Distributed Systems
CS6421

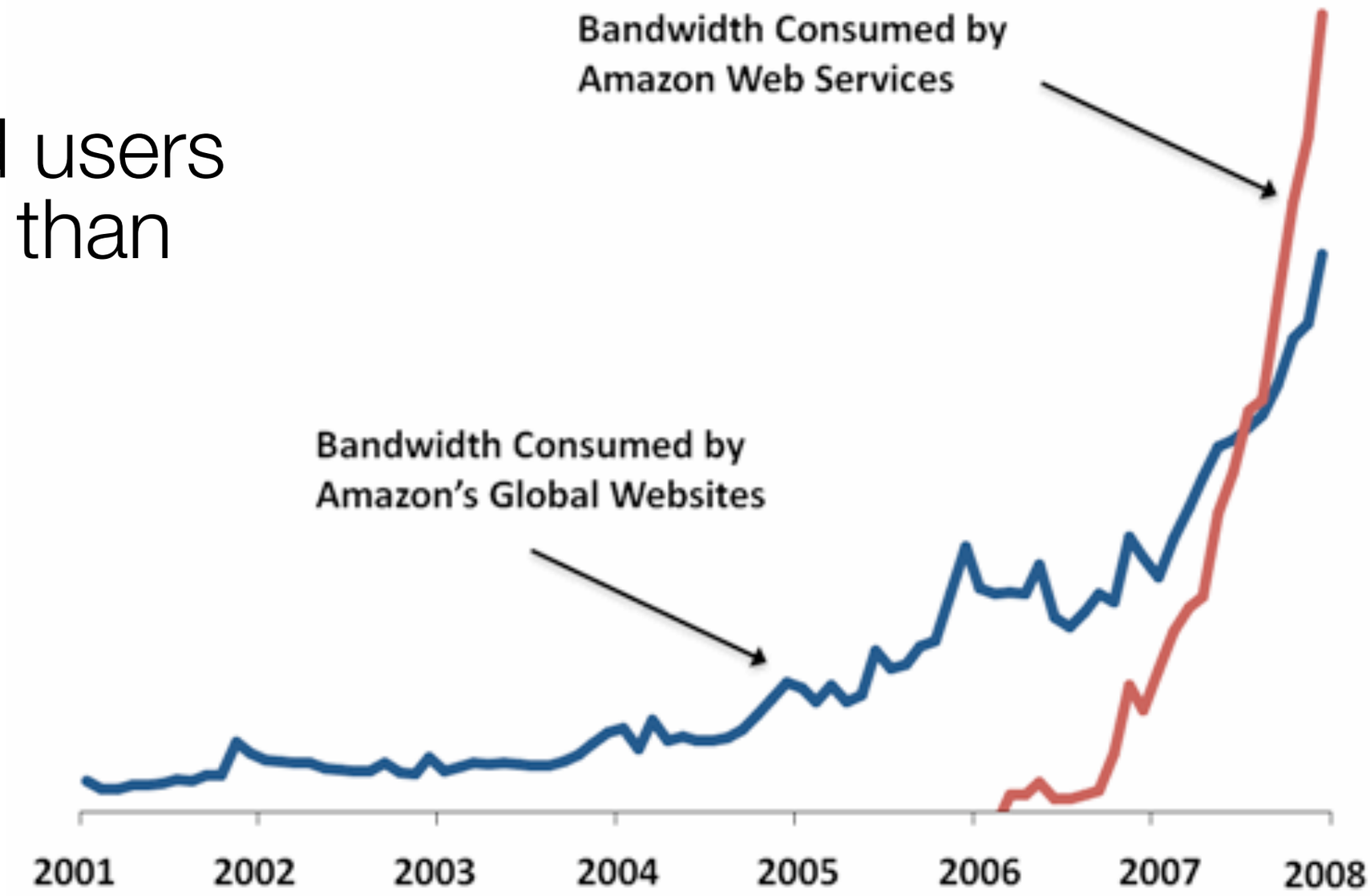
Cloud Computing: Servers and Virtualization

Prof. Tim Wood

Amazon's Cloud

Amazon built its cloud platform so that other people could pay for its infrastructure during the rest of the year…

Now its cloud users are far bigger than its own sites



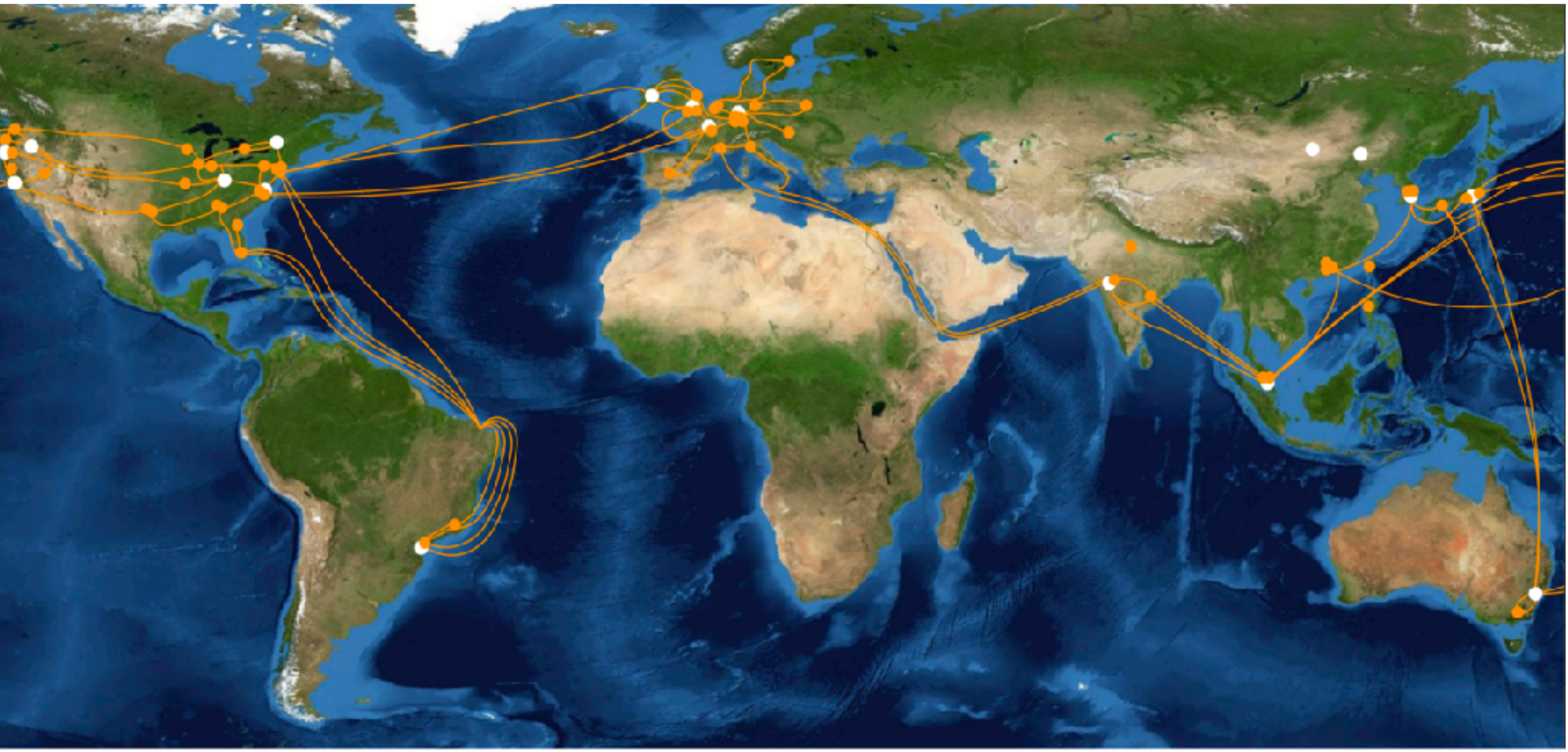
Cloud Data Centers

Microsoft's Dublin data center

Interconnections

Amazon's Internet

- Multiple private 100Gbps links between each data center site



Servers in AWS

Custom server designs

1U compute servers

- Intel CPUs
- High efficiency power supplies

Storage Racks

- 42U size
- 1100 disks
- 11 petabytes of storage space

Scale Estimates

- 1.5-2 million servers - Bloomberg 2014

- 50-80K per data center, 68 total data centers = 3.4-5.4 million
- re:Invent 2016

*Every day Amazon adds as many servers as it had in **2000** (when it was a **$2 billion** company)*
— talk at UW **2011**

*Every day Amazon adds as many servers as it had in **2005** (when it was a **$8.5 billion** company)*
— AWS re:Invent **2016**

Inside a Data Center

https://www.google.com/about/datacenters/inside/streetview/

Why use the cloud?

- Pay-as-you go
- Expand quickly on demand
- Don't need to worry about (many) IT issues
- Cheap!

... but is the cloud perfect?

[spoiler alert] no.

Infrastructure as a Service (IaaS)

Infrastructure clouds rent **raw servers**

- Connect to server remotely
- Configure OS and install whatever applications you want

Great flexibility for cloud user

Less management handled by cloud operator

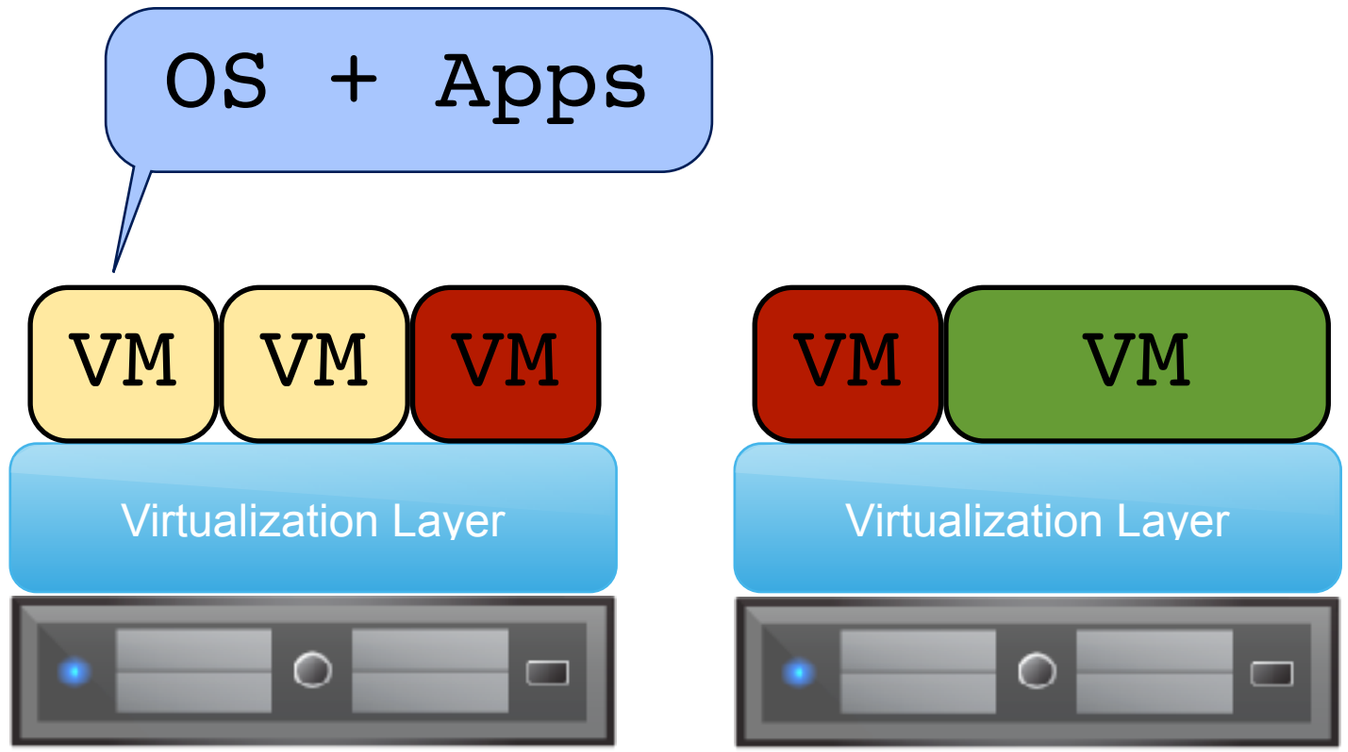
Your own computer or disk on demand!

Virtual Machines

Virtualization is used to **split up** a physical server

- Allows multiple customers to share one machine
- Simplifies management since VMs are not strictly tied to HW
- Provides isolation between cloud users

Cloud Data Center



Amazon EC2

- Infrastructure as a Service Cloud (IaaS)

- Can rent server and storage resources

	Description	Cost
t3.Micro	1GB RAM, up to 1 core, no storage	$0.01 / hour
t3.Large	8GB RAM, ~2 cores, no storage	$0.08 / hour
c5.18xlarge	144GB RAM, 72 cores, no storage	$3.06 / hour

EBS	Network attached storage	$0.10 / GB per month

Platform as a Service (PaaS)

The cloud provides a **programming platform**

Typically used to run highly scalable web apps

Cloud users write applications to run on the cloud

- Must write code to meet cloud API
- Cloud automatically scales the application based on demand
- Provides much greater scalability, but program must be specially written

Let the cloud handle your application's scalability!

Software as a Service (SaaS)

The cloud provides a **piece of software**

- Examples: email, office, project management, customer relations, supply chain, etc

Provides even greater scalability

- Entire cloud infrastructure is devoted just to one particular type of application

Benefits for customer: cheaper and simpler

Benefits for provider: economy of scale

Why bother writing or running your own application if they can do it better?

Examples

PaaS	SaaS

• Google App Engine
  • Python, Java
• Heroku
  • Ruby on Rails
• Amazon EMR
  • Java, Python, etc Hadoop
	• GMail
	• Flickr
	• Salesforce
	• Dropbox
	• iCloud

Cloud Grade Sheet

	Pay as you go	Scalability	Automation / ease of use	Flexibility	Security / Isolation
IaaS	+ +	+	-	+ +	+ +
PaaS	+ + +	++	++	- +	-
SaaS	+ + +	+++	+++	- - -	- +
Private Data Center	- - -	-	- -	+ + +	+++++ +++ +

Types of Clouds

Software as a Service

Office apps, CRM

for anybody

Platform as a Service

Software platforms

for programmers

Infrastructure as a Service

Azure

Servers & storage

for programmers and sys admins

Increased Cloud Automation

Increased Customer Control

Cloud Computing Goals

Offer fast services to customers worldwide

- Need geographic diversity and high scalability
- Low latency requests: fast responses
- High throughput: simultaneous processing

...that are highly reliable and secure

- Servers crash
- Data centers lose power
- Malicious users (or governments?) can attack

... as cheaply as possible

- Users expect services for free*
- Cloud needs to pay for servers, cooling infrastructure, energy, system administrators, etc

Let’s try out the cloud

AWS in 2012…

Welcome

The AWS Management Console provides a graphical interface to Amazon Web Services. Learn more about how to use our services to meet your needs, or get started by selecting a service.

Getting started guides

Reference architectures

Free Usage Tier

Set Start Page

Console Home

Amazon Web Services

Compute & Networking

- **EC2** — Virtual Servers in the Cloud
- **Elastic MapReduce** — Managed Hadoop Framework
- **Route 53** — Scalable Domain Name System
- **VPC** — Isolated Cloud Resources

Storage & Content Delivery

- **CloudFront** — Global Content Delivery Network
- **S3** — Scalable Storage in the Cloud
- **Storage Gateway** — Integrates on-premises IT environments with Cloud storage

Database

- **DynamoDB** — Predictable and Scalable NoSQL Data Store
- **ElastiCache** — In-Memory Cache
- **RDS** — Managed Relational Database Service

Deployment & Management

- **CloudFormation** — Templated AWS Resource Creation
- **CloudWatch** — Resource & Application Monitoring
- **Elastic Beanstalk** — AWS Application Container
- **IAM** — Secure AWS Access Control

App Services

- **CloudSearch** — Managed Search Service
- **SES** — Email Sending Service
- **SNS** — Push Notification Service
- **SQS** — Message Queue Service
- **SWF** — Workflow Service for Coordinating Application Components

Announcements

Announcing VM Export for Amazon EC2

AWS Console Enhancements for Elastic Load Balancing: Listener, Certificate, and...

