Cloud Computing Architecture

Semester project

April 29, 2021

Overview

The semester project consists of four parts, two of which are described in detail in this handout. In this project, you will explore how to schedule latency-sensitive and batch applications in a cloud cluster. You will deploy applications inside of containers and gain experience using a popular container orchestration platform, Kubernetes. Containers are a convenient and lightweight mechanism for packaging code and all its dependencies so that applications can run quickly and reliably from one computing environment to another.

You will work in groups of three students and submit a single report per group. **Please submit your report in the format of the project report template**. We will be assigning groups for the project, however you will have a chance to optionally let us know your preferences for teammates. If you know one or two other students in the class that you would like to work with on the project, please submit your group preference by March 12th, 2021. To do so, each student in your preferred group should sign up for the same group number in the Project Group Selection page on Moodle. We will notify you about final group assignments on March 15th and then you may redeem your cloud credits and begin working on the project.

Important Dates

March 12th, 2021: Deadline to submit group preferences (optional, since we will assign groups).
March 15th, 2021: Groups are assigned and announced. Start working on project.
April 13th, 2021: Deadline to submit Part 1 and 2 of the project.
May 21st, 2021: Deadline to submit Part 3 and 4 of the project.

We will release Part 3 and 4 of the project mid-April. Parts 3 and 4 are more open-ended and will require more time to complete than Part 1 and 2. Please plan your time accordingly.

Cloud Environment and Credits

To run experiments for the project, you will use Google Cloud. We will provide you with Google Cloud credits for your project. To redeem your cloud credits, please follow the steps in Part 1 (Section 1.1) *after March 15th*, when your project group assignment is confirmed. Each group member should create a Google Cloud account at `https://accounts.google.com`. Please use your ETH email address to create the account.

1 Part 1

In Part 1 of this project, you will run a latency-critical application, memcached, inside a container. Memcached is a distributed memory caching system that serves requests from clients over the network. A common performance metric for memcached is the tail latency (e.g., 95th percentile latency) under a desired query rate. You will measure tail latency as a function of queries per second and explore the impact of hardware resource interference. To add different types of hardware resource contention, you will use the iBench microbenchmark suite to apply different sources of interference (e.g., CPU, caches, memory bandwidth).

Follow the setup instructions below to deploy a Google Cloud cluster using the `kops` tool. Your cluster will consist of four virtual machines (VMs). One VM will serve as the Kubernetes cluster master, one VM will be used to run the memcached server application and iBench workloads, and two VMs will be used to run a client program that generates load for the memcached server.

In your project report (see report template), answer the questions in Section 1.2.

1.1 Setup Instructions

Installing necessary tools

For the setup of the project, you will need to install kubernetes, google-tools and kops. Instructions based on the operating system on your local machine are provided in the links above. Having installed all the tools successfully, the following three commands should return output in your terminal (for the rest of the document the $ symbol is there to declare a bash command and you shouldn't type it explicitly):

1. `$ kubectl --help`
2. `$ kops --help`
3. `$ ./google-cloud-sdk/bin/gcloud --help`

Note that the final command is relative to where you have downloaded the google cloud tools. If you have installed via a package manager or have added the gcloug tools to your `$PATH` you don't need the prefix and you can just type `gcloud`. Note that you have to open a new terminal or refresh your shell using `source` for your `$PATH` to be updated.

All the scripts that you will need for both parts of the project are available here:

```
git clone https://github.com/eth-easl/cloud-comp-arch-project.git
```

Redeeming cloud credits and creating Google Cloud project

Each group member should create a Google Cloud account at `https://accounts.google.com`. Use your ETH email address to create the account. Each group will receive a $100 Google Cloud coupon code. Select **one** group member to enter their name and ETH email address at this link. This student must use their @student.ethz.ch or @ethz.ch email address for the form. A confirmation email will be sent to the student with a coupon code. You can redeem the coupon using the following link, **using your ETH email address**.

After installing kubernetes tools, connect your local client to your google cloud account using:

`gcloud init`

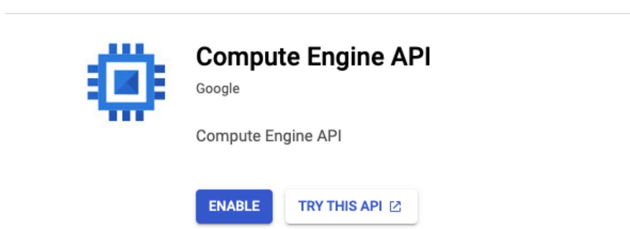
A browser window will open and you will have to login in with your ETH address. Afterwards, you will give `google-cloud-sdk` permissions to your account and then in the command line you will pick a name for the project. When creating the project name use `cca-eth-2021-group-XXX` (where XXX is your group number). **Only one group member (who also redeemed the cloud credit coupon) should create the Google Cloud project.** This person will add other group members as Project Owners (see instructions below). After the other group members are added as Project Owners, they will simply select the existing project name when they run the `gcloud init` command. All group members will have access to the project and share the cloud credits.

Do not configure any default computer region and zone. For deploying a cluster on Google Cloud we will follow the instructions here with some modifications.

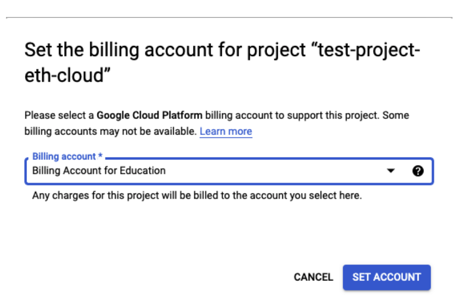
After creating the project, you will use the `gcloud compute zones list` to redeem your coupon. After typing the command you will get an error message like the following:

```
ERROR: (gcloud.compute.zones.list) Some requests did not succeed:
 - Project 610127079583 is not found and cannot be used for API calls. If it is recently created,
 enable Compute Engine API by visiting <YOUR_GOOGLE_PROJECT_LINK> then retry.
 If you enabled this API recently, wait a few minutes for the action
 to propagate to our systems and retry.
```

Follow the link provided. You will be redirected to a page with the following output on the top left:



There you will have to click the `Enable` button and then a window that has the option `Enable billing` will pop-up. Choose `Billing account for education` as below and click `Set account`:



Afterwards, if you type the `gcloud compute zones list` command again, you should see an output similar to the one below:

```
$ gcloud compute zones list
NAME                      REGION                 STATUS
us-east1-b                us-east1               UP
us-east1-c                us-east1               UP
us-east1-d                us-east1               UP
us-east4-c                us-east4               UP
us-east4-b                us-east4               UP
us-east4-a                us-east4               UP
us-central1-c             us-central1            UP
us-central1-a             us-central1            UP
us-central1-f             us-central1            UP
us-central1-b             us-central1            UP
us-west1-b                us-west1               UP
us-west1-c                us-west1               UP
us-west1-a                us-west1               UP
europe-west4-a            europe-west4           UP
europe-west4-b            europe-west4           UP
europe-west4-c            europe-west4           UP
europe-west1-b            europe-west1           UP
europe-west1-d            europe-west1           UP
europe-west1-c            europe-west1           UP
europe-west3-c            europe-west3           UP
europe-west3-a            europe-west3           UP
europe-west3-b            europe-west3           UP
europe-west2-c            europe-west2           UP
europe-west2-b            europe-west2           UP
europe-west2-a            europe-west2           UP
```

