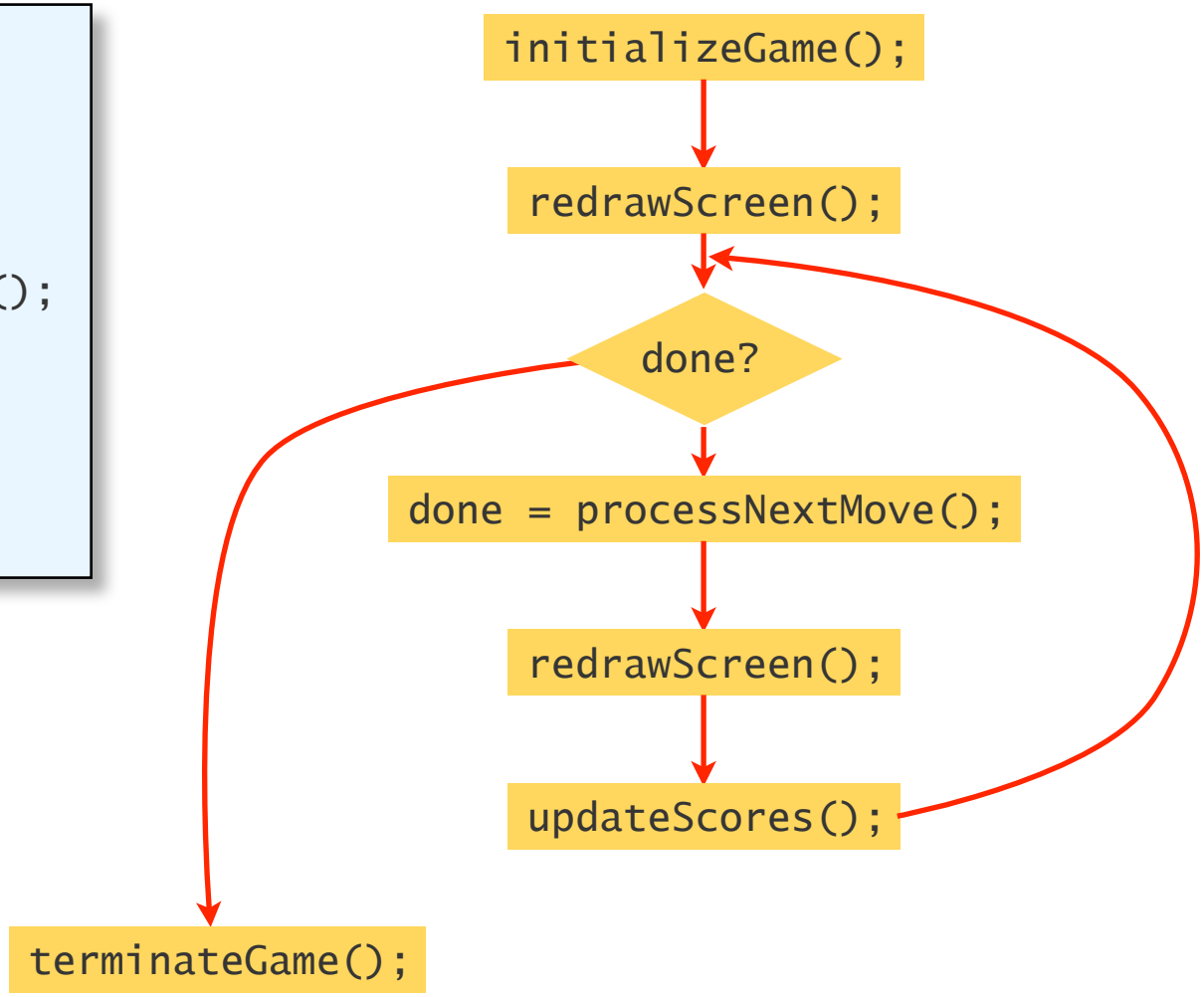
- Consider a GUI event which causes some time-consuming processing to execute.
- While this processing is going on, the GUI will "lock up"
- This is not desirable from a user's experience point of view.
- How can we prevent this?
- *Solution: perform non-GUI processing without locking up GUI thread*

Motivation: Exploiting Multiple Cores and Processors

- Due to the recent hardware trends, modern computers have multiple CPUs (cores or processors)
- If there is only a single thread of execution, only one CPU is used for our program.
- How do we exploit these other CPUs?
- Consider
  - the initialization of a large array
  - searching for an item in a large array
- *Solution: Split array into pieces and initialize (search) each piece concurrently.*

