CSx55: Distributed Systems [Threads]

The House of Heap and Stacks

Stacks clean up after themselves
But over deep recursions they fret

The cheerful heap has nary a care
Harboring memory leaks, hurtling to a crash

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Frequently asked questions from the previous class survey

- Why do we call it "wire formats"
- But … a server needs only one `ServerSocket`
  - Yes, but we are referring to multiple regular `Socket`s on the server side
- Shortest paths? Is there an optimal way, is it tractable?
  - Dijkstra's algorithm
  - $O(V^2)$ dense graphs ands arrays; $O(ElogV)$ when using a binary heap for sparse graphs

Topics covered in this lecture

- Threads
  - Thread Creation
  - Heaps and Stacks
  - Thread Lifecycle

Many hands make light work. John Heywood (1546)

THREADS

Why should you care about threads?

- CPU clock rates have tapered off
  - Days when you could count on “free” speed-up are long gone
- Manufacturers have transitioned to multicore processors
  - Each with multiple hardware execution pipelines
- A single threaded process can utilize only one of these execution pipelines
  - Reduced throughput
- But more importantly, threads are awesome!

What we will look at

- Threads and its relation to processes
- Thread lifecycle
- Contrasting approaches to writing threads
- Data synchronization and visibility
  - Avoiding race conditions
- Thread safety
- Sharing objects and confinement
- Locking strategies
- Writing thread-safe classes

What are threads?

- Miniprocesses or lightweight processes
- Why would anyone want to have a *kind of process* **within** a process?

The main reason for using threads

- In many applications *multiple activities* are going on at once
  - Some of these may block from time to time

- Decompose application into multiple sequential threads
  - Running **concurrently**

Isn't this precisely the argument for processes?

- Yes, *but* there is a new dimension …
- Threads have the ability to **share the address space** (and all of its data) among themselves
- For several applications
  - Processes (with their *separate* address spaces) don't work

Threads execute their own piece of code independently of other threads, but …

- No attempt is made to achieve high-degree of concurrency transparency
  - Especially, not at the cost of performance
- Only maintains information to allow a **CPU to be shared** among several threads
- Thread context
  - CPU Context + Thread Management info
    - List of blocked threads

