# Exercise (could be a quiz)

In the code below, assume that *(i)* all `fork` and `execvp` statements execute successfully, *(ii)* the program arguments of `execvp` do not spawn more processes or print out more characters, and *(iii)* all `pid` variables are initialized to `0`.

a. What is the total number of processes that will be created by the execution of this code?
b. How many of each character 'A' to 'G' will be printed out?

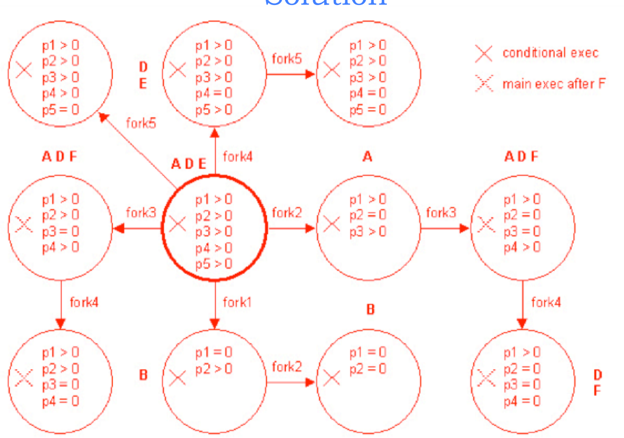
```
void main()
{
    ...
    pid1 = fork();
    pid2 = fork();
    if (pid1 != 0) {
        pid3 = fork();
        printf("A\n");
    } else {
        printf("B\n");
        execvp(...);
    }
    if (pid2 == 0 && pid3 != 0) {
        execvp(...);
        printf("C\n");
    }
    pid4 = fork();
    printf("D\n");
    if (pid3 != 0) {
        printf("E\n");
        pid5 = fork();
        execvp(...);
    }
    printf("F\n");
    execvp(...);
    pid6 = fork();
    printf("G\n");
    if (pid6 == 0)
        pid7 = fork();
}
```




```
void main()
{
    ...
    pid1 = fork();
    pid2 = fork();
    if (pid1 != 0) {
        pid3 = fork();
        printf("A\n");
    } else {
        printf("B\n");
        execvp(...);
    }
    if (pid2 == 0 && pid3 != 0) {
        execvp(...);
        printf("C\n");
    }
    pid4 = fork();
    printf("D\n");
    if (pid3 != 0) {
        printf("E\n");
        pid5 = fork();
        execvp(...);
    }
    printf("F\n");
    execvp(...);
    pid6 = fork();
    printf("G\n");
    if (pid6 == 0)
        pid7 = fork();
}
```




# Solution




# CSE 421/521 - Operating Systems
Fall 2013

## Lecture - IV
# Threads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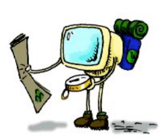
September 12th, 2013

# Roadmap

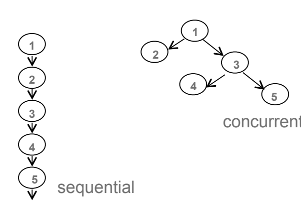
- Threads
  - Why do we need them?
  - Threads vs Processes
  - Threading Examples
  - Threading Implementation & Multi-threading Models
  - Other Threading Issues
    - Thread cancellation
    - Signal handling
    - Thread pools
    - Thread specific data





# Concurrent Programming

- In certain cases, a single application may need to run several tasks at the same time



## Motivation

- Increase the performance by running more than one tasks at a time.
  - divide the program to n smaller pieces, and run it n times faster using n processors
- To cope with independent physical devices.
  - do not wait for a blocked device, perform other operations at the background



## Divide and Compute

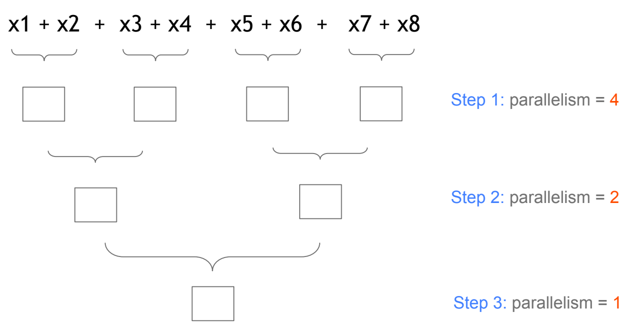
x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8

