Kubernetes on NVIDIA DGX Servers

DU-09176-001 | 2018-09-12

User Guide

Document Change History

DU-09176-001

Version	Date	Authors	Description of Change
01	2018-09-12	Michael Balint, Robert Sohigian	Initial release

Table of Contents

Chapter 1. Overview

1.1 What Is Kubernetes?

Kubernetes is an open-source platform which enables users to orchestrate containerized workloads across a cluster.

For NVIDIA® DGX™ servers, Kubernetes is an especially useful way of efficiently allowing users to distribute their work across a cluster. For example, a deep learning (DL) training job can be submitted that makes the request to use eight GPUs and Kubernetes will schedule that job accordingly as GPUs become available in the cluster. Once the job is complete, another job can start using the same GPUs. Another example is a long-standing service can be set up to receive live input data and output inferenced results. Further examples are detailed in Chapter 4.

Deploying Kubernetes and forming DGX servers as a cluster requires some setup, but it is preferable to giving users direct access to individual machines. Instead of users needing to ensure that they reserve a server, Kubernetes handles scheduling their work. It also can split up a single node so that multiple users can use it at the same time. All of this ensures that GPUs are being used as efficiently as possible. User access to the cluster can still be managed, certain nodes can be tagged for privileged use, specific jobs can have resource priority over others, and jobs can write to network storage. These topics are covered starting in Chapter 5.

1.2 Choosing a Distribution

The officially-supported distribution of Kubernetes for DGX servers is known as Kubernetes on NVIDIA GPUs.

Alternatively, it is possible to leverage mainstream Kubernetes with the NVIDIA Device Plugin or GKE Kubernetes (which has its own device plugin[1] for NVIDIA GPUs).

However, these solutions will not provide the full set of features and functionality offered by Kubernetes on NVIDIA GPUs, such as:

- Heterogeneous GPU support — If there is a mix of servers with NVIDIA Tesla® P100 and V100 GPUs, it is advantageous to be able to easily schedule jobs across this variety in the cluster. This includes a whole host of other abilities, like being able to schedule a job with a GPU memory limit as part of the resource request.
- GPU monitoring and health status — The NVIDIA distribution of Kubernetes can tap into DCGM to monitor GPU state. GPU health check is also not supported in the GKE version of Kubernetes.
- Alternative container support — The NVIDIA distribution of Kubernetes supports more than just Docker. CRI-O[2] support has been added, with makes running OCI-compliant container runtimes possible. See here for instructions on how to leverage this functionality.
- New features — NVIDIA incorporates features into Kubernetes on NVIDIA GPUs well before they get added to mainstream Kubernetes.

[1] Device plugins interface with Kubernetes to advertise resources to the cluster.
[2] CRI-O is a lightweight alternative to using Docker as the container runtime for Kubernetes and allows you to run any OCI-compliant container runtime.

1.3 Accessing the Example File Archive

This PDF contains an archive file of examples used throughout the document:

- k8s-gpu-examples.nvzip

To access the attached archive, click the **Attachments** tab from the left-hand toolbar of this PDF, then select the file and click the **Save** option to retrieve it.

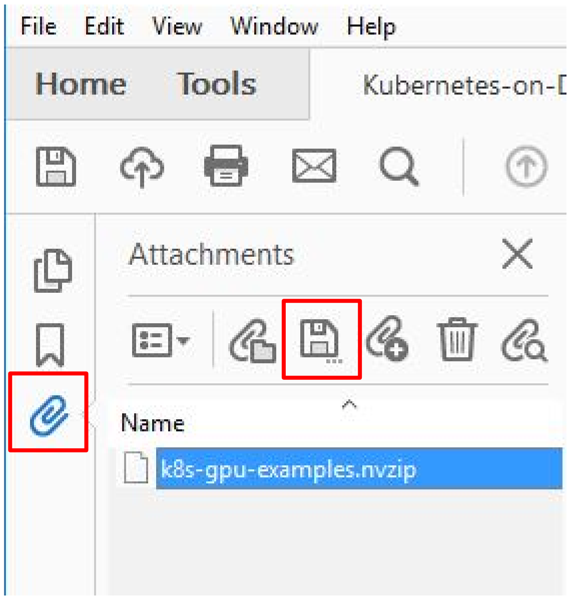


Figure 1 Accessing the Attachment

Note — The zip file attachment has been renamed with a .nvzip extension so that it can be embedded in this document. Save the attached .nvzip file and rename it to .zip before opening/extracting the file. Do not attempt to open the file from the PDF attachments tab directly.

Chapter 2. Kubernetes Basics

2.1 Getting Started

This section provides a quick introduction to getting started with Kubernetes – and may be skipped if the user is familiar with Kubernetes. For a more rigorous introduction to Kubernetes, refer to the Kubernetes Tutorials and the overall Kubernetes Documentation.

2.2 Terminology

The following table has terms that are commonly used when working with Kubernetes, which the rest of this document consistently refers to. It is helpful to be familiar with these terms and concepts.

Additional terms can be found in the Kubernetes glossary.

Term	Definition
cluster	Master and node(s)
deployment	An API object which allows an application to be deployed on a cluster. This will typically include a pod definition and the number of replicas.
job	A finite or batch task that runs to completion. Use this for scheduling DL training
kubectl	The CLI for communication with a Kubernetes cluster and deploying manifests
kubelet	The agent which runs on each node in the cluster and is responsible for making sure that containers are running in a pod.
manifest	Kubernetes is configured by editing manifest files full of metadata which define a Kubernetes object. Usually, these files are written in YAML, but they may also be written in JSON
master	Central interface for management, deployments, control, and access
namespace	Identifiers used to create virtual clusters in the same physical cluster

node	A worker machine/server in a Kubernetes cluster.
pod	Not to be confused with the hardware notion. A Kubernetes pod is the smallest atomic Kubernetes object and represents a set of running containers on a cluster. For example, a pod can include a docker container which runs an inferencing service. This pod can be deployed on a node in the cluster.
replicas	An API object which allows you to deploy an application on a cluster. This will typically include a pod definition and the number of replicas.
secret	A secret that you wish to use in pods, jobs, or deployments. For example, an API key could be saved as a secret and be leveraged when accessing a container registry.
service	An API object which describes how to access applications, such as a pod. This can be used to expose a port on a running pod and define a load-balancer.

Table 1 Commonly used Kubernetes terms

2.3 Kubernetes Manifest

Configuration in Kubernetes involves creating/editing a manifest defining a Kubernetes object and submitting them to the Kubernetes API using `kubectl`. An example manifest called `pod.yml` follows.

```
apiVersion: v1
kind: Pod
metadata:
  name: static-web
  labels:
    role: myrole
spec:
  containers:
    - name: web
      image: nginx
      ports:
        - name: web
          containerPort: 80
          protocol: TCP
```

The first line defines which version of the Kubernetes API to use when creating the object. This is typically just `v1` but can also be further specified into `batch/v1` or `apps/v1` depending on the use-case. Alpha and beta versions may also be specified. See here for more information.

Next, the `kind` of object is specified. In this case, a `Pod` is being defined. Other objects could be `Job`, `Deployment`, or `Service`.

In the `metadata` field, this object is given a name as well as any labels that should be associate with it. This is helpful for finding/filtering objects in the future.

The `spec` section then actually defines the object. Since in this case a `Pod` is being defined, the associated container(s) that should be created within it must also be defined. For this example, a `nginx` image is pulled and port 80 is opened within the `Pod`. Note that this does not make port 80 accessible for this `Pod` in the cluster. To do that, configure a `Service` object.

To deploy this pod, the `kubectl create` command would be used.

```
$ kubectl create -f pod.yml
```

Chapter 3. Installation

3.1 Choosing Between Basic and DeepOps Installs

There are two recommended methods of installation on DGX systems:

- For a basic installation, recommended for single machines (for example, an NVIDIA DGX Station™ workstation), such as a simple on-premises cluster setup or where the system administrator wishes to start from scratch and learn about each component they are implementing, install Kubernetes on NVIDIA GPUs directly per the instructions below.
- For a more advanced installation, recommended for larger clusters or more advanced usage that employ best practices, refer to the DeepOps project.

