Virtual Machines

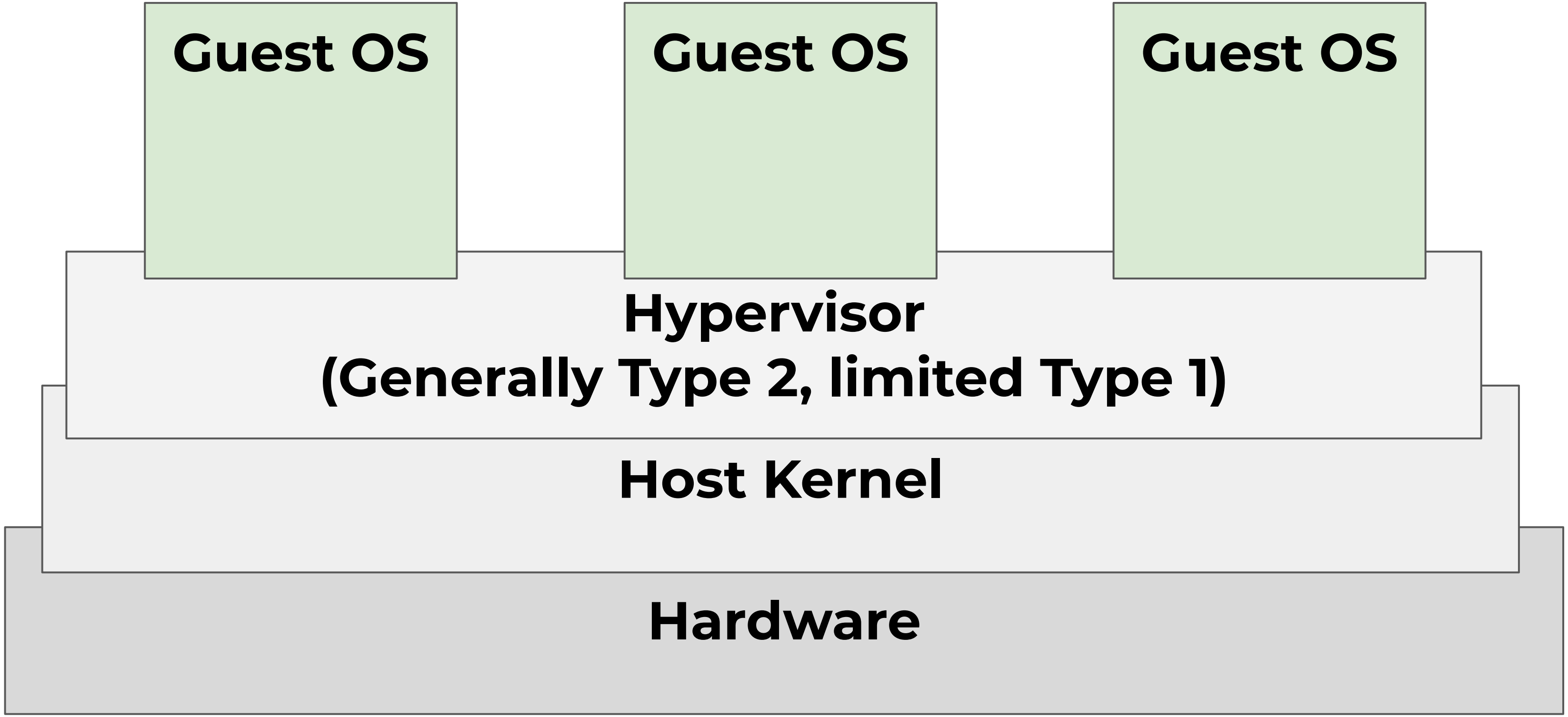
CS 423 - University of Illinois

Wade Fagen-Ulmschneider
(Slides built from Adam Bates and Tianyin Xu previous work on CS 423.)

Cloud Computing (Generation 1)

- Dominated by Infrastructure-as-a-Service (IaaS) clouds (and storage services)
  - Big winner was Amazon EC2
- Hypervisors that virtualized the hardware-software interface
- Customers were responsible for provisioning the software stack from the kernel up

Cloud Computing (Generation 1)



Guest OS

Guest OS

Guest OS

Hypervisor
(Generally Type 2, limited Type 1)

Host Kernel

Hardware

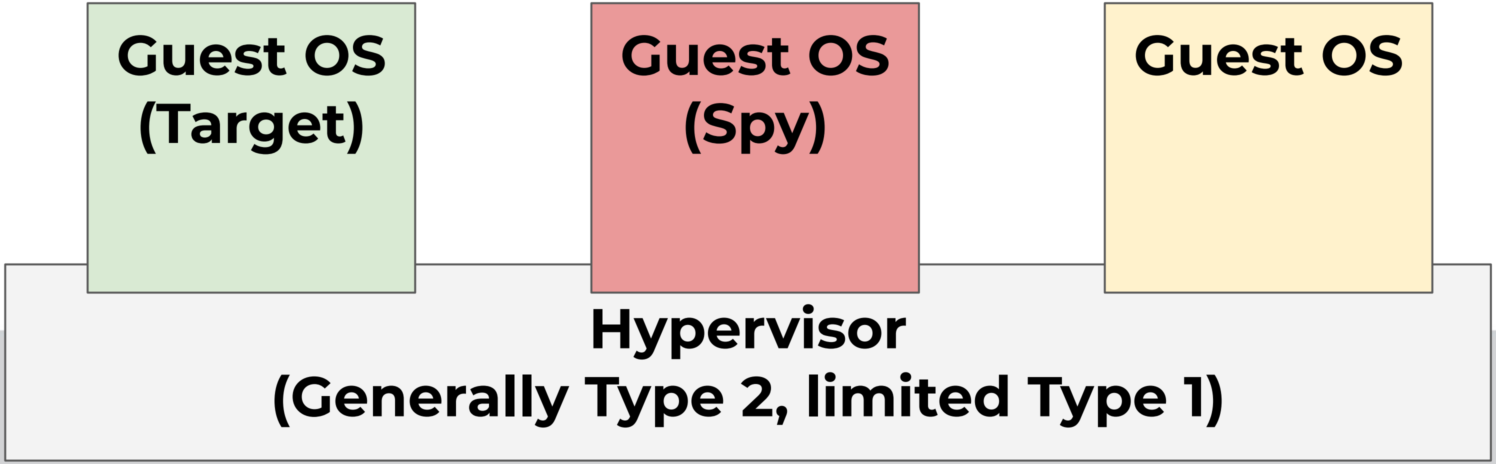
Cloud Computing (Generation 1)

- Type 2 Hypervisors:
  - Strong isolation between different customer's virtual machines
  - VMM is 'small' compared to the kernel
    - Less LoC means ⇒ less bugs
    - Fewer bugs ⇒ usually more security

Cloud Computing (Generation 1)

- ★ Most "practical" attacks on IaaS clouds relied on side channels to detect co-location between attacker and victim VM
  - ○ E.g., we could correlate the performance of a shared resource
  - ○ network RTT's, cache performance