How many operations with sequential programming?
7

Step 1: x1 + x2
Step 2: x1 + x2 + x3
Step 3: x1 + x2 + x3 + x4
Step 4: x1 + x2 + x3 + x4 + x5
Step 5: x1 + x2 + x3 + x4 + x5 + x6
Step 6: x1 + x2 + x3 + x4 + x5 + x6 + x7
Step 7: x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8



## Divide and Compute






## Gain from parallelism

In theory:

- dividing a program into n smaller parts and running on n processors results in n time speedup

In practice:

- This is not true, due to
  - Communication costs
  - Dependencies between different program parts
    - Eg. the addition example can run only in log(n) time not 1/n



## Concurrent Programming

- Implementation of concurrent tasks:
  - as separate programs
  - as a set of processes or threads created by a single program
- Execution of concurrent tasks:
  - on a single processor using multiple threads
  - ➔ Multithreaded programming
  - on several processors in close proximity
  - ➔ Parallel computing
  - on several processors distributed across a network
  - ➔ Distributed computing



## Cooperating Processes

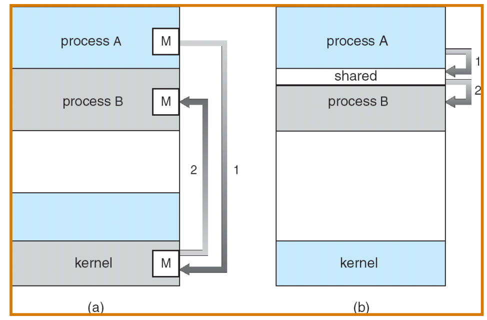
- Independent process cannot affect or be affected by the execution of another process
- Cooperating process can affect or be affected by the execution of another process
- Advantages of process cooperation
  - Information sharing
  - Computation speed-up
  - Modularity
  - Convenience
- Disadvantage
  - Synchronization issues and race conditions

## Interprocess Communication (IPC)

- Mechanism for processes to communicate and to synchronize their actions
- Shared Memory: by using the same address space and shared variables
- Message Passing: processes communicate with each other without resorting to shared variables



## Communications Models




a) Message Passing

b) Shared Memory



## Message Passing

- Message Passing facility provides two operations:
  - **send**(*message*) – message size fixed or variable
  - **receive**(*message*)
- If *P* and *Q* wish to communicate, they need to:
  - establish a *communication link* between them
  - exchange messages via send/receive
- Two types of Message Passing
  - direct communication
  - indirect communication



## Message Passing – direct communication

- Processes must name each other explicitly:
  - **send** (*P, message*) – send a message to process P
  - **receive**(*Q, message*) – receive a message from process Q
- Properties of communication link
  - Links are established automatically
  - A link is associated with exactly one pair of communicating processes
  - Between each pair there exists exactly one link
  - The link may be unidirectional, but is usually bi-directional
- Symmetrical vs Asymmetrical direct communication
  - **send** (*P, message*) – send a message to process P
  - **receive**(id, *message*) – receive a message from any process
- Disadvantage of both: limited modularity, hardcoded



## Message Passing - indirect communication

- Messages are directed and received from mailboxes (also referred to as ports)
  - Each mailbox has a unique id
  - Processes can communicate only if they share a mailbox
- Primitives are defined as:

  **send**(*A, message*) – send a message to mailbox A

  **receive**(*A, message*) – receive a message from mailbox A



## Indirect Communication *(cont.)*

- Mailbox sharing
  - $P_1$, $P_2$, and $P_3$ share mailbox A
  - $P_1$, sends; $P_2$ and $P_3$ receive
  - Who gets the message?
- Solutions
  - Allow a link to be associated with at most two processes
  - Allow only one process at a time to execute a receive operation
  - Allow the system to select arbitrarily the receiver. Sender is notified who the receiver was.

