

TCSS 562:
SOFTWARE ENGINEERING
FOR CLOUD COMPUTING

Cloud Computing
Concepts and Models - II

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma



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OFFICE HOURS – FALL 2025

■ **Thursdays:**

■ 6:00 to 7:00 pm - CP 229 & Zoom

■ **Friday – *** THIS WEEK *****

■ 12:30 pm to 1:30 pm – ONLINE via Zoom

■ Or email for appointment

➢ Office Hours set based on Student Demographics survey feedback

➢ * - Friday office hours may be adjusted or canceled due meeting conflicts or other obligations. Adjustments will be announced via Canvas.

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OBJECTIVES – 10/23

■ **Questions from 10/21**

■ Tutorials Questions

■ Tutorial 4 - to be posted...

■ From: Cloud Computing Concepts, Technology & Architecture: Chapter 4: Cloud Computing Concepts and Models:

■ Cloud computing delivery models

■ Cloud deployment models

■ AWS Overview and demo

■ **2nd hour:**

■ Activity 2 - Intro to EC2

■ Term Project Planning

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ONLINE DAILY FEEDBACK SURVEY

■ Daily Feedback Quiz in Canvas – Take After Each Class

■ **1-point Extra Credit** for completing online

■ **2-points Extra Credit** for completing in-person in class

■ 36 points possible

■ 2.5% added to final course grade for (36/36)

Announcements

Assignments

Discussions

Zoom

Grades

People

Pages

Files

Quizzes

Collaborations

UW Libraries

UW Resources

Upcoming Assignments

Class Activity 1 – Implicit vs. Explicit Parallelism
Available until Oct 13 at 11:59pm | Due Oct 7 at 7:59pm | -15 pts

Tutorial 1 - Linux
Available until Oct 19 at 11:59pm | Due Oct 13 at 11:59pm | -20 pts

Past Assignments

TCSS 562 - Online Daily Feedback Survey - 10/5
Available until Dec 18 at 11:59pm | Due Oct 6 at 8:59pm | -15 pts

TCSS 562 - Online Daily Feedback Survey - 9/30
Available until Dec 18 at 11:59pm | Due Oct 4 at 8:59pm | -15 pts

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WARNING

■ DO NOT SUBMIT BOTH A PAPER AND AN ONLINE SURVEY OR YOU WILL LOOSE POINTS

■ CANVAS WILL AUTOMATICALLY REPLACE THE PAPER SURVEY SCORE (2 PTS) WITH THE ONLINE SURVEY (1 PT)

■ *** COMPLETE ONLY ONE SURVEY FOR EACH CLASS SESSION ***

■ WE WILL NOT BE ABLE TO DUPLICATE CHECK SURVEYS FOR EACH CLASS SESSION AND MAKE CORRECTIONS

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MATERIAL / PACE

■ Please classify your perspective on material covered in today's class (38 respondents, 26 in-person, 12 online):

■ ew, 10-mostly new

■ **Average – 7.32 (↑ - previous 7.00)**

■ Please rate the pace of today's class:

■ 1-slow, 5-just right, 10-fast

■ **Average – 5.24 (↓ - previous 5.44)**

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Slides by Wes J. Lloyd

L8.1

FEEDBACK FROM 10/23

- How liable is AWS to service failure like the one seen recently?
- The disruption on Monday was the largest I recall in several years. It is quite uncommon.

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FEEDBACK - 2

- What is CPU time share in the context of cloud computing?
- For every minute, each CPU core has 60 seconds of "time".
- The "time share" is the fraction of time allocated to a VM, microVM, or container for a given time interval (i.e. minute)
- Two users can simultaneously share the same CPU core with a 50% time share (30 seconds each for 1 minute)
- In reality, many users share the CPU cores of cloud servers, each owning a different fraction of time
- Scheduling: if a user owns 30 seconds of CPU time share, the hypervisor is responsible for scheduling this time on a physical CPU core
- Cloud VMs have virtual CPU cores, and hypervisors schedule their time on the shared physical cores of servers
- This way, many users can share an expensive cloud server simultaneously

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FEEDBACK - 3

- When working on tutorial 3, I created instance but didn't connect to it. After a while the instance was gone w/o any action. Is that normal?
- The AWS console shows there's no running instance and it can't find the instance created in "Instances" section
 - For spot instances, when the cloud region and instance type is in demand, it is typical that the instance can be reclaimed within a few hours to a day
 - The positive here is the charges stop, once the instance terminates

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FEEDBACK - 4

- How can the "garbage collection" of AWS Lambda function instances be avoided?
 - In 2018, working with a UWT MSCSS Capstone student, we wrote a paper that investigated alternatives to "keeping alive" function instances by pinging them at different intervals
 - Paper: https://faculty.washington.edu/wiloyd/papers/woso_camera_ready.pdf
 - Afterwards AWS Lambda introduced "provisioned concurrency".
 - Users can pay to keep a set number of function instances in the warm state.
- Charges for provision concurrency (x86_64 INTEL):
 - \$0.0000041667 for every GB-second (WARM)
 - \$0.0000097222 for every GB-second (COMPUTE - this is discounted)
- Example 100 function instances @ 1.5 GB for 8 hours:
 - 8 hours * 3600 seconds/hour = 28,800 seconds
 - 100 function instances * 1.5 GB = 150 GB
 - 150 GB * 28,800 seconds = 4,320,000 GB-seconds
 - 4,320,000 * \$0.0000041667 = \$18

BONUS: ON EC2, what is the 8-hr cost for an instance w/ 150GB & ~100 vCPUS?

