CS 230
01 - Threading Introduction

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Resources

For a complementary view:

- The Java Tutorial Trail: Essential Classes
  - Lesson: Concurrency
- The Java Tutorial Trail: Creating a GUI With JFC/Swing
  - Lesson: Concurrency in Swing
    - Initial Threads, The Event Dispatch Thread
- *MultiThreaded toolkits: A failed dream?*, Graham Hamilton `http://weblogs.java.net/blog/kgh/archive/2004/10/multithreaded_t.html`
- The Java API (J2SE7 Documentation)

Quiz: How many threads does your program have?

- Briefly, a thread is a single sequential flow of control within a program.
- To find out (1) the number of logical cores and (2) which thread runs a particular method, use

```
1 int Runtime.getRuntime().availableProcessors()
2 long Thread.currentThread().getId()
```

- Command-line
  - Initial thread: the thread that starts the main()
- Swing
  - Initial thread: the thread that starts the main() and typically disappears soon thereafter
  - Event-dispatch thread (EDT, aka "GUI" thread): runs the event loop

Typical problems that threading solves

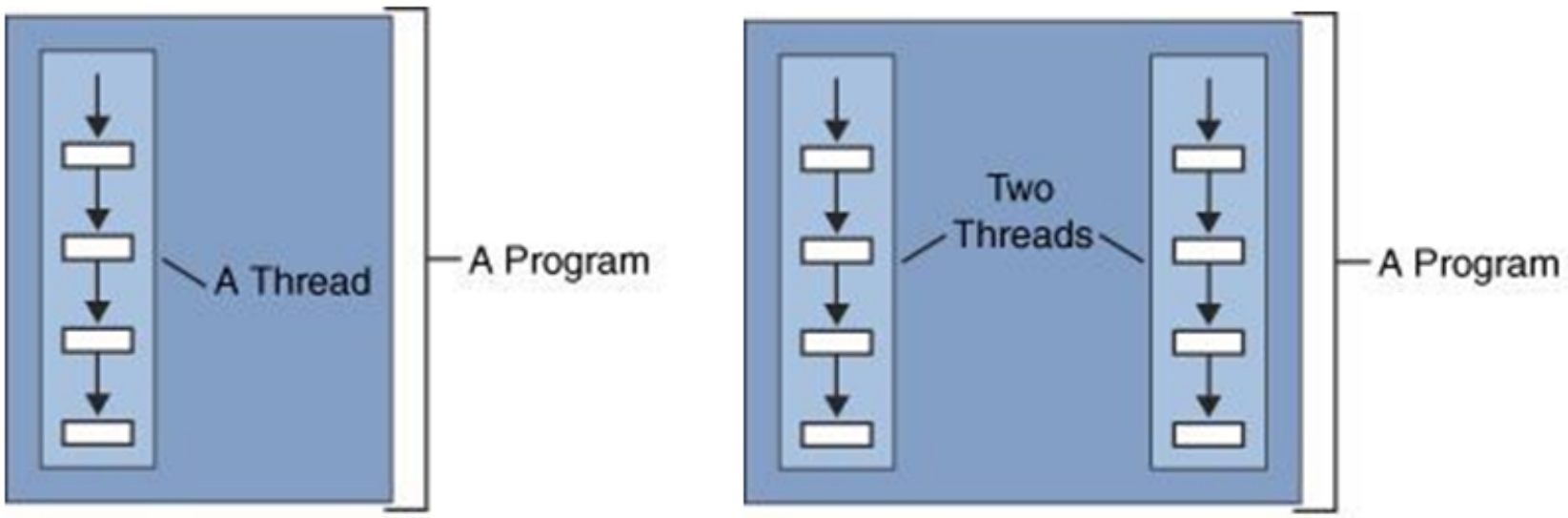
- Designing efficient applications
  - Which use all the available processing power, e.g., on multi-core machines
  - DEMO: Ray Tracing
- Designing responsive applications
  - Which remain responsive even when a GUI event handler starts a long computation (or a network/database operation)
  - DEMO: Celsius Converter
- Designing programs that must do several distinct logical tasks
  - Browsers that must download several pages in parallel
  - Servers that must service multiple clients concurrently
  - DEMO: Dining Philosophers