## Synchronization

- Message passing may be either blocking or non-blocking
- **Blocking** is considered **synchronous**
  - **Blocking send** has the sender block until the message is received
  - **Blocking receive** has the receiver block until a message is available
- **Non-blocking** is considered **asynchronous**
  - **Non-blocking** send has the sender send the message and continue
  - **Non-blocking** receive has the receiver receive a valid message or null

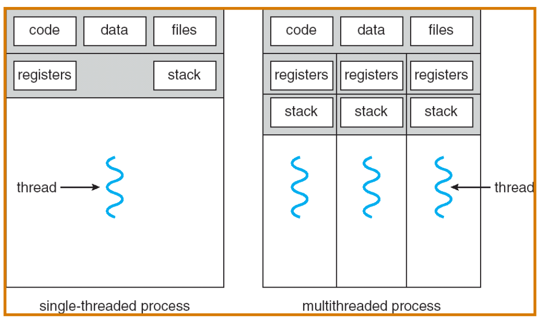


## Concurrency with Threads

- In certain cases, a single application may need to run several tasks at the same time
  - Creating a new process for each task is time consuming
  - Use a single process with multiple threads
    - faster
    - less overhead for creation, switching, and termination
    - share the same address space



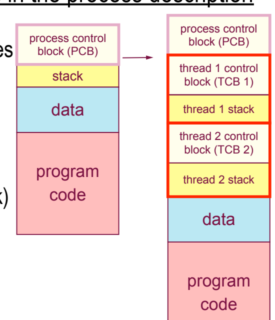
## Single and Multithreaded Processes






## New Process Description Model

- Multithreading requires changes in the process description model
  - ✓ each thread of execution receives its own control block and stack
    - own execution state ("Running", "Blocked", etc.)
    - own copy of CPU registers
    - own execution history (stack)
  - ✓ the process keeps a global control block listing resources currently used




**New process image**



## Per-process vs per-thread items

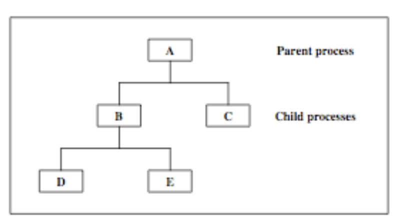
- Per-process items and per-thread items in the control block structures
  - ✓ process identification data + thread identifiers
    - numeric identifiers of the process, the parent process, the user, etc.
  - ✓ CPU state information
    - user-visible, control & status registers
    - stack pointers
  - ✓ process control information
    - scheduling: state, priority, awaited event
    - used memory and I/O, opened files, etc.
    - pointer to next PCB



## Multi-process model

Process Spawning:

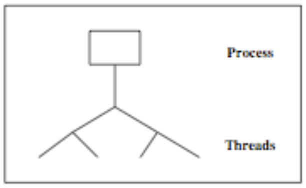
**Process creation involves the following four main actions:**
- **setting up the process control block,**
- **allocation of an address space and**
- **loading the program into the allocated address space and**
- **passing on the process control block to the scheduler**



# Multi-thread model

Thread Spawning:

- **Threads are created *within and belonging to* processes**
- **All the threads created within one process share the resources of the process including the address space**
- **Scheduling is performed on a per-thread basis.**
- **The thread model is a *finer grain scheduling model* than the process model**
- **Threads have a similar *lifecycle* as the processes and will be managed mainly in the same way as processes are**






# Threads vs Processes

- A common terminology:
  - Heavyweight Process = Process
  - **Lightweight Process = Thread**

Advantages (Thread vs. Process):

- Much quicker to create a thread than a process
  - spawning a new thread only involves allocating a new stack and a new CPU state block
- Much quicker to switch between threads than to switch between processes
- Threads share data easily

Disadvantages (Thread vs. Process):

- Processes are more flexible
  - They don't have to run on the same processor
- No security between threads: One thread can stomp on another thread's data
- For threads which are supported by user thread package instead of the kernel:
  - If one thread blocks, all threads in task block.



# Thread Creation

- **pthread_create**

```
// creates a new thread executing start_routine
int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void*), void *arg);
```

- **pthread_join**

```
// suspends execution of the calling thread until the target
// thread terminates
int pthread_join(pthread_t thread, void **value_ptr);
```



# Thread Example

```
 int main()
{
   pthread_t thread1, thread2;  /* thread variables */

   pthread_create (&thread1, NULL, (void *) &print_message_function,
                                                    (void*)"hello ");
   pthread_create (&thread2, NULL, (void *) &print_message_function,
                                                    (void*)"world!\n");

   pthread_join(thread1, NULL);
   pthread_join(thread2, NULL);

   exit(0);
}
```

**Why use pthread_join?**

To force main block to wait for both threads to terminate, before it exits. If main block exits, both threads exit, even if the threads have not finished their work.