3.1.1 Basic Install

Follow the official Kubernetes on NVIDIA GPUs Installation Guide for the latest installation instructions. If Kubernetes is being installed on a single node, follow the optional instructions to untaint[3] the master node so jobs can be run on it. If installing Kubernetes on a cluster, follow the setup steps for the master first, then set up each node thereafter.

Note — The installation requires access to the NGC registry (nvcr.io) and thus will not work if the network is behind a firewall or has limitations on external connections to the internet.

[3] Taints and tolerations involve tagging nodes in your Kubernetes cluster with special flags so that future work might be scheduled (or avoided) on them.

If any problems are encountered with installation or setup, file an issue on the NVIDIA Kubernetes github.

3.1.2 DeepOps Install

The DeepOps project facilitates deployment of multi-node GPU clusters for DL and HPC environments. It is strongly recommended that system administrators use DeepOps to bring up their DGX clusters since it employs best practices when it comes to setting up things such as storage and configuring authentication and user access.

To install, follow the instructions in the DeepOps README.

Chapter 4. Use Cases

4.1 Introduction

Most of the following use cases can be configured and executed through the Kubernetes Web UI (Dashboard). For a basic run-through on how to leverage the Kubernetes Web UI, reference the Kubernetes Web UI documentation. The following examples use the terminal on the master instead.

4.2 Using NGC Containers with Kubernetes and Launching Jobs

NVIDIA GPU Cloud (NGC) manages a catalog of fully integrated and optimized DL framework containers that take full advantage of NVIDIA GPUs in both single and multi-GPU configurations. They include NVIDIA CUDA® Toolkit, DIGITS workflow, and the following DL frameworks: NVCaffe, Caffe2, Microsoft Cognitive Toolkit (CNTK), MXNet, PyTorch, TensorFlow, Theano, and Torch. These framework containers are delivered ready-to-run, including all necessary dependencies such as the CUDA runtime and NVIDIA libraries.

To access the NGC container registry via Kubernetes, add a secret which will be employed when Kubernetes asks NGC to pull container images from it.

1. Generate an NGC API Key, which will be used for the Kubernetes secret.
   a) Login to the NGC Registry at https://ngc.nvidia.com/
   b) Go to https://ngc.nvidia.com/configuration/api-key
   c) Click on GENERATE API KEY

2. Using the NGC API Key, create a Kubernetes `secret` so that Kubernetes will be able to pull container images from the NGC registry. Create the secret by running the following command on the master (substitute the registered email account and secret in the appropriate locations).

```
$ kubectl create secret docker-registry nvcr.dgxkey –docker-
server=nvcr.io --docker-username=\$oauthtoken --docker-email=<email>
--docker-password=<NGC API Key>
secret "nvcr.dgxkey" created
```

3. Launch a Kubernetes Job using the secret.

   Now that a secret exists, a `cuda-job.yml` file for execution can be defined.

```
apiVersion: batch/v1
kind: Job
metadata:
  name: cuda-job
spec:
  backoffLimit: 5
  template:
    spec:
      imagePullSecrets:
        - name: nvcr.dgxkey
      containers:
        - name: cuda-container
          image: nvcr.io/nvidia/cuda:9.0-cudnn7.1-devel-ubuntu16.04
          command: ["nvidia-smi"]
          args: ["-L"]
          extendedResourceRequests: ["nvidia-gpu"]
      restartPolicy: Never
      extendedResources:
        - name: "nvidia-gpu"
          resources:
            limits:
              nvidia.com/gpu: 1
            requests:
              nvidia.com/gpu: 1
```

Note — the preceding yaml file uses the secret (via the imagePullSecrets definition) and connects to nvcr.io to pull the cuda container from the NGC container registry. This job has been defined to use a single GPU in the extendedResources section.

4. Execute the job.

```
$ kubectl create -f ./cuda-job.yml
```

5. Check the job.

```
$ kubectl get jobs
```

   The job will launch a pod, which will terminate upon completion.

6. Monitor it.

```
$ kubectl get pods --show-all
```

7. Follow the logs to see output (note that the pod name will differ from the job name and will have some random characters at the end of it).

   ```
   $ kubectl logs -f <cuda-pod-name>
   ```

   There will eventually see a single line listing the GPU allocated to this pod

8. To delete the job (this will also remove the pod).

   ```
   $ kubectl delete job cuda-job
   ```

For more background on Kubernetes jobs, including how they are executed and available parameters, refer to the official documentation on the topic.

4.3 Running a PyTorch Training Job

Running a DL training job follows the same convention.

1. Ensure that a Kubernetes secret is set up for access to the NGC Registry.
2. Define `pytorch-job.yml`.

   ```
   apiVersion: batch/v1
   kind: Job
   metadata:
     name: pytorch-example
   spec:
     backoffLimit: 5
     template:
       spec:
         imagePullSecrets:
           - name: nvcr.dgxkey
         containers:
           - name: pytorch-container
             image: nvcr.io/nvidia/pytorch:18.08-py3
             command: ["/bin/sh"]
             args: ["-c", "python
   /workspace/examples/upstream/mnist/main.py"]
             extendedResourceRequests: ["nvidia-gpu"]
         restartPolicy: Never
         extendedResources:
           - name: "nvidia-gpu"
             resources:
               limits:
                 nvidia.com/gpu: 4
               requests:
                 nvidia.com/gpu: 4
   ```

3. Execute the job.

   ```
   $ kubectl create -f ./pytorch-job.yml
   ```

4. Check the progress of the training job.

```
$ kubectl get pods
<pytorch-example pod name>
```

5. Observe name of `pytorch-example` pod and request the logs from the pod.

```
$ kubectl logs <pytorch-example pod name>
Downloading http://yann.lecun.com/exdb/mnist/train-images-idx3-
ubyte.gz
Downloading http://yann.lecun.com/exdb/mnist/train-labels-idx1-
ubyte.gz
Downloading http://yann.lecun.com/exdb/mnist/t10k-images-idx3-
ubyte.gz
Downloading http://yann.lecun.com/exdb/mnist/t10k-labels-idx1-
ubyte.gz
Processing...
Done!
main.py:68: UserWarning: Implicit dimension choice for log_softmax
has been deprecated. Change the call to include dim=X as an
argument.
return F.log_softmax(x)
main.py:90: UserWarning: invalid index of a 0-dim tensor. This will
be an error in PyTorch 0.5. Use tensor.item() to convert a 0-dim
tensor to a Python number
100. * batch_idx / len(train_loader), loss.data[0]))
Train Epoch: 1 [0/60000 (0%)]   Loss: 2.373651
Train Epoch: 1 [640/60000 (1%)] Loss: 2.310517
Train Epoch: 1 [1280/60000 (2%)]            Loss: 2.281828
Train Epoch: 1 [1920/60000 (3%)]            Loss: 2.315808
Train Epoch: 1 [2560/60000 (4%)]            Loss: 2.235439
Train Epoch: 1 [3200/60000 (5%)]            Loss: 2.234249
Train Epoch: 1 [3840/60000 (6%)]            Loss: 2.226109
Train Epoch: 1 [4480/60000 (7%)]            Loss: 2.228646
Train Epoch: 1 [5120/60000 (9%)]            Loss: 2.132811
```

4.4 TensorRT Inferencing as a Service

Kubernetes is particularly well-suited for deploying inferencing services since it is generally used to deploy and scale web services. Features like self-healing (auto-restarting, re-scheduling, and replicating containers to ensure they are in a `Running` state are met per deployment specifications) and hybrid scaling (the ability to run containers across multiple nodes that might not be co-located – for example, nodes that are on-premises vs nodes that are in the cloud). This section discusses a toy inferencing example and then gives some recommendations for production inferencing.

4.4.1 Inferencing Toy Example

Inferencing in a production environment has many considerations, but for a toy example, we'll keep things simple by running a single Kubernetes pod and expose it with a service. Since we want a long-standing service, we will not be using a job and instead launch our pod and corresponding service as a Kubernetes deployment. Note that this example uses an older version of TensorRT, which includes an inferencing server.

