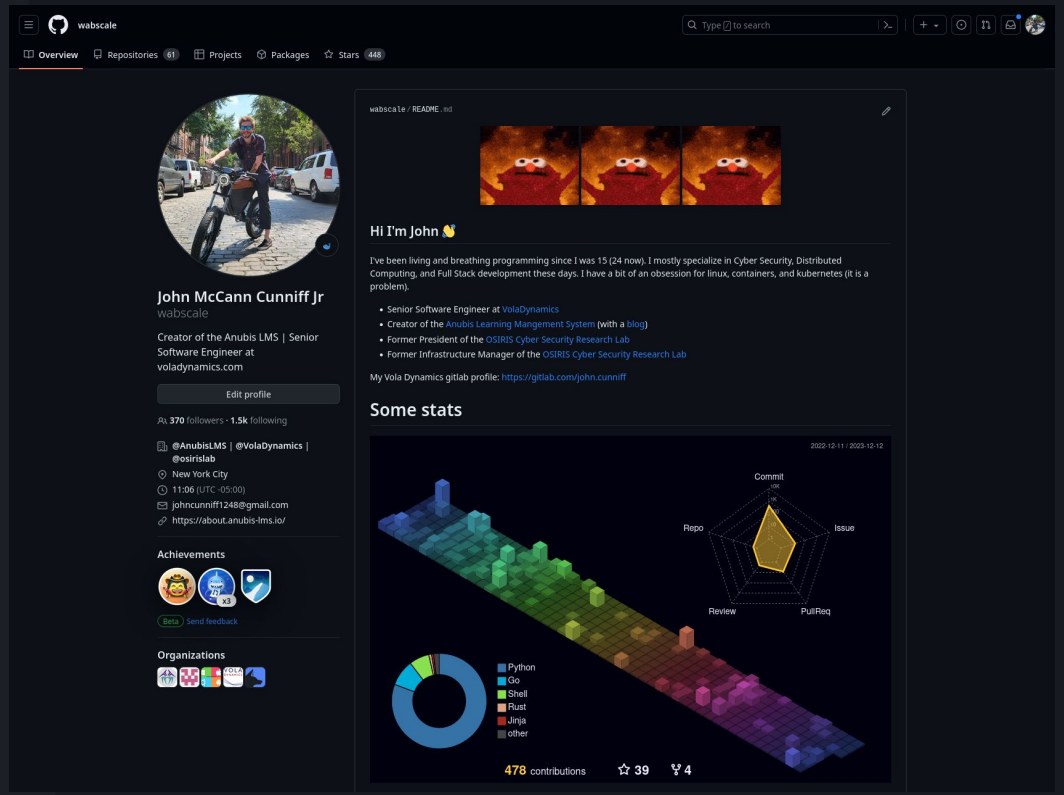
Containers & Virtualization

John Cunniff

Some slides derived from: G. Sandoval, Tanenbaum/Bo, Jérôme Petazzoni, and Brendan Dolan-Gavitt
Thanks !!

Check Anubis out! https://anubis-lms.io/

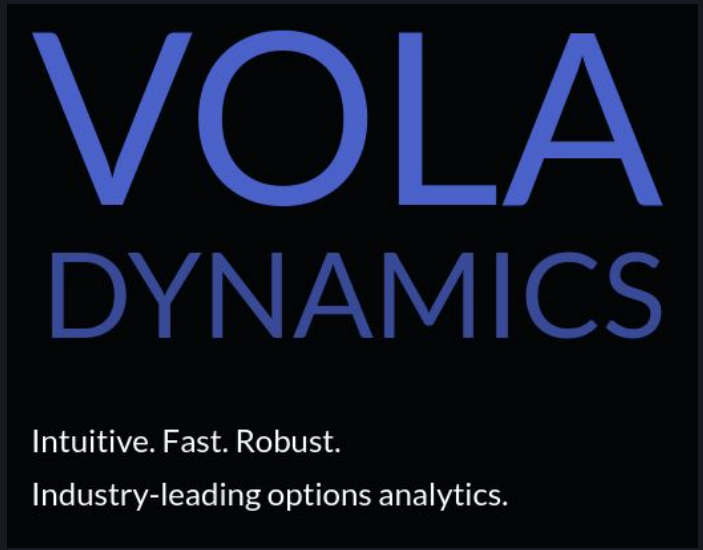
github/wabscale



whoami

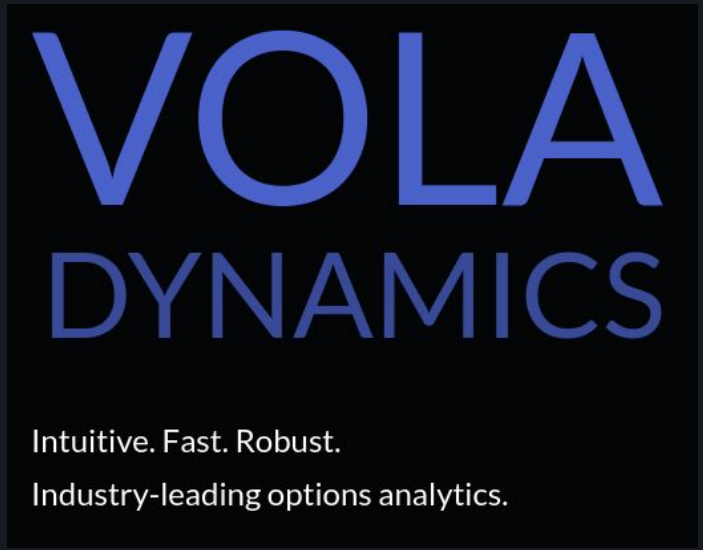
- Graduated from NYU 2+ years ago
- Was president of the **OSIRIS Lab**
- Created & maintaining **Anubis LMS**
- Senior Engineer & Partner

  at **Vola Dynamics**



What is Vola Dynamics?