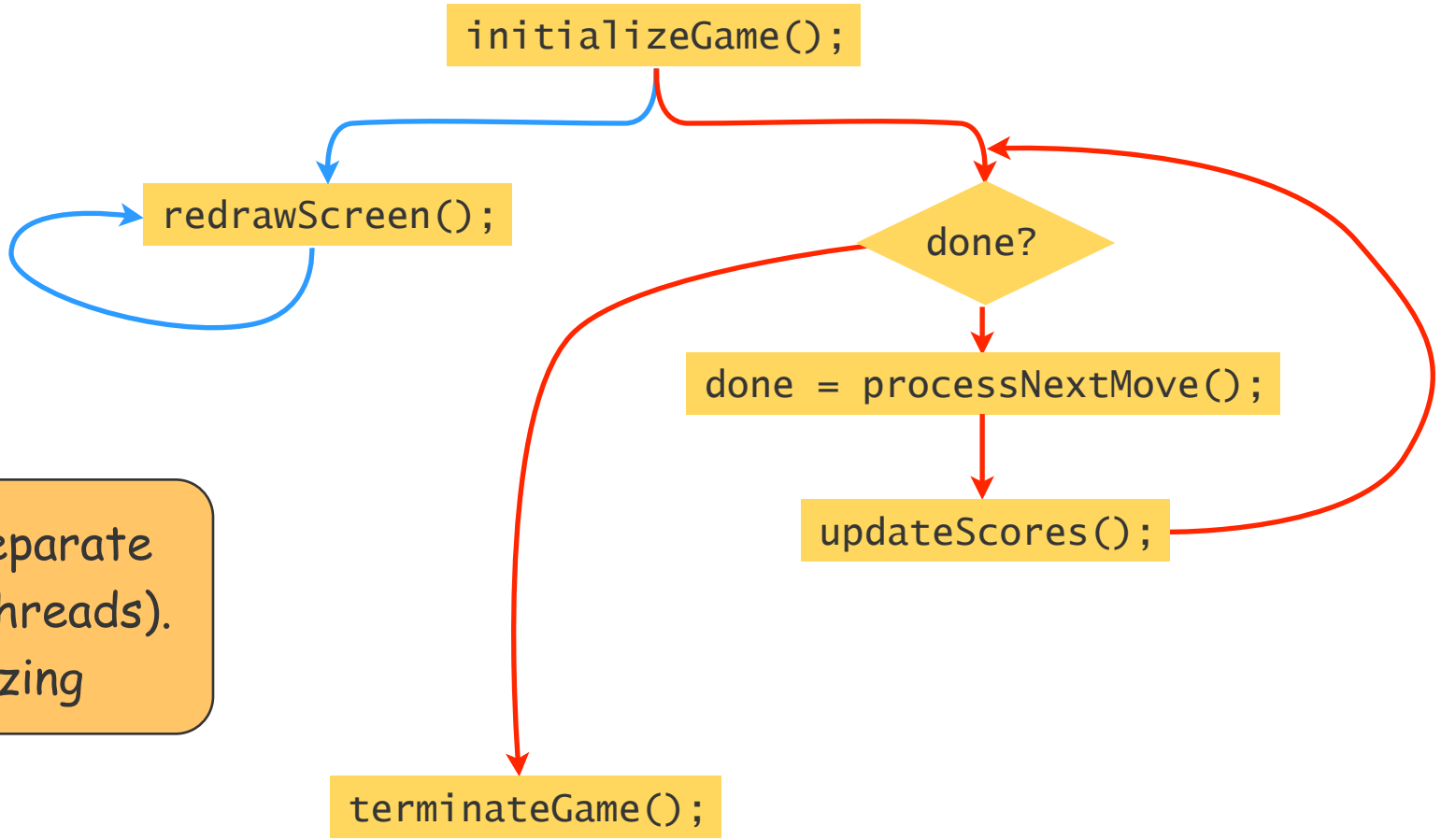
Game: sequential version

```
initializeGame();
redrawScreen();
boolean done=false;
while(!done) {
   done = processNextMove();
   redrawScreen();
   updateScores();
}
terminateGame();
```



Screen frozen while waiting for user input.

