Slinky: The Missing Link Between Slurm and Kubernetes

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Cray User Group 2025

Introduction

What is Slurm?

- Leading HPC Workload Manager
  - Workload Manager = Scheduler + Resource Manager
    - Roughly equivalent to "Orchestrator"
  - Scheduler:
    - Prioritize and decide which jobs to run on which parts of the system
  - Resource Manager:
    - Track node state and resources
    - Launch jobs
- Manages the majority of the TOP500 supercomputers
  - Also manages most AI/ML training workloads
  - Scales beyond 15,000 nodes in the cluster
- Open-Source
  - GPL-v2+

slurm

Who are SchedMD?

- Developers of Slurm – and Slinky
- Spun off from LLNL in 2012 to support Slurm's rapid adoption
  - Founders are Moe and Danny, the "MD" in SchedMD
- SchedMD provides commercial support for Slurm, alongside
  - Training
  - Consultation
  - Custom Development

What is Slinky?

What is Slinky?

- Toolkit of projects to integrate Slurm into Kubernetes
- Open Source
  - Apache-2.0
- Three major components:
  - Slurm-operator
  - Slurm-bridge
  - Associated tooling

What is Slinky?

- Slurm-operator
  - Kubernetes Operator for managing Slurm clusters
  - Manage Slurm compute nodes through Kubernetes pods
    - Autoscale in response to Slurm system load
  - Released in November 2024
    - v0.1.0 - November 2024
    - v0.2.0 - March 2025
    - v0.3.0 - June 2025

What is Slinky?

- Slurm-bridge
  - Kubernetes Scheduling Plugin
  - Enable Slurm scheduling of both Kubernetes Pods and Slurm Jobs on converged clusters
  - Will be released in June 2025
    - After Slurm 25.05 release (May 2025)

What is Slinky?

- Associated Tooling
    - Slurm Client
        - Golang Client Library for Slurm's REST API
    - Slurm Exporter
        - Prometheus Exporter for Slurm's REST API
        - Metrics to enable autoscaling
    - Helm Charts
    - Container Images

Slinky Repositories

https://github.com/SlinkyProject

Batch Workload Classification

Batch workload classification

- Massively parallel
    - AI/ML training
    - Capability HPC workloads
    - Requires close coordination between application, MPI / interconnect, scheduler
        - Commonly involves esoteric libraries such as libfabrics, PMI2 / PMIx
    - Kubernetes does not manage these workloads well today
        - Multi-node work is an afterthought, all approaches are kludges on top of the existing architecture
    - Defacto standard solution is Slurm
        - Not expecting to change within the short term
    - Slurm operator is the intended solution here
        - Longer term other Slinky projects may start to address Kubernetes limitations

Batch workload classification

- Loosely-coupled sub-node batch workloads
    - AKA "embarrassingly parallel"
    - HPC capacity workloads
    - Slurm bridge can improve scheduling performance
        - Allow for better job queuing and prioritization
    - DRA resource allocation model used to sub-divide resources
    - SchedMD is pushing for similar support for CPUs
        - Will likely publish a reference DRA CPU driver

Batch workload classification

- Full-node
  - Slurm Bridge can provide better prioritization
  - "Easiest" jobs to manage, both in traditional batch schedulers and Kubernetes

Batch workload classification

- Lightly multi-node
    - AI/ML inference workloads that no longer fit within single nodes
    - Kubernetes supports these workloads, but not efficiently
    - Target for first release of the Slurm Bridge