Concurrency with Threads

In general, we consider:

- Concurrency between processes (distinct programs inside the operating system)
- Concurrency between threads ("lightweight processes", inside the same program)
- Definition: Logically, a thread is a single sequential flow of control within a program.
- Until now, we have probably used to think that a program has a single sequential flow
- However, this seldom the case, a modern program usually has quite a few threads
- Especially OO (such as Java, .NET) and GUI systems (we'll talk more about this later)

Threads



- Left: A single thread running within a program
- Right: Two threads running within a program

Multiple threads within the same program

How do multiple threads physically run in the same program?
(abbreviations: C#=core no., T#=thread no., S#=slice no.)

- Ideally, each thread runs on its own core – on computers with several cores, but this is seldom possible

  C#1: T#1 ...
  C#2: T#2 ...

- Threads can also run interleaved, even on a single core, where each threads gets in turn a succession of time slices

  C#1: T#1.S#1 T#2.S#1 T#2.S#2 T#3.S#2 ...
  C#2: T#3.S#1 T#1.S#2 T#1.S#3 T#2.S#3 ...

Multiple threads within the same program

- In general, the order and the size of the time slices is not predictable: it is risky mistake to assume anything less than *total chaos*
- The design and coding must take extra steps to ensure a proper coordination, if this is important

Multiple threads within the same program

A thread can temporarily cease its execution:

- Voluntarily: the thread itself issues sleep or yield commands – this is known as cooperative scheduling: *imagine a voluntary zip on lane merging*
  - DEMO: Bouncer: "selfish" threads are bad, for the system and in the end for themselves
- Enforced: by the OS scheduler – on systems that support so-called preemptive time slicing: *imagine lane merging with traffic lights*

How Are Threads Reified?

- At a low level, threads (i.e. sequential statement *flows*) are typically reified into manipulable instances of class **Thread**
- The two faces of the thread:

1. Thread = a logical control flow
2. Thread = a "control panel" to manipulate threads (1)

- A class **Thread** is available in most modern languages, e.g., in Java, C#, ...
- OS Threads vs Java Threads : not always 1:1 (not further discussed here)

How To Use Threads—Bird's eye view

- Implement your own threads using the system Thread or Runnable types
  - Low-level and a bit costly (thread creations are costly operations, even a waiting thread takes up some resources, despite it seems doing "nothing")
- Use thread-pools such as provide by Executor or Swing
  - Good enough for many applications, typically pools of about 25 threads, which are recycled, to avoid the cost of thread creation and destruction.
- Implicitly, using specific API such as Timer or the updated high-level concurrency framework of Java 7, aka Fork-Join

How to implement your own custom Thread subclass

```
1 public class SimpleThread extends Thread {
2     public SimpleThread(String name) {
3         super(name);
4     }
5     @Override public void run() {
6         ...
7     }
8 }
```

- Subclass Thread and override its empty run method, so that it does something
- The constructor sets the Thread's name, which could be used later, e.g., via getName().
- The overridden run method: the *heart* of any Thread — also known as its Task

The SimpleThread's Task

```
1     @Override public void run() {
2         for (int i = 0; i < 10; i++) {
3             System.out.println(i+" "+getName());
4             try {
5                 sleep((long)(Math.random() * 1000));
6             } catch (InterruptedException ex) {}
7         }
8         System.out.println("DONE! "+getName());
9     }
```

- Here, this task *iterates* 10 times
- *prints* some results
- *sleeps* for a random time interval
- we need a try block, because a *sleeping* thread can be awaken by an exception triggered from another thread (*later*)

Testing our custom SimpleThread

```
1 public class TwoThreadsTest {
2     public static void main (String[] args) {
3         new SimpleThread("Jamaica").start();
4         new SimpleThread("Fiji").start();
5
6         // something is missing here (more a few slides later)
7     }
8 }
```