Game: concurrent version

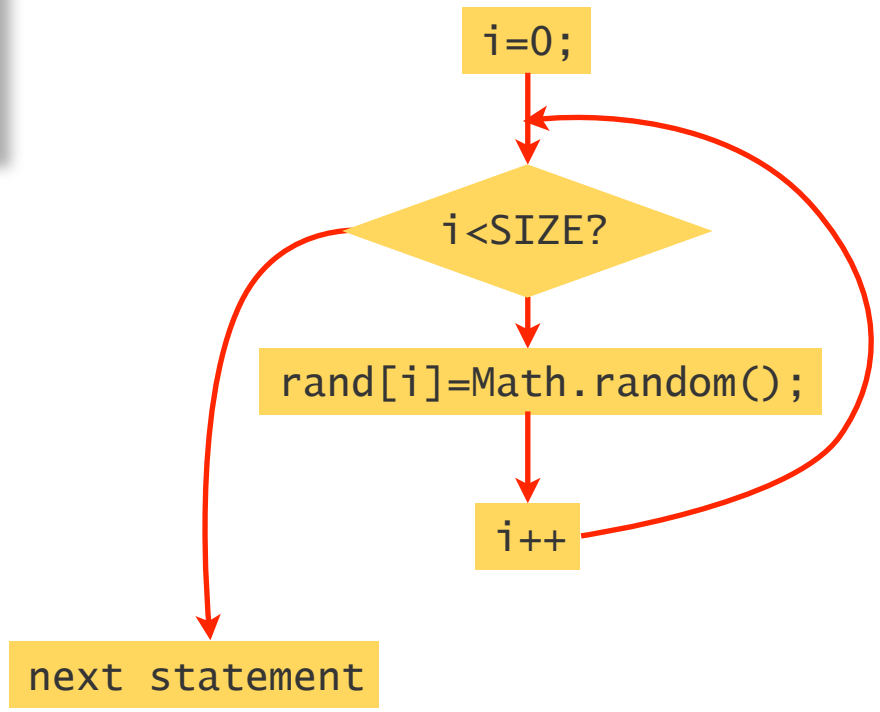


Note: separate tasks (threads). No freezing

Array: sequential version

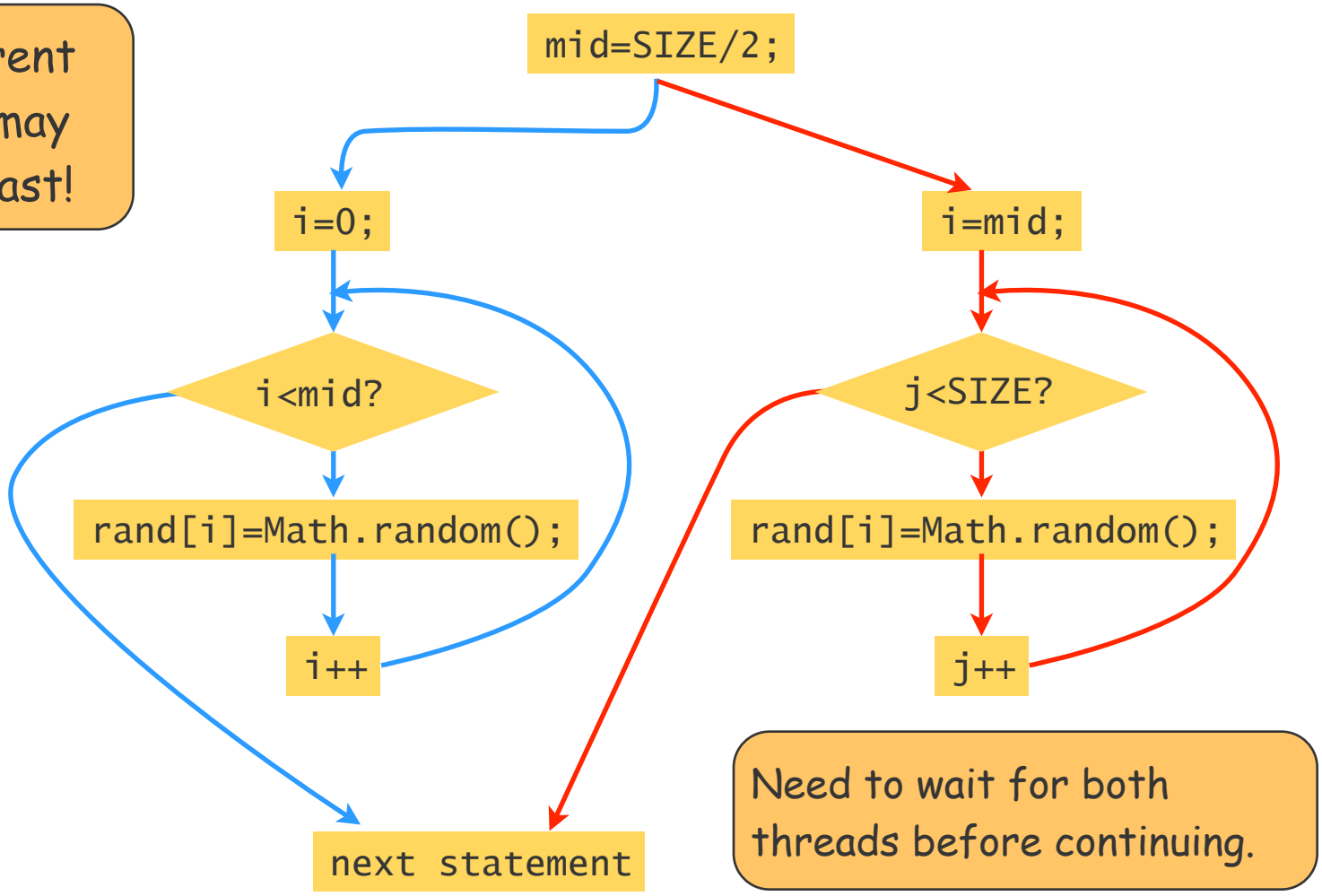
```
final int SIZE = 1000000;
double[] rand = new double[SIZE];
for(int i=0;i<SIZE;i++)
   rand[i]= Math.random();
```

Only one thread -- may take long time even though some CPUs are idle



Array: concurrent version

With concurrent execution -- may be twice as fast!



Need to wait for both threads before continuing.