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IN CLASS QUIZZES

- Anticipated dates
- Designed for 1 hour (starting at 4:40pm)
- Open notes & books
- Closed laptop, smartphone, neighbor
- No digital devices
- Quiz 1 - Thursday November 6
- Quiz 2 - Tuesday December 2

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TUTORIAL 2 – DUE OCT 21 (CLOSES OCT 25 AOE)

- Introduction to Bash Scripting
- https://faculty.washington.edu/wlloyd/courses/tcss562/tutorials/TCSS462_562_f2025_tutorial_2.pdf
- Review tutorial sections:
- Create a BASH webservice client
 1. What is a BASH script?
 2. Variables
 3. Input
 4. Arithmetic
 5. If Statements
 6. Loops
 7. Functions
 8. User Interface
- Call service to obtain IP address & lat/long of computer
- Call weatherbit.io API to obtain weather forecast for lat/long

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TUTORIAL 0

- Getting Started with AWS
- https://faculty.washington.edu/wlloyd/courses/tcss562/tutorials/TCSS462_562_f2025_tutorial_0.pdf
- Create an AWS account
- Create account credentials for working with the CLI
- Install awsconfig package
- Setup awsconfig for working with the AWS CLI

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TUTORIAL 3 – OCT 30 (TEAMS OF 2)

- Best Practices for Working with Virtual Machines on Amazon EC2
- https://faculty.washington.edu/wlloyd/courses/tcss562/tutorials/TCSS462_562_f2025_tutorial_3.pdf
- Creating a spot VM
- Creating an image from a running VM
- Persistent spot request
- Stopping (pausing) VMs
- EBS volume types
- Ephemeral disks (local disks)
- Mounting and formatting a disk
- Disk performance testing with Bonnie++
- Cost Saving Best Practices

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TUTORIAL 4 – TO BE POSTED (FRI?)

- Introduction to AWS Lambda with the Serverless Application Analytics Framework (SAAF)
- Obtaining a Java development environment
- Introduction to Maven build files for Java
- Create and Deploy "hello" Java AWS Lambda Function
 - Creation of API Gateway REST endpoint
- Sequential testing of "hello" AWS Lambda Function
 - API Gateway endpoint
 - AWS CLI Function Invocation
- Observing SAAF profiling output
- Parallel testing of "hello" AWS Lambda Function with faas_runner
- Performance analysis using faas_runner reports
- Two function pipeline development task

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CLOUD COMPUTING:
CONCEPTS AND MODELS



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CATCH UP – FROM 10/21

- Questions from 10/15
- Tutorials Questions
- Tutorial 4 – Intro to FaaS – AWS Lambda
- Background on AWS Lambda for the Term Project - II
- From: Cloud Computing Concepts, Technology & Architecture: Chapter 4: Cloud Computing Concepts and Models:**
 - Roles and boundaries**
 - Cloud characteristics
 - Cloud delivery models
 - Cloud deployment models
- Team Planning - Breakout Rooms

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ROLES

- Cloud provider**
 - Organization that provides cloud-based resources
 - Responsible for fulfilling SLAs for cloud services
 - Some cloud providers “resell” IT resources from other cloud providers
 - Example: Heroku sells PaaS services running atop of Amazon EC2
- Cloud consumers**
 - Cloud users that consume cloud services
- Cloud service owner**
 - Both cloud providers and cloud consumers can own cloud services
 - A cloud service owner may use a cloud provider to provide a cloud service (e.g. Heroku)

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ROLES - 2

- Cloud resource administrator**
 - Administrators provide and maintain cloud services
 - Both cloud providers and cloud consumers have administrators
- Cloud auditor**
 - Third-party which conducts independent assessments of cloud environments to ensure security, privacy, and performance.
 - Provides unbiased assessments
- Cloud brokers**
 - An intermediary between cloud consumers and cloud providers
 - Provides service aggregation
- Cloud carriers**
 - Network and telecommunication providers which provide network connectivity between cloud consumers and providers

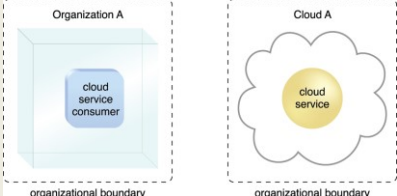
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ORGANIZATION BOUNDARY



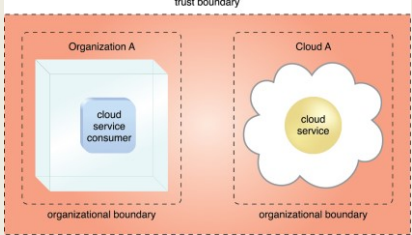
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TRUST BOUNDARY



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CLOUD CHARACTERISTICS

- On-demand usage
- Ubiquitous access
- Multitenancy (resource pooling)
- Elasticity
- Measured usage
- Resiliency

Assessing these features helps measure the value offered by a given cloud service or platform

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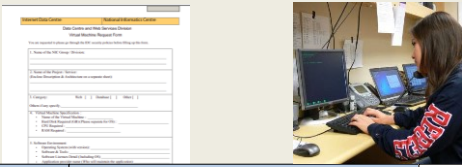
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ON-DEMAND USAGE

- The freedom to self-provision IT resources
- Generally, with automated support
- Automated support requires no human involvement
- Automation through software services interface



The image shows a screenshot of a cloud service interface on the left, displaying various service options and pricing. On the right, a person is seated at a desk, working on a laptop, illustrating the use of cloud services.

