Practical Lab

Cloud Systems Engineering

(cloud-lab)

Chair of Decentralized Systems Engineering
https://dse.in.tum.de/

Welcome to the cloud lab!

Cloud computing

- Cloud computing is powering the Internet
  - Large-scale computing resources
  - On-demand and cost effective
  - Geo-distributed data centers

Motivation: Cloud systems engineering

- Cloud systems
  - Modern cloud systems handle millions of users and TBs of data
  - Cloud software systems employ large geo-distributed data centers
- How can we build cloud systems that …
  - … scale seamlessly?
  - … are highly available?
  - … are fault tolerant?
  - … are easily configurable?
  - … are easily maintained?
- Cloud systems aim to achieve all the above in a cost-effective manner

Our focus: Learning goals

- Part I: Cloud systems workflow
  - Container: How to build applications using containers?
  - Cluster orchestrators: How to deploy jobs?
- Part II: Distributed systems system architecture
  - Sharding / re-configuration of servers
  - Fault tolerance / replication
  - Consistent hashing
  - Consistency
  - Transactions / data management
  - Distributed locking / synchronization
  - Concurrency and high-performance architectures
  - Fault detection
  - Configuration management

Learn by building an end-to-end system!

Technologies

kubernetes

APACHE ZooKeeper™

RocksDB

Format

- A set of four programming tasks:
  - Each related to a different aspect of distributed systems
  - Built on top of each other, like a stack
- For each task, we will provide
  - Necessary background via a lecture
  - Q&As: after lecture and online via Slack
- Submitted tasks will be evaluated by
  - Automated grading system (only the last commit before the deadline counts)
  - Instructors

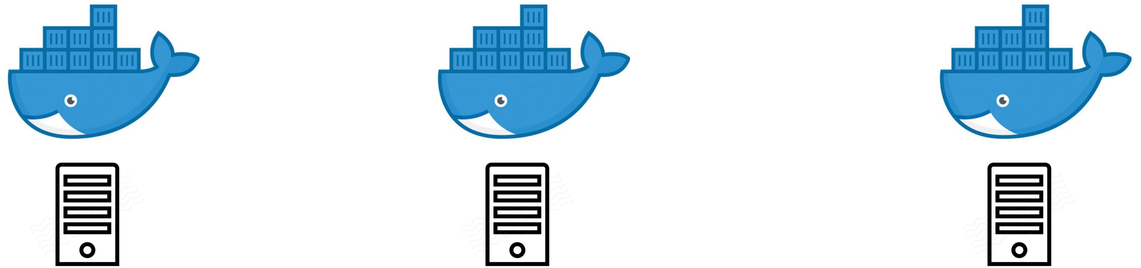
Layered architecture

#4: Distributed TXs: w/ and w/o replication

#3: Replicated distributed KVS

#2: Distributed KVS

#1: Single-node KVS	#1: Single-node KVS	…	#1: Single-node KVS



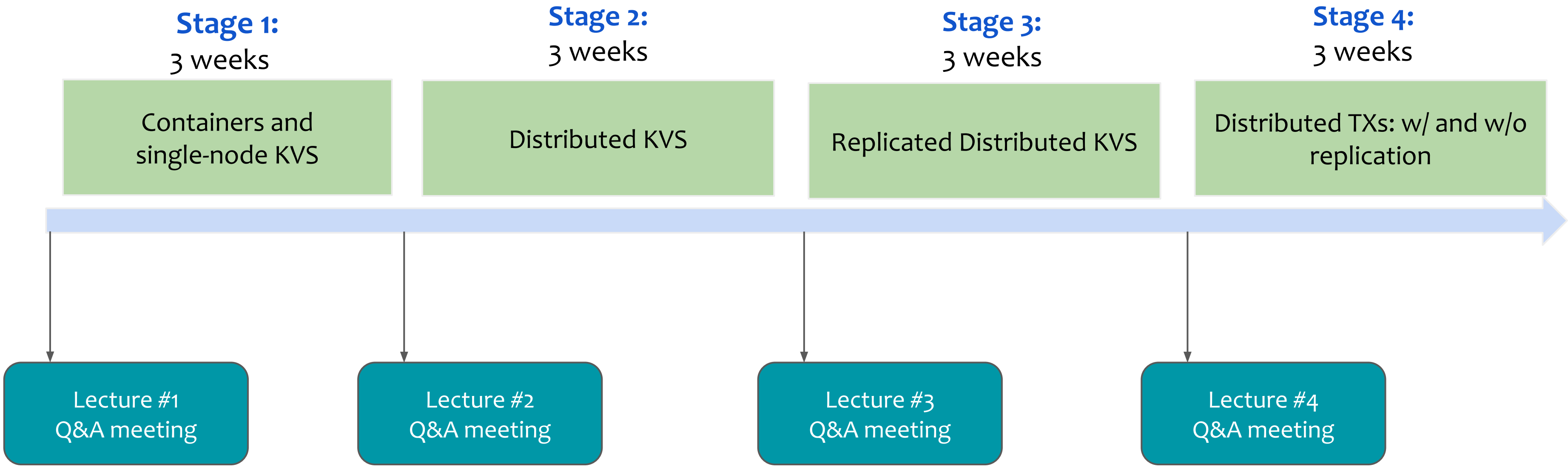
kubernetes

APACHE ZooKeeper™

Grading

Lecture	Category	Details	Grade
#1	Single-node KVS setup	Build and deploy a single node KVS	25%
#2	Distributed KVS	Shard the keys across multiple nodes: fault detection and server reconfiguration	25%
#3	Replicated distributed KVS	Replicate the KVS instances across these nodes for fault tolerance	25%
#4	Distributed Transactions	Support distributed transactions across keys and nodes: w/ and w/o replication	25%

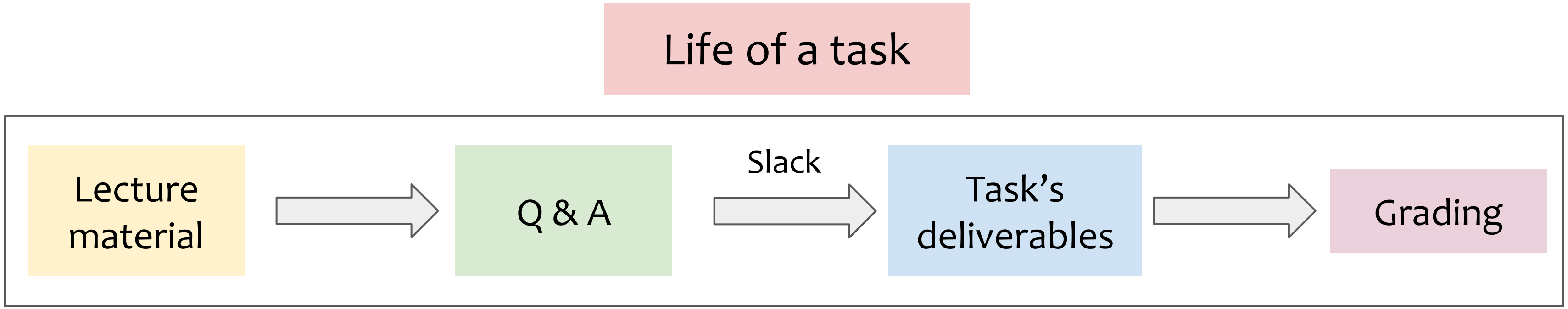
Timeline


Stage 1:
3 weeks
Containers and single-node KVS
Stage 2:
3 weeks
Distributed KVS
Stage 3:
3 weeks
Replicated Distributed KVS
Stage 4:
3 weeks
Distributed TXs: w/ and w/o replication
Lecture #1
Q&A meeting
Lecture #2
Q&A meeting
Lecture #3
Q&A meeting
Lecture #4
Q&A meeting