- The main method creates and then starts two threads (immediately following their construction)
- by calling their start method
- which in turn calls our SimpleThread's run method
- You do not call run directly; if you do so, it will be a normal method call (no threading) – more *later*

SimpleThread's sample output (many possible) ↓

```
0 Jamaica
0 Fiji
1 Jamaica
1 Fiji
2 Jamaica
3 Jamaica
```

```
2 Fiji
3 Fiji
4 Jamaica
5 Jamaica
6 Jamaica
4 Fiji
```

```
7 Jamaica
8 Jamaica
9 Jamaica
5 Fiji
6 Fiji
7 Fiji
```

```
DONE!
Jamaica
8 Fiji
9 Fiji
DONE! Fiji
```

- The output from each thread is intermingled with the output from the other
- The order is not predictable
- Worst things could happen if the two threads would attempt to use a shared data item without proper synchronization (more *later*)

How to implement your own Runnable class?

```
1  public class SimpleRunnable implements Runnable {
2    public void run() {
3      String name = Thread.currentThread().getName();
4
5      for (int i = 0; i < 10; i++) {
6        System.out.println(i+" "+name);
7        try {
8          Thread.sleep((long)(Math.random() * 1000));
9        } catch (InterruptedException ex) {}
10     }
11
12     System.out.println("DONE! "+name);
13   }
14 }
```

- Similar to SimpleThread, but we need a longer way to pick up the thread's name

Testing our custom SimpleRunnable

```
1  public class TwoRunnablesTest {
2      public static void main (String[] args) {
3          new Thread(new SimpleRunnable(), "Jamaica")
4                  .start();
5          new Thread(new SimpleRunnable(), "Fiji")
6                  .start();
7
8          // something is missing here (more a few slides later)
9      }
10 }
```

- Similar to TwoThreadsTest, but we use another Thread constructor, which takes a Runnable object (our SimpleRunnable's)

When to use a Thread subclass and when a runnable task?

- Subclassing from Thread may seem *simpler*...
- However, implementing a Runnable task offers more *flexibility*
- It allows you to subclass from a *different* type (i.e., *not* from Thread)
- It provides support for more advanced scenarios, that use the Task concept

Daemon Threads

- There are two kinds of threads: daemon threads and non-daemon threads
- Daemon threads, aka service or background threads: provide support for the non-daemon threads and don't need to exist without these
- Consequence: if all non-daemon threads terminate, then the daemon threads automatically terminate (daemon threads cannot keep the application alive)
- Non-daemon threads:
  - the main thread (for console apps)
  - the event dispatching thread (for GUI apps) – in most frameworks, only this thread is legally allowed to update the GUI (therefore, it is also known, colloquially, as the GUI thread)

Daemon Threads

- You can *check* if a thread is daemon by isDaemon()
- You can *mark* a thread as daemon by setDaemon(true) *or*
- *mark* it as non-daemon by setDaemon(false)

How to terminate an application that uses threads?

- A *single-threaded* console application terminates when its main and only thread, which is non-daemon, completes its task (e.g., reaches the final "}")
- A *multiple-threaded* console application terminates when its main thread, which is non-daemon, and all its other non-daemon threads terminate
- These two extra lines, at the end of our demos, prompt the user to terminate the main thread, which will also terminate the program, if all the other threads are daemon

```
1        System.out.println("<enter> to exit");
2        System.in.read();
```

How to terminate an application that uses threads?

- A GUI application has a non-daemon thread running the GUI event dispatching loop
- typically, closing the main form will stop this GUI thread *and*
- if there is no other non-daemon thread, all daemon threads will be stopped and the application will terminate
- An application can be also stopped by explicitly calling System.exit ...

