Threads (CSE 422S)

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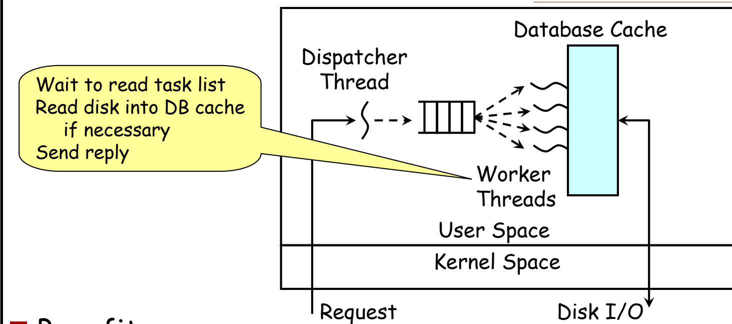
Database Server Example



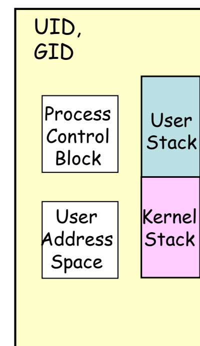
- Benefits
  - » Simplifies sharing of memory and file descriptors
  - » Concurrent execution of relatively independent tasks
  - » Increase overall throughput for some problems

A Modern Process (1)

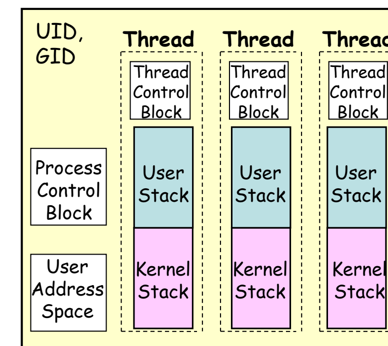
- Separate idea of *execution* from *resource grouping*
- Thread
  - » A unit of local dispatching (scheduling) and has priority
  - » Has an execution path (is a thread of control)
  - » Has a computation state (stack, set of CPU registers)
- Global variables are shared by all threads
- System state shared by threads
  - » File descriptors, working directory, etc.

A Modern Process (2)

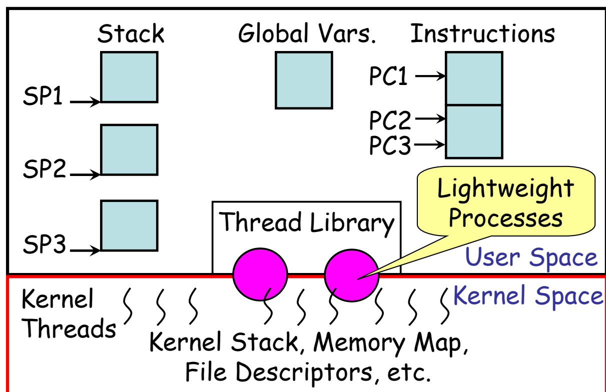
Single-Threaded Process Model



Multithreaded Process Model



A Modern Process (3)



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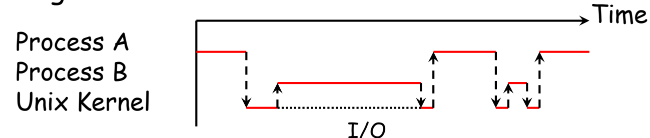
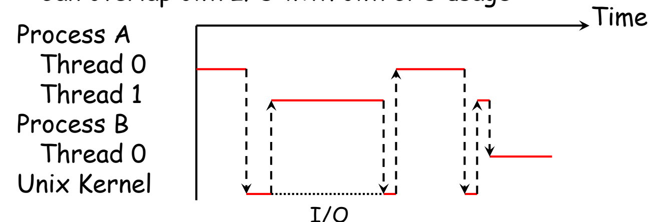
Thread Execution (1 Processor)

- Single-Threaded Processes



- Multithreaded Processes
  - Can overlap own I/O with own CPU usage



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Thread Library Implementations

- User-Space
  - Self-contained user-level library
  - All code and structures are in user-space
  - Depends on a small number of OS system calls
  - N:1 model
    - N user threads mapped to 1 kernel thread or process
- Kernel-Space
  - Thin user-space layer
  - Substantial amount of kernel code and structures
  - 1:1 model and N:M model
    - 1 user thread mapped to 1 kernel thread
    - or N user threads mapped to M kernel threads

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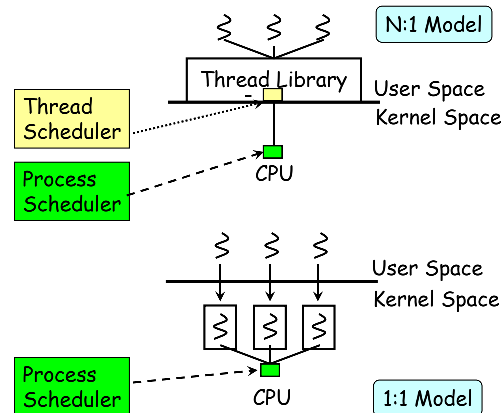
N:1 and 1:1 Model of Multithreading



