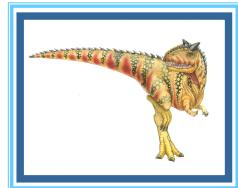


# Chapter 4: Threads & Concurrency

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## Chapter 4: Threads

- Overview
- Multicore Programming
- Multithreading Models
- Threading Issues
- Operating System Examples



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## Objectives

- Identify the basic components of a thread, and contrast threads and processes.
- Describe the major benefits and challenges in designing multithreaded processes.
- Describe how the Windows and Linux operating systems represent threads

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## Motivation

- Many applications are **multithreaded**
  - A web browser might have one thread displaying images or text while another thread retrieving data from the network
  - A word processor may have a thread for displaying graphics, another thread for responding to keystrokes from the user, and a third thread for performing spelling and grammar checking in the background
- Most operating system kernels are multithreaded
  - For example, during system boot time on Linux, several kernel threads are created. Each thread performs a specific task, such as managing devices, memory management, or interrupt handling
- It can take advantage of processing capabilities on multicore systems
  - Parallel programming widely used in applications such as data mining, graphics, and artificial intelligence
- Process creation is time consuming and resource intensive
  - Process creation is **heavy-weight** while thread creation is **light-weight**, in which different threads belonging to the same process share code, data and others



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## Examples of Multithreaded Programs

- Embedded systems
  - Elevators, planes, medical systems, wristwatches
  - Single program, concurrent operations
- Most modern OS kernels
  - Internally concurrent to deal with concurrent requests by multiple users
  - But no protection needed within kernel
- Database Servers
  - Access to shared data by many concurrent users
  - Also background utility processing must be done
- Network Servers
  - Concurrent requests from network
  - Again, single program, multiple concurrent operations
  - File server, Web server, and airline reservation systems
- Parallel Programming
  - Split a program and data into multiple threads for parallelism

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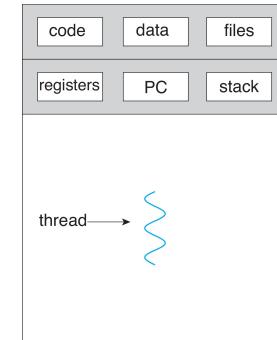
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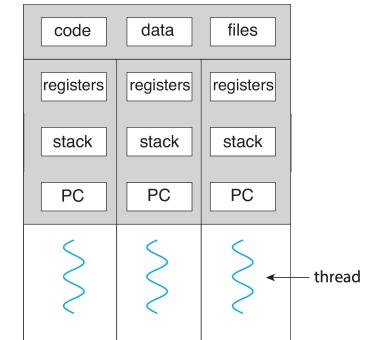


## Single and Multithreaded Processes

- Recall that a **thread** is a basic unit of CPU utilization, represented by a **thread ID**, a **program counter (PC)**, a **register set**, and a **stack**. It shares with other threads of the same process its code, data, and other operating system resources, such as open files and signals



single-threaded process



multithreaded process

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## Benefits

- **Responsiveness** – may allow continued execution if part of process (e.g., one thread of a process) is blocked, this could be especially important for interactive applications having user interfaces
- **Resource Sharing** – threads share resources of the process by default, easier than shared memory or message passing – as they essentially run within the same address space
- **Economy** – thread creation is much “cheaper” than process creation (consuming less time and memory), context switching is typically faster between threads than between processes
- **Scalability** – processes can take advantage of multicore architectures

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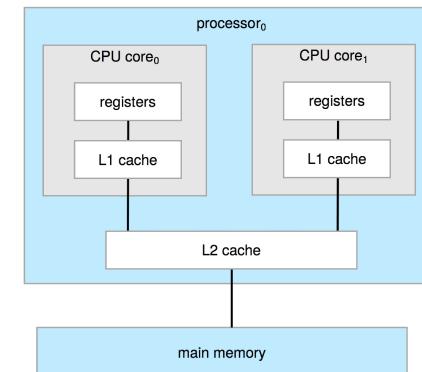
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## A Multi-Core Design

- The multithreaded programming provides a mechanism for more efficient use of multicores and improves concurrency in **multicore** systems.