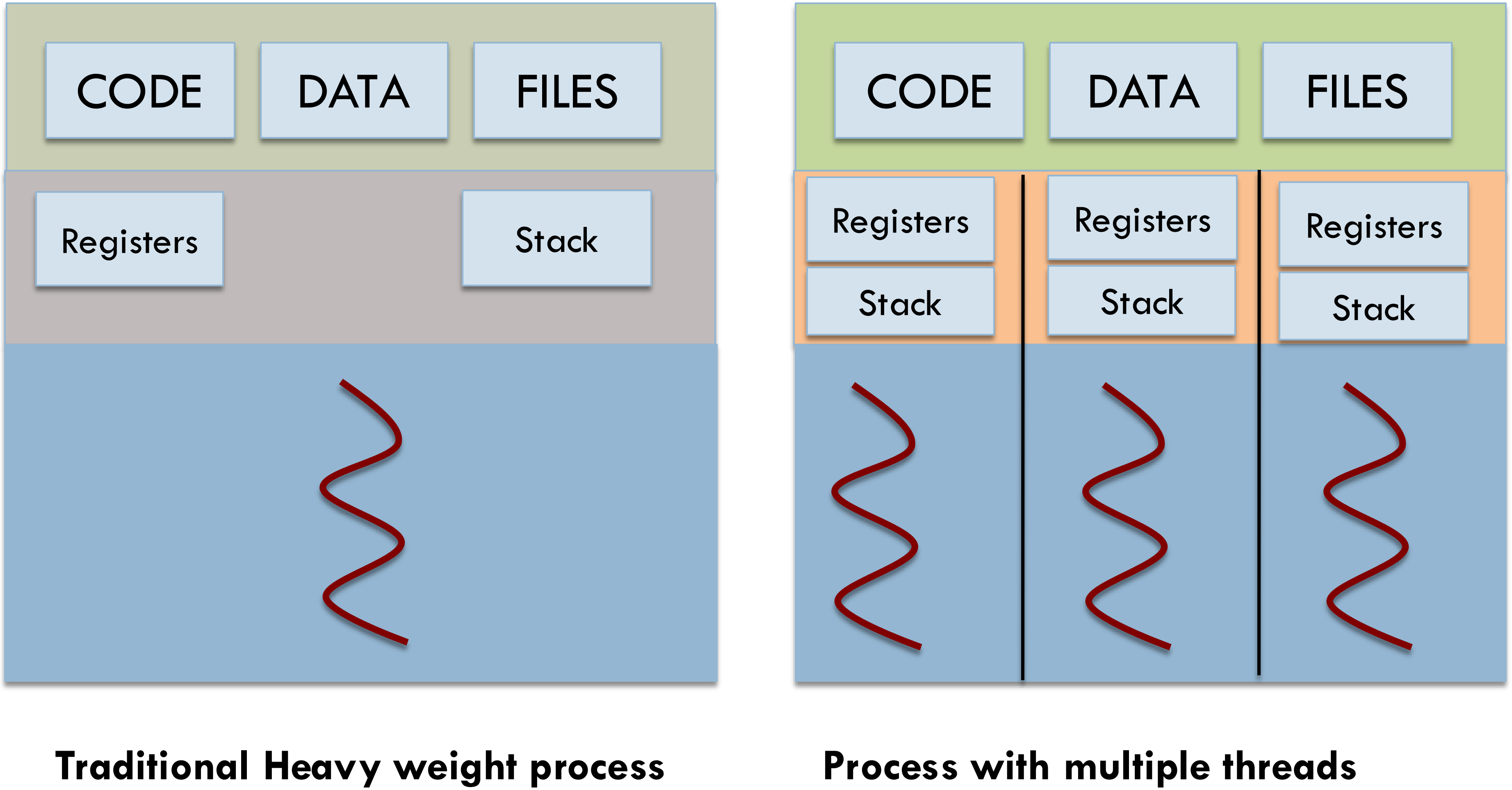
Information not strictly necessary to manage multiple threads is ignored

- Protecting data against inappropriate accesses by multiple threads *within* a process?
  - Developers must deal with this

Contrasting items unique & shared across threads

Per process items {Shared by threads with a process}	Per thread items {Items unique to a thread}
Address space	**Program Counter**
Global variables	**Registers**
Open files	**Stack**
Child Processes	**State**
Pending alarms	
Signals and signal handlers	
Accounting Information	

A process with multiple threads of control can perform more than 1 task at a time



Threads Vs. Multiple Processes

Why prefer multiple threads over multiple processes?

- Threads are **cheaper** to create and manage than processes
- Resource **sharing** can be achieved more *efficiently* between threads than processes
  - Threads within a process share the address space of the process
- Switching between threads is cheaper than for processes
- **BUT …** threads within a process are **not protected** from one another

Other costs for processes

- When a new process is **created** to perform a task there are other costs
  - In a kernel supporting virtual memory the new process will incur **page faults**
    - Due to data and instructions being referenced for the first time
- Hardware caches must *acquire new cache entries* for that particular process

Contrasting the costs for threads [1/2]

- With threads these overheads may also occur, but they are likely to be smaller

- When thread accesses code & data that was *accessed recently by other threads* in the process?
  - Automatically take advantage of any hardware or main memory caching