- ★ After co-resident, make inferences about victim's activities



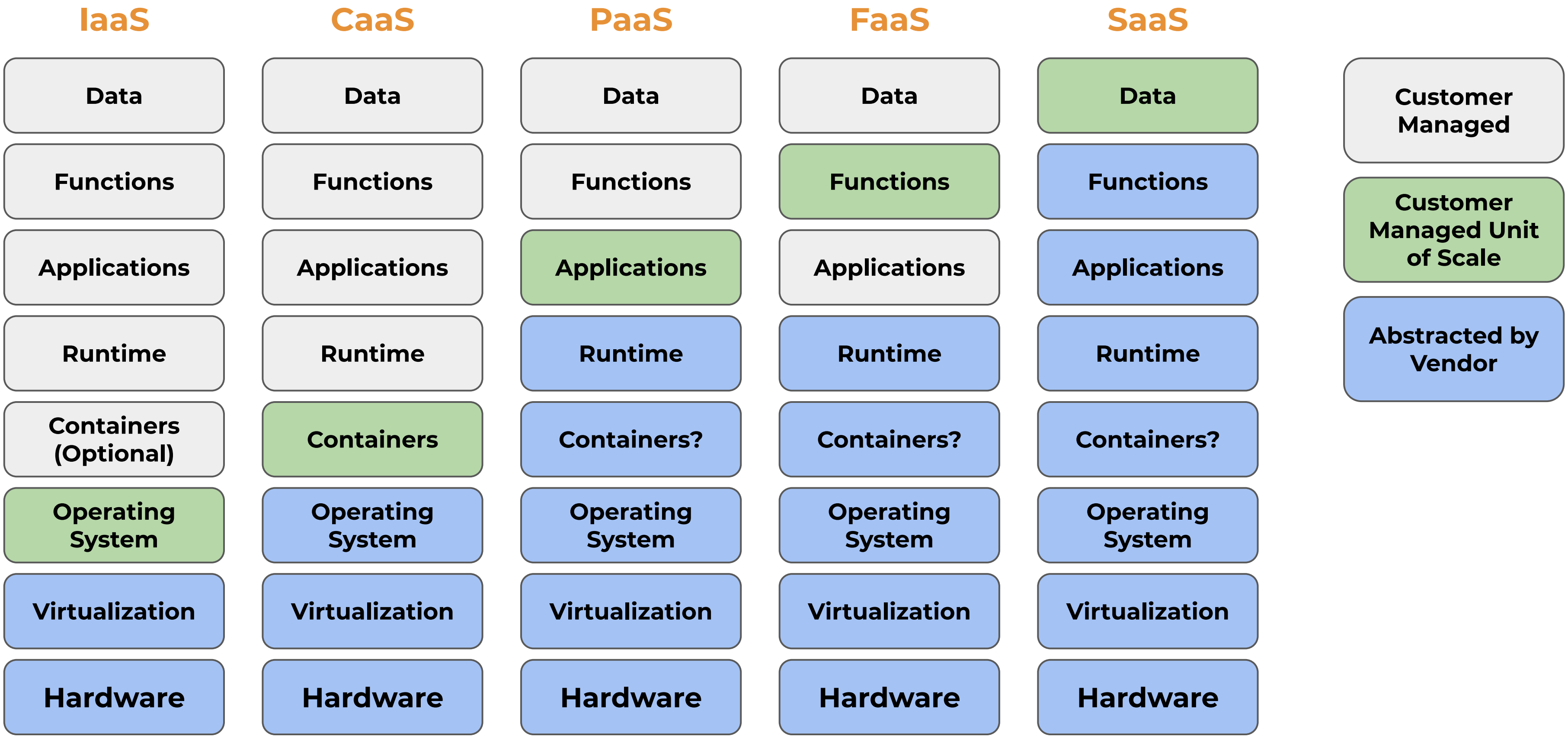
Cloud Computing (Generation 1)

- Overall:
    - Centralizing the management of hardware ⇒ Increased reliability, Decreased IT costs
    - Cheap VMs allows services to run in their own environments (further increasing reliability)
    - Extremely high flexibility (you build the OS!), but was all that flexibility needed?

Cloud Computing (Generation 2)

★ Introduction of various service models:

  ○ **CaaS**: Container as a Service
  ○ **PaaS**: Platform as a Service
  ○ **FaaS**: Function as a Service
  ○ **SaaS**: Software as a Service



IaaS	CaaS	PaaS	FaaS	SaaS
⬜ Data	⬜ Data	⬜ Data	⬜ Data	🟩 Data
⬜ Functions	⬜ Functions	⬜ Functions	🟩 Functions	🟦 Functions
⬜ Applications	⬜ Applications	🟩 Applications	⬜ Applications	🟦 Applications
⬜ Runtime	⬜ Runtime	🟦 Runtime	🟦 Runtime	🟦 Runtime
⬜ Containers (Optional)	🟩 Containers	🟦 Containers?	🟦 Containers?	🟦 Containers?
🟩 Operating System	🟦 Operating System	🟦 Operating System	🟦 Operating System	🟦 Operating System
🟦 Virtualization	🟦 Virtualization	🟦 Virtualization	🟦 Virtualization	🟦 Virtualization
🟦 Hardware	🟦 Hardware	🟦 Hardware	🟦 Hardware	🟦 Hardware

⬜ Customer Managed

🟩 Customer Managed Unit of Scale

🟦 Abstracted by Vendor

Why Choose CaaS?

- Containers provide a known, configurable runtime environment (“user land”) without managing an OS or Kernel.

- **AWS**: Elastic Container Service (ECS)
- **Google**: Google App Engine
- *...many others...*

Why Choose PaaS?

★ Lots of user-level services require configuration, maintenance, and performance optimization (“systems knowledge”). What if this is provided for us?

★ **Databases:** SQL, NoSQL (mongodb), In-Memory (redis), etc

★ **AI/ML Algorithms**: AutoML, Speech Recognition, Image Classification, etc

★ **Build Tools**: Test Suites, Data Pipelines, etc

★ *…hundreds of development platforms…*

Why Choose FaaS?