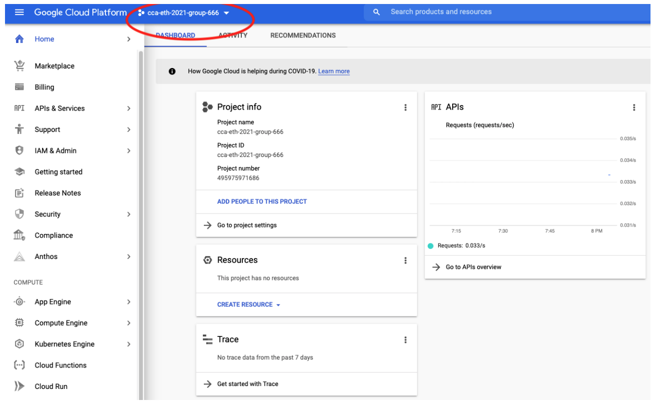
Then you will need to configure your default credentials using:

```
$ gcloud auth application-default login
```

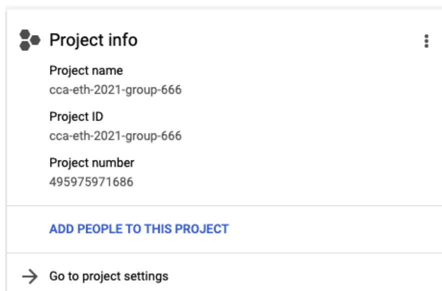
This will redirect you to a browser window where you will login with the same account you used when you setup the `gloud init` command.

Giving your teammates owner permission to the project

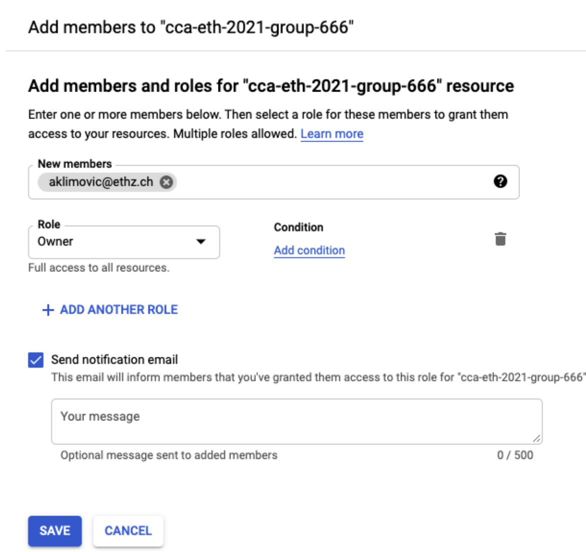
After creating the `cca-eth-2021-group-XXX` project on Google Cloud, give your group members access to the project and cloud credits by navigating to the Google Cloud console menu. Make sure your project is properly displayed on the top left as below:



In the project info click `Add people to this project`.



Type the email addresses of your teammates, select `Owner` as a role and click `Save`. **Note that your teammates should have created a google cloud account with their ETH address in advance to put them as project owners.**



Deploying a cluster using kops

At this point you will deploy a cluster using `kops`. First of all you will need to create an empty bucket to store the configuration for your clusters. Do this by running:

```
$ gsutil mb gs://cca-eth-2021-group-XXX-ethzid/
```

where `XXX` is your group number and `ethzid` is your ETH username. Then run the following command to have the `KOPS_STATE_STORE` command to your environment for the subsequent steps:

```
$ export KOPS_STATE_STORE=gs://cca-eth-2021-group-XXX-ethzid/
```

If you open another terminal this and other environmental variables will not be preserved. You can preserve it by adding it with an `export` command to your .bashrc You should substitute the number of your group and your ETH username as before.

For the first part of the exercise you will need a 3 node cluster. Two VMs will have 2 cores. One of these VMs will be the node where `memcached` and `iBench` will be deployed and another will be used for for the `mcperf` memcached client which will measure the round-trip latency of memcached requests. The third VM will have 8 cores and hosts the `mcperf` client which generates the request load for the experiments.

Before you deploy the cluster with `kops` you will need an ssh key to login to your nodes once they are created. Execute the following commands to go to your `.ssh` folder and create a key:

```
$ cd ~/.ssh
$ ssh-keygen -t rsa -b 4096 -f cloud-computing
```

Once you have created the key, go to lines 16 and 43 of the `part1.yaml` file (provided in the github link above) and **substitute the placeholder values with your group number and ethzid**. Then run the following commands to create a kubernetes cluster with 1 master and 2 nodes.

```
$ PROJECT=`gcloud config get-value project`
$ export KOPS_FEATURE_FLAGS=AlphaAllowGCE # to unlock the GCE features
$ kops create -f part1.yaml
```

We will now add the key as a login key for our nodes. Type the following command:

```
$ kops create secret --name part1.k8s.local sshpublickey admin -i ~/.ssh/cloud-computing.pub
```

We are ready now to deploy the cluster by typing:

```
$ kops update cluster --name part1.k8s.local --yes --admin
```

Your cluster should need around 5-10 minutes to be deployed. You can validate this by typing:

```
$ kops validate cluster --wait 10m
```

The command will terminate when your cluster is ready to use. If you get a `connection refused` or `cluster not yet healthy` messages, wait while the previous command automatically retries. When the command completes, you can type

```
kubectl get nodes -o wide
```

to get the status and details of your nodes as follows:

```
NAME                        STATUS   ROLES    AGE    VERSION   INTERNAL-IP   EXTERNAL-IP
master-europe-west3-a-2s21  Ready    master   3m2s   v1.19.7   10.156.0.63   34.107.107.152
memcache-server-jrk4        Ready    node     102s   v1.19.7   10.156.0.61   34.107.94.26
client-agent-vg5v           Ready    node     98s    v1.19.7   10.156.0.62   34.89.236.52
client-measure-ngwk         Ready    node     102s   v1.19.7   10.156.0.60   35.246.185.27
```

You can connect to any of the nodes by using your generated ssh key and the node name. For example to connect to the client-agent node, you can type:

```
$ gcloud compute ssh --ssh-key-file ~/.ssh/cloud-computing ubuntu@client-agent-vg5v \
                     --zone europe-west3-a
```

Running memcached and the mcperf load generator

To launch memcached using Kubernetes, run the following:

```
$ kubectl create -f memcache-t1-cpuset.yaml
$ kubectl expose pod some-memcached --name some-memcached-11211  \
                                    --type LoadBalancer --port 11211 \
                                    --protocol TCP
$ sleep 60
$ kubectl get service some-memcached-11211
```