- “Swiss army knife” for options analytics
- 100x faster, robust & accurate option pricer & volatility fitter



Jobs Jobs Jobs

Vola Dynamics is also hiring!
(SWEs & Options Quants)

- Send your resumes to **resumes@voladynamics.com**

Applied Containers & Orchestration

I may be teaching a class next semester!

Applied Containers & Orchestration

Put in your course reviews that you want a modern containers course!


Unit Tests
Staging
Production
gifmemes.io

Virtualization in VMs

- Virtualization in VMs
- Containers
  - Namespacing
  - Cgroups
- Where containers run
- Cloud / k8s / Anubis

Virtualization in VMs

Until today we've been talking about operating systems running on **physical machines**: a collection of

1. **real hardware** resources,
2. that the operating system has **exclusive** access
3. through **hardware interfaces** (instruction set architectures, device I/O ports, etc.

Virtualization in VMs

Operating systems can also run inside **virtual machines (VMs)**.

- We refer to an operating system running inside a virtual machine as a ***guest OS.***
- Virtual machines differ from physical machines in important ways.
- They ***do not*** **provide** the guest OS with **exclusive** access to the underlying physical machine.
- Equivalently, they ***do not*** **provide** the guest OS with **privileged** (or fully-privileged) access to the physical machine.

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Virtualization in VMs

Virtualization adds a **new layer** to the software stack: the **hypervisor** (*aka Virtual Machine Monitor or **VMM***). The VMM mediates shared access to hardware by the different OSes and is:

- a piece of software running on an operating system (the **host OS**)
- that can allow another operating system (the **guest OS**) to be run as an application
- alongside other applications.

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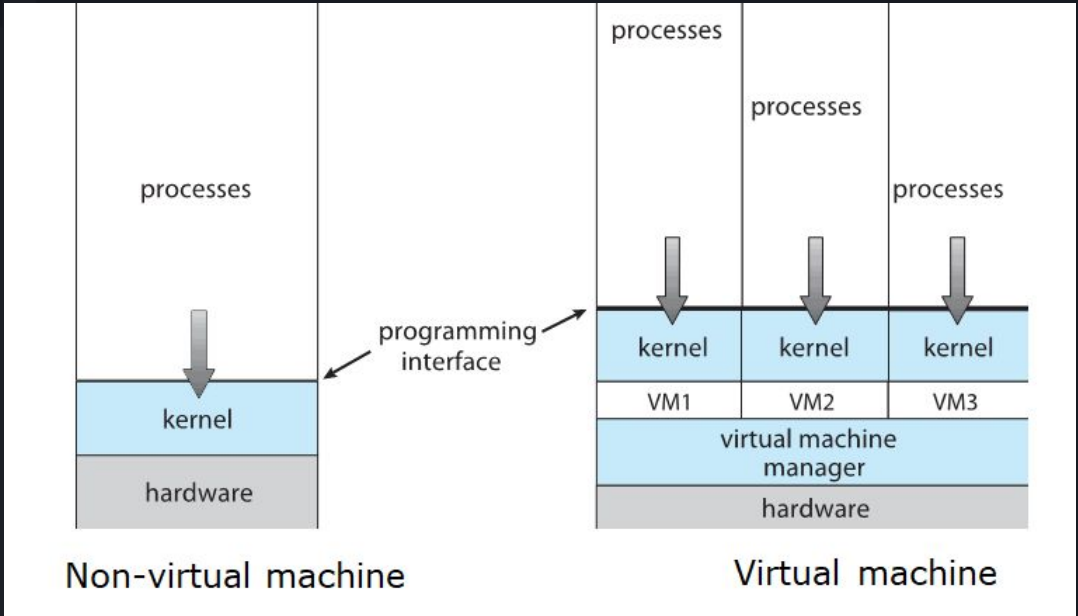
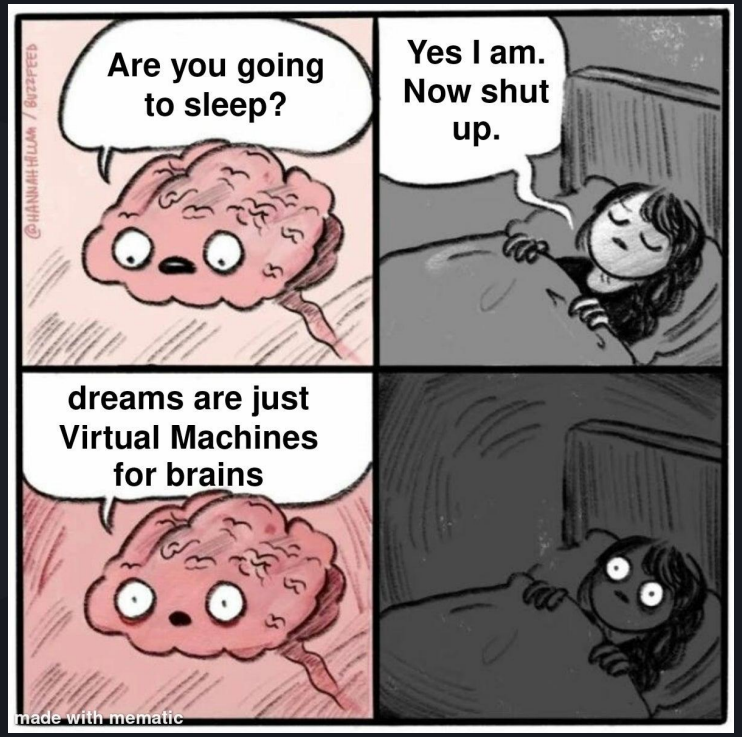
No-VM vs VM



Silberschatz, Galving and Gagne. 2018

Questions?