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## Multicore Programming

- Multicore or multiprocessor systems, programming challenges include:
  - Dividing tasks – how to divide into separate, concurrent tasks
  - Balance – each task perform “equal” amount of work
  - Data splitting - data used by tasks must be divided to run on separate cores
  - Data dependency – if there is a data dependency, synchronization is required
  - Testing and debugging – different path of executions makes debugging difficult
- Parallelism - a system can perform more than one task simultaneously
- Concurrency supports more than one task for making progress
  - Multiplexed over time, single processor core, scheduler provides concurrency
- The advent of multicore systems require an entirely new approach in designing software systems with particular emphasis on parallel programming.

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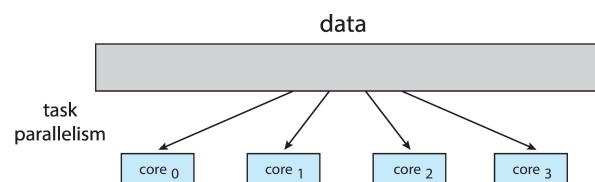
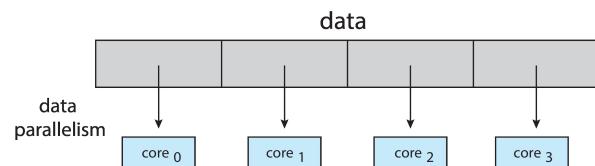
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## Data and Task Parallelism

- Data parallelism – distributes subsets of the same data across multiple cores, same operation on each core (common in distributed machine learning tasks)
- Task parallelism – distributing threads across cores, each thread performing unique operation
- Data and task parallelism are not mutually exclusive, an application may use both - hybrid



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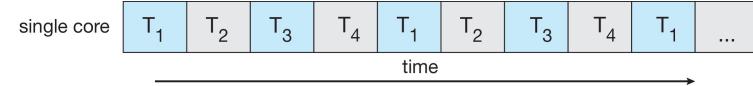
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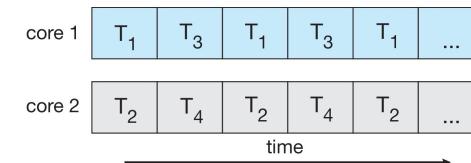


## Concurrency vs. Parallelism

- Concurrent execution on single-core system – multiplexing over time



- Parallel execution on a multi-core system:



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## Amdahl's Law

- Identifies performance gains from adding additional cores to an application that has both serial and parallel components
- S is serial portion
- N processing cores

$$\text{speedup} \leq \frac{1}{S + \frac{(1-S)}{N}}$$

- That is, if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times
- As  $N$  approaches infinity, speedup approaches  $1/S$

Serial portion of an application has a disproportionate effect on performance gained by adding additional cores

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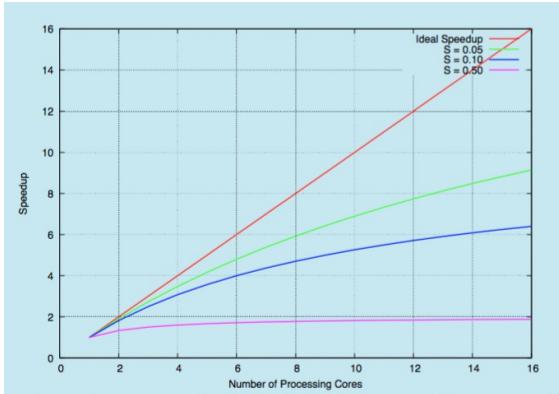
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## Amdahl's Law

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## Multithreaded Process

- A multi-threaded process has more than one **instance of execution** - multiple program counters, and each of which is being fetched and executed from
- A thread is similar to a process, except they share the same address space and thus can access the same set of data with other thread(s) in a process
- The state of a single thread is also very similar to that of a process - It has a program counter (PC) that tracks where the program is fetching instructions from. Each thread has its own private set of registers for computation
- If two threads run on a single processor, when switching from running one (T1) to running the other (T2), a **context switch** must also take place
  - The register state of T1 must be saved and the register state of T2 restored before running T2
  - The address space remains the same, the context switch overhead is much smaller
  - When switching to a thread belonging to a different process, overhead is more
- This provides **parallelism** in process (multithreaded) execution and can enable **overlap** of I/O with other activities within a single program
  - One thread is running on CPU, and another thread of the process is doing I/O

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## Thread

- **Thread:** The single unique execution context - **lightweight process**
  - Program counter, registers, execution flags, stack
  - A thread is executing on a processor when it is resident in the registers.
  - PC register holds the address of executing instruction in the thread
  - Registers hold the root state of the thread (other state in memory)
- Each thread has a **Thread Control Block (TCB)**
  - **Execution state:** CPU registers, program counter, pointer to stack
  - **Scheduling info:** state (more later), priority, CPU time
  - **Accounting Info**
  - **Various Pointers** (for implementing scheduling queues)
  - **Pointer to enclosing process:** PCB, which process it belongs to

