Distributed Systems

(3rd Edition)

Chapter 03: Processes

Version: August 29, 2017

Introduction to threads

Basic idea

We build virtual processors in software, on top of physical processors:

Processor: Provides a set of instructions along with the capability of automatically executing a series of those instructions.

Thread: A minimal software processor in whose context a series of instructions can be executed. Saving a thread context implies stopping the current execution and saving all the data needed to continue the execution at a later stage.

Process: A software processor in whose context one or more threads may be executed. Executing a thread, means executing a series of instructions in the context of that thread.

Context switching

Contexts

- Processor context: The minimal collection of values stored in the registers of a processor used for the execution of a series of instructions (e.g., stack pointer, addressing registers, program counter).
- Thread context: The minimal collection of values stored in registers and memory, used for the execution of a series of instructions (i.e., processor context, state).
- Process context: The minimal collection of values stored in registers and memory, used for the execution of a thread (i.e., thread context, but now also at least MMU register values).

Context switching

Observations

1. Threads share the same address space. Thread context switching can be done entirely independent of the operating system.
2. Process switching is generally (somewhat) more expensive as it involves getting the OS in the loop, i.e., trapping to the kernel.
3. Creating and destroying threads is much cheaper than doing so for processes.

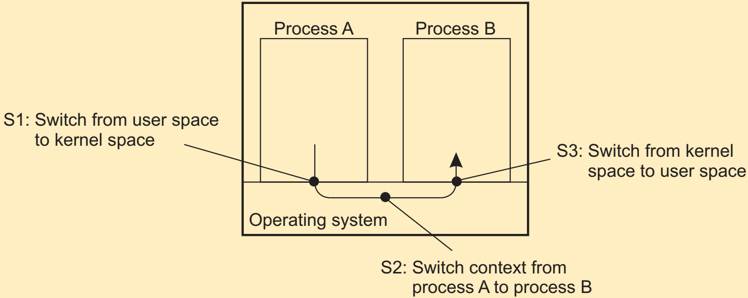
Why use threads

Some simple reasons

- Avoid needless blocking: a single-threaded process will block when doing I/O; in a multi-threaded process, the operating system can switch the CPU to another thread in that process.
- Exploit parallelism: the threads in a multi-threaded 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



Trade-offs

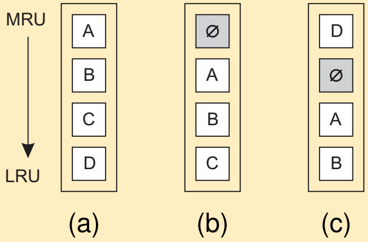
- Threads use the same address space: more prone to errors
- No support from OS/HW to protect threads using each other's memory
- Thread context switching may be faster than process context switching

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*.

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

Threads and operating systems

Kernel solution

The whole idea is to have the kernel contain the implementation of a thread package. This means that all operations return as system calls:

- Operations that block a thread are no longer a problem: the kernel schedules another available thread within the same process.
- handling external events is simple: the kernel (which catches all events) schedules the thread associated with the event.
- The problem is (or used to be) the loss of efficiency due to the fact that each thread operation requires a trap to the kernel.

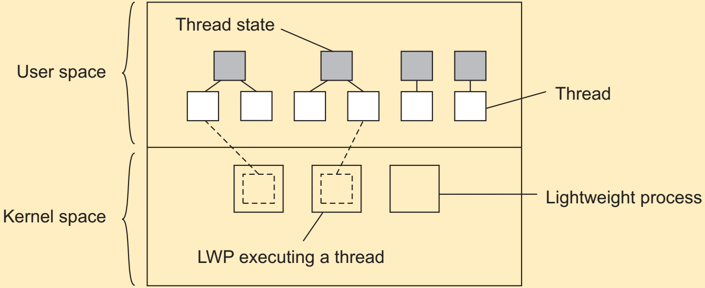
Conclusion – but

Try to mix user-level and kernel-level threads into a single concept, however, performance gain has not turned out to outweigh the increased complexity.

Lightweight processes

Basic idea

Introduce a two-level threading approach: lightweight processes that can execute user-level threads.



