Introduction

Motivation

Reference: Vahalia 3.1

- Many applications involve several independent tasks that can be done concurrently

Examples

1. GUI based applications e.g. web browser

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2. Standard client-server setup: processing client requests concurrently

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2. Standard client-server setup: processing client requests concurrently
3. Parallelisable programs that can take advantage of multiprocessor architecture e.g. `make` utility

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  1. GUI based applications e.g. web browser
  2. Standard client-server setup: processing client requests concurrently
  3. Parallelisable programs that can take advantage of multiprocessor architecture e.g. `make` utility

- Using multiple processes to achieve concurrency is avoidable:
  - memory load/system overhead increases substantially
  - explicit interprocess communication mechanism must be used

Motivation

- Solution: use lightweight processes / threads
- Thread / lightweight process $\equiv$ sub-processes within a process
- Threads : process = processes : machine
  - if a thread is blocked, another thread can run
  - timesharing + parallel execution on a multiprocessor

Parallelism vs. concurrency

- **Parallelism:** (physical)
  - actual degree of parallel execution achieved
  - limited by number of physical processors available
- **Concurrency:** (conceptual)
  - maximum parallelism achievable with unlimited processors
  - determined by application and its design

Parallelism vs. concurrency

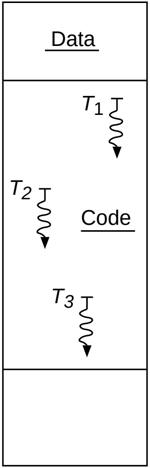
Parallelism

Concurrency

	Uniprocessor	Multiprocessor
Single thread	* Time sharing * Several processes with nearly identical address space	* Separate processes run in parallel
Multi thread	* If one thread blocks, process can continue * Lower memory overhead, easier comm./synch.	* True parallelism (N threads multiplexed on n processors) * Synchronization harder

Basic features

- Process = set of threads + collection of shared resources
- Shared resources:
  - address space (code + data)
  - user credentials
  - open files
  - child processes
- Private resources for each thread:
  - PC, stack, register context
  - child threads
  - state
- No protection between threads ⇒ programmer is reponsible for synchronization to prevent data corruption



User threads, kernel threads, LWPs

User threads

Reference: Vahalia 3.2.3

- Threads abstraction provided by user level library
- Library provides functions for creation, destruction, switching, scheduling of threads without kernel support
- Each user thread has:
  - user stack
  - area to save user-level register context
  - signal mask
  - state information, etc.

Can be saved and restored without kernel intervention.

User threads

Synchronisation

- Global data structures shared
  $\Rightarrow$ must be protected using synchronisation primitives e.g., lock variables/semaphore
- Thread library provides implementation of semaphores (or similar)
- Synchronisation operations can block threads and switch to other thread (if necessary)

User threads: asynchronous I/O

- Allows processes to perform I/O without blocking
- Read/write request simply queues the operation and returns; when I/O completes, process is informed via SIGPOLL
- Programming using AIO is complex
- Threads library uses asynchronous methods internally and provides applications a synchronous programming environment
  - each request is synchronous w.r.t. calling thread (thread blocks until I/O completes)
  - library invokes asynchronous I/O operation and schedules another thread
  - on I/O completion, library reschedules blocked thread

User threads: advantages

- Natural, synchronous programming model
- Thread operations / interactions involve only user-level context (no system call / kernel mode switch required)
  $\Rightarrow$ extremely lightweight (fast, low memory overhead)

  Example:
  SPARC 2: user thread creation - 50-60μs
  process creation - 1700μs

User threads: disadvantages

- Kernel schedules processes without knowledge of constituent threads / thread-level priorities
  - when process is pre-empted, all its threads are pre-empted
  - process running a high priority user thread may be pre-empted in favour of a process running a low priority thread
- No parallelism even on a multiprocessor
- Thread switching
  - clock interrupts occur periodically $\Rightarrow$ scheduler can be run
  - once a thread starts running, no other thread will run until the thread voluntarily gives up CPU (calls thread library function)

Kernel threads

Reference: Vahalia 3.2.1

- Created/destroyed as needed by the kernel for executing a specific function
- *Not visible to user programs*
- Shares kernel text, global data
- Private resources:
  - thread table entry
  - kernel stack
  - register context
  - scheduling / synchronization info
- Relatively inexpensive to create, context switching is quick
  (memory mappings do not have to be changed)

