6.1800 Spring 2024

Lecture #6: Virtual Machines

even more virtualization, plus kernel designs
The South Pacific island of Niue is one of the most remote places in the world. Its closest neighbors, Tonga and American Samoa, are hundreds of miles away. The advent of the internet promised, in a small way, to make Niue and its 2,000 or so residents more connected to the rest of the world.

In the late 1990s, an American businessman offered to hook up the island to the internet. All he wanted in exchange was the right to control the .nu suffix that Niue was assigned for its web addresses. The domain did not seem as lucrative as .tv — which was slotted to Tuvalu, another South Pacific nation — and the leaders of Niue (pronounced New-ay) signed off on the deal. But the two sides were soon at odds.

Now, after more than two decades of back and forth, the disagreement is finally nearing a resolution in a court of law. Disputes over domain names were not uncommon during the internet’s infancy but experts are hard pressed to recall one that has lasted this long.

It turned out that .nu was, in fact, very valuable. “Nu” means now in Swedish, Danish and Dutch, and thousands of Scandinavians registered websites with that suffix, creating a steady business for Niue’s business partner, Bill Semich.

The Two-Decade Fight for Two Letters on the Internet

The South Pacific island of Niue says it was cheated out of .nu, a domain that turned out to be very lucrative on the other side of the world.
in the case of DNS, names have meaning outside of the system, even if they were only originally intended to denote “administrative zones that divide the web into domains”

many of the decisions we make when we build our systems **impact** people who might not even be aware of the system

“We are victims of digital colonialism,” Prime Minister Dalton Tagelagi of Niue said over a crackling video link from his office in the capital of Alofi. “This domain, the .nu, recognizes Niue as a sovereign country. This is how important it is to our identity.”

Critics question that assessment, as there is formally no such thing as sovereignty in cyberspace, only administrative zones that divide the web into domains like .nu and, for instance, the .nz **suffix** assigned to New Zealand.

Winning the case could help ensure the long-term survival of Niue, Mr. Tagelagi said. The island’s population is now about a third of what it was in the 1960s, and the empty homes that dot the island are a reminder of the people who left for better economic opportunities. A victory could help fund its bid to join the United Nations, similar to how Tuvalu obtained U.N. membership after monetizing .tv.

If Niue manages to get .nu back, it could bring in up to $2 million in revenue a year, according to Par Brumark, a domain name expert who is acting on Niue’s behalf in the Swedish case.
Operating systems enforce modularity on a single machine using virtualization in order to enforce modularity and have an effective operating system, a few things need to happen:

1. Programs shouldn’t be able to refer to (and corrupt) each others’ memory

2. Programs should be able to communicate with each other

3. Programs should be able to share a CPU without one program halting the progress of the others

Today’s goal: Run multiple operating systems at once
**virtual machine monitor** virtualizes the physical hardware for the guest OSes.

Virtual machine monitor (VMM) virtualizes the physical hardware for the guest OSes running guest OS.

Physical hardware (including U/K, PTR, page table, ...).

Guest OSes run in user mode.

Privileged instructions in guest OS will cause an exception, which the VMM will intercept ("trap") and **emulate**.

If the VMM can’t emulate an instruction, it will send the exception back to the guest OS for handling.

**First question:** what does it mean to emulate?
virtual machine monitor virtualizes the physical hardware for the guest OSes

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first example: virtualizing memory (again!)

```
<table>
<thead>
<tr>
<th>guest OS</th>
<th>guest OS</th>
</tr>
</thead>
<tbody>
<tr>
<td>virtual hardware</td>
<td>virtual hardware</td>
</tr>
<tr>
<td>U/K, PTR, page table, ...</td>
<td>U/K, PTR, page table, ...</td>
</tr>
<tr>
<td>virtual machine monitor (VMM)</td>
<td>virtual machine monitor (VMM)</td>
</tr>
<tr>
<td>physical hardware</td>
<td>physical hardware</td>
</tr>
<tr>
<td>U/K, PTR, page table, ...</td>
<td>U/K, PTR, page table, ...</td>
</tr>
</tbody>
</table>
```

**first question:** what does it mean to emulate?

in this example, it means that the VMM needs to step in and translate guest physical addresses to host physical addresses
virtual machine monitor virtualizes the physical hardware for the guest OSes

first example: virtualizing memory (again!)

1. guest OS loads its PTR, which triggers an exception; the VMM intercepts
2. VMM combines the guest page table with its own page table to create a host page table
3. physical hardware uses the host page table
**virtual machine monitor** virtualizes the physical hardware for the guest OSes

first example: virtualizing memory (again!)

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guest OS page tables are marked as **read-only memory** so that modifications to these page tables also trigger exceptions (and thus allow the VMM to update the other tables)
**virtual machine monitor** virtualizes the physical hardware for the guest OSes

**first example: virtualizing memory (again!)**

1. guest OS loads its PTR, which triggers an exception; the VMM intercepts

In modern hardware, the physical hardware is aware of both page tables, and performs the translation from guest virtual to host physical itself.
**Virtual Machine Monitor (VMM)** virtualizes the physical hardware for the guest OSes.

- guest OS
  - virtual hardware
    - U/K
    - PTR
    - page table
    - ...
  - virtual machine monitor (VMM)
  - physical hardware
    - U/K, PTR, page table, ...

Guest OSes run in user mode.

Privileged instructions in guest OS will cause an exception, which the VMM will intercept ("trap") and emulate.

If the VMM can't emulate an instruction, it will send the exception back to the guest OS for handling.

Figuring out how to emulate an instruction is not enough; we also need to make sure that the VMM is trapping all relevant instructions.
**virtual machine monitor** virtualizes the physical hardware for the guest OSes

describe the process of virtualization in the context of guest OSes and physical hardware.

- **Guest OS**
  - virtual hardware
    - U/K
    - PTR
    - page table
  - virtual machine monitor (VMM)
  - physical hardware
    - U/K, PTR, page table, ...

- **Para-virtualization**: modify guest OS slightly

- **Binary translation**: VMM replaces problematic instructions with ones that it can trap and emulate

- **Hardware support**: architecture provides a special operating mode for VMMs in addition to user mode, kernel mode

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VMMs work by **trapping** and **emulating** important instructions.

The actual **emulation** looks different depending on what we’re trying to do. At times — e.g., in the case of virtual memory — it’s a fairly straightforward extension of what the OS does.

Modern architectures build support for virtualization into their CPUs, which allow the VMM to operate **efficiently**.

This is all yet another application of **virtualization**. The details change depending on what problem we’re solving, but the goal of virtualization remains the same.
monolithic kernel: no enforced modularity within the kernel itself

microkernels: enforce modularity by putting subsystems in user programs

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despite the modularity, it’s not clear that redesigning an operating system from a monolithic kernel to a microkernel is a good idea, in part for reasons of performance
**virtual machines** allow us to run multiple **isolated** OSes on a single physical machine, similar to how we used an OS to run multiple programs on a single CPU

**monolithic kernels** provide no enforced modularity within the kernel. **microkernels** do, but redesigning monolithic kernels as microkernels is challenging

we have cared about **performance** in all aspects of our operating systems journey so far, and next time we’ll start to think about performance more generally

you have now seen **virtualization** applied as a solution to many different problems. the details change depending on what problem we’re solving, but the goal of virtualization remains the same.