Thread Joins

To allow one thread to wait for the completion of another thread, use the method Thread.join(), e.g.:

```
1  Thread tj = new SimpleThread("Jamaica");
2  Thread tf = new SimpleThread("Fiji");
3
4  tj.start();
5  tf.start();
6
7  tj.join();
8  tf.join();
9
10 System.out.println("JOINED!");
```

Thread interruptions

To interrupt another thread, use the method Thread.interrupt(), e.g.:

```
1 Thread tj = new SimpleThread("Jamaica");
2 tj.start();
3
4 ...
5
6 tj.interrupt();
```

This requires some cooperation from the interrupted thread, such as *tj*

Thread interruptions

Methods such as Thread.sleep(...), Thread.join(...) and Object.wait(...) *automatically check* if the current thread has received an interrupt(), and, if so, will raise an InterruptedException

Without such methods, such a check should be periodically performed by calling Thread.interrupted()

```
1     if (interrupted()) ...
```

Thread interruptions

Consequently, threads which use Thread.sleep(...), Thread.join(...) or Object.wait(...) must provide adequate exception handling, e.g.:

```
1   try {
2       sleep((long)(Math.random() * 2000));
3   } catch (InterruptedException ex) {
4       System.out.println("INTERRUPTED! "+getName());
5       return;
6   }
```

Summary of Thread class API – check Java Doc

```
1  public interface Runnable {
2      void run()
3  }
```

```
1  public class Thread implements Runnable {
2      Thread()
3      Thread(String name)
4      Thread(Runnable target)
5      Thread(Runnable target, String name)
6
7      public void start() // call this to start the run
8      public void run()   // fill this but never call it directly
9
10     // continued on next slide
```

Summary of Thread class API – check Java Doc

```
1  public class Thread implements Runnable {
2      // continued from previous slide
3
4      public static Thread currentThread()
5      public String getName()
6      public boolean isDaemon()
7      public void setDaemon(boolean on)
8      public void join() throws InterruptedException
9      public void join(long millis)
10                          throws InterruptedException
11     public void sleep(long millis)
12                          throws InterruptedException
13     public void interrupt()
14     public static boolean interrupted()
15     public static void yield()
16 }
```

Thread interference

Consider an object of the following class, concurrently used by several threads:

```
1 class Counter {
2     private int c = 0;
3     public int value() { return c; }
4     public void increment() { c++; }
5     public void decrement() { c--; }
6 }
```

What can go wrong?

Thread interference

- Imagine that two threads call increment(), successively. If initially c==0, then the result should and will be c==2.
- Imagine now that two threads call increment(), at about the same time. What can go wrong?
- Even a simple operation such as c++ is not atomic; it corresponds to a sequence of atomic operations such as the following (where *r* is one the thread's arithmetic registers):

```
1  1. LOAD  r, c   // LOAD is a read operation
2  2. INC   r      // INC is a modify operation
3  3. STORE r, c   // STORE is a write operation
```

- What can go wrong?

Thread interference

- The two threads can interleave in many ways, some of them with unexpected wrong results:

```
1  Thread t1
2  .
3  LOAD r1, c
4  INC r1
5  .
6  .
7  .
8  STORE r1, c
```

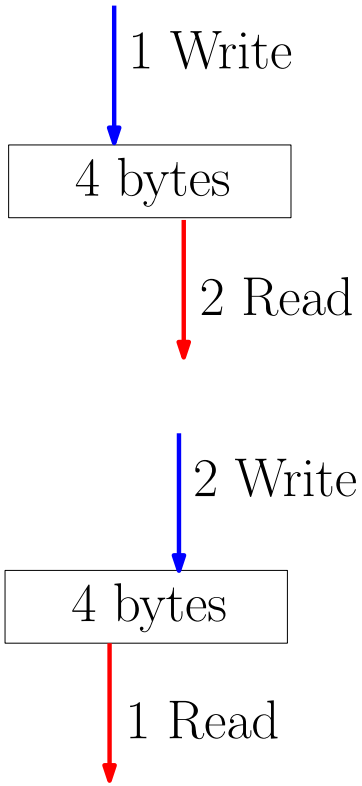
```
1  Thread t2
2  .
3  .
4  .
5  LOAD r2, c
6  INC r2
7  STORE r2, c
8  .
```

- In the above case, the final value of both r1 and r2 will be 1!
- This value 1 will be stored twice in c, with the net wrong result c==1, instead of the expected 2!