Kernel threads

Examples: system processes

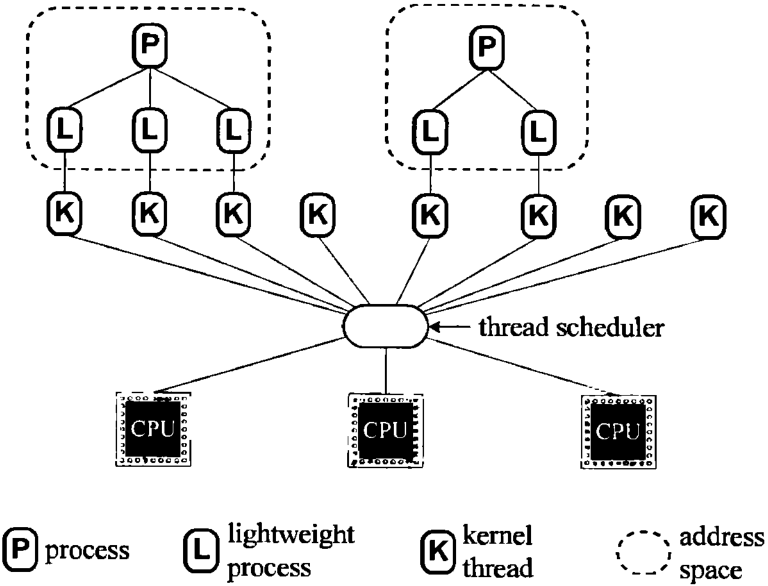
- Implemented as *processes* in traditional systems since there is no provision for kernel threads
  - daemon processes start at user level, but execute entirely in kernel mode $\Rightarrow$ functionally equivalent to kernel threads
    (process specific admin. info == unnecessary overhead)
- Implemented as *kernel threads* in modern multi-threaded kernels

Lightweight processes

Reference: Vahalia 3.2.2

- LWP $\equiv$ kernel-supported user thread / *kernel thread "visible" to users*
- Process contains one or more LWPs
  - each LWP is supported by a separate kernel thread
  - LWPs share address space and other resources of process

Lightweight processes



Lightweight processes

- LWPs are independently scheduled by kernel
- On a multiprocessor, each LWP can be despatched to run on a different processor
- Resource or I/O wait blocks individual LWPs (not entire process)
- Access to shared data has to be synchronized
  - if an LWP tries to access locked data, it will block / busy-wait
  - busy waiting
    - user mode operation $\Rightarrow$ low overhead
    - good option for small critical sections / resources that are held only briefly

LWP: disadvantages

- Creation/destruction/synchronisation/scheduling of LWPs require system calls
  - mode switch + copy between user and kernel address space required
  - unsuitable for applications that
    - use a large number of threads
    - create/destroy threads frequently
    - control is frequently transferred from thread to thread
- LWPs are useful if each thread is fairly independent of the others (frequent access of shared data $\Rightarrow$ synchronization overhead $\uparrow$)

Design issues

Design issues: stack growth

Reference: Vahalia 3.3.5

- Single-threaded process:
  - dedicated stack segment
  - stack overflow $\rightarrow$ protection fault $\rightarrow$ kernel automatically extends stack (instead of sending a signal)
- Multi-threaded process:
  - several user stacks
  - stacks allocated by threads library, possibly from heap/data region
  - library may protect against overflow by allocating a write-protected page just beyond the end of stack
  - stack overflow $\rightarrow$ SIGSEGV $\rightarrow$ thread handles it appropriately

Design issues: fork

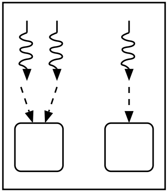
Reference: Vahalia 3.3.1

Duplicate all LWPs of parent or only the one that invokes fork?

Option1: Copy only the calling LWP into the new process

Advantages:

- more efficient
- preferable if child calls *exec* to invoke another program after *fork*



Disadvantages: LWPs may be used to support user-level thread libraries (user thread $\equiv$ data structure in user space)

- new process may contain user-level threads that are not bound to any LWP
- if child process tries to acquire locks held by a non-existent thread, deadlock may occur

Design issues: fork

Duplicate all LWPs of parent or only the one that invokes fork?

