Processes and Threads

Processes

- Non-determinism & concurrency
- Why multiple processes
- Process creation, termination, switching and PCBs
- Linux Case Study

Threads

- Concepts and models
- Threads vs processes
- Posix PThread case study
- Kernel and user threads

Introduction to Processes

One of the oldest abstractions in computing

- An abstraction of a running program
- Encapsulates code and state of a program

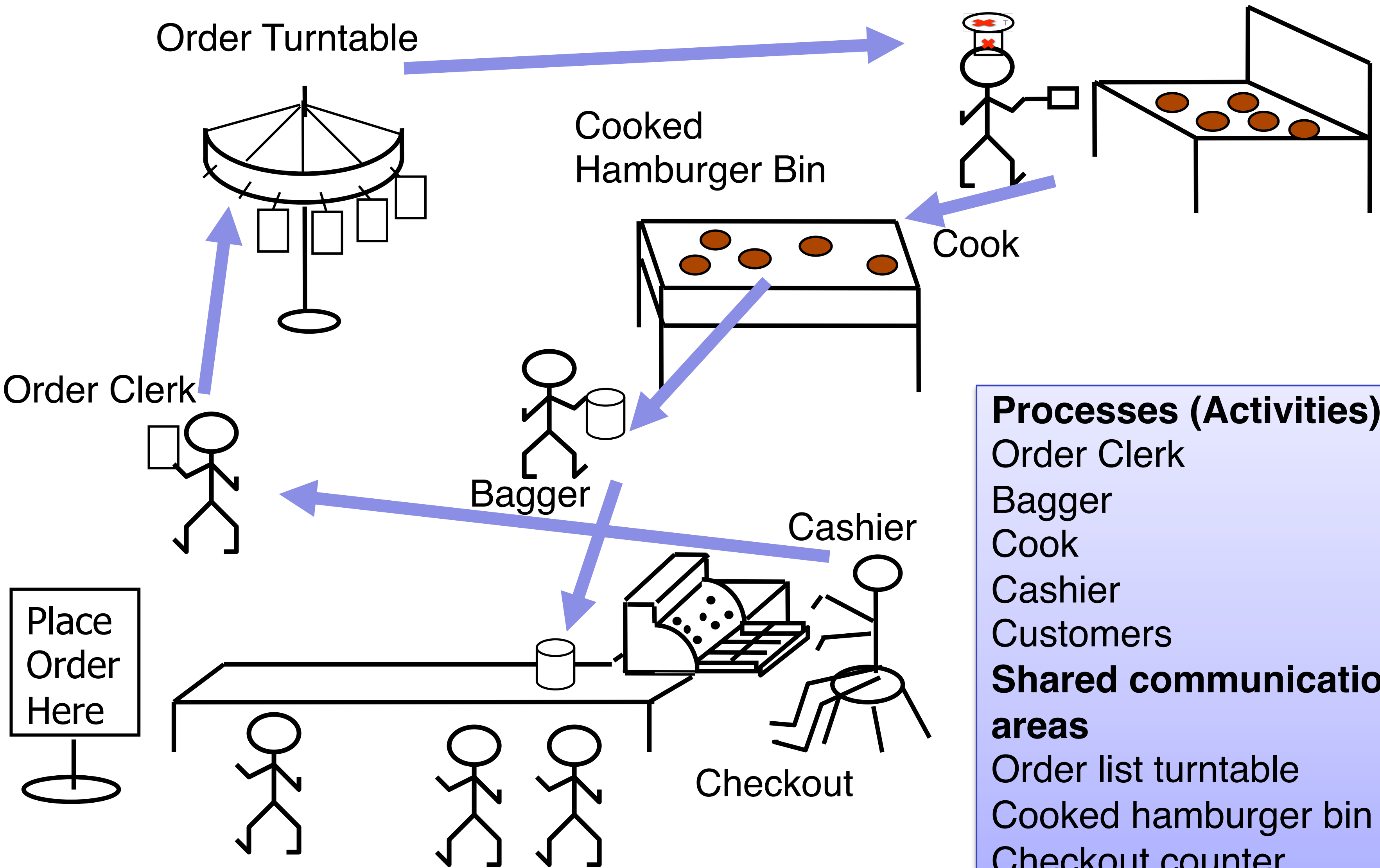
Allows a single processor to run multiple programs “simultaneously”

- Processes turn a single CPU into multiple virtual CPUs
- Each process runs on a virtual CPU

Why Have Processes?

- Provide (the illusion of) concurrency
  - Real vs. apparent concurrency
- Provide isolation
  - Each process has its own address space
- Simplicity of programming
  - E.g. Firefox does not need to worry about gcc
- Allow better utilization of machine resources
  - Different processes require different resources at a certain time

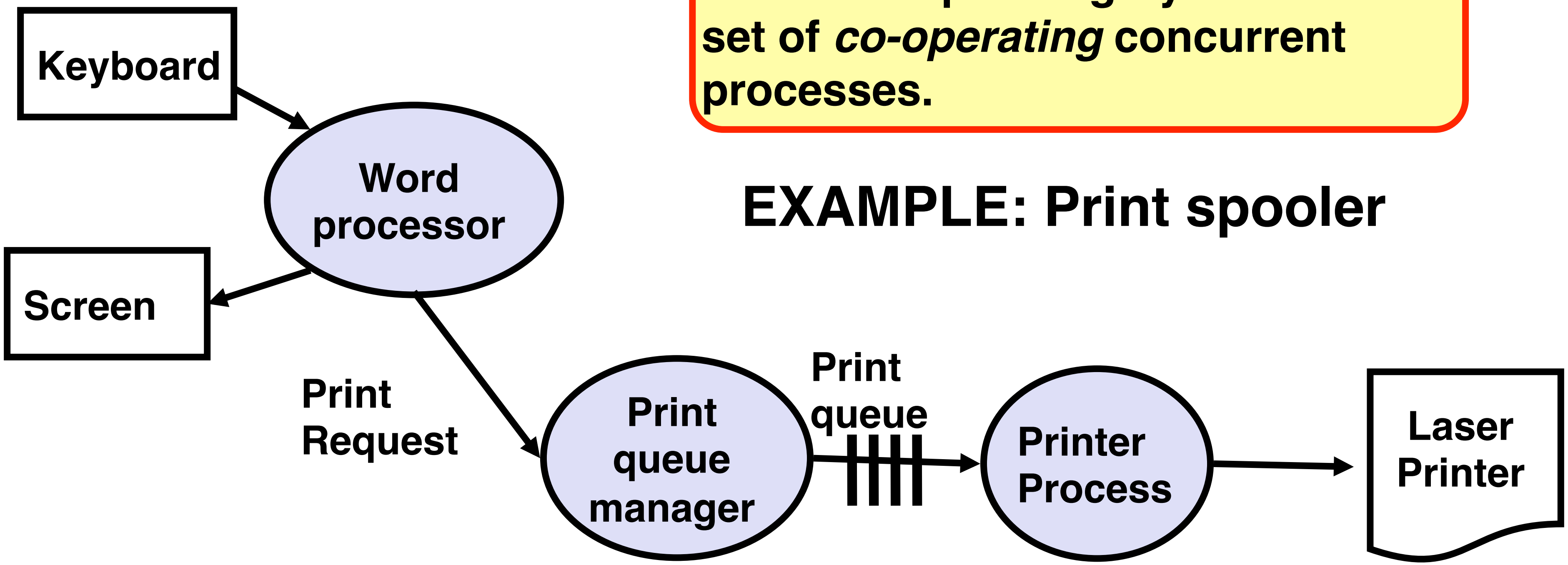
Example Concurrent Activities



Processes (Activities)
Order Clerk
Bagger
Cook
Cashier
Customers
Shared communication areas
Order list turntable
Cooked hamburger bin
Checkout counter

Processes for OS Structuring

Consider Operating System as a set of *co-operating* concurrent processes.