Are you going to sleep?
Yes I am. Now shut up.
dreams are just Virtual Machines for brains
@HANNAHILLUM / BUZZFEED
made with mematic

Why Virtualize?

- **Flexibility**: virtual machines are easier to instantiate and tear down, can be ***migrated*** between physical hosts
- **Stability**: by splitting services across different virtual machines, if one crashes it will not affect the others
- **Security**: virtual machines are isolated from one another, so (e.g.) the web server can't access data on the email server

Some Terminology for VMs

- The running hypervisor is known as the **host**
- The virtual machines running under the hypervisor are **guests**
- If there is a special guest VM that is used for managing the rest, it is usually called **domain 0** or the **control domain**

Three approaches to Virtualization

- **Full virtualization**. Should be able to run an **unmodified** guest OS. **Example**: VirtualBox, VMWare.
- **Paravirtualization**. Includes **small changes** to the **guest operating system** to improve interaction with the virtual machine monitor. **Example**: Xen, Amazon EC2.
- **Container virtualization**. **Namespace** and other isolation techniques performed *by* ***the operating system*** to isolate sets of applications from each other. **Example**: Docker

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Requirements for Virtualization

- On most CPUs, there are **sensitive** instructions –those that **behave differently in kernel vs user mode**
  - Performing I/O, changing MMU mappings, etc.
- There are also **privileged** instructions – those that cause a **trap** into kernel mode
- Popek and Goldberg showed that an architecture is virtualizable only if the sensitive instructions are a *subset* of the privileged instructions

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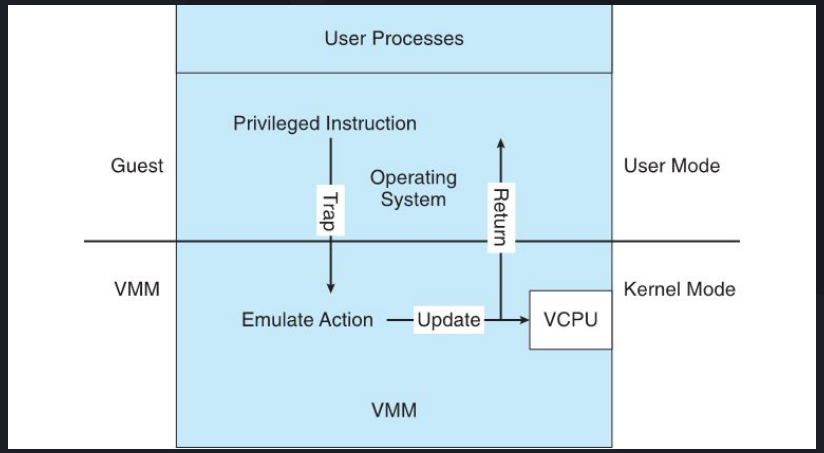
x86 Hardware Virtualization

- In 2005 Intel fixed these issues by introducing VT-x
  - Around the same time AMD also fixed them... with an incompatible set of virtualization extensions 😑
- VT-x introduced two new processor modes: ***root mode*** and ***non-root mode***
- When the processor is running in non-root mode, **sensitive instructions** cause a **vmexit** – aka, a **trap to the hypervisor**

Virtualization Implementation



1. Priv. Instruction
2. Trap
3. Emulate Action
4. Update VCPU
5. Return

Silberschatz, Galving and Gagne. 2018

I/O Virtualization

- Two final issues exist with virtualized I/O: DMA and interrupts
- For DMA, the problem is that the DMA hardware will be programmed with physical addresses, which must be **remapped** by the hypervisor
  - (~2009) Intel added an **IOMMU** that allows device memory accesses to be remapped without hypervisor intervention
- Interrupts from devices must also be **remapped** – the interrupt number seen by the guest virtual machine may not be the same as the interrupt number seen by the host

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Review: Virtualization

How did we create a virtual machine (VM)?

- Start with a **physical machine**
- Create software (hypervisor) responsible for **isolating** the guest OS inside the VM
- VM resources (memory, disk, networking, etc.) are provided by the physical machine but **visibility outside of the VM is limited**

Review: Virtualization

What were the implications?

- VM and physical machine *share same instruction set*, so must the host and guest
- Guest OS can provide a *different application binary interface* (ABI) inside the VM
- Lots of challenges in getting this to work because guest OS expects to have privileged hardware access

Questions?

Containers

- Virtualization in VMs
- Containers
  - Namespacing
  - Cgroups
- Where containers run
- Cloud / k8s / Anubis

OS Virtualization ⇒ Containers

How do we create a virtual operating system (container)?