Then run:

```
$ kubectl get pods -o wide
```

The ouput should look like:

```
NAME            READY   STATUS    RESTARTS   AGE   IP           NODE
some-memcached  1/1     Running   0          42m   100.96.3.3   memcache-server-zns8
```

Use the IP address above (`100.96.3.3` in this example) as the `MEMCACHED_IPADDR` in the remaining instructions. Now ssh into both the `client-agent` and `client-measure` VMs and run the following commands to compile the `mcperf` memcached load generator:

```
$ sudo apt-get update
$ sudo apt-get install libevent-dev libzmq3-dev git make g++ --yes
$ sudo cp /etc/apt/sources.list /etc/apt/sources.list~
$ sudo sed -Ei 's/^# deb-src /deb-src /' /etc/apt/sources.list
$ sudo apt-get update
$ sudo apt-get build-dep memcached --yes
$ cd && git clone https://github.com/shaygalon/memcache-perf.git
$ cd memcache-perf
$ make
```

On the `client-agent` VM, you should now run the following command to launch the `mcperf` memcached client load agent with 16 threads:

```
$ ./mcperf -T 16 -A
```

On the `client-measure` VM, run the following command to first load the memcached database with key-value pairs and then query memcached with throughput increasing from 5000 queries per second (QPS) to 55000 QPS in increments of 5000:

```
$ ./mcperf -s MEMCACHED_IP --loadonly
$ ./mcperf -s MEMCACHED_IP -a INTERNAL_AGENT_IP  \
           --noload -T 16 -C 4 -D 4 -Q 1000 -c 4 -t 5 \
           --scan 5000:55000:5000
```

where `MEMCACHED_IP` is from the output of `kubectl get pods -o wide` above and `INTERNAL_AGENT_IP` is from the Internal IP of the client-agent node from the output of `kubectl get nodes -o wide`. You should look at the output of `./mcperf -h` to understand the different flags in the above commands.

Introducing Resource Interference

Now we are going to introduce different types of resource interference with iBench microbenchmarks. Run the following commands:

```
$ kubectl create -f interference/ibench-cpu.yaml
```

This will launch a CPU interference microbenchmark. You can check it is running correctly with:

```
$ kubectl get pods -o wide
```

When you have finished collecting memcached performance measurements with CPU interference, you should kill the job by running:

```
$ kubectl delete pods ibench-cpu
```

Then repeat the three steps in this section with `ibench-l1d, ibench-l1i, ibench-l2, ibench-llc`, and `ibench-membw` interference microbenchmarks.

Deleting your cluster

IMPORTANT: you must delete your cluster when you are not using it! Otherwise, you will easily use up all of your cloud credits! When you are ready to work on the project, you can easily re-launch the cluster with the instructions above.
To delete your cluster, run on your local machine the command:

```
$ kops delete cluster part1.k8s.local --yes
```

1.2 Questions

Please answer the following questions in the report you submit.

1. **[10 points]** Using the instructions above, run memcached alone (i.e., no interference), and with each iBench source of interference (cpu, l1d, l1i, l2, llc, membw). Plot a single line graph with 95th percentile latency on the y-axis (the y-axis should range from 0 to 10 ms) and QPS on the x-axis (the x-axis should range from 0 to 55K) for each configuration (7 lines in total). Label your axes. State how many runs you averaged across (we recommend a minimum of 3) and include error bars. The readability of your plot will be part of your grade. **The shape of the curves depends on many factors and may differ across groups. However, that does not imply that your solutions are wrong.**

2. **[6 points]** How is the tail latency and saturation point (the "knee in the curve") of memcached affected by each type of interference? Why? Briefly describe your hypothesis.

3. **[2 points]** Explain the use of the taskset command in the container commands for memcached and iBench in the provided scripts. Why do we run some of the iBench benchmarks on the same core as memcached and others on a different core?

4. **[2 point]** Assuming a service level objective (SLO) for memcached of up to 2 ms 95th percentile latency at 40K QPS, which iBench source of interference can safely be collocated with memcached without violating this SLO?

2 Part 2

In Part 2 of this project, you will run six different throughput-oriented ("batch") workloads from the PARSEC benchmark suite: blackscholes, fft, dedup, ferret, freqmine, and canneal. You will first explore each workload's sensitivity to resource interference using iBench on a small 2 core VM (e2-standard-2). This is somewhat similar to what you did in Part 1 for memcache. Next, you will investigate how each workload benefits from parallelism by measuring the performance of each job with 1, 2, 4, 8 threads on a large 8 core VM (e2-standard-8). In the latter scenario, no interference is used.

Follow the setup instructions below to deploy a Google Cloud cluster and run the batch applications. In your project report, answer the questions in Section 2.2.

2.1 Setup

In order to complete this Part of the project, we will have to study the behavior of PARSEC in two different contexts. For both, we will require that kubectl, kops and gcloud sdk are set up. This should already be the case if you have completed Part 1.

We have provided you with a set of yaml files which are useful towards spawning kubectl jobs for workloads and interference. The interference files are the same as in Part 1, **but you must change the nodetype from memcached to parsec**. The PARSEC workloads are in the parsec-benchmarks/part2a folder in the github repo. All these files cover the workloads in the PARSEC suite, as well as the iBench interference sources relevant for this part: cpu, l1d, l1i, l2, llc, memBW.

2.1.1 PARSEC Behavior with Interference

For the first half of Part 2, you will have to set up a single node cluster consisting of a VM with 8 CPUs. For this, we will employ kops and make use of the part2a.yaml file (make sure to update the file with values for your GCP project):

```
$ export KOPS_STATE_STORE=<your-gcp-state-store>
$ export KOPS_FEATURE_FLAGS=AlphaAllowGCE
$ PROJECT=`gcloud config get-value project`
$ kops create -f part2a.yaml
$ kops update cluster part2a.k8s.local --yes --admin
$ kops validate cluster --wait 10m
$ kubectl get nodes -o wide
```

If successful, you should see something like this:

```
NAME                         STATUS   ROLES    AGE    VERSION   INTERNAL-IP   EXTERNAL-IP
master-europe-west3-a-9nxl   Ready    master   3m2s   v1.19.7   10.156.0.46   34.107.0.118
parsec-server-s28x           Ready    node     104s   v1.19.7   10.156.0.47   35.234.110.58
```

Now you should be able to connect to the parsec-server VM using either ssh:

```
$ ssh -i ~/.ssh/cloud-computing ubuntu@35.234.110.58
```

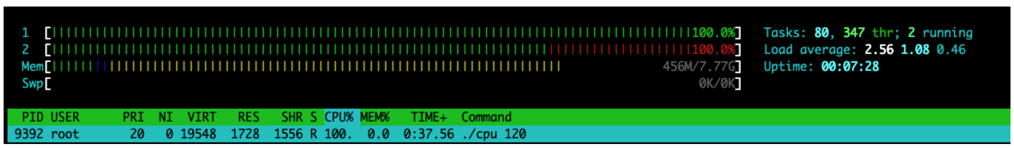
Or by using gcloud:

```
$ gcloud compute ssh --ssh-key-file ~/.ssh/cloud-computing ubuntu@parsec-server-s28x \
                     --zone europe-west3-a
```