Amazon RDS announces support for MySQL Read Replica in Amazon VPC

More...

Service Health

Edit

Click Edit to add at least one service and at least one region to monitor.

Service Health Dashboard

AWS in 2015…

Amazon Web Services

Compute

- **EC2** — Virtual Servers in the Cloud
- **EC2 Container Service** — Run and Manage Docker Containers
- **Elastic Beanstalk** — Run and Manage Web Apps
- **Lambda** — Run Code in Response to Events

Storage & Content Delivery

- **S3** — Scalable Storage in the Cloud
- **CloudFront** — Global Content Delivery Network
- **Elastic File System** PREVIEW — Fully Managed File System for EC2
- **Glacier** — Archive Storage in the Cloud
- **Import/Export Snowball** — Large Scale Data Transport
- **Storage Gateway** — Integrates On-Premises IT Environments with Cloud Storage

Database

- **RDS** — Managed Relational Database Service
- **DynamoDB** — Predictable and Scalable NoSQL Data Store
- **ElastiCache** — In-Memory Cache
- **Redshift** — Managed Petabyte-Scale Data Warehouse Service

Networking

- **VPC** — Isolated Cloud Resources
- **Direct Connect** — Dedicated Network Connection to AWS
- **Route 53** — Scalable DNS and Domain Name Registration

Developer Tools

- **CodeCommit** — Store Code in Private Git Repositories
- **CodeDeploy** — Automate Code Deployments
- **CodePipeline** — Release Software using Continuous Delivery

Management Tools

- **CloudWatch** — Monitor Resources and Applications
- **CloudFormation** — Create and Manage Resources with Templates
- **CloudTrail** — Track User Activity and API Usage
- **Config** — Track Resource Inventory and Changes
- **OpsWorks** — Automate Operations with Chef
- **Service Catalog** — Create and Use Standardized Products
- **Trusted Advisor** — Optimize Performance and Security

Security & Identity

- **Identity & Access Management** — Manage User Access and Encryption Keys
- **Directory Service** — Host and Manage Active Directory
- **Inspector** PREVIEW — Analyze Application Security
- **WAF** — Filter Malicious Web Traffic

Analytics

- **EMR** — Managed Hadoop Framework
- **Data Pipeline** — Orchestration for Data-Driven Workflows
- **Elasticsearch Service** — Run and Scale Elasticsearch Clusters
- **Kinesis** — Work with Real-time Streaming data
- **Machine Learning** — Build Smart Applications Quickly and Easily

Internet of Things

- **AWS IoT** BETA — Connect Devices to the cloud

Mobile Services

- **Mobile Hub** BETA — Build, Test, and Monitor Mobile apps
- **Cognito** — User Identity and App Data Synchronization
- **Device Farm** — Test Android, Fire OS, and iOS apps on real devices in the Cloud
- **Mobile Analytics** — Collect, View and Export App Analytics
- **SNS** — Push Notification Service

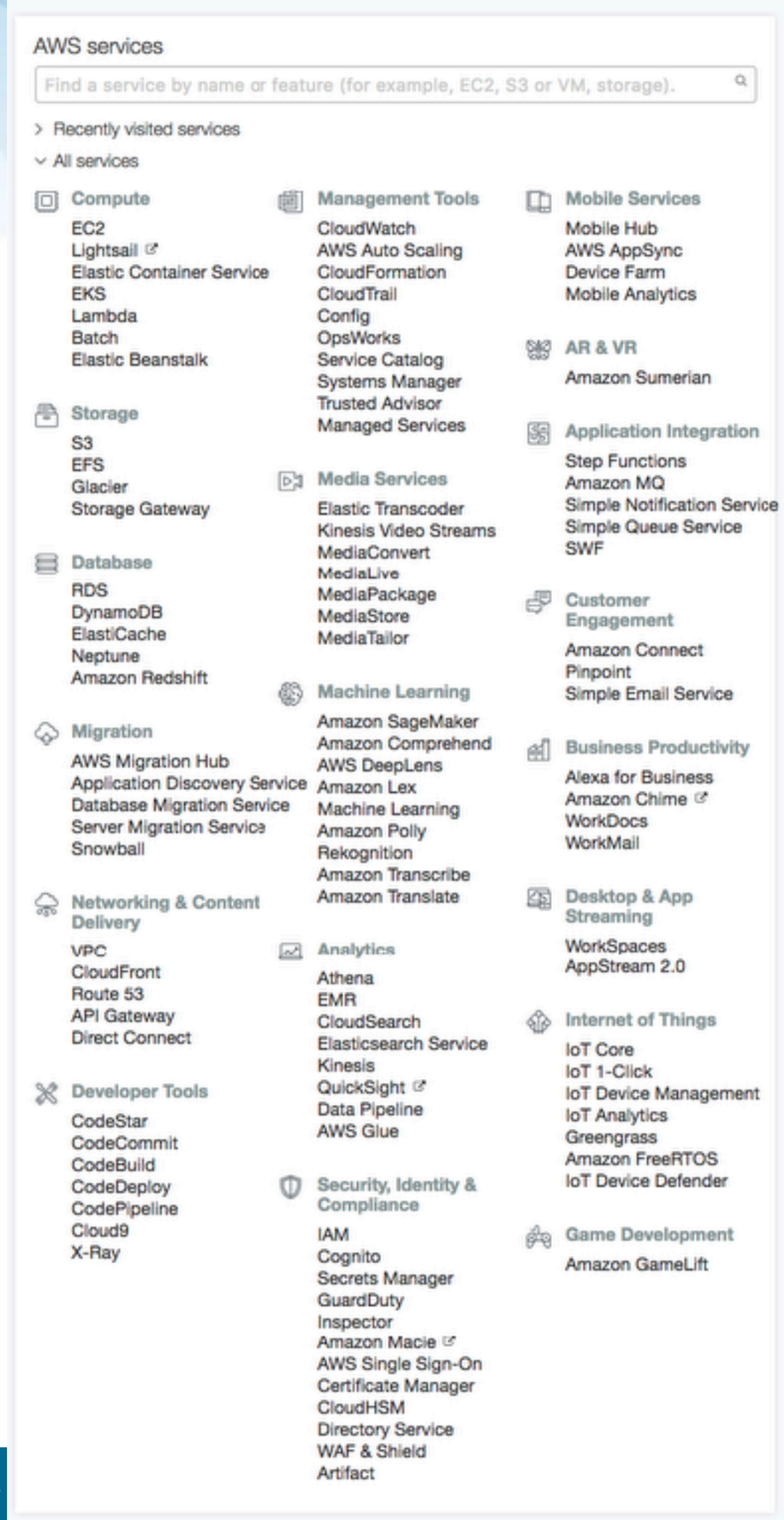
Application Services

- **API Gateway** — Build, Deploy and Manage APIs
- **AppStream** — Low Latency Application Streaming
- **CloudSearch** — Managed Search Service
- **Elastic Transcoder** — Easy-to-use Scalable Media Transcoding
- **SES** — Email Sending Service
- **SQS** — Message Queue Service
- **SWF** — Workflow Service for Coordinating Application Components

Enterprise Applications

- **WorkSpaces** — Desktops in the Cloud
- **WorkDocs** — Secure Enterprise Storage and Sharing Service
- **WorkMail** PREVIEW — Secure Email and Calendaring Service

AWS in 2018!


AWS services
Find a service by name or feature (for example, EC2, S3 or VM, storage).
Recently visited services
All services
Compute
EC2
Lightsail
Elastic Container Service
EKS
Lambda
Batch
Elastic Beanstalk
Storage
S3
EFS
Glacier
Storage Gateway
Database
RDS
DynamoDB
ElastiCache
Neptune
Amazon Redshift
Migration
AWS Migration Hub
Application Discovery Service
Database Migration Service
Server Migration Service
Snowball
Networking & Content Delivery
VPC
CloudFront
Route 53
API Gateway
Direct Connect
Developer Tools
CodeStar
CodeCommit
CodeBuild
CodeDeploy
CodePipeline
Cloud9
X-Ray
Management Tools
CloudWatch
AWS Auto Scaling
CloudFormation
CloudTrail
Config
OpsWorks
Service Catalog
Systems Manager
Trusted Advisor
Managed Services
Media Services
Elastic Transcoder
Kinesis Video Streams
MediaConvert
MediaLive
MediaPackage
MediaStore
MediaTailor
Machine Learning
Amazon SageMaker
Amazon Comprehend
AWS DeepLens
Amazon Lex
Machine Learning
Amazon Polly
Rekognition
Amazon Transcribe
Amazon Translate
Analytics
Athena
EMR
CloudSearch
Elasticsearch Service
Kinesis
QuickSight
Data Pipeline
AWS Glue
Security, Identity & Compliance
IAM
Cognito
Secrets Manager
GuardDuty
Inspector
Amazon Macie
AWS Single Sign-On
Certificate Manager
CloudHSM
Directory Service
WAF & Shield
Artifact
Mobile Services
Mobile Hub
AWS AppSync
Device Farm
Mobile Analytics
AR & VR
Amazon Sumerian
Application Integration
Step Functions
Amazon MQ
Simple Notification Service
Simple Queue Service
SWF
Customer Engagement
Amazon Connect
Pinpoint
Simple Email Service
Business Productivity
Alexa for Business
Amazon Chime
WorkDocs
WorkMail
Desktop & App Streaming
WorkSpaces
AppStream 2.0
Internet of Things
IoT Core
IoT 1-Click
IoT Device Management
IoT Analytics
Greengrass
Amazon FreeRTOS
IoT Device Defender
Game Development
Amazon GameLift

Let's try it out!

https://console.aws.amazon.com

Instance details:

- Auto-assign Public IP -> Enable

```
sudo apt-get update

sudo apt-get install -y sysbench

sysbench --test=cpu --num-threads=100 --max-requests=50000 run
```

Why is it so cheap?

c5.18xlarge - **$3.06 per hour**

- 144GB RAM, 72x ~3Ghz CPU cores, 25Gbps

If busy 24x365 = $26,805.60 per year!

Could just buy from Dell…

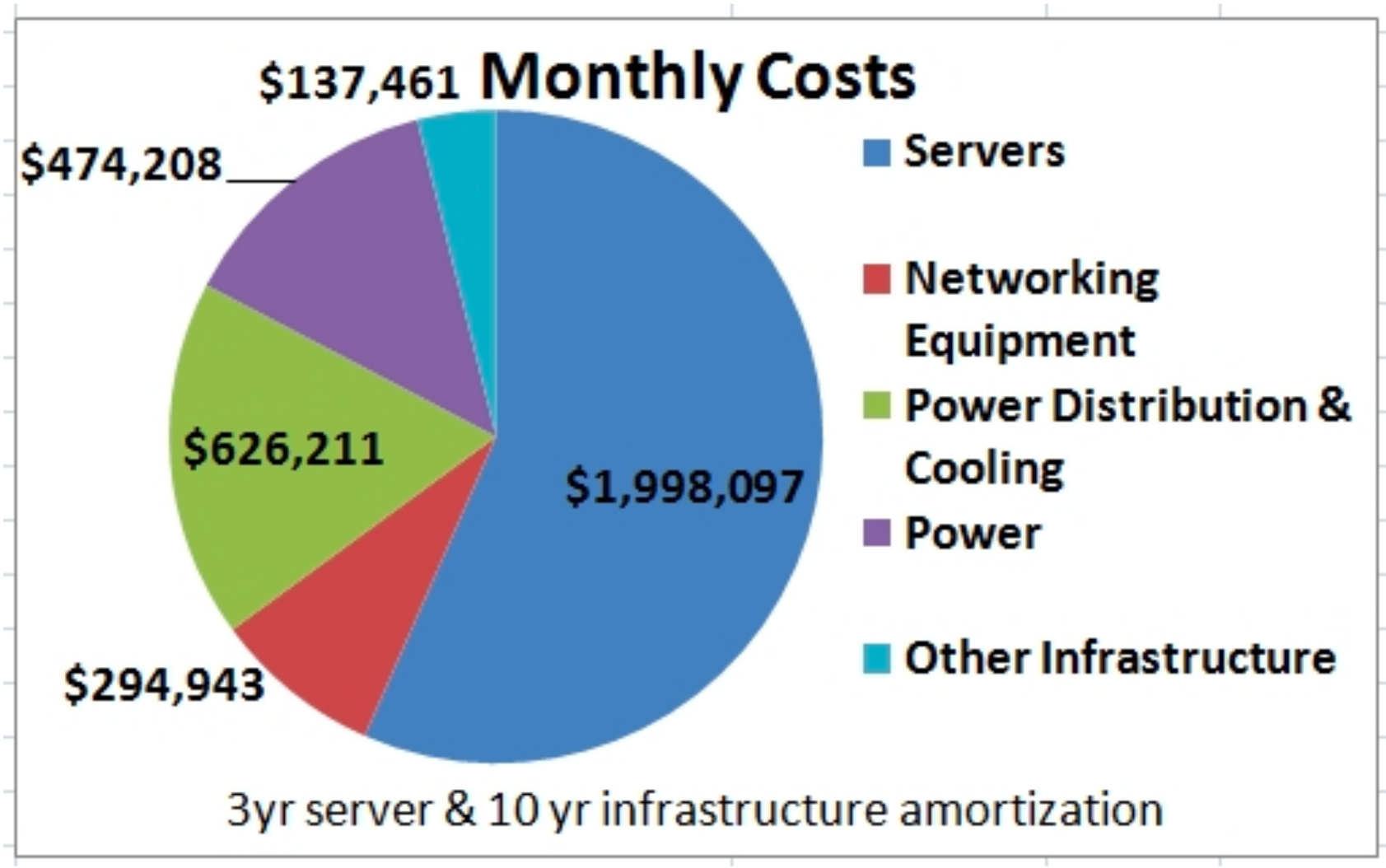
PowerEdge R930 Rack Server Summary

Dell Price $37,245.40

Starting at Price	~~$59,210.00~~
Total Savings	$21,964.60
Standard Delivery	Free

It's not cheap

The cost to run a 50,000 server data center (2010):

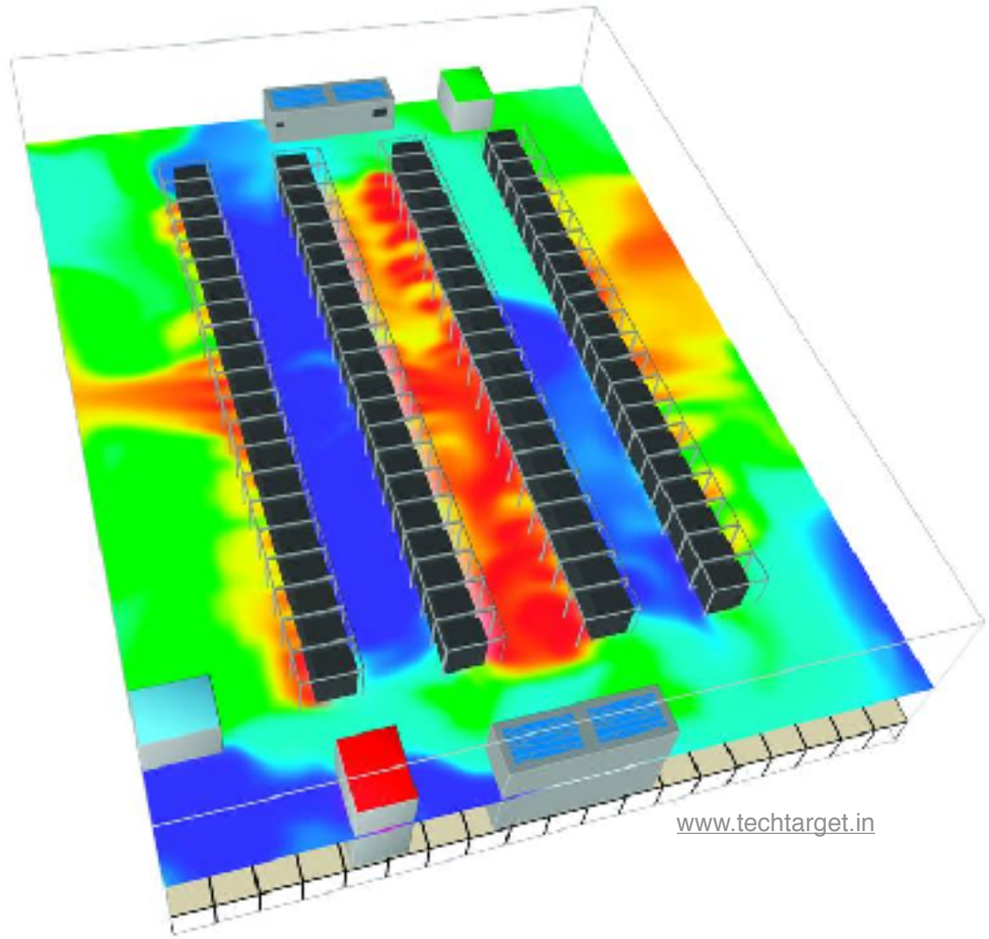


James Hamilton's Blog

Heat and Power

Computers are hot!