- Start with a real operating system.
- Create software responsible for isolating guest software inside the container
- (That software seems to lack a canonical name—and today it's actually a bunch of different tools.)
  - runc, rkt, lxc, and docker to name a few
- Container resources (processes, files, network sockets, etc.) are provided by the real operating system but **visibility outside the container is limited**

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Containers

What are they exactly

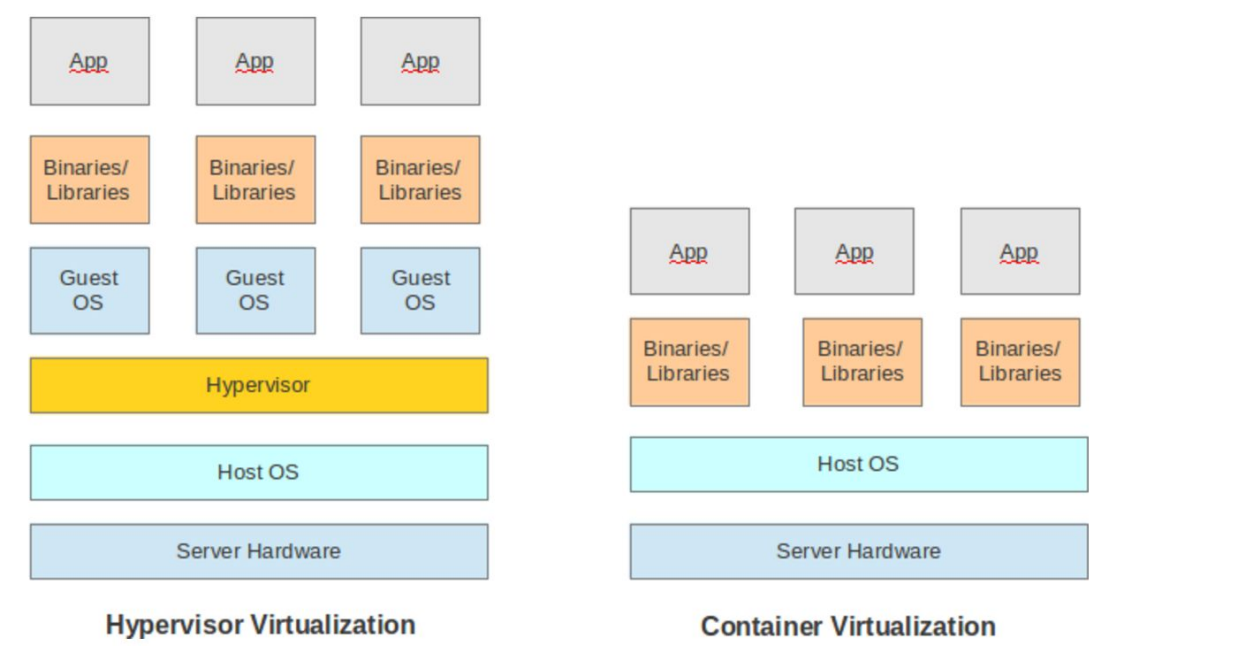
- Sort of like chroot on steroids
- They are implemented through user level Container Engines / Runtime, **not by the kernel itself**
- You probably already know Docker
  - Docker itself uses containerd/runc for the actual containers
- There is also lxc, rkt (pronounced rocket), and runc for example

Containers

What are the implications?

- Container and real OS *share* ***same kernel***
- So applications inside and outside the kernel must ***share the same ABI*** (Application Binary Interface)
- Challenges is getting this to work are due to *shared OS namespaces*

VM vs Container



Containers vs VMs (T/F)

You can run a Windows container on GNU/Linux.

- False. Container shares the kernel with the host.

You can run a Debian container from Glorious Arch Linux.

- True. As long as the container uses the same kernel

Containers vs VMs (T/F)

Running ps inside the container will show all processes running on the machine.

- **False**. Container process namespaces is isolated from the host.

Questions?

Why use containers at all?

Shares many (but not all) of the benefits of hardware virtualization with **much lower overhead**.

- Can **package** a program / service into something that will run exactly the same on most any machine.
- Can **adjust / limit** hardware container resources to system needs.
- Can **split a system** up into **microservices**, then use a CNI (container networking interface) to let them connect to each other.

Why use containers at all?

Isolation

- Container should not leak information inside and outside the container
- Can isolate all of the configuration and software dependencies a particular application needs to run

Containers

Container system call path:
Application inside the container **makes a system call**

- **Trap** to the host OS
- It is then up to the **kernel to consider** resource namespacing

Containers

On GNU/Linux you are always in a container!

- **Linux starts in a container** with **no limits** that can see everything
- So if you think you're getting a performance benefit by not using containers you're wrong!

Containers

- Virtualization in VMs
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Namespacing

- When you run a container, your container runtime creates a set of namespaces for that container
- Provide a layer of isolation. Limits what you can see/affect/use
- Implemented within the kernel
- Multiple types of resource **namespaces**

Types of Namespaces

- pid
- net
- mnt
- uts
- ipc
- user

Check Anubis out! https://anubis-lms.io/

Namespacing

`ls -l /proc/self/ns` to see what namespaces you are in

```
jc@athena ~/jcs  ‹master›
  ls -l /proc/self/ns
total 0
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 cgroup -> 'cgroup:[4026531835]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 ipc -> 'ipc:[4026531839]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 mnt -> 'mnt:[4026531840]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 net -> 'net:[4026531992]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 pid -> 'pid:[4026531836]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 pid_for_children -> 'pid:[4026531836]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 time -> 'time:[4026531834]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 time_for_children -> 'time:[4026531834]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 user -> 'user:[4026531837]'
lrwxrwxrwx 1 jc jc 0 Apr 10 18:08 uts -> 'uts:[4026531838]'
```

Number is what pid namespace the current process is in

PID Namespacing

- Processes within a PID namespace only see processes in the **same PID namespace**
- Each PID namespace has its **own numbering** starting at 1
- If PID 1 exits, the whole namespace is killed

PID Namespacing

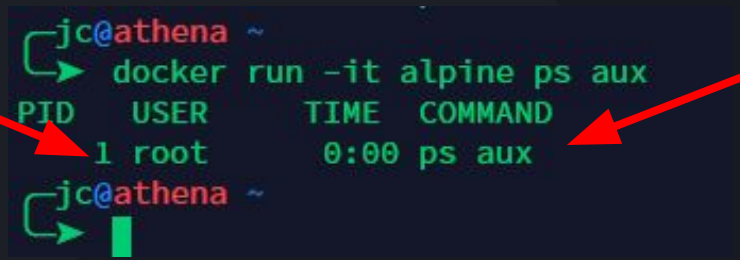
- Those namespaces can be **nested**
- A process ends up having different PIDs **depending on namespace**

PID Namespacing

What happens when you run ps in a container?

