A thread is an execution state of a process (e.g. the next instruction to execute, the values of CPU registers, the stack to hold local variables, etc.)

- Thread state is separate from global process state, such as the code, open files, global variables (on the heap), etc.

Single and Multithreaded Processes

- **Single-threaded process**
  - Code
  - Data
  - Files
  - Registers
  - Stack

- **Multithreaded process**
  - Code
  - Data
  - Files
  - Registers
  - Registers
  - Registers
  - Stack
  - Stack
  - Stack

thread

single-threaded process

multithreaded process

thread
Benefits of Threads

- **Responsiveness** - user interaction in a GUI can be responded to by a separate thread from that, say, doing long running computation (e.g. saving a file, running some algorithm, etc.)
- **Resource Sharing** - Threads within a certain process share its address space and can therefore use shared variables to communicate, which is more efficient than passing messages.
- **Economy** - Threads are often referred to as light-weight processes, since running a system with multiple threads has a smaller memory footprint than the equivalent with multiple processes.
- **Scalability** - For multi-threaded processes it is much easier to make use of parallel processing (e.g. multi-core processors, and distributed systems)
- **Reduce programming complexity** - Since problems can be broken down into parallel tasks, rather than more complex state machines.
Multithreaded Server Architecture

1. Request
2. Create new thread to service the request
3. Resume listening for additional client requests
Multithreaded Processes

Overview
Concurrent and Parallel Execution
User and Kernel Threads

Multicore Programming

- Multicore systems are putting pressure on programmers, with challenges that include:
  - Dividing activities - How can we make better use of parallel processing?
  - Balance - How should we balance the parallel tasks on the available cores to get maximum efficiency?
  - Data splitting - How can data sets be split for processing in parallel and then rejoined (e.g. SETI@home)
  - Data dependency - Some processing must be performed in a certain order, so synchronisation of tasks will be necessary.
  - How to test and debug such systems?
Concurrent and Parallel Execution

Single-core Concurrent Thread Execution

\[\text{single core} \quad \begin{array}{cccccccc}
T_1 & T_2 & T_3 & T_4 & T_1 & T_2 & T_3 & T_4 & T_1 & \ldots
\end{array}\]

Multicore Parallel Thread Execution

\[\begin{array}{cccccccc}
\text{core 1} & T_1 & T_3 & T_1 & T_3 & T_1 & \ldots \\
\text{core 2} & T_2 & T_4 & T_2 & T_4 & T_2 & \ldots \\
\end{array}\]
User Threads

- Thread management done by user-level threads library
- Three primary thread libraries:
  - POSIX Pthreads
  - Win32 threads
  - Java threads
Kernel Threads

- Threading is supported by modern OS Kernels
- Examples:
  - Windows XP/2000
  - Solaris
  - Linux
  - Mac OS X
Threading Models

- A particular kernel (e.g. on an embedded device, or an older operating system) may not support multi-threaded processes, though it is still possible to implement threading in the user process.
- Therefore many threading models exist for mapping user threads to kernel threads:
  - Many-to-One
  - One-to-One
  - Many-to-Many
Many-to-One

- Many user-level threads mapped to single kernel thread/process
- Useful if the kernel does not support threads
- But what if one user thread calls a blocking kernel function?
  - This will block the whole process \((i.e.\) all the other user threads)\)
  - Complex solutions exist where the user-mode thread package intercepts blocking calls, changes them to non-blocking and then implements a user-mode blocking mechanism.
Many-to-One

You could implement something like this yourself, by having a process respond to timer events that cause it to perform a context switch in user space (e.g. store current registers, CPU flags, instruction pointer, then load previously stored ones)

- Since most high-level languages cannot manipulate registers directly, you would have to write a small amount of assembler code to make the switch.

Examples:

- GNU Portable Threads: http://www.gnu.org/software/pth/
Many-to-One

![Diagram showing the Many-to-One threading model]

- The diagram illustrates the Many-to-One threading model where one kernel thread manages multiple user threads.