In the following `tensorrt-service-deployment.yml` file, a Kubernetes deployment which launches a TensorRT pod is defined.

```
apiVersion: apps/v1
kind: Deployment
metadata:
  name: tensorrt-deployment
  labels:
    app: tensorrt
spec:
  replicas: 1
  selector:
    matchLabels:
      app: tensorrt
  template:
    metadata:
      labels:
        app: tensorrt
    spec:
      imagePullSecrets:
        - name: nvcr.dgxkey
      containers:
        - name: tensorrt-container
          image: nvcr.io/nvidia/tensorrt:17.12
          command: ["/bin/sh"]
          args: ["-c", "tensorrt_server/onnx_inception_v1"]
          ports:
            - containerPort: 8000
          extendedResourceRequests: ["nvidia-gpu"]
      extendedResources:
        - name: "nvidia-gpu"
          resources:
            limits:
              nvidia.com/gpu: 4
            requests:
              nvidia.com/gpu: 4
---
apiVersion: v1
kind: Service
metadata:
  labels:
    run: tensorrt-service
  name: tensorrt-service
spec:
  ports:
    - port: 8000
      targetPort: 8000
  selector:
    app: tensorrt-server
  type: NodePort
```

Scale in this deployment can be increased by incrementing the `replicas` count. Port 8000 is also exposed, which is leveraged by the service definition at the end of the file. For more on services, the various service types, and how to expose specific ports, refer to the official Kubernetes documentation.

1. To run this deployment, execute the following on the master.

   ```
   $ kubectl create -f ./tensorrt-deployment.yml
   deployment "tensorrt-deployment" created
   service "tensorrt-service" created
   ```

2. Ensure the pod is running.

   ```
   $ kubectl get pods
   NAME                   READY     STATUS    RESTARTS   AGE
   tensorrt-deployment    1/1       Running   0          47m
   ```

3. Make a request to the exposed service endpoint to run inferencing on the data.

   ```
   $ curl --data-binary @rex.jpg \
       http://127.0.0.1:8000/api/classify
   { "confidence" : 0.5003, "label" : "DINGO" },
   { "confidence" : 0.4035, "label" : "KELPIE" },
   { "confidence" : 0.0692, "label" : "BASENJI" }
   ]
   ```

4.4.2 Deploying Inferencing in a Production Environment

4.4.2.1 Using the NGC Inference Server Container

For running inferencing in production, use the latest version of the Inference Server container provided on NGC. Consult the Inference Server User Guide for more information on leveraging this container.

4.4.2.2 Deploying a Load Balancer or Ingress Service

The deployment in the toy example above only uses one replica and is exposed through a service using the `NodePort` type. Scaling the deployment can be done by increasing the number of replicas. Production deployments should consider leveraging a LoadBalancer service type or committing to using an Ingress resource.

4.5 Leveraging Kubeflow Across the Cluster

Kubeflow runs on Kubernetes, creating an easy-to-use, scalable way of building ML models in TensorFlow and PyTorch, as well as leveraging those models in production. Additionally, a multi-tenant Jupyter notebook frontend can be enabled, allowing users on the cluster to request GPU resources and write their code without needing to know anything about Kubernetes or containers. Users simply point their browser to the Kubeflow service, request resources, and start coding in python.

See this video for a demo of Kubeflow in action.

4.5.1 Installation

For comprehensive installation instructions, follow the Kubeflow User Guide. Below are abbreviated instructions on how to get set up quickly.

1. Download ksonnet[4].

   Download the latest ksonnet Linux amd64 release to the master.

   ```
   $ wget
   https://github.com/ksonnet/ksonnet/releases/download/v0.12.0/ks_0.12
   .0_linux_amd64.tar.gz
   ```

2. Unpack the release.

   ```
   $ tar -xzf ks_0.12.0_linux_amd64.tar.gz
   ```

3. Move the `ks` binary to `/usr/local/bin/`.

   ```
   $ sudo cp ks_0.12.0_linux_amd64/ks /usr/local/bin/
   ```

4. Install Kubeflow.

   ```
   $ export KUBEFLOW_VERSION=0.2.5
   ```

   Kubeflow 0.2.5 is recommended by this guide as it was tested to work with Kubernetes on NVIDIA GPUs v1.9.7. Installing a more recent release may be attempted. For kubeflow releases see: https://github.com/kubeflow/kubeflow/releases

5. Run the deployment script for a quick and easy setup.

   ```
   $ mkdir kubeflow && cd kubeflow
   $ curl
   https://raw.githubusercontent.com/kubeflow/kubeflow/v${KUBEFLOW_VERS
   ION}/scripts/deploy.sh | bash
   ```

[4] Ksonnet is a tool which allows you to write, package, and deploy apps on Kubernetes. It leverages reusable json snippets to define the app.

4.5.2 Ensure That Storage Is Connected (Or Disable It)

Kubeflow (specifically Jupyter) expects persistent volumes to be attached. Before launching a Jupyter Notebook server, ensure that storage is connected. For NFS, refer to the section in this document on how to define a PersistentVolume for NFS.

Alternatively, the requirement for storage may be disabled by running the following commands. Be aware that any code created in a Jupyter Notebook won't persist, should the cluster be taken down.

(cd to the kubeflow_ks_app directory…)

```
$ ks param set kubeflow-core jupyterNotebookPVCMount "null"
$ ks apply default
```

4.5.3 Turn Usage Reporting Off (Optional)

Note that usage reporting is turned on by default. To disable it, run the following commands…

(cd to the kubeflow_ks_app directory…)

```
$ ks param set kubeflow-core reportUsage false
$ ks apply default
$ kubectl delete deploy spartakus-volunteer
```

4.5.4 Bringing Up a Jupyter Notebook

1. Connect to the Jupyter Notebook on the master.

   ```
   $ PODNAME=`kubectl get pods --namespace=${NAMESPACE} --
   selector="app=tf-hub" --output=template --template="{{with index
   .items 0}}{{.metadata.name}}{{end}}"`
   $ kubectl port-forward --namespace=${NAMESPACE} $PODNAME 8000:8000
   ```

2. Open a browser and go to `http://localhost:8000`

3. To expose Kubeflow externally so it can be accessed anywhere on the same network, change the service type and expose it.

   ```
   $ ks param set kubeflow-core jupyterHubServiceType NodePort
   $ ks apply default
   $ kubectl get services
   ```

4. Look for the NodePort `tf-hub` service and associated port.

   ```
   $ kubectl get services | grep tf-hub
   tf-hub-0    ClusterIP   None            <none>    8000/TCP       2m
   tf-hub-lb   NodePort    10.97.38.143    <none>    80:30303/TCP   2m
   ```

   The tf-hub-port in this case is 30303.