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N:1 Model of Multithreading (1)

- Many threads mapped onto ONE process
- Implementation
  - » Put thread package entirely in user space
    - Thread creation-scheduling-synchronization done in user space
    - Allocate stack for each thread
    - Kernel has no knowledge of threads
  - » Thread Table
    - Analogous to process table, but contains only thread state
  - » Dispatcher
    - An ordinary function called during startup; calls main()
    - Use setjmp(3)/longjmp(3) in place of function call/return

```
Choose thread to run;
if (context switch)      Load new hardware state;
Resume selected thread execution (load PC);
```


N:1 Model of Multithreading (2)

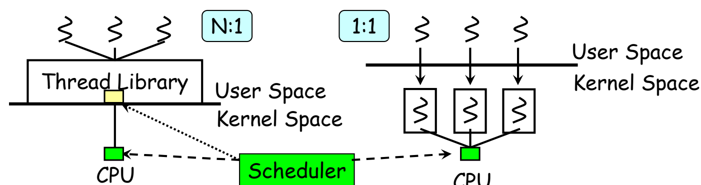
- Implementation (cont)
  - » Non-Blocking I/O Wrapper

```
while (iorequest(...) is incomplete) {
  Update thread table (I/O wait; thread state);
  Jump to dispatcher;
  // Return here when dispatcher returns control
}
```

- Advantages
  - » Coroutine style control flow
  - » Fast, but no speed-up on a multiprocessor
    - One process and threads are unknown to OS kernel
  - » Scheduling done by user-thread package (within context of process)
- Disadvantages
  - » Non-preemptive scheduling within a process

1:1 Model of Multithreading

- Features
  - » Many threads can run simultaneously on different CPUs
  - » Allows 1 or more threads to issue blocking system calls while others run (even on a uniprocessor)
  - » Thread creation requires LWP creation (and a system call)
  - » Each LWP takes up kernel resources ➔ Limited total number of threads

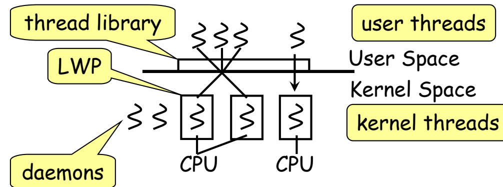


Lightweight Processes (LWPs)

- Kernel Thread
  - » Created/Destroyed by OS kernel
  - » Has own kernel stack but shares text and globals
  - » Used for kernel operations (e.g., I/O, paging daemon)
- Lightweight Process (LWP)
  - » User thread with kernel support
    - Each LWP is associated with a unique kernel thread
  - » Shares address space with other LWPs of same process
  - » Maintains some of user state (register context, ...), kernel stack, and kernel register context
  - » Scheduled by kernel
  - » Most LWP operations (create/destroy, synchronize) require system call ➔ High overhead

N:M Model of Multithreading

- Strict N:M (N ≥ M)
  - » Thread creation, scheduling, and some synchronization done in user space
- N:M + 1:1
  - » Combines the best of N:M and 1:1
  - » Used in Solaris, IRIX, HP-UX
  - » Win32 fibers is a rough approximation



Resources Used

- Kernel Thread
  - » Copy of kernel registers
  - » Priority and scheduling into
  - » Ptrs to scheduler queue or resource wait queues for each thread
  - » Ptrs to LWP and proc structure (if any)
  - » Ptrs to list of all threads in a process and all threads in system
  - » LWP info
- LWP
  - » Copy of user-level registers
  - » System call args, results, error code
  - » Signal handling info
  - » Resource usage and profiling info
  - » Virtual time alarms
  - » Ptr to kernel thread
  - » Ptr to proc structure

Threads Standards

- Defines an API and behavior of a threads paradigm
  - » About 50 function calls
- POSIX Threads
  - » IEEE 1003.1c (Pthreads)
  - » Portable (Implementations on almost all Unix Systems)
  - » Not adopted by Microsoft
- Win32 and OS/2 Threads
  - » Not compatible with Pthreads
  - » Proprietary (vendor-specific)
- Solaris Threads (UI Threads)
  - » Used in Solaris 2 and developed before Pthreads standard was finalized
  - » Virtually the same as Pthreads

POSIX Synchronization Primitives

- Each synchronization facility has a named data structure called a *synchronization variable*
- Counting Semaphores
  - » Typically used to coordinate access to shared variable
- Mutual Exclusion (mutex) Locks
  - » Used to serialize the execution of code
- Condition Variables
  - » Enables threads to atomically block until a conditoin is satisfied
- Multiple Readers, Single Writer Locks
  - » Allows many threads to have simultaneous read-only access to data while allowing only one thread to have write access at any given time

Examples of pthreads Functions (1)

- Thread Creation/Termination
  - » int pthread_create(pthread_t * T, pthread_attr_t *Attr, void *(*start((void *), void *arg);
  - » void pthread_exit(void * ret);
  - » int pthread_join(pthread_t T, void **ret);
- Mutex Lock
  - » int pthread_mutex_lock(pthread_mutex_t *M)
  - » int pthread_mutex_trylock(pthread_mutex_t *M)
  - » int pthread_mutex_unlock(pthread_mutex_t *M)
  - » int pthread_mutex_init(pthread_mutex_t *M, const pthread_mutexattr_t *Attr))