- Thermostat set to 55-72 degrees
- Hot and cold air aisles
- Infrared mapping to find hotspots
- Complex thermodynamic models
- A Finnish data center pipes the heat to warm 1,000 nearby homes



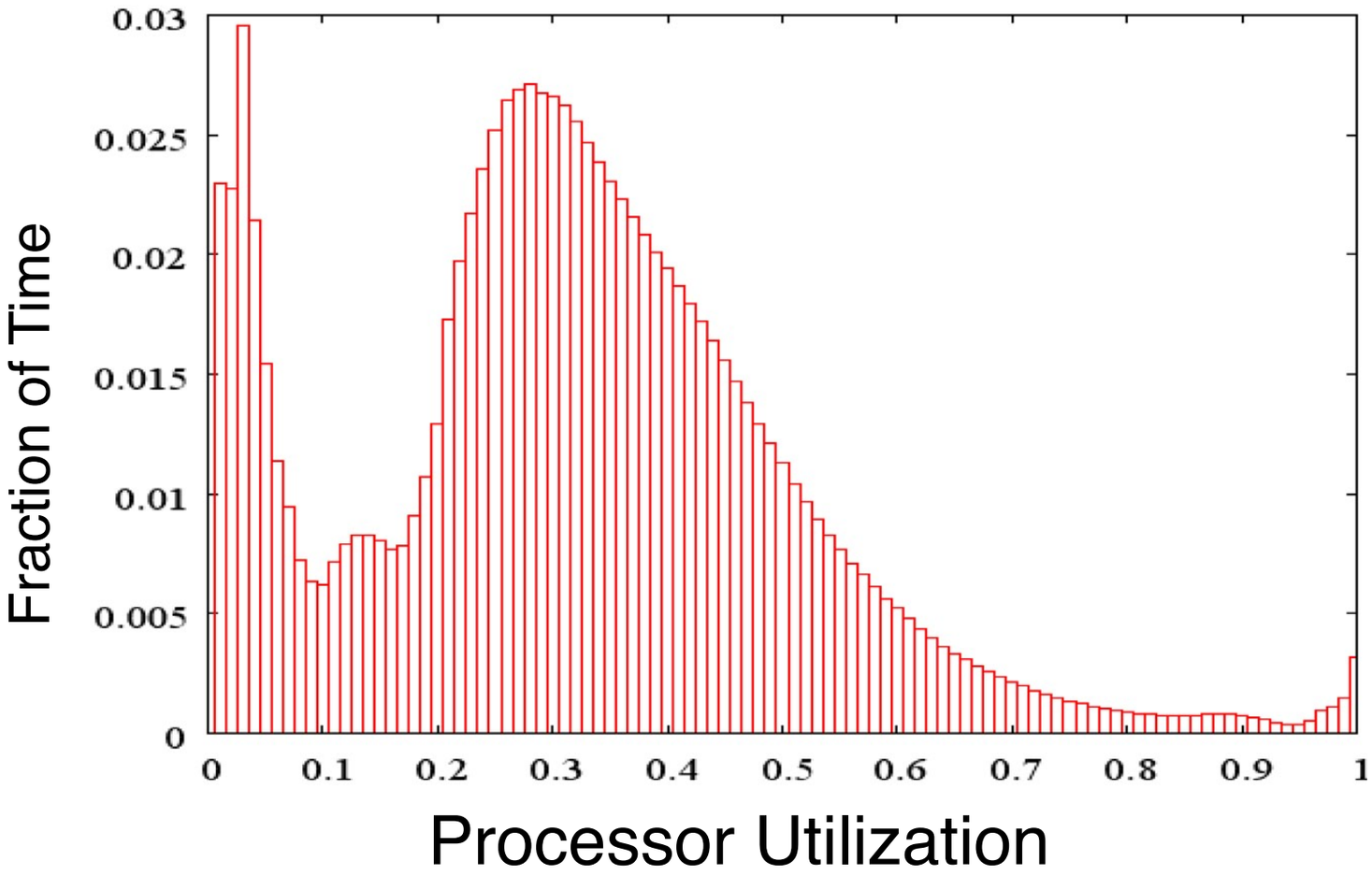
www.techtarget.in

Computers use power!

- Several megawatts per data center
- 1.3% of world electricity usage
- Often, only 50% of a data center's energy goes to actual IT equipment

Server (In)Efficiency

Many servers are poorly utilized



How can we improve this?

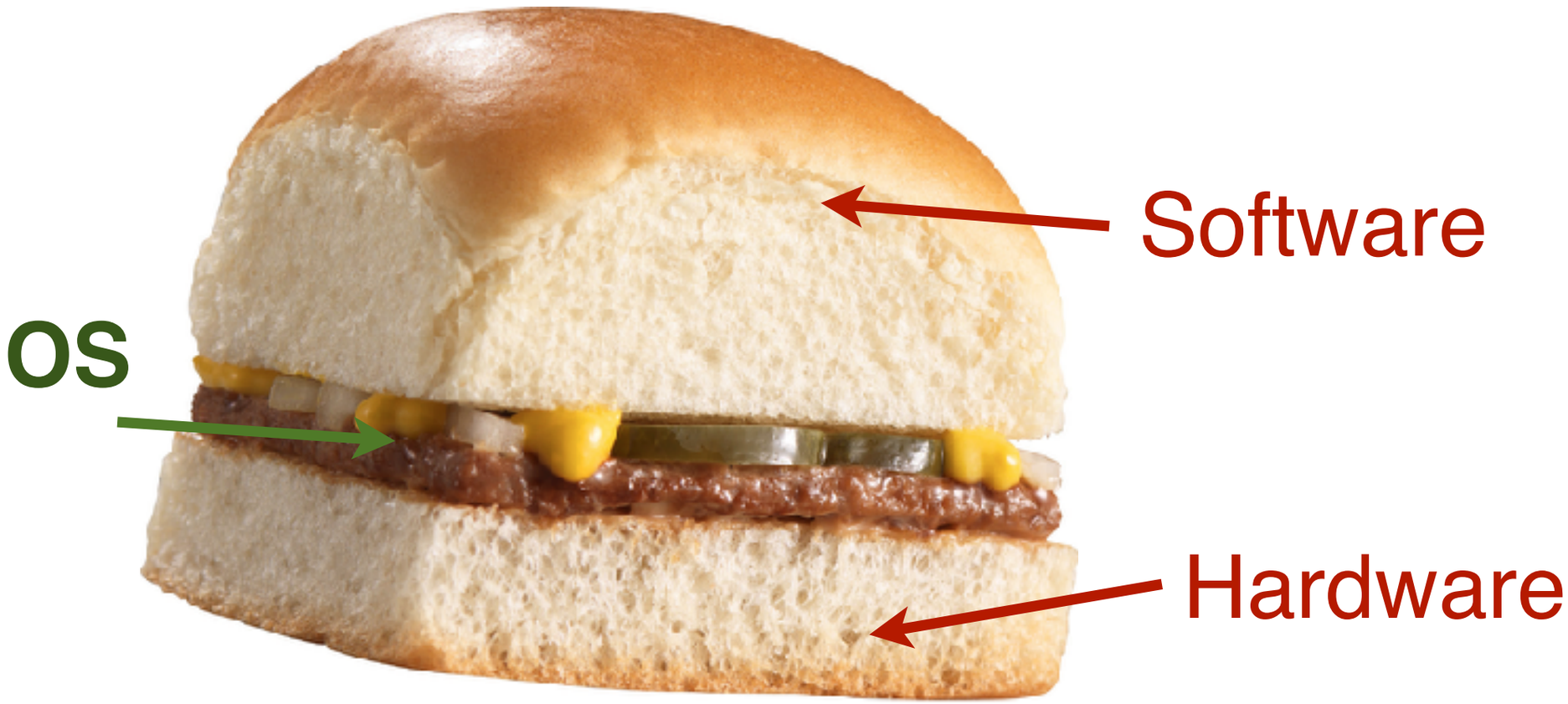
Figure from: The Data Center as a Computer by Luiz André Barroso and Urs Hölzle

Break?

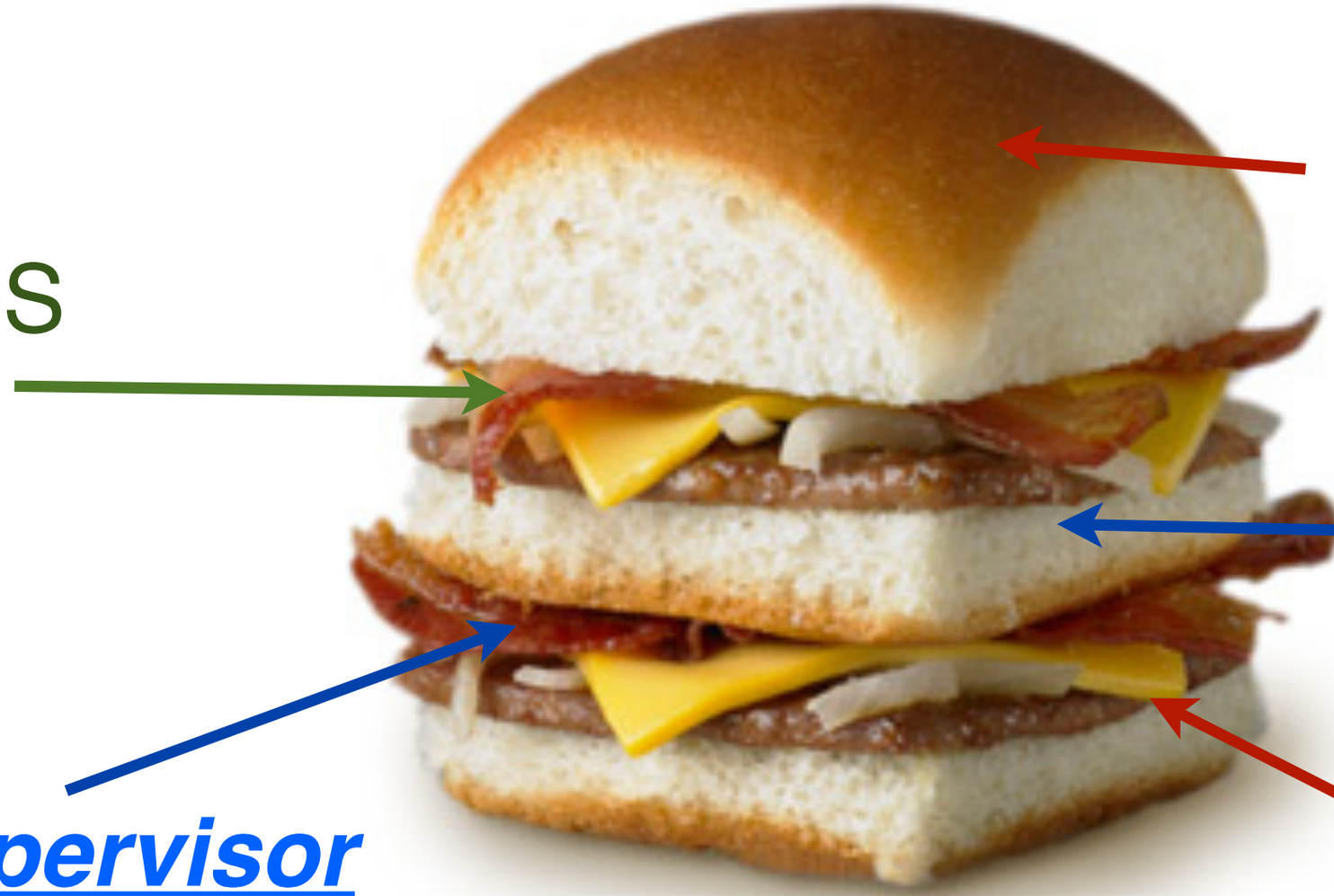
Virtualizing Resources

Question...

What's better than an operating system?



Virtualization

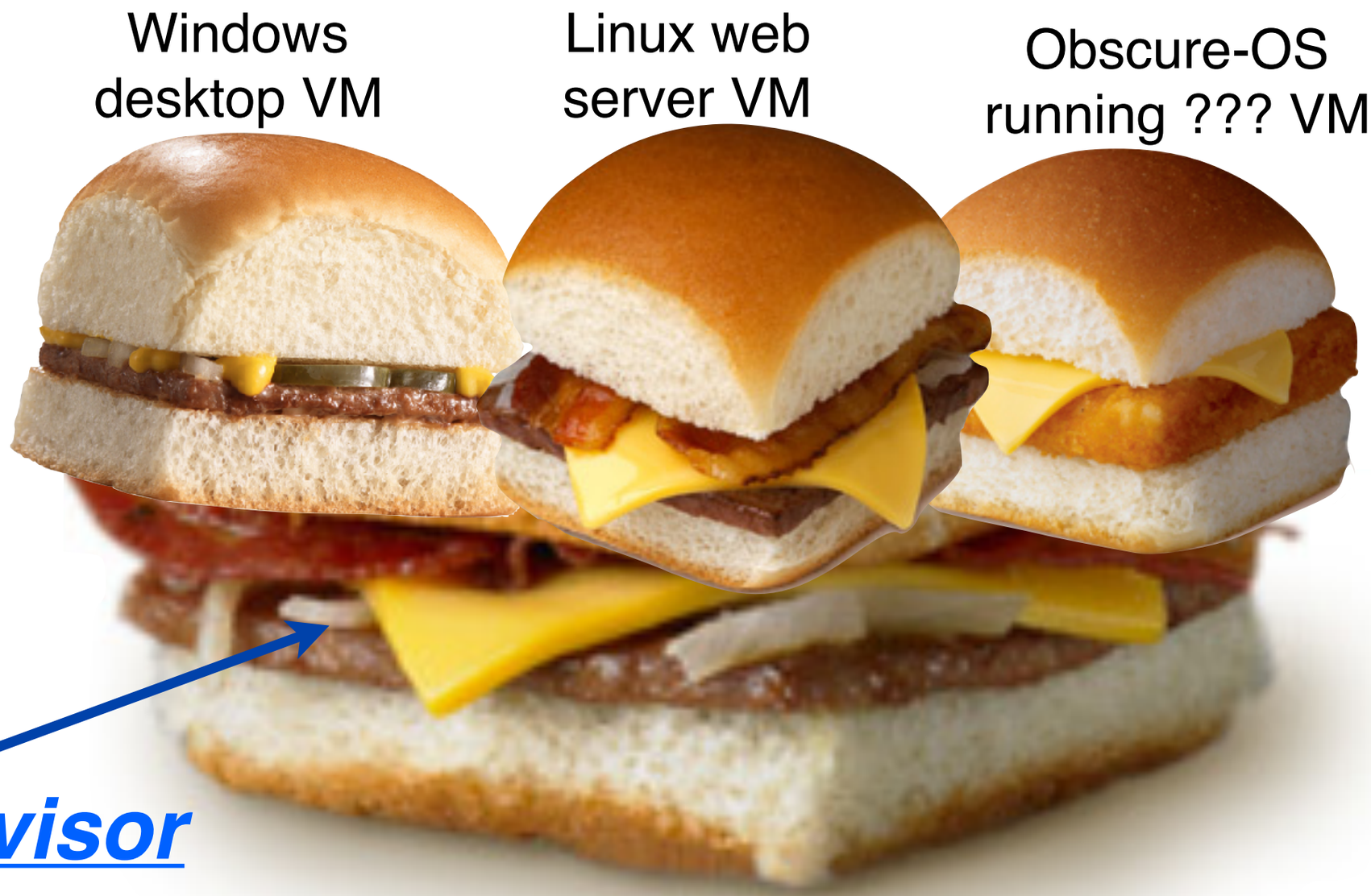


(another operating system)