# Exercise

Consider a process with two concurrent threads T1 and T2. The code being executed by T1 and T2 is as follows:

Shared Data:
X:= 5; Y:=10;

| <u>T1:</u> | <u>T2:</u> |
|---|---|
| Y = X+1; | U = Y-1; |
| X = Y; | Y = U; |
| Write X; | Write Y; |

Assume that each assignment statement on its own is executed as an atomic operation. What is the outputs of this process?



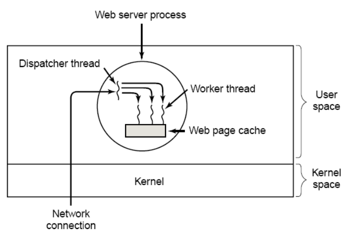
# Solution

All six statements can be executed in any order. Possible outputs are:

1) 65
2) 56
3) 55
4) 99
5) 66
6) 69
7) 96

## Threading Examples

- **Web server**
  - as each new request comes in, a “dispatcher thread” spawns a new “worker thread” to read the requested file (worker threads may be discarded or recycled in a “thread pool”)



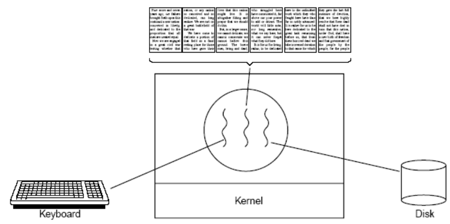

Tanenbaum, A. S. (2001) Modern Operating Systems (2nd Edition).

A multithreaded Web server



## Threading Examples

- **Word processor**
  - one thread listens continuously to keyboard and mouse events to refresh the GUI; a second thread reformats the document (to prepare page 600); a third thread writes to disk periodically



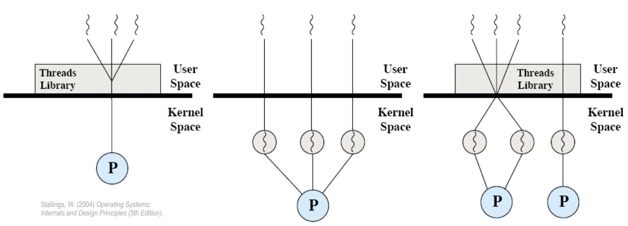

A word processor with three threads

Tanenbaum, A. S. (2001) Modern Operating Systems (2nd Edition).



## Thread Implementation

- **Two broad categories of thread implementation**
  - User-Level Threads (ULTs)
  - Kernel-Level Threads (KLTs)



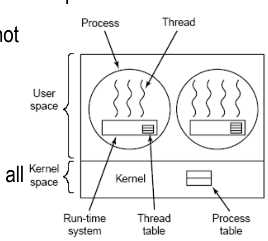

Stallings, W. (2004) Operating Systems: Internals and Design Principles (5th Edition).

Pure user-level (ULT), pure kernel-level (KLT) and combined-level (ULT/KLT) threads



## Thread Implementation

- **User-Level Threads (ULTs)**
  - the kernel is not aware of the existence of threads, it knows only processes with one thread of execution (one PC)
  - each user process manages its own private thread table
    - light thread switching: does not need kernel mode privileges
    - cross-platform: ULTs can run on any underlying O/S
    - if a thread blocks, the entire process is blocked, including all other threads in it



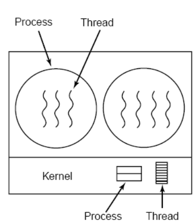

Tanenbaum, A. S. (2001) Modern Operating Systems (2nd Edition).

A user-level thread package



## Thread Implementation

- **Kernel-Level Threads**
  - the kernel knows about and manages the threads: creating and destroying threads are system calls
    - fine-grain scheduling, done on a thread basis
    - if a thread blocks, another one can be scheduled without blocking the whole process
    - heavy thread switching involving mode switch




Tanenbaum, A. S. (2001) Modern Operating Systems (2nd Edition).