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## Thread State

- Threads encapsulate **concurrency**: “**active**” component of a process
- Address space encapsulates protection: “**passive**” part of a process
  - Keeps buggy program from thrashing the system
- State shared by all threads in process/address space
  - Contents of memory (global variables, heap)
  - I/O state (file descriptors, network connections, etc.)
- State “**private**” to each thread
  - Kept in **TCB = Thread Control Block**
  - CPU registers (including, program counter)
  - Execution stack (parameters, temporary variables, PC saved)

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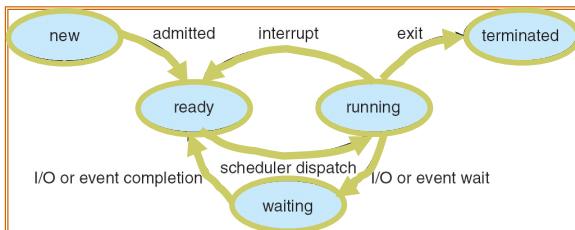
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## Lifecycle of a Thread



- As a thread executes, it changes state:
  - **new**: The thread is being created
  - **ready**: The thread is waiting to run
  - **running**: Instructions are being executed
  - **waiting**: Thread waiting for some event to occur
  - **terminated**: The thread has finished execution
- “Active” threads are represented by their TCBs
  - TCBs organized into queues based on their states

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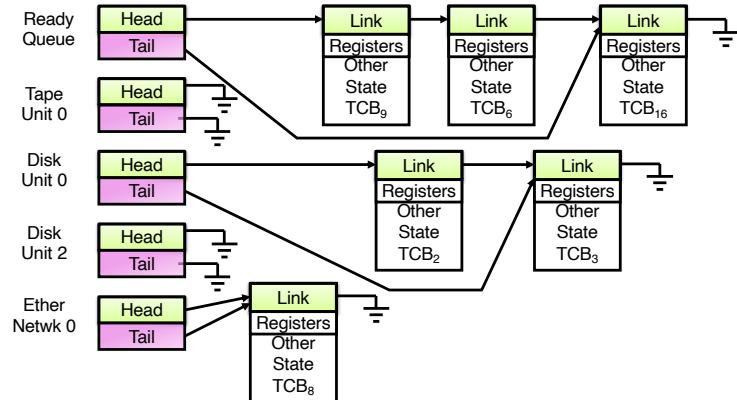
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## Ready Queue And Various I/O Device Queues

Thread not running  $\Rightarrow$  TCB is in some other queue

- Queue for each device/signal/condition, each with its own scheduling policy



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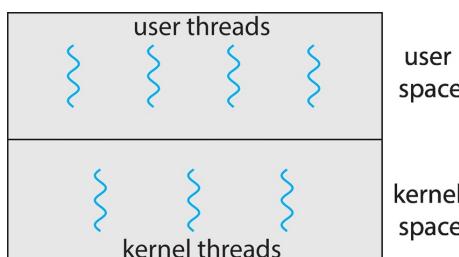
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## User Threads and Kernel Threads

- **User threads** - management done by user-level threads library
- **Kernel threads** - supported and managed by the operating system
- Examples – virtually all general purpose operating systems, including:
  - Windows, Linux, Mac OS X iOS, Android



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## Multithreading Models

- User-level threads are visible only to programmers and unknown to the operating system or kernel, consequently they can not be scheduled to run on CPU. In another word, OS only manages and schedules kernel threads
- **Threads libraries** provide APIs for creating and managing user threads in programs. There are three primary thread libraries - POSIX Pthreads, Windows threads and Java threads
  - In a way, user-level threads provide the concurrent and modular entities in a program, which the OS can potentially take advantage of
- Ultimately, a mapping must exist between user threads and kernel threads. There are three common ways of establishing such a relationship:
  - **Many-to-One**: many user-level threads mapped to one kernel thread
  - **One-to-One**: each user-level thread mapped to a kernel thread
  - **Many-to-Many**: many user-level threads mapped to many kernel threads