Multiple VMs

Hypervisor can manage many virtual machines

- Just like OS manages many processes



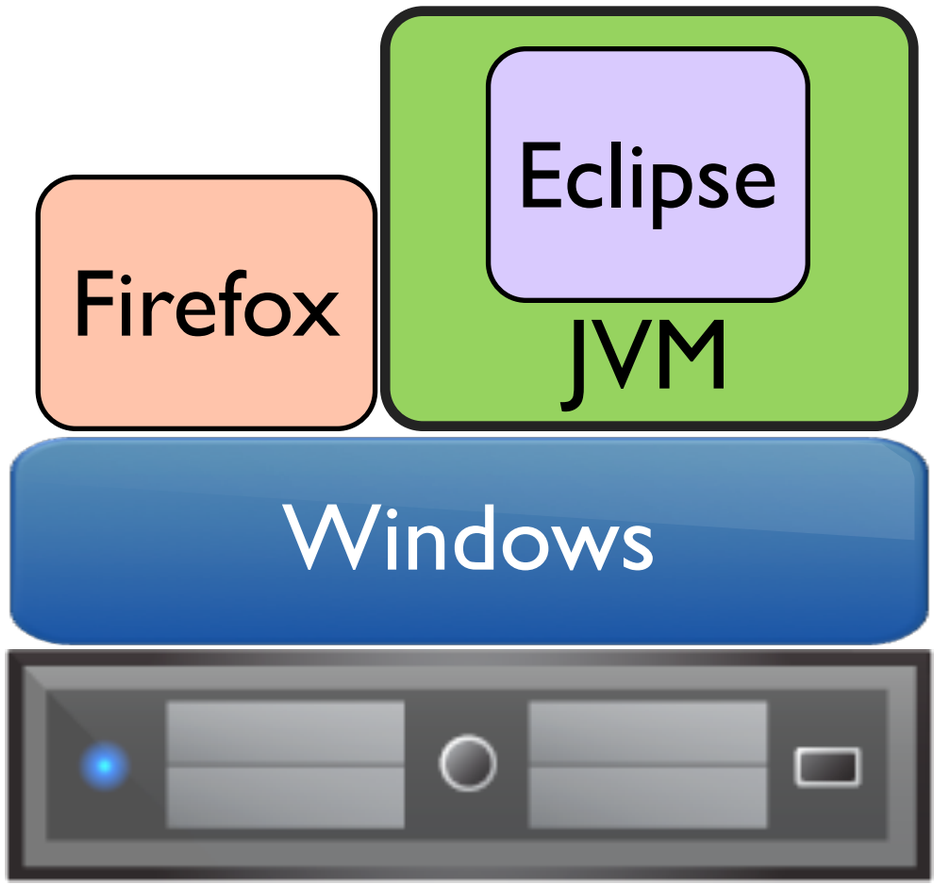
The Most Common VM

Java Virtual Machine

- Execution environment for running Java code
- Interprets/compiles programs and translates them to the host environment

Abstraction layer to OS

- Java code is platform independent
- Can add overhead



What is virtualization?

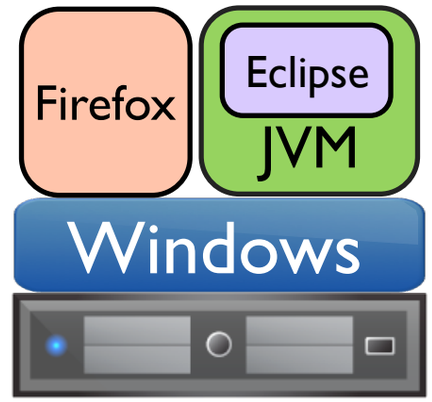
An extra **interface** that mimics the behavior of a lower layer

Used since 1970s so new mainframes could support legacy applications

Types of Virtualization

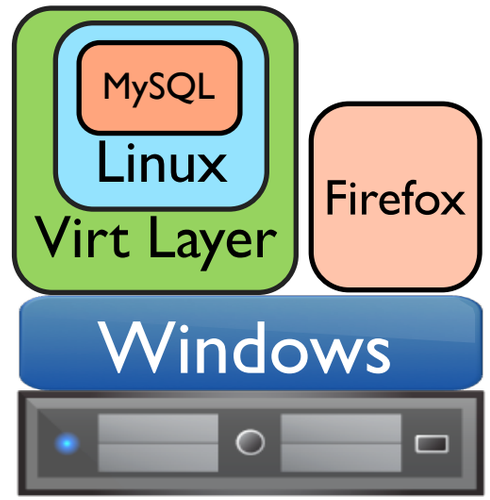
Application Virtualization

- Runs application code
- *Java JVM, WINE*



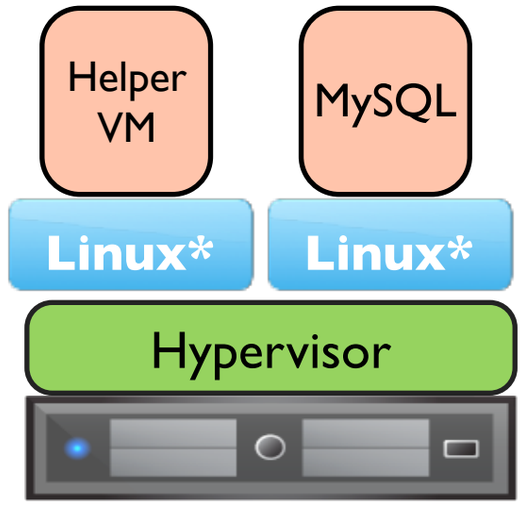
Hosted Virtualization

- Virtualizes a full OS and apps
- *VMware Player, VirtualBox*



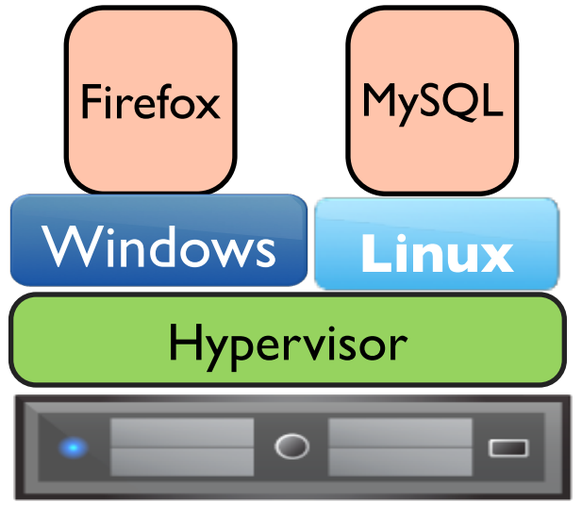
Paravirtualization

- Modify OS to simplify hypervisor
- *Xen*



Full Virtualization

- Runs directly on HW
- *VMware ESXi*



Why Virtualize?

Consolidation

- Can split a physical server into many smaller servers

Security

- VMs are isolated from one another

Resource management

- Can dynamically adjust a VM's CPU and memory share

Convenience

- VM is abstracted away from physical hardware
- Great for development

How to Virtualize?

Virtualization layer replaces an interface

Must intercept calls and translate them

- Java - interpret/compile code to match host
- Hosted VM - translate system calls for host OS
- Full Virtualization - trap on sensitive instructions

How to allocate resources?

- VMs must share memory and CPU time

How to handle I/O?

- Abstraction layer separates VM from physical hardware

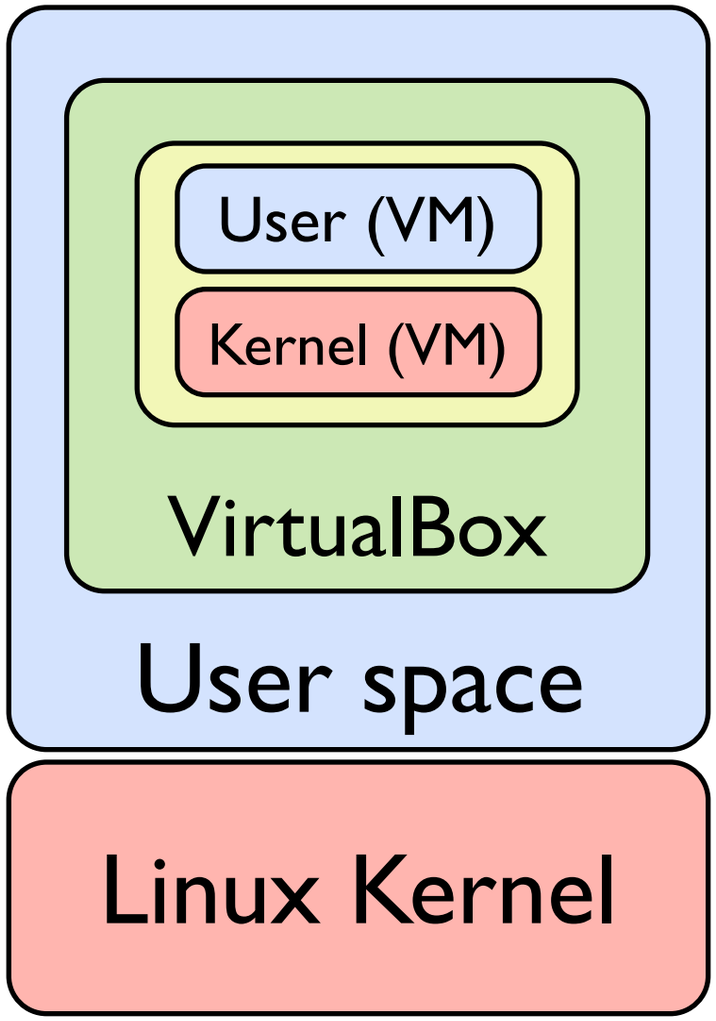
Hosted Virtualization

Normal OS divided into Kernel and User modes

Protected instructions only work in kernel mode

- I/O, memory allocation, etc
- Traps to kernel if run in user mode

How to run a VM in user mode?

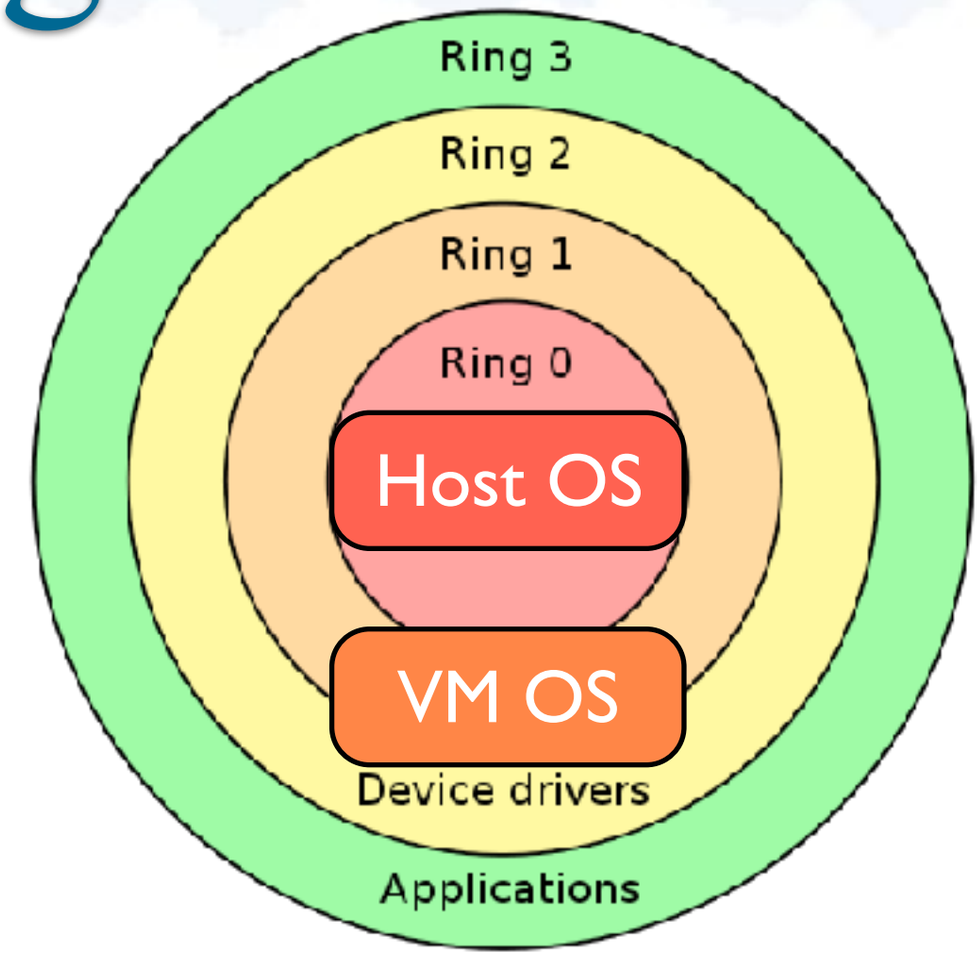


CPU Rings

User and kernel mode are controlled by CPU

Modern CPUs support multiple protection rings

- Ring 0 = kernel mode
- Ring 3 = user mode
- Rings 1-2 = drivers or unused



Hosted virtualization runs VM OS in Ring 1

- Must detect and translate any CPU instructions that require Ring 0

Ring 0 ops

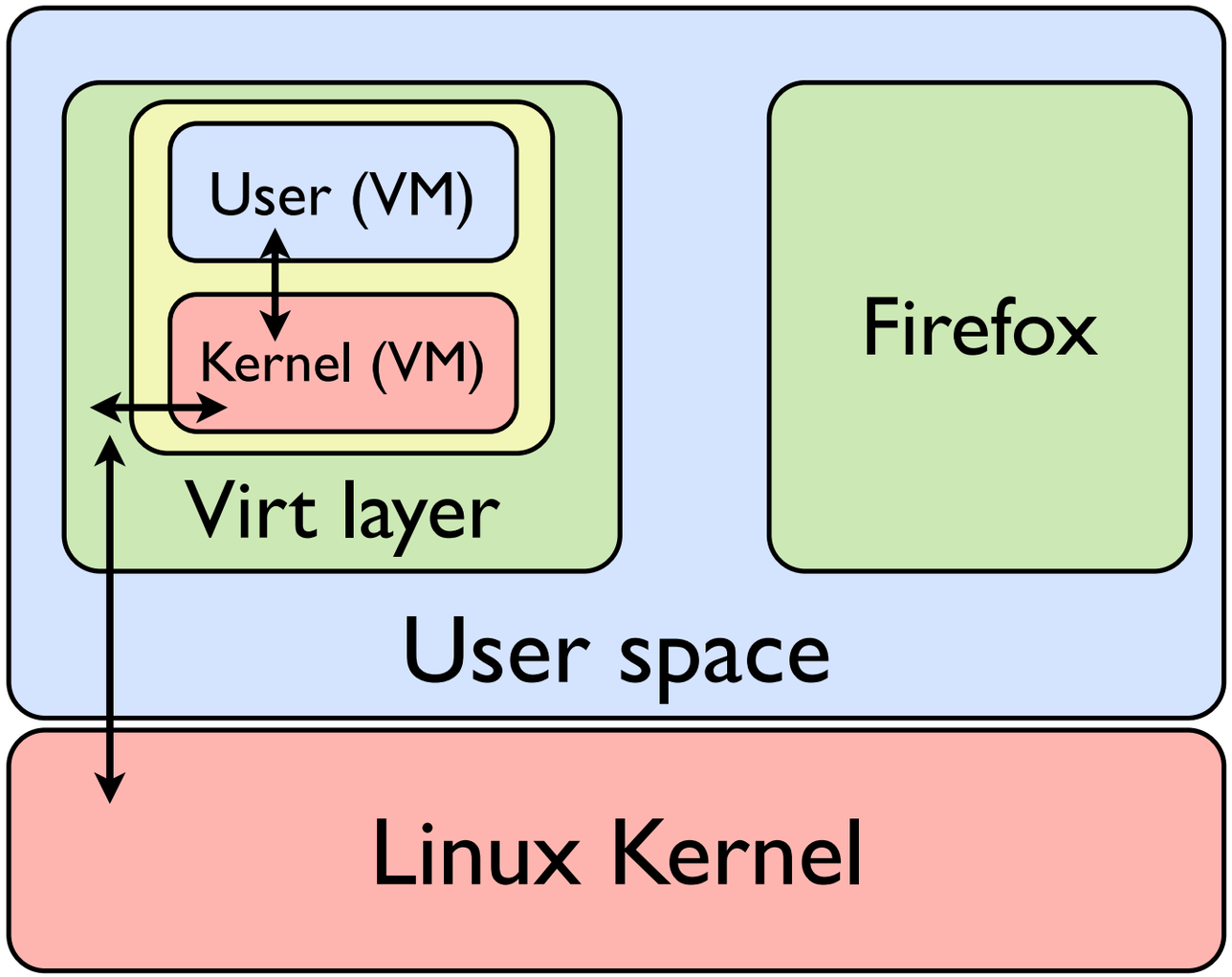
set time
power on/off
memory management
etc

Hosted Virtualization

Dynamic translation

- Preprocess all code being run by the OS inside the VM
- Detect sensitive instructions
- Repackage and call into parent OS
- Return result to guest OS

How to optimize?