For this part of the study we will sometimes require to set up some form of interference, and also deploy a `PARSEC` job. For this example, we will use the `PARSEC fft` job together with `iBench` CPU interference. Here is where we will use `kubectl` together with some of the `yaml` files we provide. The following code snippet spins up the interference, and runs the `PARSEC fft` job:

```
$ kubectl create -f ibench-cpu.yaml  # Wait for interference to start
$ kubectl create -f parsec-fft.yaml
```

Make sure that the interference has properly started **before** running the `PARSEC` job. One way to see if the interference and the `PARSEC` job has started refers to `ssh`-ing into the VM and using the `htop` command to inspect running processes. You should see an image like below:



You can get information on submitted jobs using:

```
$ kubectl get jobs
```

In order to get the output of the `PARSEC` job, you will have to collect the logs of its pods. To do so, you will have to run the following commands.

```
$ kubectl logs $(kubectl get pods --selector=job-name=<job_name> \
        --output=jsonpath='{.items[*].metadata.name}')
```

Run experiments sequentially and wait for one benchmark to finish before you spin up the next one. *Since fft, ferret, freqmine, and canneal jobs take over 5 minutes to complete with the native dataset, you must use a smaller dataset called simlarge (use -i simlarge in the YAML file) for these jobs. Use the native dataset (-i native) for dedup and blackscholes jobs. The .yaml files provided have the correct configuration.* Once you are done with running one experiment, make sure to terminate the started jobs. You can terminate them all together using:

```
$ kubectl delete jobs --all
$ kubectl delete pods --all
```

Alternatively, you can do so one-by-one using the following command:

```
$ kubectl delete job <job_name>
```

IMPORTANT: you must delete your cluster when you are not using it! Otherwise, you will easily use up all of your cloud credits! When you are ready to work on the project, you can easily re-launch the cluster with the instructions above. To delete your cluster, use the command:

```
$ kops delete cluster part2a.k8s.local --yes
```

2.1.2 PARSEC Parallel Behavior

For the second half of Part 2, you will have to look into the parallel behavior of PARSEC, more specifically, how does the performance of various jobs in PARSEC change as more threads are added (more specifically 1, 2, 4 and 8 threads). For this part of the study, no interference is used.

You will first have to spawn a cluster as in section 2.1.1, however, this time use the `part2b.yaml` file we provided (make sure to update the file with values for your GCP project). Once more, this will be a single node cluster with an 8 CPU VM. You will have to vary the number of threads for each PARSEC job. To do so, change the value of the `-n` parameter in the relevant `yaml` files. You should run all these benchmarks with the *native* dataset. The corresponding .yaml files are in `parsec-benchmarks/part2b` of the github repo.

Other relevant instructions for this task can be found in section 2.1.1.

IMPORTANT: you must delete your cluster when you are not using it! Otherwise, you will easily use up all of your cloud credits! When you are ready to work on the project, you can easily re-launch the cluster with the instructions above. To delete your cluster, use the command:

```
$ kops delete cluster part2b.k8s.local --yes
```

2.2 Questions

Please answer the following questions in the report you submit.

1. **[12 points]** Using a Kubernetes cluster with a single 2-core node, fill in the following table with the normalized execution time of each batch job with each source of interference. Include two decimal points. The execution time should be normalized to the job's execution time with no interference. For the execution time, consider the compute time only (not the initialization time) from the PARSEC container logs. Color-code each field in the table as follows: green if the normalized execution time is less than or equal to 1.3, yellow if the normalized execution time is greater than 1.3 and up to and including 2, and red if the normalized execution time is greater than 2. The setup for this question is detailed in Section 2.1.1.

Workload	none	cpu	l1d	l1i	l2	llc	memBW
dedup	1.00						
blackscholes	1.00						
ferret	1.00						
freqmine	1.00						
canneal	1.00						
fft	1.00						

Summarize in a paragraph the resource interference sensitivity of each batch job.

2. **[3 points]** What does the interference profile table tell you about the resource requirements for each application? Which jobs (if any) seem like good candidates to collocate with memcached from Part 1, without violating the SLO of 2 ms P95 latency at 40K QPS?

3. **[10 points]** In a Kubernetes cluster with a single 8-core node, run each of the six batch jobs individually and measure their execution time. Note that you should **not** use any interference for this part of the study. Vary the number of threads (1, 2, 4, and 8). Plot a single line graph

with the speedup on the y-axis (normalized time to the single thread performance: $\frac{t_1}{t_n}$ where t_i is the execution time for i threads) and the number of threads on the x-axis. Briefly discuss the scalability of each application, mentioning if it is linear, sub-linear or super-linear. Which of the applications, if any, gain a significant speedup with more threads? Explain what you consider to be "significant". The setup for this question is detailed in Section 2.1.2.

3 Part 3

In Part 3, you will put the previous two parts of the project together. You will now co-schedule the latency critical memcached application from Part 1 and all six batch applications from Part 2 in a heterogeneous cluster consisting of VMs with different numbers of cores. Your cluster will consist of a VM for the Kubernetes master (same as in Part 1), 3 VMs for the memcperf clients (2 agents and 1 measure machine), and 3 heterogeneous VMs (each with 2, 4, and 8 cores) which will be labelled `node-a-2core`, `node-b-4core`, `node-c-8core`, respectively, and used to run memcached and the PARSEC batch applications.

Your goal is to design a scheduling policy to minimize the time it takes for all six batch workloads to complete while guaranteeing a tail latency service level objective (SLO) for the long-running memcached service. You must take into account the characteristics of the PARSEC jobs that you noted in part 2 (e.g. speedup across cores, total running time). For this part of the project, the memcached service will receive requests from the client at a steady rate and you will measure the request tail latency. Your scheduling policy should minimize the total time to complete all the PARSEC apps, without violating a strict service level objective for memcached of **2 ms** 95th percentile latency at **30K QPS**. You must ensure that all six PARSEC apps succeed because a job may stop due to errors (e.g., out of memory). Use the native dataset size for all PARSEC jobs. At every point, you must use as many resources of your cluster as possible.

To design and implement your scheduling policy, you will experiment with different job collocations and resource management strategies using mechanisms in Kubernetes. Use what you learned about the performance characteristics of each application in Parts 1 and 2 to decide with which degree of parallelism to run each workload and which applications to collocate on shared resources.

Hint: You may modify the YAML files provided, write a script for launching the batch jobs, or apply any other techniques you choose, as long as you describe them clearly in your report. You can choose which jobs to collocate, which degree of parallelism to use for the batch and memcached workloads, and when to launch particular batch jobs. Use any Kubernetes mechanism you wish to implement a scheduling policy. You may find node/pod affinity and/or resource requests/limits particularly useful. You may also want to use `taskset` in the container command arguments to pin containers to certain CPU cores on a node. Keep in mind that a job may fail due to lack of resources. Use `kubectl describe jobs` to monitor jobs.