Motivation for concurrency

- Need for asynchrony
  - need to perform separate tasks
    - e.g., game, GUI examples
  - potential for increased speed with multiple CPUs/cores
    - e.g, matrix example
- Achieving these goals is not straight-forward

Sequential processing

- In a non-concurrent (sequential) program there is only one thread: the main thread.
- This thread executes the main method and then terminates.
  - the flow of control is determined by the main method
- With GUI elements,
  - a separate thread handle event: Event Dispatch Thread

Concurrent processing

- How do we create a separate thread of execution?
- The Thread class provides a facility for creating separate threads.
  - Declare a class to be a descendant of Thread
  - Override the run() method to perform the necessary task(s) for the new thread
- When the start() method is called, the thread starts executing concurrently

Game: concurrent version

```
public class Game extends Thread{
    public static void main(String[] args){
        Game game = new Game();
        game.playGame();
    }

    public void playGame(){
        boolean done=false;
        initializeGame();
        start();
        while(!done) {
            done = processNextMove();
            updateScores();
        }
        terminateGame();
    }

    public void run(){
        while(true)
            redrawScreen();
        }
}
```

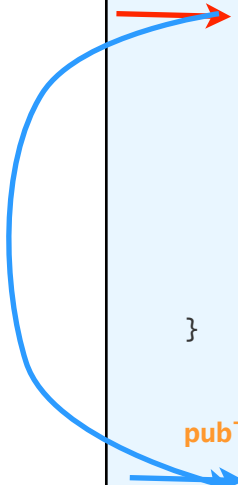
NOTE!!

Game: concurrent version

```
public class Game extends Thread{
    public static void main(String[] args){
        Game game = new Game();
        game.playGame();
    }

    public void playGame(){
        boolean done=false;
        initializeGame();
        start();
        while(!done) {
            done = processNextMove();
            updateScores();
        }
        terminateGame();
    }

    public void run(){
        while(true)
            redrawScreen();
        }
}
```



Array: concurrent version

```
public class ProcessArray {
   static final int SIZE = 1000000;
   static int[] data = new int[SIZE];

   public static void main(String[] args){
      int mid = SIZE/2;
      InitArray thread1 = new InitArray(0,mid, data);
      InitArray thread2 = new InitArray(mid, SIZE, data);
      thread1.start();
      thread2.start();
      ...
   }
}
```

```
public class InitArray extends Thread {
   int start, end;
   int array[];
   public InitArray(int from, int to,
   int[] array){
      start = from;
      end = to;
      this.array = array;
   }
   public void run(){
      for(int i=start;i<end;i++)
         array[i]= Math.random();
   }
}
```

NOTE!!

Array: concurrent version

```
public class ProcessArray {
   static final int SIZE = 1000000;
   static int[] data = new int[SIZE];

   public static void main(String[] args){
      int mid = SIZE/2;
      InitArray thread1 = new InitArray(0,mid, data);
      InitArray thread2 = new InitArray(mid, SIZE, data);
      thread1.start();
      thread2.start();
      ...
   }
}
```

```
public class InitArray extends Thread {
   int start, end;
   int array[];
   public InitArray(int from, int to,
   int[] array){
      start = from;
      end = to;
      this.array = array;
   }
   public void run(){
      for(int i=start;i<end;i++)
         array[i]= Math.random();
   }
}
```

Rejoining threads

- In the last example, it is necessary to wait for both threads to finish before moving on.
- This is achieved by calling the join() method
  - the thread that calls join is suspended until the thread on which it is called terminates.
  - this method can throw the (checked) InterruptedException so we should catch this exception

Array: concurrent version 2

```
public class ProcessArray {
   static final int SIZE = 1000000;
   static int[] odd = new int[SIZE];

   public static void main(String[] args){
      int mid = SIZE/2;
      InitArray thread1 = new InitArray(0,mid);
      InitArray thread2 = new InitArray(mid, SIZE);
      thread1.start();
      thread2.start();
      try{
         thread1.join();
         thread2.join();
      } catch (InterruptedException e){
         System.out.println("Error in thread");
      }
      . . .
   }
}
```

```
public class InitArray extends Thread {
   int start, end;
   int array[];
   public InitArray(int from, int to,
   int[] array){
      start = from;
      end = to;
      this.array = array;
   }
   public void run(){
      for(int i=start;i<end;i++)
         array[i]= Math.random();
   }
}
```

The join() method

- A call to the join method blocks (i.e., does not return) until the thread on which it is called terminates
  - returns from its run() method, or
  - propagates an exception from run()
- While being blocked, the calling thread may get interrupted which is why the join method throws the exception.
- Do not use the stop() method to stop a thread -- deprecated.

Speedup

- Two key reasons for concurrency:
  - liveness (e.g., game keeps redrawing screen)
  - speedup (with more cores, programs run faster)
- Speedup can be measured using the System class methods:
  - public static long currentTimeMillis()
    - time elapsed since 1/1/1970 12:00am, in ms
  - public static long nanoTime()
    - current value of computer's timer in ns.

Game: concurrent version

NOTE!!

```
public class Game extends Thread{
   public static void main(String[]
   args){
      Game game = new Game();
      game.playGame();
   }
   public void playGame(){
      boolean done=false;
      initializeGame();
      start();
      while(!done) {
         done = processNextMove();
         updateScores();
      }
      terminateGame();
   }
   public void run(){
      while(true)
         redrawScreen();
   }
}
```

Array: concurrent version

```
public class ProcessArray {
   static final int SIZE = 1000000;
   static int[] data = new int[SIZE];

   public static void main(String[] args){
      int mid = SIZE/2;
      InitArray thread1 = new InitArray(0,mid, data);
      InitArray thread2 = new InitArray(mid, SIZE, data);
      thread1.start();
      thread2.start();
      ...
   }
}
```

```
public class InitArray extends Thread {
   int start, end;
   int array[];
   public InitArray(int from, int to,
   int[] array){
      start = from;
      end = to;
      this.array = array;
   }
   public void run(){
      for(int i=start;i<end;i++)
         array[i]= Math.random();
   }
}
```

NOTE!!