Organization

- Four lectures
  - One for each task – Recorded videos
    - Necessary material and deliverables will be explained
  - Q&A – Online on Thursdays via Zoom
- Online help
  - Slack channel will be monitored by the instructors/tutors

- Format:



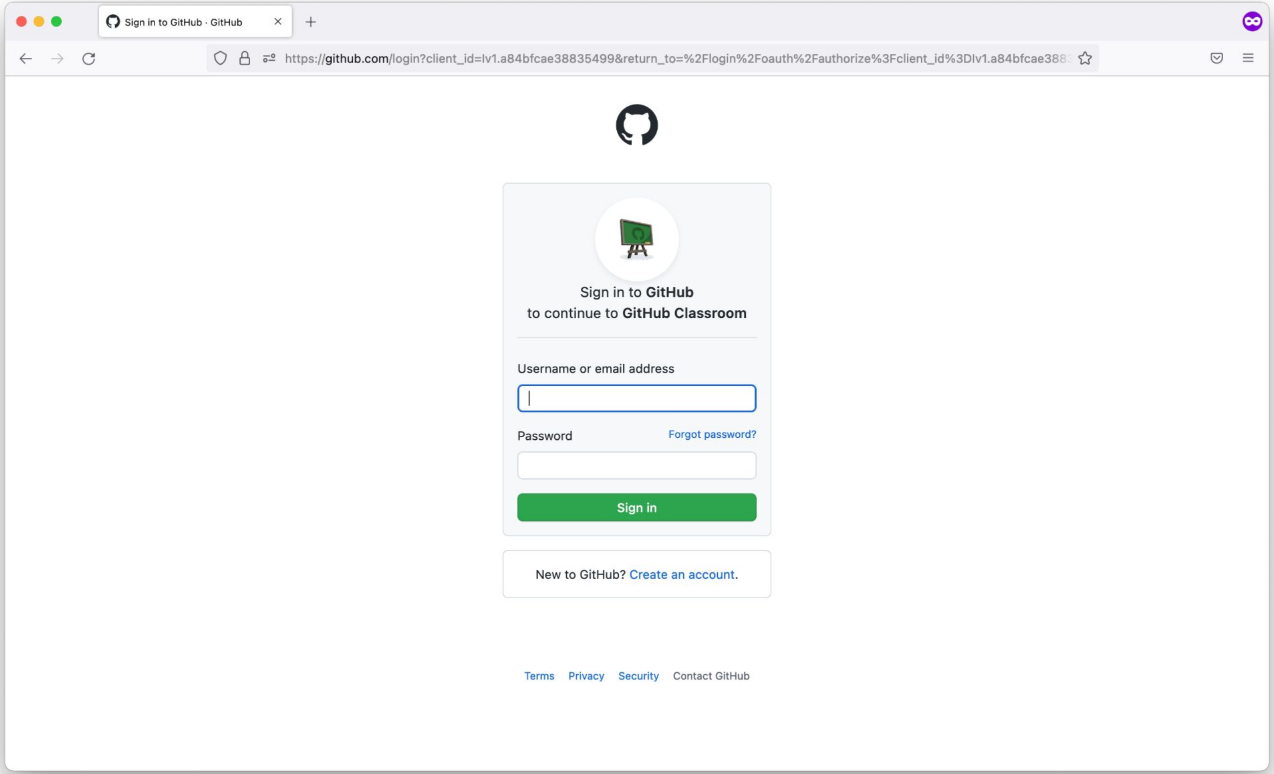
The assignments

- Code should be preferably written in C++
  - Other system programming languages like Rust may be used as well but there is no support by us
- We provide a detailed task description in the README.md of the task
- Code is hosted on GitHub and will be auto-graded via GitHub classroom
  - You will need to create a GitHub account
  - We will send you invitation links for each assignment via Slack
- Use Linux for the tasks

Our CI runners

- Fancy kubernetes cluster
- Three servers, each equipped with
  - 2x Intel Xeon 5215
    (10 cores / 20 threads each)
  - 128 GiB RAM
  - 10G NICs

Getting the assignment code



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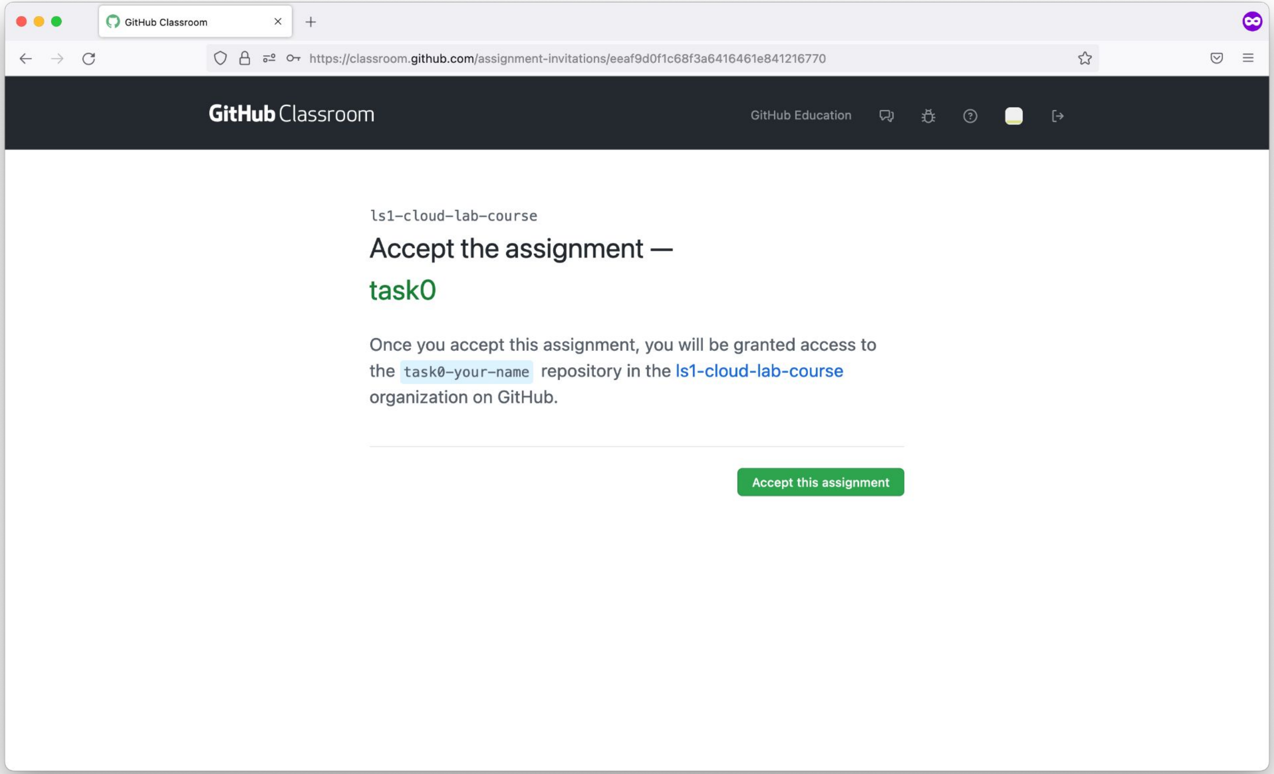