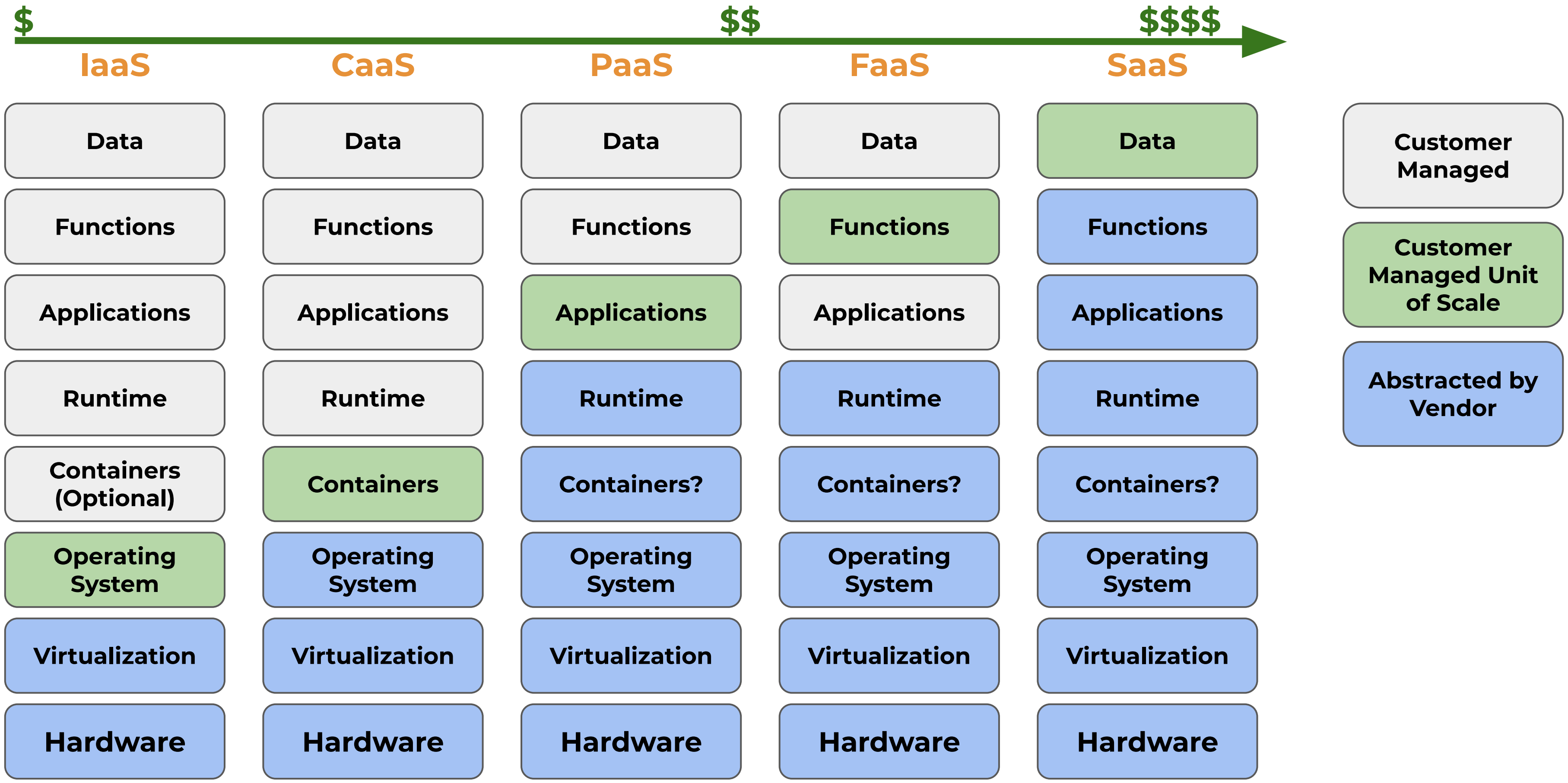
- Common to need software to run “on-demand” to some event for short bursts of computation.
  - **Examples**:
    - Profile Photo Upload ⇒ Need conversation to many different sizes for various layouts
    - On-Demand Data ⇒ Need creation of a CSV w/ processed data based on user inputs
    - Many computational tasks that are expensive but uncommon

- **AWS**: Lambdas
- **Google**: Cloud Functions

Why Choose SaaS?

- What if you never want to see source code?
  - Almost any website you log into can be considered “SaaS”

- **Systems tools are used to create SaaS platforms** -- but generally SaaS is beyond the scope of systems.



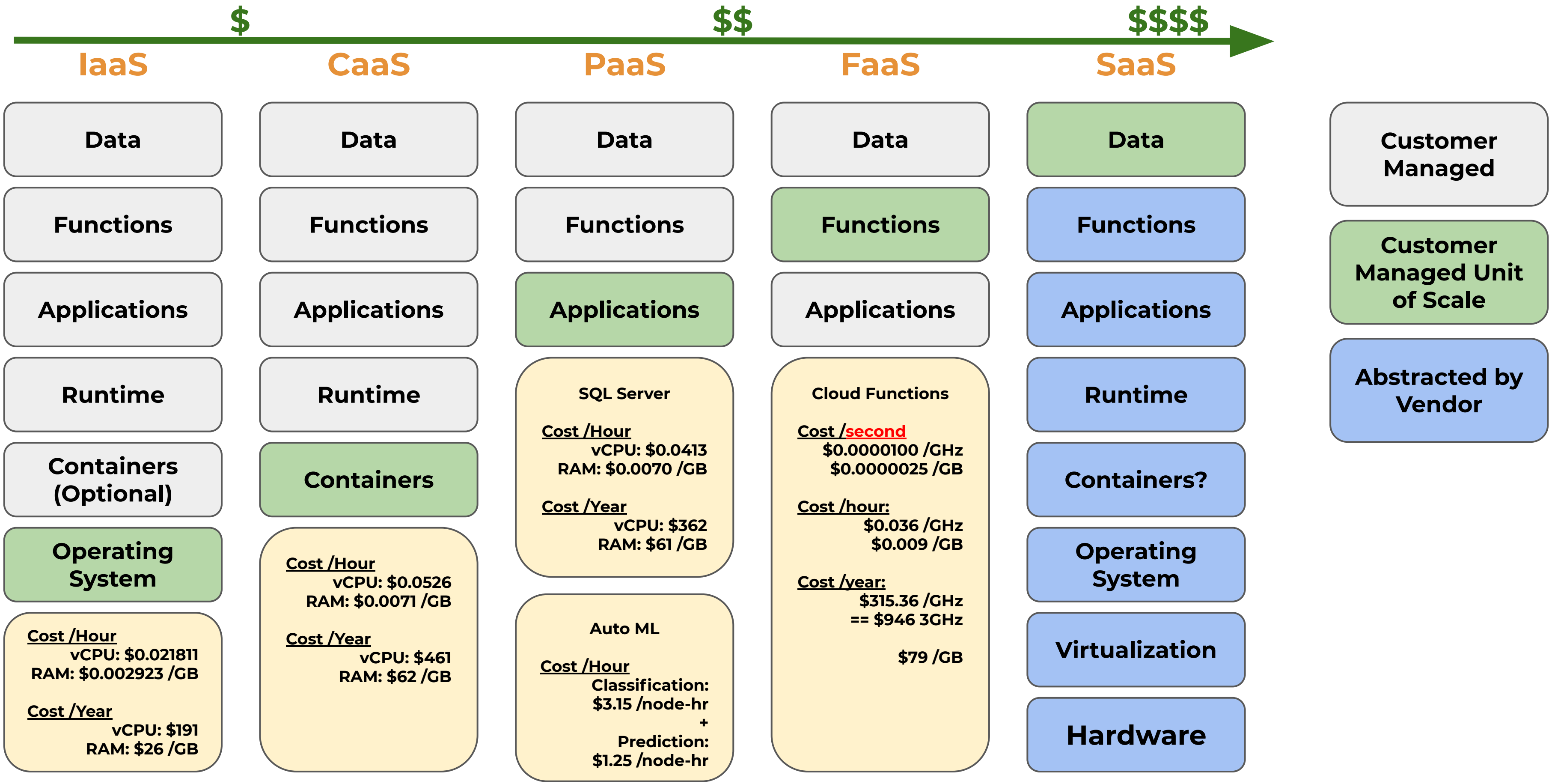
$ → $$ → $$$$

IaaS	CaaS	PaaS	FaaS	SaaS
⬜ Data	⬜ Data	⬜ Data	⬜ Data	🟩 Data
⬜ Functions	⬜ Functions	⬜ Functions	🟩 Functions	🟦 Functions
⬜ Applications	⬜ Applications	🟩 Applications	⬜ Applications	🟦 Applications
⬜ Runtime	⬜ Runtime	🟦 Runtime	🟦 Runtime	🟦 Runtime
⬜ Containers (Optional)	🟩 Containers	🟦 Containers?	🟦 Containers?	🟦 Containers?
🟩 Operating System	🟦 Operating System	🟦 Operating System	🟦 Operating System	🟦 Operating System
🟦 Virtualization	🟦 Virtualization	🟦 Virtualization	🟦 Virtualization	🟦 Virtualization
🟦 Hardware	🟦 Hardware	🟦 Hardware	🟦 Hardware	🟦 Hardware