Lightweight processes

Principle operation

- User-level thread does system call ⇒ the LWP that is executing that thread, blocks. The thread remains bound to the LWP.
- The kernel can schedule another LWP having a runnable thread bound to it. Note: this thread can switch to any other runnable thread currently in user space.
- A thread calls a blocking user-level operation ⇒ do context switch to a runnable thread, (then bound to the same LWP).
- When there are no threads to schedule, an LWP may remain idle, and may even be removed (destroyed) by the kernel.

Note

This concept has been virtually abandoned – it's just either user-level or kernel-level threads.

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

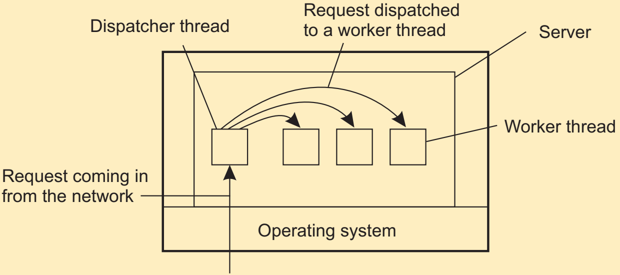
- Starting a thread is cheaper than starting a new process.
- Having a single-threaded server prohibits simple scale-up to a multiprocessor system.
- As with clients: hide network latency by reacting to next request while previous one is being replied.

Better structure

- Most servers have high I/O demands. Using simple, well-understood blocking calls simplifies the overall 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



Overview

Model	Characteristics
Multithreading	Parallelism, blocking system calls
Single-threaded process	No parallelism, blocking system calls
Finite-state machine	Parallelism, nonblocking system calls

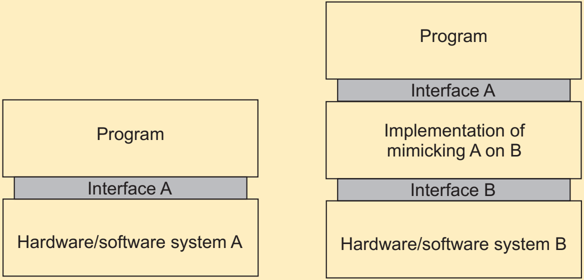
Virtualization

Observation

Virtualization is important:

- Hardware changes faster than software
- Ease of portability and code migration
- Isolation of failing or attacked components

Principle: mimicking interfaces



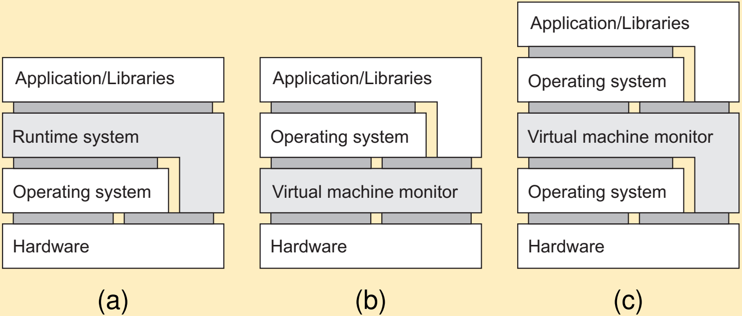
Mimicking interfaces

Four types of interfaces at three different levels

1. Instruction set architecture: the set of machine instructions, with two subsets:
   - Privileged instructions: allowed to be executed only by the operating system.
   - General instructions: can be executed by any program.
2. System calls as offered by an operating system.
3. Library calls, known as an application programming interface (API)

Ways of virtualization

(a) Process VM, (b) Native VMM, (c) Hosted VMM

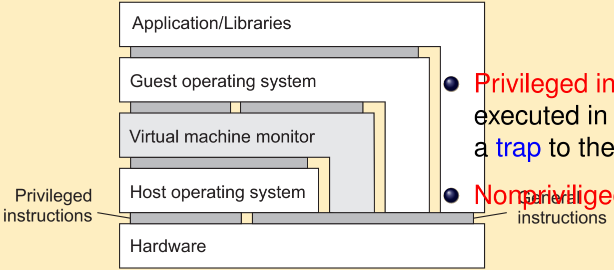


Differences

(a) Separate set of instructions, an interpreter/emulator, running atop an OS.
(b) Low-level instructions, along with bare-bones minimal operating system
(c) Low-level instructions, but delegating most work to a full-fledged OS.