Slurm Operator

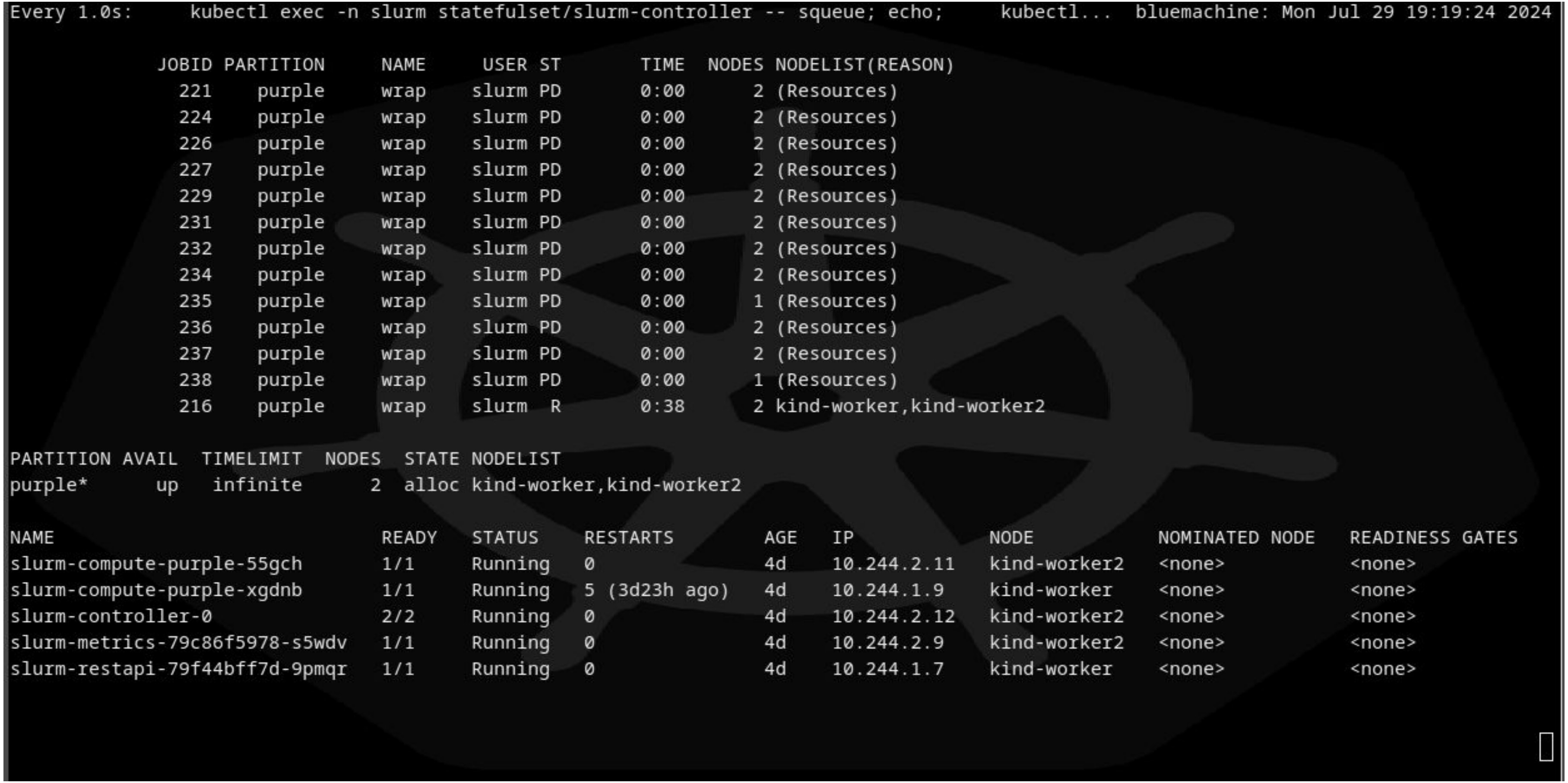
Slurm Operator Use Cases

- Manage Slurm clusters within a Kubernetes environment
- Each compute node maps to a Kubernetes pods running the slurmd process
- Support autoscaling based on cluster utilization metrics
- Run Slurm jobs natively
  - Users interact with Slurm through traditional CLI tools
    - Through one or more "login node" pods they can SSH into
- Kubernetes is not involved in scheduling or managing compute jobs
  - Slurm runs Slurm workloads directly
    - Allows for fine-grained resource limits
    - Backfill scheduling
    - Respect network topology - especially for NVIDIA NVL interconnects
  - Allow large training workloads to run efficiently
  - Provide access to traditional HPC tooling such as PMI/PMIx