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UBIQUITOUS ACCESS

- Cloud services are widely accessible
- Public cloud: internet accessible
- Private cloud: throughout segments of a company's intranet
- 24/7 availability

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CLOUD CHARACTERISTICS

- On-demand usage
- Ubiquitous access
- Multitenancy (resource pooling)
- Elasticity
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Assessing these features helps measure the value offered by a given cloud service or platform

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MULTITENANCY

- Cloud providers pool resources together to share them with many users
- Serve multiple cloud service consumers
- IT resources can be dynamically assigned, reassigned based on demand
- Multitenancy can lead to performance variation

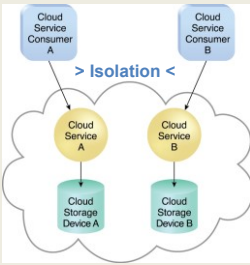
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SINGLE TENANT MODEL



The diagram illustrates the Single Tenant Model. It shows two separate paths for Cloud Service Consumer A and Cloud Service Consumer B. Each consumer is connected to its own Cloud Service (A and B) and Cloud Storage Device (A and B). The entire setup is enclosed in a cloud shape, with the word 'Isolation' written across the middle, indicating that resources are dedicated and isolated for each tenant.

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MULTITENANT MODEL

- Resource is "multiplexed" and share amongst multiple users
- Goal is to increase utilization
- Often server resources are underutilized
- There are many "sunk costs" whether usage is 0% or 100%
- Cloud computing tries to maximize "sunk cost" investments through **multi-tenancy**

Cloud Service Consumer A, Cloud Service Consumer B, Cloud Service A, Cloud Service B, shared cloud storage device

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MULTITENANT DATABASE

Isolated, Semi-shared, Shared, Tenant A, Tenant B, Tenant C, Separate database, Shared database, Separate schema, Shared schema, E1, E2, E3

- Many users on a single database instance
- What Issues may occur when sharing a single database Instance?**

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MULTITENANCY OF RESOURCES

- Where is the multitenancy?
- >> What is shared? What is isolated?

Traditional On Premise, Single Tenant (Hosted), Multi-Tenant, Virtual Appliance, Users, Customer, VPM, SSL, Application, Database, Server, Virtualization

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RESOURCE CONTENTION FROM MUTLI-TENANCY

- Despite best efforts at isolation, co-resident VMs on a single cloud server running identical benchmarks simultaneously do not perform equally.

Percentage Change, VM Tenants, sysbench (CPU), y-cruncher (CPU), pgbench (CPU + I/O), iperf (network I/O), Up to 48 VMs sharing same server !!

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RESOURCE CONTENTION FROM MUTLI-TENANCY - 2

- Performance variation from multi-tenancy is increasing as cloud servers add more CPU cores
- Running many idle operating system instances can impose significant overhead for some workloads

total performance variance (%), EC2 Instance family, iperf (network), pgbench (CPU + I/O), sysbench (CPU), y-cruncher (CPU), c3, c4, z1d, m5d (t)

Maximum potential resource contention (i.e. worst-case scenario) →

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ELASTICITY

- Automated ability of cloud to transparently scale resources
- Scaling based on runtime conditions or pre-determined by cloud consumer or cloud provider
- Threshold based scaling
 - CPU-utilization > threshold_A, Response_time > 100ms
 - Application agnostic vs. application specific thresholds
 - Why might an application agnostic threshold be non-ideal?
- Load prediction
 - Historical models
 - Real-time trends

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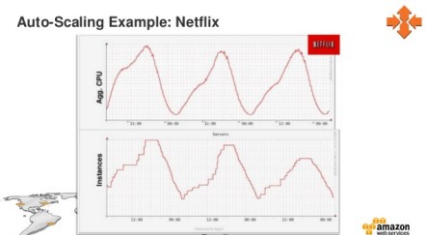
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PREDICTABLE DEMAND

AWS EC2 Scaling Example:

Auto-Scaling Example: Netflix



From Katerndahl, B. 2019.3 March. Techniques for scaling cloud footprint. In 2019 IEEE Int. Conf. on Cloud Engineering (IC2E), pp. 258-266.

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MEASURED USAGE

Cloud platform tracks usage of IT resources

For billing purposes

Enables charging only for IT resources actually used

Can be time-based (millisec, second, minute, hour, day)

- Granularity is increasing...

Can be throughput-based (data transfer: MB/sec, GB/sec)

Can be resource/reservation based (vCPU/hr, GB/hr)

Not all measurements are for billing

Some measurements can support auto-scaling

For example CPU utilization

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EC2 CLOUDWATCH METRICS

EC2 Instances: i-12670377

Description

Monitoring

Tags

Graphs are for 1 instance that has monitoring enabled. Times are displayed in UTC.

Time Range: Last Hour

Refresh

Avg CPU Utilization (Percent)

Avg Disk Reads (Bytes)

Avg Disk Writes (Bytes)

Max Network In (Bytes)

Max Network Out (Bytes)



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EC2 CLOUDWATCH METRICS

CPU Utilization (Percent)

Disk Reads (Bytes)

Disk Read Operations (Operations)

Disk Writes (Bytes)

Disk Write Operations (Operations)

Network In (Bytes)

Network Out (Bytes)

Network Packets In (Count)



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RESILIENCY

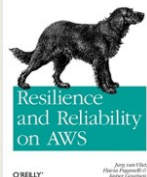
Distributed redundancy across physical locations (regions on AWS)

Used to improve reliability and availability of cloud-hosted applications

Very much an engineering problem

No "resiliency-as-a-service" for user deployed apps

Unique characteristics of user applications make a one-size fits all service solution challenging



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Elasticity is often provided using threshold based scaling. When can threshold based scaling (i.e. CPU utilization > 80%) under or over provision resources?

When the application is primarily I/O bound, a CPU threshold may never be met, or be met too late to scale up.

When the current resource utilization does not reflect future system demand.

When the current resource utilization (e.g. CPU) is temporarily increased as a result of external factors (i.e. resource contention from other tasks) that does not correlate to system demand.

When an application will soon complete a parallel phase, before executing a largely sequential phase.