⬜ Customer Managed

🟩 Customer Managed Unit of Scale

🟦 Abstracted by Vendor



IaaS	CaaS	PaaS	FaaS	SaaS
⬜ Data	⬜ Data	⬜ Data	⬜ Data	🟩 Data
⬜ Functions	⬜ Functions	⬜ Functions	🟩 Functions	🟦 Functions
⬜ Applications	⬜ Applications	🟩 Applications	⬜ Applications	🟦 Applications
⬜ Runtime	⬜ Runtime	SQL Server **Cost /Hour** vCPU: $0.0413 RAM: $0.0070 /GB **Cost /Year** vCPU: $362 RAM: $61 /GB	Cloud Functions **Cost /second** $0.0000100 /GHz $0.0000025 /GB **Cost /hour:** $0.036 /GHz $0.009 /GB **Cost /year:** $315.36 /GHz == $946 3GHz $79 /GB	🟦 Runtime
⬜ Containers (Optional)	🟩 Containers			🟦 Containers?
🟩 Operating System	**Cost /Hour** vCPU: $0.0526 RAM: $0.0071 /GB **Cost /Year** vCPU: $461 RAM: $62 /GB	Auto ML **Cost /Hour** Classification: $3.15 /node-hr + Prediction: $1.25 /node-hr		🟦 Operating System
Cost /Hour vCPU: $0.021811 RAM: $0.002923 /GB **Cost /Year** vCPU: $191 RAM: $26 /GB				🟦 Virtualization
				🟦 Hardware

⬜	Customer Managed
🟩	Customer Managed Unit of Scale
🟦	Abstracted by Vendor

Based on Google Cloud prices for non-preemptable, always-on, and on-demand services with no long-term commitment, sourced from https://cloud.google.com/appengine/pricing in April 2021

Containers

CS 423 - University of Illinois

Wade Fagen-Ulmschneider

(Slides built from Adam Bates and Tianyin Xu previous work on CS 423.)

Motivation

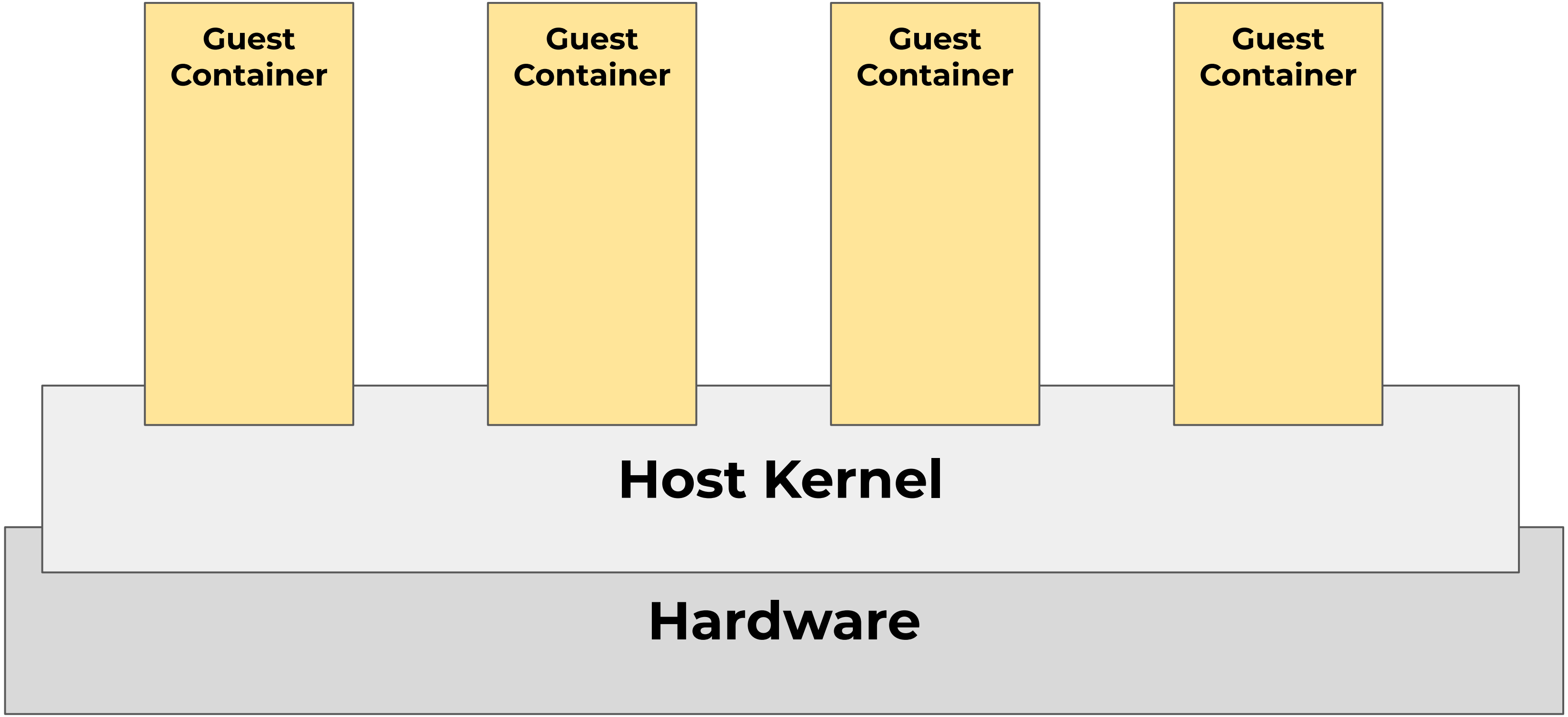
- ★ Rather than virtualize both user space and kernel space… why not just ‘virtualize’ user space?

- ★ Meets the needs of most customers, who don’t require significant customization of the OS.

- ★ Sometimes called ‘OS virtualization,’ which is highly misleading given our existing taxonomy of virtualization techniques

- ★ Running natively on host, containers enjoy bare metal performance without reliance on advanced virtualization support from hardware.

Cloud Computing (Generation 1)