PIDs start at 1

Only the ps process visible



Net Namespacing

Net namespace in practice

- **Typical use-case:** use virtual ethernet (veth) pairs (two virtual interfaces acting as a cross-over cable)
  - eth0 in container network namespace
    paired with vethXXX in host network namespace
    all the vethXXX are bridged together
- But also: the magic of --net host shared localhost (and more!)

Net Namespacing

Let's think about what this lets us do

- Create a virtual interface with its own network
- Use net namespace in multiple containers
- **You then have multiple docker containers that are connected to each other on a virtual network**

This is where things get really powerful

Questions?

Containers

- Virtualization in VMs
- Containers
  - Namespacing
  - Cgroups
- Where containers run
- Cloud / k8s / Anubis

Cgroups

- **Control Group**
  - Implemented within the kernel
  - limits what resources you are allowed to use
  - cpu and memory cgroups very common with containers
  - It is up to your container engine to handle the cgroup

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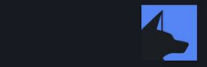
CPU Cgroups

- CPU cgroup Keeps track of user/system
- CPU time Keeps track of usage per CPU Allows to set weights
- Because of variations in things like core clock speed, and instruction time execution, there is no 100% precise way to limit CPU

CPU Cgroups

Try systemd-cgtop to see cgroup usage!

Control Group	Tasks	%CPU	Memory	Input/s	Output/s
/	1689	5.0	6.0G	0B	254.7K
user.slice	1122	4.4	37.8G	0B	127.3K
user.slice/user-1000.slice	1122	4.4	37.8G	-	-
user.slice/user-1000.slice/session-9.scope	821	3.2	5.5G	-	-
user.slice/user-1000.slice/session-8.scope	268	1.1	31.0G	-	-
system.slice	102	0.3	1.0G	-	-
system.slice/tailscaled.service	21	0.2	137.9M	-	-
user.slice/user-1000.slice/user@1000.service	32	0.0	89.6M	-	-
system.slice/systemd-oomd.service	1	0.0	1.6M	-	-
system.slice/containerd.service	21	0.0	88.7M	-	-
dev-hugepages.mount	-	-	56.0K	-	-
dev-mqueue.mount	-	-	80.0K	-	-
init.scope	1	-	7.2M	-	-
sys-fs-fuse-connections.mount	-	-	8.0K	-	-
sys-kernel-config.mount	-	-	24.0K	-	-
sys-kernel-debug.mount	-	-	4.0K	-	-
sys-kernel-tracing.mount	-	-	4.0K	-	-
system.slice/boot-efi.mount	-	-	36.0K	-	-
system.slice/dbus.service	1	-	1.8M	-	-
system.slice/docker.service	39	-	639.7M	-	-
system.slice/home.mount	-	-	84.0K	-	-
system.slice/polkit.service	3	-	4.9M	-	-



There's so much more!

- Some stuff we're not covering but is very cool
  - Linuxkit
  - Storage drivers
  - Overlay networks
  - Copy-on-Write!
  - Container registries
  - selinux + capabilities
  - Rootless docker
  - Build-kit
  - Breaking security

Docker on Linux

Docker on Mac

Docker on Windows

Questions?

Containers

- Virtualization in VMs
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  - Namespacing
  - Cgroups
- Where containers run
- Cloud / k8s / Anubis

Where containers run

- LXC (or linux containers) were initially released in 2008
- Since then there have been many more engines / container runtimes that have come about
- **containerd**, **rkt**, **podman**, etc…

Where containers run

- **They all revolve around Linux**
- There has since been windows containers added (*but they are awful*)

Where containers run

You may be asking how docker works on MacOS and Windows since it’s kernel is not GNU/Linux

- **It doesn’t**
- Docker for MacOS runs a **linux virtual machine** that then runs docker
- The networking and volumes do not always work as expected

Where containers run

Some of you may have only used docker on MacOS or Windows and hate it

- The things you hate are all from docker-desktop not from docker itself!
- **Docker runs like a dream on GNU/Linux**
- On GNU/Linux it has barely any overhead