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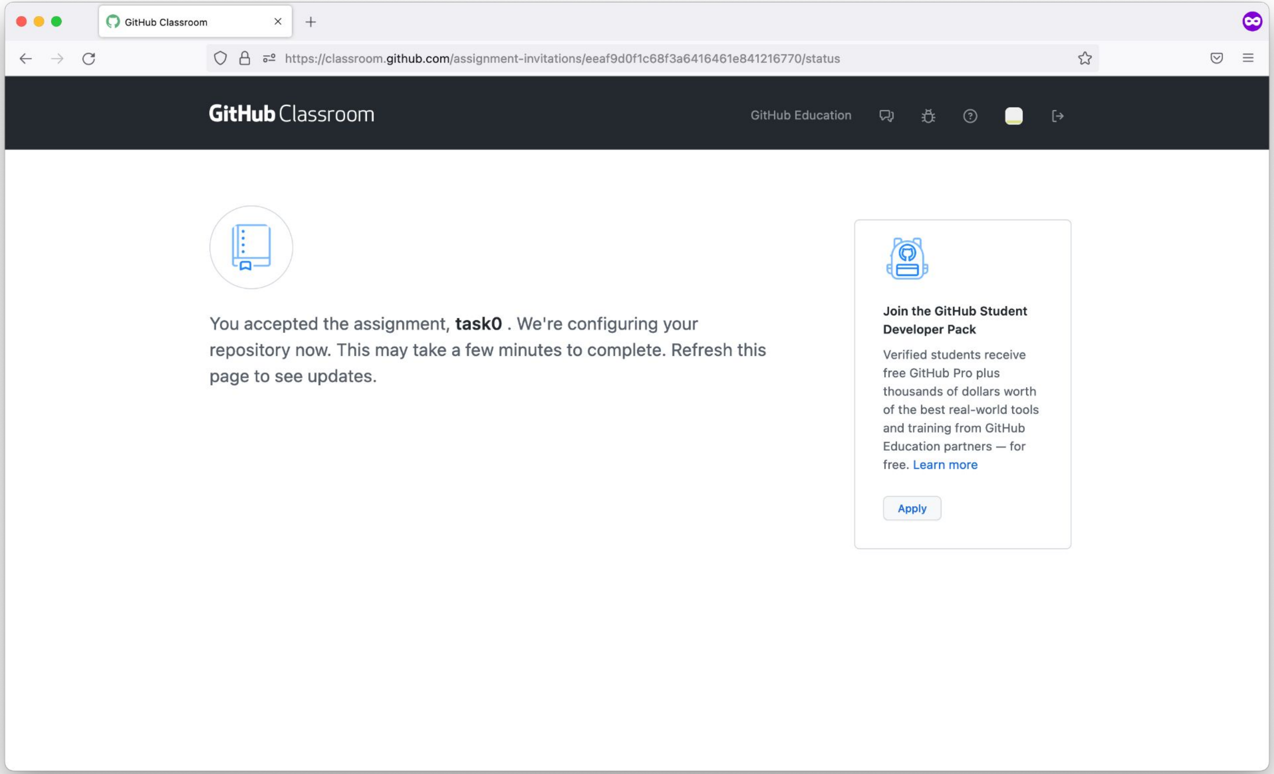

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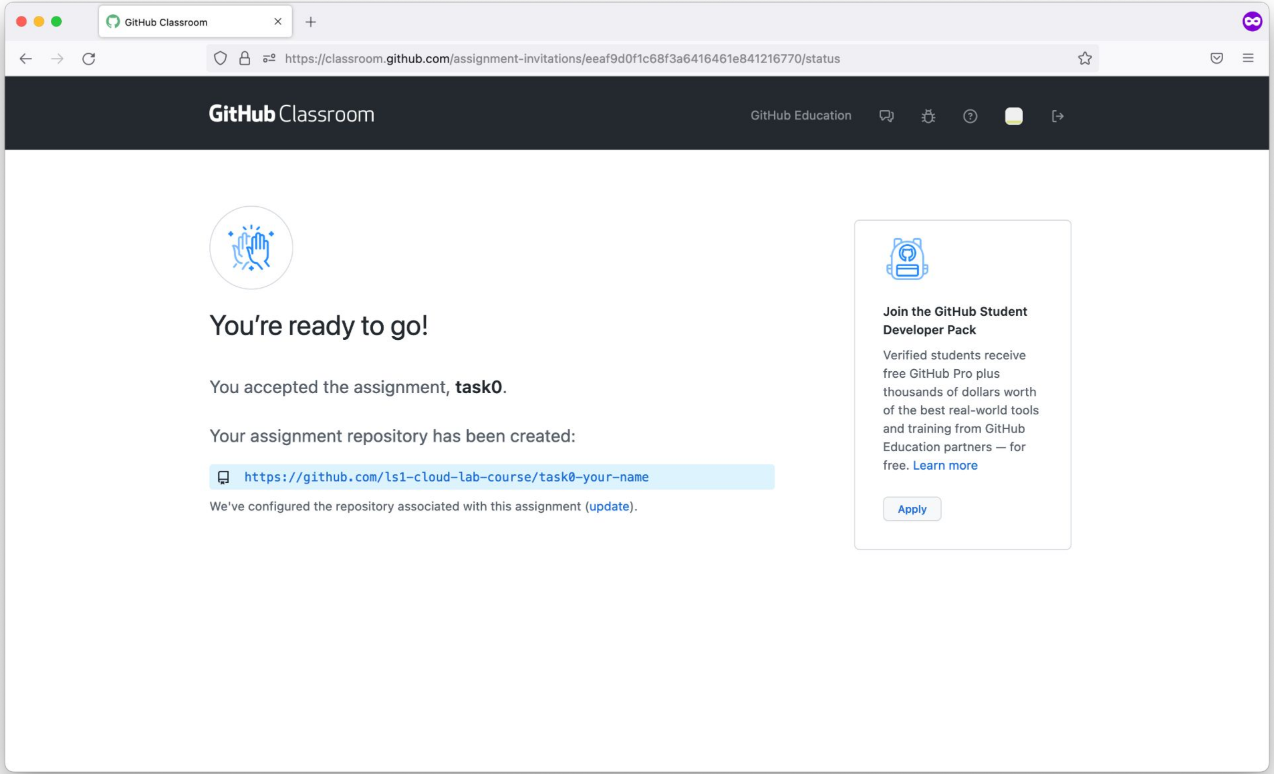

