Useful information

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- Mailing list: os@liralab.it
## Outline of the course

- Processes, threads, scheduling
- IPC
- Memory management
- I/O
- Filesystem
- Embedded systems

## The exam consists of:
- 1 problem set
  - C++ programming 1/3
- 1 oral exam:
  - Theory and short exercises 2/3
Background

- **Required**
  - Programming C/C++

- **Helpful**
  - Linux/Unix, Windows

- Main idea is to learn, so, don’t freak out even if it might seem hard!
References

This slide is intentionally left blank
What’s inside the computer?

**Layers:**

<table>
<thead>
<tr>
<th>Web browser</th>
<th>Banking system</th>
<th>Airline reservation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compilers</td>
<td>Editors</td>
<td>Command interpreter (shell)</td>
</tr>
</tbody>
</table>

- Operating system
- Machine language
- Microarchitecture
- Physical devices

} application programs

} system programs

} hardware
Meaning of the layers

- Physical devices: self explaining
- Microarchitecture: define data path within the microprocessor (using registers) sometimes using a microprogram
- Machine language/Assembly language: instruction set (e.g. 50-300 instructions)
Where does the OS start?

<table>
<thead>
<tr>
<th>Kernel mode</th>
<th>User mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervisor mode</td>
<td></td>
</tr>
<tr>
<td>Hardware protection (on modern microprocessors)</td>
<td></td>
</tr>
<tr>
<td>All instructions allowed</td>
<td>Certain instructions not allowed</td>
</tr>
<tr>
<td>Timer interrupt handler</td>
<td>Compiler, editor, web browser</td>
</tr>
</tbody>
</table>
Microkernel RTOS. In QNX Neutrino, only the most fundamental OS primitives (e.g. signals, timers, scheduling) are handled in the kernel itself. All other components – drivers, file systems, protocol stacks, user applications – run outside the kernel as separate, memory-protected processes.
Operating system’s job

- Manage the hardware (all the devices)
- Provide user programs with simpler interface to the hardware (extended machine)
Example: floppy drive

- Specific chip (NEC PD765)
- 16 different commands
- Load between 1 and 9 bytes into a device register
- Read/Write require 13 parameters packed into 9 bytes
- Reply from the device consists of 7 bytes (23 parameters)
- Control of the motor (on/off)
Abstraction

- Better to think in terms of *files* with *names* rather than specific floppy drive commands
- Other unpleasant hardware:
  - Interrupts
  - Timers
  - Memory management
  - ...
- **Extended or virtual machine**
OS as resource manager

- Allocation of resources:
  - Processors, memory, I/O devices among a set of programs competing for them

- Example: allocating the printer
  - Buffering output rather than just print at random

- Multiple users: sharing of resources and avoid conflicts (share vs. security)
• *Time* and *space* multiplexing
• Multiplexing in time: e.g. printer, processor
  ○ Print one job at a time
• Multiplexing in space: e.g. memory, disks
  ○ Divide memory among many processes
- Processors
- Memory
- I/O devices
- Buses
## Processors

### Registers
- Program counter (PC): next instruction
- Stack pointer (SP): stack in memory
- Program Status Word (PSW): condition bits (e.g. kernel vs. user mode)
- Base register: relocation of executables

\{ Context switch \}

### System call
- SW interrupt
- From User to Kernel mode

### Complexity of the CPU HW
- Pipeline architecture
- Superscalar
• Ideally...
  ○ Extremely fast (faster than the CPU in executing an instruction)
  ○ Abundantly large
  ○ Dirt cheap
Memory (for real)

Typical access time

<table>
<thead>
<tr>
<th>Access Time</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 nsec</td>
<td>Registers</td>
</tr>
<tr>
<td>2 nsec</td>
<td>Cache</td>
</tr>
<tr>
<td>10 nsec</td>
<td>Main memory</td>
</tr>
<tr>
<td>10 msec</td>
<td>Magnetic disk</td>
</tr>
<tr>
<td>100 sec</td>
<td>Magnetic tape</td>
</tr>
</tbody>
</table>

Size

- Registers: < 1K
- Cache: ~ 1M
- Main memory: ~ 1-4G
- Magnetic disk: ~ 5-100G
- Magnetic tape: > 20G
Memory cntd.