   Go to http://<master>:<tf-hub-port>

5. At the sign-in prompt, sign-in using any username/password. Sign in using any username/password

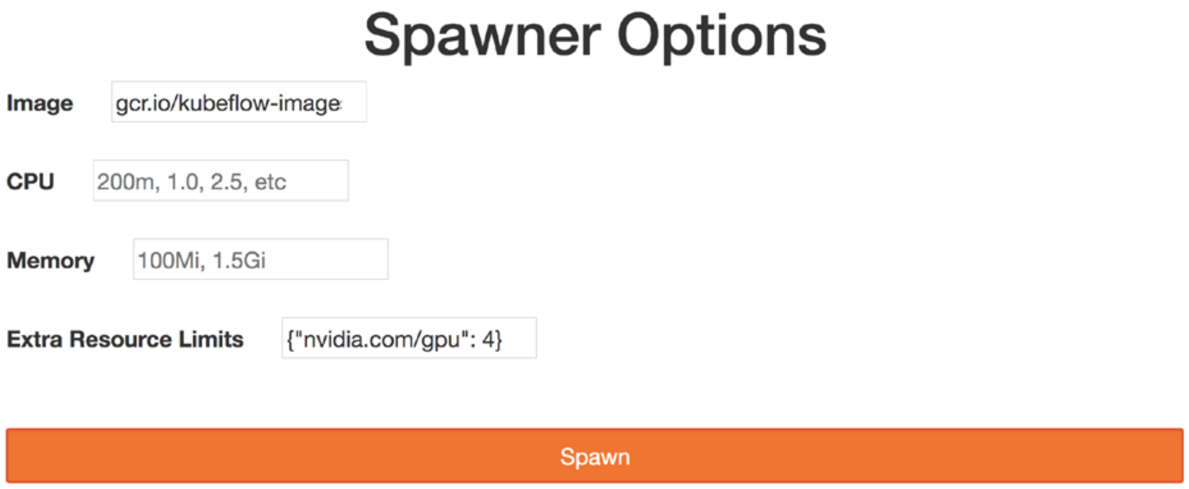

Spawner Options

Image: gcr.io/kubeflow-image

CPU: 200m, 1.0, 2.5, etc

Memory: 100Mi, 1.5Gi

Extra Resource Limits: {"nvidia.com/gpu": 4}

6. Select a CPU or GPU image from the Image dropdown menu depending on what type of training is being done. CPU and GPU images for each TensorFlow minor version(e.g.: 1.4.1,1.5.1,1.6.0) are available. Another option is to enter the name of any TF image to be run.
7. Allocate memory, CPU, GPU, or other resources as needed.

   Request GPU resources by specifying the following json in Extra Resource Limits section: `{"nvidia.com/gpu": 1}`
8. Click Spawn (note that the images are tens of GBs in size and can take a long time to download depending on the network connection).

   The Jupyter Notebook interface should launch.
9. Test that the instance has access to GPUs via in a new Jupyter Notebook:

```
!!nvidia-smi
```

The resulting output should show a line for each GPU that was requested for the instance.

10. Run a script leveraging TensorFlow with MNIST data.

```
from tensorflow.examples.tutorials.mnist import input_data
mnist = input_data.read_data_sets("MNIST_data/", one_hot=True)
import tensorflow as tf
x = tf.placeholder(tf.float32, [None, 784])
W = tf.Variable(tf.zeros([784, 10]))
b = tf.Variable(tf.zeros([10]))
y = tf.nn.softmax(tf.matmul(x, W) + b)
y_ = tf.placeholder(tf.float32, [None, 10])
cross_entropy = tf.reduce_mean(-tf.reduce_sum(y_ * tf.log(y), reduction_indices=[1]))
```

```
train_step = tf.train.GradientDescentOptimizer(0.05).minimize(cross_entropy)
sess = tf.InteractiveSession()
tf.global_variables_initializer().run()
for _ in range(1000):
  batch_xs, batch_ys = mnist.train.next_batch(100)
  sess.run(train_step, feed_dict={x: batch_xs, y_: batch_ys})
correct_prediction = tf.equal(tf.argmax(y,1), tf.argmax(y_,1))
accuracy = tf.reduce_mean(tf.cast(correct_prediction, tf.float32))
print(sess.run(accuracy, feed_dict={x: mnist.test.images, y_: mnist.test.labels}))
```

Chapter 5. Using Persistent Storage

5.1 Introduction

Kubernetes pods are meant to be stateless and thus on-disk files in pod containers are ephemeral. Setting up a more permanent storage source is crucial for saving users' work.

5.2 Using NFS

Several storage objects must be deployed in Kubernetes before pods can access them as a permanent storage source. A `PersistentVolume` must first be defined to represent a storage volume. For this example, we will leverage NFS via one of the servers in our cluster, but it is possible to swap this configuration for another volume type. Then, a `PersistentVolumeClaim` can be defined to serve as a binding between a `Pod` and the previously defined `PersistentVolume`. Finally, when deploying a pod, the `PersistentVolumeClaim` can be specified in the `Pod` definition to reserve the disk space. It is assumed that an NFS server is already running and accessible from the cluster.

1. Define a `nfs-pv.yml` file for the `PersistentVolume`.

```
apiVersion: v1
kind: PersistentVolume
metadata:
  name: nfs-pv
spec:
  capacity:
    storage: 10Gi
  accessModes:
    - ReadWriteMany
  nfs:
    server: <nfs_server>
    path: <nfs_mount_path>
```

Note that this defines the capacity for the volume as 10 GB with a `ReadWriteMany` access mode (meaning that this volume can be mounted as read-write by many nodes). Also observe that the spec references the NFS driver, defining a server IP and directory path to mount from. Make sure to change both values (`<nfs_server>` and `<nfs_mount_path>`). Consult the official Kubernetes documentation on persistent volumes to learn more about additional options, such as defining a reclaim policy or mount options.

2. Create the persistent volume.

```
$ kubectl apply -f ./nfs-pv.yml
persistentvolume "nfs-pv" created
```

3. Verify that the persistent volume was created.

```
$ kubectl get pv
NAME    LABELS  CAPACITY ACCESSMODES STATUS     CLAIM  REASON  AGE
nfs-pv  <none>  10Gi     RWX         Available                 10s
```

4. Define a `nfs-pvc.yml` file for the `PersistentVolumeClaim`.

```
kind: PersistentVolumeClaim
apiVersion: v1
metadata:
  name: nfs-pvc
spec:
  accessModes:
    - ReadWriteMany
  storageClassName: ""
  resources:
    requests:
      storage: 10Gi
```

This persistent volume claim (PVC) will search for a compatible persistent volume (PV) to bind with - using the access mode and storage request as matching criteria. Note that we define the `storageClassName` as an empty string to avoid the PVC searching for storage on the default storage class. Alternatively, a storage class could be defined for both the PV and PVC.

Once bound, the PV will not be able to bind with another PVC, but multiple pods in the same cluster can use the same PVC.

5. Create the persistent volume claim.

```
$ kubectl apply -f ./nfs-pvc.yml
persistentvolumeclaim "nfs-pvc" created
```

6. Verify that the persistent volume claim was created.

```
$ kubectl get pvc
NAME     LABELS  STATUS  VOLUME  CAPACITY   ACCESSMODES   AGE
nfs-pvc  <none>  Bound   nfs-pv  10Gi       RWO           10s
```

7. Use the PVC in a pod.

```
apiVersion: v1
kind: Pod
metadata:
  name: nfs-pod
spec:
  imagePullSecrets:
    - name: nvcr.dgxkey
  containers:
    - name: pytorch-container
      image: nvcr.io/nvidia/pytorch:18.05-py3
      command: [ "/bin/bash", "-c", "--" ]
      args: [ "while true; do sleep 30; done;" ]
      extendedResourceRequests: ["nvidia-gpu"]
      volumeMounts:
        - name: nfs-vol
          mountPath: /nfs
  volumes:
    - name: nfs-vol
      persistentVolumeClaim:
        claimName: nfs-pvc
  extendedResources:
    - name: "nvidia-gpu"
      resources:
        limits:
          nvidia.com/gpu: 1
        requests:
          nvidia.com/gpu: 1
```

This pod will spin up the PyTorch container from NGC (as shown in a previous example) and will mount the NFS share within the container at the `/nfs` mount point. Since the PV and corresponding PVC were defined to retain data, all files written to this location within the container will remain on the NFS after the pod is restarted or deleted.

8. Deploy the pod.

```
$ kubectl create -f nfs-pod.yml
Pod "nfs-pod" was created
```

9. Use a shell on the running pod to verify the mount point.

```
$ kubectl exec -it nfs-pod -- /bin/bash
root@nfs-pod:/workspace# cd /nfs && touch test123
```

The new file `test123` should now exist on the nfs share (check by verifying the share).

5.3 Using Rook with Ceph

Rook provides an abstraction layer for orchestrating, managing, and scaling, cluster storage. We recommend using Rook with Ceph as a means for providing persistent storage on Kubernetes clusters of DGX servers.

Ceph is advantageous because 1) it is capable of multiple storage types (block, object, and file storage), 2) it provides a means to scale-out storage on multiple nodes but present itself as a single system, and 3) it has many enterprise storage features including replication (or erasure encoding), snapshots, thin provisioning, tiering (ability to shift data between flash and hard drives), and self-healing capabilities.