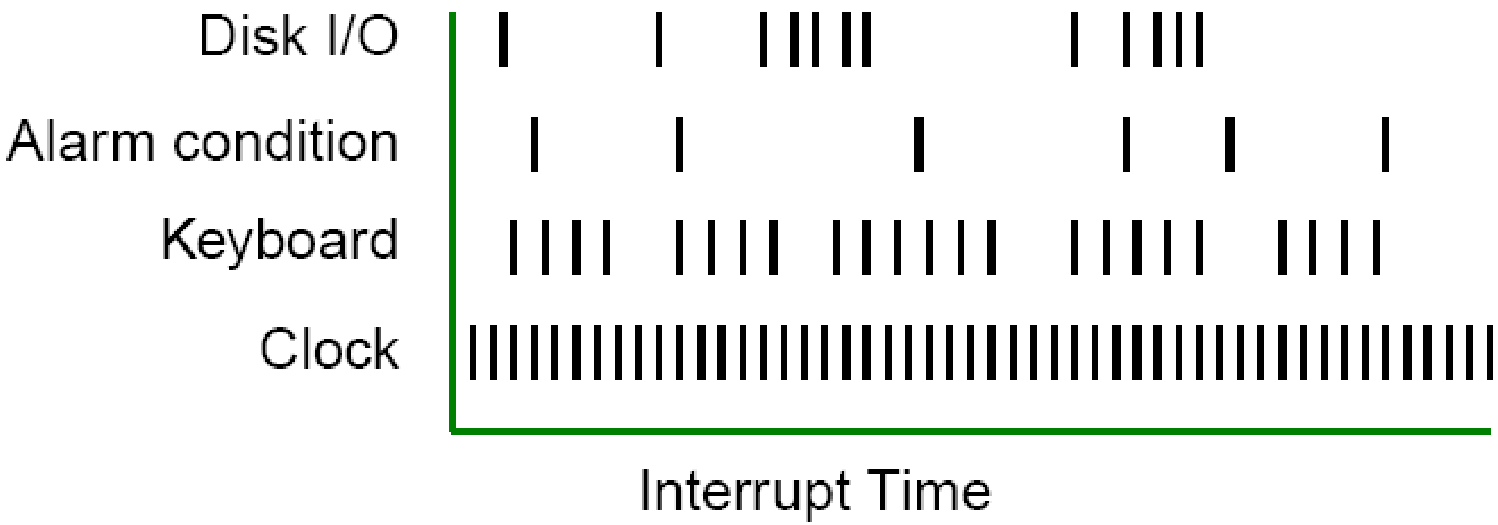


EXAMPLE: Print spooler

Keyboard & screen: processes to manage these devices
Word processor: User edits document, requests printing
Print queue manager: Maintains queue of jobs for printer. If queue was previously empty, starts printer process.
Printer Process: Translates document to printer commands, and sends them to it. On completion, removes job from queue, and repeats. Terminates when queue is empty.

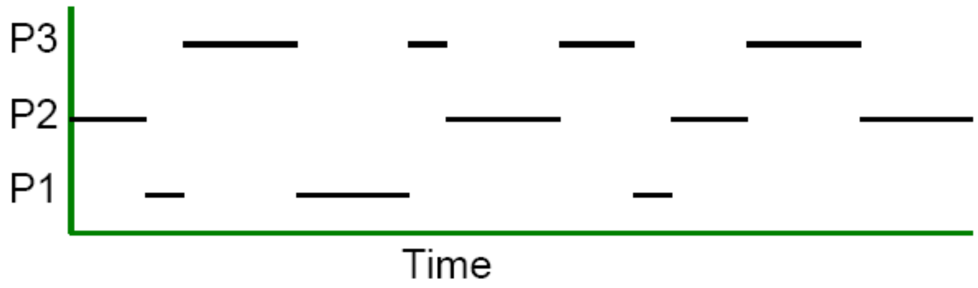
Non - Determinism

- Operating Systems and Real-Time systems are **non-deterministic**
- They must respond to events (I/O) which occur in an unpredictable order, and at any time

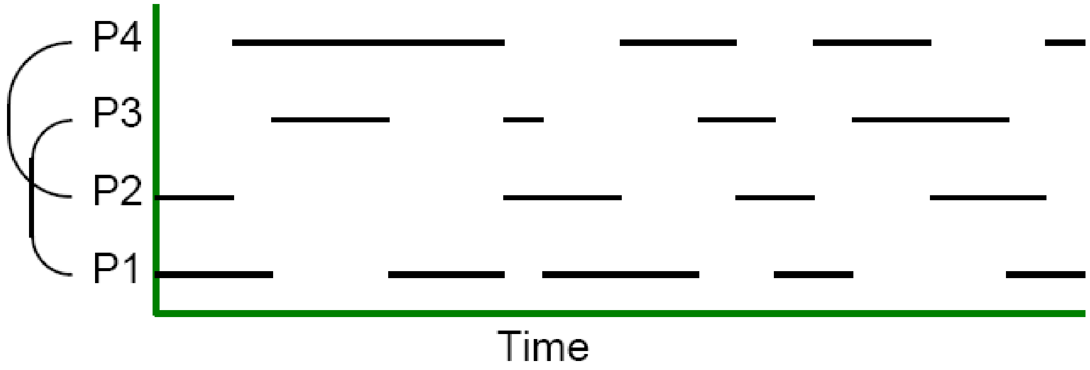


Concurrency

- **Apparent Concurrency (pseudo-concurrency):** A single hardware processor which is switched between processes by interleaving. Over a period of time this gives the illusion of concurrent execution.



- **Real Concurrency**: Multiple hardware processors; usually less processors than processes



Process Switches

Events (or interrupts) cause process switches.

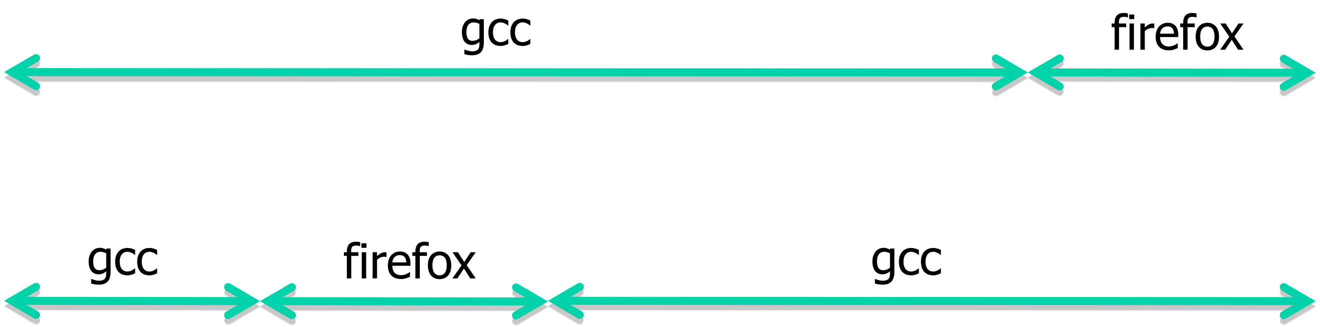
– For example, an I/O completion interrupt will cause the OS to switch to an I/O process

The way an OS switches between processes cannot be pre-determined, since the events which cause the switches are not deterministic

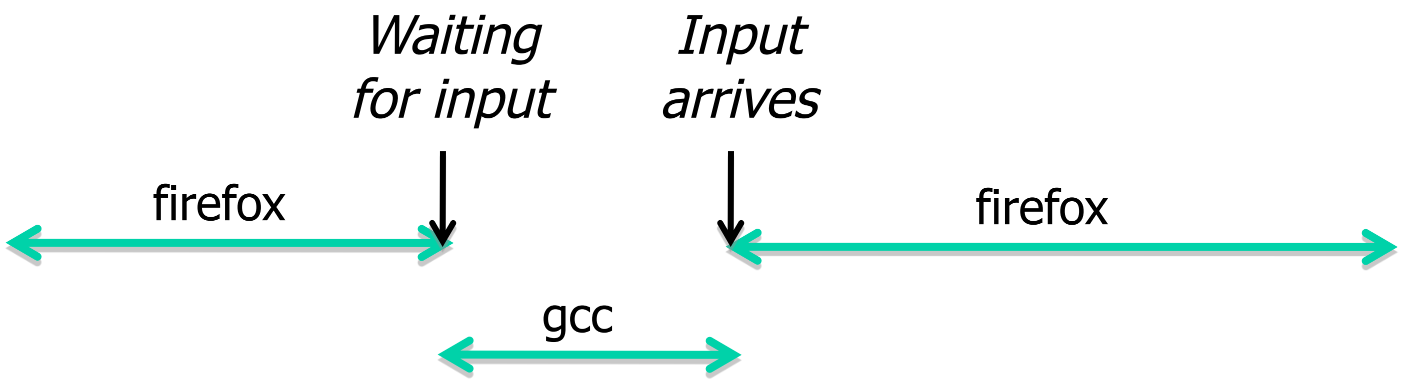
The interleaving of instructions, executed by a processor, from a set of processes is non-deterministic