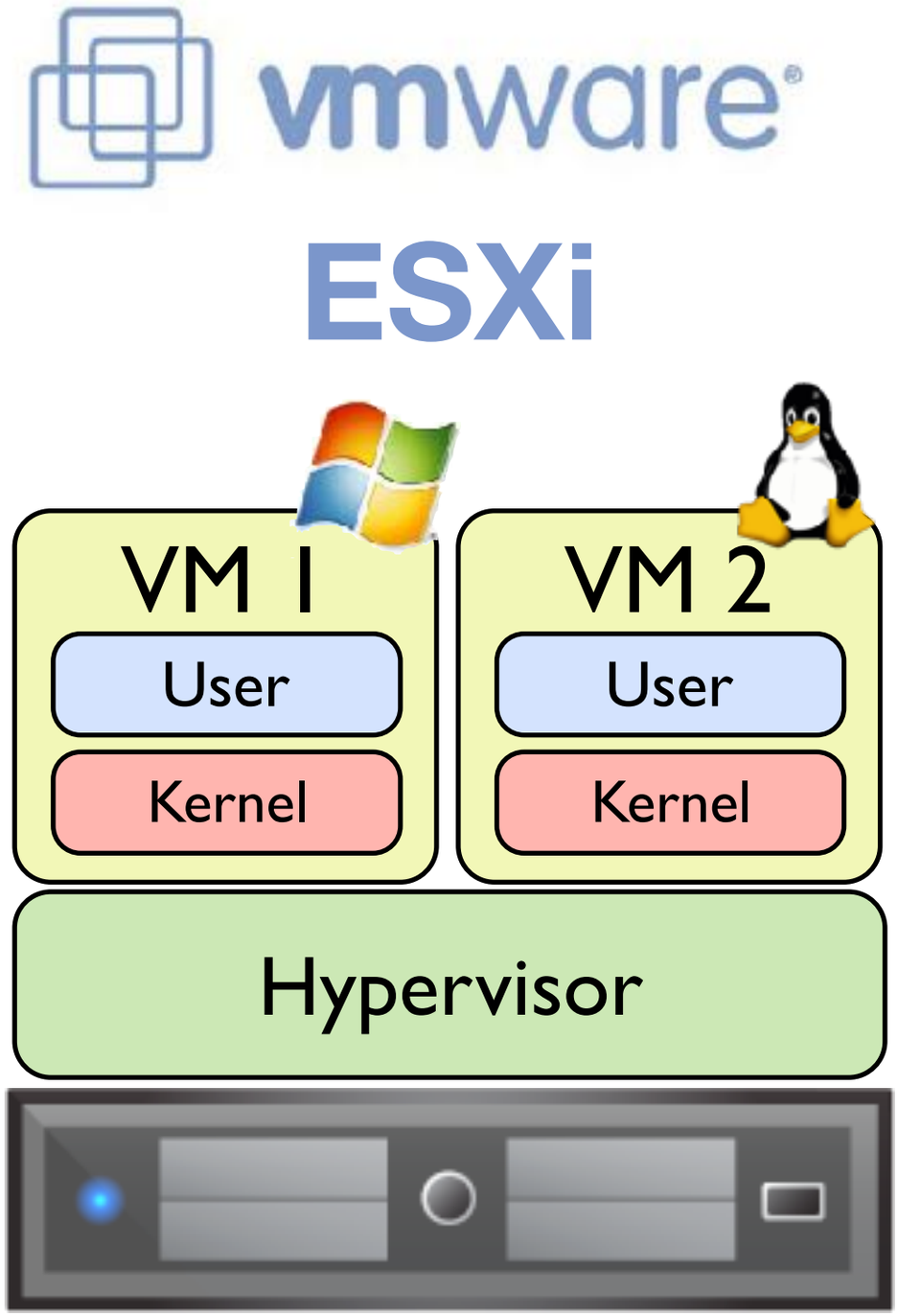
Full Virtualization

Hypervisor runs directly on hardware in Ring 0

Manages VMs

Uses dynamic translation to rewrite protected instructions

Hosts device drivers for VMs



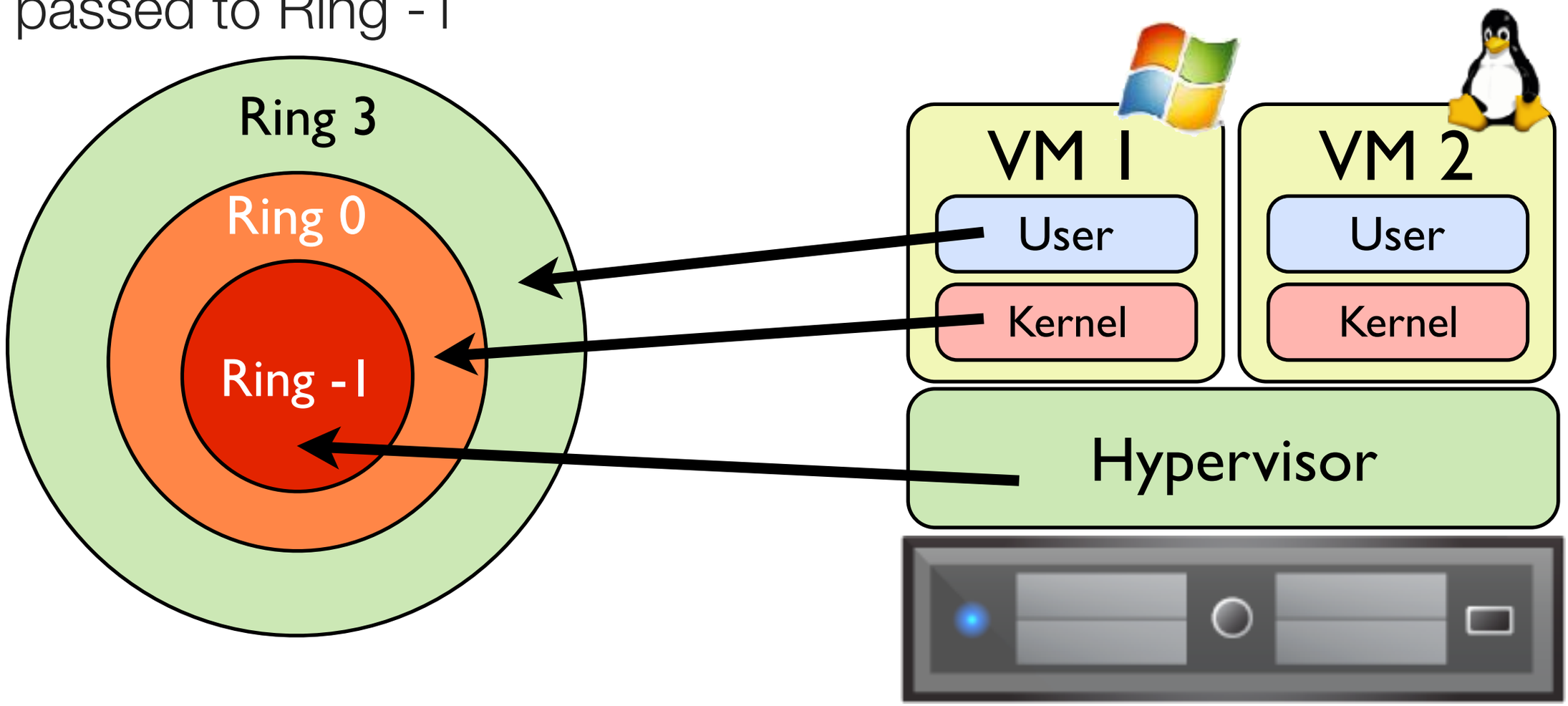
HW Virtualization

Newer CPUs have support for virtualization

- AMD-V and Intel-VT

Provides an extra ring for running a hypervisor

- Protected instructions in VM OS are trapped and passed to Ring -1



Getting help from the VM

Hosted and Full virtualization are VM OS agnostic

- Guest OS does not know it is being virtualized
- Translate binary code (slow)
- Get help from hardware (expensive)

What if we ask the VM's OS for help?

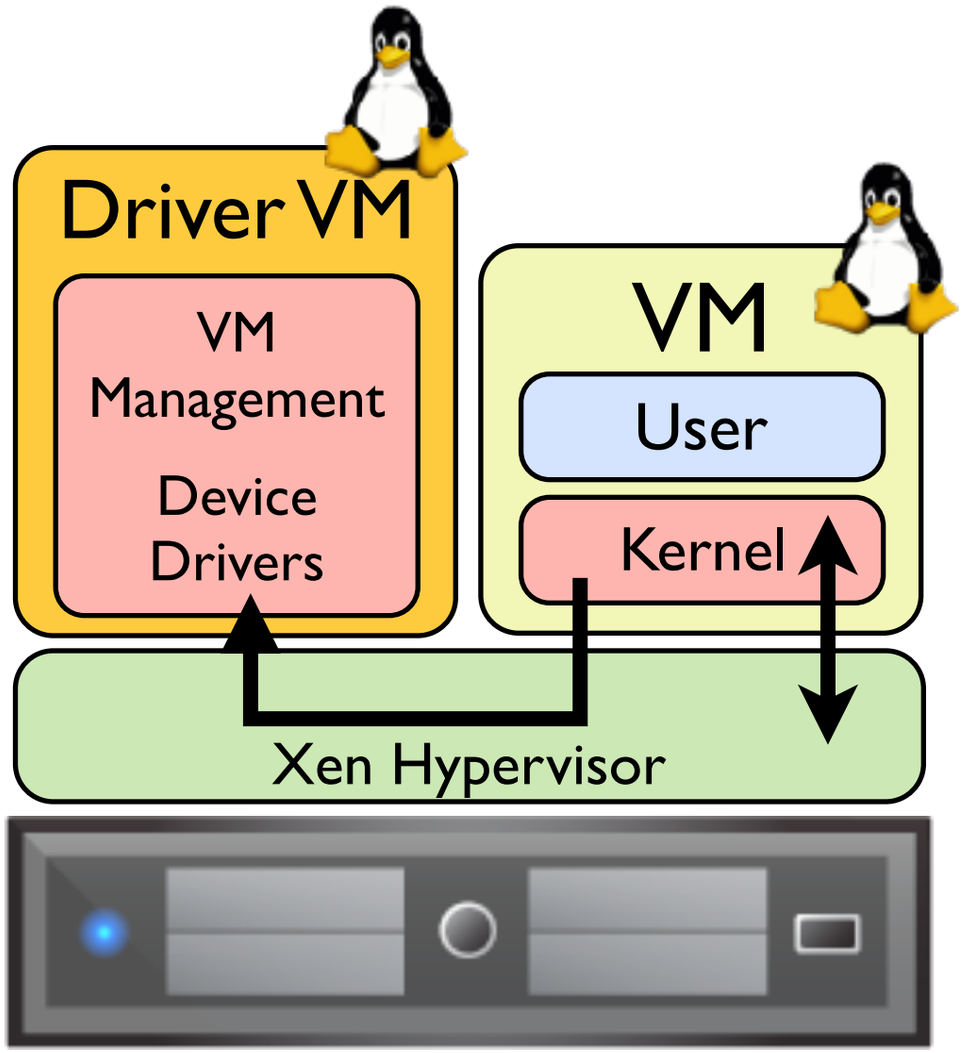
- Have guest OS notify hypervisor of special instructions
- Guest OS can help with device drivers

Benefits and drawbacks?

Paravirtualization in Xen™

Modifies Linux so that it is virtualization aware

OS asks hypervisor for help to run special instructions



Driver VM is special management VM

- Starts/stops VMs
- Contains Linux device drivers

Very simple hypervisor

- Reduces overhead
- No need for HW virtualization

Trade-offs

Hosted Virtualization

- easier to install, and turn off, great for testing/development
- neg: fewer resources available, because need host OS

Full Virtualization

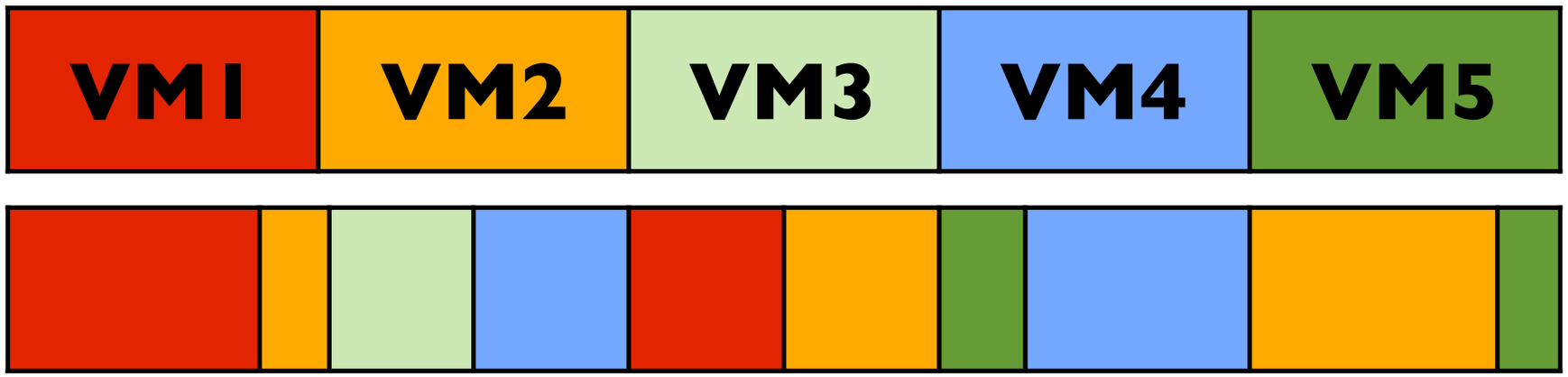
- With or without HW assist
- strong isolation
- greater performance than hosted, better scalability
- neg: needs drivers for all HW

Paravirtualization

- neg: VM is aware it is in a virtual environment (security)
- may be able to optimize b/c it knows it is virtual
- need to modify OS

Virtualizing Memory

System's memory must be shared by all VMs



How should we allocate memory to each VM?