5.3.1 Performing a DeepOps or Manual Installation

DeepOps is the preferred method for installing Rook and Ceph. It automates the setup of Kubernetes clusters through Ansible scripts that systems administrators can pick and choose from or run entirely.

If DeepOps is not to be used, instructions for a manual installation of Rook and Ceph are also given.

5.3.1.1 DeepOps Installation

DeepOps is the preferred method for installing Rook and Ceph. It automates the setup of Kubernetes clusters through Ansible scripts that systems administrators can pick and choose from or run entirely. Directions on using it are available via the Management Server Setup instructions.

5.3.1.2 Manual Installation

If DeepOps is not leveraged, the Rook GitHub repository can be used instead. Setup is facilitated by using the examples directory contained within it.

1. Clone the repository.

   This step requires git.

   ```
   $ git clone https://github.com/rook/rook.git
   ```

2. cd to examples in the cluster/examples/kubernetes directory.

   ```
   $ cd cluster/examples/kubernetes/ceph
   ```

3. Use the operator and cluster manifests to start rook and ceph.

   ```
   $ kubectl create -f operator.yaml
   $kubectl create -f cluster.yaml
   ```

4. Verify that rook-ceph-operator, rook-ceph-agent, and rook-discover pods are in the `Running` state before proceeding.

   ```
   $ kubectl -n rook-ceph-system get pods
   ```

```
NAME                                READY     STATUS      RESTARTS   AGE
rook-ceph-operator-6f5cf4cc77-mj92t 1/1       Running     0          1m
rook-ceph-agent-flw5v               1/1       Running     0          1m
rook-discover-l6q8r                 1/1       Running     0          1m
```

5.3.2 Using Rook Storage

Rook storage can be leveraged as a block, object, or shared file system.

Follow these links for examples of how to use Rook and Ceph with pods:

- Block: Create block storage to be consumed by a pod
- Object: Create an object store that is accessible inside or outside the Kubernetes cluster
- Shared File System: Create a file system to be shared across multiple pods

5.3.3 Teardown

To remove the Rook setup, follow the teardown directions.

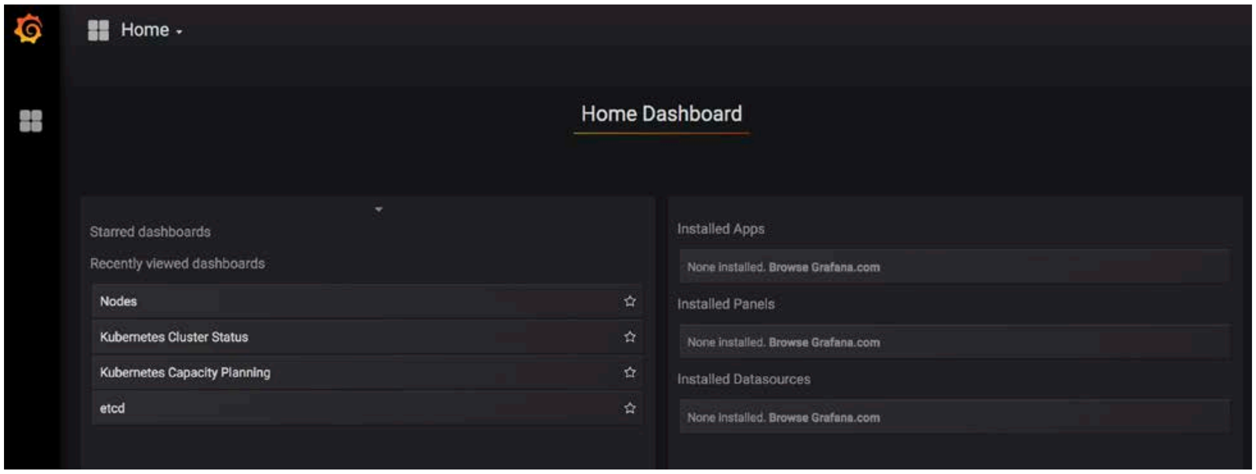
Chapter 6. Monitoring the Cluster

6.1 Leveraging DCGM, Prometheus, and Grafana for Monitoring

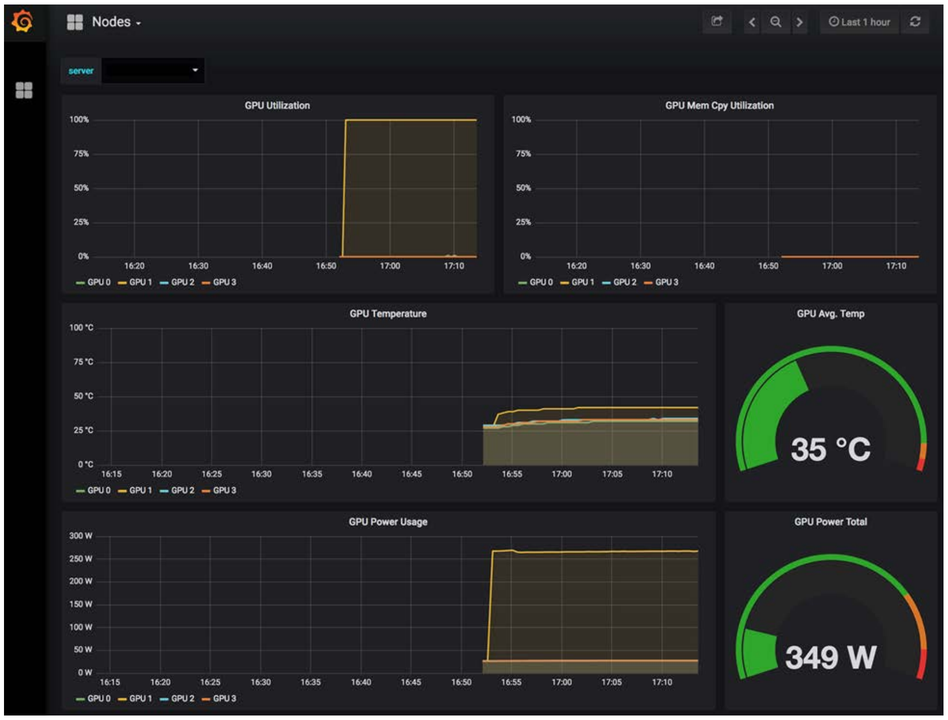
An integrated monitoring stack is provided with NVIDIA Kubernetes deployments. It can be initialized by following the directions in the installation guide. Once set up, access must be done either through a browser on the master (go to http://localhost:3000) or by looking for the Grafana service port.

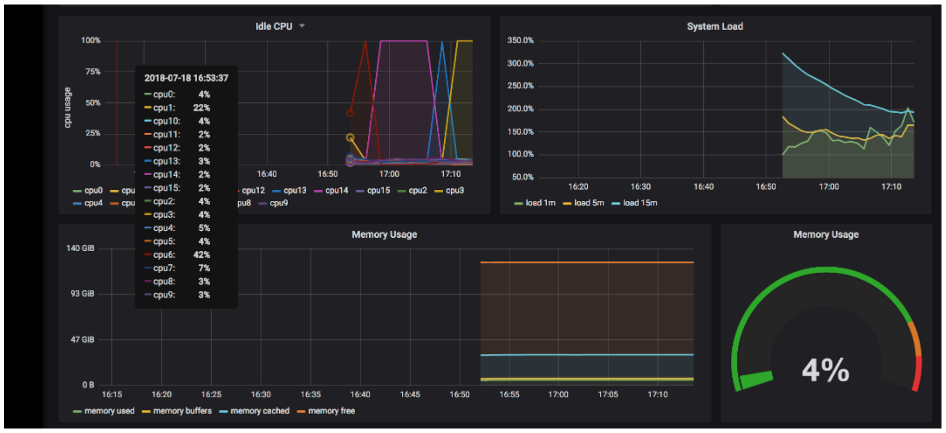
```
$ kubectl get services --all-namespaces |grep grafana
monitoring grafana NodePort 10.x.x.x <none> 3000:30902/TCP 14m
```

In this example, navigating to http://<machine_ip>:30902 shows the grafana home page.