3.1 Setup

Run the following command to create a kubernetes cluster with 1 master and 6 nodes.

```
$ export KOPS_STATE_STORE=<your-gcp-state-store>
$ PROJECT='gcloud config get-value project'
$ export KOPS_FEATURE_FLAGS=AlphaAllowGCE # to unlock the GCE features
$ kops create -f part3.yaml
```

We are ready now to deploy the cluster by typing:

```
$ kops update cluster --name part3.k8s.local --yes --admin
```

Your cluster should need around 5-10 minutes to be deployed. You can validate the cluster with the command:

```
$ kops validate cluster --wait 10m
```

The command will terminate when your cluster is ready to use. Afterwards you can type

```
kubectl get nodes -o wide
```

to get the status and details of your nodes as follows:

```
NAME                          STATUS   ROLES    AGE   VERSION   INTERNAL-IP     EXTERNAL-IP
client-agent-a-d81z           Ready    node     23m   v1.19.7   10.156.15.222   35.234.120.124
client-agent-b-xpt7           Ready    node     23m   v1.19.7   10.156.15.224   34.107.4.82
client-measure-x1xw           Ready    node     23m   v1.19.7   10.156.15.223   35.242.212.158
master-europe-west3-a-cdp2    Ready    master   24m   v1.19.7   10.156.15.225   34.89.196.131
node-a-2core-qtrb             Ready    node     23m   v1.19.7   10.156.15.221   34.89.217.203
node-b-4core-gq6s             Ready    node     23m   v1.19.7   10.156.15.220   34.107.20.21
node-c-8core-3kz9             Ready    node     23m   v1.19.7   10.156.15.226   34.107.23.202
```

To connect to any of the machines you can run:

```
$ gcloud compute ssh --ssh-key-file ~/.ssh/cloud-computing ubuntu@<MACHINE_NAME> \
                     --zone europe-west3-a
```

Modify the memcached and PARSEC batch job YAML files from Parts 1 and 2 of the project and use the `kubectl create` commands to launch the workloads in the cluster. Write scripts to launch the jobs. The memcached job should start first and continue running throughout the whole experiment while receiving constant load of 30K QPS from the `mcperf` client). After you have started memcached and the client load, you can start the PARSEC batch jobs in whichever order you choose. Your goal if to minimize the time from the start of the first PARSEC job to the time the last PARSEC job completes while ensuring that the 95th percentile latency for memcached remains below 2ms.

To setup the `mcperf` load generator on the `client-agent` and `client-measure` machines, follow the instructions from Part 1. Instead of sweeping request throughput as you did in Part 1, you now want to generate load at a constant rate of approximately 30K QPS while reporting latency periodically (e.g., every 20 seconds). To do this, run the following command on the `client-agent-a` machine:

```
$ ./mcperf -T 2 -A
```

and the following command on the `client-agent-b` machine:

```
$ ./mcperf -T 4 -A
```

and the following command on the `client-measure` VM:

```
$ ./mcperf -s MEMCACHED_IP --loadonly
$ ./mcperf -s MEMCACHED_IP -a INTERNAL_AGENT_A_IP -a INTERNAL_AGENT_B_IP  \
          --noload -T 6 -C 4 -D 4 -Q 1000 -c 4 -t 20 \
          --scan 30000:30500:10
```

You can get the execution time of the batch jobs by parsing the JSON output of the `kubectl` command that returns information about each job, including its start and completion time. To do that, after all jobs have completed run:

```
$ kubectl get pods -o json > results.json
$ python3 get_time.py results.json
```

where `get_time.py` is a python script that we have provided you with.
IMPORTANT: you must delete your cluster when you are not using it! Otherwise, you will easily use up all of your cloud credits! When you are ready to work on the project, you can easily re-launch the cluster with the instructions above.
To delete your cluster, use the command:

```
$ kops delete cluster part3.k8s.local --yes
```

3.2 Questions

Please answer the following questions in the report you submit.

1. **[17 points]** With your scheduling policy, run the entire workflow 3 separate times. For each run, measure the execution time of each PARSEC job, as well as the latency outputs of memcached running with a steady client load of 30K QPS. For each PARSEC application, compute the mean and standard deviation of the execution time across three runs. Also compute the mean and standard deviation of the total time to complete all jobs. Fill in the table below. Finally, compute the SLO violation ratio for memcached for the three runs; the number of datapoints with 95th percentile latency > 2ms, as a fraction of the total number of datapoints. Do three plots (one for each run) of memcached p95 latency (y-axis) over time (x-axis) with annotations showing when each parsec job started.

job name	mean time [s]	std [s]
dedup		
blackscholes		
ferret		
freqmine		
canneal		
fft		
total time		

2. **[17 points]** Describe and justify the "optimal" scheduling policy you have designed. This is an open question, but you should at minimum answer the following questions:

   - Which node does memcached run on?
   - Which node does each of the 6 PARSEC apps run on?
   - Which jobs run concurrently / are collocated?
   - In which order did you run 6 PARSEC apps?
   - How many threads you used for each of the 6 PARSEC apps?

   Describe how you implemented your scheduling policy. Which files did you modify or add and in what way? Which Kubernetes features did you use? Please attach your modified/added YAML files, run scripts and report as a zip file. **Important: The search space of all the possible policies is exponential and you do not have enough credit to run all of them. We do not ask you to find the policy that minimizes the total running time, but rather to design a policy that has a reasonable running time, does not violate the SLO and takes into account the characteristics of the first two parts of the project.**

4 Part 4

In Part 4, you will co-schedule PARSEC batch jobs on a single 4-core server running memcached. In contrast to Part 3, we will now dynamically vary the load on the long-running memcached service, such that the number of cores needed by the memcached server to meet the tail latency service level objective (SLO) ranges from 1 to 2 cores. Your will design a scheduling policy that grows and shrinks the resource allocation of memcached and opportunistically uses temporarily available cores to complete the PARSEC jobs as quickly as possible. Your scheduling policy must still guarantee a memcached tail latency SLO of 2ms 95th percentile latency. For this part you will be using a cluster consisting of 4 nodes: a 2 core VM cluster master, a 4 core VM for the `memcached` server and PARSEC jobs, a 16 core VM for the `mcperf` agent, and a 2 core VM for the `mcperf` measurement machine.

You will need to implement your own controller to launch jobs and dynamically adjust their available resources, based on your scheduling policy. In this part of the project, we will not use Kubernetes because Kubernetes does not provide an API to change a container's resource allocation during run time. Instead, you will use Docker to launch containers to run the PARSEC benchmarks and dynamically adjust their resources. For memcached, we provide instructions for installing and running memcached directly on the VM (rather than in a Docker container) and using the `taskset` command to dynamically adjust resources. The reason we do not use Docker to run memcached in this part of the assignment is because we have observed that memcached's resources are not effectively constrained with `docker --cpuset-cpus`, since most of the processing in memcached application is network packet processing, which executes in kernel threads. Your controller should monitor CPU utilization and/or other types of resources and metrics to decide if resources need to be adjusted to meet the SLO. Your controller should make dynamic resource allocation decisions, such that the PARSEC batch jobs are completed as quickly as possible while still enforcing memcached's SLO.