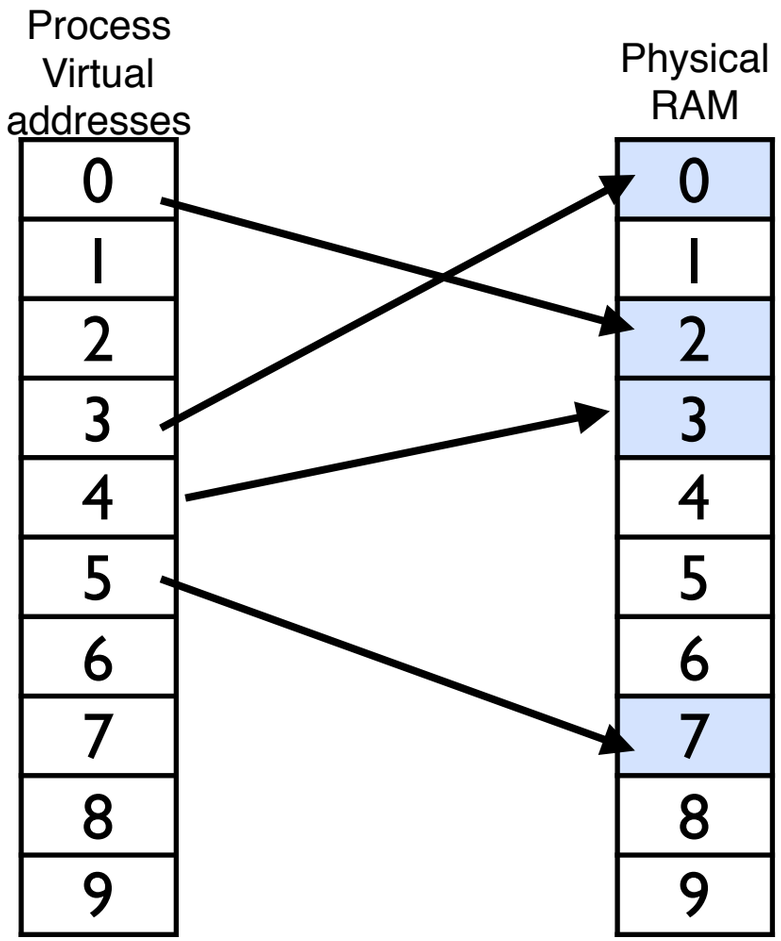
- Contiguous or non-contiguous?

Page tables let us use non-contiguous memory...

- Creating and modifying page tables uses privileged instructions!
- Guest does not even know the real physical addresses!

Page Tables

OS has page table for each process

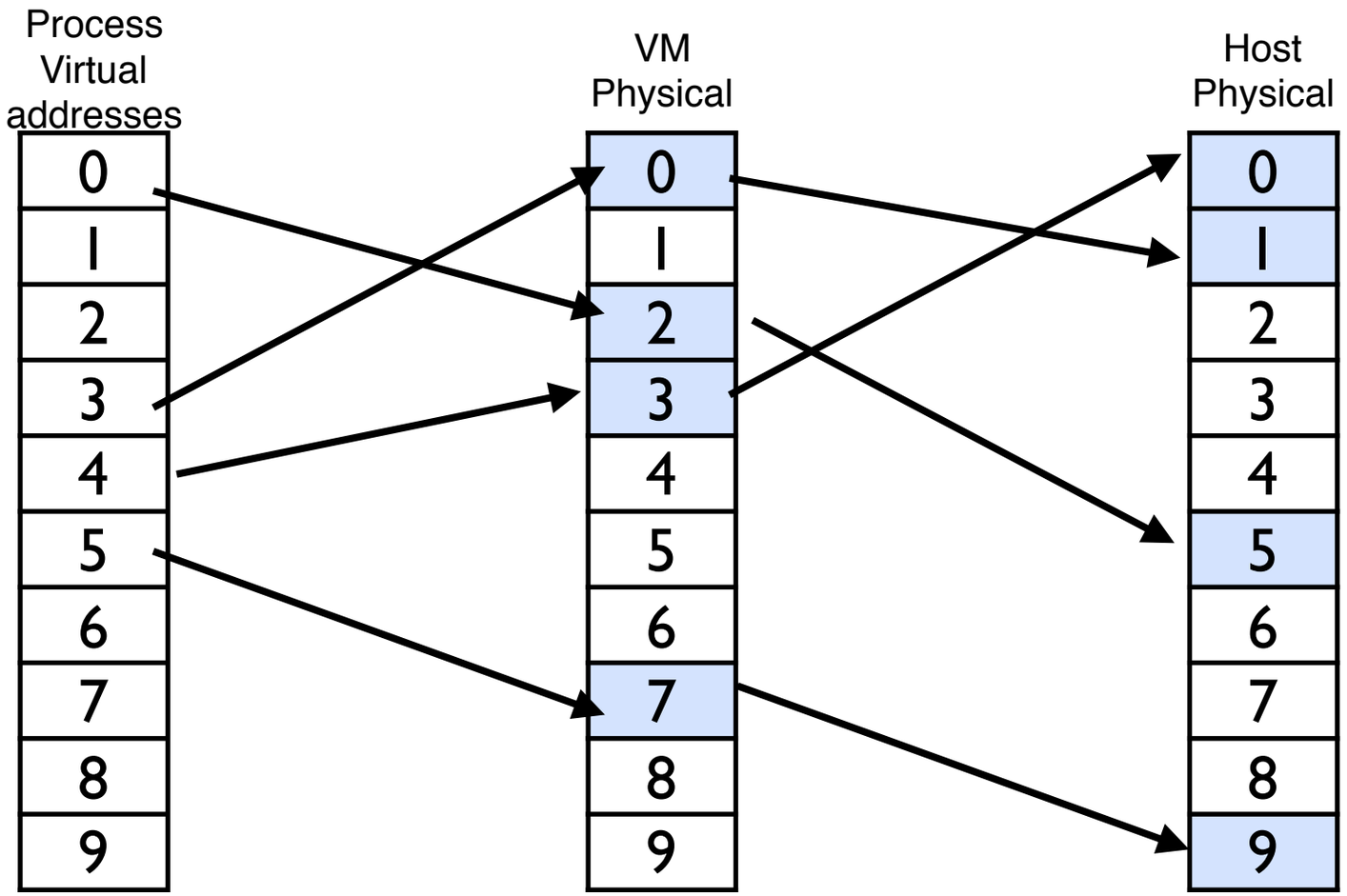


Virt Address	Physical RAM
0	2
1	-
2	-
3	0
4	3
5	7
6	-
7	-

Maps **virtual addresses** to **physical address**

Page Tables

We can do the same thing with VMs



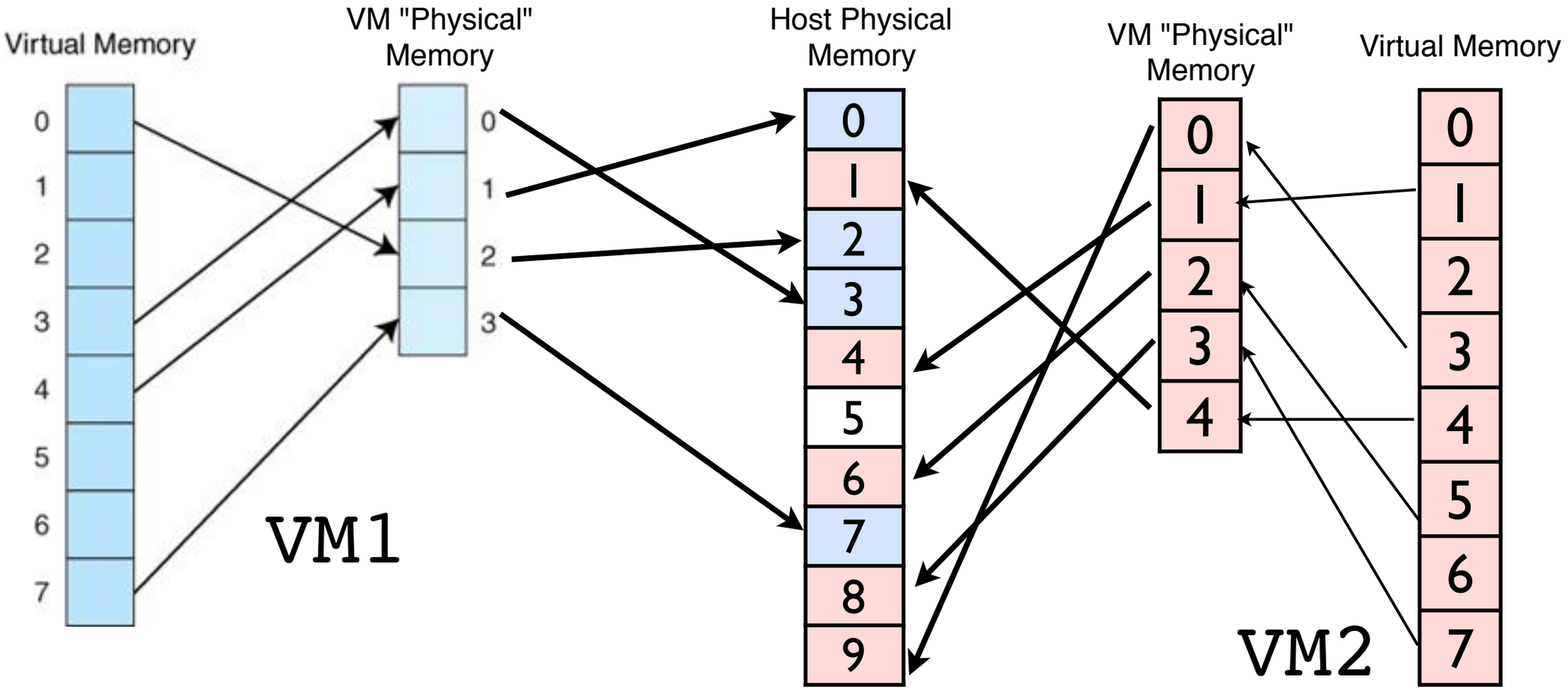
Virt Address	VM "Physical"	Physical RAM
0	2	5
1	-	-
2	-	-
3	0	1
4	3	0
5	7	9
6	-	-
7	-	

We need another layer of mappings

- Virtual Memory -> VM "Phys" Memory -> Host Phys Memory
- Only the hypervisor knows the true mapping to physical memory

Multiple VMs

Can extend this for multiple VMs



Virtualization layer manages mappings to ensure isolation between VMs and to allocate the right amount of resources to each one

Shadow Page Tables

Shadow Page Tables

- VM's OS thinks it has a regular PT
- Hypervisor adds another translation layer
- Keeps a "shadow" PT with the real mappings

What is the cost?

- of a memory access?
- of a page table update?

Virt Address	VM "Physical"	Host Physical
0	2	2
1	6	4
2	-	-

Virt Address	VM "Physical"
0	2
1	6
2	-

VM PT

Virt Address	Host Physical
0	2
1	4
2	-

Shadow PT

MMU / TLB use this

Containers

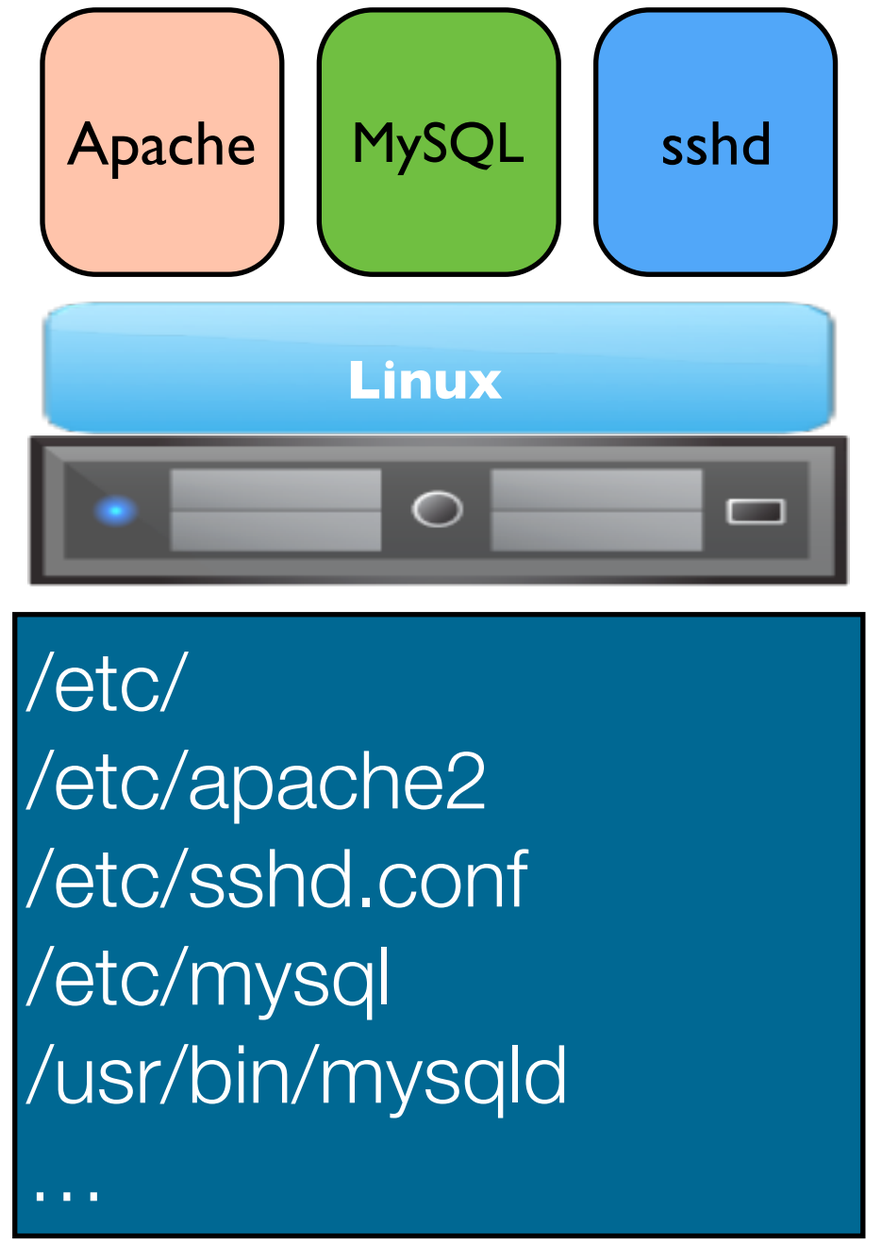
Lightweight virtualization

Process Isolation

Processes
- OS provides isolation

Isolated:
- Memory

Shared:
- File system
- Network
- Devices
- OS Kernel



Containers

Containers

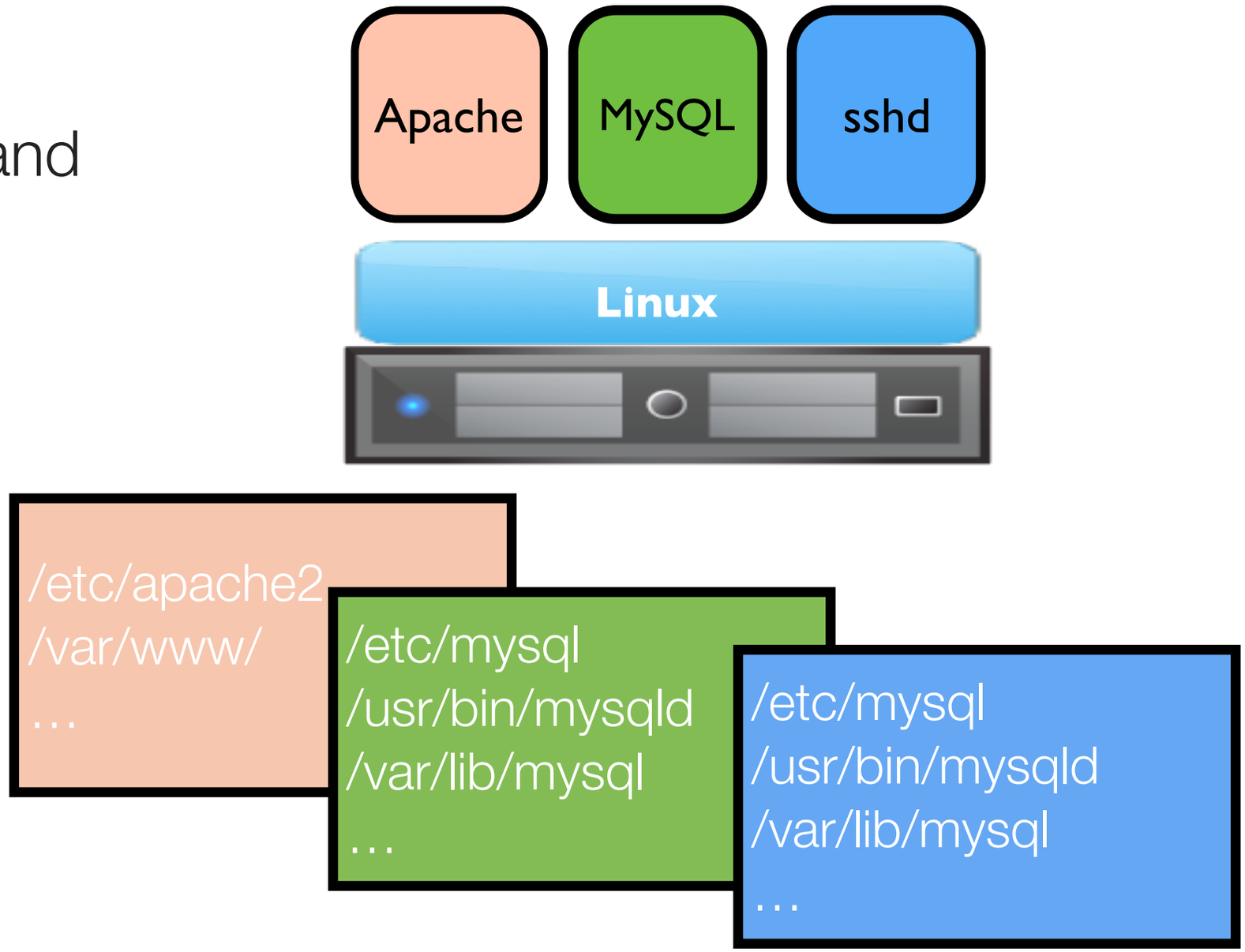
- Namespace-based isolation using LXC and cgroups

