Multiprocessor Operating Systems

CS 256/456

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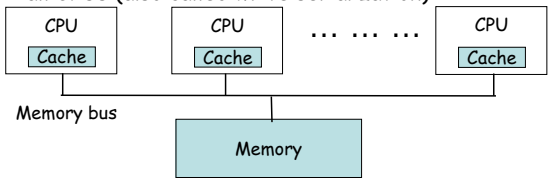
Multiprocessor Hardware

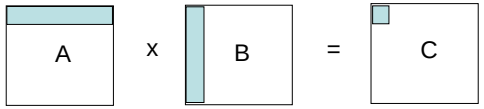
- A computer system in which two or more CPUs share full access to the main memory
- Each CPU might have its own cache and the coherence among multiple caches is maintained
  - write operation by a CPU is visible to all other CPUs
  - writes to the same location is seen in the same order by all CPUs (also called write serialization)



  - bus snooping and cache invalidation

Multiprocessor Applications

- Multiprogramming
  - Multiple regular applications running concurrently
- Concurrent servers
  - Web servers, … …
- Parallel programs
  - Utilizing multiple processors to complete one task (parallel matrix multiplication, Gaussian elimination)

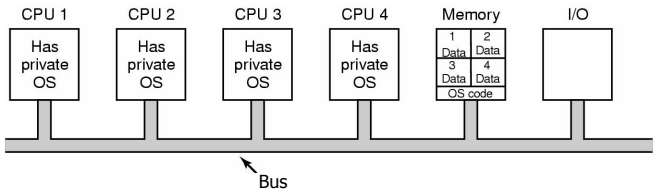


  - Strong synchronization

Single processor OS vs. Multi-processor OS

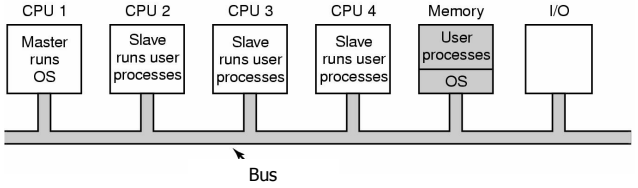
- Single-processor OS
  - easier to support kernel synchronization
    - fine-grained locking vs. coarse-grained locking
    - disabling interrupts to prevent concurrent executions
  - easier to perform scheduling
    - which to run, not where to run
- Multi-processor OS
  - evolution of OS structure
  - synchronization
  - scheduling

Multiprocessor OS



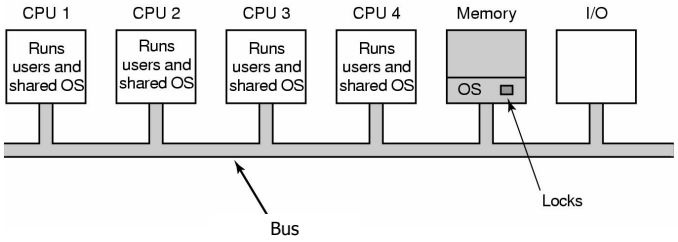
- Each CPU has its own operating system
  - quick to port from a single-processor OS
- Disadvantages
  - difficult to share things (processing cycles, memory, buffer cache)

Multiprocessor OS – Master/Slave



- All operating system functionality goes to one CPU
  - no multiprocessor concurrency in the kernel
- Disadvantage
  - OS CPU consumption may be large so the OS CPU becomes the bottleneck (especially in a machine with many CPUs)

Multiprocessor OS – Shared OS



- A single OS instance may run on all CPUs
- The OS itself must handle multiprocessor synchronization
  - multiple OS instances from multiple CPUs may access shared data structure

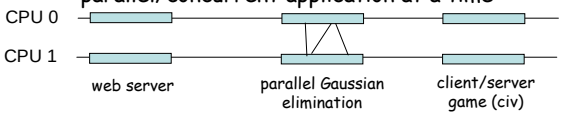
Synchronization (Fine/Coarse Grain Locking)

- Fine-grain locking – only locking necessary for critical section
- Coarse-grain locking – locking large piece of code, much of which is unnecessary
  - simplicity, robustness
  - prevent simultaneous execution

Simultaneous execution is not possible on uniprocessor anyway

Multiprocessor Scheduling

- Timesharing
  - similar to uni-processor scheduling – one queue of ready tasks (protected by synchronization), a task is dequeued and executed when a processor is available
- Space sharing
- cache affinity
  - affinity-based scheduling – try to run each process on the processor that it last ran on
- caching sharing and synchronization of parallel/concurrent applications
  - gang/cohort scheduling – utilize all CPUs for one parallel/concurrent application at a time