For this part we also provide an augmented version of `mcperf` which is capable of generating random loads on the memcached server, as well as specific load traces. We provide instructions on how to set this up further below in Section 4.1.1.

Implementing the controller and scheduling policy

We recommend implementing your controller in python and using the Docker Python SDK to manage containers. Alternatively, you may implement the controller in Go using the Docker Go SDK. You can find examples of managing containers using the Docker SDK, for both Python and Go. If you plan on using such and SDK, you might find it useful to use the shell command `sudo usermod -a -G docker <your-username>`. This will allow you to use the SDK programmatically without encountering permission errors. You will also be able to run docker commands without using `sudo`.

In addition to *running* containers, you will need to *update* containers while they are running. Updating a container refers to dynamically adjust properties of the container, such as the CPU allocation. You can read more about updating containers in the Docker update command documentation. You can update docker containers using Docker SDK commands. In case you find it helpful for your scheduling policy (though it is not required), you can also pause and unpause containers. Pausing a container has the effect of temporarily stopping the execution of the processes in the container (i.e., releasing CPU resources) while retaining the container's state (i.e., keeping the container's memory resources). Unpausing containers resumes the execution of processes in the container.

Your controller should run on the 4-core memcached server and monitor CPU utilization. The controller should use CPU utilization statistics to make dynamic scheduling decisions. You can monitor CPU utilization on the server by reading and post-processing data from `/proc/stat` files on the VM. There are also language specific options for monitoring metrics, such as psutil for Python.

In addition to CPU utilization, you may use other inputs for your scheduling policy, if you wish. This is not required, but may let you implement an even better policy. Please explain in your report any additional inputs you choose to consider in your scheduling policy at the controller.

Evaluating the scheduling policy

You will evaluate your scheduling policy with a dynamic `mcperf` load trace that we provide (see instructions below). You should use `mcperf` to investigate the performance of your scheduling policy with various load traces (e.g., try different random seeds and time intervals). Experimenting with various load traces will allow you to analyze when and why your policy performs well and understand in which scenarios the policy does not adapt appropriately.

Generating the plots

In this part of the project, you will be asked to generate some plots which often require that you aggregate data gathered from different VMs. This can be challenging since you'll need to temporally correlate this data across the VMs. A straight forward way to do this is to save the Unix time whenever you log an event, as this time is roughly synchronized across VMs. You can further use other information such as dynamic mcperf's `--qps_interval` or `-t` parameter (see documentation here). Our dynamic mcperf version should also by default print the simulation's start and end Unix times in the output logs. Another alternative is to use the shell command `date +%s`. These times can then be used when generating the plots to synchronize events that take place on different VMs.

4.1 Setup

4.1.1 Installation

Run the following command to create a kubernetes cluster with 1 master and 3 nodes.

```
$ export KOPS_STATE_STORE=<your-gcp-state-store>
$ PROJECT='gcloud config get-value project'
$ export KOPS_FEATURE_FLAGS=AlphaAllowGCE # to unlock the GCE features
$ kops create -f part4.yaml
```

We are ready now to deploy the cluster by typing:

```
$ kops update cluster --name part4.k8s.local --yes --admin
```

Your cluster should need around 5-10 minutes to be deployed. You can validate the cluster with the command:

```
$ kops validate cluster --wait 10m
```

The command will terminate when your cluster is ready to use. Afterwards you can type

```
kubectl get nodes -o wide
```

to get the status and details of your nodes as follows:

```
NAME                    STATUS   ROLES    AGE     VERSION   INTERNAL-IP    EXTERNAL-IP
client-agent-bf7q       Ready    node     111s    v1.19.7   10.138.0.33    35.230.78.193
client-measure-5v6m     Ready    node     116s    v1.19.7   10.138.0.32    35.227.161.236
master-us-west1-a-kh69  Ready    master   3m23s   v1.19.7   10.138.0.34    35.247.63.197
memcache-server-qmql    Ready    node     111s    v1.19.7   10.138.0.31    34.83.56.78
```

You will first need to manually install memcached on the `memcache-sever` VM. To do so, you must first use the following commands:

```
$ sudo apt update
$ sudo apt install -y memcached libmemcached-tools
```

To make sure the installation succeeded, run the following command

```
$ sudo systemctl status memcached
```

you should see and ouput similar to the following being produced:

```
 memcached.service - memcached daemon
   Loaded: loaded (/lib/systemd/system/memcached.service; enabled; vendor preset: enabled)
   Active: active (running) since Thu 2021-04-01 08:21:26 UTC; 10min ago
     Docs: man:memcached(1)
 Main PID: 11796 (memcached)
    Tasks: 10 (limit: 4915)
   CGroup: /system.slice/memcached.service
           -11796 /usr/bin/memcached -m 64 -p 11211 -u memcache -l 127.0.0.1 ...
```

You will need to expose the service to the outside world, and increase its default starting memory. To do so, open memcached's configuration file using the command:

```
$ sudo vim /etc/memcached.conf
```

To update memcached's memory limit, look for the line starting with `-m` and update the value to 1024. Similarly, to expose the memcached server to external requests, locate the line starting with `-l` and replace the localhost address with the internal IP of the `memcache-sever` VM. You can also specify the number of memcached threads here by introducing a line starting with `-t` followed by the number of threads. Save the file, then execute the next command to restart memcached with the new configuration:

```
$ sudo systemctl restart memcached
```

Running `sudo systemctl status memcached` again should yield an output similar as before, however, you should see the updated parameters in the command line. If you completed these steps successfully, memcached should be running and listening for requests on the VMs internal IP on port 11211.

To install the augmented version of mcperf on the other 2 VMs, one can follow the instructions below:

```
$ sudo apt-get update
$ sudo apt-get install libevent-dev libzmq3-dev git make g++ --yes
$ sudo apt-get build-dep memcached --yes
$ git clone https://github.com/eth-easl/memcache-perf-dynamic.git
$ cd memcache-perf
$ make
```

On the `client-agent` VM, you should now run the following command to launch the `mcperf` memcached client load agent with 16 threads:

```
$ ./mcperf -T 16 -A
```

On the `client-measure` VM, run the following command to first load the memcached database with key-value pairs and then query memcached with a dynamic load generator which will produce a random throughput between 5000 and 100000 queries per second during each interval. The throughput target will change and will be assigned to another QPS for the next interval. In the example the interval duration is set to 10 seconds, whilst the overall execution time is 30 seconds, which will result in three different QPS intervals:

```
$ ./mcperf -s INTERNAL_MEMCACHED_IP --loadonly
$ ./mcperf -s INTERNAL_MEMCACHED_IP -a INTERNAL_AGENT_IP  \
           --noload -T 16 -C 4 -D 4 -Q 1000 -c 4 -t 10 \
           --qps_interval 2 --qps_min 5000 --qps_max 100000
```

The `INTERNAL_MEMCACHED_IP` and `INTERNAL_AGENT_IP` are the internal IPs of the `memcache-sever` and `client-agent` retrieved from the output of `kubectl get nodes -o wide`.