Isolated:

- Memory
- File system
- Network
- Devices

Shared:

- OS Kernel

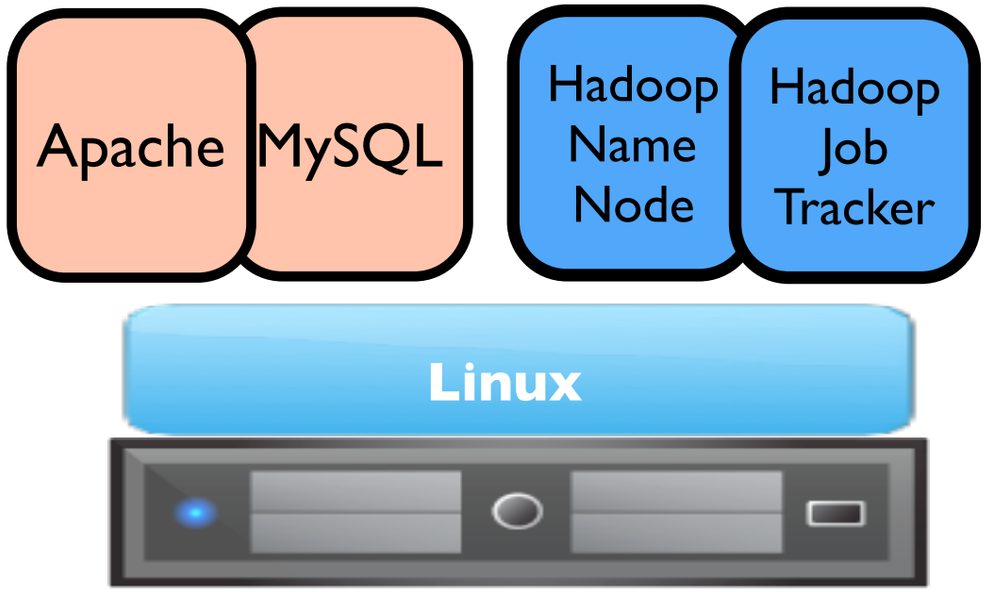


Containers

docker

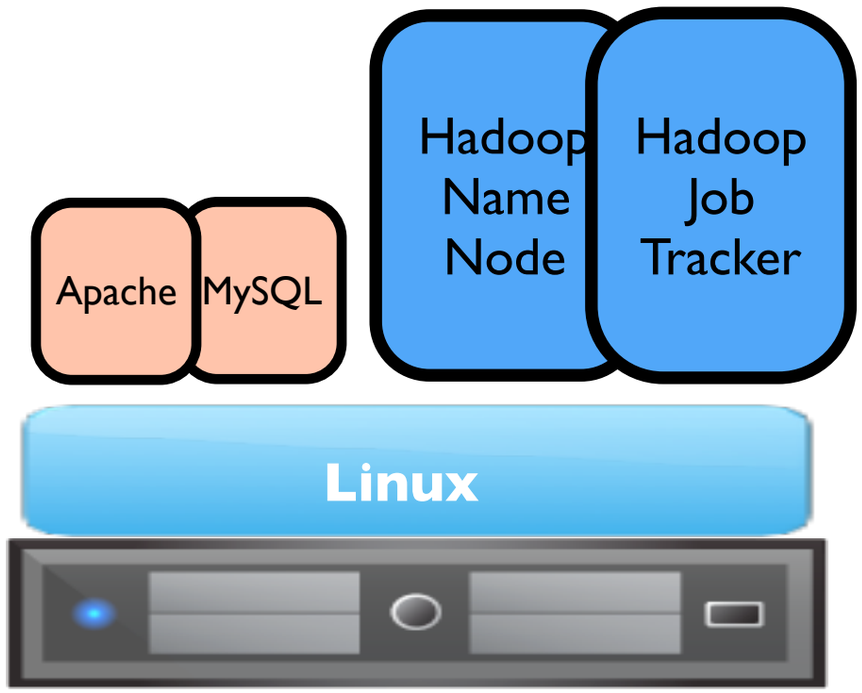
Multi-process containers

- Can run multiple processes in the same container group



Resources:

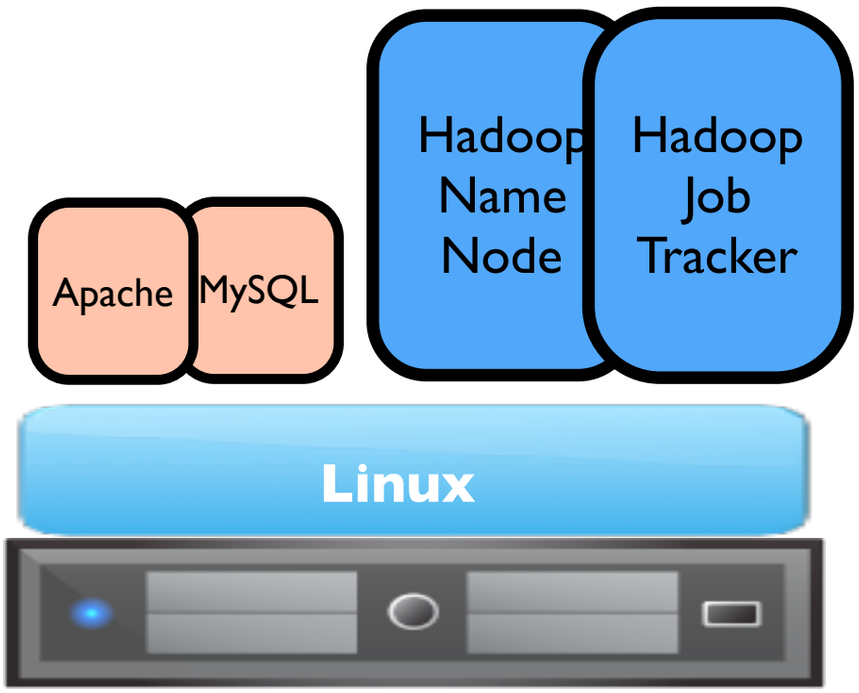
- Can assign CPU weights and memory limits for each group



Shared Kernel

Shared Kernel provides

- Page tables (memory)
- Scheduler (CPU)
- Networking stack
- File system virtualization



What's the difference between the linux kernel and a linux distribution?

- Linux kernel 4.13 vs Linux Kernel 3.5 vs Ubuntu 14.04 vs RedHat 7?

Distro vs Kernel

Kernel = core operating system functionality

- kernel 4.7

Distribution = collection of software and kernel

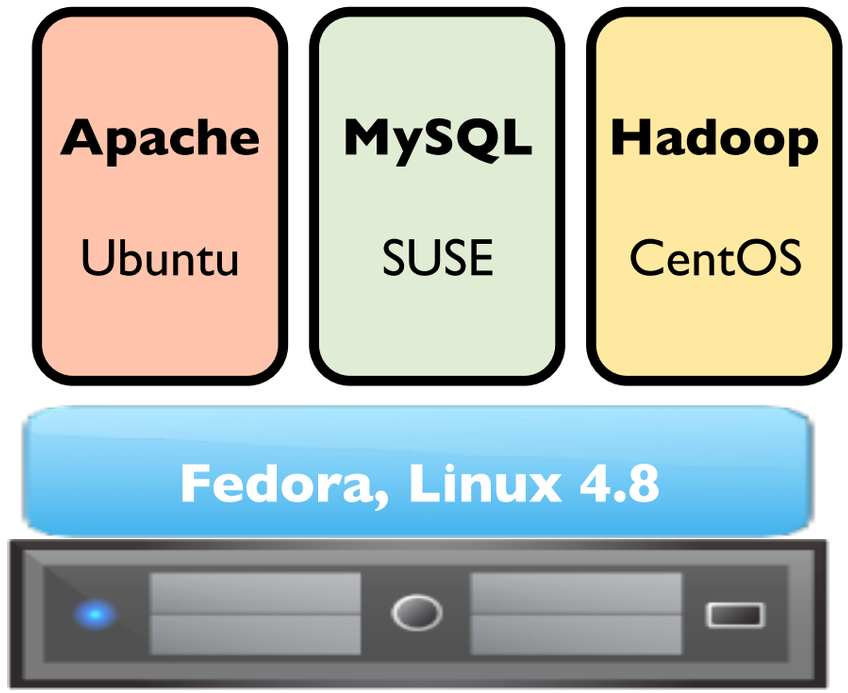
- Ubuntu, CentOS, RedHat

Distributions can work with many different kernels

Containers and Distros

Each container can have its own distribution

Must share the same host kernel



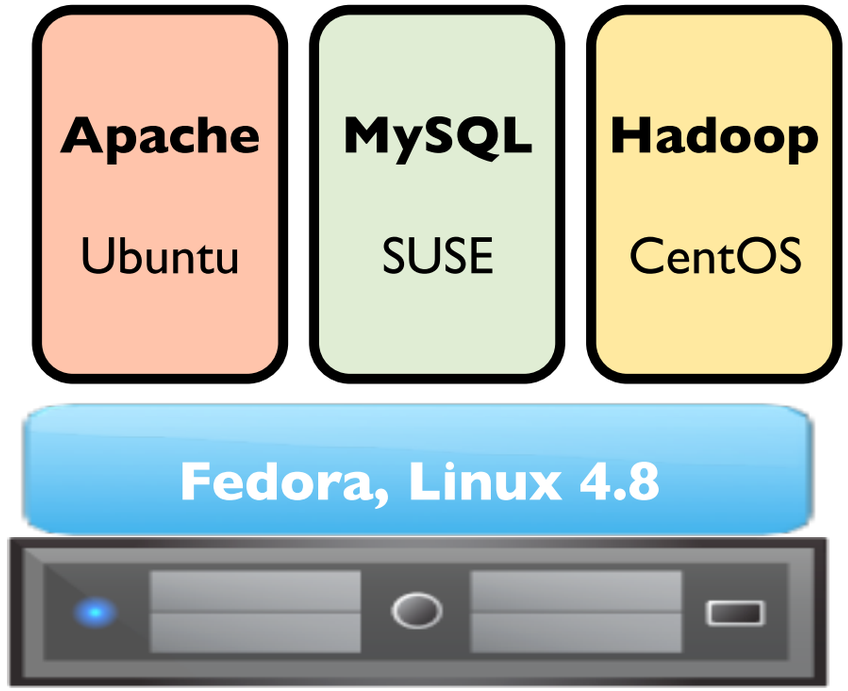
Container Packaging

Deployment - big benefit of containers/virtualization

- Lets you package up an application and all of its requirements
- Even the distribution and 3rd party utilities!
- Very helpful for system administrators

Container “image” includes:

- Linux distribution base files
- Dependency libs/utils
- Configuration files
- Application to run



Does not include…?

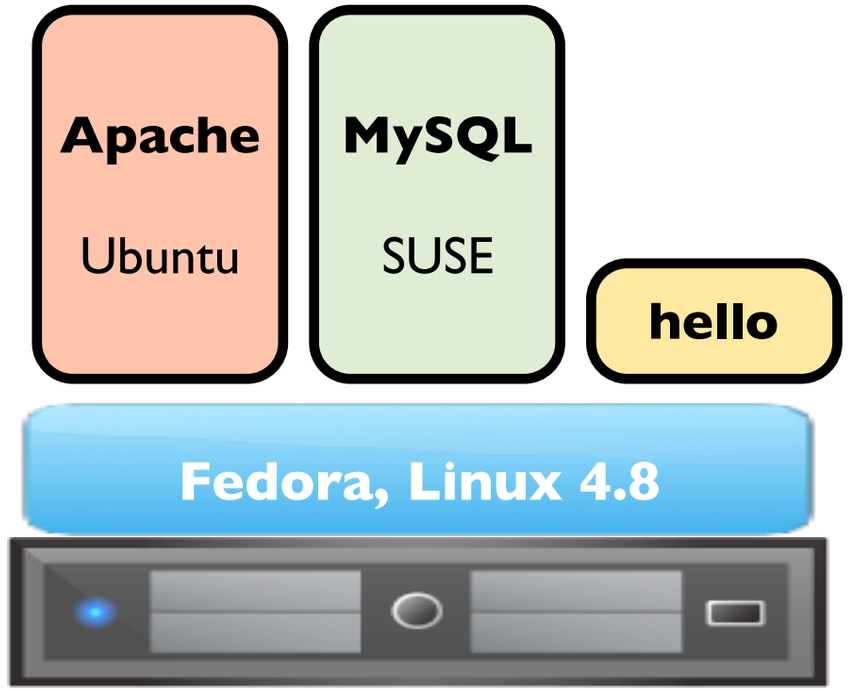
Container Packaging

Deployment - big benefit of containers/virtualization

- Lets you package up an application and all of its requirements
- Even the distribution and 3rd party utilities!
- Very helpful for system administrators

Container “image” includes:

- Linux distribution base files
- Dependency libs/utils
- Configuration files
- Application to run



Can inherit files/libraries from host to reduce size of the container package!