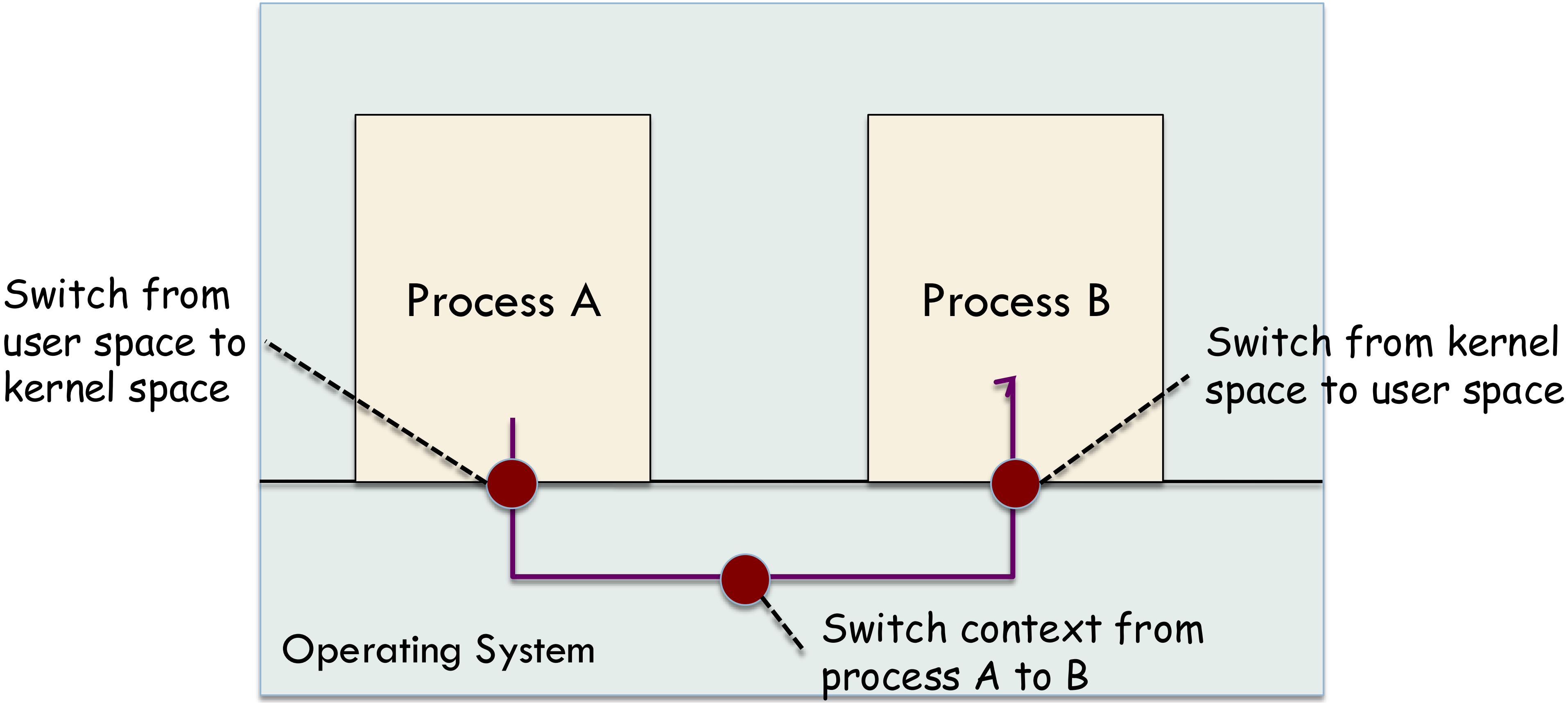
Contrasting the costs for threads [2/2]

- **Switching** between threads is much faster than that between processes
- This is a cost that is incurred *many times* throughout the lifecycle of the thread or process