- **Registers**: typical 32 in a 32 bit CPU
- **Cache**: divided into cache lines (64 bytes each)
  - Cache hit – no main memory access, no bus involvement
  - Cache miss – costly
- **Main memory**
- **Disk** (multiple plates, heads, arms)
  - Logical structure: sectors, tracks, cylinders
- **Magnetic tape**: backup, cheap, removable
Multiple programs in memory

- Base and Limit registers (Limit represents the size of the memory block)
- Hardware support for relocation and multiple programs in memory

<table>
<thead>
<tr>
<th>Fetch:</th>
<th>0xFFFFFFFF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Instruction</strong></td>
<td></td>
</tr>
<tr>
<td>if (PC&lt;Limit) Fetch(PC+Base)</td>
<td>User program and data</td>
</tr>
<tr>
<td>elseTroubles(SigFault)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>0x00000000</td>
</tr>
<tr>
<td>if (Addr&lt;Limit) Fetch(Addr+Base)</td>
<td>Operating system</td>
</tr>
<tr>
<td>else Troubles(SigFault)</td>
<td></td>
</tr>
</tbody>
</table>
DLL’s (in principle)

- Requires an MMU with multiple Base/Limit register pairs

Diagram:

- 0xFFFFFFFF
- DLL
- Limit
- User program
- Base
- Data 1
- Data 2
- Operating system
- 0x00000000

OS 2008-09
• Managing the MMU is one of the OS tasks:
  ○ Balancing context switches since they impact on performances: e.g. MMU registers have to be saved, cache emptied, etc.
I/O devices

- Usually a controller + the actual device
  - For example: a disk controller may hide the details of driving the arm and heads to the appropriate location to read a certain piece of data
  - Sometimes the controller is a small embedded microprocessor in itself

- The interface to the OS is somewhat standardized:
  - IDE disk drives conform to a standard

- Device driver: a piece of the OS. Device drivers run in kernel mode since they have to access I/O instructions and device registers
Device drivers

1. Unix. Compiled and linked with the kernel (although Linux supports dynamic loading of DD)
2. Windows. An entry into an OS table. Loaded at boot
3. Dynamic. USB, IEEE1394 (firewire). At boot time the OS detects the hardware, finds the DD, and loads them
I/O registers

- E.g. small number of registers used to communicate
- Memory mapped: the registers appear at particular locations within the OS address space
- I/O instructions: some CPUs have special privileged (kernel mode) I/O instructions (IN/OUT). Registers are mapped to special locations in I/O space
Ways of doing I/O

1. Polling
2. Interrupt based
3. DMA
Polling

- User makes a system call
- OS calls DD
- DD talks to device, prepares I/O, starts I/O and sits waiting (busy waiting) for I/O completion

*Busy waiting* means that the CPU is busy polling a flag
A piece of hardware called “interrupt controller”

1. CPU issues the I/O request via the device driver
2. On termination the device signals the CPU’s interrupt controller (if the interrupt controller is not busy servicing another higher priority interrupt)
3. If the interrupt can be handled then the controller asserts a pin on the CPU.
4. The interrupt controller puts the address of the device into the bus
Interrupt (cntd.)

- When the CPU decides to take the interrupt:
  - Stores registers (push them into the stack)
  - Switches into kernel mode
  - Uses the device’s address to index a table (interrupt vector)
  - Calls the handler contained at the location located in the interrupt vector
  - Once the handler is executed it returns from the handler by popping the registers from the stack
• Yet another piece of hardware: DMA controller
  ○ Communication between memory and device can be carried out by the DMA controller with little CPU intervention
  ○ When the DMA is completed the controller asserts an interrupt as before
Buses

- Multiple buses (cache, local, memory, PCI, USB, IDE...)
- OS must be aware of all of them to manage things appropriately
- Plug&Play – dynamic allocation of I/O and memory addresses (BIOS code)
This slide is intentionally left blank
Concepts

- Processes
- Deadlocks
- Memory management
- I/O
- Files
- Security
- ...