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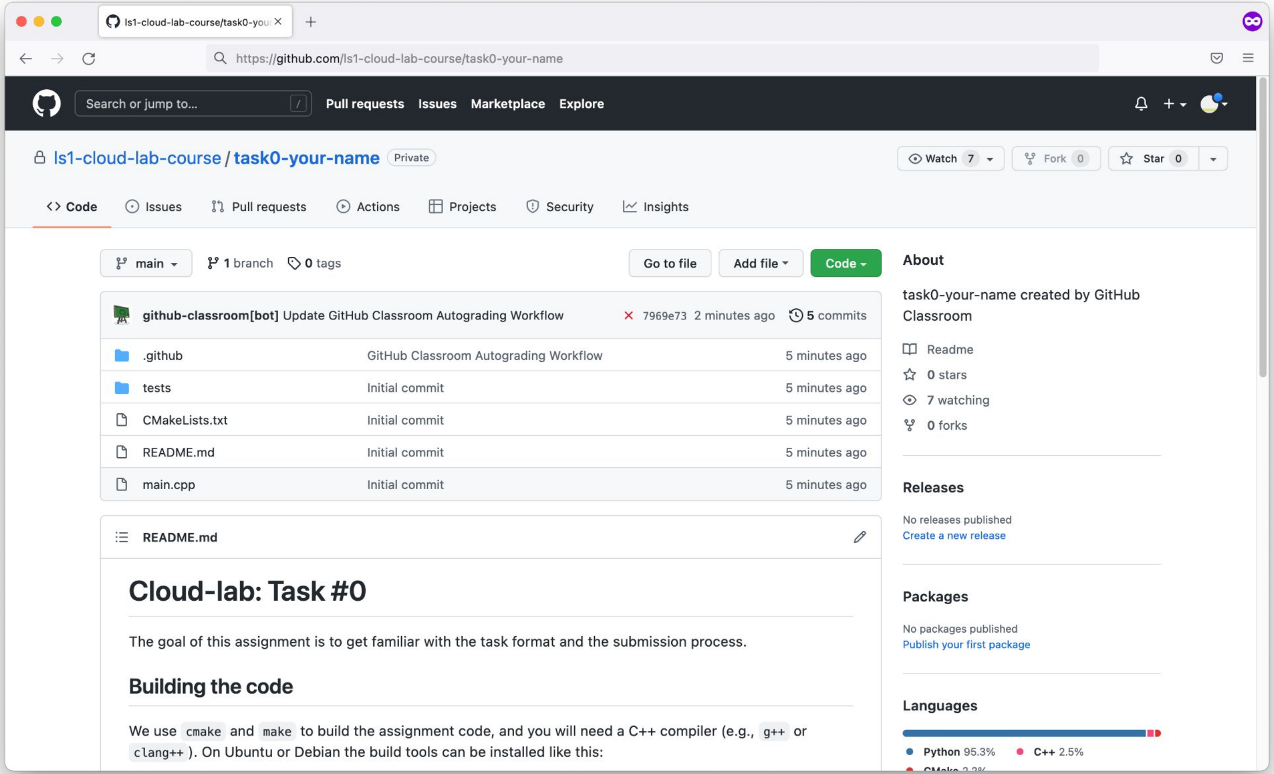
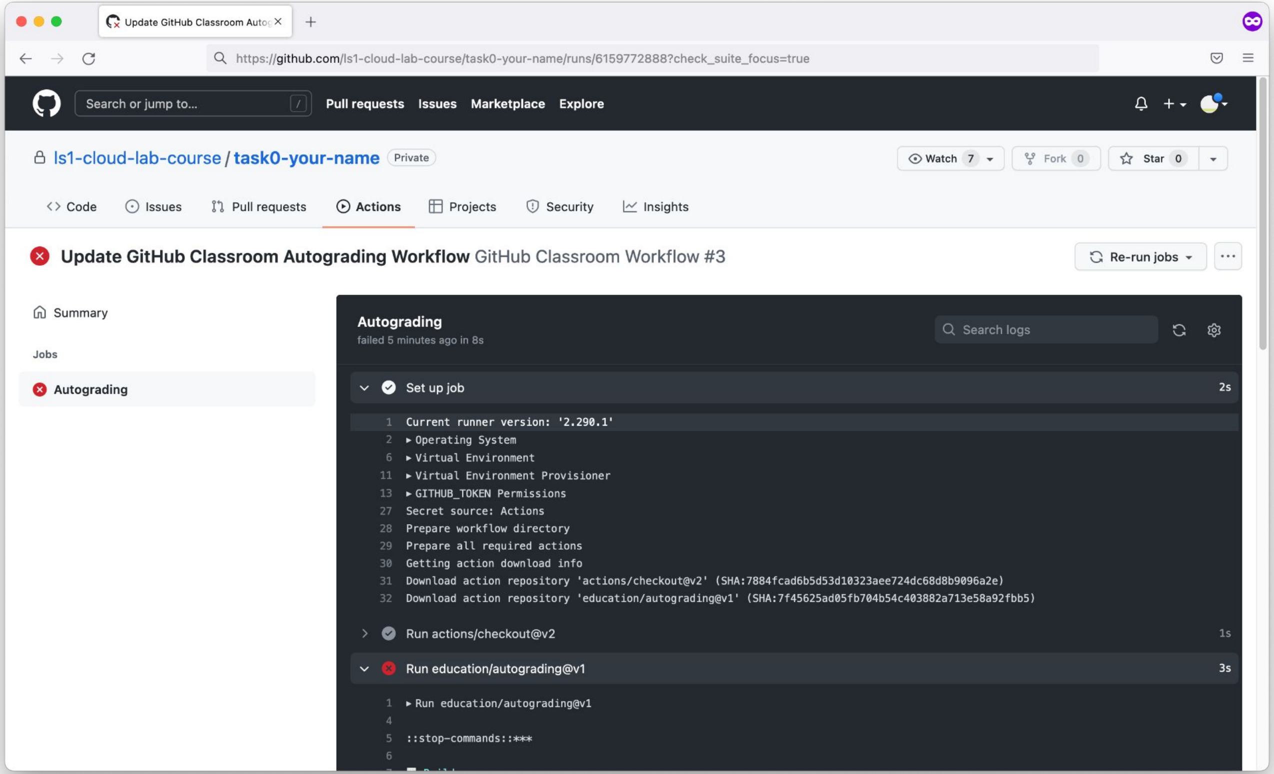
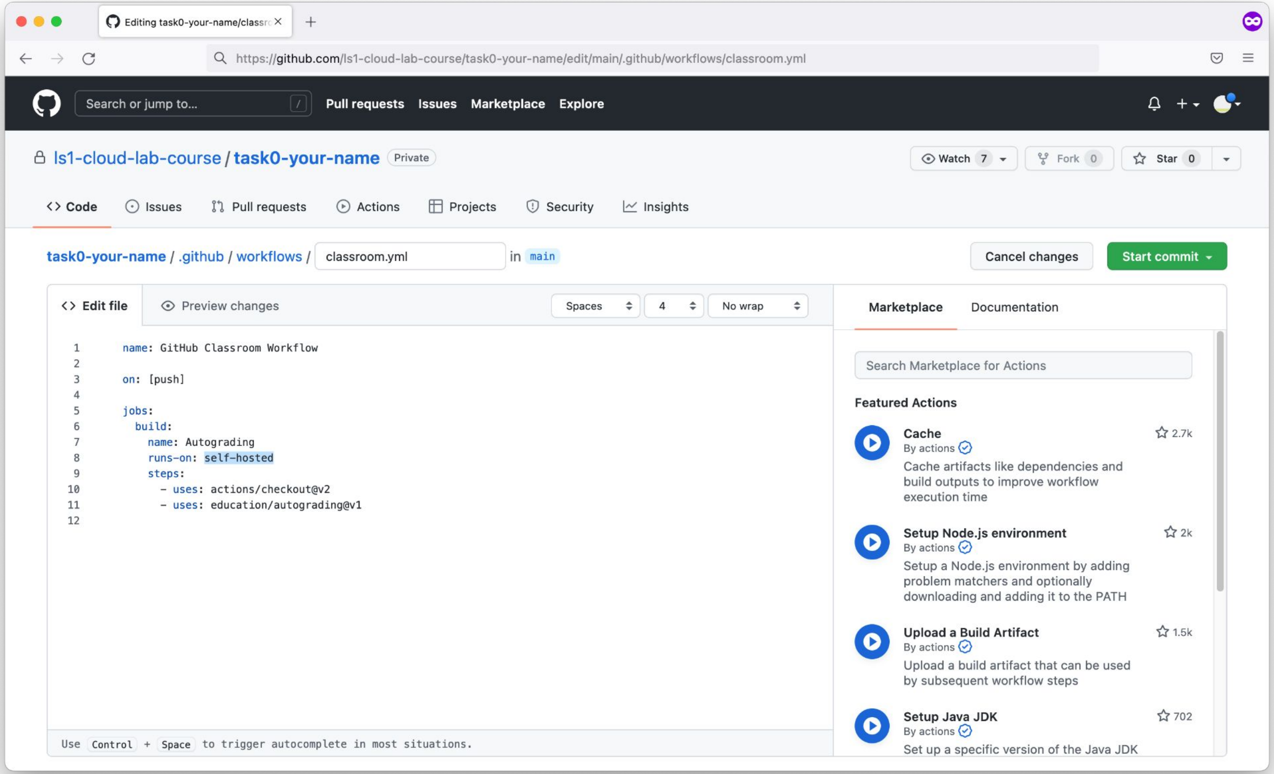