Containers

- Virtualization in VMs
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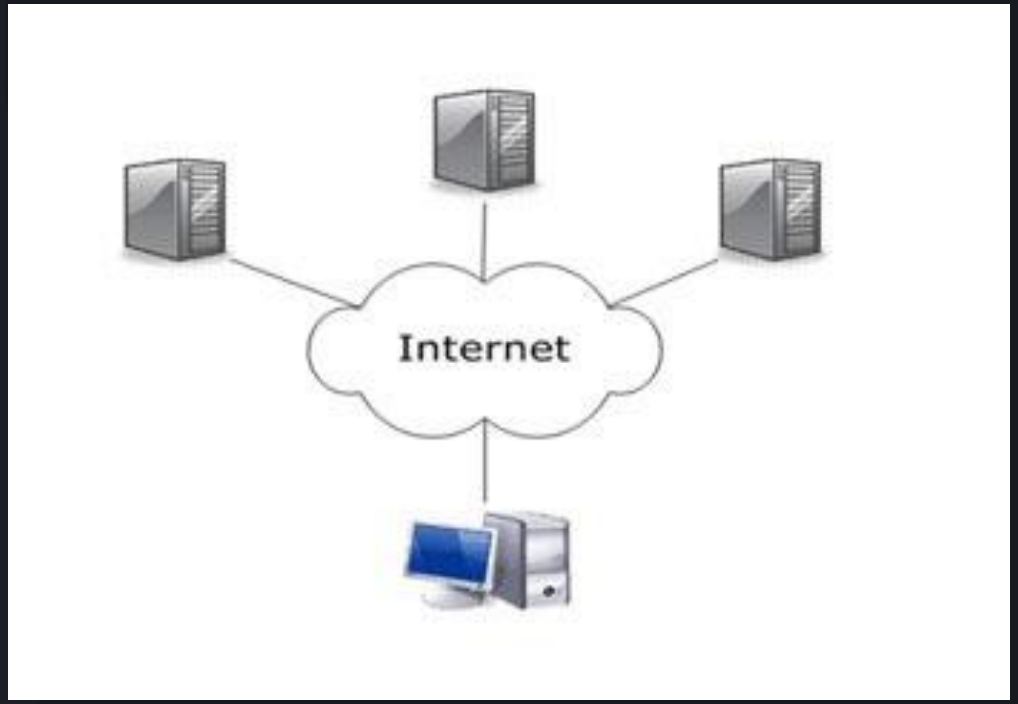
The Cloud

- With the resurgence of virtualization, it has become popular to talk about the **cloud**
- This **somewhat nebulous concept** traces back to old network diagrams
- Usually used a **buzzword**

The Cloud



The Cloud

- In modern usage, the cloud refers to a **large number of physical servers** that rent out virtual machines for various services
- Clients get access to a **full virtual machine**
- Billing usually works according to how and what resources you use

The Cloud

- Importantly, creating and destroying virtual servers can be accomplished **without human interaction**
- This ability to **flexibly acquire computing resources** can allow services to scale in response to changes on demand

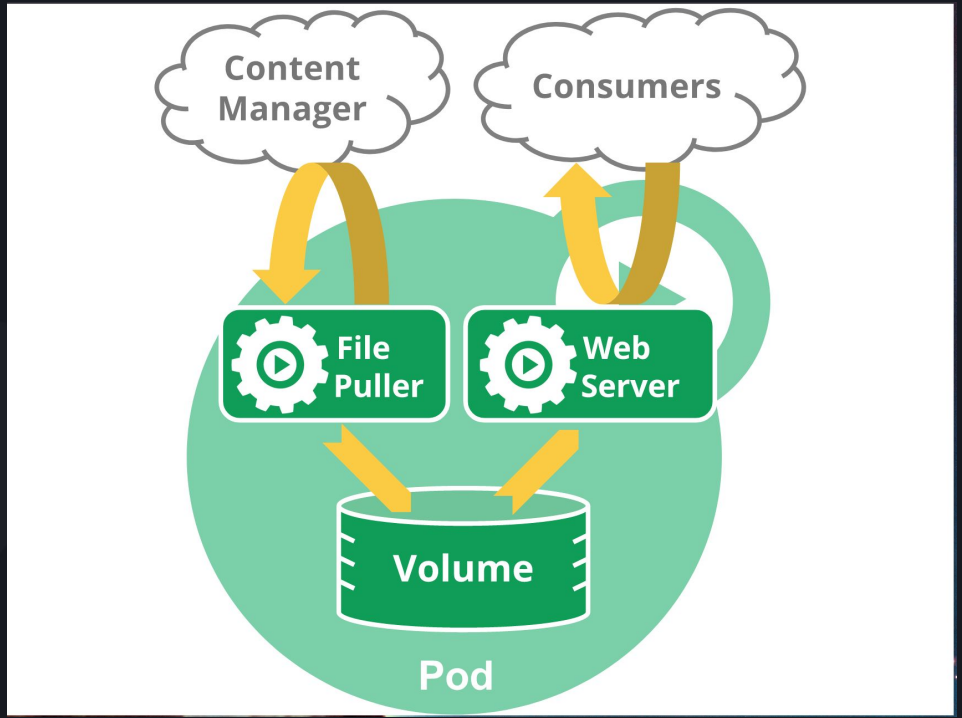
Questions?

Kubernetes

- Anubis runs on a **container orchestration tool** called **Kubernetes** or k8s (the 8 is for the number of letters in between k and s)
- Kube allows for things like CNI (**container networking interfaces**) and CSI (**container storage interface**) to be extended to many, many machines connected on a network
- This lets us design and easily implement large systems that rely on ***many many*** **individual containers** communicating at once

Kubernetes Pod

- A single unit of work in kubernetes
- Pods contain **containers**, **volumes**, **config-maps**, **secrets**, …
- Designed to be easy to **share resources** between containers in a pod