Guest Container

Guest Container

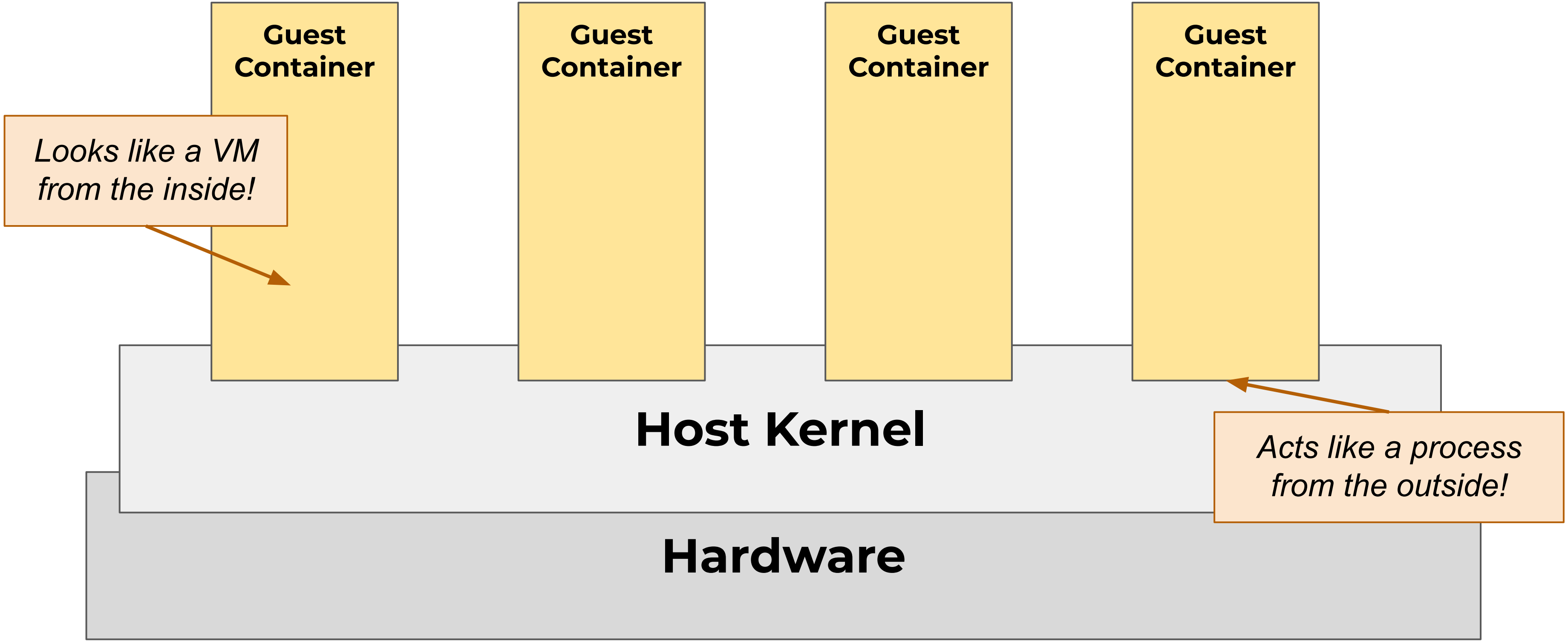
Guest Container

Guest Container

Host Kernel

Hardware

Cloud Computing (Generation 1)

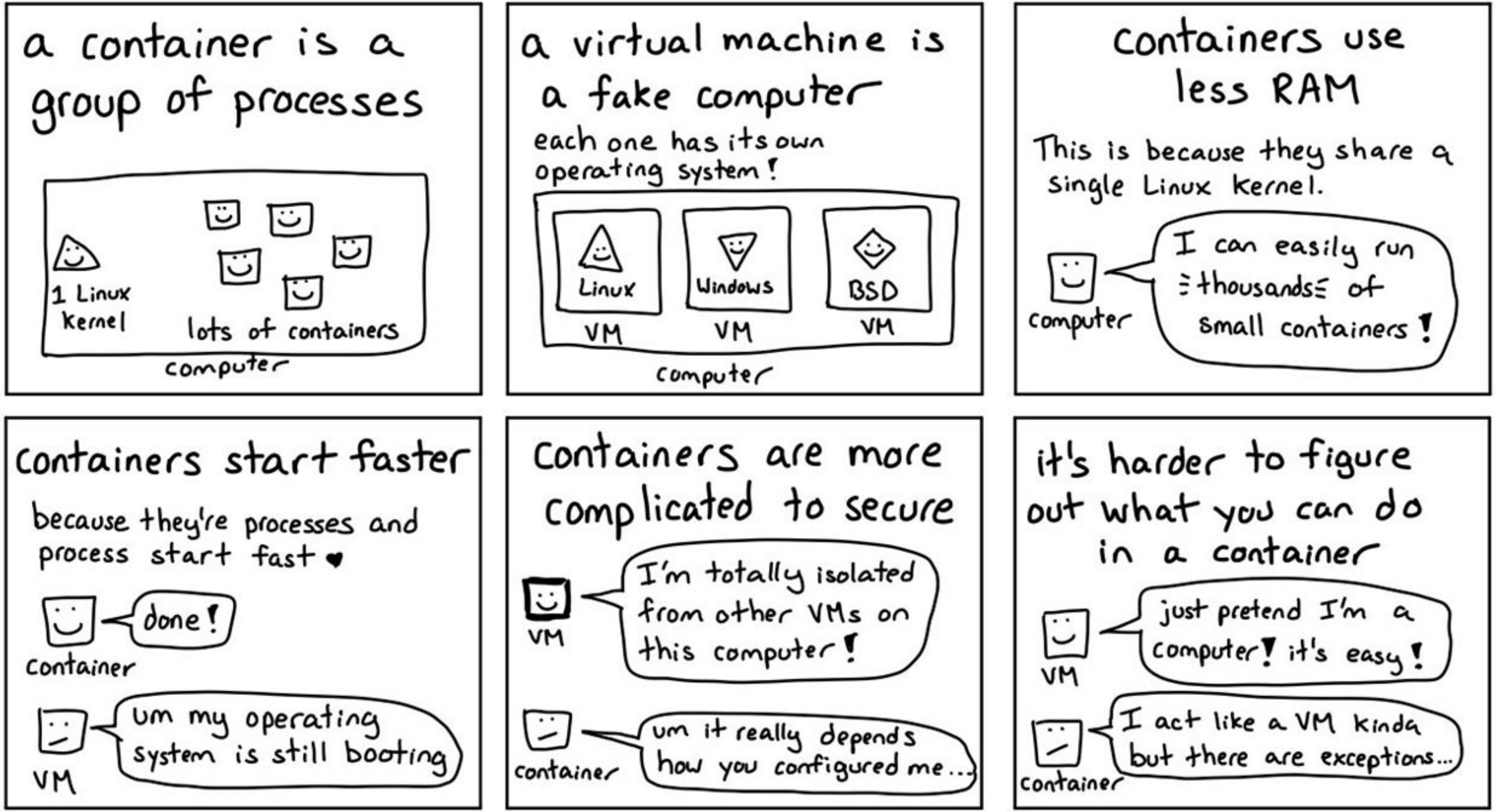


Looks like a VM from the inside!

Acts like a process from the outside!