– Not reproducible, no built-in assumptions about timing

Fairness



Better CPU utilization



CPU Utilization in Multiprogramming

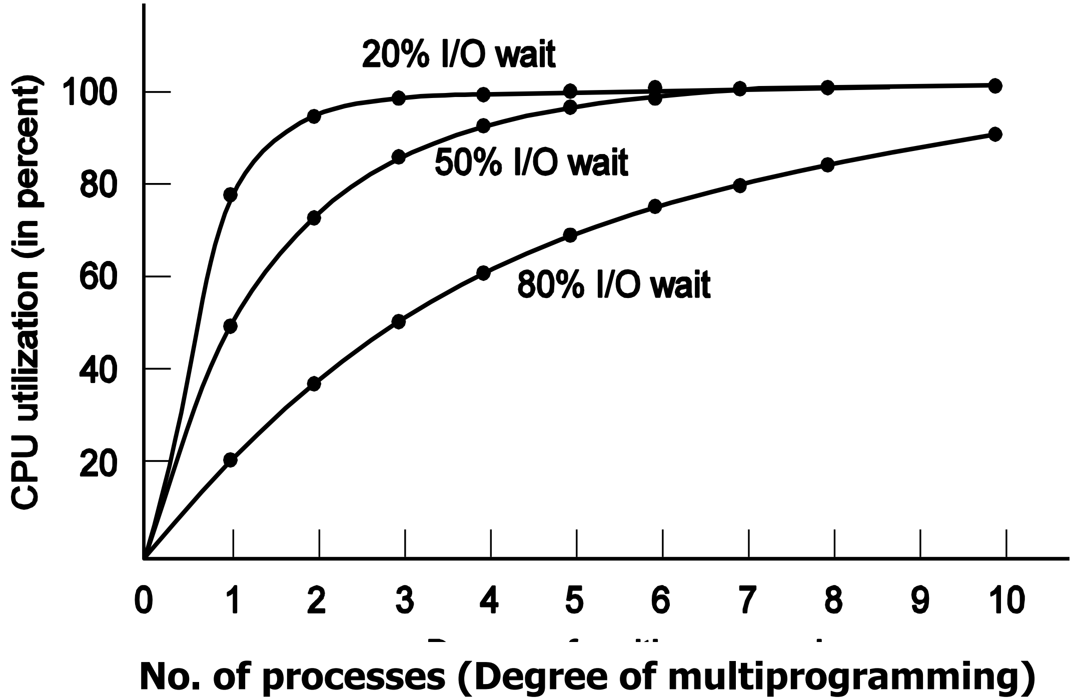
Q: Average process computes 20% time, then with five processes we should have 100% CPU utilization, right?

A: In the ideal case, if the five processes never wait for I/O at the same time

- Better estimate
  - **n** = total number of processes
  - **p** = fraction of time a process is waiting for I/O
  - p^n = probability that all processes are waiting for I/O

$$\text{CPU utilization} = 1 - p^n$$

CPU Utilization = $1 - p^n$



Q: How many processes need to be in memory to only waste 10% of CPU where we know that processes spend 80% waiting for IO (e.g. data oriented or interactive systems)

A: $1 - 0.8^n = 0.9 \quad \Rightarrow 0.8^n = 0.1 \quad \Rightarrow n = \log_{0.8} 0.1 \approx 10$

Context Switches

On a context switch, the processor switches from executing process A to executing process B, because:

- Time slice expired (periodic)
- Process A blocked waiting for e.g. I/O or a resource
- Process A completed (run to completion)
- External event results in a higher priority process B to be run (priority preemption)

Non-deterministic process switches as events causing them are non-deterministic.

Context Switches

On a context switch, the processor switches from executing process A to executing process B

Process A may be restarted later, therefore, all information concerning the process, needed to restart safely, should be stored

For each process, all this data is stored in a *process descriptor*, or *process control block* (PCB), which is kept in the *process table*

Process Control Block (PCB)

A process has its own virtual machine, e.g.:

- Its own virtual CPU
- Its own address space (stack, heap, text, data etc.)
- Open file descriptors, etc.

What state information should be stored?

- Program counter (PC), page table register, stack pointer, etc.
- Process management info:
  - Process ID (PID), parent process, process group, priority, CPU used, etc.
- File management info
  - Root directory, working directory, open file descriptors, etc.

Simplified Process Control Block (PCB)

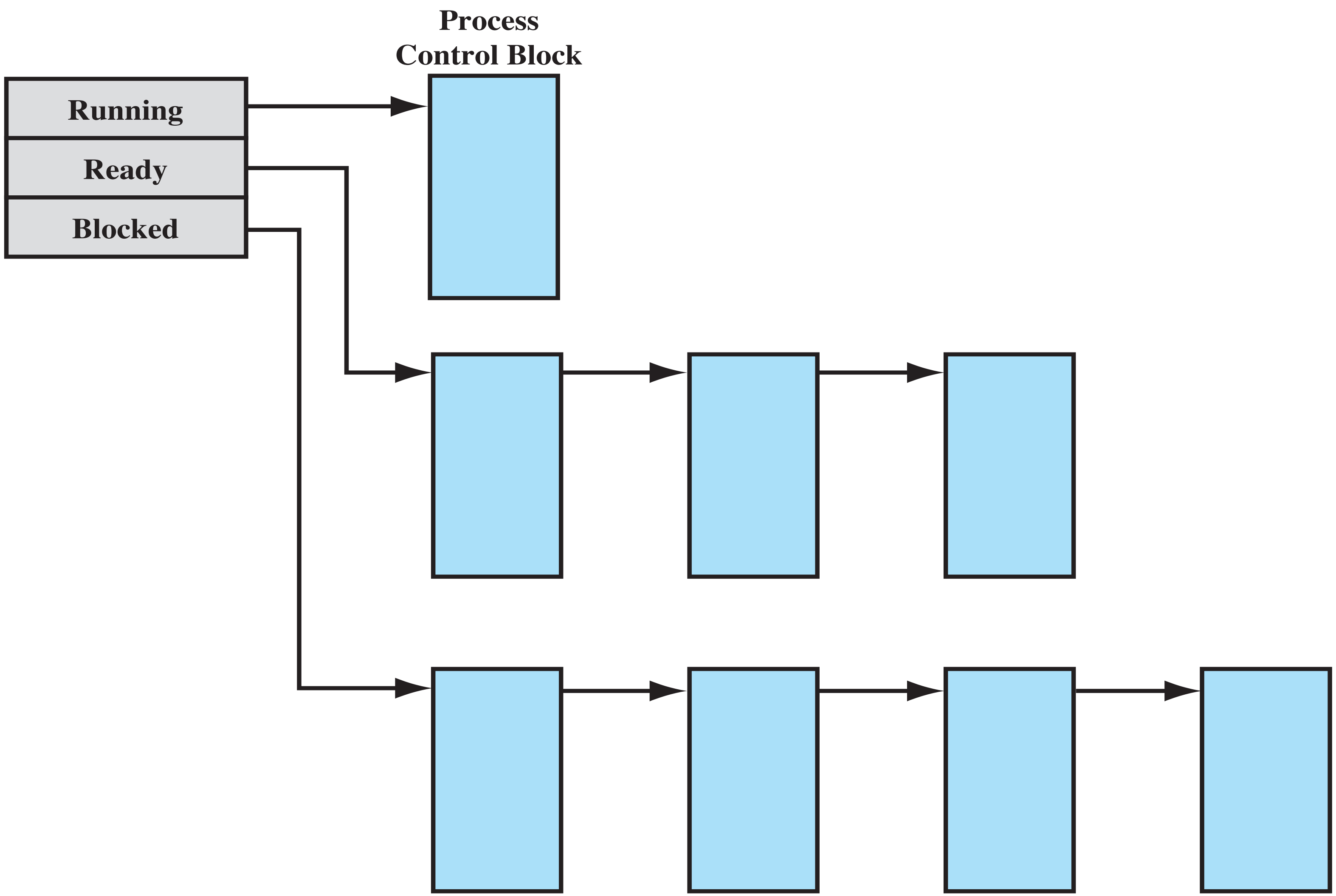
PCB: Data structure representing a process in the kernel

- **Process IDs:** unique identifier to distinguish it from other processes.
- **State:** running, waiting, ready etc. (details later)
- **Priority:** priority level relative to other processes
- **Program counter:** address of next instruction in program to be executed
- **Context data:** data saved from registers
- **Memory pointers:** to program code, data associated with process and shared memory with other processes
- **I/O status:** I/O requests outstanding, I/O devices allocated
- **File Management:** Required directories, list of open files
- **Accounting information:** processor time used, time limits, memory limits, file usage + limits etc