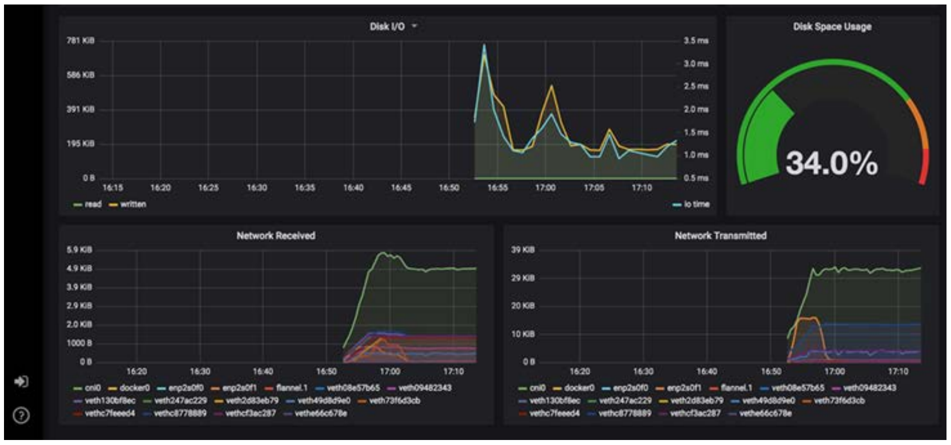

Home
Home Dashboard
Starred dashboards
Recently viewed dashboards
Nodes
Kubernetes Cluster Status
Kubernetes Capacity Planning
etcd
Installed Apps
None installed. Browse Grafana.com
Installed Panels
None installed. Browse Grafana.com
Installed Datasources
None installed. Browse Grafana.com

Click on Home → Nodes to view GPU stats for the nodes.



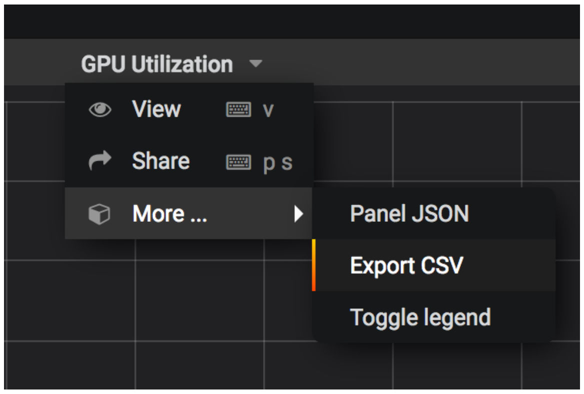


```
2018-07-18 16:53:37
cpu0:    4%
cpu1:   22%
cpu10:   4%
cpu11:   2%
cpu12:   2%
cpu13:   3%
cpu14:   2%
cpu15:   2%
cpu2:    4%
cpu3:    4%
cpu4:    5%
cpu5:    4%
cpu6:   42%
cpu7:    7%
cpu8:    3%
cpu9:    3%
```

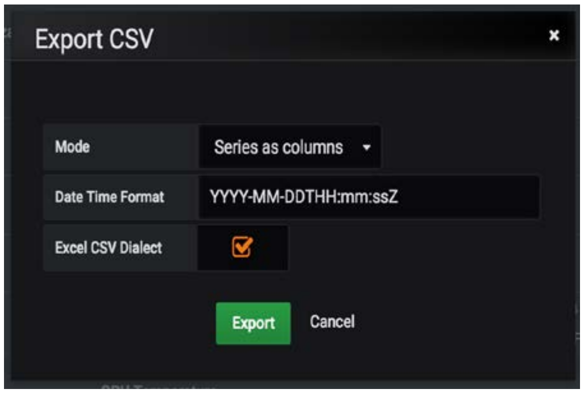


6.2 Generating a Usage Report

Exporting data from grafana dashboards is a useful way of generating a usage report. In the upper right hand corner of the dashboard, click on the time-period to be covered. Then, click on a title bar of the graph and select More → Export CSV.



For GPU Utilization, using “series as columns” generates the best results.


Export CSV

Mode: Series as columns
Date Time Format: YYYY-MM-DDTHH:mm:ssZ
Excel CSV Dialect: ✓

Chapter 7. Additional Setup

The setup documented in this section is not required but is useful to refer to as necessary.

7.1 Adding a Node to the Cluster

Whether adding a new node on-premises or in the cloud, all that is required is

1. Install and run Kubernetes on the node to be added.

   Follow the instructions in the installation guide.

2. Instruct the node to join the cluster.

```
$ sudo kubeadm join --token <token> <master-ip>:<master-port> --
discovery-token-ca-cert-hash sha256::<hash> --ignore-preflight-
errors=all
```

3. Retrieve the `token` on the master by running the following command.

```
$ sudo kubeadm token create --print-join-command
```

7.2 Using Helm to Manage Kubernetes Software

Helm is a tool that streamlines installation and management of Kubernetes applications. Think of it like apt/yum/homebrew for Kubernetes. Helm charts are the equivalents of packages on Kubernetes - complete with package release versions and the ability to roll back from new installations. For more on Helm, how to make Helm charts, and other information on Helm, refer to the official docs.

Helm has two parts: the Helm client (`helm`) and the Helm server (Tiller).

Tiller runs inside of a Kubernetes cluster, and manages releases (installations) of charts. `helm` runs on a laptop, CI/CD, etc.

Refer to Helm releases page for the latest version of Helm.

1. Use the installation script for the release on the master to install Tiller.

```
$ wget https://storage.googleapis.com/kubernetes-helm/helm-v2.9.1-
linux-amd64.tar.gz -O get-helm.run && chmod 777 get-helm.run && bash
./get-helm.run
```

2. Ensure that Tiller is running on the Kubernetes cluster.

```
$ kubectl get pods --all-namespaces |grep tiller
kube-system   tiller-deploy-689869587f-pq5nt  1/1  Running  0  5m
```

3. Start `helm` by setting up the ServiceAcount, ClusterRoleBinding, and initializing it.

```
kubectl create sa tiller --namespace kube-system
kubectl create clusterrolebinding tiller --clusterrole cluster-admin
--serviceaccount=kube-system:tiller
helm init --service-account tiller --node-selectors node-
role.kubernetes.io/master=true
```

4. Use the `helm search` command to explore available charts.

```
$ helm search
<lists available packages>
$ helm search tensorflow
stable/distributed-tensorflow  0.1.1  1.6.0   A Helm chart for
running distributed TensorFlow...
stable/tensorflow-notebook     0.1.2  1.6.0   A Helm chart for
tensorflow notebook and tensor...
stable/tensorflow-serving      0.1.2  1.14.0  TensorFlow Serving is
an open-source software l…
Inspect a chart…
$ helm inspect stable/tensorflow-serving
<shows details of chart>
Install the chart…
$ helm install stable/tensorflow-serving
<installs the chart on the cluster>
```

7.3 Configuring User Access with RBAC

Role-based access control (RBAC) provides a way to regulate access to the Kubernetes cluster based upon roles that can be defined by the cluster administrator. Additionally, authentication may be performed through an Identity Provider (IdP), such as Google or LDAP via OpenID token. This section covers a basic use case for leveraging RBAC and namespaces. Namespaces are virtual clusters backed by the same physical cluster which are a convenient way of segmenting deployments, especially for clusters that have many users and teams.

For more information on RBAC, refer to the Kubernetes guide on the topic. A more automated setup of users with admin privileges in the cluster can leverage the DeepOps scripts.

Note —RBAC should be enabled by default. If it is not, it might be necessary to start the apiserver with `--authorization-mode=RBAC`.

In this example, a user with limited namespace access will be created with the following account information:

- Username: employee
- Group: nvidia

The necessary RBAC policies will be added so this user can fully manage deployments (i.e. use kubectl run command) only inside the office namespace. At the end, the policies will be tested to make sure they work as expected.

1. Create the nvidia-team Namespace.

Execute the kubectl create command to create the namespace (as the admin user):

```
$ kubectl create namespace nvidiateam
```

As previously mentioned, Kubernetes does not have API Objects for User Accounts. Of the available ways to manage authentication (see Kubernetes official documentation for a complete list), we will use OpenSSL certificates for their simplicity. The necessary steps are:

2. Create a private key for the user.

   In this example, the file is named `employee.key`.