Creating Sub-Tasks

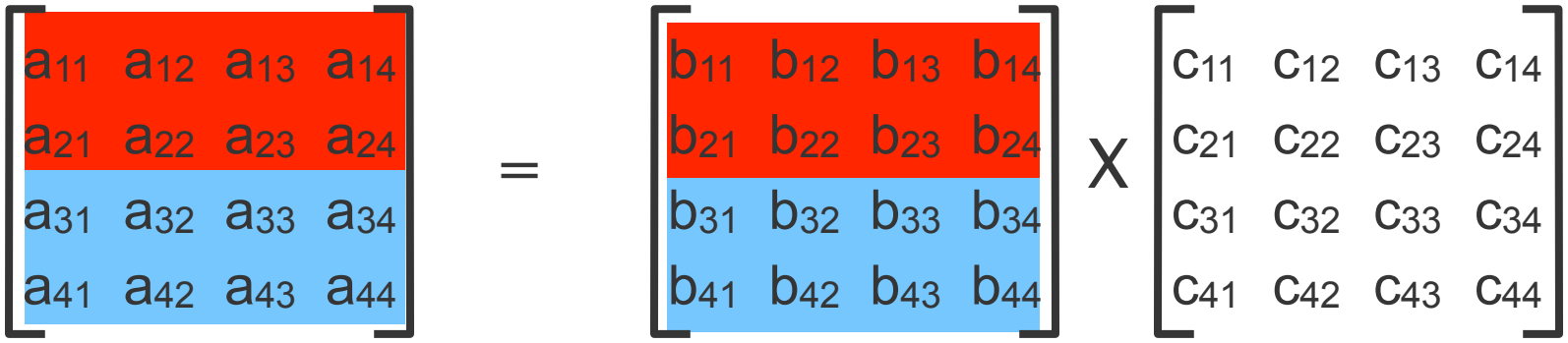
- To achieve concurrent processing, we need to divide a task into multiple pieces that can be assigned to concurrent threads.
- Two main approaches
  - Task decomposition
    - divide the type of work being performed
      - e.g., game example
  - Domain decomposition
    - divide the data on which the same task is performed
      - e.g. matrix initialization

Array multiplication

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix} X \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix}$$

$$a_{ij} = \sum_{k=1}^{4} b_{ik} * c_{kj} = b_{i1} * c_{1j} + b_{i2} * c_{2j} + b_{i3} * c_{3j} + b_{i4} * c_{4j}$$