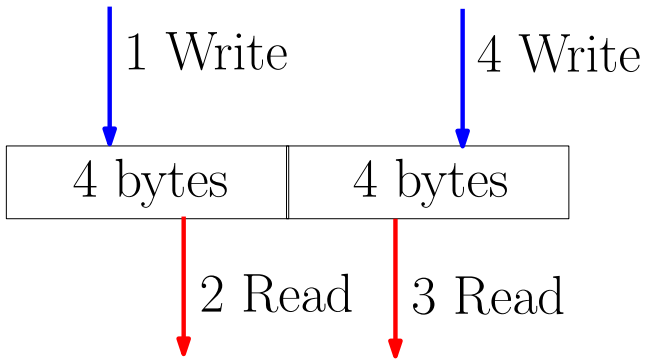
Atomic operations

- A *single* read or a write for reference variables and most primitive values: int, float, but not long and double.
- A *single* read or a write for variables declared volatile (including long and double)
- Problem: How to protect non-atomic operations or longer operation sequences (e.g., read+modify+write) against interference?
- We'll see this over the next lectures

Left: **int** R/W atomic $\surd$; Right: **long** R/W ?



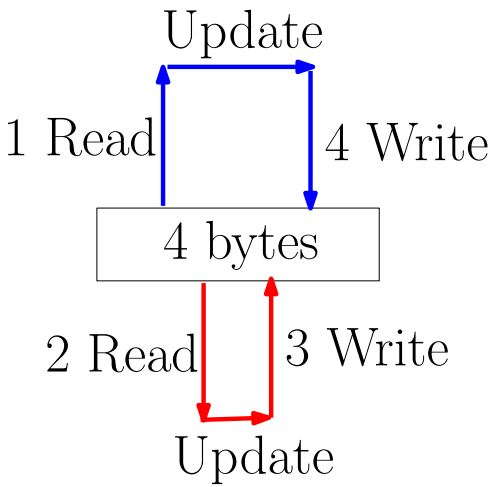
As for read, but inconsistent scenarios are also possible, e.g.:

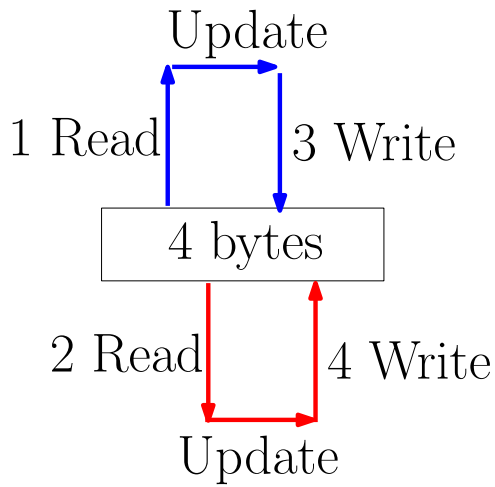


You can fix this, by declaring that **long** variable **volatile**

Note that **volatile** does *not* help in more complex scenarios, e.g., if each thread executes a read+update+write operation (*next slide*)

int R/U/W scenarios with inconsistent results





Making the **int** variable **volatile** does *not* help here

Memory consistency errors

Assume that x and y start with the initial value 0.

```
1 Thread t1
2 STORE 1, x // x = 1;
3 ...
4 STORE 2, y // y = 2;
```

```
1 Thread t2
2 LOAD r2, y // ... = y;
3 ...
4 LOAD r2, x // ... = x;
```

In "pathological" cases, thread $t2$ may see y==2, but still x==0!

Causes for memory consistency errors:

- Compilers attempt optimizations which may *reorder* existing statements:
  `x = 1; y = 2;` ⇒ `y = 2; x = 1;`
- *next slide*

Memory consistency errors–Not required

Sample scenario where reordering may occur:

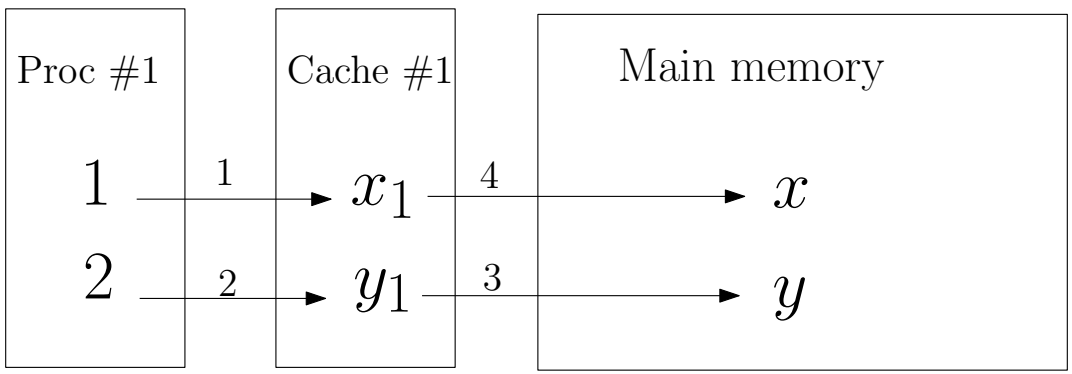
```
1  Source code
2  x = ...
3  y = ...
4  z = ... y ...
```

```
1  Reordered code
2  y = ...
3  x = ...
4  z = ... y ...
```

Variable y is evaluated first, before x, to make pipelined evaluation of z more likely (here given by an expression which uses y, but not x)

Memory consistency errors–Not required

Another cause for memory consistency errors: cache consistency model (architecture dependent)



- Besides main memory, copies of the variables are kept in cache memories or registers — thus the same variable may have *multiple copies*, not always synchronized (simplified diagram)

Memory consistency errors–Not required

- Memory consistency is treated differently by different Java versions, using different *happens-before* and *memory barrier* models.
- It also depends on the *physical architecture* of the machine.
- Such errors are avoided by the *synchronization* and *lock* techniques which will be taught (if properly applied).
- We do not further this topic in this course.

Single Threaded GUIs

As mentioned in a previous handout, Swing is NOT thread-safe: there are important restrictions concerning GUI access from other threads

- Most Swing component methods (create, update, repaint, ...) must be invoked from the GUI (event dispatch) thread only!
- There a few exceptions, mentioned in the API as "thread safe"
- Programs that ignore these rules may appear to function correctly, most of the time, but are subject to unpredictable errors
- This is true, not only for Swing, but for all modern GUI toolkits, including .NET

Failed dreams — thought-provoking article

Graham Hamilton, *Multithreaded toolkits: A failed dream?*

> *There are certain ideas in Computer Science that I think of as the "Failed Dreams" (borrowing a term from Vernor Vinge).*
>
> *The Failed Dreams seem like obvious good ideas. So they get periodically reinvented, and people put a lot of time and thought into them.*
>
> *They typically work well on a research scale and they have the intriguing attribute of almost working on a production scale. Except you can never quite get all the kinks ironed out...*
>
> *For me, multithreaded GUI toolkits seem to be one of the Failed Dreams. ...*

Swing specific threads

- Initial thread: the thread that starts the main()
- Event-dispatch thread (EDT, aka "GUI" thread): runs the event loop, executes drawing and short event handling code - should not run time-consuming tasks
- Worker (background) threads: for time consuming tasks - MUST NOT interact directly with the GUI (few exceptions)
- Two *high-level* solutions for the proper interaction with the GUI thread
  - Using SwingUtilities: here
  - Using SwingWorker: in the last course section (optionally)

SwingUtilities.invokeLater(*runnable-task*)

- usually invoked by the initial thread, to safely create and start the GUI
- also, often invoked from a worker thread
- schedules a given task to be asynchronously executed by the even-dispatch thread and returns immediately (without waiting the actual execution)

```
1 SwingUtilities.invokeLater(new Runnable()) {
2   public void run() {
3     // this code will be executed by the event-dispatch thread,
4     // e.g., to update the GUI
5   }
6 });
```

SwingUtilities.invokeAndWait(*runnable-task*)

- invokeAndWait() is similar to invokeLater(), but synchronously, i.e., the calling thread waits until the event-dispatch thread completes the given task