All of the above

A

B

C

D

E

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L10.4

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When poll is active, respond at polllev.com/wesleylloyd641
Text **WESLEYLLOYD641** to **22333** once to join

W The scaling threshold of "when CPU utilization > 80% scale up", is:

An application specific threshold

An application agnostic threshold

Start the presentation to see live content. For screen share software, share the entire screen. Get help at polllev.com/app

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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS)**
- Platform-as-a-Service (PaaS)
- Software-as-a-Service (SaaS)

Serverless Computing:

- Function-as-a-Service (FaaS)
- Container-as-a-Service (CaaS)
- Other Delivery Models

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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS) delivery model
- Virtualization is a key-enabling technology of IaaS cloud
- Uses virtual machines to deliver cloud resources to end users

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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS) delivery model
- Virtualization is key to sharing powerful servers among users by running *many* isolated private virtual computers known as virtual machines (VMs)
...VMs are the basis of cloud v1.0

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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS) delivery model
- Virtual Machines are the building blocks for "Cloud Service Delivery Models"
They are the "vehicles" used to deliver compute resources to end users...
cloud 1.0

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CLOUD COMPUTING DELIVERY MODELS

- What is the appropriate level of **abstraction**?
- How should applications be deployed?
 - IaaS, PaaS, SaaS, DbaaS, FaaS
- How do we ensure Quality-of-Service?
 - Performance, Availability, Responsiveness, Fault Tolerance
- How is **scalability** provided?
- As users, how do we minimize hosting costs?
 - How do we estimate hosting costs?

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CLASSIC CLOUD COMPUTING DELIVERY MODELS

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LS.50

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CLASSIC CLOUD COMPUTING DELIVERY MODELS

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EXAMPLE CLOUD SERVICES

SaaS Software as a Service	PaaS Platform as a Service	IaaS Infrastructure as a Service
Email CRM Collaborative ERP	Application Development Decision Support Web Streaming	Caching Legacy Networking File Technical Security System Mgmt
CONSUME	BUILD ON IT	MIGRATE TO IT

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END USER APPLICATIONS

Many different "cloud" providers (especially SaaS)

Many cloud providers are also cloud consumers

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INFRASTRUCTURE-AS-A-SERVICE

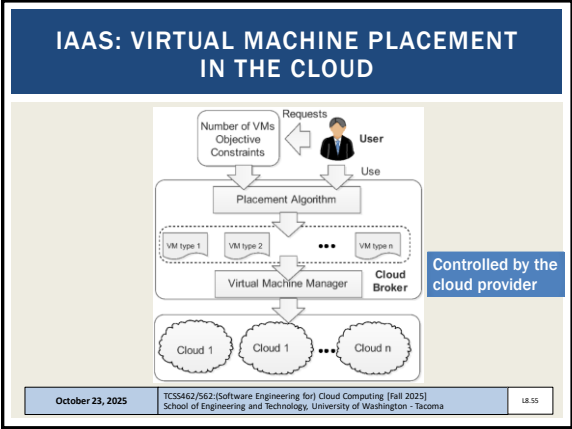
- Compute resources, on demand, as-a-service
 - Generally raw "IT" resources
 - Hardware, network, containers, operating systems
- Typically provided through virtualization
- Generally, not-preconfigured
- Administrative burden is owned by cloud consumer
- Best when high-level control over environment is needed
- Scaling is generally **not** automatic...
- Resources can be managed in bundles
- AWS CloudFormation**: Scripts to specify creation of cloud infrastructures using JSON/YAML for app deployment