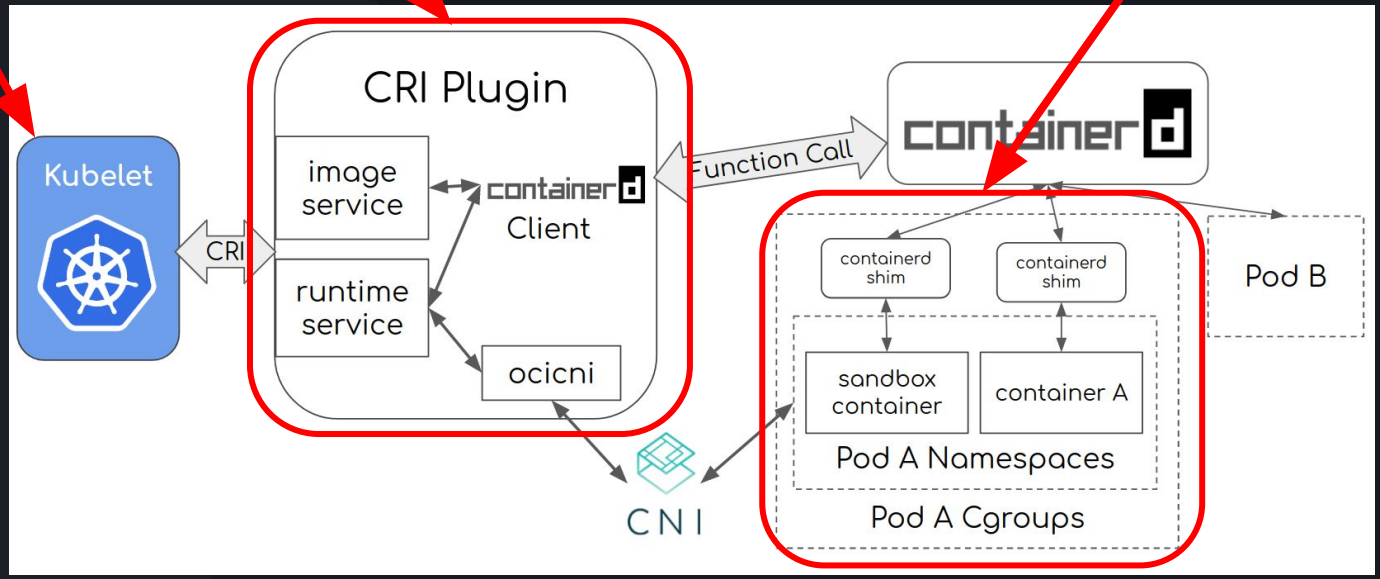


Kubernetes Pod Containerd

Primary K8S Node Agent

Container Resource Interface Plugin

Containerd Creates Pod Containers



Check Anubis out! https://anubis-lms.io/

Kubernetes in Production

Questions?

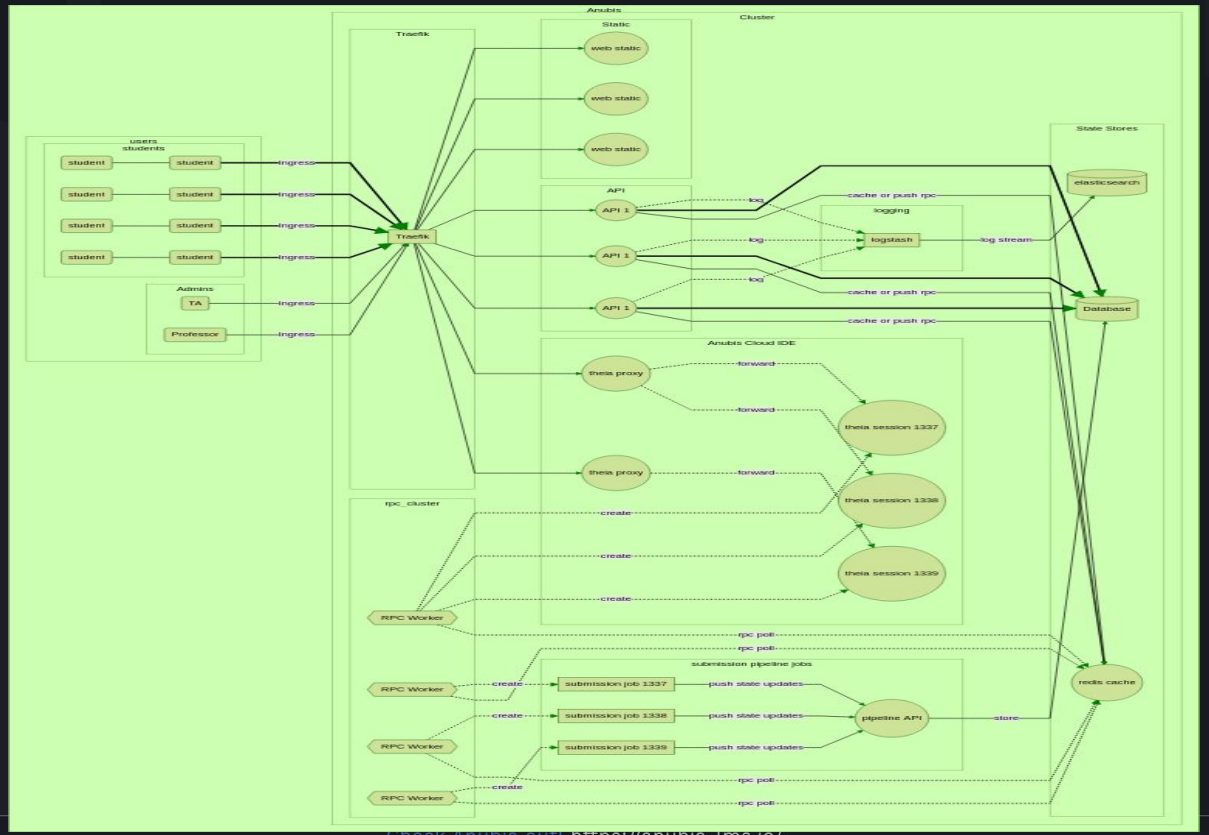
Anubis

- Anubis is a large system split up into **microservices**
  - Example: the web static (html and js) is separate from the python api
- There can be **many containers** within those microservices

Anubis

- There may be up to **1000+ containers running at any one time**
- (2022-05-01) there were ~535 IDEs that were opened over the day

Anubis



Check Anubis out! https://anubis-lms.io/

Questions?