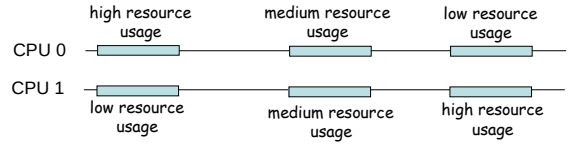


Resource Contention-Aware Scheduling I

- Hardware resource sharing/contention in multi-processors
  - SMP processors share memory bus bandwidths
  - Multi-core processors share L2 cache
  - SMT processors share a lot more stuff
- An example: on an SMP machine
  - a web server benchmark delivers around 6300 reqs/sec on one processor, but only around 9500 reqs/sec on an SMP with 4 processors
- Contention-reduction scheduling
  - co-scheduling tasks with complementary resource needs (a computation-heavy task and a memory access-heavy task)
  - In [Fedorova et al. USENIX2005], IPC is used to distinguish computation-heavy tasks from memory access-heavy tasks

Resource Contention-Aware Scheduling II

- What if contention on a resource is unavoidable?
- Two evils of contention
  - high contention ⇒ performance slowdown
  - fluctuating contention ⇒ uneven application progress over the same amount of time ⇒ poor fairness
- [Zhang et al. HotOS2007] Scheduling so that:
  - very high contention is avoided
  - the resource contention is kept stable



Anderson et al. 1989 (IEEE TOCS)

- Raises issues of
  - Locality (per-processor data structures)
  - Granularity of scheduling tasks
  - Lock overhead
  - Tradeoff between throughput and latency
    - Large critical sections are good for best-case latency (low locking overhead) but bad for throughput (low parallelism)

Performance Measures

- Latency
  - Cost of thread management under the best case assumption of no contention for locks
- Throughput
  - Rate at which threads can be created, started, and finished when there is contention

Optimizations

- Allocate stacks lazily
- Store deallocated control blocks and stacks in free lists
- Create per-processor ready lists
- Create local free lists for locality
- Queue of idle processors (in addition to queue of waiting threads)

Ready List Management

- Single lock for all data structures
- Multiple locks, one per data structure
- Local freelists for control blocks and stacks, single shared locked ready list
- Queue of idle processors with preallocated control block and stack waiting for work
- Local ready list per processor, each with its own lock

Multiprocessor Scheduling in Linux 2.6

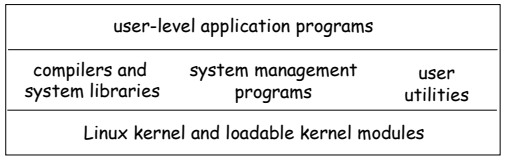
- One ready task queue per processor
  - scheduling within a processor and its ready task queue is similar to single-processor scheduling
- One task tends to stay in one queue
  - for cache affinity
- Tasks move around when load is unbalanced
  - e.g., when the length of one queue is less than one quarter of the other
  - which one to pick?
- No native support for gang/cohort scheduling or resource-contention-aware scheduling

History of Linux

- Linux is a modern, open-source operating system that is mostly POSIX-compliant.
- First developed as a small but self-contained kernel in 1991 by Linus Torvalds, with the major design goal of UNIX compatibility.
- Collaboration by many users all around the world, corresponding almost exclusively over the Internet.

Linux Kernel/System/Distribution

- Kernel
  - the OS code that runs in privileged mode
- System
  - essential system components, but runs in user mode
  - compilers, system libraries
- Linux distribution
  - extra system-installation and management utilities
  - precompiled and ready-to-install tools & packages
  - popular distributions: Redhat/Fedora, Debian, SuSE, Caldera, …



Processes and Threads

- Linux uses the same internal representation for processes and threads; a thread is simply a new process that happens to share the same address space as its parent
- A distinction is only made when a new thread is created by the clone system call
  - a process is a task with its own entirely new context (including address space)
  - a thread is a task with its own identity, but not a dedicated address space

Linux Task Scheduling

- Linux uses two task-scheduling classes:
  - time-sharing and real-time
- A prioritized, epoch-based algorithm for time-sharing
  - Each task has a static credit (default=20) and a dynamic quantum
  - Scheduling is prioritized based on quantum at the beginning of each epoch; each tasks runs its quantum length of time
  - The initial process quantum at its first epoch is credit
  - An epoch ends when no runnable tasks have any quantum; new quantum is calculated for new epoch

$$\text{initial quantum in new epoch} = \frac{\text{remaining quantum}}{2} + \text{priority}$$

  - This quantum crediting system automatically prioritizes interactive or I/O-bound tasks.