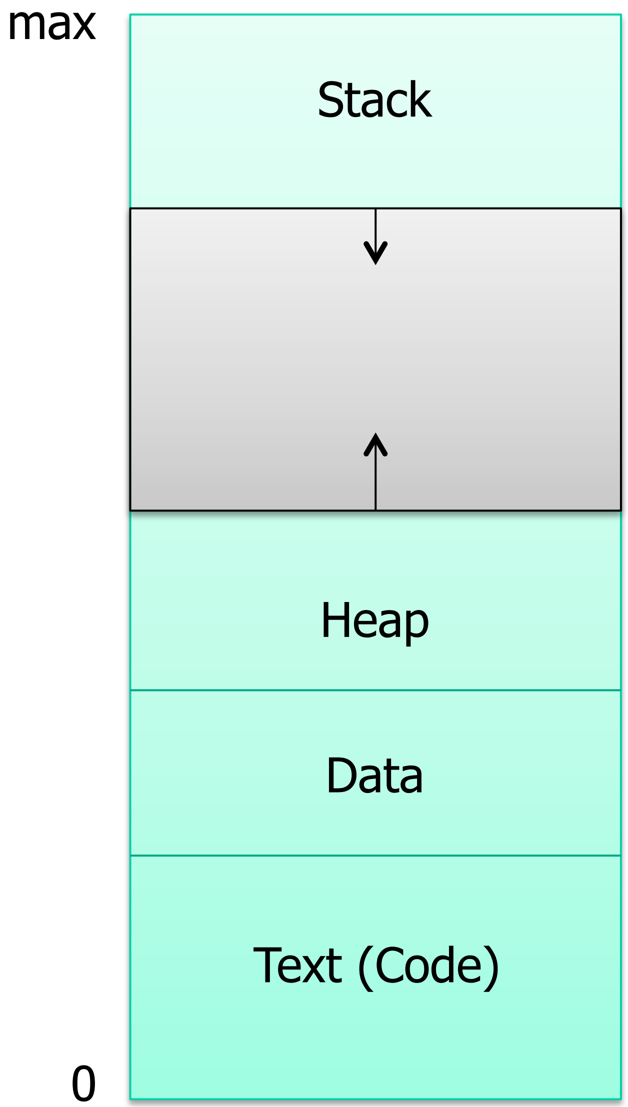
Detailed PCB

Process management	Memory management	File management
Registers Program counter Program status word Stack pointer Process state Priority Scheduling parameters Process ID Parent process Process group Signals Time when process started CPU time used Children’s CPU time Time of next alarm	Pointer to text segment Pointer to data segment Pointer to stack segment	Root directory Working directory File descriptors User ID Group ID

Process List Structures



Process in Memory



Stack: temporary data e.g. function parameters, return addresses, local variables.

Heap: dynamically allocated data structures.

Data: global variables

Text: program code
Multiple processes can share code e.g. 2 concurrent word processors can edit different files, using same code.

Process Switch Implementation

1. Each IO class has interrupt vector containing the address of interrupt service procedure
2. On interrupt the PC, PSW, some registers pushed onto the (current) stack by the *interrupt hardware*
3. Hardware jumps to address (PC from Interrupt vector) to service interrupt
4. Assembly language routine saves registers to PCB then calls device specific interrupt service routine
5. C interrupt service runs (typically reads, writes & buffers data)
6. Scheduler decides which process to run next
7. C procedure returns control to assembly code
8. Assembly procedure starts up new current process

Context (Process) Switches are Expensive

Direct cost: save/restore process state

Indirect cost: perturbation of memory caches, memory management registers etc.

Important to avoid unnecessary context switches

Process Creation

When are processes created?

- System initialisation
- User request
- System call by a running process

Processes can be

- Foreground processes: interact with users
- Background processes: handle incoming mail, printing requests, etc. (**daemons**)

Process Termination

- **Normal completion:** Process completes execution of body
- **System call:**
  - `exit()` in UNIX
  - `ExitProcess()` in Windows
- **Abnormal exit:** The process has run into an error or an unhandled exception, e.g. illegal instruction, memory violation
- **Aborted:** The process stops because another process has overruled its execution (e.g., killed from terminal)
- **Never:** Many real-time processes run in endless loop and never terminate unless error occurs

Process Hierarchies

Some OSes (e.g., UNIX) allow processes to create **process hierarchies** e.g. parent, child, child's child, etc.

- E.g., when UNIX boots it starts running **`init`**
- It reads a file saying how many terminals to run, and forks off one process per terminal
- They wait for someone to login
- When login successful login process executes a shell to accept commands which in turn may start up more processes etc.
- All processes in the entire system form a process tree with **init** as the root (***process group***)

Windows has no notion of hierarchy

- When a child process is created the parent is given a token (***handle***) to use to control it
- The handle can be passed to other processes thus no hierarchy

Case Study: Linux

Creating processes

```
int fork(void)
```

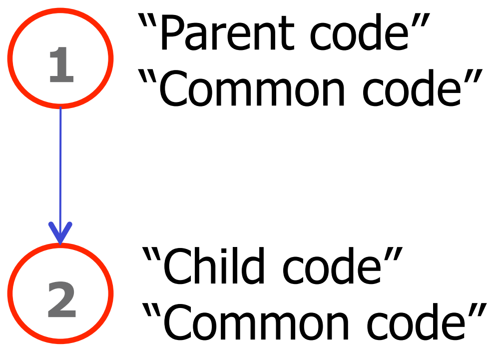
- Creates a new child process by making an exact copy of the parent process image.
- The child process inherits the resources of the parent process and will be executed concurrently with the parent process.
- **`fork()`** returns twice:
  - In the parent process: **`fork()`** returns the process ID of the child
  - In the child process: **`fork()`** returns 0
- On error, no child is created and -1 is returned in the parent
- How can fork() fail?
  - Global process limit exceeded, per-user limit exceeded, not enough swap space

`fork()` example (1)

```c
#include <unistd.h>
#include <stdio.h>

int main() {
  if (fork() != 0)
    printf("Parent code\n");
  else printf("Child code\n");

  printf("Common code\n");
}
```



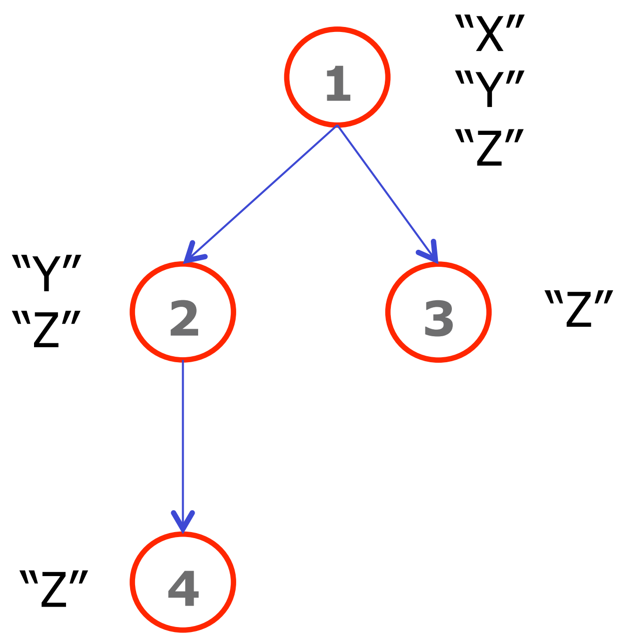
fork() example (2)

```
#include <unistd.h>
#include <stdio.h>

int main() {
  if (fork() != 0)
    printf("X\n");

  if (fork() != 0)
    printf("Y\n");

  printf("Z\n");
}
```



Executing processes

```
int execve(const char *path, char *const argv[],
           char *const envp[])
```

Arguments:

- **path** – full pathname of program to run
- **argv** – arguments passed to main
- **envp** – environment variables (e.g., $PATH, $HOME)

Changes process image and runs new process

Lots of useful wrappers:

E.g., execl, execle, execvp, execv, etc.

```
man execve
```

Consult man(ual) pages!