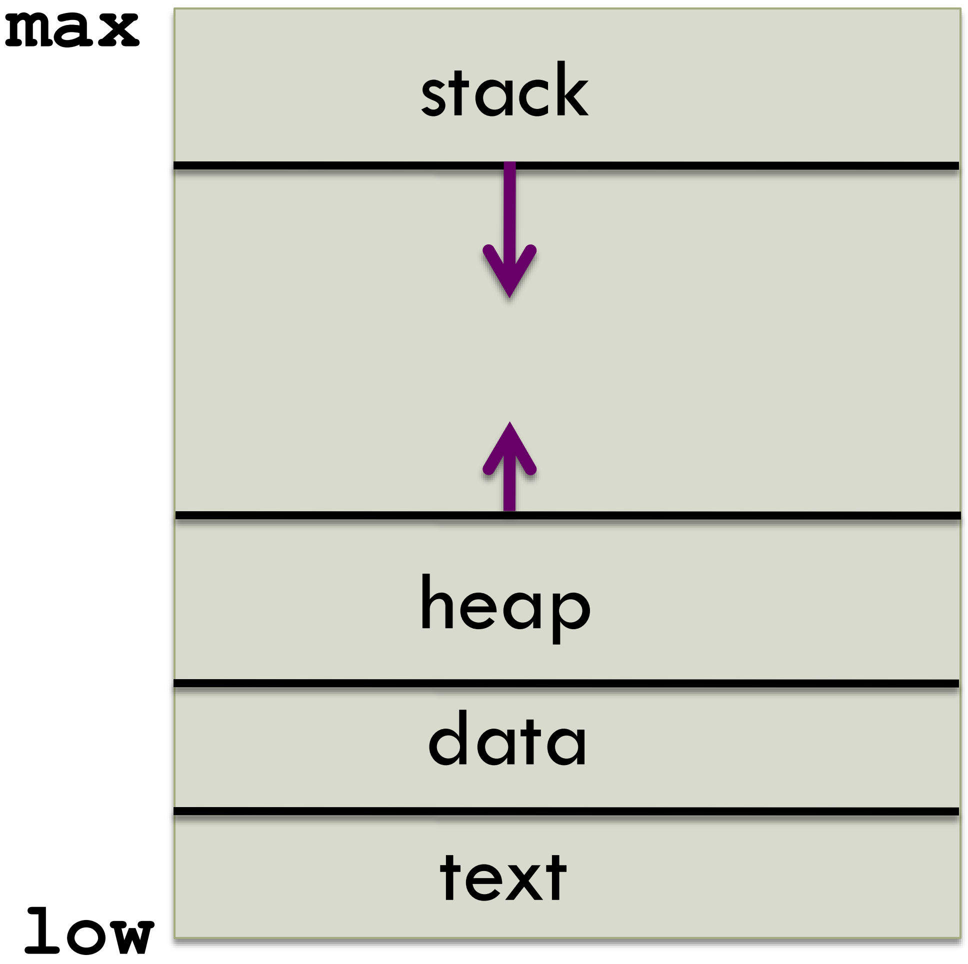
Implications?

- **Performance** of a multithreaded application is seldom worse than a single threaded one
  - Actually, leads to performance gains
- Development requires **additional effort**
  - No automatic protection against each other

Another drawback of processes is the overheads for IPC (Inter Process Communications)



A process in memory



{Function parameters,
return addresses,
and local variables}

{Memory allocated dynamically
during runtime}

{Global variables}

{Program code}

Why each thread needs its own stack [1/2]

- Stack contains one **frame** for each procedure *called but not returned from*
- Frame contains
  - Local variables
  - Procedure's return address

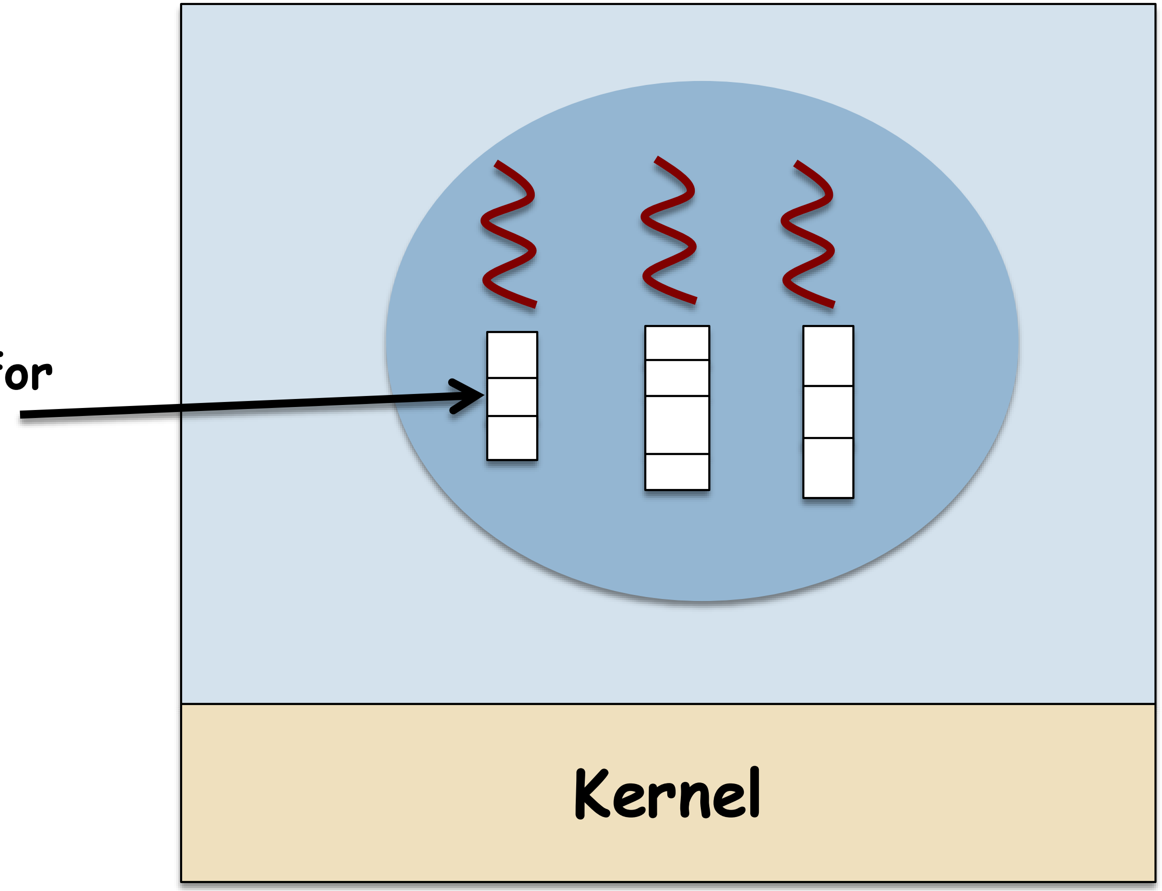
Why each thread needs its own stack [2/2]