Submitting your code



Submitting your code



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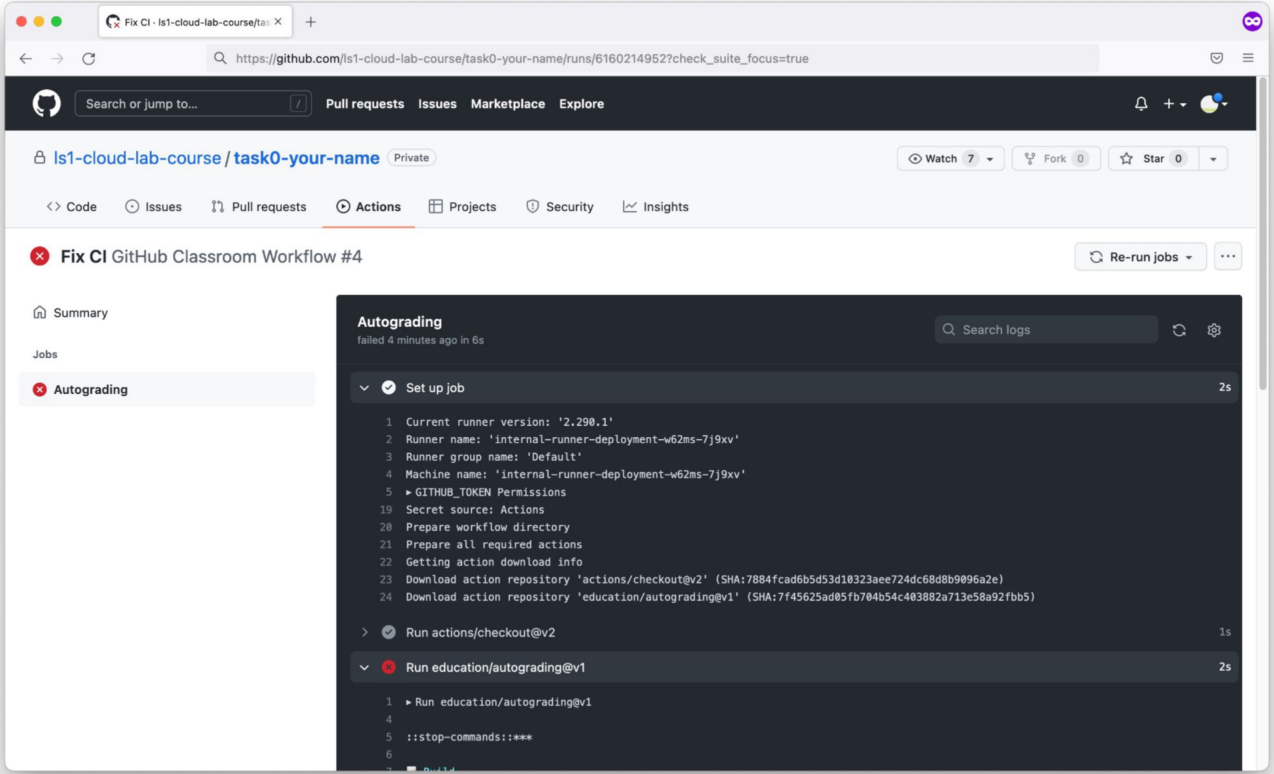
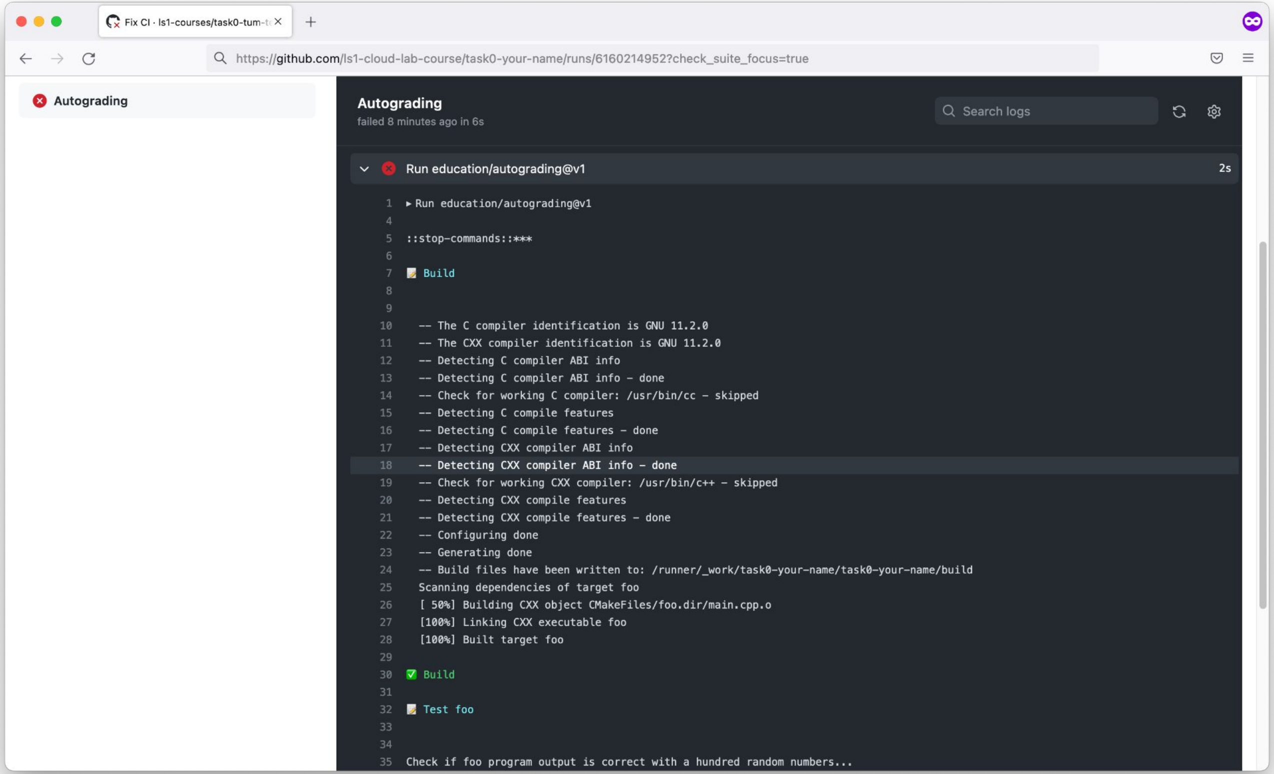