Task sub-division

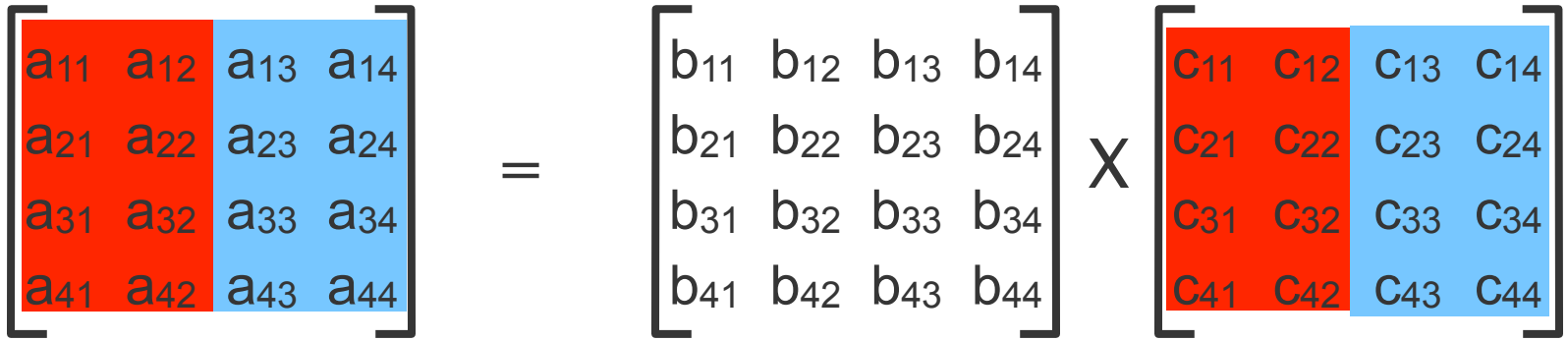


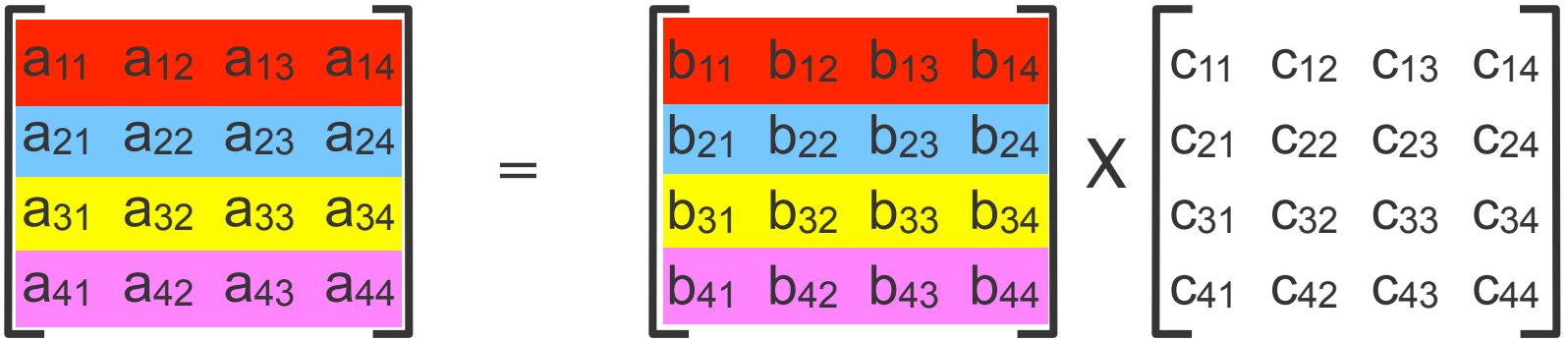
Array Multiplication Example

```
public class ArrayMult {
   public static void main(String[] args){
      final int M=4, N=4, K=4;
      int[][] a = new int[M][N];
      int[][] b = new int[M][K];
      int[][] c = new int[K][N];
       . . .  //initialize values;
      ArrayMult mult1 = new ArrayMult(0,M/2,a,b,c);
      ArrayMult mult2 = new ArrayMult(M/2,M,a,b,c);
      mult1.start();
      mult2.start();
      try{
         mult1.join();
         mult2.join();
      } catch (InterruptedException e) {
         System.out.println("Unexpected
         Interrupt");
      }
   }
}
```

```
public class ArrayMult extends Thread {
   int start, end;
   int[][] a,b,c;
   public ArrayMult(int from, int to, int
   [][] a, int[][] b, int[][] c){
      start = from;
      end = to;
      this.a = a;
      this.b = b;
      this.c = c;
   }
   public void run(){
      for(int i=start;i<end;i++)
        for(int j=0;j<a[0].length;j0++){
            a[i][j] = 0;
            for(int k=0;k<b.length;k++)
               a[i][j]+=b[i][k]*c[k][j];
        }
   }
}
```

Task sub-division





```
public class ArrayMult {
   public static void main(String[] args){
      final int NUM_THREADS=5;
      ArrayMult[] threads = new ArrayMult[NUM_THREADS];
       . . .
      int subsetSize=(int) Math.ceil(a.length /(float)NUM_THREADS);
      int startRow = 0;
      for(int i=0;i<NUM_THREADS;i++){
         threads[i]=new ArrayMult(startRow, Math.min(startRow+subsetSize,a.length), a,
         b, c);
         threads[i].start();
         start+=subsetSize;
      }
      try{
         for(int i=0;i<NUM_THREADS;i++)
            threads[i].join();
      } catch (InterruptedException e) {
         System.out.println("Unexpected Interrupt");
      }
   }
}
```

Processes

- Modern operating systems support multi-tasking
  - painting the screen, listening to the keyboard, printing, running several programs, ...
- Even with a single core multiple tasks are concurrently running
- Achieved by sharing the processor among multiple processes
  - the CPU runs a little of each process in turn
  - this is called *process scheduling*

Threads

- A process often corresponds to a program
  - Browser, editor, ...
- Modern processes often have multiple threads of execution.
- Roughly,
  - different processes are largely independent of each other;
  - different threads of the same process often share the same memory space.

Thread Scheduling

- Within a single thread, instructions are processed one at a time.
- However, different threads can run at different times/rates.
- When a thread runs is determined by many factors:
  - Java implementation;
  - Operating system
  - Instructions being executed
  - ....