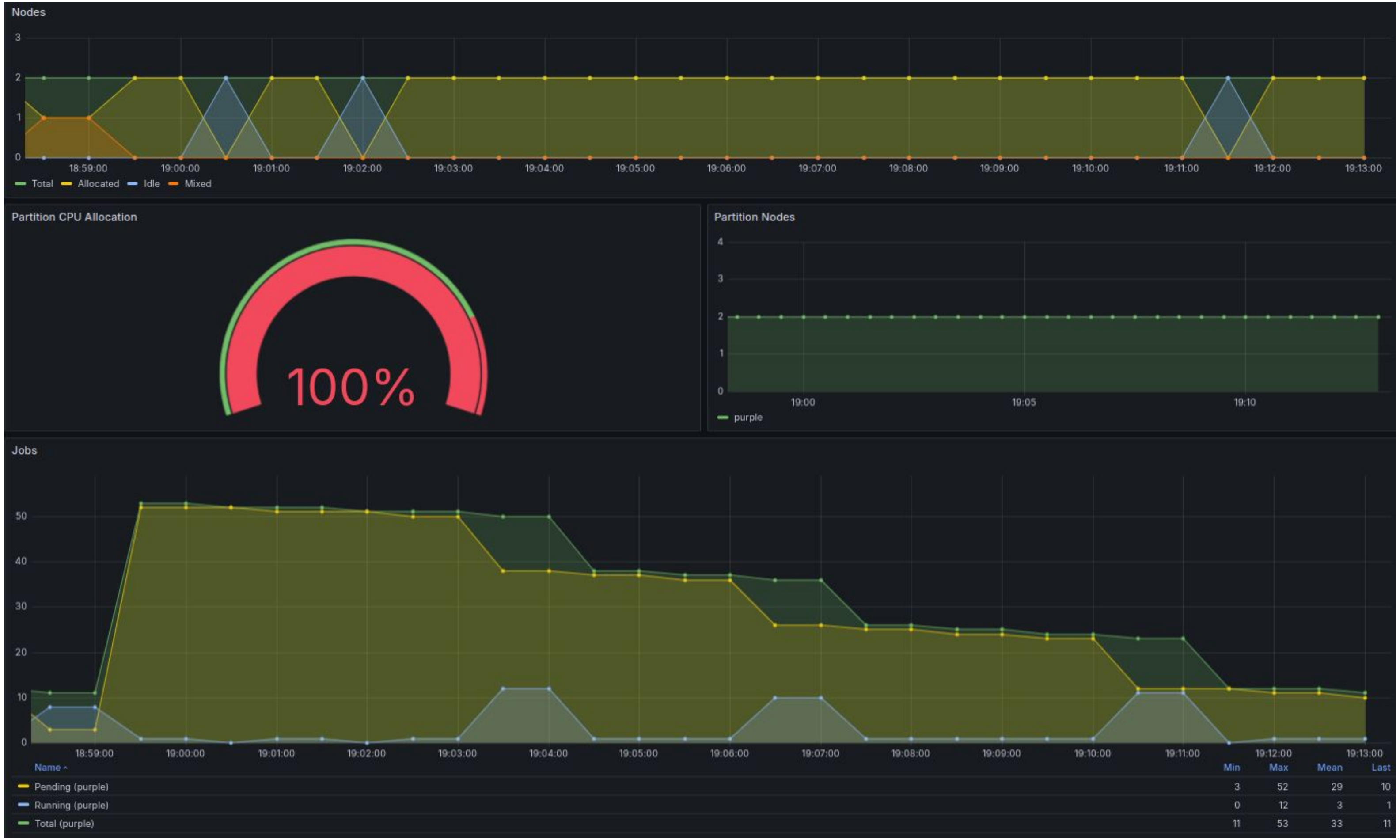
Documentation

- Initial documentation – https://slinky.schedmd.com/

Slurm Operator Demo Screenshots



```
Every 1.0s:    kubectl exec -n slurm statefulset/slurm-controller -- squeue; echo;    kubectl...  bluemachine: Mon Jul 29 19:19:24 2024

             JOBID PARTITION     NAME     USER ST       TIME  NODES NODELIST(REASON)
               221    purple     wrap    slurm PD       0:00      2 (Resources)
               224    purple     wrap    slurm PD       0:00      2 (Resources)
               226    purple     wrap    slurm PD       0:00      2 (Resources)
               227    purple     wrap    slurm PD       0:00      2 (Resources)
               229    purple     wrap    slurm PD       0:00      2 (Resources)
               231    purple     wrap    slurm PD       0:00      2 (Resources)
               232    purple     wrap    slurm PD       0:00      2 (Resources)
               234    purple     wrap    slurm PD       0:00      2 (Resources)
               235    purple     wrap    slurm PD       0:00      1 (Resources)
               236    purple     wrap    slurm PD       0:00      2 (Resources)
               237    purple     wrap    slurm PD       0:00      2 (Resources)
               238    purple     wrap    slurm PD       0:00      1 (Resources)
               216    purple     wrap    slurm  R       0:38      2 kind-worker,kind-worker2

PARTITION AVAIL  TIMELIMIT  NODES  STATE NODELIST