For more information on the dynamic load generator, and the available options it provides, check the guide in the README.md of the public repository.

PARSEC jobs can be started using Docker. For instance, one can start the `blackholes` job on core 0 (`--cpuset-cpus="0"` parameter) and with 2 threads (`-n 2` parameter) using the following command:

```
docker run --cpuset-cpus="0" -d --rm --name parsec \
    anakli/parsec:blackscholes-native-reduced \
    ./bin/parsecmgmt -a run -p blackscholes -i native -n 2
```

You can also inspect the yaml files for the PARSEC jobs from the previous parts to further understand their command lines. You can find the rest of the docker images here. Make sure to use the these image versions:

- splash2x.fft: `anakli/parsec:splash2x-fft-native-reduced`
- freqmine: `anakli/parsec:freqmine-native-reduced`
- ferret: `anakli/parsec:ferret-native-reduced`
- canneal: `anakli/parsec:canneal-native-reduced`
- dedup: `anakli/parsec:dedup-native-reduced`
- blackscholes: `anakli/parsec:blackscholes-native-reduced`

IMPORTANT: you must delete your cluster when you are not using it! Otherwise, you will easily use up all of your cloud credits! When you are ready to work on the project, you can easily re-launch the cluster with the instructions above.
To delete your cluster, use the command:

```
$ kops delete cluster part4.k8s.local --yes
```

4.1.2 Setting resource limits

`taskset` is an essential command for setting the CPU affinity of processes. For instance, running `taskset -a -cp 0-2 <pid>` will bind all threads (`-a` switch) of the running process indicated by `<pid>` (`-p` parameter) to the CPUs 0, 1 and 2 (`-c` parameter). One can also use this command when starting up processes. More information on `taskset` can be obtained here.

For Docker, the `--cpuset-cpus` parameter is used to set the cores a container is able to use. This parameter can be set both when spinning up a container (e.g. `sudo docker run --cpuset-cpus="0-2" ...`) or updated when a container is already running (e.g. `docker container update --cpuset-cpus="0-2" CONTAINER`).

You are also free to use other means to dynamically adjust resource allocation for your running jobs. This can refer to resources other than CPU cores.

4.2 Questions

Please answer the following questions in the report you submit.

1. **[10 points]** How does memcached performance vary with the number of threads (T) and number of cores (C) allocated to the job? In a single graph, plot the 95th percentile latency (y-axis) vs. QPS (x-axis) of memcached (running alone, with no other jobs collocated on the server) for the following configurations (one line each):

   - Memcached with T=1 thread, C=1 core
   - Memcached with T=1 thread, C=2 cores
   - Memcached with T=2 threads, C=1 core
   - Memcached with T=2 threads, C=2 cores

   For this question, use the following `mcperf` command to vary QPS from 5K to 120K:

   ```
   $ ./mcperf -s INTERNAL_MEMCACHED_IP --loadonly
   $ ./mcperf -s INTERNAL_MEMCACHED_IP -a INTERNAL_AGENT_IP  \
             --noload -T 16 -C 4 -D 4 -Q 1000 -c 4 -t 5 \
             --scan 5000:120000:5000
   ```

   Label the axes in your plot. State how many runs you averaged across (we recommend three runs) and include error bars. The readability of your plot will be part of your grade.

   What do you conclude from the results in your plot? Summarize in 2-3 brief sentences how memcached performance varies with the number of threads and cores.

2. **[8 points]** Now assume you need to support a memcached request load that ranges from 5K to 100K QPS while guaranteeing a 2ms 95th percentile latency SLO.

   a) To support the highest load in the trace (100K QPS) without violating the 2ms latency SLO, how many memcached threads (T) and CPU cores (C) will you need? i.e., what value of T and C would you select?

   b) Assume you can change the number of cores allocated to memcached dynamically as the QPS varies from 5K to 100K, but the number of threads is fixed when you launch the memcached job. How many memcached threads (T) do you propose to use to guarantee the 2ms 95th percentile latency SLO while the load varies between 5K to 100K QPS? i.e., what values of T would you select?

   c) Run memcached with the number of threads T that you proposed in b) above and measure performance with $C = 1$ and $C = 2$. Use the following `mcperf` command to sweep QPS from 5K to 100K:

```
$ ./mcperf -s INTERNAL_MEMCACHED_IP --loadonly
$ ./mcperf -s INTERNAL_MEMCACHED_IP -a INTERNAL_AGENT_IP  \
          --noload -T 16 -C 4 -D 4 -Q 1000 -c 4 -t 5 \
          --scan 5000:100000:5000
```

   Measure the CPU utilization on the memcached server at each 5-second load time step.

   Plot the performance of memcached using 1-core ($C = 1$) and using 2 cores ($C = 2$) in **two separate graphs**, for $C = 1$ and $C = 2$, respectively. In each graph, plot QPS on the x-axis, ranging from 5K to 100K. In each graph, use two y-axes. Plot the 95th percentile latency on the left y-axis. Draw a dotted horizontal line at the 2ms latency SLO. Plot the CPU utilization (ranging from 0% to 100% for $C = 1$ or 200% for $C = 2$) on the right y-axis. For simplicity, we do not require error bars for these plots.

3. **[15 points]** You are now given a dynamic load trace for memcached, which varies QPS randomly between 5K and 100K in 10 second time intervals. Use the following command to run this trace:

```
$ ./mcperf -s INTERNAL_MEMCACHED_IP --loadonly
$ ./mcperf -s INTERNAL_MEMCACHED_IP -a INTERNAL_AGENT_IP \
          --noload -T 16 -C 4 -D 4 -Q 1000 -c 4 -t 1800 \
          --qps_interval 10 --qps_min 5000 --qps_max 100000
```

   Note that you can also specify a random seed in this command using the `--qps_seed` flag.

   Design and implement a controller to schedule memcached and the PARSEC benchmarks on the 4-core VM. The goal of your scheduling policy is to successfully complete all PARSEC jobs as soon as possible without violating the 2ms 95th percentile latency for memcached. **Your controller should not assume prior knowledge of the dynamic load trace. You should design your policy to work well regardless of the random seed.** Also make sure to check that all the PARSEC jobs complete successfully and do not crash. Note that PARSEC jobs may fail if given insufficient resources.

