Principles of Distributed Systems

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Section 3: Processes and Threads

This content is based on the following public resources: https://www.distributed-systems.net/index.php/books/ds4/

Processes and Threads

Introduction to Processes and Threads

- **Definition**: A process is an independent program in execution with its own memory space, while a thread is a lightweight unit of execution within a process, sharing the process's memory.
- **Memory**: A process has its own isolated memory space (address space), whereas threads within the same process share the same memory space, including code, data, and resources.
- **Overhead**: Processes are heavier, requiring more system resources and time for creation and context switching, while threads are lighter, with lower overhead for creation and switching.
- **Communication**: Inter-process communication (IPC) is complex and slower (e.g., pipes, sockets), while threads communicate faster via shared memory but require synchronization (e.g., locks).

Context switching

Observations

1. Threads share the same address space. Thread context switching is much faster than process context switching:
    1. only registers and program counter need to be saved and restored
2. Process context switching is more expensive (in time and space) as
    1. TLB needs to be flushed
    2. page table is reloaded
    3. address space changes
3. Creating and destroying threads is much cheaper than doing so for processes.

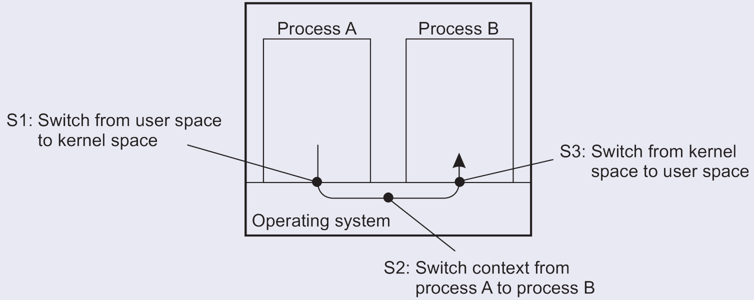
Why use threads

Some simple reasons

- Avoid needless blocking: a single-threaded process will block when doing I/O; in a multithreaded process, the operating system can switch the CPU to another thread in that process.
- Exploit parallelism: the threads in a multithreaded process can be scheduled to run in parallel on a multiprocessor or multicore processor.
- Avoid process switching: structure large applications not as a collection of processes, but through multiple threads.

Avoid process switching

Avoid expensive context switching


Process A
Process B
S1: Switch from user space to kernel space
S3: Switch from kernel space to user space
Operating system
S2: Switch context from process A to process B

Trade-offs

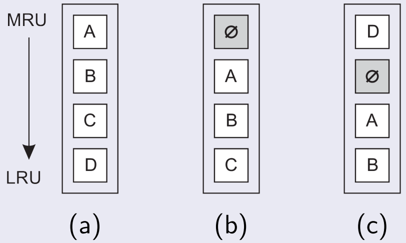
- Threads use the same address space: more prone to errors
- No support from OS/HW to protect threads using each other's memory
- Thread context switching may be faster than process context switching

The cost of a context switch

Consider a simple clock-interrupt handler

- direct costs: actual switch and executing code of the handler
- indirect costs: other costs, notably caused by messing up the cache

What a context switch may cause: indirect costs



(a) before the context switch
(b) after the context switch
(c) after accessing block *D*.

Thread Switch vs Process Context Switch

Thread Switch

- Switch between threads of the *same process*
- Address space remains unchanged
- Page tables and memory mappings are reused
- Faster than process switches
- Typically used for concurrency within applications

Overhead:

- Save/restore registers
- Update stack pointer and program counter

Process Context Switch

- Switch between threads of *different processes*
- Address space changes
- Page tables must be switched
- TLB often flushed or invalidated
- Slower than thread switches

Overhead:

- Save/restore registers
- Switch address space
- Update memory management state

Threads and operating systems

Main issue

Should an OS kernel provide threads, or should they be implemented as user-level packages?

User-space solution

- All operations can be completely handled within a single process ⇒ implementations can be extremely efficient.
- All services provided by the kernel are done on behalf of the process in which a thread resides ⇒ if the kernel decides to block a thread, the entire process will be blocked.
- Threads are used when there are many external events: threads block on a per-event basis ⇒ if the kernel can't distinguish threads, how can it support signaling events to them?

Linux Kernel Threads

- **Task Struct Representation**: In the Linux kernel, threads are implemented as lightweight processes, each represented by a `task_struct` (defined in `include/linux/sched.h`), sharing memory but maintaining separate execution contexts for scheduling.
- **Scheduling with CFS**: The Completely Fair Scheduler (CFS) in `kernel/sched/fair.c` manages kernel threads, treating them as virtual processors and allocating CPU time fairly using a red-black tree.
- **POSIX Threads Integration**: User-space threads (e.g., via `pthread_create`) map to kernel threads, enabling Java's 1:1 threading model to leverage Linux's scheduling for efficient concurrency.

Using threads at the client side

Multithreaded web client

Hiding network latencies:

- Web browser scans an incoming HTML page, and finds that more files need to be fetched.
- Each file is fetched by a separate thread, each doing a (blocking) HTTP request.
- As files come in, the browser displays them.

Multiple request-response calls to other machines (RPC)

- A client does several calls at the same time, each one by a different thread.
- It then waits until all results have been returned.
- Note: if calls are to different servers, we may have a linear speed-up.

Multithreaded clients: does it help?

Thread-level parallelism: TLP

Let c_i denote the fraction of time that exactly i threads are being executed simultaneously.

$$TLP = \frac{\sum_{i=1}^{N} i \cdot c_i}{1 - c_0}$$

with N the maximum number of threads that (can) execute at the same time.