- Procedure **`X`** calls procedure **`Y`**, **`Y`** then calls **`Z`**
  - When **`Z`** *is executing*?
    - Frames for **`X`**, **`Y`** and **`Z`** will be on the stack

- Each thread calls *different* procedures
  - So has a *different execution* history

Each thread has its own stack

Stack for thread



Almost impossible to write programs in Java without threads

- We use multiple threads without even realizing it

Blocking I/O: Reading data from a socket

- Program blocks *until data is available* to satisfy the `read()` method
- Problems:
  - Data may not be available
  - Data may be delayed (*in transit*)
  - The other endpoint sends data sporadically
- If program **block**s when it tries to read from socket?
  - Unable to do anything else *until data is actually available*

Three techniques to handle such such situations

- **I/O multiplexing**
  - Take all input sources and use system call, `select()`, to notify data availability on any of them
- **Polling**
  - Test if data is available from a particular source
    - System call such as `poll()` is used
    - In Java, `available()` on the `FilterInputStream`
- **Signals**
  - File descriptor representing signal is set
  - *Asynchronous* signal delivered to program when data is available
  - Java does not support this

Writing to a socket may also block

- If there is a **backlog** getting data onto the network
  - Does not happen in fast LAN settings
  - But if it's over the Internet? Possible.
- So, often handling TCP connections requires both a sender and receiver thread

Writing programs that do I/O in Java?

- Use multiple threads
  - Handle traditional, blocking I/O
- Use the NIO library
- Or both

We are trained to think linearly

- Often don’t see *concurrent paths* our programs may take
- No reason why processes that we conventionally think of as single-threaded should remain so

Thread Abstraction

- A **thread** is a *single execution sequence* that represents a separately schedulable task
  - **Single execution sequence**
    - Each thread executes sequence of instructions – assignments, conditionals, loops, procedures, etc. – just as the sequential programming model
  - **Separately schedulable task**
    - The OS can run, suspend, or resume a thread at any time

Thread Creation & Management

Computing the factorial of a number

```
public class Factorial {

   public static void main(String[] args)  {
      int n = Integer.parseInt(args[0]);

      int factorial = 1;
      while (n>1) {
        factorial *=n;
         n--;
      }
      System.out.println(factorial);
   }
}
```

Behind the scenes …

- Instructions are executed as machine-level assembly instructions
  - Each logical step requires many machine instructions to execute
- Applications are executed as a series of instructions
  - The *execution path* of these instructions?
    - **Thread**

Every program has at least one thread

- Thread executes the body of the application
  - In Java, this is called the **main thread**
    - Begins executing statements starting with the first statement of the `main()` method
- In Java every program has more than 1 thread
  - E.g., threads that do *garbage collection*, *compile bytecodes* into machine-level instructions, etc.
  - Programs are highly threaded
    - You may add additional application threads to this

Let's add another task to our program

- Say, computing the square-root of a number
- What if we wrote these as separate threads?
  - JVM has two distinct lists of instructions to execute
- Threads can be thought of *as tasks that we execute at roughly the same time*
- But in that case, why not just write multiple applications?