File System Virtualization

Container's file system is built by layering

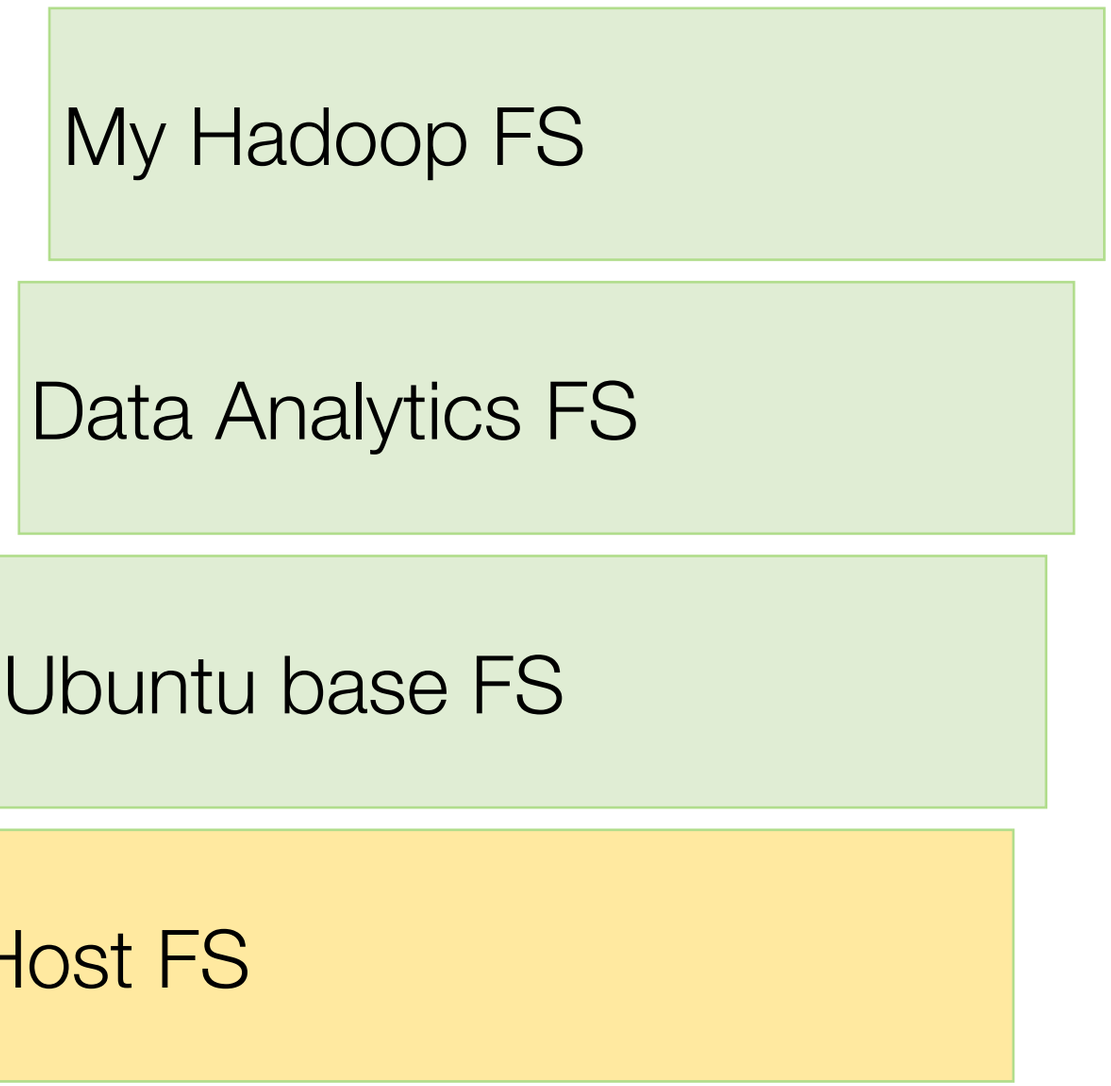
- Several containers can use the same FS layers

Read/Write

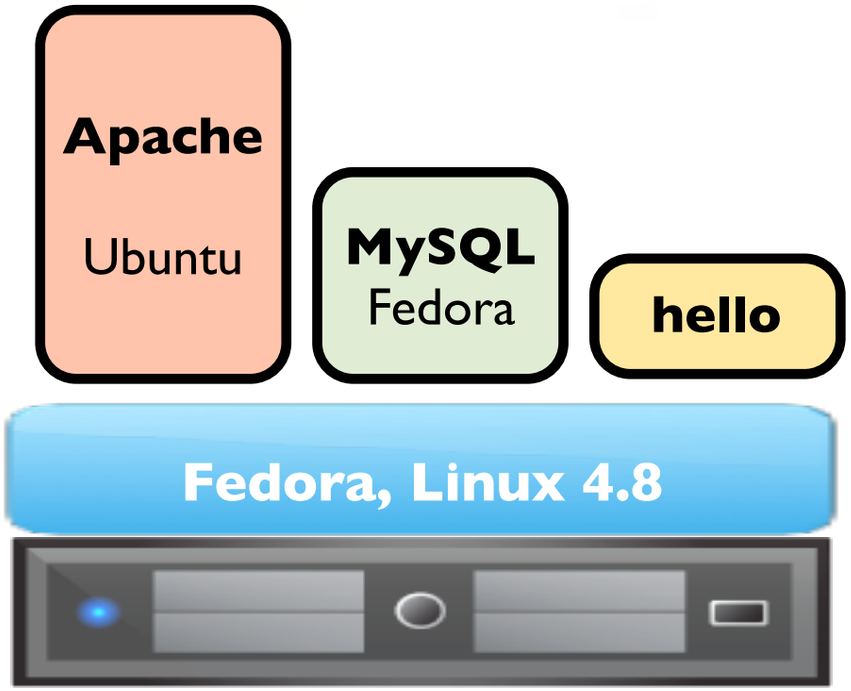
- Allow multiple containers to manipulate data on host FS

Copy on Write

- Each container thinks it has its own version of the FS
- Only duplicate the specific files (data blocks) that are written to

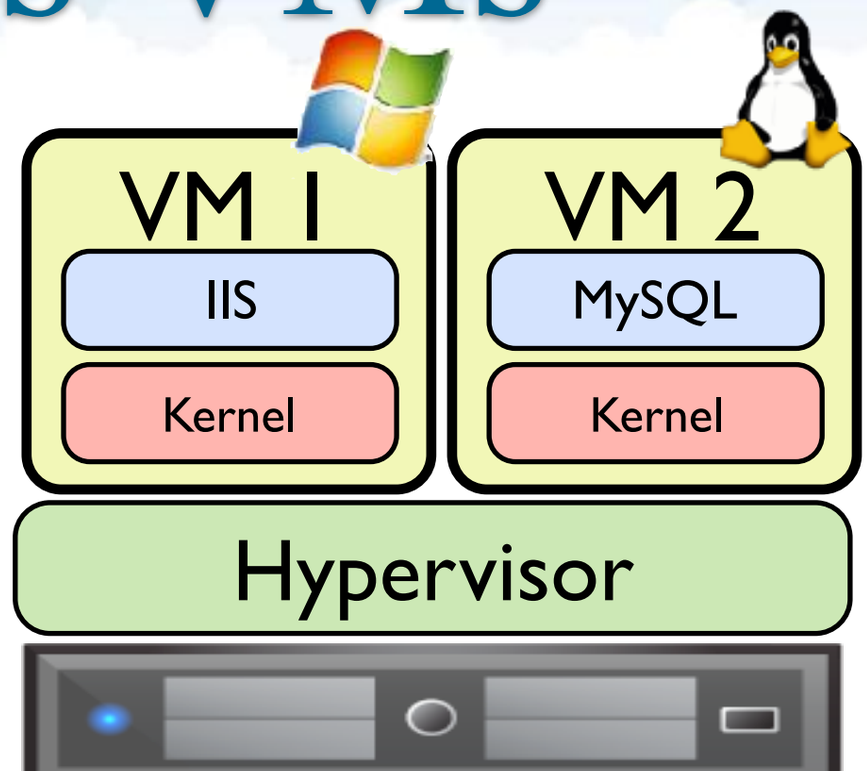


Container vs VMs



Pros:

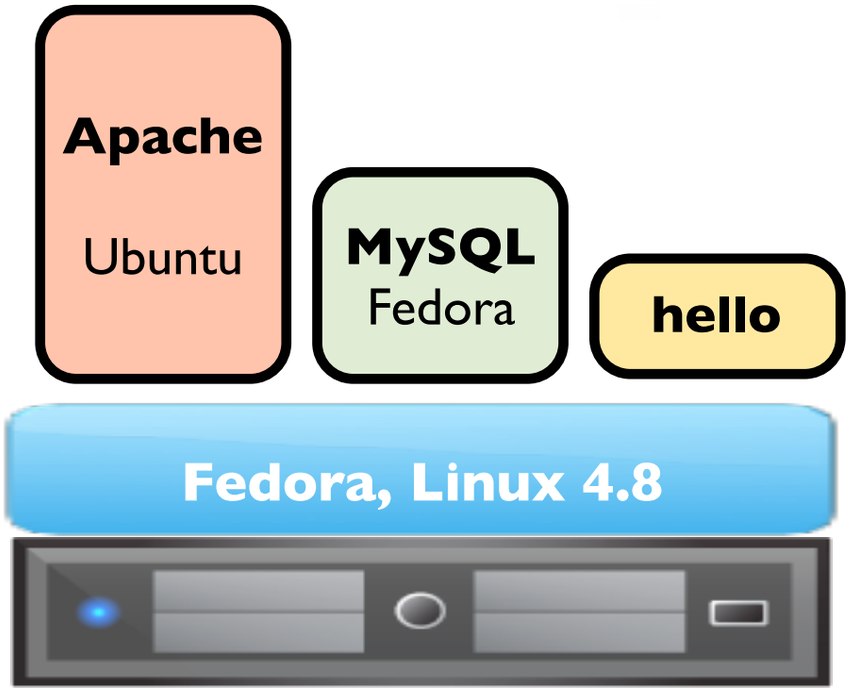
- lightweight (no duplication)
- less resource consumption
- easier to deploy
- specify resources just for application
- startup time



Pros:

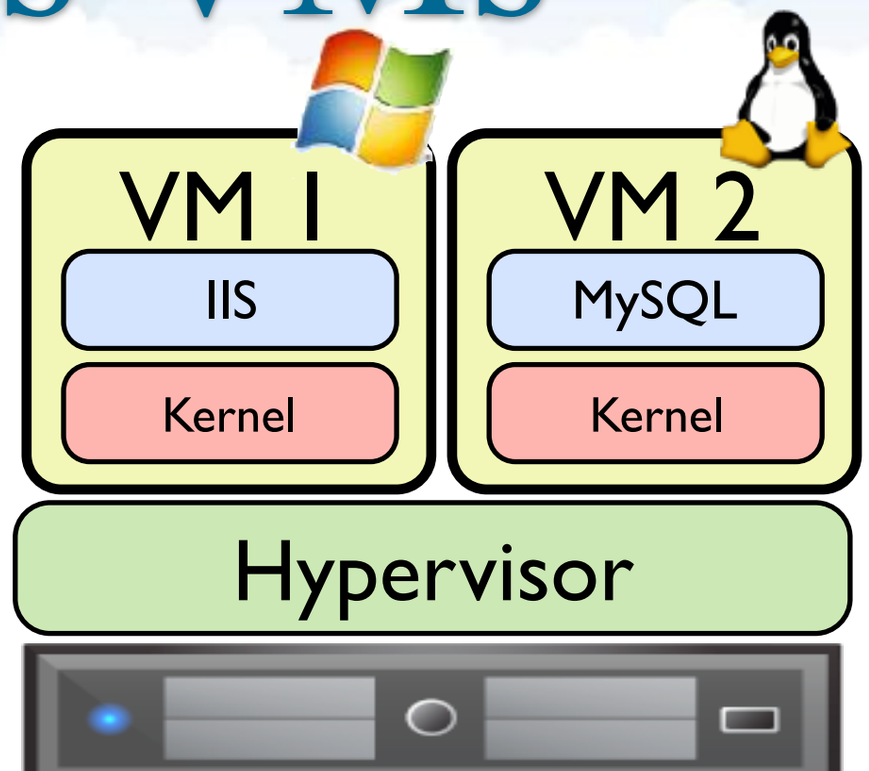
- stronger isolation
- different kernel versions/ OSes
- fault tolerance / isolation
- combine with containers

Container vs VMs



Pros:

- ???



Pros:

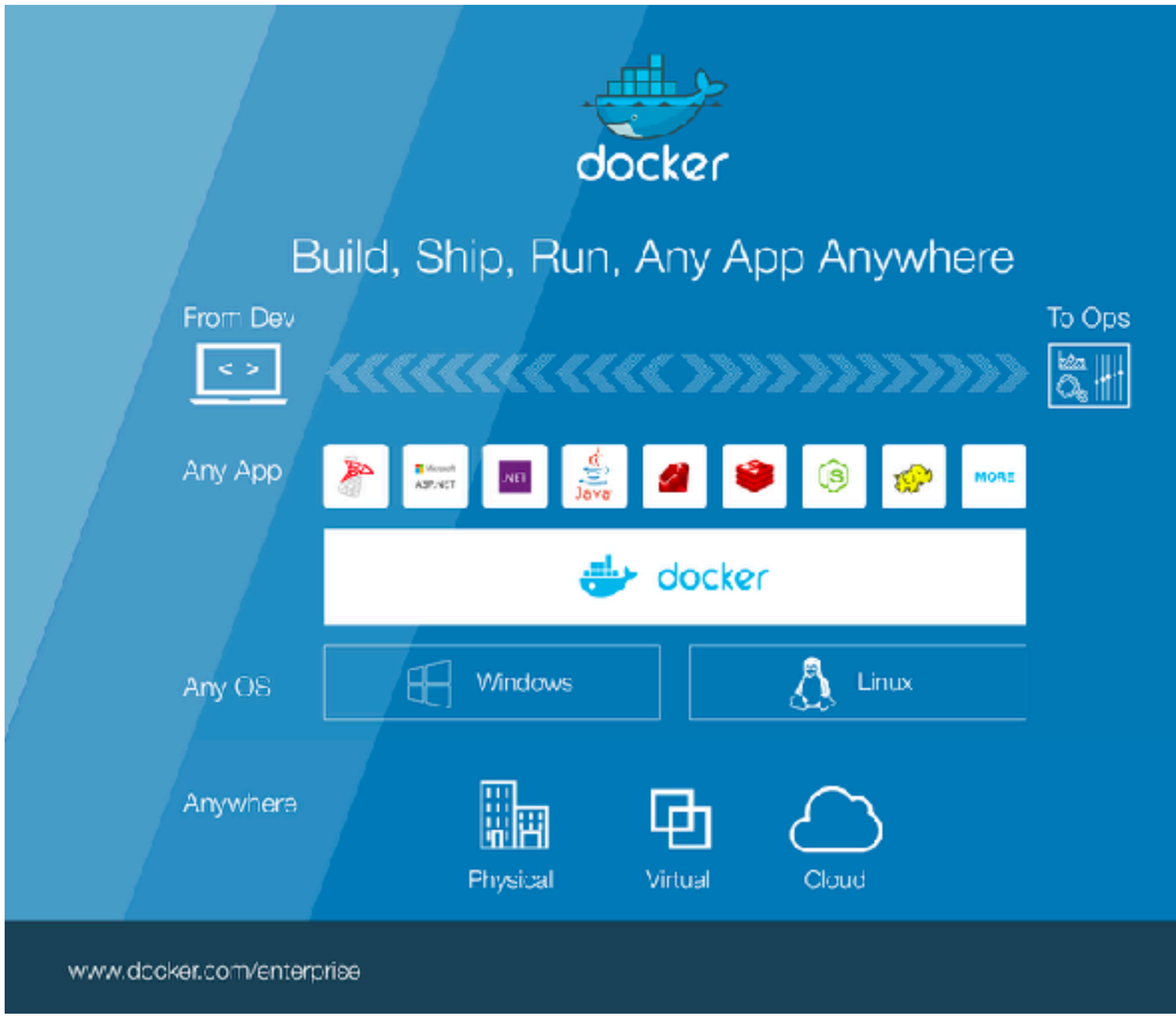
- ???

Containers + VMs

Containers can be combined with virtualization tools

Docker on Windows

- Lets you run windows containers using OS isolation tools
- Lets you run Linux containers by starting a linux VM automatically for you and dividing it up into containers



Distributed Systems Challenges?

Clouds, VMs, Containers

Challenges

Heterogeneity

Openness

Security

Failure Handling

Concurrency

Quality of Service

Scalability

Transparency

Challenges

Heterogeneity: *different HW, SW, workloads*

Openness: *interoperability, shared protocols*

Security: *confidentiality, integrity, availability*

Failure Handling: *crashes, bugs, malicious*

Concurrency: *parallelism, consistency*

Quality of Service: *latency, throughput*

Scalability: *performance gain with more resources*

Transparency: *abstraction layers, interfaces*

Challenges

Heterogeneity

Openness

Security

Failure Handling

Concurrency

Quality of Service

Scalability

Transparency

Clouds

- IaaS

- PaaS

- SaaS

Virtual Machines

Containers

Heterogeneity

Openness

Security

Failure Handling

Concurrency

Quality of Service

Scalability

Transparency

Sources

https://www.geekwire.com/2017/amazon-web-services-secret-weapon-custom-made-hardware-network/

https://perspectives.mvdirona.com/2010/09/overall-data-center-costs/

https://aws.amazon.com/ec2/pricing/on-demand/

https://aws.amazon.com/ec2/instance-types/

https://www.linkedin.com/pulse/20141118134543-2339144-the-cloud-is-amazon/

https://gist.github.com/stevenringo/108922d042c4647f2e195a98e668108a - reInvent 16

https://aws.amazon.com/compliance/data-center/data-centers/

https://www.zdnet.com/article/aws-cloud-computing-ops-data-centers-1-3-million-servers-creating-efficiency-flywheel/

https://www.bloomberg.com/news/2014-11-14/5-numbers-that-illustrate-the-mind-bending-size-of-amazon-s-cloud.html

https://youtu.be/AyOAjFNPAbA - reInvent 16 keynote