Waiting for Process Termination

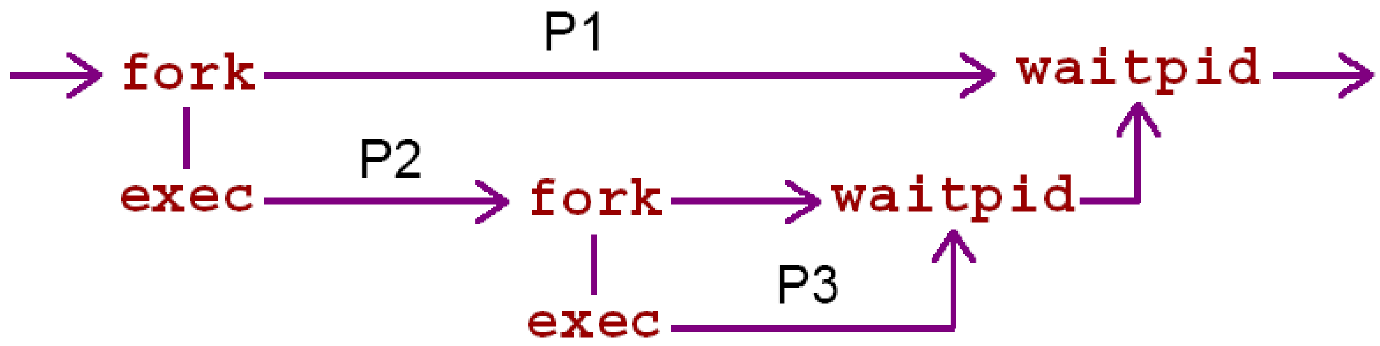
```
int waitpid(int pid, int* stat, int options)
```

- Suspends execution of the calling process until the process with PID pid terminates normally or a signal is received
- Can wait for more than one child:
  - pid = -1 wait for any child
  - pid = 0 wait for any child in the same process group as caller
  - pid = -gid wait for any child with process group gid
- Returns:
  - pid of the terminated child process
  - 0 if WNOHANG is set in options (indicating the call should not block) and there are no terminated children
  - -1 on error, with errno set to indicate the error

Example: Command Interpreter

Use of `fork`, `execve` and `waitpid`

```
while (TRUE)  { /* repeat forever */
  read_command (command,parameters)
  if (fork () != 0)     /* fork off child process */
    waitpid(-1, &status, 0);   /* Parent code */
  else          /* Child code */
    execve (command, parameters, 0);
                /* execute command */
}
```



Why both fork() and execve() ?

UNIX design philosophy: **simplicity**

– Simple basic blocks that can be easily combined

Contrast with Windows:

– CreateProcess() => equivalent of fork() + execve()
– Call has 10 parameters!
  - program to be executed
  - parameters
  - security attributes
  - meta data regarding files
  - priority,
  - pointer to the structure in which info regarding new process is stored and communicated to the caller
  - …

Windows `CreateProcess()`

```
BOOL WINAPI CreateProcess(
    __in_opt LPCTSTR lpApplicationName,
    __inout_opt LPTSTR lpCommandLine,
    __in_opt LPSECURITY_ATTRIBUTES lpProcessAttributes,
    __in_opt LPSECURITY_ATTRIBUTES lpThreadAttributes,
    __in BOOL bInheritHandles,
    __in DWORD dwCreationFlags,
    __in_opt LPVOID lpEnvironment,
    __in_opt LPCTSTR lpCurrentDirectory,
    __in LPSTARTUPINFO lpStartupInfo,
    __out LPPROCESS_INFORMATION lpProcessInformation )
```

Linux Termination

```
void exit(int status)
```

- Terminates a process
- Called implicitly when program finishes execution
- Never returns in the calling process
- Returns an exit status to the parent.

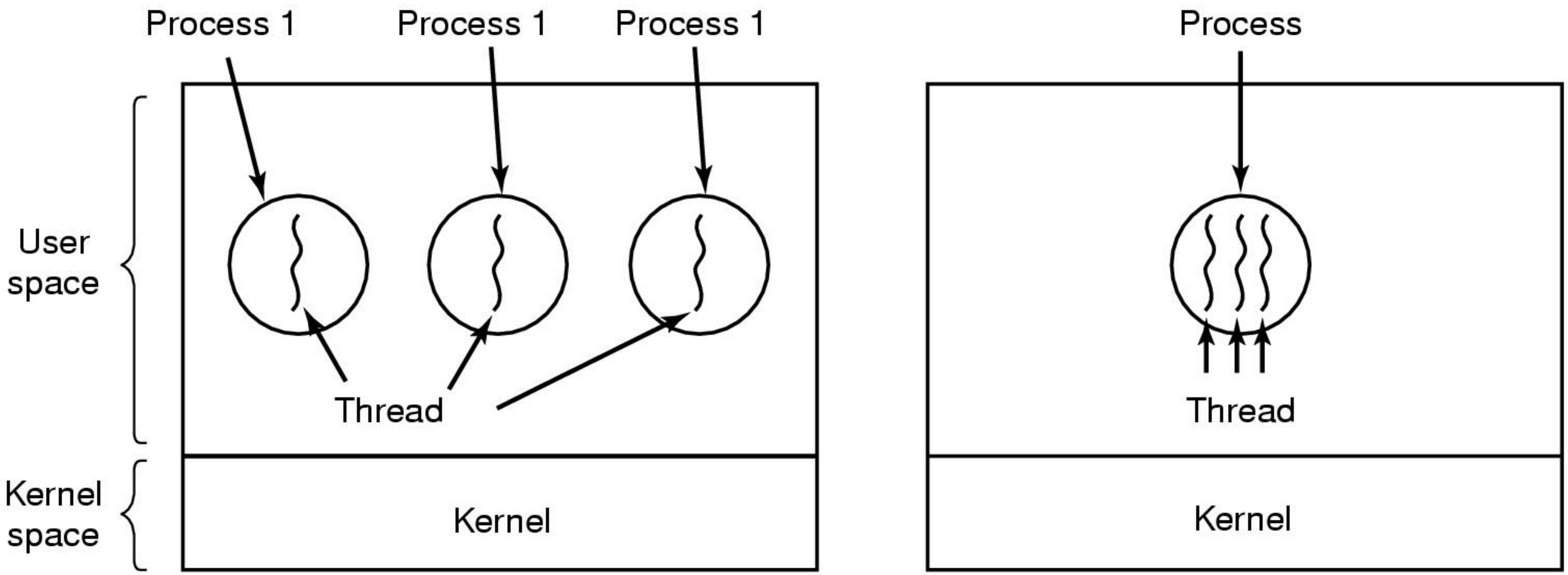
```
void kill(int pid, int sig)
```

- Sends signal sig to process pid to terminate it.

Threads

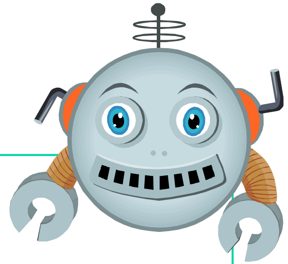
What Are Threads?

- Execution streams that share *the same address space*
- When multithreading is used, each process can contain one or more threads
  – a *lightweight mini-process* within a user process



3 Processes, each with 1 thread   1 process with 3 threads

One or More Threads in a Process



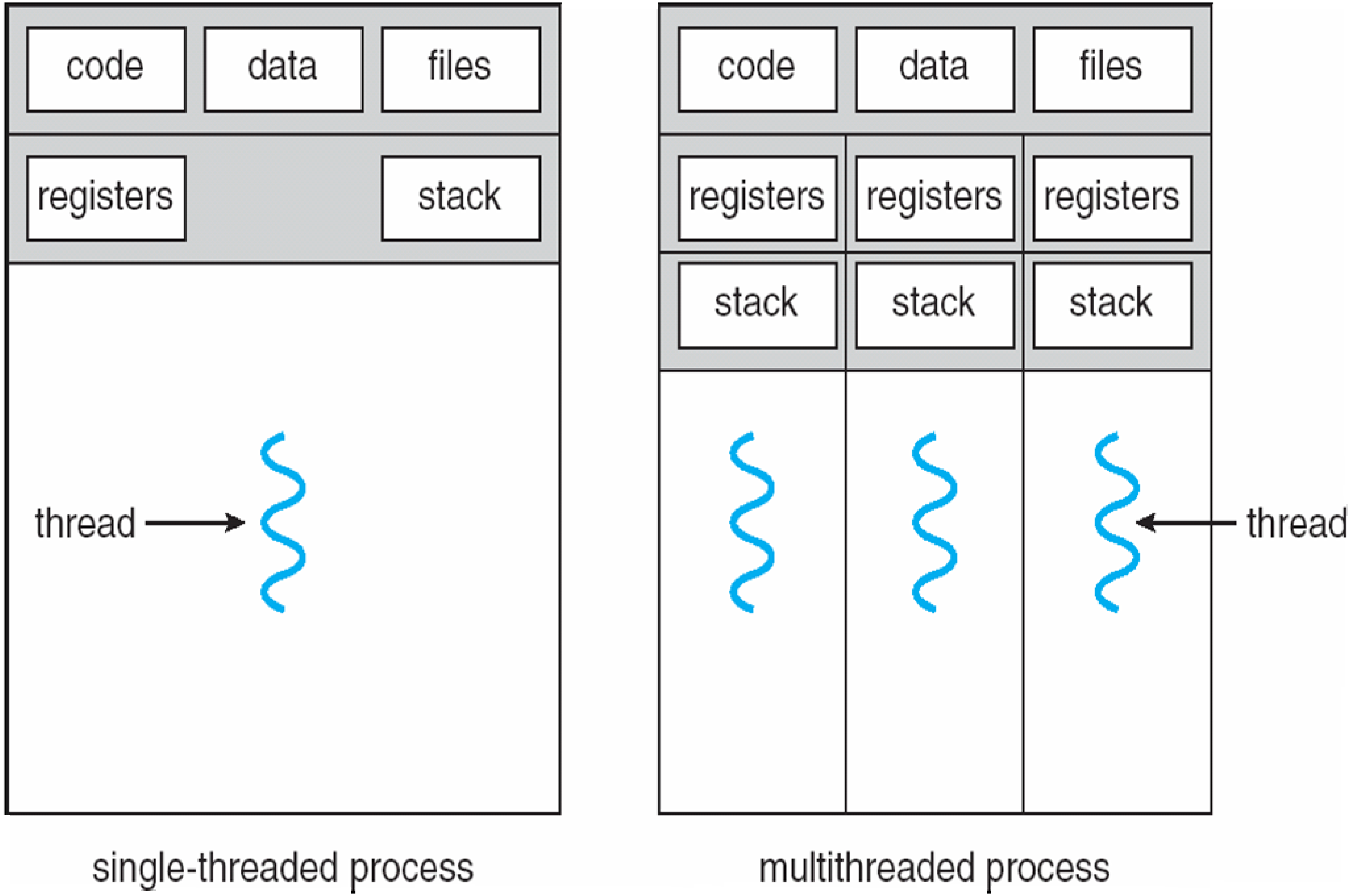
Each thread has:

- an execution state (Running, Ready, etc.)
- saved thread context when not running
- an execution stack
- some per-thread static storage for local variables
- access to the memory and resources of its process (all threads of a process share this)

Thread Model

Per process items	**Per thread items**
Address space	Program counter (PC)
Global variables	Registers
Open files	Stack
Child processes	State
Pending alarms	
Signals and signal handlers	
Accounting information	

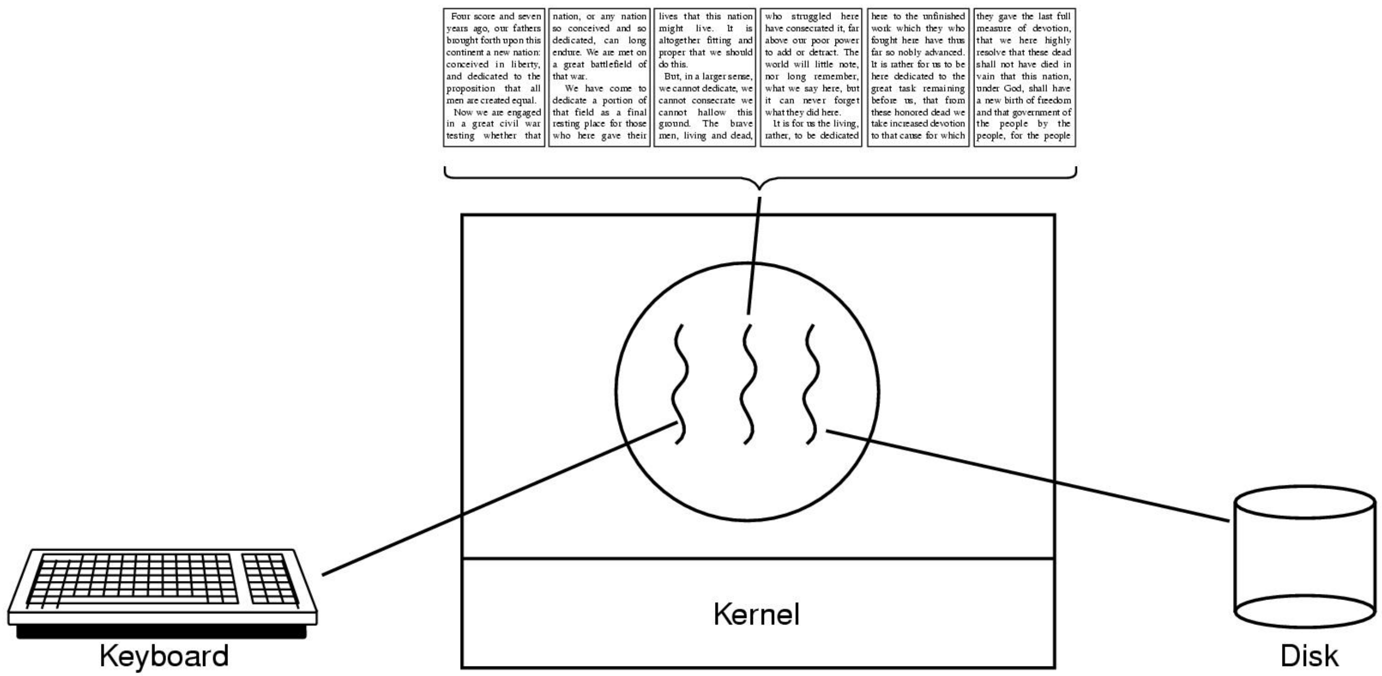
Thread Model (2)



Each thread has its own stack & context

Example Word Processor

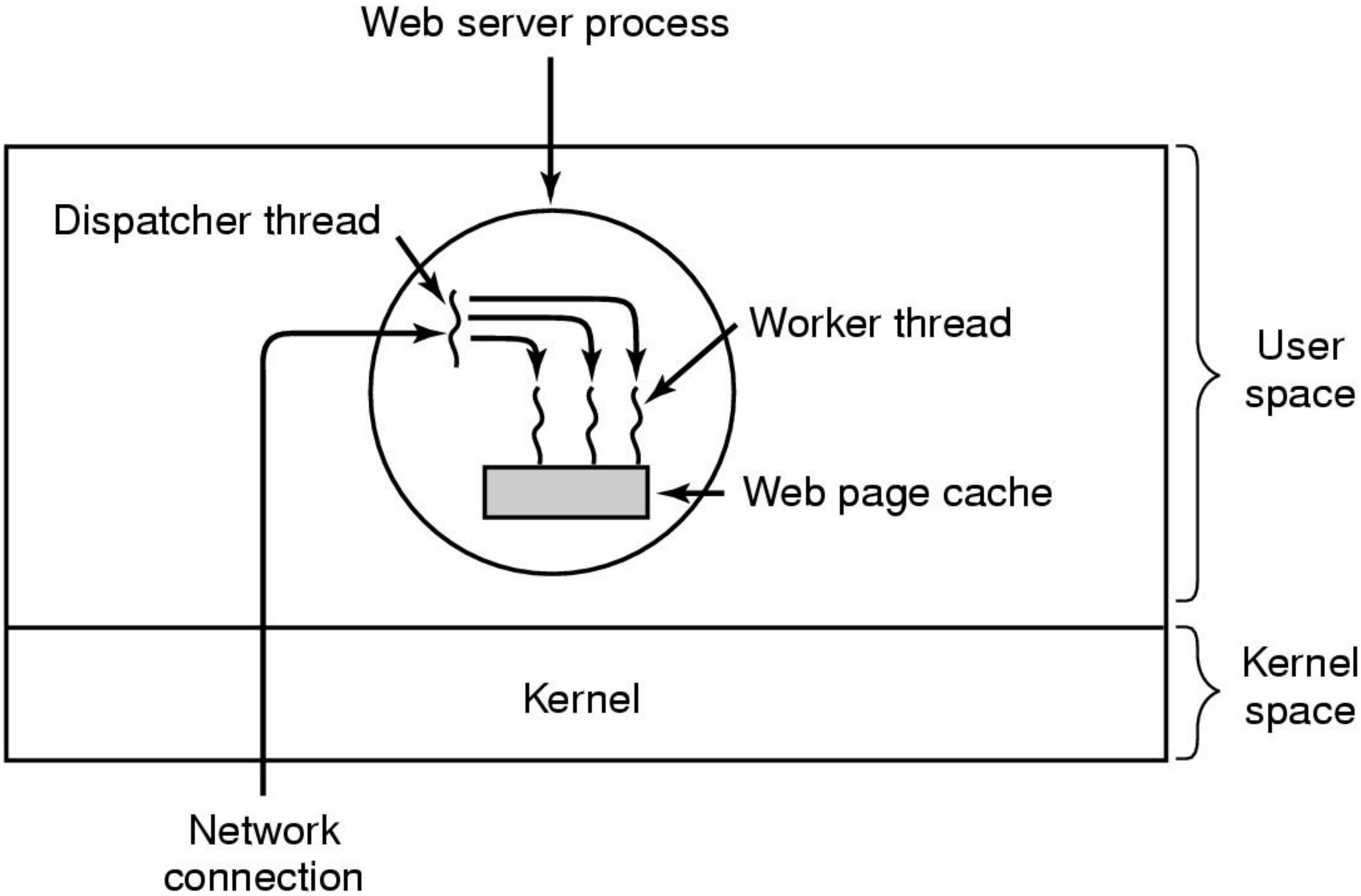
Processing thread
- processes input buffer
- writes result into output buffer



Input thread
- reads data into buffer

Output thread
- writes output buffer to disk

Example Multi-threaded Web Server



Threads vs Proceses

Processes are too heavyweight

- Expensive to create/destroy activities
- Difficult to communicate between different address spaces
- An activity that blocks might switch out the entire application
- Expensive to context switch between activities

Threads are lightweight

- Create/delete up to 100 times quicker
- Activities can share data
- Efficient communication between threads
- Reflect parallelism within application, where some activities may block

Threads – Problems/Concerns

Shared address space
- Memory corruption
  - One thread can write another thread's stack
- Concurrency bugs
  - Concurrent access to shared data (e.g., global variables)

Forking
- What happens on a `fork()`?
  - Create a new process with the same number of threads
  - Create a new process with a single thread?