OS 2008-09
The Shell

- Unix command interpreter (or similarly the “command” in windows)
- Clearly, it’s not part of the OS
Processes

- Associated with each process:
  - Address space (program + data + stack)
  - Entry into the process table (a list of processes)
    - Set of registers (e.g. PC, PSW, etc.)
    - MMU status, registers
- Processes can be created, terminated, signaled (SW interrupt)
- They form a tree (a hierarchy) on some systems
- Process cooperation is obtained by means of IPC (inter-process communication) mechanisms
- Processes start with the privileges of the user who starts them
ps (process status) command

<table>
<thead>
<tr>
<th>Name</th>
<th>OS 2008-09</th>
<th>Process ID</th>
<th>Parent ID</th>
<th>Owner UID</th>
<th>Starting time</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>dr-xr-xr-x</td>
<td>None</td>
<td>3404</td>
<td>1</td>
<td>1003</td>
<td>18:33:59</td>
<td>/usr/bin/bash</td>
</tr>
<tr>
<td>drwrxr-xr-x</td>
<td>None</td>
<td>3404</td>
<td>3404</td>
<td>1003</td>
<td>18:44:59</td>
<td>/usr/bin/ps</td>
</tr>
<tr>
<td>drwrxr-xr-x</td>
<td>None</td>
<td>1176</td>
<td>3404</td>
<td>1628</td>
<td>18:44:59</td>
<td></td>
</tr>
<tr>
<td>drwrxr-xr-x</td>
<td>None</td>
<td>1176</td>
<td>1176</td>
<td>1003</td>
<td>18:44:59</td>
<td></td>
</tr>
</tbody>
</table>
Deadlocks

- Two or more processes mutually requesting the same set of resources
- Example: two processes trying to use simultaneously a tape and CD burner in reverse order
Memory management

- **Virtual memory**
  - Allowing processes requesting more memory than the computer main memory to run
  - Swap space/swapping. Storing some of the process’ memory in the disk
Files

- Concept of directory (group files together)
- A tree-like structure similar to the process hierarchy
- A file is specified by its path name
  - E.g. /usr/bin/ps
- In UNIX there’s a root directory (/)
  - Windows has a root for each drive: A:, B:, C:, etc.
- Working directory (a process property)
  - Where path not beginning with slash are looked for
- Interface between OS and program code is through a small integer called file descriptor
mount

Before mount

After mount
Special file

- A device driver gets a special entry into the file system (usually under /dev)
- Block special files
  - Randomly addressable blocks: a disk
- Character special files
  - A stream of character data: modem, printer
Special file (ctnd.)

<table>
<thead>
<tr>
<th>block</th>
<th>character</th>
</tr>
</thead>
<tbody>
<tr>
<td>brw----</td>
<td>root</td>
</tr>
<tr>
<td>brw----</td>
<td>root</td>
</tr>
<tr>
<td>brw----</td>
<td>root</td>
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<td>brw----</td>
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<tr>
<td>brw----</td>
<td>root</td>
</tr>
<tr>
<td>crw----</td>
<td>root</td>
</tr>
<tr>
<td>crw----</td>
<td>root</td>
</tr>
<tr>
<td>crw-rw-rw</td>
<td>root</td>
</tr>
</tbody>
</table>

iuno lira/pasa>
Security

```
dr-xr-xr-x 4 pasa None 0 Jul 18 11:20 Motorola
dr-xr-xr-x 6 pasa None 0 Sep 11 12:44 My Bibliography
dr-xr-xr-x 2 pasa None 0 Sep 19 17:30 My Chat
dr-xr-xr-x 11 pasa None 0 Jul 10 02:30 My Music
dr-xr-xr-x 31 pasa None 0 Aug 21 11:12 My Pictures
```

```
-rwxrwxrwx 1 pasa None 600 Jul 31 05:52 PUTTY.RND
```

```
-rwxrwxrwx 10 pasa None 0 Sep 1 14:14 Paper reviews
```

```
-rwxrwxrwx 68 pasa None 0 Aug 25 13:47 Papers
```

```
-rwxrwxrwx 5 pasa None 0 Apr 30 23:25 Repository
```

```
-rwxrwxrwx 2 pasa None 0 Mar 29 2002 RtOS
```

```
-rwxrwxrwx 18 pasa None 0 Jul 2 00:23 SU
```

```
-rwxrwxrwx 1 pasa None 16896 Jul 31 04:23 Thumbs.db
```

```
-rwxrwxrwx 17 pasa None 0 Jan 16 2003 Trash
```

```
-rwxrwxrwx 3 pasa None 0 Sep 14 2002 WINDOWS
```

```
-rwxrwxrwx 1 pasa None 75 Jan 16 2003 desktop.ini
```

```
-rwxrwxrwx 11 pasa None 0 Apr 22 22:48 index
```

```
-rwxrwxrwx 1 pasa None 954 Sep 10 09:16 index.pdx
```