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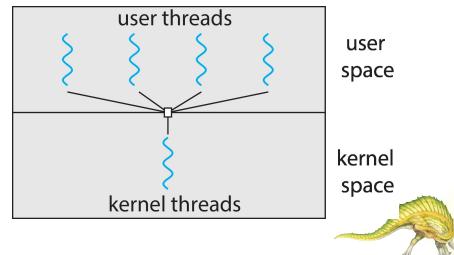
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## Many-to-One

- Many user-level threads mapped to single kernel thread
- Which thread is currently mapped to the kernel thread is a scheduling problem, known as [process-contention scope](#) or PCS (to be discussed in Chapter 5)
- One thread blocking causes all threads mapped to this thread to block, i.e., the entire process is blocked
- Multiple threads may not run in parallel on multicore system because only one kernel thread can be active at a time
- Few systems currently use this model
- Examples:
  - Solaris Green Threads
  - GNU Portable Threads



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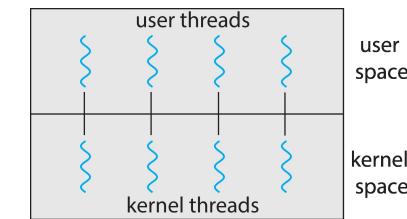
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## One-to-One

- Each user-level thread maps to one kernel thread
- It provides more concurrency than many-to-one model, and it also allows multiple threads to run in parallel on multiprocessor or multicore systems
- This implies that creating a user-level thread mandates creating a corresponding kernel thread – the number of threads per process sometimes can be restricted due to overhead (kernel threads consume resources such as memory, I/O and etc.)
- Examples
  - Windows
  - Linux

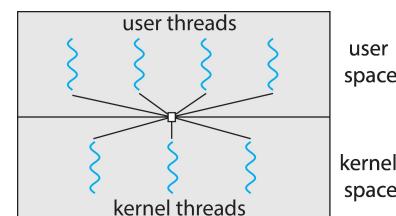


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## Many-to-Many Model

- Multiplexes many user-level threads to a smaller or equal number of kernel threads, specific to a particular application or machine
- This allows the operating system to create a sufficient number of kernel threads in advance – thread pool
- Windows with the ThreadFiber package
- Otherwise not very common



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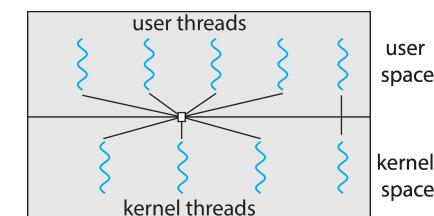
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## Two-level Model

- Similar to Many-to-Many model, except that it allows a user thread to be **bound** to kernel thread



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## Multithreading Mapping Models

- The many-to-many model most flexible, but can be difficult to implement in practice
  - For instance, an application may be allocated more kernel threads on a system with eight processing cores than on a system with four cores
- With an increasing number of processing cores in modern computer systems, limiting the number of kernel threads has become less important.
- Most operating systems now use the one-to-one model

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## Threading Issues

- Semantics of `fork()` and `exec()` system calls
- Signal handling
  - Synchronous and asynchronous
- Thread cancellation of target thread
  - Asynchronous or deferred cancellation

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## Semantics of fork() and exec()

- Does `fork()` called by a thread duplicate only the calling thread or all threads?
- Some UNIX systems have chosen to have two versions of `fork()` - If `exec()` is called immediately after forking, then duplicating all threads is unnecessary, as the program specified in the parameters to `exec()` will replace the process. In this instance, duplicating only the calling thread is appropriate.
- `exec()` usually works as normal – replace the entire process including all threads

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## Signal Handling

- **Signals** are used in UNIX systems to notify a process that a particular event has occurred. A signal may be received either *synchronously* or *asynchronously*, depending on the source of and the reason
  - Synchronous signals include illegal memory access and division by 0 - delivered to the same process that performed the operation that caused the signal (why they are considered *synchronous*)
  - When a signal is generated by an event external to a running process – asynchronous signals. Examples include terminating a process with specific keystrokes (such as <control><C>) and having a timer expires
- Signals are handled in different ways
  - Some signals may be ignored, while others (for example, an illegal memory access) are handled by terminating the program

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## Signal Handling (Cont.)