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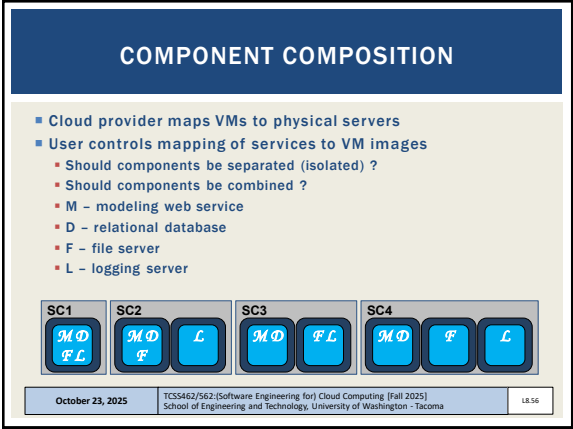
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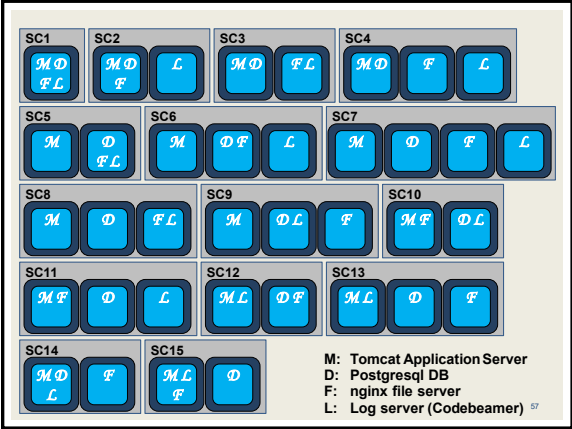
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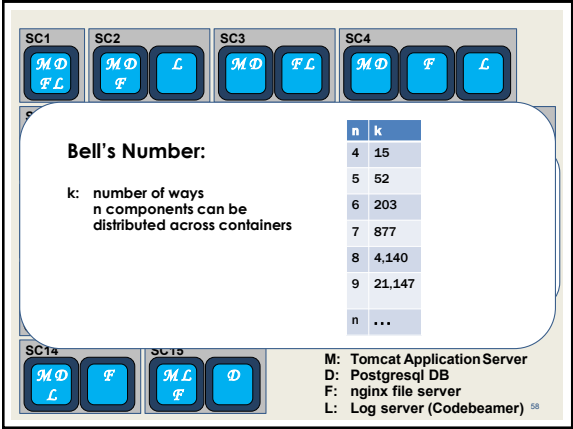
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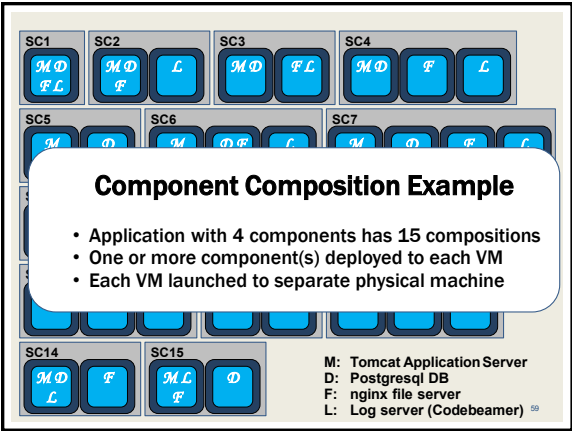
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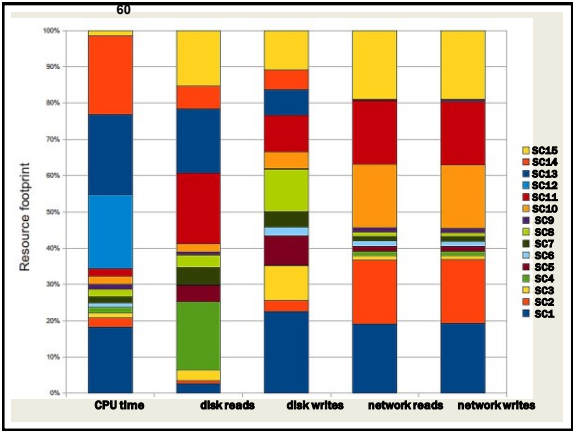
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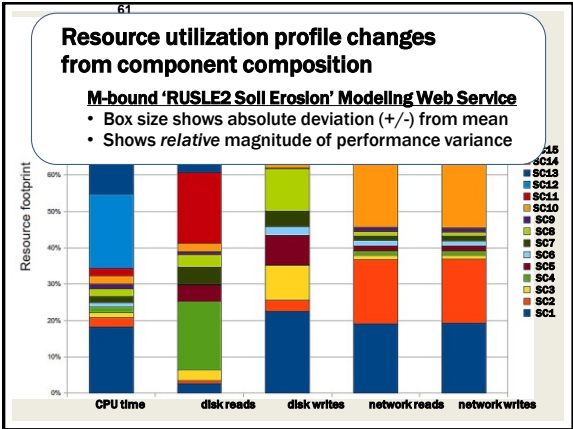
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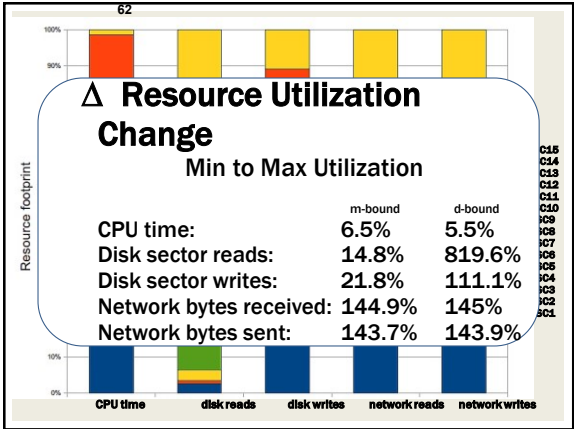
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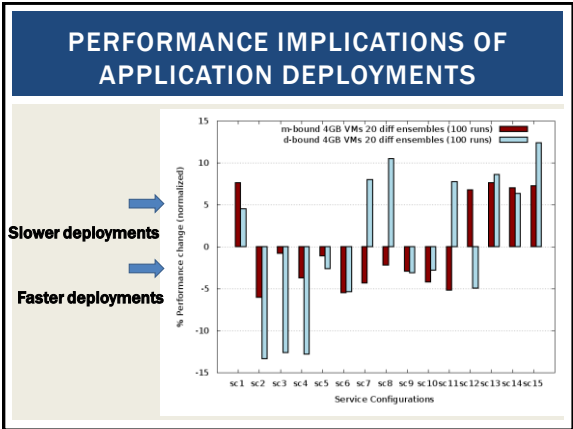
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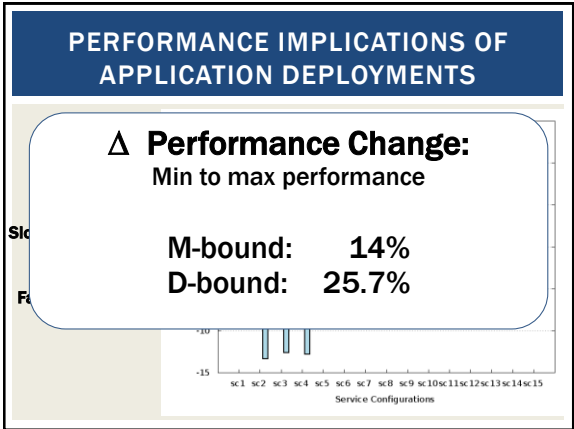
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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS)
- Platform-as-a-Service (PaaS)
- Software-as-a-Service (SaaS)

Serverless Computing:

- Function-as-a-Service (FaaS)
- Container-as-a-Service (CaaS)
- Other Delivery Models

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PLATFORM-AS-A-SERVICE

- Predefined, ready-to-use, hosting environment
- Infrastructure is further obscured from end user
- Scaling and load balancing may be automatically provided and automatic
- Variable to no ability to influence responsiveness

Examples:

- Google App Engine
- Heroku
- AWS Elastic Beanstalk
- AWS Lambda (FaaS)