JULIA EVANS
@b0rk

containers vs VMs

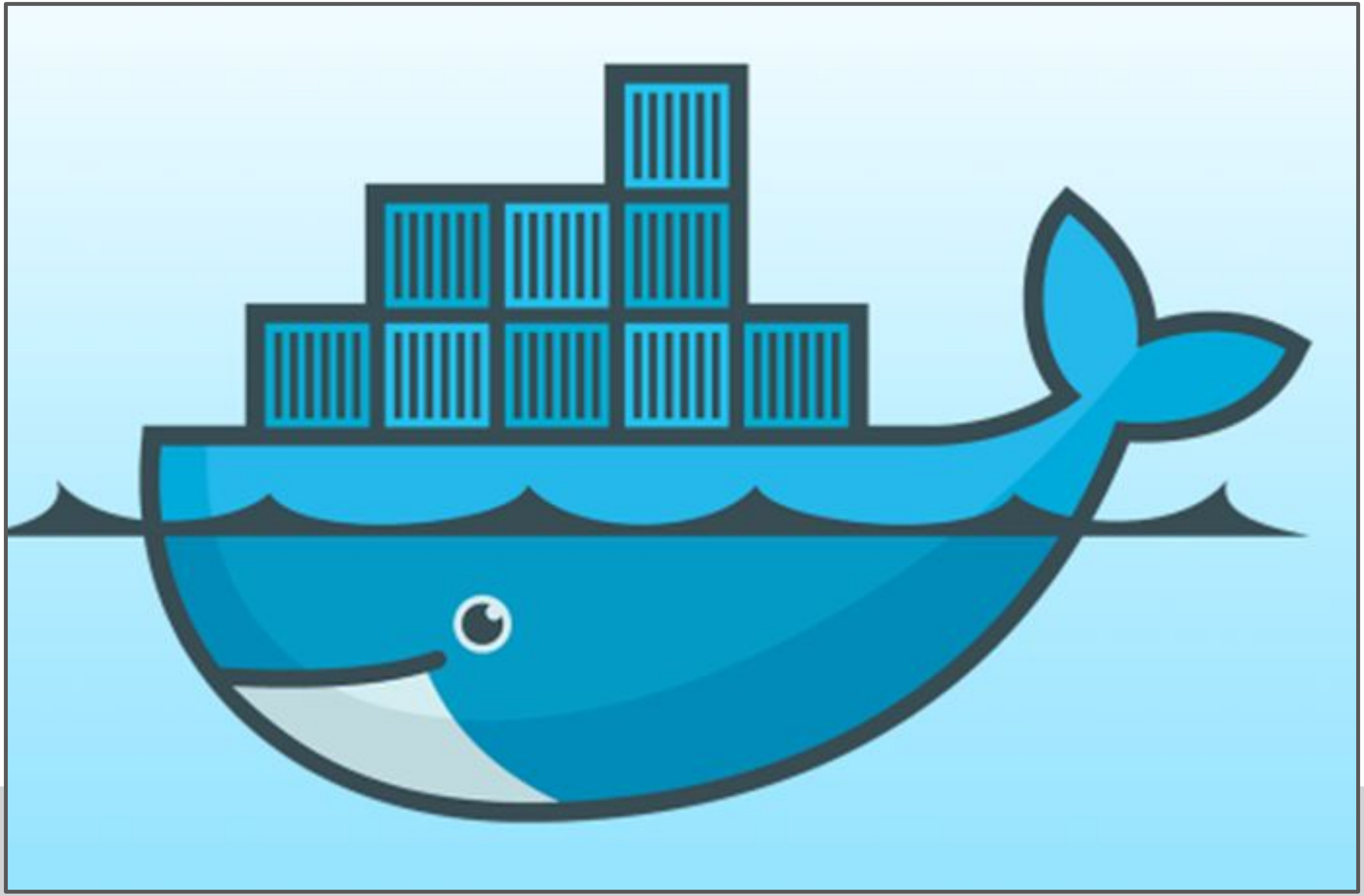

a container is a group of processes
1 Linux kernel
lots of containers
computer
a virtual machine is a fake computer
each one has its own operating system!
Linux
Windows
BSD
VM
VM
VM
computer
containers use less RAM
This is because they share a single Linux kernel.
computer
I can easily run thousands of small containers!
containers start faster
because they're processes and process start fast ♥
container
done!
VM
um my operating system is still booting
containers are more complicated to secure
VM
I'm totally isolated from other VMs on this computer!
container
um it really depends how you configured me...
it's harder to figure out what you can do in a container
VM
just pretend I'm a computer! it's easy!
container
I act like a VM kinda but there are exceptions...

Containers Aren’t New…

- Lots of work on containers dating back decades:
  - BSD Jails
  - Solaris Zones
  - Linux containers
  - …etc…

- …but weren’t well advertised, not user-friendly (used low-level system interfaces), not easily deployable (usually required root).

Enter: Docker



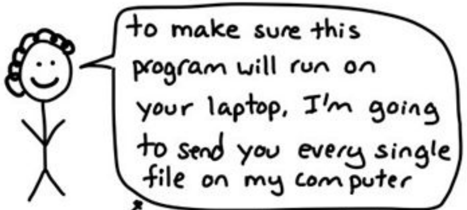
Docker

- **Big Idea**: “Build, Ship, and Run App, Anywhere”
  - Debug your app, not your environment
  - Securely build and share any application, anywhere
  - Accomplished by including **everything** in a container

JULIA EVANS
@børk

the big idea: include EVERY dependency

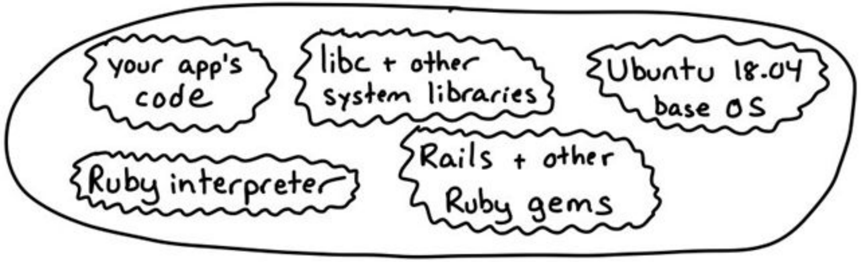
containers package EVERY dependency together


to make sure this program will run on your laptop, I'm going to send you every single file on my computer

exaggeration but it's the basic idea

a container image is a tarball of a filesystem

Here's what's in a typical Rails app's container:



your app's code

libc + other system libraries

Ubuntu 18.04 base OS

Ruby interpreter

Rails + other Ruby gems

how images are built

0. start with a base OS
1. install program + dependencies
2. configure it how you want
3. make a tarball of the WHOLE FILESYSTEM

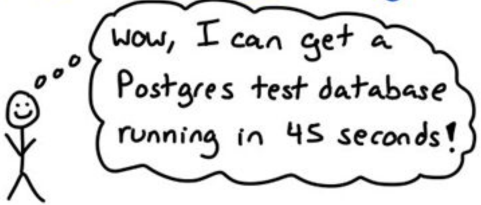
(this is what 'docker build' does)

running an image

1. download the tarball
2. unpack it into a directory
3. Run a program and pretend that directory is its whole filesystem

(this is what 'docker run' does)

images let you "install" programs really easily


wow, I can get a Postgres test database running in 45 seconds!

Container Support on OSes

CS 423 - University of Illinois

Wade Fagen-Ulmschneider

(Slides built from Adam Bates and Tianyin Xu previous work on CS 423.)

Containers are Build on Linux Utilities

- Linux Containers (LXC):
  - chroot
  - namespace
    - PID, Network, User, IPC, uts, mount
  - cgroups for HW isolation
  - Security profiles and policies
  - Apparmor, SELinux, Seccomp

Containers are Build on Linux Utilities

- Linux Containers (LXC):
  - chroot
  - namespace
    - PID, Network, User, IPC, uts, mount
  - cgroups for HW isolation
  - Security profiles and policies
  - Apparmor, SELinux, Seccomp

Containers are Build on Linux Utilities

- `chroot` changes the apparent root directory for a given process and all of its children.
  - An old idea! POSIX call dating back to 1979
  - **Ex: /usr/home/waf/myapp ⇒ /**
    - *Process is no longer able to "see" below myapp directory!*

- Not intended to defend against privileged attackers.
  - With root access you can do all sorts of things to break out (like chroot'ing again)

- Does not hide processes, network, etc!