purple*      up   infinite      2  alloc kind-worker,kind-worker2

NAME                             READY   STATUS    RESTARTS         AGE   IP            NODE           NOMINATED NODE   READINESS GATES
slurm-compute-purple-55gch       1/1     Running   0                4d    10.244.2.11   kind-worker2   <none>           <none>
slurm-compute-purple-xgdnb       1/1     Running   5 (3d23h ago)    4d    10.244.1.9    kind-worker    <none>           <none>
slurm-controller-0               2/2     Running   0                4d    10.244.2.12   kind-worker2   <none>           <none>
slurm-metrics-79c86f5978-s5wdv   1/1     Running   0                4d    10.244.2.9    kind-worker2   <none>           <none>
slurm-restapi-79f44bff7d-9pmqr   1/1     Running   0                4d    10.244.1.7    kind-worker    <none>           <none>
```



Name ^	Min	Max	Mean	Last
Pending (purple)	3	52	29	10
Running (purple)	0	12	3	1
Total (purple)	11	53	33	11

Slurm Bridge

Why Slurm Bridge

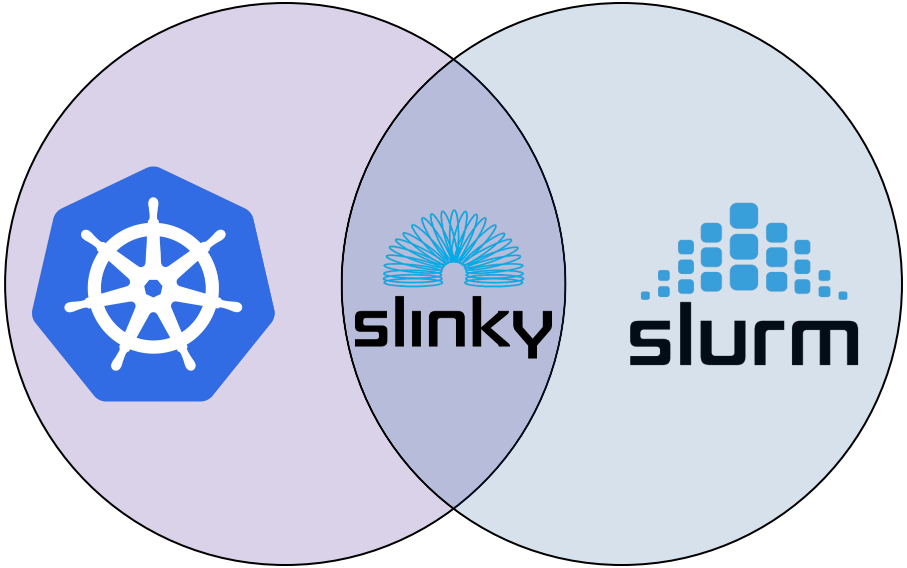
- Kubernetes lacks fine-grained control of native resources (CPU, Memory)
  - HPC and AI training workloads are generally more efficient when dedicated resources are assigned
    - Avoid jitter and cache contention
- Ability to have fast scheduling that is not possible in kubelet
- Ability to use both Kubernetes and Slurm workloads on the same set of nodes
  - Allow researchers to use their preferred tooling, without needing separate dedicated compute systems