OS 2008-09
Pipe

- It’s a sort of pseudofile
- Allows connecting two processes as they were issuing read/write system calls to a regular file
Pipe example
This slide is intentionally left empty
count = read(fd, buffer, nbytes);

OS 2008-09
count = read(fd, buffer, nbytes);

1. Push nbytes into the stack
2. Push buffer into the stack
3. Push fd into the stack
4. Library calls read
5. Put sys call code into register
6. Trap to kernel
7. Examines the call code, query table
8. Call handler, execute read code
9. Return to caller (maybe)
10. Pop stack (i.e. increment SP)
11. Continue execution
read(2) - Linux man page

NAME

read - read from a file descriptor

SYNOPSIS

#include <unistd.h>

ssize_t read(int fd, void *buf, size_t count);

DESCRIPTION

read() attempts to read up to count bytes from file descriptor fd into the buffer starting at buf.

If count is zero, read() returns zero and has no other results. If count is greater than SSIZE_MAX, the result is unspecified.

RETURN VALUE

On success, the number of bytes read is returned (zero indicates end of file), and the file position is advanced by this number. It is not an error if this number is smaller than the number of bytes requested; this may happen for example because fewer bytes are actually available right now (maybe because we were close to end-of-file, or because we are reading from a pipe, or from a terminal), or because read() was interrupted by a signal. On error, -1 is returned, and errno is set appropriately. In this case it is left unspecified whether the file position (if any) changes.

ERRORS

EINTR The call was interrupted by a signal before any data was read.
EAGAIN Non-blocking I/O has been selected using O_NONBLOCK and no data was immediately available for reading.
EIO I/O error. This will happen for example when the process is in a background process group, tries to read from
EAGAIN
Non-blocking I/O has been selected using \texttt{O\_NONBLOCK} and no data was immediately available for reading.

EIO
I/O error. This will happen for example when the process is in a background process group, tries to read from its controlling tty, and either it is ignoring or blocking SIGTIN or its process group is orphaned. It may also occur when there is a low-level I/O error while reading from a disk or tape.

EISDIR
\texttt{fd} refers to a directory.

EBADF
\texttt{fd} is not a valid file descriptor or is not open for reading.

EINVAL
\texttt{fd} is attached to an object which is unsuitable for reading.

EFAULT
\texttt{buf} is outside your accessible address space.

Other errors may occur, depending on the object connected to \texttt{fd}. POSIX allows a \texttt{read} that is interrupted after reading some data to return -1 (with \texttt{errno} set to \texttt{EINTR}) or to return the number of bytes already read.

CONFORMING TO
SVr4, SVID, AT&T, POSIX, X/OPEN, BSD 4.3

REstrictions
On NFS file systems, reading small amounts of data will only update the time stamp the first time, subsequent calls may not do so. This is caused by client side attribute caching, because most if not all NFS clients leave atime updates to the server and client side reads satisfied from the client’s cache will not cause atime updates on the server as there are no server side reads. UNIX semantics can be obtained by disabling client side attribute caching, but in most situations this will substantially increase server load and decrease performance.

Many filesystems and disks were considered to be fast enough that the implementation of \texttt{O\_NONBLOCK} was deemed unnecessary. So, \texttt{O\_NONBLOCK} may not be available on files and/or disks.