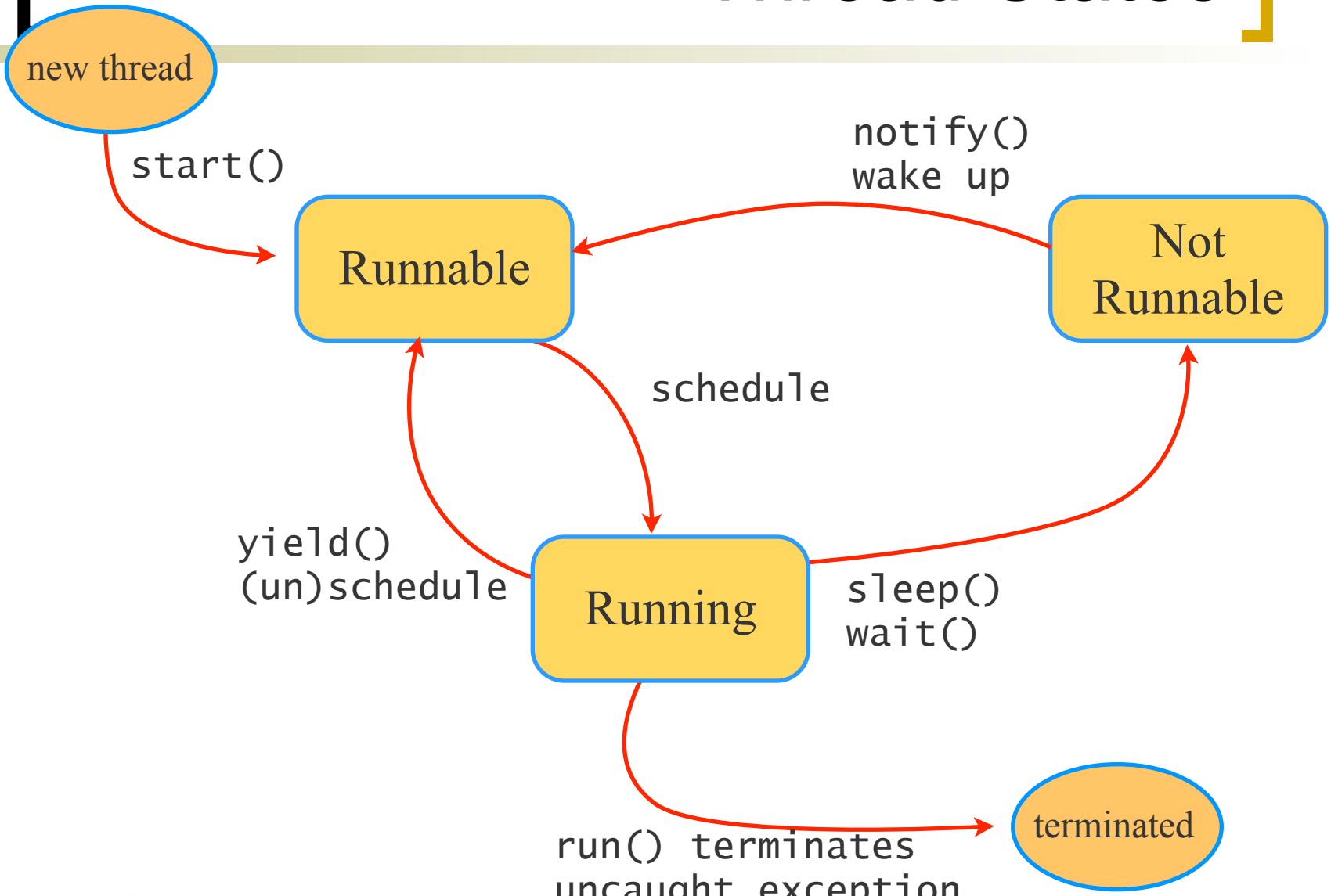
Non-determinism

- An important property of threads is that it is not possible to know exactly when a given thread will be scheduled
  - cannot assume anything about relative ordering between threads (more later)
- Order of concurrent threads (and consequently the result of the output) may change from run to run!
- Programmer must anticipate all possible orderings and protect against possible errors.

Controlling thread scheduling

- As a programmer we have several mechanism available:
  - sleep()
    - thread cannot be scheduled for some time
  - yield()
    - voluntarily give up your turn for the CPU
  - wait()
    - wait for some condition to be true
  - Priority
    - Each thread has a priority. Can set priorities for threads we create (with some limitations).

Thread States



Thread scheduling

- At any given time there may be a number of threads that are runnable
  - each has a priority
  - usually the same as the creating thread's priority
- Periodically, the OS schedules one of the threads with the highest priority for some time.

Synchronization example

- Say we want to try to control the relative ordering of two threads:
  - thread1 prints: “Left, Left, Left” then “Left”
  - thread2 prints: “Right”
- Suppose we want to ensure the following output:
  - “Left, Left, Left, Right, Left” multiple times.
  - How can we ensure that the timing of the threads ensures this output?
  - I.e., how to avoid non-determinism?

Attempt 1: using sleep()

```
public class LeftThread extends Thread {
   public void run(){
      for(int i=0;i<10;i++){
         System.out.print("Left ");
         System.out.print("Left ");
         System.out.print("Left ");
         try {
            Thread.sleep(50);
         } catch (InterruptedException e){
            e.printStackTrace();
         }
         System.out.println("Left ");
      }
   }
}
```

```
public class RightThread extends Thread {
   public void run(){
      try {
         Thread.sleep(10);
      } catch (InterruptedException e) {
         e.printStackTrace();
      }
      for(int i=0;i<10;i++){
         System.out.print("Right ");
         try {
            Thread.sleep(50);
         } catch (InterruptedException e) {
            e.printStackTrace();
         }
      }
   }
}
```

Problems with sleep()

- Doesn't work
  - There is no guarantee that with the sleeping we will get synchronized each time
  - With enough chances, will get out of sync
- There may be unnecessary waiting
- Hard to tune the sleep times

Attempt 2: using yield()

```
public class LeftThread extends Thread {
   public void run(){
      for(int i=0;i<10;i++){
         System.out.print("Left ");
         System.out.print("Left ");
         System.out.print("Left ");
         Thread.yield();
         System.out.println("Left ");
      }
   }
}
```

```
public class RightThread extends Thread {
   public void run(){
      Thread.yield();
      for(int i=0;i<10;i++){
         System.out.print("Right ");
         Thread.yield();
      }
   }
}
```

Problems with yield()