- A **signal handler** is used to process signals, following the pattern below
  - Signal is generated by a particular event (e.g., process termination)
  - Signal is delivered to a process
  - Signal is handled by one of two signal handlers, **default** or **user-defined**
- Every signal has **default handler** that kernel uses to handle that signal
  - **User-defined signal handler** can override default handler
- For a single-threaded process, signals are delivered to that process
- Where should signal be delivered for a multi-threaded process?
  - 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



## Signal Handling (Cont.)

- The method for delivering a signal depends on the type of signal generated
  - For example, synchronous signals need to be delivered to the thread causing the signal and not to other threads in the process
  - Some asynchronous signals—such as a signal that terminates a process (<control><C>, for example)—should be sent to all threads
- UNIX function for delivering signal **kill(pid t pid, int signal)**, which specifies the process (**pid**) to which a particular signal (**signal**) is to be delivered
- POSIX Pthreads function allows a signal to be delivered to a specified thread (**tid**): **pthread\_kill(pthread t tid, int signal)**



## Thread Cancellation

- Terminating a thread before it has finished, and thread to be canceled is **target thread**. The cancellation occurs in two different scenarios
  - **Asynchronous cancellation** terminates the target thread immediately
  - **Deferred cancellation** The target thread periodically checks whether it should terminate, allowing it an opportunity to terminate itself in an orderly fashion
- Invoking thread cancellation requests cancellation, but actual cancellation depends on thread **state** and **type**
- In Pthreads, if thread has cancellation disabled, cancellation remains pending until thread enables it – the default type is **deferred**

Mode	State	Type
Off	Disabled	–
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous



## Thread Cancellation (Cont.)

- Pthread code to create and cancel a thread:
  - Pthreads: POSIX standard for thread programming
  - Need to #include <pthread.h>

```

pthread_t tid;
/* create the thread */
pthread_create(&tid, 0, worker, NULL);
. . .
/* cancel the thread */
pthread_cancel(tid);
/* wait for the thread to terminate */
pthread_join(tid,NULL);

```

Start routine





## Operating System Examples

- Windows Threads
- Linux Threads

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## Windows Threads

- A Windows application runs as a separate process, and each process may contain one or more threads
- Windows API – primary API for Windows applications
- Windows uses the one-to-one mapping, where each user-level thread maps to an associated kernel thread
- The general components of a Window thread include:
  - A thread ID identifying the thread
  - Register set representing the state of the processor
  - A program counter (PC)
  - Separate user and kernel stacks when thread runs in user mode or kernel mode
  - Private data storage area used by run-time libraries and dynamic link libraries (DLLs)
- The register set, stacks, and private storage area are known as the [context](#) of the thread

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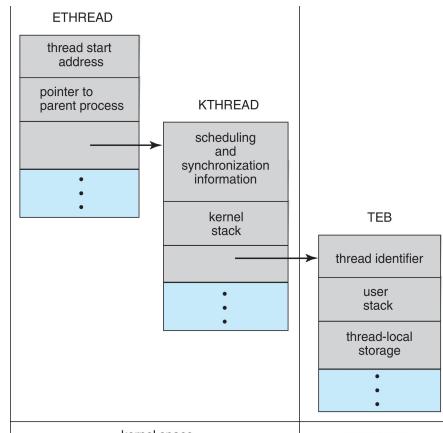
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## Windows Threads (Cont.)

The primary data structures of a thread include:

- ETHREAD (executive thread block) – includes pointer to process to which thread belongs and to KTHREAD,
- KTHREAD (kernel thread block) scheduling and synchronization info, kernel-mode stack, pointer to TEB, in kernel space
- TEB (thread environment block) – thread id, user-mode stack, thread-local storage, in user space



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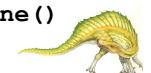
## Linux Threads

- Linux uses the term **task** rather than process or thread
- Thread creation can be done through `clone()` system call
- `clone()` allows a child task to share the part of the execution context with the parent, such as address space, file descriptors, signal handler
- Flags control behavior

flag	meaning
<code>CLONE_FS</code>	File-system information is shared.
<code>CLONE_VM</code>	The same memory space is shared.
<code>CLONE_SIGHAND</code>	Signal handlers are shared.
<code>CLONE_FILES</code>	The set of open files is shared.

```
int clone(int (*fn)(void *), void *child_stack,
          int flags, void *arg, ... );
```

- Instead of copying all data structures like `fork()`, new task points to data structures of parent task, depending on set of flags passed to `clone()`



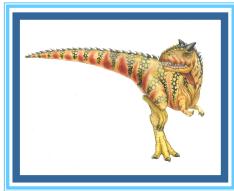
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## End of Chapter 4

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