Programmers
Anything stupid happening
I bet Microsoft did this.
made with mematic

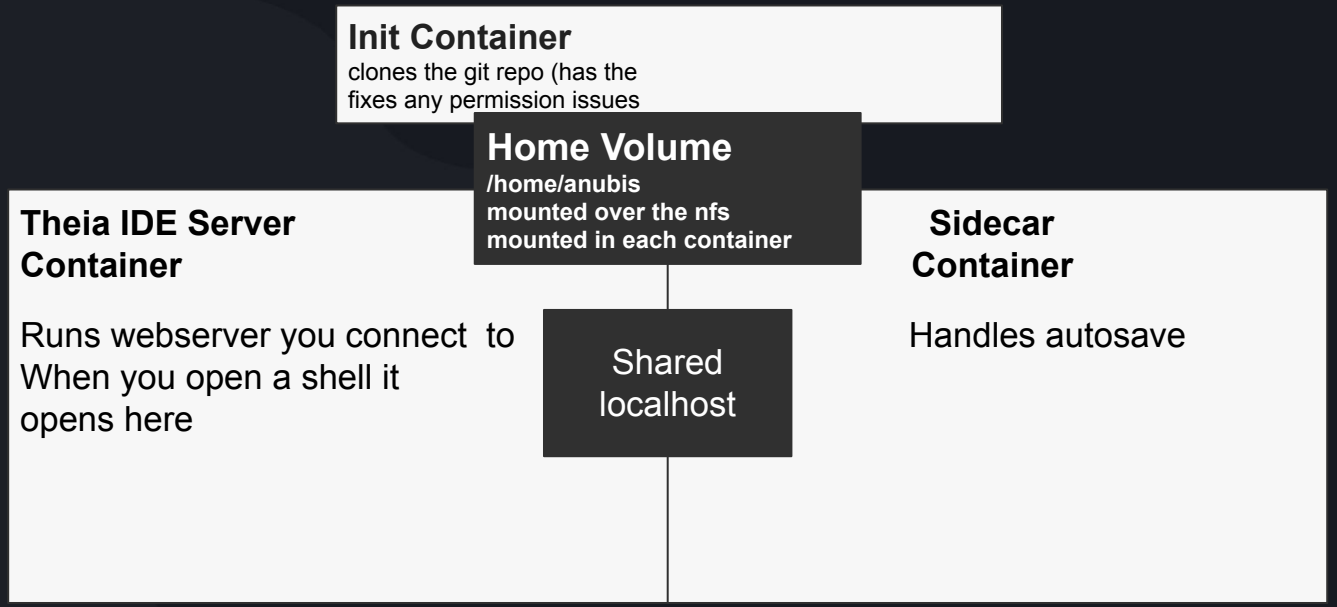
Anubis IDEs

- Anubis Cloud IDEs are made up of **individual containers**
- Each student gets their own IDE pod (and therefore **separate environment/filesystem**)
- The IDEs have **CPU and Memory limits** handled by cgroups

Anubis IDEs

- Each Anubis Cloud IDE is itself made up of **3+ containers**
  - An “init container” that clones your repo
  - IDE server
  - Autosave “sidecar”
- The containers work together to make the Cloud IDEs possible

Anubis IDEs

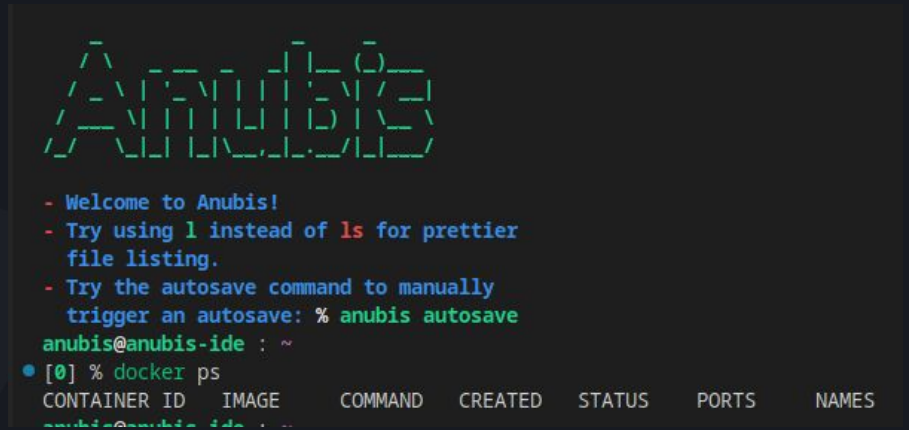

Init Container
clones the git repo (has the
fixes any permission issues
Home Volume
/home/anubis
mounted over the nfs
mounted in each container
Theia IDE Server Container
Runs webserver you connect to
When you open a shell it opens here
Shared localhost
Sidecar Container
Handles autosave

Anubis IDEs

- The **containers work together** to make the Cloud IDEs possible
- It is all about **breaking up responsibilities**

Anubis IDEs

- Recently I have added a **dockerd** sidecar container
- This means **docker in IDEs**!



Questions?

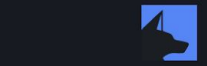
Containers

DEMO **Up to you!**

1. **Look at bomblab stuff**
2. **Take a look at container security in Anubis**

Future Readings

- Container Security by Liz Rice
  - github/lizrice
- Basically everything by Jess Frazelle
  - github/jessfraz
- Presentations by Jérôme Petazzoni
  - github/jpetazzo



Code to Read (All in Go)

- runC - OCI container spawning tool
  - github/opencontainers/runc
- containerd - container runtime
  - github/containerd/containerd
- kubernetes
  - github/kubernetes/kubernetes

Check Anubis out! https://anubis-lms.io/