Containers are Build on Linux Utilities

- Linux Containers (LXC):
  - chroot
  - namespace
    - PID, Network, User, IPC, uts, mount
  - cgroups for HW isolation
  - Security profiles and policies
  - Apparmor, SELinux, Seccomp

Namespaces

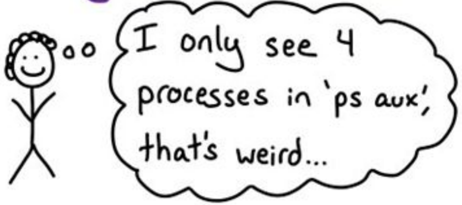
- ★ **`namespaces`** are the key feature enabling containerization!
  - Partition practically all OS functionalities so that different process domains see different things

  - **Mount (mnt)**: Controls mount points
  - **Process ID (pid)**: Exposes a new set of process IDs distinct from other namespaces (i.e., the hosts)
  - **Network (net)**: Dedicated network stack per container; each interface present in exactly one namespace at a time.
  - **IPC (inter-process comm.)**: Isolate processes from various methods of POSIX IPC
    - *No shared memory between containers!*
  - **UTS**: Allows the host to present different host/domain names to different containers.
  - **User ID (user)** and **cgroup** namespace -- allows the container to **think** its root!
  - ...

JULIA EVANS
@b0rk

namespaces

inside a container, things look different

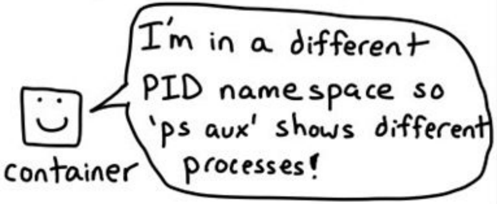


commands that will look different

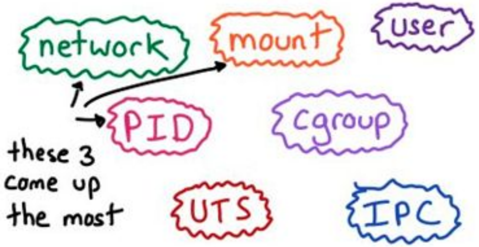
- → ps aux (less processes!)
- → mount & df
- → netstat -tulpn (different open ports!)
- → hostname

... and LOTS more

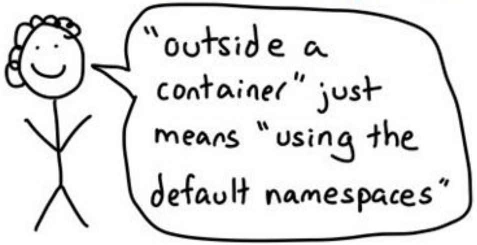
why those commands look different: namespaces


I'm in a different PID namespace so 'ps aux' shows different processes!
container

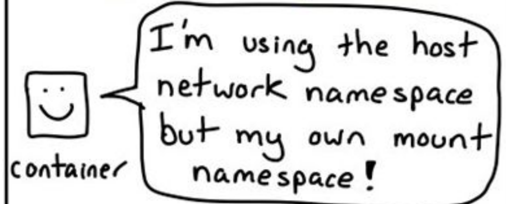
every process has 7 kinds of namespaces



there's a default ("host") namespace


"outside a container" just means "using the default namespaces"

processes can have any combination of namespaces


I'm using the host network namespace but my own mount namespace!
container

Containers are Build on Linux Utilities

- Linux Containers (LXC):
  - chroot
  - namespace
    - PID, Network, User, IPC, uts, mount
  - cgroups for HW isolation
  - Security profiles and policies
  - Apparmor, SELinux, Seccomp

Namespaces

- **cgroups** limit, track and isolate utilization of hardware resources including CPU, memory, and disk.
    - Important for ensuring QoS between customers! Protects against bad neighbors

- **Features:**
    - Resource limitation
    - Prioritization
    - Accounting (for billing customers!)
    - Control, e.g., freezing groups
    - The cgroup namespace prevents containers from viewing or modifying their own group assignment…

Containers are Build on Linux Utilities

- Linux Containers (LXC):
  - chroot
  - namespace
    - PID, Network, User, IPC, uts, mount
  - cgroups for HW isolation
  - Security profiles and policies (Apparmor, SELinux, Seccomp)

Security

“Containers do not contain.”

  - Dan Walsh (SELinux contributor)

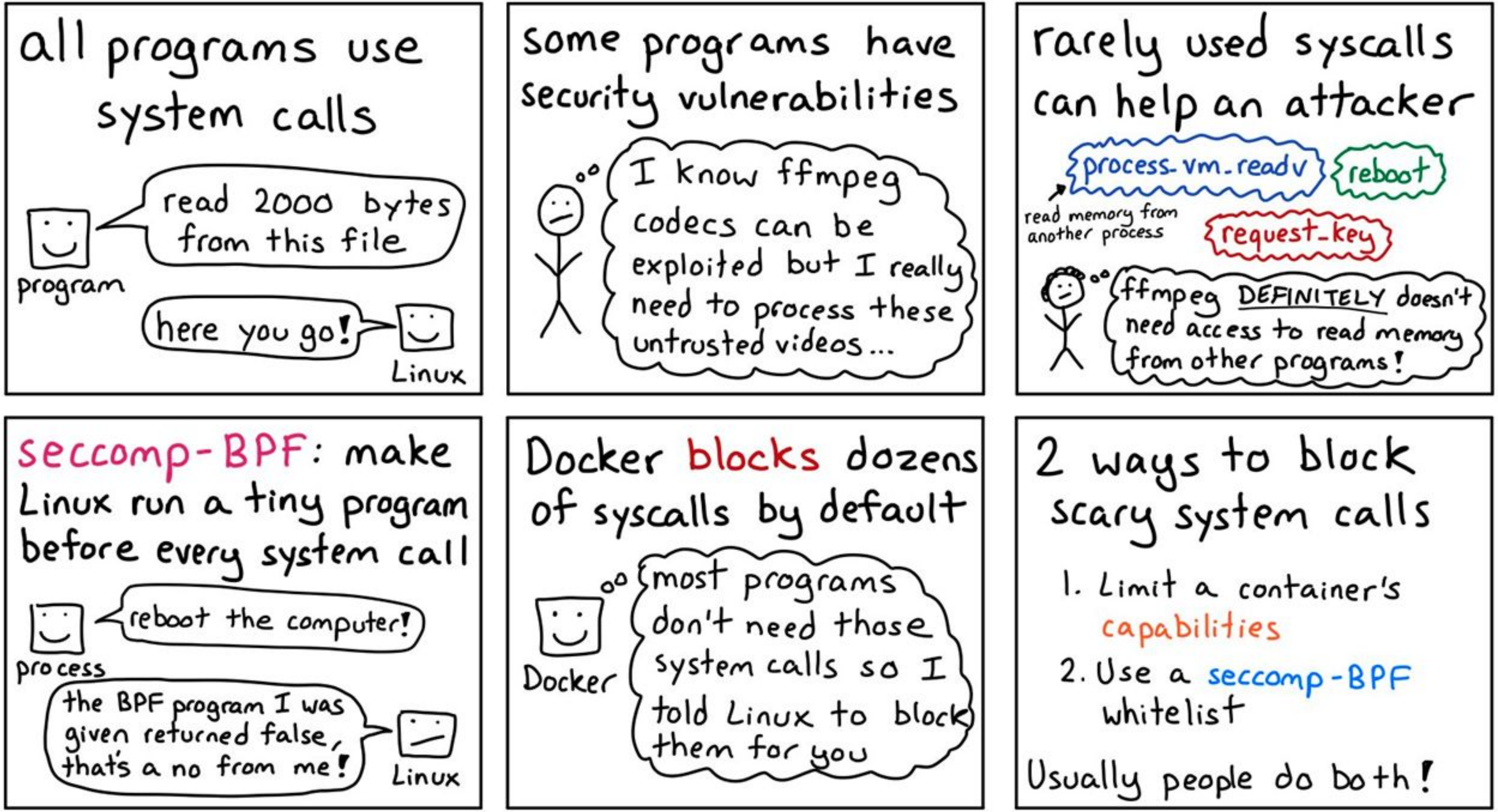
Containers are Build on Linux Utilities

- It is **real hard** to prove that every feature of the operating system is namespaced.
  - /sys? /proc? /dev? LKMs? kernel keyrings?
  - Root access to any of these enables pwning the host

- Solution?
  - Secure linux distributions (ex: SELinux) provide good support for namespace labeling. *Does not prevent against physical attacks (physical security is part of security)!*
  - Much easier to express a correct isolation policy over a coarse-grained namespace than, say, individual processes.