Clients Load Balancer Servers

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USES FOR PAAS

- Cloud consumer
 - Wants to extend on-premise environments into the cloud for "web app" hosting
 - Wants to entirely substitute an on-premise hosting environment
 - Cloud consumer wants to become a cloud provider and deploy its own cloud services to external users
- PaaS spares IT administrative burden compared to IaaS

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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS)
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SOFTWARE-AS-A-SERVICE

- Software applications as shared cloud service
- Nearly all server infrastructure management is abstracted away from the user
- Software is generally configurable
- SaaS can be a complete GUI/UI based environment
- Or UI-free (database-as-a-service)
- SaaS offerings
 - Google Docs
 - Office 365
 - Cloud9 Integrated Development Environment
 - Salesforce

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CLOUD COMPUTING DELIVERY MODELS

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- Platform-as-a-Service (PaaS)
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SERVERLESS COMPUTING

Introducing Cloud 2.0

Serverless Computing

Deploy Applications Without Fiddling With Servers

Image from <https://mcbssoftfotech.com/resources/blog/serverless-computing-deploy-applications-without-fiddling-with-servers/>

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SERVERLESS COMPUTING

How should my app
without a server **fail**?

How can I tell if a
server has been
compromised?

How can I increase
utilization of my servers?

Which **OS** should my
servers run?

How much remaining
security do my servers have?

How should I implement dynamic
configuration changes on my servers?

How will I keep my server
OS patched?

How can I control
access from my servers?

How will new code be
deployed to my servers?

What size server is
right for my **performance**?

How many users create
too much load for my servers?

How many servers
should I budget for?

When should I decide to
scale out my servers?

Which packages should
be baked into my **server images**?

What **size** servers are
right for my budget?

How will the application
handle server **hardware failure**?

Which users should have
access to my servers?

Should I **turn OS settings**
to optimize my application?

Servers
(AAHHHHHHHHH!)

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SERVERLESS COMPUTING

What is
serverless?

Build and run applications
without thinking about servers



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amazon
aws

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SERVERLESS COMPUTING - 2

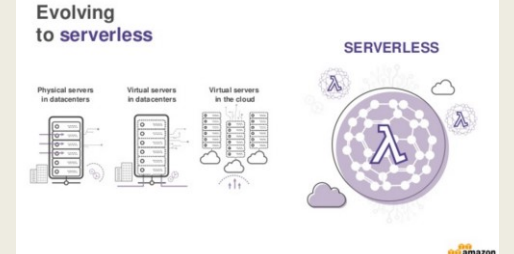
Evolving
to **serverless**

Physical servers
in datacenters

Virtual servers
in datacenters

Virtual servers
in the cloud

SERVERLESS



amazon
aws

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SERVERLESS COMPUTING

Pay only for
CPU/memory utilization

High Availability

Fault Tolerance

Infrastructure Elasticity

No Setup

Function-as-a-Service
(FAAS)

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SERVERLESS COMPUTING

Why Serverless Computing?

Many features of distributed systems,
that are challenging to deliver, are
provided automatically

...they are built into the platform

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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS)
- Platform-as-a-Service (PaaS)
- Software-as-a-Service (SaaS)

Serverless Computing:

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SERVERLESS VS. FAAS

- **Serverless Computing**
- Refers to the avoidance of managing servers
- Can pertain to a number of "as-a-service" cloud offerings
- **Function-as-a-Service (FaaS)**
 - Developers write small code snippets (microservices) which are deployed separately
- **Database-as-a-Service (DBaaS)**
- **Container-as-a-Service (CaaS)**
- Others...
- Serverless is a buzzword
- This space is evolving...

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FAAS PLATFORMS

```
graph LR
    subgraph Commercial
        AWS[AWS Lambda]
        Azure[Azure Functions]
        IBM[IBM Cloud Functions]
        Google[Google Cloud Functions]
    end
    subgraph OpenSource
        Apache[Apache OpenWhisk]
        Fn[Fn Oracle]
    end
```

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AWS LAMBDA

Using AWS Lambda

Bring your own code

- Node.js, Java, Python, C#
- Bring your own libraries (even native ones)

Simple resource model

- Select power rating from 128 MB to 3 GB
- CPU and network allocated proportionately

Flexible use

- Synchronous or asynchronous
- Integrated with other AWS services

Flexible authorization

- Securely grant access to resources and VPCs
- Fine-grained control for invoking your functions

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FAAS PLATFORMS - 2

- New cloud platform for hosting application code
- Every cloud vendor provides their own:
 - AWS Lambda, Azure Functions, Google Cloud Functions, IBM OpenWhisk
- Similar to platform-as-a-service
- Replace opensource web container (e.g. Apache Tomcat) with abstracted vendor-provided **black-box** environment

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FAAS PLATFORMS - 3

- Many challenging features of distributed systems are provided automatically
- **Built Into the platform:**
- Highly availability (24/7)
- Scalability
- Fault tolerance

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CLOUD NATIVE SOFTWARE ARCHITECTURE

- Every service with a different pricing model

```
graph LR
    S3[S3] --> User[User clicks on link to get local weather information]
    User --> API[API GATEWAY]
    API --> Lambda[Lambda is triggered]
    Lambda --> DynamoDB[DYNAMODB]
    DynamoDB --> User
```

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IAAS BILLING MODELS

- Virtual machines as-a-service at \$ per hour
- No premium to scale:
$$= \frac{1000 \text{ computers}}{1 \text{ computer}} @ \frac{1 \text{ hour}}{1000 \text{ hours}}$$
- Illusion of infinite scalability to cloud user
- As many computers as you can afford
- Billing models are becoming increasingly granular
 - By the minute, second, 1/10th sec
- Auction-based instances:
Spot instances →