Signals
- When a signal arrives, which thread should handle it?

Case Study: PThreads

PThreads (Posix Threads)

Defined by IEEE standard 1003.1c

– Implemented by most UNIX systems

```
#include <pthread.h>
#include <sys/types.h>

pthread_t        → type representing a thread
pthread_attr_t   → type representing the attributes of a thread
```

Creating Threads

```
int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine)(void*), void *arg);
```

Creates a new thread

- The newly created thread is stored in **`*thread`**
- The function returns 0 if thread was successfully created, or error code

Arguments:

- **`attr`** -> specifies thread attributes, can be **`NULL`** for default attributes
  - Attributes include: minimum stack size, guard size, detached/ joinable, etc.
- **`start_routine`** -> the C function the thread will start to execute once created
- **`arg`** -> The argument to be passed to start_routine (of pointer type **`void*`**). Can be **`NULL`** if no arguments are to be passed.

Terminating Threads

```
void pthread_exit(void *value_ptr);
```

Terminates the thread and makes **`value_ptr`** available to any successful join with the terminating thread

Called implicitly when the thread's start routine returns

- But not for the initial thread which started main()
- If **`main()`** terminates before other threads, w/o calling **`pthread_exit()`**, the entire process is terminated
- If **`pthread_exit()`** is called in **`main()`** the process continues executing until the last thread terminates (or **`exit()`** is called)

PThread Example

```c
#include <pthread.h>
#include <stdio.h>

void *thread_work(void *threadid) {
  long id = (long) threadid;
  printf("Thread %ld\n", id);
}

int main (int argc, char *argv[]) {
  pthread_t threads[5];
  long t;
  for (t=0; t<5; t++)
      pthread_create(&threads[t], NULL,
                     thread_work, (void *)t);

}
```

```
$ gcc pt.c -lpthread
$ ./a.out
Thread 0
Thread 1
Thread 2
Thread 3
Thread 4
$ ./a.out
Thread 0
Thread 3
Thread 1
Thread 2
```

Passing Arguments to Threads

What if we want to pass more than one argument to the start routine?

- Create a structure containing the arguments and pass a pointer to that structure to **`pthread_create()`**

Yielding the CPU

```
int pthread_yield(void)
```

- Releases the CPU to let another thread run
- Returns 0 on success, or an error code
  - Always succeeds on Linux

Joining Other Threads

```
int pthread_join(pthread_t thread, void **value_ptr);
```

Blocks until `thread` terminates

The value passed to `pthread_exit()` by the terminating thread is available in the location referenced by `value_ptr`

- `value_ptr` **can be** `NULL`

Join Example

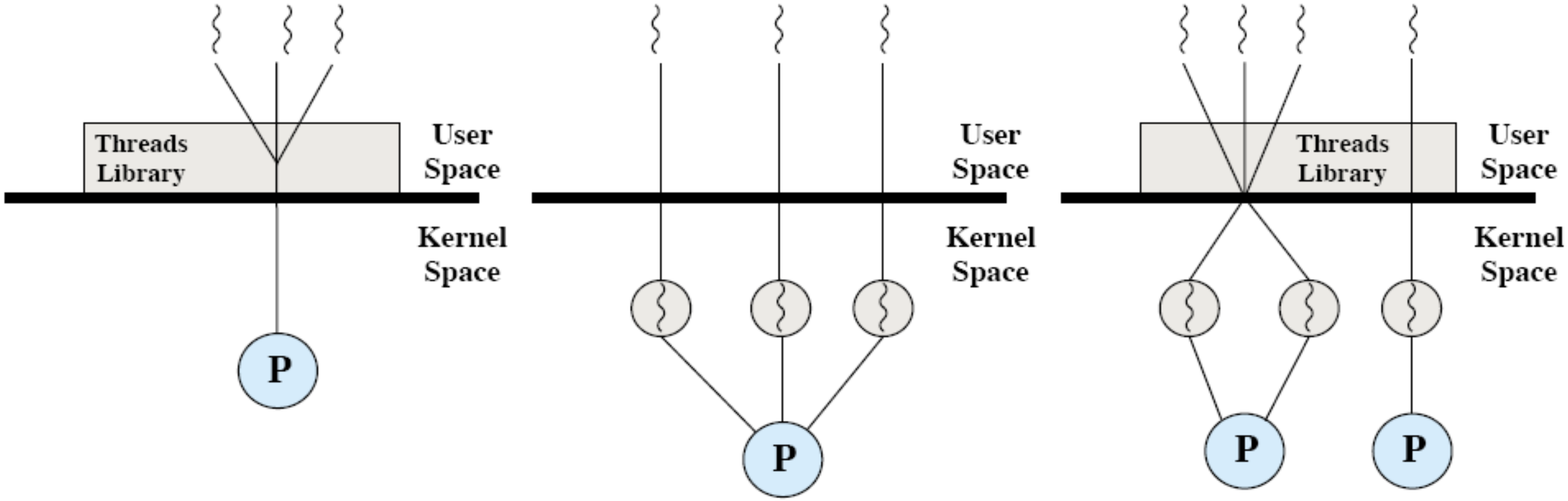
```c
#include <pthread.h>
#include <stdio.h>

long a, b, c;
void *work1(void *x) { a = (long)x * (long)x;}
void *work2(void *y) { b = (long)y * (long)y;}

int main (int argc, char *argv[]) {
  pthread_t t1, t2;
  pthread_create(&t1, NULL, work1, (void*) 3);
  pthread_create(&t2, NULL, work2, (void*) 4);
  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
  c = a + b;
  printf("3^2 + 4^2 = %ld\n", c);
}
```

```
$ ./a.out
3^2 + 4^2 = 25
```