Examples of pthreads Functions (2)

- Condition Variable
  - » int pthread_cond_wait(pthread_cond_t *Cv, pthread_mutex_t *M)
  - » int pthread_cond_signal(pthread_cond_t *Cv)
  - » int pthread_cond_init(pthread_cond_t *Cv, const pthread_condattr_t *Attr)
- Semaphores
  - » int sem_wait(sem_t *S);
  - » int sem_post(sem_t *S);
  - » int sem_init(sem_t *S, int isShared, unsigned int V);

Mutex Lock Implementation

```
pthread_mutex_lock(L) {
  while (TestAndSet(L)) {  // someone has lock
    Put thread on wait queue for L;
    Suspend thread;
  }
  return;
}
pthread_mutex_unlock(L) {
  Unsuspend next thread in wait queue for L;
  L = 0;
  return;
}
```

- Mutexes
  - » Simple enough to implement entirely in user space
- Variation
  - » Spin for a short time instead of suspending in hopes of short blocking time

Spin Locks

- Blocking on a mutex lock will cause two context switches (switch out, switch in)
  - » 150 usec on SC2000/Solaris 2.4
  - » 25 usec on 300 MHz Pentium II/NetBSD
  - » 35 usec on 167 MHz SPARC 5/Solaris 2.5
- A spin lock can be used to avoid the context switching, but wastes CPU time

```
while (pthread_mutex_trylock(&mylock) == EBUSY)
          // ... Do Nothing ...   ;
  ... Critical Section ...
pthread_mutex_unlock(&mylock);
```

Advantage Over Semaphore

- Uses little memory and is fast

	Type of Synchronization	Time (usec) on 20-Proc. 40 MHz SPARC
Full context switch	Unbound Semaphore	292.0
Full context switch	Bound Semaphore	326.0
	Unbound Mutex	2.1
	Bound Mutex	2.3

Condition Variables (1)

- Use
  - Wait until a condition is satisfied without busy waiting
  - NOT used for mutual exclusion, but ...
  - Must be used in conjunction with a mutex lock
- Primitives
  - int pthread_cond_wait(pthread_cond_t *Cv, pthread_mutex_t *M)
    - Block until condition is signaled
    - Atomically release mutex lock before blocking and atomically reacquire it before returning
  - int pthread_cond_signal(pthread_cond_t *Cv)
    - Unblock one thread waiting for the condition
    - No thread blocked on Cv ➔ No Effect
    - Call under protection of mutex associated with Cv
      - Retest condition after thread becomes unblocked

Condition Variable Example

- Wait for W threads to finish

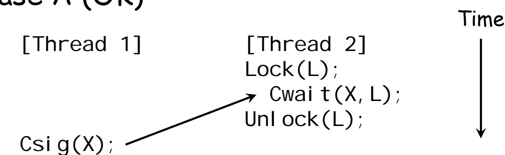
```
pthread_mutex_t      doneLock;
pthread_cond_t       doneCv;

//Main thread:
  pthread_mutex_lock(&doneLock);
    if (nDone < W)       pthread_cond_wait(&doneCv, &doneLock);
  pthread_mutex_unlock(&doneLock);

// Other threads
  pthread_mutex_lock(&doneLock);
    nDone++;
    if (nDone == 0)      pthread_cond_signal(&doneCv);
  pthread_mutex_unlock(&doneLock);
```


CVs are Stateless Signals (1)

- Abbreviations
  - Csig pthread_cond_signal
  - Cwait pthread_cond_wait
  - Lock pthread_mutex_lock
  - Unlock pthread_mutex_unlock
  - Set(x) Lock(L); cond = x; Unlock(L);
- Case A (OK)



CVs are Stateless Signals (2)

- Case B (Lost Signal Problem)

```
[Thread 1]    LOST!!! [Thread 2]
Csig(X);    ------->
                      Lock(L);
                        Cwait(X, L);
                      Unlock(L);
```

- Case B' (Solve Lost Signal Problem)

```
[Thread 1]            [Thread 2]
Lock(L);
  cond = 1;
  Csig(X);  -------> LOST!!!
Unlock(L);
                      Lock(L);
                        while (!cond)    Cwait(X, L);
                      Unlock(L);
```


CVs are Stateless Signals (3)

- Case B" (Alternative Solution)

```
[Thread 1]            [Thread 2]
Set(1);
Csig(X);  ---------> LOST!!!
                      Lock(L);
                        while (!cond)    Cwait(X, L);
                      Unlock(L);
```


Thread Scheduling

- Local Scheduling (Process Contention Scope)
  - Scheduling done by the threads library
    - Very fast except for preemption (requires system call)
  - Scheduling of LWP is global, but is independent of local scheduling
  - Scheduling is by thread priority
    - Set by programmer; not adjusted by threads library
- Global Scheduling (System Contention Scope)
  - Scheduling done by OS kernal
  - Thread blocks ➔ LWP goes to sleep