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PRICING OBFUSCATION

- VM pricing:** hourly rental pricing, billed to nearest second is intuitive...
- FaaS pricing:** non-intuitive pricing policies
- FREE TIER:**
first 1,000,000 function calls/month → FREE
first 400,000 GB-sec/month → FREE
- Afterwards:** obfuscated pricing (AWS Lambda):
\$0.0000002 per request
\$0.00000208 to rent 128MB / 100-ms
\$0.00001667 GB / second

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WEBSERVICE HOSTING EXAMPLE

- ON AWS Lambda**
- Each service call: 100% of 2 CPU-cores
100% of 4GB of memory
- Workload: uses 2 continuous threads
- Duration: 1 month (30.41667 days)
- ON AWS EC2:** Amazon EC2 c5.large 2-vCPU VM x 4GB
- c5.large: 8.5\$/hour, 24 hrs/day x 30.41667 days
- Hosting cost: \$62.05/month
- How much would hosting this workload cost on AWS Lambda?**

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PRICING OBFUSCATION

Assume 1 month = 30.41667 days (365d / 12)

- Workload: (4 GB) 10,512,000 GB-sec
- Worst-case FaaS scenario = ~2.72x !**
- AWS EC2: \$62.05
- AWS Lambda: \$168.91
- Break Even: 3,702,459 GB-sec
@4GB ~10.71 days
- BREAK-EVEN POINT: \$62.05 - \$0.33 (calls) = \$61.72**
\$61.72 / .00001667 GB-sec = ~3,702,459 GB-sec-mon / 4GB/call =
~925,614 sec or ~10.71 days
Point at which using FaaS costs the same as IaaS

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FAAS PRICING

- Break-even point is the point where renting VMs or deploying to a serverless platform (e.g. Lambda) is exactly the same.
- Our example is for one month
- Could also consider one day, one hour, one minute
- What factors influence the break-even point for an application running on AWS Lambda?**

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FAAS CHALLENGES

- Vendor architectural lock-in – how to migrate?
- Pricing obfuscation – is it cost effective?
- Memory reservation – how much to reserve?
- Service composition – how to compose software?
- Infrastructure freeze/thaw cycle – how to avoid?
- Performance – what will it be?

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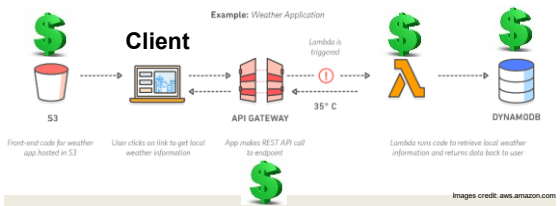
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VENDOR ARCHITECTURAL LOCK-IN

- Cloud native (FaaS) software architecture requires external services/components



- Increased dependencies → increased hosting costs

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PRICING OBFUSCATION

- VM pricing:** hourly rental pricing, billed to nearest second is intuitive...

- FaaS pricing:**

AWS Lambda Pricing

- FREE TIER:** first 1,000,000 function calls/month → FREE
first 400,000 GB-sec/month → FREE

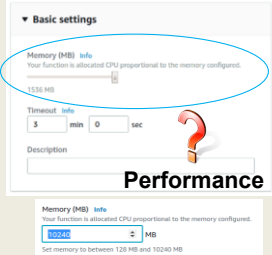
- Afterwards:** \$0.0000002 per request
\$0.00000208 to rent 128MB / 100-ms

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MEMORY RESERVATION QUESTION...

- Lambda memory reserved for functions
- UI provides text box formerly "slider bar" to set function's memory
- Resource capacity (CPU, disk, network) coupled to slider bar: "every doubling of memory, doubles CPU..."

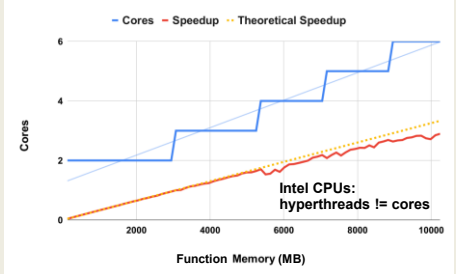


- But how much memory do FaaS functions require?

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AWS LAMBDA COUPLES FUNCTION MEMORY TO CPU CORES & TIME SHARE

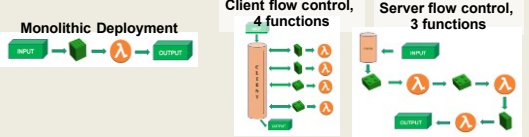


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SERVICE COMPOSITION

- How should application code be composed for deployment to serverless computing platforms?



- Recommended practice: Decompose into many microservices
- Platform limits: code + libraries ~250MB
- How does composition Impact the number of function invocations, and memory utilization?

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INFRASTRUCTURE FREEZE/THAW CYCLE

- Unused infrastructure is deprecated
 - But after how long? (varies by platform)
- Infrastructure: microVMs (on AWS Lambda), containers on some platforms
- COLD**
 - Code image - built/transferred to physical host & cached
- WARM**
 - Host has local code cache - create function instance (microVM) on host
- HOT**
 - Function instance ready to use

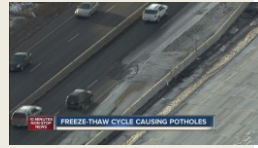


Image from: Denier7 - The Denier Channel News

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AWS LAMBDA - FREEZE/THAW

- Experiment: 50 concurrent calls, 5 or 10-min calling interval
- Evaluate % cold function instances

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FACTORS IMPACTING PERFORMANCE OF FAAS COMPUTING PLATFORMS

- Infrastructure scaling/elasticity
- Resource contention (CPU, network, memory caches)
- Hardware heterogeneity (CPU types, hyperthread, etc)
- Load balancing / provisioning variation
- Infrastructure retention: COLD vs. WARM
 - Infrastructure freeze/thaw cycle
- Function memory reservation size
- Application service composition