Threads Implementation



User-level threads

- The kernel is not aware of threads
- Each process manages its own threads

Kernel-level threads

- Managed by the kernel

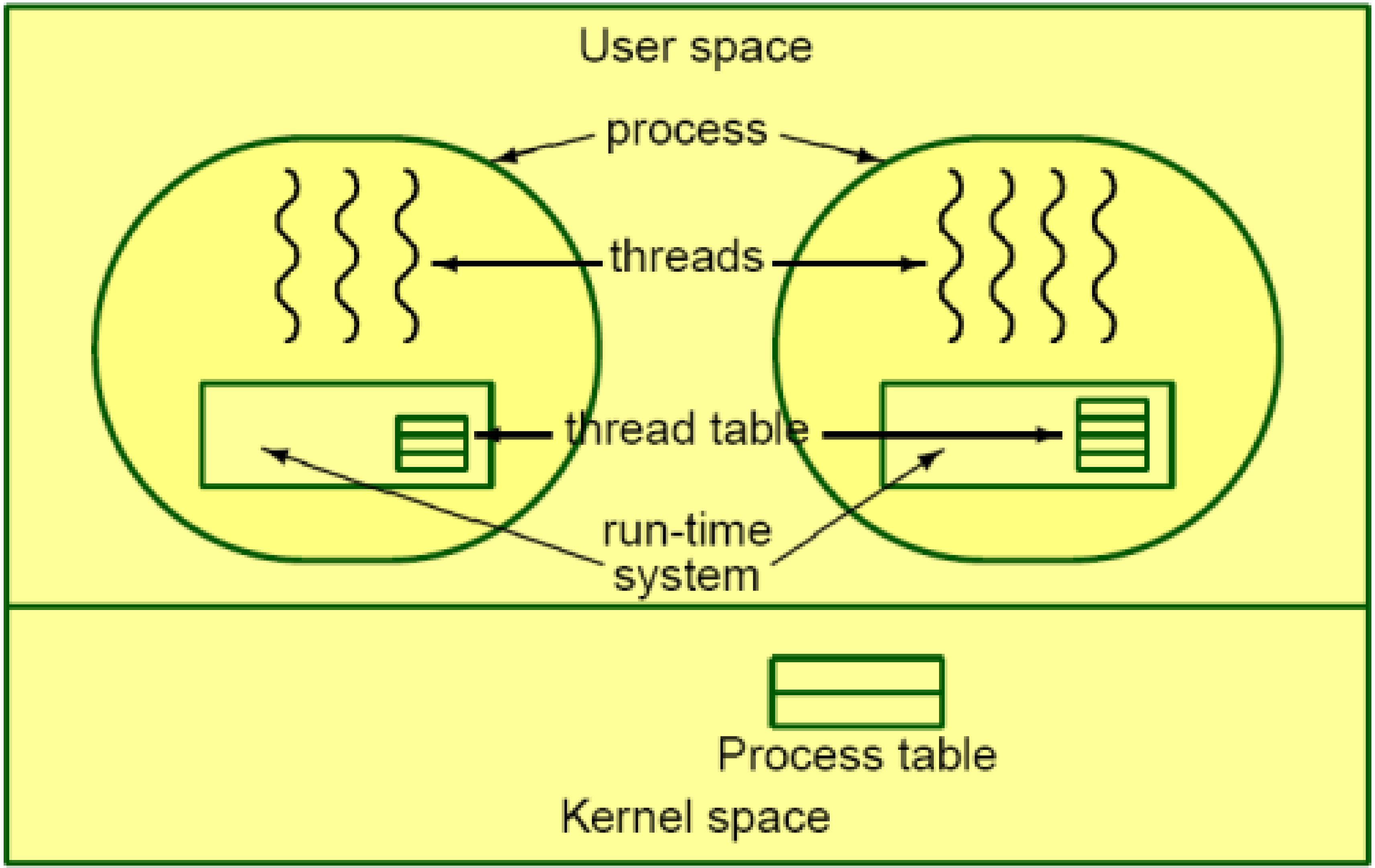
Hybrid

- Combined Kernel and user level threads
- User threads map onto kernel threads

User-Level Threads

- Kernel thinks it is managing processes only
- Threads implemented by software library
- Thread switching does not require kernel mode privileges
- Process maintains a thread table and does thread scheduling
- PThread is user level

USER Level Threads



Advantages of User-Level Threads

Better performance

- Thread creation and termination are fast
- Thread switching is fast
- Thread synchronization (e.g., joining other threads) is fast
- All these operations do not require any kernel activity

Allows application-specific run-times

- Each application can have its own scheduling algorithm

Disadvantages of User-Level Threads

Blocking system calls stops *all threads* in the process

- Denies one of the core motivations for using threads

Non-blocking I/O can be used (e.g., `select()`)

- Harder to use and understand, inelegant

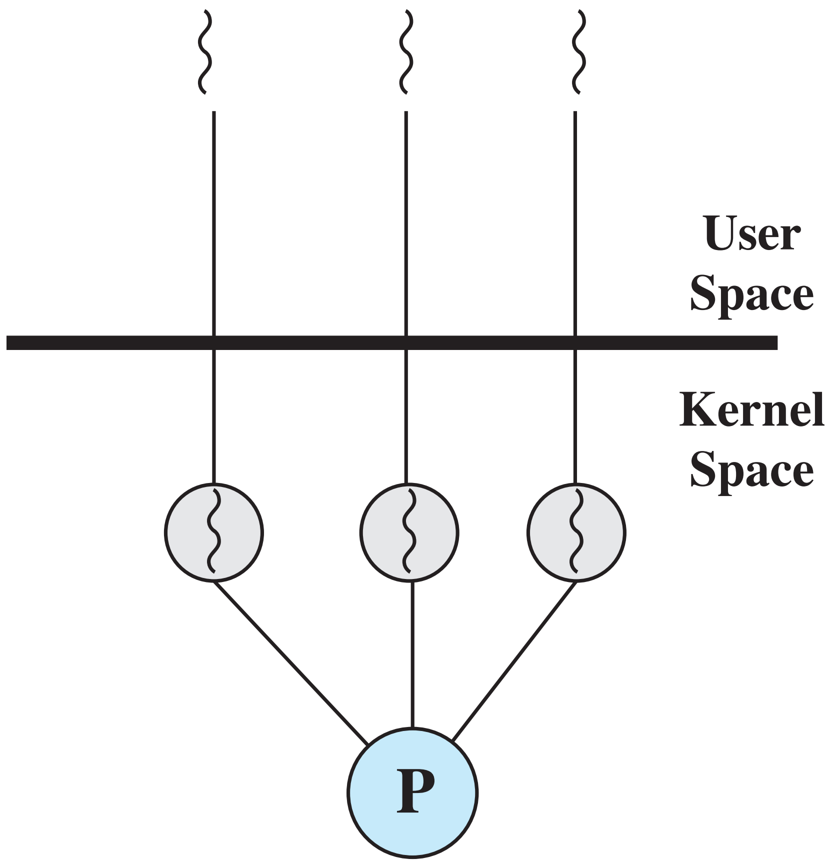
During a page fault the OS blocks the whole process…

- But other threads might be runnable

Difficult to implement preemptive scheduling

- Run-time can request a clock interrupt
  - Messy to program
  - High-frequency clock interrupts not always available
  - Individual threads may also need to use a clock interrupt

Kernel Threads



Thread management is done by the kernel

- no thread management is done by the application
- Windows is an example of this approach
- Recent Linux implementations also support this.

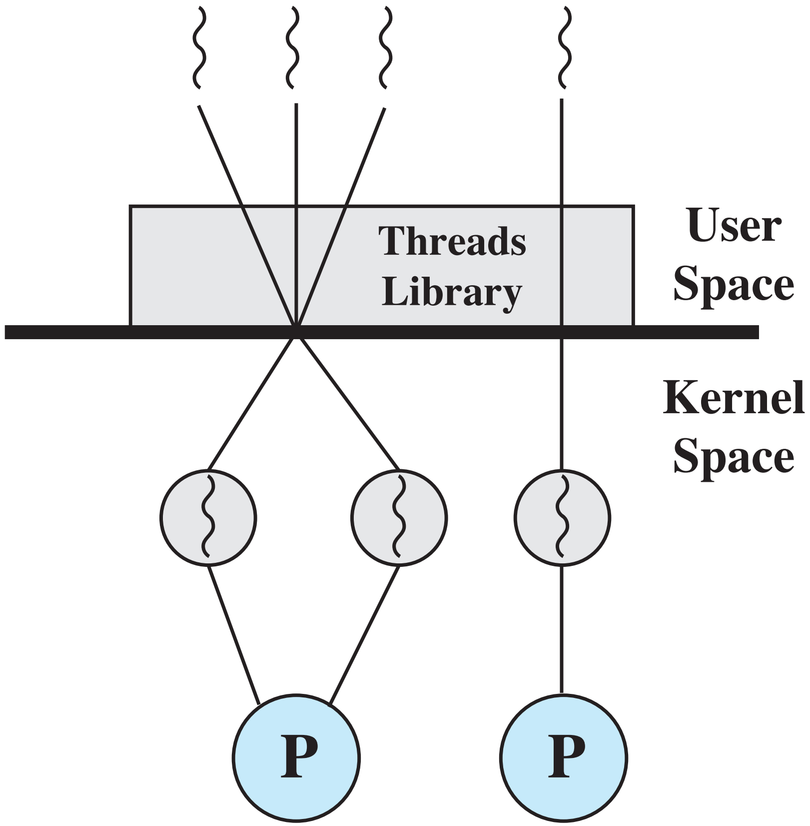
Advantages of Kernel Threads

- The kernel can simultaneously schedule multiple threads from the same process on multiple processors
- Blocking system calls/page faults can be easily accommodated
  - If one thread calls a blocking system call or causes a page fault, the kernel can schedule a runnable thread from the same process
- Kernel routines can be multithreaded

Disadvantages of Kernel Threads

- Thread creation and termination more expensive
  - Require kernel call
  - But still much cheaper than process creation/termination
  - One mitigation strategy is to recycle threads (*thread pools*)
- Thread synchronization more expensive
  - Requires blocking system calls
- Thread switching is more expensive
  - Requires kernel call
  - But still much cheaper than process switches
    - Same address space
- No application-specific scheduler

Hybrid Approaches



- Thread creation is done in the user space
- Use kernel threads and multiplex user-level threads onto some (or all) kernel threads
- Bulk of scheduling and synchronization of threads is by the application

Process and Thread Summary

Non-determinism ➔ concurrency ➔ multiple processes ➔ better utilization

Processes: creation, termination, switching & PCBs

- Heavyweight management

Linux – supports process hierarchies

- – Child is clone of parent process
- – Load new code to execute different process

Threads: lightweight concurrency with shared data

Posix threads case study

Thread implementation – user vs kernel level

Shared memory in threads requires synchronisation.