Why Not Slurm Bridge

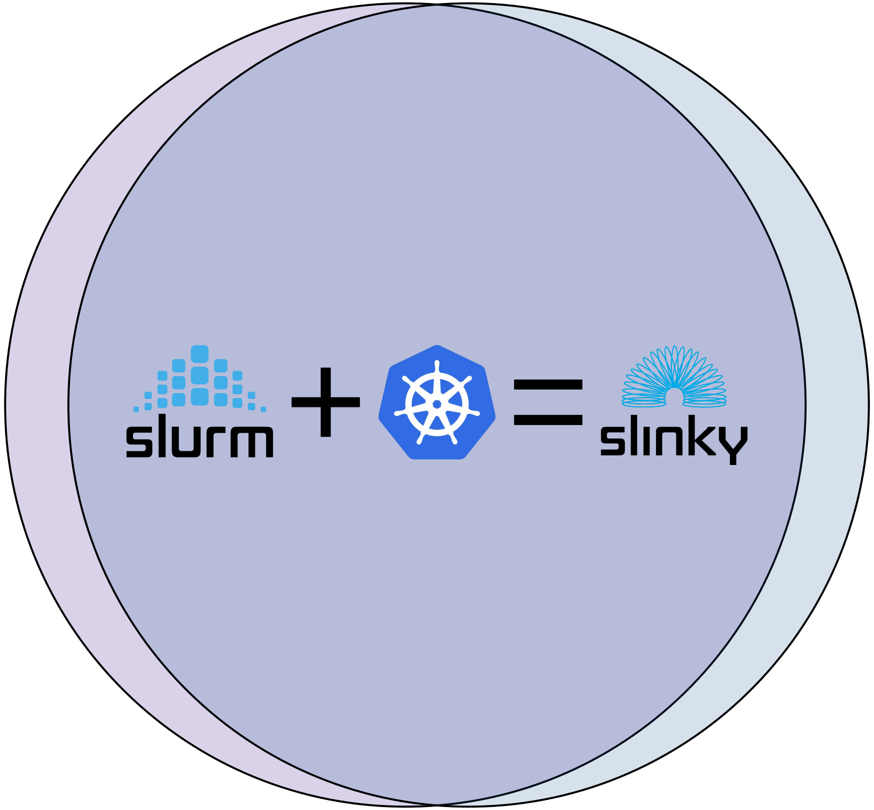
- Slurm Bridge is not meant to replace the default scheduler
    - Another alternative
        - Kubernetes API makes it possible to provision multiple schedulers
        - Same approach taken by Kueue, Volcano, MPI Operator, …
    - However… as the Kubernetes API doesn't provide a clean way to sub-divide resources within a node, it does assume that - for any node it's meant to schedule - that is is the only workload scheduler
        - Disregard core infrastructure - such as daemon sets - that are still scheduled through the default scheduler
- Slurm Bridge may not be appropriate for your system
    - Intended for clusters that are predominantly dedicated to batch-oriented process
        - Or closely related domains - such as AI/ML interference
            - Especially for managing multi-node inference workloads

Domain Pools

- Kubernetes manages its nodes
  - Running kubelet
- Slurm manages its nodes
  - Running slurmd
- The Slurm-Bridge manages workloads running on converged nodes shared by both
- Nodes are not required to run both, but for most deployments they likely will



Domain Pools - Expected Deployment Pattern



Design Goals

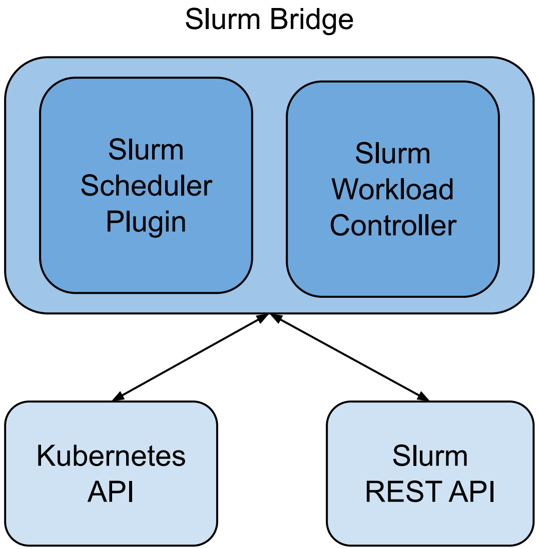
- Run both Slurm and Kubernetes workloads on pools of nodes
- Slurm bridge will translate resource requirements for Kubernetes workloads into Slurm jobs
    - Reconstruct multi-node workloads, and submit single job to Slurm
        - PodGroup and JobSet currently
            - Likely LeaderWorkerSet as well
- Handle Device Plugins, such as GPUs
- Filter out nodes that Slurm is not to manage, through the current set of labels provided
- Filter out pods out via designated namespaces
    - Will have an allow-list of namespaces we handle
        - "slurm-bridge" in our demo