Submitting your code



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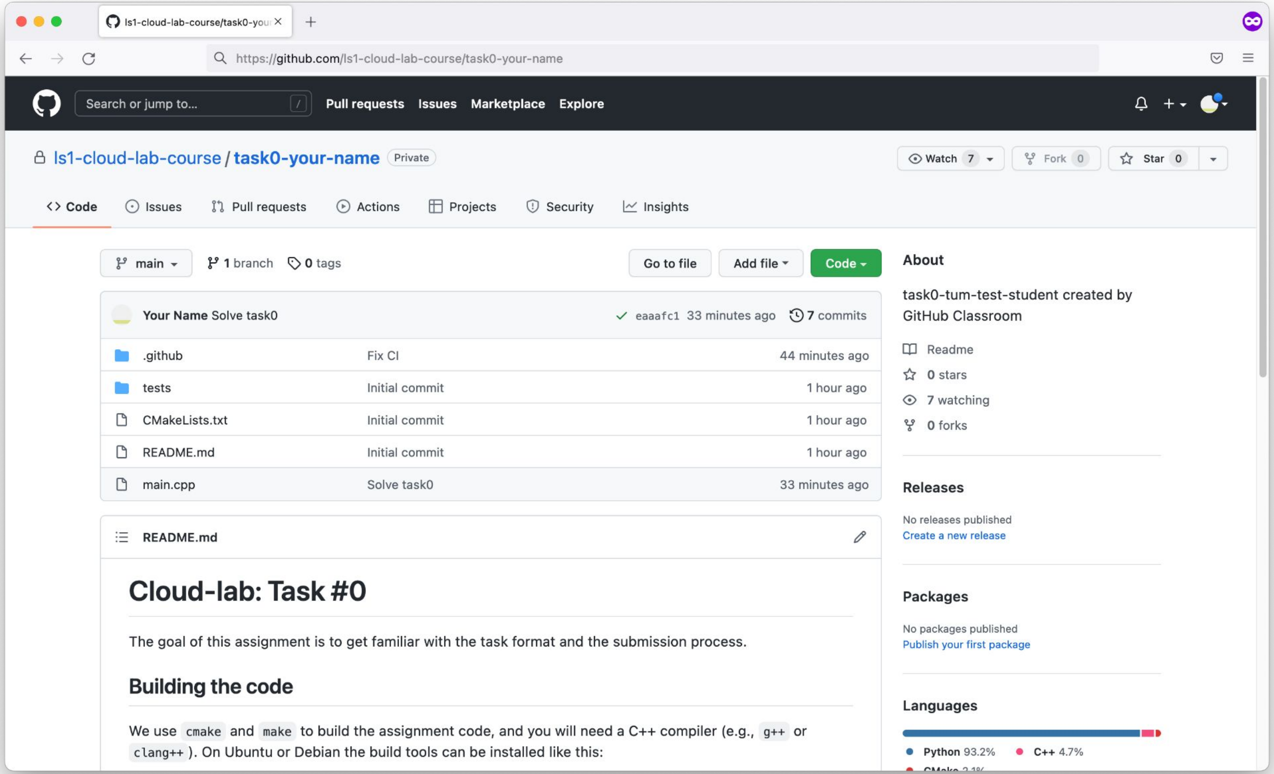


Task #1:
Single-node KVS

Learning goals

In this task you will learn about:

- Client-server architecture(s)
- Single node key-value stores (KVSs), e.g., RocksDB

Background

Containers

Motivation

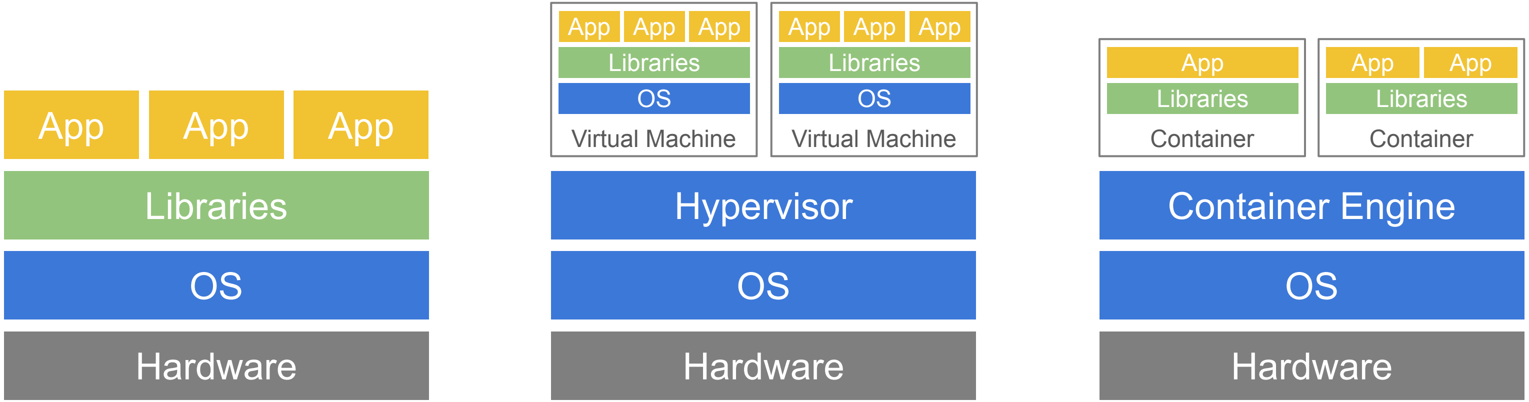
Share resources (IaaS, PaaS, …) in a flexible and cost-effective way

→ split applications into microservices

Advantages:

- Greater hardware resource-utilization
- Simply maintainable
- Scalable

Containers



Traditional system | Virtual machines | Containers

Containers

Unlike virtual machines …

- containers often contain only one application
- containers do not include an operating system (OS)
- containers limit access to resources through host OS mechanisms

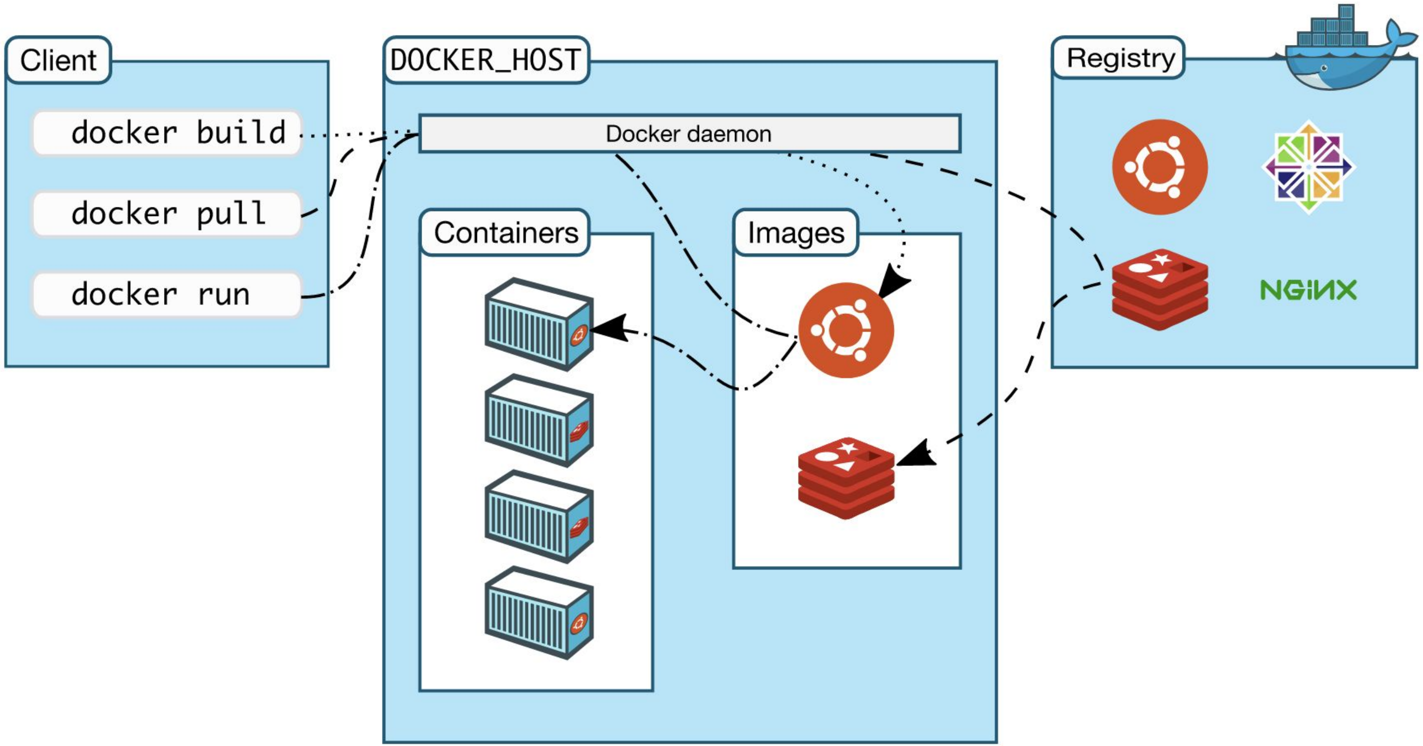
Container solutions

LXC

Docker

- Application container engine
  - Unlike LXC which is a system container engine
- Uses the resource isolation mechanisms of the Linux kernel
  - Namespaces
  - Cgroups
  - Layered filesystems
- Consists of three components: Software, objects and registry

Docker


Client
docker build
docker pull
docker run
DOCKER_HOST
Docker daemon
Containers
Images
Registry
NGINX

Getting started

1. Install Docker on your system, e.g.: `# apt install docker-ce`
2. Run some container: `$ docker run -it ubuntu /bin/bash`

Hints:

- List all containers: `$ docker ps -a`
- Get a shell for a running container: `$ docker exec -it <container name> /bin/sh`

Getting started

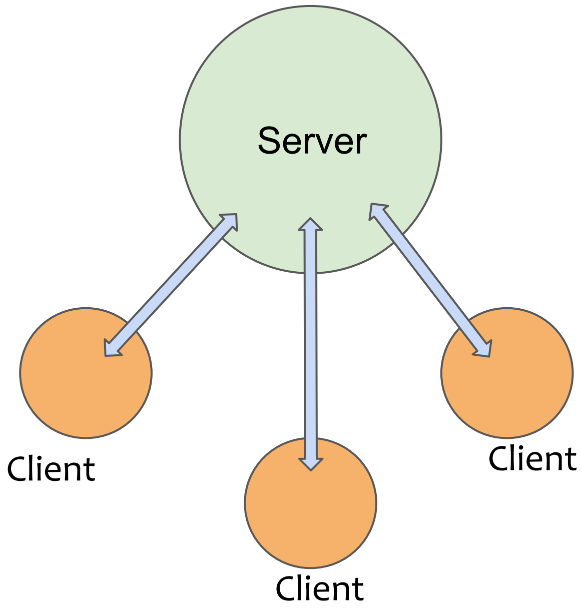
1. Create a simple Dockerfile (see Docker's docs)
2. Build an image based on the Dockerfile: `$ docker build -t <image name> .`
3. Run the container: `$ docker run -d <image name>`
4. Create and run multiple containers using Docker compose

Hints:

- Force clean rebuild of image: `$ docker build --no-cache -t <image name> .`
- To prevent a container from exiting early when debugging, add `CMD tail -f /dev/null` to the end of the Dockerfile

Client-server architecture

- Server
  - Usually a long running process (*daemon process*)
  - Manages some resources
  - Receives and process requests
- Client(s)
  - Sends one or more requests to the server
  - Wait for the server's reply
- Transport layer
  - Network medium
  - Transfers the data

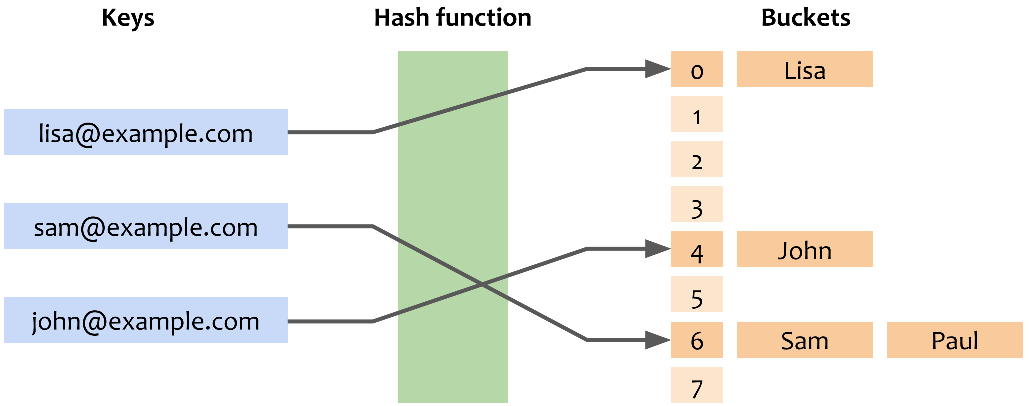


Key-Value store (KVs)