Zooming into VMs: performance

Refining the organization



- Privileged instruction: if and only if executed in user mode, it causes a trap to the operating system
- Nonpriviliged instruction: the rest

Special instructions

- Control-sensitive instruction: may affect configuration of a machine (e.g., one affecting relocation register or interrupt table).
- Behavior-sensitive instruction: effect is partially determined by context (e.g., `POPF` sets an interrupt-enabled flag, but only in system mode).

Condition for virtualization

Necessary condition

For any conventional computer, a virtual machine monitor may be constructed if the set of sensitive instructions for that computer is a subset of the set of privileged instructions.

Problem: condition is not always satisfied

There may be sensitive instructions that are executed in user mode without causing a trap to the operating system.

Solutions

- Emulate all instructions
- Wrap nonprivileged sensitive instructions to divert control to VMM
- Paravirtualization: modify guest OS, either by preventing nonprivileged sensitive instructions, or making them nonsensitive (i.e., changing the context).

VMs and cloud computing

Three types of cloud services

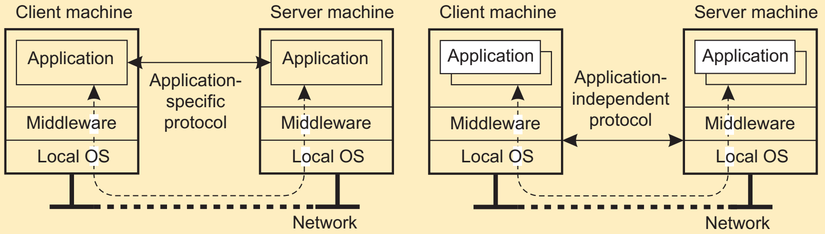
- Infrastructure-as-a-Service covering the basic infrastructure
- Platform-as-a-Service covering system-level services
- Software-as-a-Service containing actual applications

IaaS

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

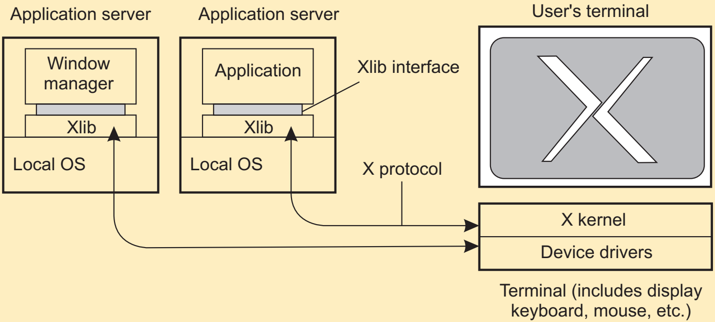
Client-server interaction

Distinguish application-level and middleware-level solutions



Example: The X Window system

Basic organization



X client and server

The application acts as a client to the X-kernel, the latter running as a server on the client's machine.

Improving X

Practical observations

- There is often no clear separation between application logic and user-interface commands
- Applications tend to operate in a tightly synchronous manner with an X kernel

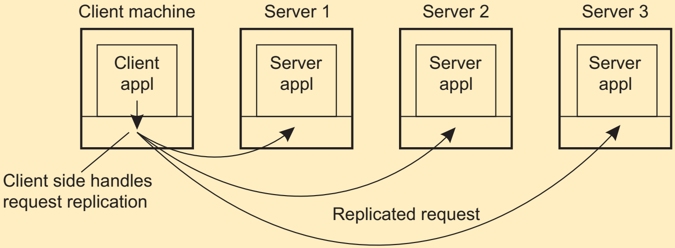
Alternative approaches

- Let applications control the display completely, up to the pixel level (e.g., VNC)
- Provide only a few high-level display operations (dependent on local video drivers), allowing more efficient display operations.

Client-side software

Generally tailored for distribution transparency

- Access transparency: client-side stubs for RPCs
- Location/migration transparency: let client-side software keep track of actual location
- Replication transparency: multiple invocations handled by client stub:



- Failure transparency: can often be placed only at client (we're trying to mask server and communication failures).

Servers: General organization

Basic model

A process implementing a specific service on behalf of a collection of clients. It waits for an incoming request from a client and subsequently ensures that the request is taken care of, after which it waits for the next incoming request.

Concurrent servers

Two basic types

- Iterative server: Server handles the request before attending a next request.
- Concurrent server: Uses a dispatcher, which picks up an incoming request that is then passed on to a separate thread/process.