Restrictions

- Each node can run Slurm **or** Kubernetes workloads, not both concurrently
  - The kubelet will manage Kubernetes pods
  - The slurmd will manage Slurm jobs
- Configure the Slurm-bridge plugin as Kubernetes scheduling profile
  - Plugin will take control of all workloads in allow-list of namespaces
  - The Default Scheduler will handle all other workloads
- Slurm can only schedule to nodes with slurmd running
  - Even if you don't want to run native Slurm workloads
  - Need detailed CPU information that the Kubernetes API doesn't provide
    - Can use the Slurm Operator to manage these slurmd processes
      - Or run slurmd directly on base-metal

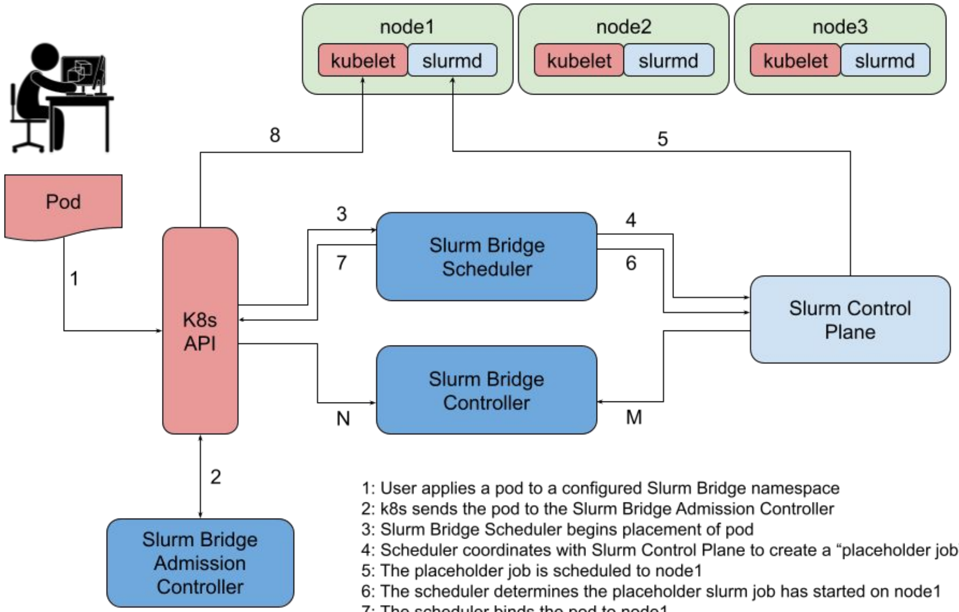
Slurm Bridge Scheduler + Controller

- Responsible for managing Slurm as the source of truth and enforcing scheduling decisions from Slurm
- Slurm Scheduler Plugin
  - Hooks into the Kubernetes scheduling API to utilize the Slurm Control Plane to make scheduling decisions
- Slurm Workload Controller
  - Reconciles pod drift/desync using Slurm as the source-of-truth for Slurm scheduled workloads