- Data structure
  - stores, retrieves and manages data
  - e.g., dictionaries, hash-tables

Key	Value
K1	AAA,BBB,CCC
K2	AAA,BBB
K3	AAA,DDD
K4	AAA,2,01/01/2022
K5	3,ZZZ,5623

dictionary



hash map

Motivation

Key-value stores play an important role at tech giants:

memcached	Redis	Voldemort	Dynamo
Facebook Twitter Zynga	GitHub Digg Blizzard Interactive	LinkedIn	Amazon

Motivation

Key-value stores play an important role in the scientific community:

- FASTER: A Concurrent Key-Value Store with In-Place Updates
  [SIGMOD ‘18]
- KVell: Design and Implementation of a Fast Persistent Key-value Store
  [SOSP ‘19]
- Nova-LSM: A Distributed, Component-based LSM-tree Key-value Store
  [SIGMOD ‘21]

KVs operations

Key-value stores typically implement a set of operations:

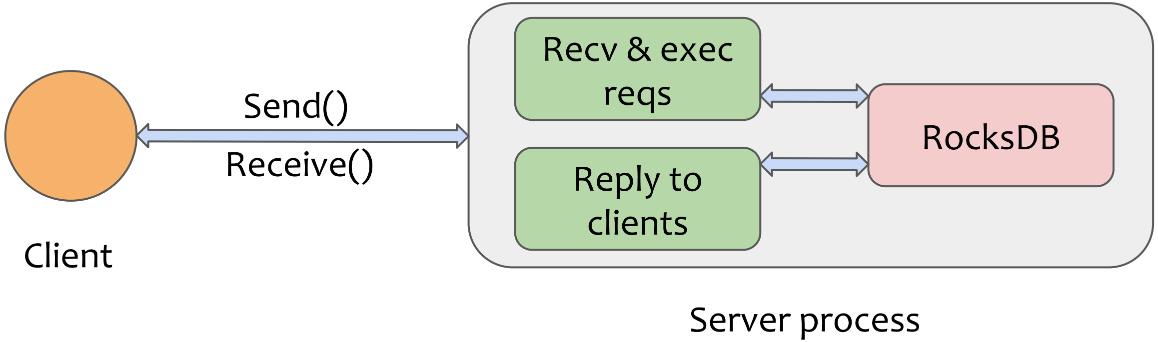
- GET
  - Retrieve a value by key
- PUT
  - Insert or update a key-value pair
- DELETE
  - Deletes a key-value pair (if it exists)
- Range Queries
  - Queries applying to a range of KV pairs

Challenges - design goals

- Performance
  - lock contention, significant write-traffic, complex memory management
  - low-latency operations and high throughput (I/O, batching)
  - parallelism (e.g., keys hashing)

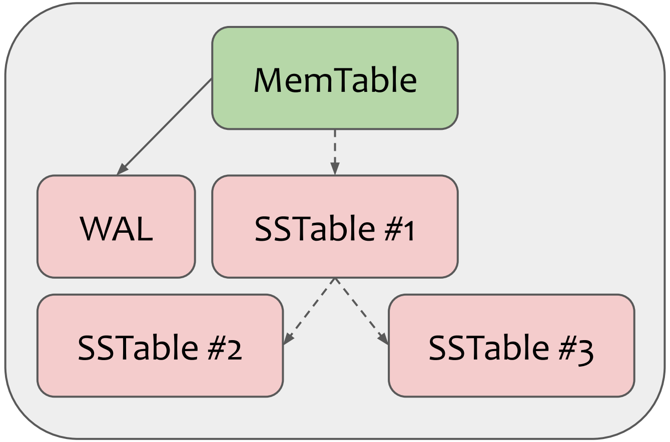
- Data properties
  - Persistency, e.g., persistent KVs or in-memory KVs
  - Consistency, e.g., linearizability or sequential consistency
  - Durability or crash consistency (for persistent KVs)

Task #1: Client/server arch + RocksDB



RocksDB architecture

- LSM-data structure
  - In-memory skiplist (MemTable)
  - SSTable files (persistent) organized on levels with (sorted) KV pairs
  - Compaction (background, multithreaded)
- Data properties
  - Linearizable reads, a read always "sees" the latest write
  - Durability, SSTables are persistent
  - Crash-consistency through Write-Ahead-Log (WAL)
- API
  - supports PUT, GET, DELETE queries



RocksDB

References

Talks & documentation:

- Rocksdb: https://github.com/facebook/rocksdb
- Rocksdb 101: https://www.youtube.com/watch?v=V_C-T5S-w8g
- Rocksdb talk: https://www.youtube.com/watch?v=tgzkgZVXKB4
- Protobufs: https://developers.google.com/protocol-buffers

Useful tutorials:

- Rocksdb tutorial: https://rocksdb.org/docs/getting-started.html
- Protobufs tutorial: https://developers.google.com/protocol-buffers/docs/cpptutorial
- Socket tutorial: https://www.linuxhowtos.org/C_C++/socket.htm
- Libevent tutorial: http://www.wangafu.net/~nickm/libevent-book/

Task #1

Your task for the next three weeks:

- Implement the network connection between client-server in a KVS architecture
- Implement the KVS operations
- Use
  - (1) RocksDB as the KV store
  - (2) kernel sockets for the networking
  - (3) google protobufs as the serialization protocol

Contacts

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Workspace: http://ls1-courses-tum.slack.com/

Website: https://dse.in.tum.de/

GitHub: https://github.com/TUM-DSE/cloud-lab/

Channel: #ws-22-cloud-lab

Join us with TUM email address (@tum.de)

Thank you for listening!

See you in the Q&A session

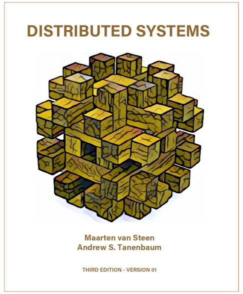
Code of conduct

- University plagiarism policy
  - https://www.in.tum.de/en/current-students/administrative-matters/student-code-of-conduct/

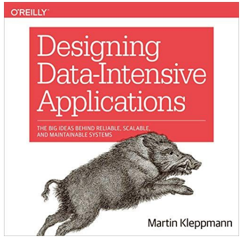
- Decorum
  - Promote freedom of thoughts and open exchange of ideas
  - Cultivate dignity, understanding and mutual respect, and embrace diversity
  - Racism and bullying will not be tolerated

Recommended readings

“Distributed Systems”
— Maarten van Steen and Andrew s. Tanenbaum



“Designing Data-Intensive Applications: The Big Ideas Behind Reliable, Scalable, and Maintainable Systems”
— Martin Kleppmann



“Designing Distributed Systems: Patterns and Paradigms for Scalable, Reliable Services Book”
— Brendan Burns