Threads that run within the same application process

- **Share the memory space** of the process
  - Information sharing is seamless
- Two diverse applications within the same machine may not communicate so well
  - For e.g., mail client and music application

In a multi-process environment data is separated by default

- This is fine for **dissimilar programs**
- Not OK for certain types of programs; e.g., a network server sends stock quotes to clients
  - Discrete task: Sending quote to client
    - Could be done in a separate thread
  - Data sent to the clients is the same
    - *No point having a separate server for each client* and …
    - *Replicating data* held by the network server

Threads and sharing

- Threads within a process can access and share any object on the **heap**
  - Each thread has space for its own local variables (stack)

- A thread is a discrete task that operates on data **shared** with other threads

Thread Creation

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Thread creation

- Using the `Thread` class
- Using the `Runnable` interface

The Thread class

```
package java.lang;

public class Thread implements Runnable {
   public Thread();
   public Thread(Runnable target);
   public Thread(ThreadGroup group, Runnable target);
   public Thread(String name);
   public Thread(ThreadGroup group, String name);
   public Thread(Runnable target, String name);
   public Thread(ThreadGroup group, Runnable target,
                 String name);
   public Thread(ThreadGroup group, Runnable target,
                 String name, long stackSize);

   public void start();
   public void run();

}
```

Threads require 4 pieces of information

- Thread **name**
  - Default is Thread-N; N is a unique number
- **Runnable target**
  - *List of instructions* that the thread executes
  - Default: `run()` method of the thread itself
- Thread **group**
  - A thread is assigned to the thread group of the thread that calls the constructor
- **Stack size**
  - Store temporary variables during method execution
  - Platform-dependent: range of legal values, optimal value, etc.

A simple thread

```
public class RandomGen extends Thread {
   private Random random;
   private int nextNumber;
   public RandomGen() {random = new Random();}

   public void run() {
     for (;;) {
       nextNumber = random.nextInt();
       try {

       } catch (InterruptedException ie) {
            ... return;
       }
     }
   }
}
```

About the code snippet

- Extends the `Thread` class

- Actual instructions we want to execute is in the `run()` method
  - Standard method of the `Thread` class
    - Place where `Thread` begins execution

Contrasting the `run()` and `main()` methods

- `main()` method
  - This is where the *first thread starts executing*
  - The **main thread**

- The `run()` method
  - *Subsequent threads* start executing with this method

Threads and …
Heaps And Stacks

Threads and heaps

- For performance reasons, heaps may **internally subdivide** their space into per-thread regions
  - Threads can allocate objects at the same time *without interfering* with each other
  - By allocating objects used by the same thread from the same memory region?
    - Cache hit rates may improve
- Each subdivision of the heap has thread-local variables
  - Track parts of thread-local heap in use, those that are free, etc.
- New memory allocations (`malloc()` and `new()`) can take memory from **shared heap**, only if local heap is used up

How big a stack? [1/2]

- The size of the stack must be large enough to accommodate the **deepest nesting level** needed during the thread's *lifetime*
- Kernel threads
  - Kernel stacks are allocated in physical memory
  - The nesting depth for kernel threads tends to be small
  - E.g., 8KB default in Linux on an Intel x86
  - Buffers and data structures are allocated on the heap and never as procedure local variables

How big a stack? [2/2]

- User-level stacks are allocated in virtual memory
- To catch program errors
  - Most OS will trigger **error** if the program stack grows too large too quickly
    - Indication of an unbounded recursion
  - Google's GO will automatically grow the stack as needed … this is very uncommon
  - POSIX, for e.g., allows default stack size to be library dependent (e.g. larger on a desktop, smaller on a phone)
    - "Exceeding default stack limit is very easy to do, with the usual results"
      - Program termination