Option2: Copy entire process (all LWPs)

Advantages:

- preferable when the entire process needs to be cloned (rather than *exec*)

Disadvantages:

- if cloned LWP is manipulating shared data structures, then shared data may become corrupted

Design issues

Reference: Vahalia 3.3.4

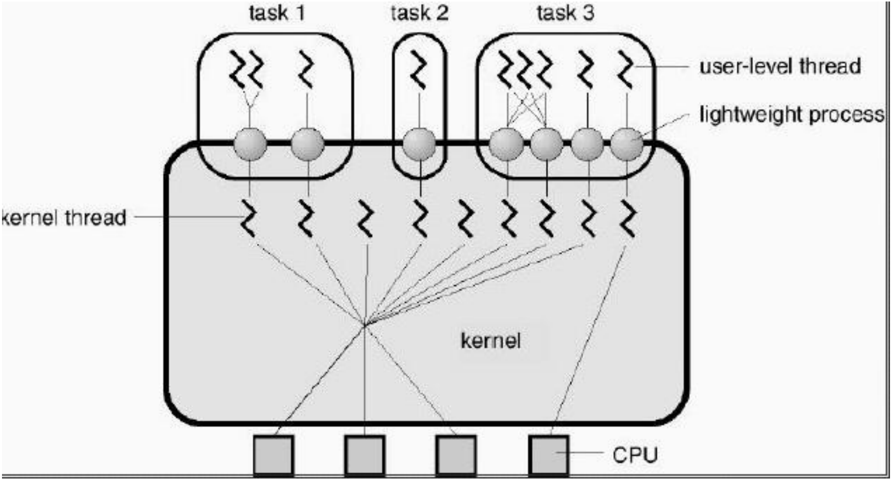
Visibility: Should LWPs be visible outside the process?

- Not visible to other processes
- LWPs within a process can see / signal each other

Solaris threads

Solaris/SVR4 threads

Reference: Vahalia 3.6



Solaris/SVR4 threads

Kernel threads:

- Solaris kernel is organized as a set of kernel threads
- Kernel threads independently scheduled / dispatched
- May run LWP or execute internal kernel function (i.e. not associated with any process)
- Fully pre-emptible
- Context switching between threads is less expensive than context switching between processes (virtual address space does not have to be remapped)

Kernel thread specific resources:

- stack, pointer to stack
- saved copy of kernel registers
- priority / scheduling information
- pointers to connect thread record in a scheduler queue / blocked queue
- pointers to associated *lwp* and *proc* structures
- pointers to maintain a queue of all threads in a process, all threads in the system

Solaris/SVR4 threads

Lightweight processes:

- Bound to its own kernel thread throughout its lifetime
  - LWPs are scheduled independently and may execute in parallel on multiprocessors
- Traditional *proc* structure + *u area* replaced by:
  - *proc* structure – holds all per-process data (including process specific part of traditional *u area*)
  - *lwp* structure to hold all per-LWP data
    - saved values of user-level registers
    - system call arguments, results, error code
    - signal handling information
    - resource usage, timing information, profiling data
    - alarms
    - pointers to kernel thread structure + parent *proc* structure

Solaris/SVR4 threads

User threads:

- Implemented by the threads library
  - provides commonly used API
  - threads created, destroyed, managed without kernel interference
- Run on top of LWPs
  - details taken care of by threads library
    - library creates a pool of LWPs
    - all user threads are multiplexed on this pool of LWPs
    - threads may be *bound* to a dedicated LWP, or *unbound*
  - relation between LWPs and user threads similar to relation between standard I/O library routines (high-level API) and UNIX systems calls (low-level API, more control)

Solaris/SVR4 threads

- Single LWP created by kernel when program is started; executes thread compiled as the main program
  - additional threads created by library calls

```
thread_id_t thread_create(char *stack_addr,
                          u int stack_size,
                          void (*func)(), void *arg,
                          int flag)
```

where `flag` determines whether
new LWP is to be created,
thread is to be permanently bound to this LWP

Solaris/SVR4 threads

Thread data structure:

- thread id (allows threads within a process to communicate with each other)
- saved register state
- user stack - allocated by library
- signal mask
- within process priority - used by thread scheduler (not known to kernel)
- thread local storage - statically allocated data that is not shared between threads

  ```
  #pragma unshared errno
  extern int errno;
  ```

System calls:

- *fork*
  - duplicates each LWP of parent in child
  - any LWPs that were in the middle of a system call return with EINTR error
- *fork1*
  - duplicates only the thread that invokes the function
  - useful when child process expects to invoke new program
- *pread, pwrite*
  - enables concurrent random I/O by taking seek offset as an argument
- *exec*
  - first forces all but the calling LWP to exit