- Assumes that the yield() calls will give control to the other thread
  - many threads may be running on the machine
  - can cause unexpected switches between our 2 threads
- With multiple cores, each will be running on a separate core -- yielding does not provide anything!
- Also doesn't work

Polling

```
public class LeftThread extends Thread {
   private RightThread right;
   private boolean done = false;
   public void setRight(RightThread right){
      this.right=right;
   }
   public void run(){
      for(int i=0;i<reps;i++){
         System.out.print("Left ");
         System.out.print("Left ");
         System.out.print("Left ");
         done = true;
         while(!right.isDone());
         right.setDone(false);
         Thread.yield();
         System.out.println("Left ");
      }
  }
  public boolean isDone() {return done;}
  public void setDone(boolean value) {done = value;}
}
```

```
public class RightThread extends Thread {
    private LeftThread left;
   private boolean done = false;
   public void setLeft(LeftThread left){
       this.left = left;
   }
   public void run(){
      for(int i=0;i<reps;i++){
         while(!left.isDone()) ;
         left.setDone(false);
         System.out.print("Right ");
         done = true;
       }
   }
   public boolean isDone() {return done;}
   public void setDone(boolean value) {
       done = value;
    }
}
```

Polling solution?

- This works
  - always produces correct output.
- However,
  - No real concurrency!
  - Only one thread running at a time.
  - Busy waiting (wastes resources)
- Technicality:
  - should ensure that *done* variables are visible to the other thread immediately: use the **volatile** modifier.

Shared Memory Architecture

- Two common approaches to concurrent programs:
  - message passing
  - shared memory
- Java uses shared memory
  - multiple threads of the same application (program) essentially have access to the same memory space (i.e., variables)
  - memory on each core/CPU is not shared
  - can lead to delays in visibility of modifications (use volatile to avoid these if multiple threads will modify the same variable).

Concurrency is tricky

- Writing concurrent programs that work as expected can be tricky
- Need to deal with
  - non-determinism of scheduling
  - ensuring access to shared data is correct (see slides on Synchronization)
- Achieving speed up is not always easy

Examples

- Factorization of a large integer
  - need to find the two prime factors of a large integer value
  - divide the task by domain decomposition
- Array summation
  - compute the sum of the sine of all values of a large array
  - divide by domain decomposition
  - need to synchronize after sub-tasks are done

Factorization

```
public class FactorThread extends Thread {
    private long lower;
    private long upper;
    public static final int THREADS = 4;
    public static final long NUMBER = 59984005171248659L;
    public FactorThread(long lower, long upper){
        this.lower = lower;
        this.upper = upper;
    }
    public void run(){
        if(lower%2==0)
            lower++;
        while(lower<upper) {
            if(NUMBER%lower == 0) {
                System.out.println("Security Code: " + (lower + NUMBER/lower));
                return;
            }
            lower += 2;
        }
  }
    public static void main (String[] args ) {...}
}
```

Factorization (main)

```
public static void main(String[] args){
   FactorThread[] threads  = new FactorThread[THREADS];
   long root = (long)Math.sqrt(NUMBER);
   long start = 3;
   long numbers = (long)Math.ceil((root-2)/(float)THREADS);

   for(int i=0;i<THREADS;i++){
      threads[i] = new FactorThread(start, Math.min(start
      +numbers, root+1));
      threads[i].start();
      start+=numbers;
   }
   try{
      for(int i=0;i<THREADS;i++)
         threads[i].join();
   } catch (InterruptedException e){
      e.printStackTrace();
   }
}
```

Matrix Sum

```
import java.util.Random ;
public class SumThread extends Thread {
   private static double [] data ;
   private static SumThread [] threads ;
   private double sum = 0;
   private int lower, upper, index ;
   public static final int SIZE = 1000000;
   public static final int THREADS = 8;
   public SumThread (int lower, int upper, int index) {
      this.lower = lower;
      this.upper = upper;
      this.index = index;
   }
   public double getSum () { return sum ; }
   public void run () { //next slide }
   public static void main ( String [] args ) { // next slide }
}
```

Matrix Sum (contd.)

```
public void run () {
   for ( int i = lower ; i < upper ; i++ )
      sum += Math.sin( data [i]);
      int power = 2;
      int neighbor;
      while (index % power == 0 && power < THREADS) {
         neighbor = index + power / 2;
         try { threads [ neighbor ].join (); }
         catch ( InterruptedException e ) {
            e. printStackTrace ();
         }
         sum += threads [ neighbor ].getSum ();
         power *= 2;
      }
   }
   . . .
```

Matrix (contd.)

```
   public static void main ( String [] args ) {
      data = new double [ SIZE ];
      Random random = new Random ();
      int start = 0;
      for ( int i = 0; i < SIZE ; i++ )
         data [i] = random . nextDouble ();
      threads = new SumThread [ THREADS ];
      int range = ( int) Math . ceil ( data . length / ( float ) THREADS );
      for ( int i = 0; i < THREADS ; i++ ) {
         threads [i] = new SumThread ( start, Math . min( start + range , SIZE ), i );
         threads [i]. start ();
         start += range ;
      }
      try { threads [0]. join (); }
      catch ( InterruptedException e ) {
         e. printStackTrace ();
      }
      System .out. println ("Sum: " + threads [0]. getSum ());
   }
}
```