Observation

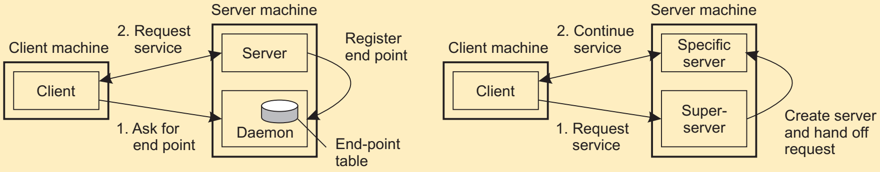
Concurrent servers are the norm: they can easily handle multiple requests, notably in the presence of blocking operations (to disks or other servers).

Contacting a server

Observation: most services are tied to a specific port

ftp-data	20	File Transfer [Default Data]
ftp	21	File Transfer [Control]
telnet	23	Telnet
smtp	25	Simple Mail Transfer
www	80	Web (HTTP)

Dynamically assigning an end point



Out-of-band communication

Issue

Is it possible to interrupt a server once it has accepted (or is in the process of accepting) a service request?

Solution 1: Use a separate port for urgent data

- Server has a separate thread/process for urgent messages
- Urgent message comes in $\Rightarrow$ associated request is put on hold
- Note: we require OS supports priority-based scheduling

Solution 2: Use facilities of the transport layer

- Example: TCP allows for urgent messages in same connection
- Urgent messages can be caught using OS signaling techniques

Servers and state

Stateless servers

Never keep accurate information about the status of a client after having handled a request:

- Don't record whether a file has been opened (simply close it again after access)
- Don't promise to invalidate a client's cache
- Don't keep track of your clients

Consequences

- Clients and servers are completely independent
- State inconsistencies due to client or server crashes are reduced
- Possible loss of performance because, e.g., a server cannot anticipate client behavior (think of prefetching file blocks)

Question

Does connection-oriented communication fit into a stateless design?

Servers and state

Stateful servers

Keeps track of the status of its clients:

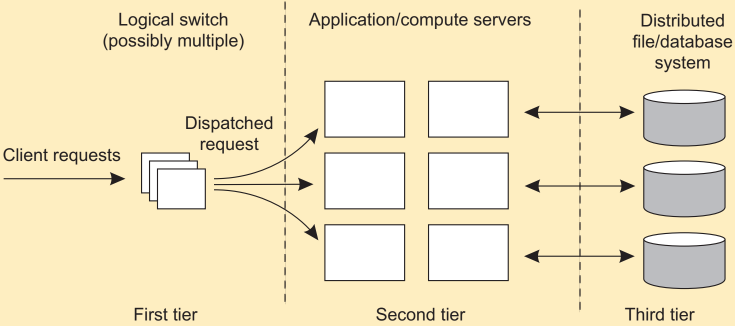
- Record that a file has been opened, so that prefetching can be done
- Knows which data a client has cached, and allows clients to keep local copies of shared data

Observation

The performance of stateful servers can be extremely high, provided clients are allowed to keep local copies. As it turns out, reliability is often not a major problem.

Three different tiers

Common organization



Crucial element

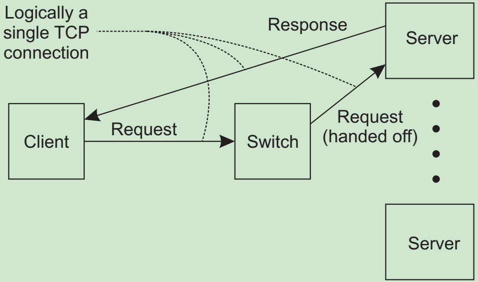
The first tier is generally responsible for passing requests to an appropriate server: request dispatching

Request Handling

Observation

Having the first tier handle all communication from/to the cluster may lead to a bottleneck.