   ```
   $ openssl genrsa -out employee.key 2048
   ```

3. Create a certificate sign request employee.csr using the private key was just created.

   Make sure to specify the username and group in the `-subj` section (`CN` is for the username and `O` for the group

   ```
   $ openssl req -new -key employee.key -out employee.csr -subj
   "/CN=employee/O=nvidia"
   ```

4. Locate the Kubernetes cluster certificate authority (CA).

   This will be responsible for approving the request and generating the necessary certificate to access the cluster API. Its location is normally /etc/kubernetes/pki/. Check that the files ca.crt and ca.key exist in the location.

5. Generate the final certificate employee.crt by approving the certificate sign request, employee.csr, made earlier.

   Substitute the CA_LOCATION placeholder with the location of the cluster CA. In this example, the certificate will be valid for 500 days.

```
$ openssl x509 -req -in employee.csr -CA CA_LOCATION/ca.crt -CAkey
CA_LOCATION/ca.key -CAcreateserial -out employee.crt -days 500
```

6. Save both employee.crt and employee.key in a safe location.

   In this example, `/home/employee/.certs/` will be used.

7. Add a new context with the new credentials for the Kubernetes cluster.

```
$ kubectl config set-credentials employee --client-
certificate=/home/employee/.certs/employee.crt  --client-
key=/home/employee/.certs/employee.key
$ kubectl config set-context employee-context --namespace=nvidiateam
--user=employee
```

8. An access denied error should be generated when using the kubectl CLI with this configuration file. This is expected as permitted operations have not yet been defined for this user.

```
$ kubectl --context=employee-context get pods
```

9. Create the Role for Managing Deployments

   Create a role-deployment-manager.yaml file with the content below. This yaml file creates a rule that allows a user to execute several operations on Deployments, Pods and ReplicaSets (necessary for creating a Deployment), which belong to the core (expressed by "" in the yaml file), apps, and extensions API Groups.

```
kind: Role
  apiVersion: rbac.authorization.k8s.io/v1beta1
  metadata:
    namespace: office
    name: deployment-manager
  rules:
  - apiGroups: ["", "extensions", "apps"]
    resources: ["deployments", "replicasets", "pods"]
    verbs: ["get", "list", "watch", "create", "update", "patch",
"delete"] # You can also use ["*"]
```

10. Create the Role in the cluster.

```
$ kubectl create -f role-deployment-manager.yaml
```

11. Bind the role to the Employee User.

Create a rolebinding-deployment-manager.yaml file with the content below. In this file, the deployment-manager Role is being bound to the User Account employee inside the office namespace.

```
kind: RoleBinding
  apiVersion: rbac.authorization.k8s.io/v1beta1
  metadata:
    name: deployment-manager-binding
    namespace: office
  subjects:
  - kind: User
    name: employee
    apiGroup: ""
  roleRef:
    kind: Role
    name: deployment-manager
    apiGroup: ""
```

12. Deploy the RoleBinding.

```
$ kubectl create -f rolebinding-deployment-manager.yaml
```

13. Test the RBAC Rule.

```
$ kubectl --context=employee-context run --image nginx nginx
$ kubectl --context=employee-context get pods
```

Running the same command with the `--namespace=default` argument will fail, as the employee user does not have access to this namespace.

```
$ kubectl --context=employee-context get pods --namespace=default
```

7.4 Securing a Cluster

Securing the cluster is important — and there are many potential security pitfalls that can be exposed when leveraging Kubernetes. For a basic setup, consider the following.

- **Restrict access to kubectl:** Prevent unauthorized users from accessing the cluster
- **Use RBAC and namespaces:** Use role-based access control to define roles with rules containing a set of permissions
- **Use a Network Policy**: Control pod-to-pod traffic (open by default)
- **Protect Kubernetes UI / Dashboard:** Either disable it or restrict access, as it uses a highly-privileged Kubernetes service account
- **Disable account token:** Disable the automatic mounting of the service account token, as it can be abused by an attacker
- **Use pod Security Policy:** Enable Docker seccomp and other security restrictions

A security benchmark analyzer, such as the Kubernetes Auto Analyzer, can also be run on the cluster.

APPENDIX A. Kubernetes Web UI (Formerly Dashboard)

A.1. Running the Kubernetes Web UI

The Kubernetes Web UI (formerly Dashboard) is a useful way of maintaining a Kubernetes cluster via a browser. It will perform most of the operations that would normally be done from the command line on the master (via kubectl). The Web UI also provides information on the state of Kubernetes resources in the cluster and any errors that maybe have occurred.

A.2. Installing the Kubernetes Web UI

By default, the Kubernetes Web UI is not deployed. To do so, use the officially-recommended setup deployment yaml.

```
$ kubectl create -f
https://raw.githubusercontent.com/kubernetes/dashboard/master/src/deplo
y/recommended/kubernetes-dashboard.yaml
```

A.3. Accessing the Kubernetes Web UI

There are multiple ways to access the Web. Granting access to the Web UI publicly presents huge security risks and should be avoided unless the intent is to grant all users on-site access to the Kubernetes cluster.

The default method of accessing the Web UI is via the master.

1. Open a proxy up to the Kubernetes Dashboard service.

```
$ kubectl proxy
```

2. On the master, navigate the browser to the dashboard.

   http://localhost:8001/api/v1/namespaces/kube-system/services/https:kubernetes-dashboard:/proxy/

3. A login page is presented - to log in, it is necessary to create a service account and retrieve its associated token.

```
$ kubectl create serviceaccount my-dashboard-sa
serviceaccount "my-dashboard-sa" created
```

4. Give the service account `cluster-admin` permissions on the cluster.

Caution — Ensure this change conforms to company security policies..

```
$ kubectl create clusterrolebinding my-dashboard-sa \
  --clusterrole=cluster-admin \
  --serviceaccount=default:my-dashboard-sa
clusterrolebinding "my-dashboard-sa" created
```

5. Get the name of the secret associated with the newly-created cluster role binding.

```
$ kubectl get secrets | grep my-dashboard-sa
my-dashboard-sa-token-wb7lf kubernetes.io/service-account-token 3
10s
```

6. Get the token from the secret description (substitute the name of the secret).

```
$ kubectl describe secret my-dashboard-sa-token-wb7lf
```