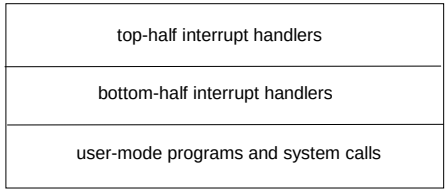
Linux Task Scheduling: O(1) Scheduler

- Linux O(1) scheduler
  - the scheduling overhead is constant, which is independent of the number of processes in the system
- Main operations in Linux scheduler
  - schedule(), epoch transition
- Using two priority arrays
  - one for active array, one for those who have used up their entire quantum (called "expired")
  - array index indicates the priority (multiple tasks with the same priority chained in a link list pointed to from the array index)
- O(1) scheduling
  - fixed number of priorities (bit search instruction like for speed)
- O(1) epoch transition
  - swap active and expired arrays.

Interrupt Handling

- Interrupt handling is usually atomic
  - new interrupts are disabled during the handling of an interrupt
- Linux's kernel allows long interrupt service routines to run without having interrupts disabled for too long
- Interrupt service routines are separated into a *top half* (urgent) and a *bottom half* (not so urgent)
  - The top half runs with interrupts disabled
  - The bottom half is run later, with interrupts enabled
  - Bottom halves run one by one (they do not interrupt each other)

Interrupt Protection Levels



- Each level may be interrupted by code running at a higher level, but will never be interrupted by code running at the same or a lower level.

Synchronization in Linux

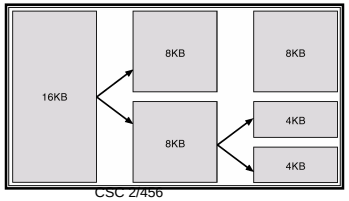
- Per-CPU variables to avoid synchronization
- Atomic variables (non-blocking)
- Read-copy-update (non-blocking)
- Spin-locks – basic, r/w (blocking)
- Semaphores (sleeping)
- Local interrupt disabling

Goal: Maximize concurrency

Managing Physical Memory

Keeping track of free memory

- Linux page allocator can allocate ranges of physically-contiguous pages on request.
- The allocator uses a *buddy-heap* algorithm to keep track of available physically-contiguous memory regions
  - A free region list is maintained for each region size: 4KB, 8KB, 16KB, 32KB, … …
  - A large region can be split into multiple smaller regions if necessary



Memory Page Replacement

- All memory pages are managed together
  - stack/heap/code, …
  - file system buffer cache
- Memory pages are managed in two LRU lists: active list and inactive list
  - each LRU list is managed using a CLOCK (second-chance) LRU approximation
  - pages evicted from the active list go to the inactive list; pages evicted from the inactive list are out of the system
  - pages in the inactive list may be promoted to the active list under certain circumstances

Ext2fs File System

- Disks are divided into contiguous block groups
  - the hope is that there is not much seeking within each block group
  - there is a section for inodes in each block group
  - the FS tries to keep inodes and corresponding file blocks in the same block group
- Ext2fs tries to place logically adjacent blocks of a file into physically adjacent blocks on disk
  - with the help of the free block bitmap
- Ext3fs supporting file system journaling

The Linux /proc File System

- The **proc** file system does not store data, rather, its contents are computed on demand according to user file I/O requests
  - When data is read from one of these files, **proc** collects the appropriate information, formats it into text form and places it into the requesting process's read buffer

Prefetching and I/O Scheduling

- File prefetching/read-ahead
  - prefetching sequentially when the I/O access is considered as sequential
  - how to detect sequential pattern?
- Disk I/O scheduling
  - an elevator-style seek-reduction scheduling
  - non-work conserving scheduling: anticipatory scheduling
  - deadline to prevent starvation

Robustness and Dependability

- Modern operating systems are complex and potentially contain bugs
  - Linux is no exception – including memory errors, synchronization errors (races, deadlocks, …), etc.
- A study [Chou et al. sosp2001] finds that:
  - device drivers are 3-7 times more error-prone
  - average bugs live for 1.8 years
  - errors cluster significantly

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