A solution: TCP handoff

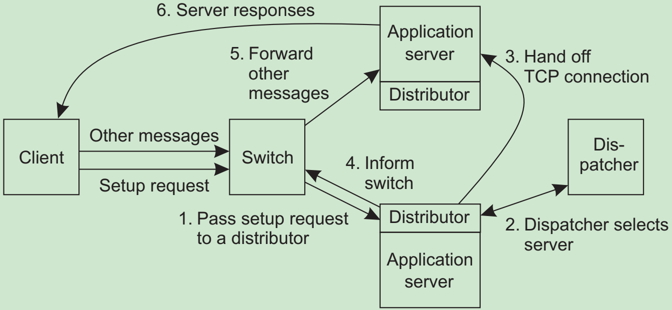


Server clusters

The front end may easily get overloaded: special measures may be needed

- Transport-layer switching: Front end simply passes the TCP request to one of the servers, taking some performance metric into account.
- Content-aware distribution: Front end reads the content of the request and then selects the best server.

Combining two solutions



When servers are spread across the Internet

Observation

Spreading servers across the Internet may introduce administrative problems. These can be largely circumvented by using data centers from a single cloud provider.

Request dispatching: if locality is important

Common approach: use DNS:

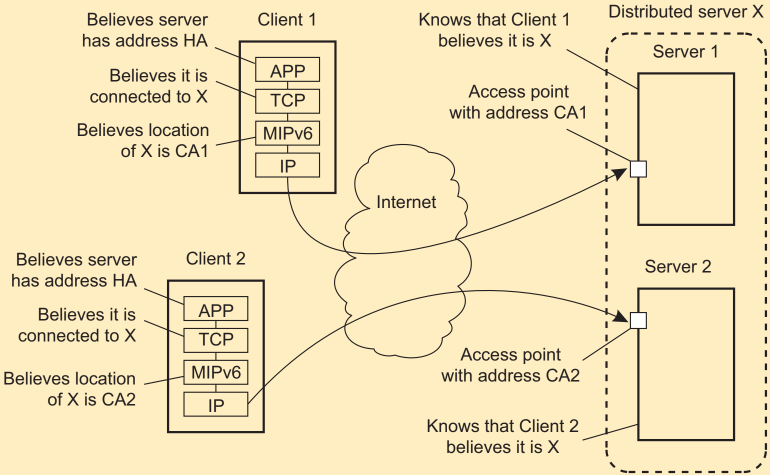
1. Client looks up specific service through DNS - client's IP address is part of request
2. DNS server keeps track of replica servers for the requested service, and returns address of most local server.

Client transparency

To keep client unaware of distribution, let DNS resolver act on behalf of client. Problem is that the resolver may actually be far from local to the actual client.

Distributed servers with stable IPv6 address(es)

Transparency through Mobile IP



Distributed servers: addressing details

Essence: Clients having MobileIPv6 can transparently set up a connection to any peer

- Client *C* sets up connection to IPv6 home address *HA*
- *HA* is maintained by a (network-level) home agent, which hands off the connection to a registered care-of address *CA*.
- *C* can then apply route optimization by directly forwarding packets to address *CA* (i.e., without the handoff through the home agent).

Example: PlanetLab

Essence

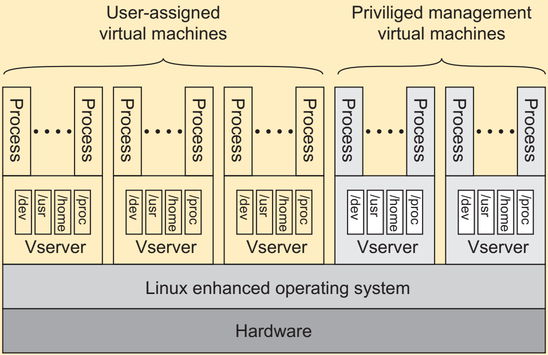
Different organizations contribute machines, which they subsequently share for various experiments.

Problem

We need to ensure that different distributed applications do not get into each other's way $\Rightarrow$ virtualization

PlanetLab basic organization

Overview



Vserver

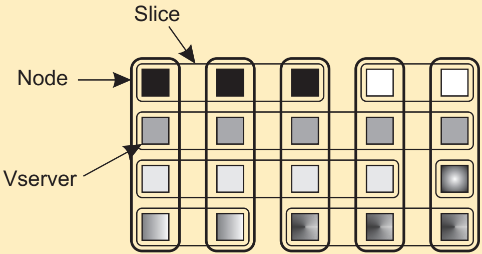
Independent and protected environment with its own libraries, server versions, and so on. Distributed applications are assigned a collection of vservers distributed across multiple machines

PlanetLab VServers and slices

Essence

- Each Vserver operates in its own environment (cf. `chroot`).
- Linux enhancements include proper adjustment of process IDs (e.g., `init` having ID 0).
- Two processes in different Vservers may have same user ID, but does not imply the same user.