Slurm Bridge
User's Perspective

Slurm Bridge - User's Perspective

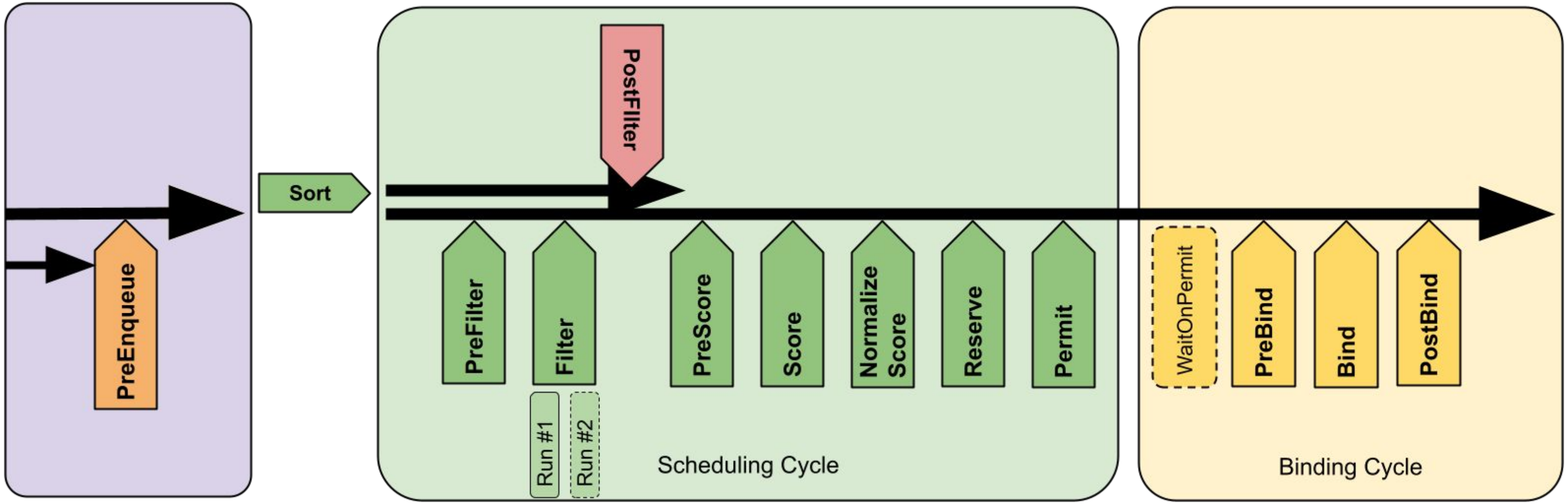


1: User applies a pod to a configured Slurm Bridge namespace
2: k8s sends the pod to the Slurm Bridge Admission Controller
3: Slurm Bridge Scheduler begins placement of pod
4: Scheduler coordinates with Slurm Control Plane to create a “placeholder job”
5: The placeholder job is scheduled to node1
6: The scheduler determines the placeholder slurm job has started on node1
7: The scheduler binds the pod to node1
8: kubelet starts the pod on node1

N: Slurm Bridge Controller reconciles k8s node and pod events
M: Slurm Bridge Controller reconciles Slurm node and job events

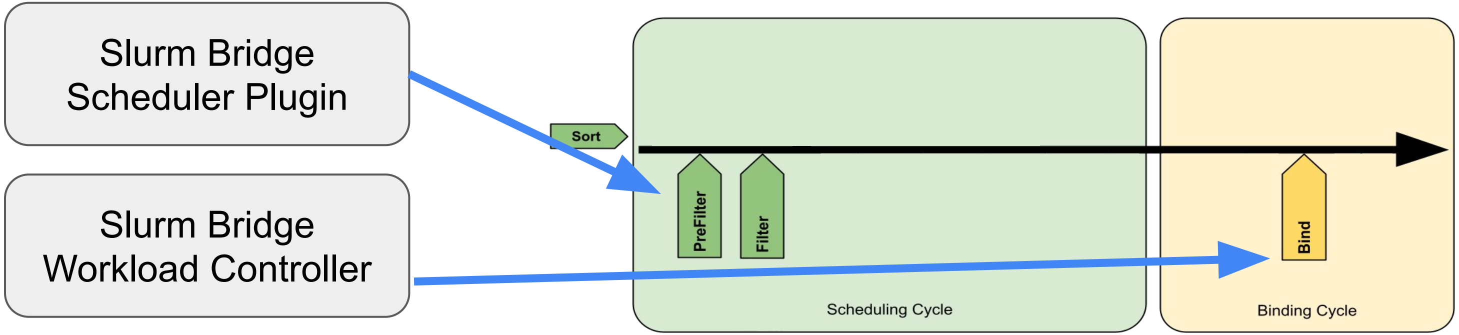
Slurm Bridge
Kubernetes Scheduler Plugin