A kernel-level thread package

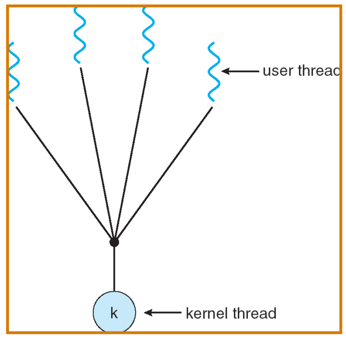


## Different Multi-threading Models

- Many-to-One
- One-to-One
- Many-to-Many
- Hybrid

## Many-to-One Model

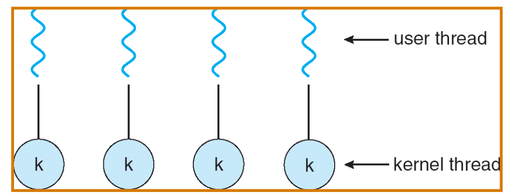
- Several user-level threads mapped to single kernel thread
- Thread management in user space → efficient
- If a thread blocks, entire process blocks
- One thread can access the kernel at a time → limits parallelism
- Examples:
  - Solaris Green Threads
  - GNU Portable Threads






## One-to-One Model

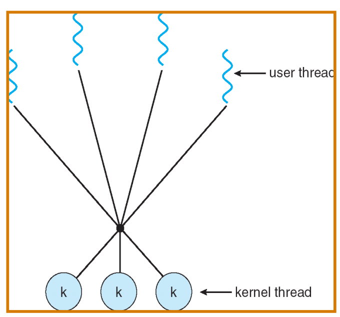
- Each user-level thread maps to a kernel thread
- A blocking thread does not block other threads
- Multiple threads can access kernel concurrently → increased parallelism
- Drawback: Creating a user level thread requires creating a kernel level thread → increased overhead and limited number of threads
- Examples: Windows NT/XP/2000, Linux, Solaris 9 and later






## Many-to-Many Model

- Allows many user level threads to be mapped to a smaller number of kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Increased parallelism as well as efficiency
- Solaris prior to version 9
- Windows NT/2000 with the *ThreadFiber* package






## Threading Issues

- Thread pools
- Thread specific data
- Semantics of **fork()** and **exec()** system calls
- Thread cancellation
- Signal handling



## Thread Pools

- Threads come with some overhead as well
- Unlimited threads can exhaust system resources, such as CPU or memory
- Create a number of threads at process startup) and put them in a pool, where they await work
- When a server receives a request, it awakens a thread from this pool
- Advantages:
  - Usually 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
- Number of threads in the pool can be setup according to:
  - Number of CPUs, memory, expected number of concurrent requests



## Semantics of fork() and exec()

- Semantics of **fork()** and **exec()** system calls change in a multithreaded program
  - Eg. if one thread in a multithreaded program calls fork()
    - Should the new process duplicate all threads?
    - Or should it be single-threaded?
  - Some UNIX systems implement two versions of fork()
  - If a thread executes exec() system call
    - Entire process will be replaced, including all threads

## Thread Cancellation

- Terminating a thread before it has finished
  - If one thread finishes searching a database, others may be terminated
  - If user presses a button on a web browser, web page can be stopped from loading further
- Two approaches to cancel the target thread
  - **Asynchronous cancellation** terminates the target thread immediately
  - **Deferred cancellation** allows the target thread to periodically check if it should be cancelled
    - More controlled and safe



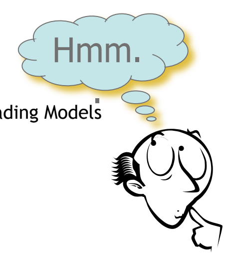
## Signal Handling

- Signals are used in UNIX systems to notify a process that a particular event has occurred
- All signals follow this pattern:
  1. Signal is generated by particular event
  2. Signal is delivered to a process
  3. Once delivered, a signal must be handled
- In multithreaded systems, there are 4 options:
  - 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



## Summary

- Why do we need them?
- Threads vs Processes
- Threading Examples
- Threading Implementation & Multi-threading Models
- Other Threading Issues
  - Thread cancellation
  - Signal handling
  - Thread pools
  - Thread specific data




- HW1 out today
- Next Lecture: CPU Scheduling
- Reading Assignment: Chapter 5 from Silberschatz.



## Acknowledgements

- "Operating Systems Concepts" book and supplementary material by A. Silberschatz, P. Galvin and G. Gagne
- "Operating Systems: Internals and Design Principles" book and supplementary material by W. Stallings
- "Modern Operating Systems" book and supplementary material by A. Tanenbaum
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