SEE ALSO
\texttt{close(2)}, \texttt{fcntl(2)}, \texttt{ioctl(2)}, \texttt{lseek(2)}, \texttt{readdir(2)}, \texttt{readlink(2)}, \texttt{select(2)}, \texttt{write(2)}, \texttt{fread(2)}, \texttt{readv(2)}
## System call interface (part of)

<table>
<thead>
<tr>
<th>Call</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>pid = fork()</code></td>
<td>Create a child process identical to the parent</td>
</tr>
<tr>
<td><code>pid = waitpid(pid, &amp;statloc, options)</code></td>
<td>Wait for a child to terminate</td>
</tr>
<tr>
<td><code>s = execve(name, argv, environp)</code></td>
<td>Replace a process’ core image</td>
</tr>
<tr>
<td><code>exit(status)</code></td>
<td>Terminate process execution and return status</td>
</tr>
<tr>
<td><code>fd = fopen(file, how, ...)</code></td>
<td>Open a file for reading, writing or both</td>
</tr>
<tr>
<td><code>s = close(fd)</code></td>
<td>Close an open file</td>
</tr>
<tr>
<td><code>n = read(fd, buffer, nbytes)</code></td>
<td>Read data from a file into a buffer</td>
</tr>
<tr>
<td><code>n = write(fd, buffer, nbytes)</code></td>
<td>Write data from a buffer into a file</td>
</tr>
<tr>
<td><code>position = lseek(fd, offset, whence)</code></td>
<td>Move the file pointer</td>
</tr>
<tr>
<td><code>s = stat(name, &amp;buf)</code></td>
<td>Get a file’s status information</td>
</tr>
<tr>
<td><code>s = mkdir(name, mode)</code></td>
<td>Create a new directory</td>
</tr>
<tr>
<td><code>s = rmdir(name)</code></td>
<td>Remove an empty directory</td>
</tr>
<tr>
<td><code>s = link(name1, name2)</code></td>
<td>Create a new entry, name2 pointing to name1</td>
</tr>
<tr>
<td><code>s = ulink(name)</code></td>
<td>Remove a directory entry</td>
</tr>
<tr>
<td><code>s = mount(special, name, flag)</code></td>
<td>Mount a file system</td>
</tr>
<tr>
<td><code>s = umount(special)</code></td>
<td>Unmount a file system</td>
</tr>
</tbody>
</table>
System call interface (cntd.)

<table>
<thead>
<tr>
<th>Call</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>s = chdir(dirname)</code></td>
<td>Change the working directory</td>
</tr>
<tr>
<td><code>s = chmod(name, mode)</code></td>
<td>Change a file's protection bits</td>
</tr>
<tr>
<td><code>s = kill(pid, signal)</code></td>
<td>Send a signal to a process</td>
</tr>
<tr>
<td><code>seconds = time(&amp;seconds)</code></td>
<td>Get elapsed time in seconds since Jan 1st, 1970</td>
</tr>
</tbody>
</table>
while (1)
{
    type_prompt();
    read_command(command, parameters);

    if (fork() != 0)
    {
        waitpid(-1, &status, 0);
    }
    else
    {
        execve(command, parameters, 0);
    }
}
lseek

position = lseek(fd, offset, whence)

- Random access to a file
- Imagine the file as accessed through a pointer
- \texttt{lseek} moves the pointer
Directory (in UNIX)

- Each file is identified by an *i-number*
- The *i-number* is an index into a table of *i-nodes*
- A directory is a file containing a list of
  *i-number* – *ASCII name*
- Called a shortcut in some versions of Windows

<table>
<thead>
<tr>
<th>/usr/ast</th>
<th>/usr/jim</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 mail</td>
<td>31 bin</td>
</tr>
<tr>
<td>81 games</td>
<td>70 memo</td>
</tr>
<tr>
<td>40 test</td>
<td>38 progl</td>
</tr>
</tbody>
</table>

\[
\text{link(“/usr/jim/memo”, “usr/ast/note”)}
\]

<table>
<thead>
<tr>
<th>/usr/ast</th>
<th>/usr/jim</th>
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<tr>
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</tr>
<tr>
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<td>38 progl</td>
</tr>
<tr>
<td>70 note</td>
<td></td>
</tr>
</tbody>
</table>
Win32 API