Practical measurements

A typical Web browser has a TLP value between 1.5 and 2.5 $\Rightarrow$ threads are primarily used for logically organizing browsers.

Using threads at the server side

Improve performance

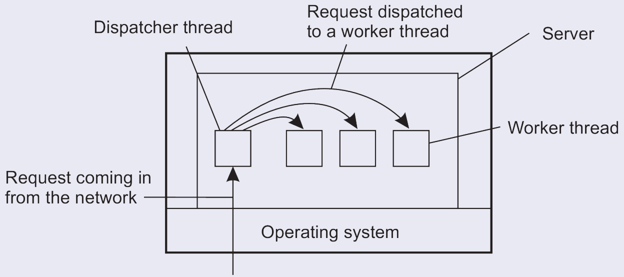
- Starting a thread is cheaper than starting a new process.
- Having a single-threaded server prohibits simple scale-up to a multiprocessor system.
- As with clients: hide network latency by reacting to next request while previous one is being replied.

Better structure

- Most servers have high I/O demands. Using simple, well-understood blocking calls simplifies the structure.
- Multithreaded programs tend to be smaller and easier to understand due to simplified flow of control.

Why multithreading is popular: organization

Dispatcher/worker model


Dispatcher thread
Request dispatched to a worker thread
Server
Worker thread
Request coming in from the network
Operating system

Overview

Multithreading	Parallelism, blocking system calls
Single-threaded process	No parallelism, blocking system calls

Virtualization

Problem Statement and Scope

Objective

Virtualization provides multiple isolated execution environments on shared hardware while preserving operating system semantics and acceptable performance.

- Motivation: consolidation, isolation, manageability, and cloud-scale deployment
- Focus: virtual machines, virtual machine monitors (VMMs), and hypervisors
- Perspective: contemporary hardware-assisted virtualization

The Virtual Machine Abstraction

Definition

A virtual machine is a software-defined abstraction of a physical computer, including CPU, memory, devices, and firmware.

- Presents a conventional hardware interface to the guest OS
- Preserves OS assumptions about privilege, memory, interrupts, and devices
- Enables independent failure, security, and resource control domains

Design requirement

The abstraction must be sufficiently faithful to run unmodified operating systems.

System Structure: VMM and Hypervisor

Component roles

- **Hypervisor (core)**: CPU and memory protection, scheduling, VM entry/exit
- **VMM / device model**: virtual devices, firmware, and I/O backends
- **Management layer**: VM lifecycle, configuration, and policy

- Type-1 systems execute directly on hardware, often with a privileged service domain
- Type-2 systems execute atop a general-purpose host operating system

Key consideration

The primary distinction is the size and placement of the trusted computing base (TCB).

CPU Virtualization Mechanisms

Fundamental approach

Guest code executes natively when safe; sensitive operations are intercepted by the hypervisor.

- Hardware virtualization extensions support VM entry and exit
- Privileged instructions and control register updates cause traps
- Hypercalls provide explicit guest-to-hypervisor interfaces
- vCPU scheduling multiplexes physical cores among virtual CPUs

Performance implication

Execution cost is dominated by the frequency and cost of VM exits.

Memory Virtualization Mechanisms

Address translation

- Guest virtual address (GVA) to guest physical address (GPA)
- Guest physical address (GPA) to host physical address (HPA)

- Nested paging implements two-dimensional translation in hardware
- Enforces isolation between VMs at page granularity
- Enables memory overcommit through reclamation techniques
- NUMA-aware placement improves locality and predictability

Operational concern

Memory translation and locality significantly influence VM performance.

I/O Virtualization Mechanisms

I/O virtualization approaches

- Device emulation for compatibility
- Paravirtual interfaces for reduced overhead
- Direct device assignment using IOMMUs
- SR-IOV for hardware-assisted device sharing

- I/O paths account for a large fraction of virtualization complexity
- Trade-offs exist among performance, portability, and isolation

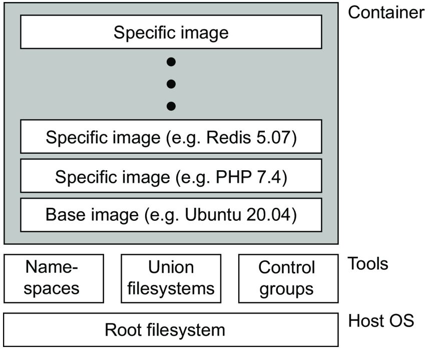
Current Directions in Virtualization

- MicroVMs reduce device models and trusted code size
- Confidential VMs protect memory from privileged software
- Virtual machines serve as isolation boundaries for containerized workloads
- Integration with cluster schedulers and cloud control planes

Summary

Modern virtualization systems combine hardware support, minimal hypervisor cores, and optimized I/O paths to provide strong isolation with predictable performance.

Containers



- Namespaces: a collection of processes in a container is given their own view of identifiers
- Union file system: combine several file systems into a layered fashion with only the highest layer allowing for `write` operations (and the one being part of a container).
- Control groups: resource restrictions can be imposed upon a collection of processes.

VMs and cloud computing

Three types of cloud services

- Infrastructure-as-a-Service covering the basic infrastructure
- Platform-as-a-Service covering system-level services
- Software-as-a-Service containing actual applications

IaaS

Instead of renting out a physical machine, a cloud provider will rent out a VM (or VMM) that may be sharing a physical machine with other customers ⇒ almost complete isolation between customers (although performance isolation may not be reached).

Summary

Summary and Conclusions

We have discussed processes and threads in Distributed Systems, namely:

- Processes and Threads
- Context Switching
- Multithreading
- Virtualization
- Containerization