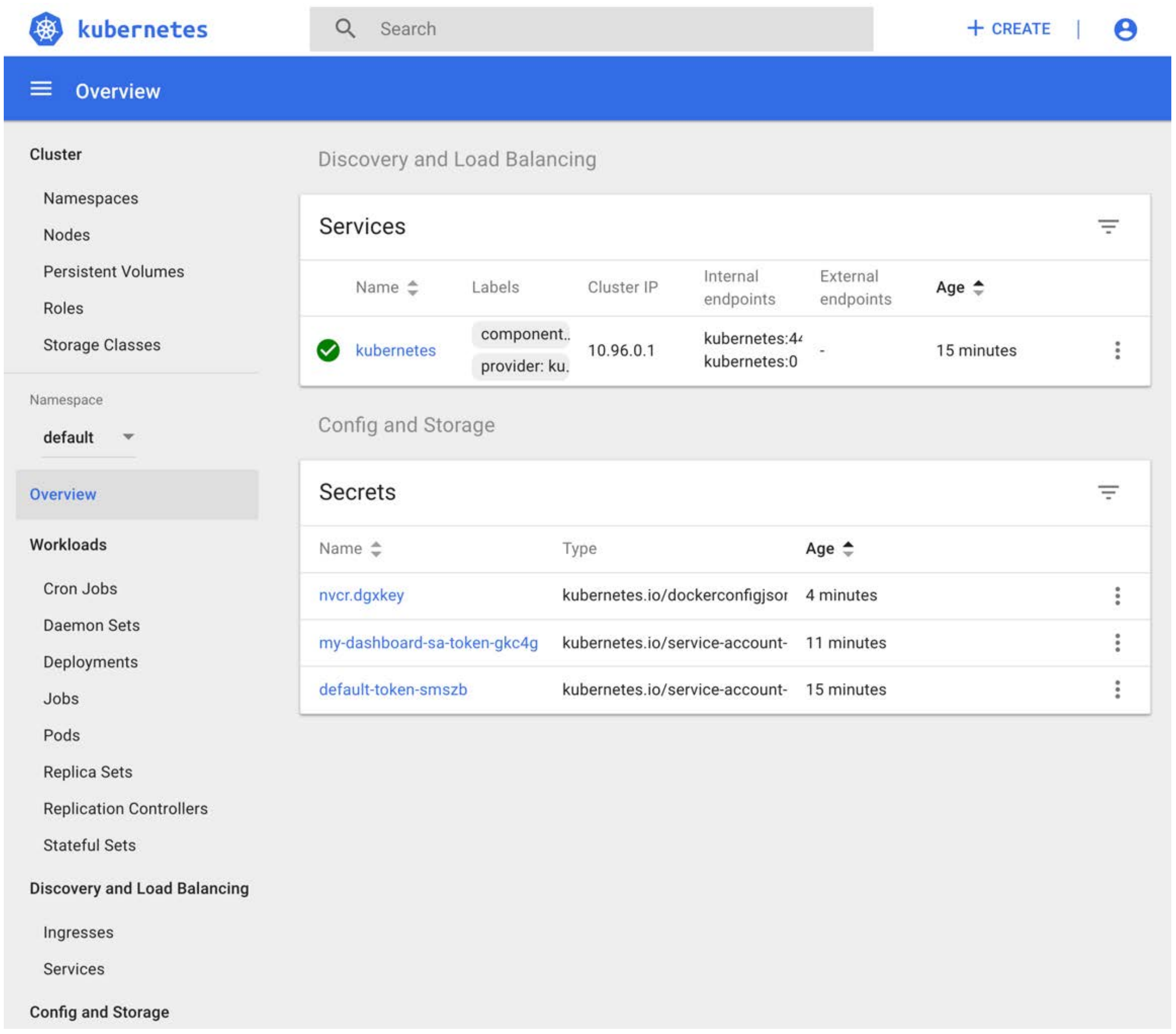
The resulting token can be used to authenticate on the login screen.

A.4. Ideal Access for Kubernetes Web UI

An ideal Kubernetes deployment for many users that need to access and control Kubernetes via the Web UI would involve implementing an SSO-like experience where each user has specific permissions to access the interface. This is outside of the scope of this document. For more information, consult the official Kubernetes authentication documentation.

A.5. Using the Kubernetes Web UI

Everything from managing roles to setting up namespaces and launching pods, jobs, and deployments can be done through the Web UI. For most users, leveraging the kubectl CLI will be more efficient, but the UI presents a good way for new users to see most of the available options and provides a useful way to observe and monitor existing Kubernetes objects.



Discovery and Load Balancing

Services

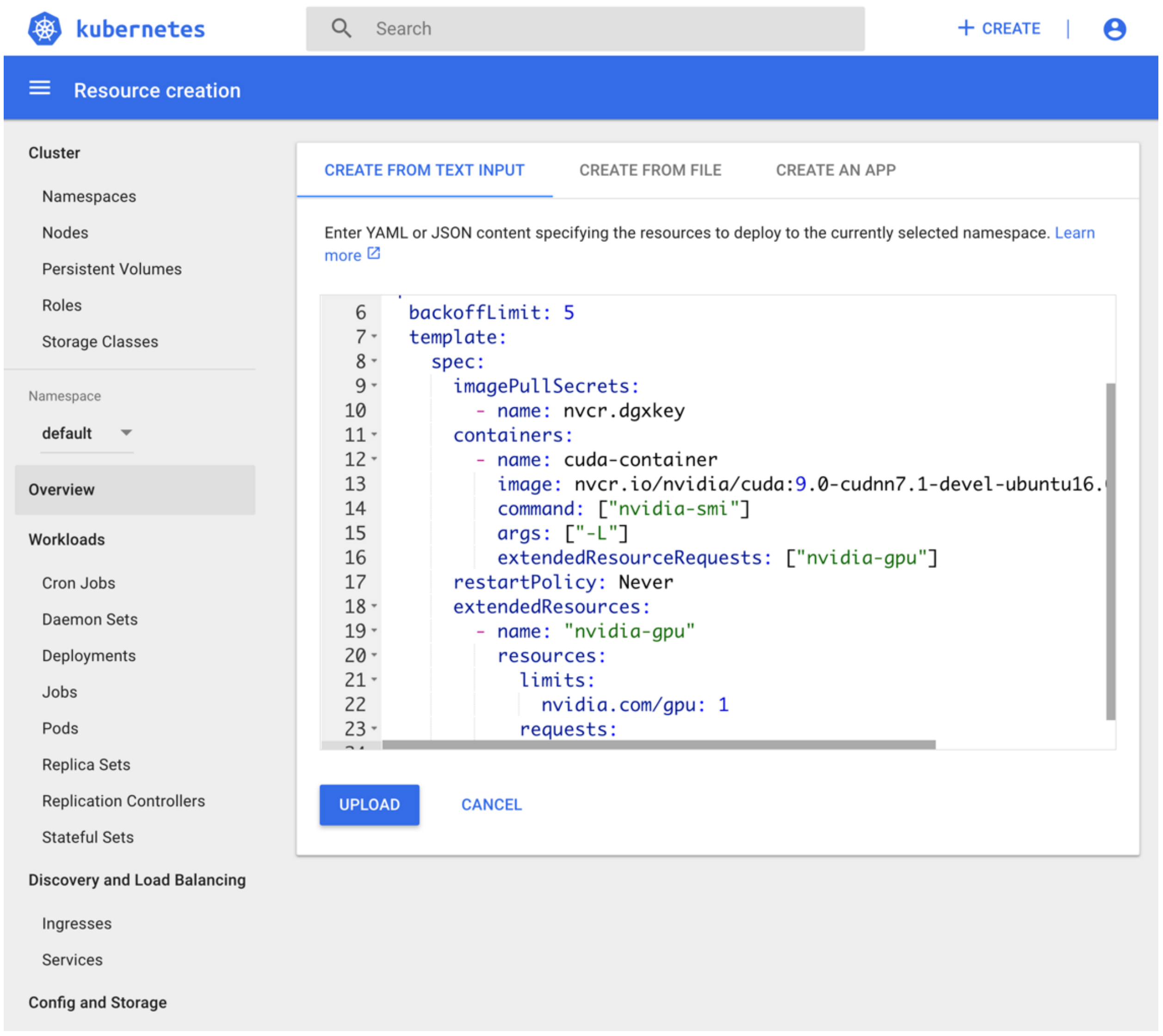
Name	Labels	Cluster IP	Internal endpoints	External endpoints	Age
✓ kubernetes	component.. provider: ku.	10.96.0.1	kubernetes:44 kubernetes:0	-	15 minutes

Config and Storage

Secrets

Name	Type	Age
nvcr.dgxkey	kubernetes.io/dockerconfigjsor	4 minutes
my-dashboard-sa-token-gkc4g	kubernetes.io/service-account-	11 minutes
default-token-smszb	kubernetes.io/service-account-	15 minutes

A new Kubernetes object can be created by- clicking on the CREATE button in the upper-right hand corner of the Web UI. From there, a manifest file can be pasted into the text input field.



Enter YAML or JSON content specifying the resources to deploy to the currently selected namespace. Learn more

```
  backoffLimit: 5
  template:
    spec:
      imagePullSecrets:
        - name: nvcr.dgxkey
      containers:
        - name: cuda-container
          image: nvcr.io/nvidia/cuda:9.0-cudnn7.1-devel-ubuntu16.
          command: ["nvidia-smi"]
          args: ["-L"]
          extendedResourceRequests: ["nvidia-gpu"]
      restartPolicy: Never
      extendedResources:
        - name: "nvidia-gpu"
          resources:
            limits:
              nvidia.com/gpu: 1
            requests:
```