- Different philosophy
- Many calls (API – Application Program Interface), not all of them are actually system calls
- GUI included into the API (in comparison X-Windows is all user level code)
## Example of Win32

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fork</td>
<td>CreateProcess</td>
</tr>
<tr>
<td>waitpid</td>
<td>WaitForSingleObject</td>
</tr>
<tr>
<td>execve</td>
<td>None</td>
</tr>
<tr>
<td>exit</td>
<td>ExitProcess</td>
</tr>
<tr>
<td>open</td>
<td>CreateFile</td>
</tr>
<tr>
<td>close</td>
<td>CloseHandle</td>
</tr>
<tr>
<td>read</td>
<td>ReadFile</td>
</tr>
<tr>
<td>Write</td>
<td>WriteFile</td>
</tr>
<tr>
<td>Lseek</td>
<td>SetFilePointer</td>
</tr>
<tr>
<td>stat</td>
<td>GetFileAttributeEx</td>
</tr>
<tr>
<td>mkdir</td>
<td>CreateDirectory</td>
</tr>
<tr>
<td>rmdir</td>
<td>RemoveDirectory</td>
</tr>
<tr>
<td>link</td>
<td>None</td>
</tr>
<tr>
<td>unlink</td>
<td>DeleteFile</td>
</tr>
<tr>
<td>mount</td>
<td>None</td>
</tr>
<tr>
<td>umount</td>
<td>None</td>
</tr>
<tr>
<td>chdir</td>
<td>SetCurrentDirectory</td>
</tr>
<tr>
<td>chmod</td>
<td>None</td>
</tr>
<tr>
<td>kill</td>
<td>None</td>
</tr>
<tr>
<td>time</td>
<td>GetLocalTime</td>
</tr>
</tbody>
</table>
Operating system structure

- Monolithic systems
- Layered systems
- Virtual machines
- Exokernels
- Client-Server model
Monolithic systems

- The “big mess”
- No organized structure
- A bit of structure anyway:
  - System calls requires parameters in a well defined place (e.g. the stack)
  - Three layers:
    - Application program
    - Service procedures
    - Helper procedures
Layered systems

- Each layer relies only on services provided by lower level layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>User/operator</td>
</tr>
<tr>
<td>4</td>
<td>User programs</td>
</tr>
<tr>
<td>3</td>
<td>I/O management</td>
</tr>
<tr>
<td>2</td>
<td>Operator-process communication</td>
</tr>
<tr>
<td>1</td>
<td>Memory and disk management</td>
</tr>
<tr>
<td>0</td>
<td>Processor allocation and multiprogramming</td>
</tr>
</tbody>
</table>
Virtual machines

- Timesharing provides:
  - Multiprogramming
  - Extended machine
- Decouple the two functions:
  - Virtual machine monitor (a SW layer)
  - It does the multiprogramming providing a “simulation” of the bare HW
- On top of the monitor any compatible OS could be run
- Also the Pentium (8086 mode, running DOS applications) and Java VM provide a similar mechanism (slightly different though)
## Virtual machines

<table>
<thead>
<tr>
<th>Applications</th>
<th>CMS</th>
<th>CMS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>syscall</td>
<td>VM/370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/O instruction</td>
<td>370 Bare Hardware</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Each process is given a subset of the resources (at any given moment) and NOT a simulation of the whole machine

- Simpler
- Saves a layer of mapping
- Each VM in this case is given a subset of memory, disk space, etc.
- The OS checks for conflicts
Client-Server model

- Microkernel
- Services are moved into user-space processes (e.g. the filesystem)
- The kernel handles message passing mechanisms to make communication possible between user code and services
- Easy to “remote” the message passing (distributed system)
- Resilient: a crash in one module doesn’t compromise the whole system (which can then recover from the crash)
- I/O and HW access must be done into the kernel (spoils a bit the nice client-server model) for example in device drivers
Microkernel RTOS. In QNX Neutrino, only the most fundamental OS primitives (e.g., signals, timers, scheduling) are handled in the kernel itself. All other components – drivers, file systems, protocol stacks, user applications – run outside the kernel as separate, memory-protected processes.