Separation leads to slices

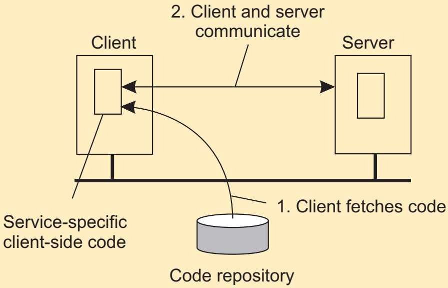


Reasons to migrate code

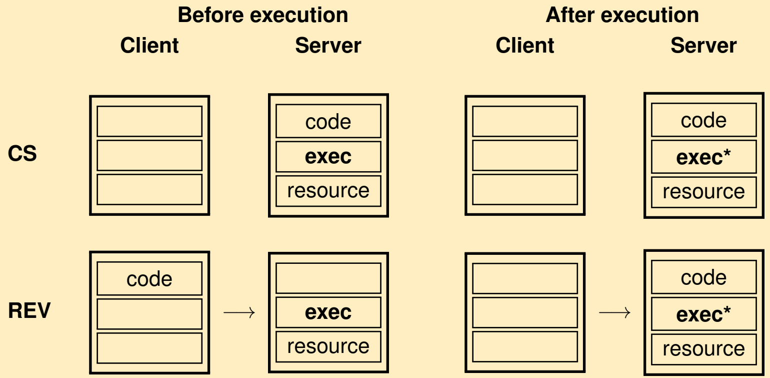
Load distribution

- Ensuring that servers in a data center are sufficiently loaded (e.g., to prevent waste of energy)
- Minimizing communication by ensuring that computations are close to where the data is (think of mobile computing).

Flexibility: moving code to a client when needed



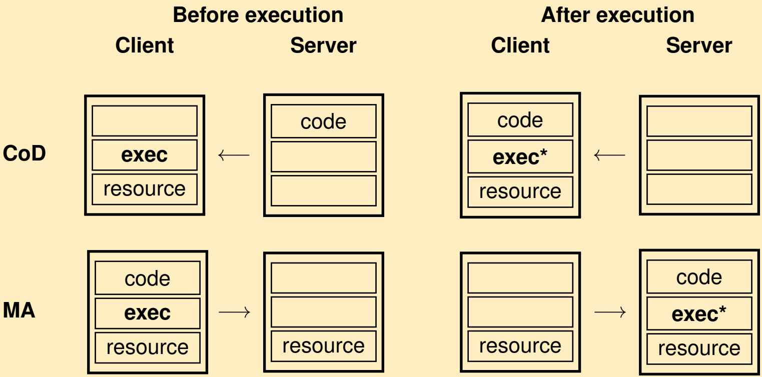
Models for code migration



CS: Client-Server

REV: Remote evaluation

Models for code migration



CoD: Code-on-demand MA: Mobile agents

Strong and weak mobility

Object components

- Code segment: contains the actual code
- Data segment: contains the state
- Execution state: contains context of thread executing the object's code

Weak mobility: Move only code and data segment (and reboot execution)

- Relatively simple, especially if code is portable
- Distinguish code shipping (push) from code fetching (pull)

Strong mobility: Move component, including execution state

- Migration: move entire object from one machine to the other
- Cloning: start a clone, and set it in the same execution state.

Migration in heterogeneous systems

Main problem

- The target machine may not be suitable to execute the migrated code
- The definition of process/thread/processor context is highly dependent on local hardware, operating system and runtime system

Only solution: abstract machine implemented on different platforms

- Interpreted languages, effectively having their own VM
- Virtual machine monitors

Migrating a virtual machine

Migrating images: three alternatives

1. Pushing memory pages to the new machine and resending the ones that are later modified during the migration process.
2. Stopping the current virtual machine; migrate memory, and start the new virtual machine.
3. Letting the new virtual machine pull in new pages as needed: processes start on the new virtual machine immediately and copy memory pages on demand.

Performance of migrating virtual machines

Problem

A complete migration may actually take tens of seconds. We also need to realize that during the migration, a service will be completely unavailable for multiple seconds.

Measurements regarding response times during VM migration