JULIA EVANS
@b0rk

seccomp-bpf



all programs use system calls
read 2000 bytes from this file
program
here you go!
Linux
some programs have security vulnerabilities
I know ffmpeg codecs can be exploited but I really need to process these untrusted videos...
rarely used syscalls can help an attacker
process_vm_readv
reboot
read memory from another process
request_key
ffmpeg DEFINITELY doesn't need access to read memory from other programs!
seccomp-BPF: make Linux run a tiny program before every system call
reboot the computer!
process
the BPF program I was given returned false, that's a no from me!
Linux
Docker blocks dozens of syscalls by default
most programs don't need those system calls so I told Linux to block them for you
Docker
2 ways to block scary system calls
1. Limit a container's capabilities
2. Use a seccomp-BPF whitelist
Usually people do both!

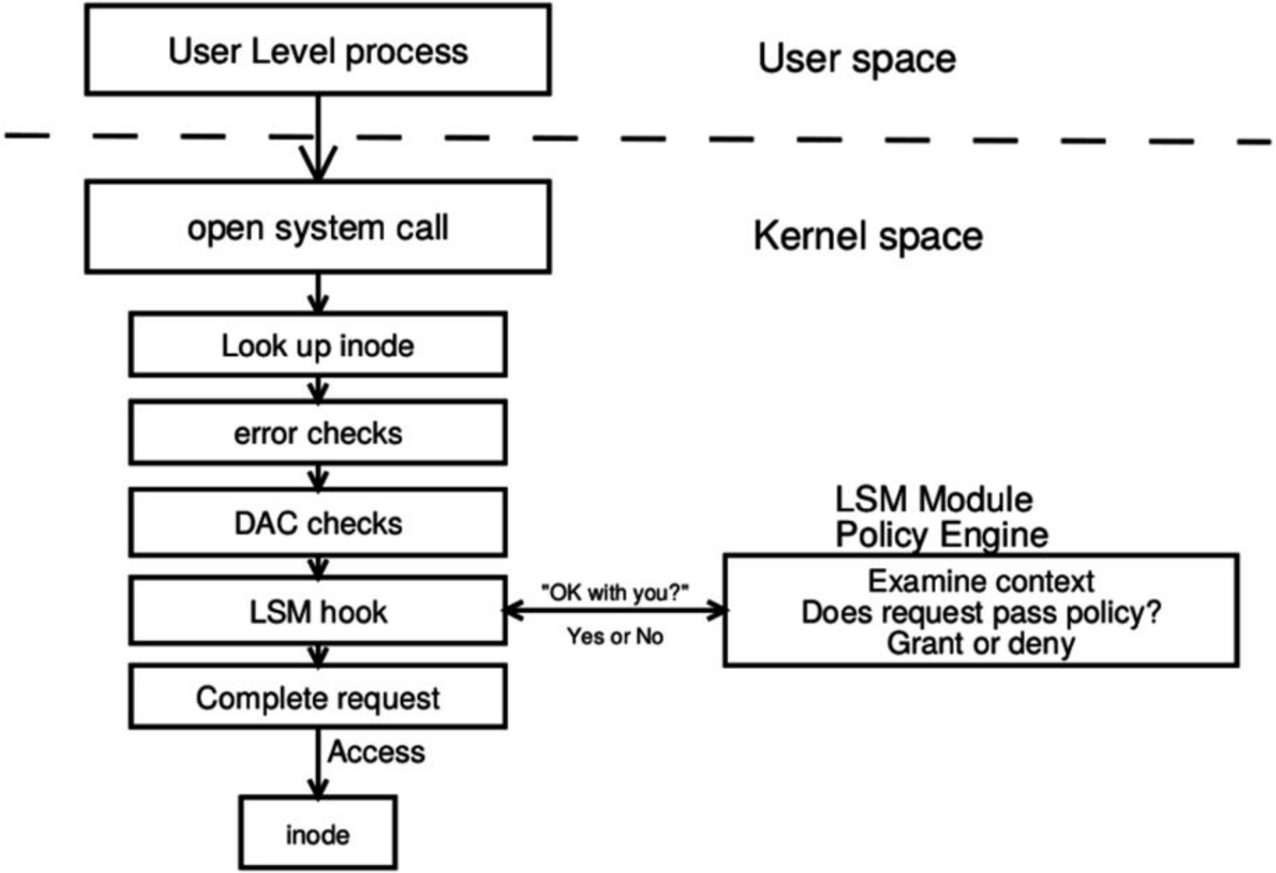
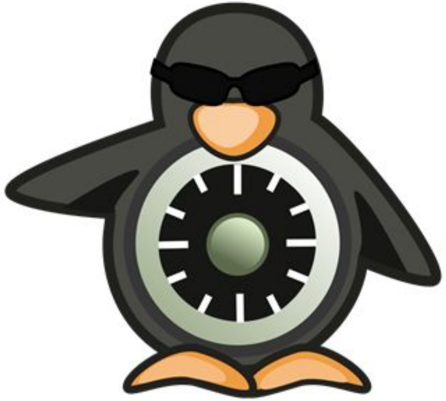


Figure 1: LSM Hook Architecture



JULIA EVANS
@b0rk

Containers aren't magic

These 15 lines of bash will start a container running the fish shell. Try it!
(download this script at bit.ly/containers-arent-magic)

```
wget bit.ly/fish-container -O fish.tar       # 1. download the image
mkdir container-root; cd container-root      #
tar -xf ../fish.tar                          # 2. unpack image into a directory
cgroup_id="cgroup_$(shuf -i 1000-2000 -n 1)" # 3. generate random cgroup name
cgcreate -g "cpu,cpuacct,memory:$cgroup_id"  # 4. make a cgroup &
cgset -r cpu.shares=512 "$cgroup_id"         #    set CPU/memory limits
cgset -r memory.limit_in_bytes=1000000000 \  #
      "$cgroup_id"                           #
cgexec -g "cpu,cpuacct,memory:$cgroup_id" \  # 5. use the cgroup
    unshare -fmuipn --mount-proc \           # 6. make + use some namespaces
    chroot "$PWD" \                          # 7. change root directory
    /bin/sh -c "                             #
        /bin/mount -t proc proc /proc &&     # 8. use the right /proc
        hostname container-fun-times &&      # 9. change the hostname
        /usr/bin/fish"                       # 10. finally, start fish!
```