Thread Lifecycle

Lifecycle of a thread

- Creation
- Starting
- Terminating
- Pausing, suspending, and resuming

Thread: Methods that impact the thread's lifecycle

```
public class Thread implements Runnable {
   public void start();
   public void run();
   public void stop();
   public void resume();
   public void suspend();
   public static void sleep(long millis);
   public boolean isAlive();
   public void interrupt();
   public boolean isInterrupted();
   public static boolean interrupted();
   public void join();
}
```

Deprecated, do not use (stop(), resume(), suspend())

Thread creation

- Threads are represented by instances of the `Thread` class
- When you extend the `Thread` class?
  - Your instances are also `Threads`
- We looked at the 4 constructor arguments in the `Thread` class

Starting a thread [1/2]

- Thread exists once it's been constructed
  - But it is *not executing* … it's in a **waiting** state
- In the waiting state, other threads can *interact* with the existing **thread object**
  - Object state may be changed by other threads
    - Via method invocations

Starting a thread [2/2]

- When we're ready for a thread to begin executing code
  - Call the **`start()`** method
  - `start()` performs internal house-keeping and *then calls* the **`run()`** method
- When the `start()` method returns?
  - **Two threads** are executing in parallel
    1. The original thread which just returned from calling **`start()`**
    2. The newly started thread that is executing its **`run()`** method

After a thread's `start()` method is called

- The new thread is said to be **alive**
- The `isAlive()` method tells you about the state
  - `true`: Thread has been started and *is executing* its `run()` method
  - `false`: Thread may *not be started* yet or may be *terminated*

Terminating a thread

- Once started, a thread executes only one method: `run()`
- This `run()` may be complicated
  - May *execute forever*
  - Call *several other methods*
- Once the `run()` *finishes* executing, the thread has **completed** its execution

Like all Java methods, `run()` finishes when it …

1. Executes a `return` statement
2. Executes the last statement in its method body
3. When it *throws an exception*
   - Or fails to catch an exception thrown *to it*

The only way to terminate a thread?

- Arrange for its `run()` method to **complete**
- But the documentation for the `Thread` class lists a `stop()` method?
  - This has a *race condition* (unsafe), and has been deprecated

Some more about the `run()` method

- Cannot throw a ***checked*** exception
- But it can throw an ***unchecked*** exception
  - Exception that extends the `RuntimeException`
- A thread can be **stopped** by:
  1. *Throwing* an unchecked exception in `run()`
  2. *Failing to catch* an unchecked exception thrown by something that `run()` has called

Pausing, suspending and resuming threads

- Some thread models support the concept of **thread suspension**
  - Thread is told to *pause* execution and then told to *resume* its execution
- Thread contains `suspend()` and `resume()`
  - Suffers from vulnerability to *race conditions*: **deprecated**
- Thread can *suspend its own execution* for a specified period
  - By calling the `sleep()` method

But sleeping is not the same thing as thread suspension

- With true thread suspension
  - One thread can suspend (and later resume) *another thread*
- `sleep()` affects only the thread that executes it
  - Not possible to tell another thread to go to sleep

But you can achieve the functionality of suspension and resumption

- Use `wait` and `notify` mechanisms
- Threads **must be coded** to use this technique
  - This is not a generic suspend/resume that is imposed by another thread

Thread cleanup

- As long as some other active object holds a reference to the terminated thread object
  - Other threads can execute methods on the terminated thread … retrieve information
- If the object representing the terminated thread goes *out of scope*?
  - The thread object is **garbage collected**

Holding onto a thread reference allows us to determine if work was completed

- Done using the `join()` method
- The `join()` method
  - **Blocks** until the thread has completed
  - *Returns immediately* if
    - The thread has already completed its `run()` method
      - You can call `join()` any number of times
- Don't use `join()` to poll if the thread is still running
  - Use `isAlive()`

The contents of this slide-set are based on the following references

- *Java Threads. Scott Oaks and Henry Wong. . 3rd Edition. O'Reilly Press. ISBN: 0-596-00782-5/978-0-596-00782-9.* [Chapters 3, 4]