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AWS LAMBDA PERFORMANCE VARIATION

- NLP processing pipeline use case
- Performance variance from: diurnal changes in load (e.g. resource contention), Intel hyperthreading

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AWS LAMBDA PERFORMANCE VARIATION - 2

- NLP use case: Less performance variance using ARM-based CPUs (less resource contention), and w/o hyperthreading

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FUNCTION-AS-A-SERVICE

AWS Lambda Demo

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CLOUD COMPUTING DELIVERY MODELS

- Infrastructure-as-a-Service (IaaS)
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CONTAINER-AS-A-SERVICE

- Cloud service model for deploying application containers (e.g. Docker containers) to the cloud
- Deploy containers without worrying about managing infrastructure:
 - Servers
 - Or container orchestration platforms
 - Container platform examples: Kubernetes, Docker swarm, Apache Mesos/Marathon, Amazon Elastic Container Service
 - Container platforms support creation of container clusters on the using cloud hosted VMs
- CaaS Examples:
 - AWS Fargate
 - Google Cloud Run
 - Azure Container Instances

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CLOUD COMPUTING DELIVERY MODELS

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OTHER CLOUD SERVICE MODELS

- IaaS
 - Storage-as-a-Service
- PaaS
 - Integration-as-a-Service
- SaaS
 - Database-as-a-Service
 - Testing-as-a-Service
 - Model-as-a-Service
- ?
 - Security-as-a-Service
 - Integration-as-a-Service

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OBJECTIVES – 10/23

- Questions from 10/21
- Tutorials Questions
- Tutorial 4 - to be posted...
- From: Cloud Computing Concepts, Technology & Architecture:
Chapter 4: Cloud Computing Concepts and Models:
 - Cloud computing delivery models
 - Cloud deployment models
- AWS Overview and demo
- 2nd hour:
 - Activity 2 - Intro to EC2
 - Term Project Planning

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CLOUD DEPLOYMENT MODELS

- Distinguished by ownership, size, access
- Four common models
 - Public cloud
 - Community cloud
 - Hybrid cloud
 - Private cloud

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PUBLIC CLOUDS

The diagram illustrates the concept of public clouds. At the top, several cloud providers are listed in circles: Salesforce, Microsoft, Amazon, Google, Yahoo, Zoho, and Rackspace. Arrows from each of these providers point downwards towards a central point labeled 'organizations', which is represented by three server rack icons. This visualizes how multiple public cloud providers can serve a single organization.

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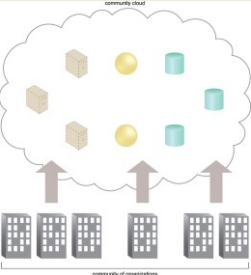
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COMMUNITY CLOUD

- Specialized cloud built and shared by a particular community
- Leverage economies of scale within a community
- Research oriented clouds
- Examples:
 - Bionimbus - bioinformatics
 - Chameleon
 - CloudLab



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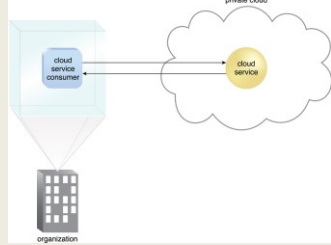
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PRIVATE CLOUD

- Compute clusters configured as IaaS cloud
- Open source software
 - Eucalyptus
 - Openstack
 - Apache Cloudstack
 - Nimbus
- Virtualization: XEN, KVM, ...



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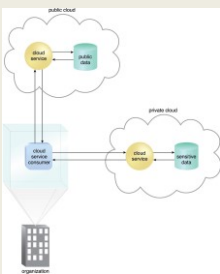
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HYBRID CLOUD

- Extend private cloud typically with public or community cloud resources
- Cloud bursting: Scale beyond one cloud when resource requirements exceed local limitations
- Some resources can remain local for security reasons



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OTHER CLOUDS

- Federated cloud
 - Simply means to aggregate two or more clouds together
 - Hybrid is typically private-public
 - Federated can be public-public, private-private, etc.
 - Also called inter-cloud
- Virtual private cloud
 - Google and Microsoft simply call these virtual networks
 - Ability to interconnect multiple independent subnets of cloud resources together
 - Resources allocated private IPs from individual network subnets can communicate with each other (10.0.1.0/24) and (10.0.2.0/24)
 - Subnets can span multiple availability zones within an AWS region

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WE WILL RETURN AT 5:50 PM



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OBJECTIVES - 10/23

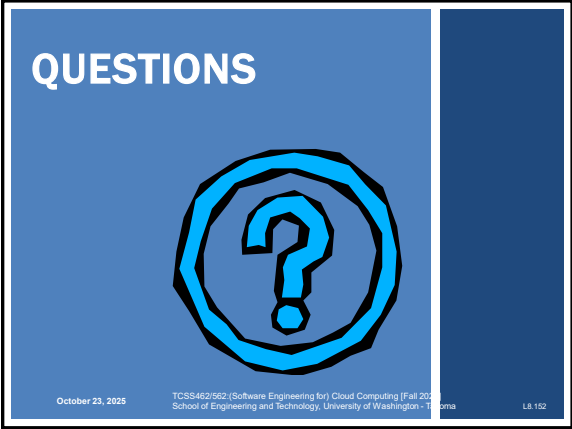
- Questions from 10/21
- Tutorials Questions
- Tutorial 4 - to be posted...
- From: Cloud Computing Concepts, Technology & Architecture: Chapter 4: Cloud Computing Concepts and Models:
 - Cloud computing delivery models
 - Cloud deployment models
- AWS Overview and demo
- 2nd hour:
 - Activity 2 - Intro to EC2
 - Term Project Planning

October 23, 2025

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