Threading Models

- Many-to-One
- One-to-One
- One-to-One
- Many-to-Many
- Two-Level Model
One-to-One

- Each user-level thread maps to kernel thread
- But, to switch between threads a context switch is required by the kernel.
- Also, the number of kernel threads may be limited by the OS
- Examples:
  - Windows NT/XP/2000
  - Linux
  - Solaris 9 and later
One-to-One

- user thread
- kernel thread

Threading Models
- Many-to-One
- One-to-One
  - One-to-One
  - Many-to-Many
  - Two-Level Model
Many-to-Many

- Allows many user level threads to be mapped to many kernel threads
  - Best of both worlds
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9
- Windows NT/2000 with the ThreadFiber package
Many-to-Many

- User thread
- Kernel thread

- Many-to-Many threading model
Similar to many-to-many, except that it allows a user thread optionally to be bound directly to a kernel thread

Examples:

- IRIX
- HP-UX
- Tru64 UNIX
- Solaris 8 and earlier
Two-Level Model

- User threads are managed by kernel threads.
- Kernel threads handle the scheduling and resource allocation.
- This model provides a balance between user and kernel processes.
Unclear Semantics of UNIX \texttt{fork()} system call

- Does \texttt{fork()} duplicate only the calling thread or all threads?
- Sometimes we want this, and sometimes we don’t, so some UNIX systems provide alternative fork functions.
Thread Cancellation

- How to terminate a thread before it has finished?
- Two general approaches use by programmers:

  - **Asynchronous cancellation** terminates the target thread immediately
    - Useful as a last resort if a thread will not stop (e.g. due to a bug, etc.)

  - **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
    - This approach is often considered to be much cleaner, since the thread can perform any clean-up processing (e.g. close files, update some state, etc.)
Signals are used in UNIX systems to notify a process that a particular event has occurred.

A signal handler is used to process signals:
- Signal is generated by particular event
- Signal is delivered to a process
- Signal is handled by some function

Not so straightforward for a multi-threaded process. Options are:
- Deliver the signal to the thread to which the signal applies
- Deliver the signal to every thread in the process
- Deliver the signal to certain threads in the process
- Assign a specific thread to receive all signals for the process

In most UNIX systems a thread can be configured to receive or block (i.e. not handle) certain signals to help overcome these issues.
Thread Pools

- Under a high request-load, multithreaded servers can waste a lot processing time simply creating and destroying threads.

  **Solution:**
  - Pre-create a number of threads in a pool, where they await work

  **Advantages:**
  - Usually slightly faster to service a request with an existing thread than create a new thread
  - Allows the number of threads in the application(s) to be bound to the size of the pool, to ensure some level of service for a finite number of clients.
Thread Libraries

- Thread library provides programmer with API for creating and managing threads
- Two primary ways of implementing
  - Library entirely in user space
  - Kernel-level library supported by the OS
Pthreads

- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
- API specifies behaviour of the thread library, implementation is up to development of the library
- Common in UNIX operating systems (Solaris, Linux, Mac OS X)
- Example: threadtest.c. Note, this is an implementation of POSIX Pthreads, so compiles differently!
Windows XP Threads

- Implements the one-to-one mapping (i.e. kernel-level threads)
- Each thread contains
  - A thread id
  - Register set
  - Separate user and kernel stacks
  - Private data storage area
- The register set, stacks, and private storage area are known as the context of the threads
- The primary data structures of a thread include:
  - ETHREAD (executive thread block) - Stores general info about a thread: its parent process, address of the instruction where the thread starts execution.
  - KTHREAD (kernel thread block) - Stores kernel-level state of the thread: kernel stack, etc.
  - TEB (thread environment block) - Stores user-level state of the thread: user stack, thread-local storage.
Windows XP Threads

- Ethread
  - thread start address
  - pointer to parent process

- Kthread
  - scheduling and synchronization information
  - kernel stack

- TEB
  - thread identifier
  - user stack
  - thread-local storage

Kernel space vs. user space
Linux Threads

- Linux refers to them as tasks rather than threads
- Thread creation is done through `clone()` system call
- `clone()` allows a child task to share the address space of the parent task (process) and can be passed flags to control exactly what resources are shared.

<table>
<thead>
<tr>
<th>flag</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLONE_FS</td>
<td>File-system information is shared.</td>
</tr>
<tr>
<td>CLONE_VM</td>
<td>The same memory space is shared.</td>
</tr>
<tr>
<td>CLONE_SIGHAND</td>
<td>Signal handlers are shared.</td>
</tr>
<tr>
<td>CLONE_FILES</td>
<td>The set of open files is shared.</td>
</tr>
</tbody>
</table>
Java Threads

- Java threads are managed by the JVM
- Typically implemented using the threads model provided by underlying OS
- Java threads may be created by:
  - Extending Thread class
  - Implementing the Runnable interface