Describe how you designed and implemented your scheduling policy. Include the source code of your controller in the zip file you submit. To describe your scheduling policy, you should at minimum answer the following questions. For each, also **explain why**:

- How do you decide how many cores to dynamically assign to memcached?
- How do you decide how many cores to assign each PARSEC job?
- How many threads do you use for each of the PARSEC apps?
- Which jobs run concurrently / are collocated and on which cores?
- In which order did you run the PARSEC apps?
- How does your policy differ from the policy in Part 3?
- How did you implement your policy? e.g., docker cpu-set updates, taskset updates for memcached, pausing/unpausing containers, etc.

4. **[23 points]** Run the following `mcperf` memcached dynamic load trace:

```
$ ./mcperf -s INTERNAL_MEMCACHED_IP --loadonly
$ ./mcperf -s INTERNAL_MEMCACHED_IP -a INTERNAL_AGENT_IP \
           --noload -T 16 -C 4 -D 4 -Q 1000 -c 4 -t 1800 \
           --qps_interval 10 --qps_min 5000 --qps_max 100000 \
           --qps_seed 42
```

Measure memcached and PARSEC performance when using your scheduling policy to launch workloads and dynamically adjust container resource allocations. Run this workflow 3 separate times. For each run, measure the execution time of each PARSEC job, as well as the latency outputs of memcached. For each PARSEC application, compute the mean and standard deviation of the execution time across three runs. Also compute the mean and standard deviation of the total time to complete all jobs. Fill in the table below. Also compute the SLO violation ratio for memcached for each of the three runs; the number of datapoints with 95th percentile latency > 2ms, as a fraction of the total number of datapoints.

job name	mean time [s]	std [s]
dedup		
blackscholes		
ferret		
freqmine		
canneal		
fft		
total time		

Include six plots – two plots for each of the three runs – with the following information. Label the plots as 1A, 1B, 2A, 2B, 3A, and 3B where the number indicates the run and the letter indicates the type of plot (A or B), which we describe below. In all plots, time will be on the x-axis and you should annotate the x-axis to indicate which PARSEC benchmark starts executing at which time. If you pause/unpause any workloads as part of your policy, you should also indicate the timestamps at which jobs are paused and unpaused. All the plots will have have two y-axes. The right y-axis will be QPS. For Plots A, the left y-axis will be the 95th percentile latency. For Plots B, the left y-axis will be the number of CPU cores that your controller allocates to memcached.

5. **[20 points]** Repeat Part 4 Question 4 with a modified `mcperf` dynamic load trace with a 5 second time interval (`qps_interval`) instead of 10 second time interval. Use the following command:

```
$ ./mcperf -s INTERNAL_MEMCACHED_IP --loadonly
$ ./mcperf -s INTERNAL_MEMCACHED_IP -a INTERNAL_AGENT_IP \
           --noload -T 16 -C 4 -D 4 -Q 1000 -c 4 -t 1800 \
           --qps_interval 5 --qps_min 5000 --qps_max 100000 \
           --qps_seed 42
```

You do not need to include the plots or table from Question 4 for the 5-second interval. Instead, summarize in 2-3 sentences how your policy performs with the smaller time interval (i.e., higher load variability) compared to the original load trace in Question 4. What is the SLO violation ratio for memcached (i.e., the number of datapoints with 95th percentile latency $>$ 2ms, as a fraction of the total number of datapoints) with the 5-second time interval trace?

What is the smallest `qps_interval` you can use in the load trace that allows your controller to respond fast enough to keep the memcached SLO violation ratio under 3%? Use this `qps_interval` in the command above and collect results for three runs. Include the same types of plots (1A, 1B, 2A, 2B, 3A, 3B) and table as in Question 4.

job name	mean time [s]	std [s]
dedup		
blackscholes		
ferret		
freqmine		
canneal		
fft		
total time		

5 FAQ

- When running `kops create`, if you get the following error: `failed to create file as already exists: gs://cca-eth-2021-group-XXX-ethzid/part1.k8s.local/config. error: error creating cluster: file already exists`, you need to delete the contents of your Google Cloud storage bucket, the recreate it with the following commands:

```
$ gsutil rm -r gs://cca-eth-2021-group-XXX-ethzid/
$ gsutil mb gs://cca-eth-2021-group-XXX-ethzid/
```

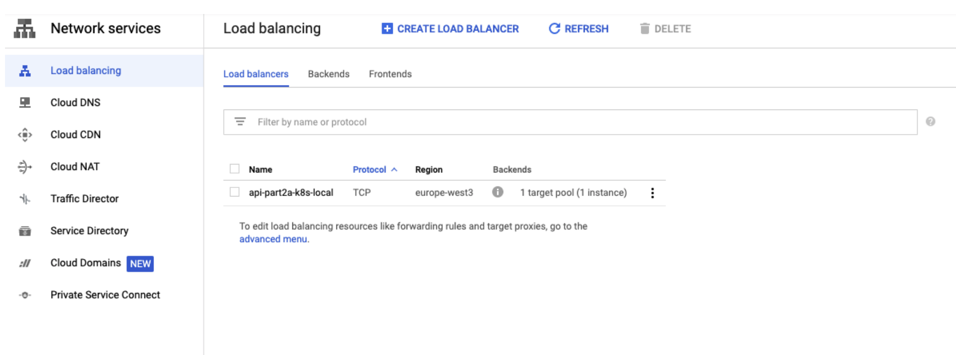
- When ssh-ing into a cluster node, if you get an error like

```
WARNING: REMOTE HOST IDENTIFICATION HAS CHANGED!
...
Offending ED25519 key in /Users/username/.ssh/known_hosts:9
...
Host key verification failed
```

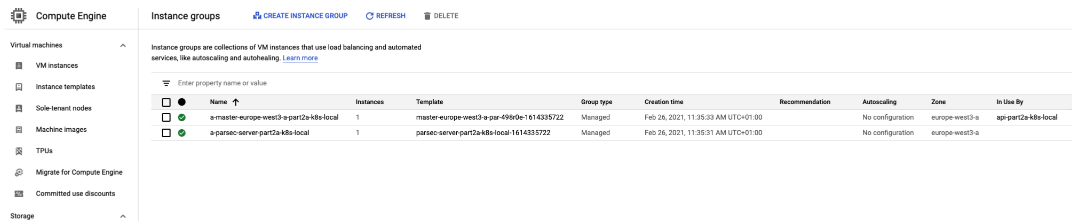
  then you need to run `ssh-keygen -R <host>` where `<host>` is the IP address of the server you want to access.

- If `kubectl` commands prompt you for a username and password, delete the cluster and recreate it from scratch.

- If for any reason you cannot delete the cluster with the `kops` command do the following:
  - Go to `console.cloud.google.com`
  - Type in the search bar the term "Load balancers". You should be redirected to a page similar to the one below:



  - Select and delete the load balancer.
  - Then type in the search bar the term "Instance groups". You should be redirected to a page similar to the one below:



  - Select and delete all the instance groups.
  - Delete your Google Cloud storage bucket by typing:
    `$ gsutil rm -r gs://cca-eth-2021-group-XXX-ethzid/`

- If you run out of credits for your project, please email cloud-arch-ta@lists.inf.ethz.ch to request additional cloud credits.