Kubernetes Scheduler Framework

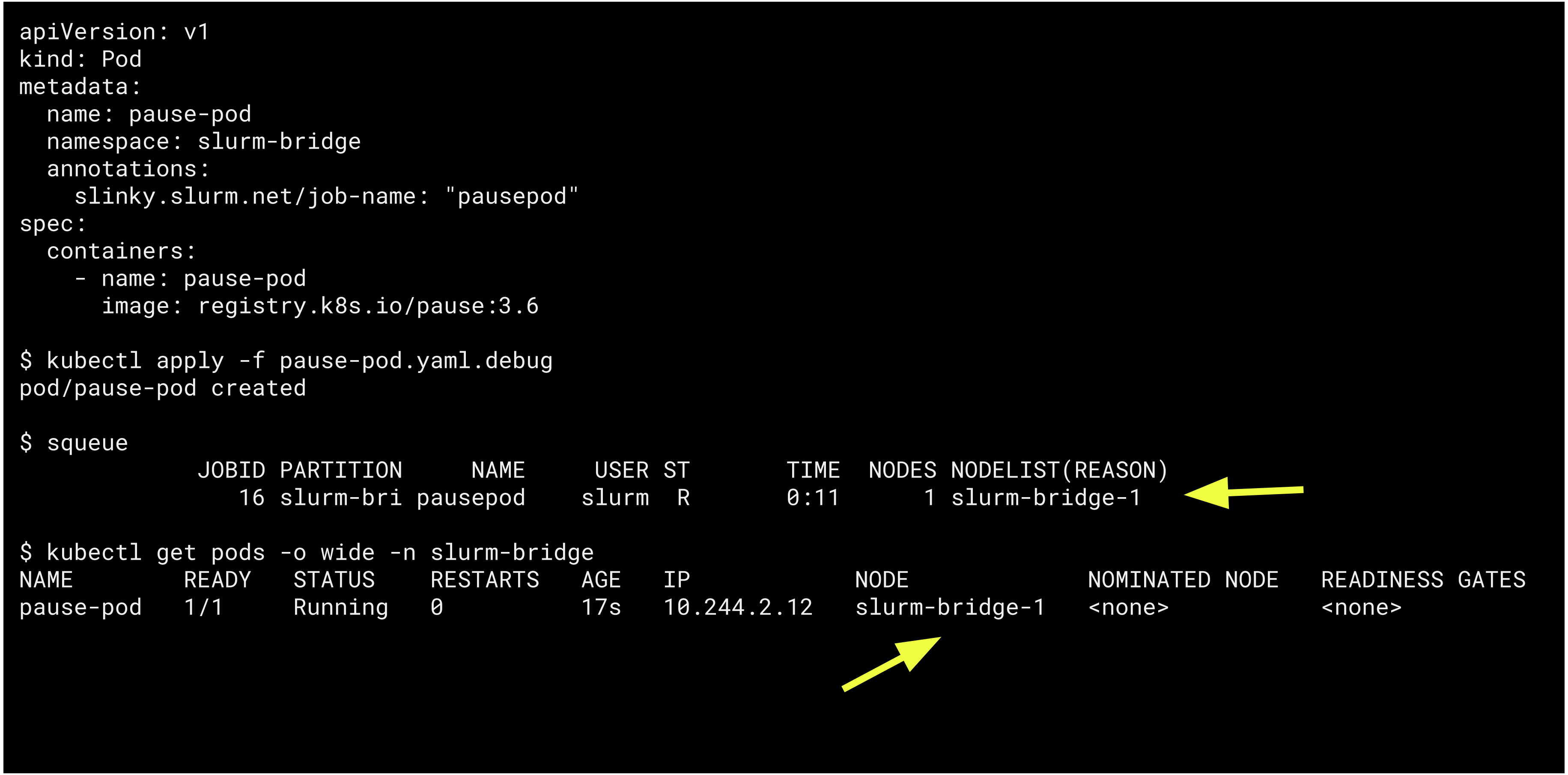


Slurm Scheduler Plugin

- Only implement PreFilter/Filter and Bind
- PreFilter to capture new pod requests
  - To translate Pod into Slurm job and submit into Slurm's queues
- Bind to communicate the node allocation back to Kubernetes
  - Technically managed by the workload controller, not the scheduler plugin
- Does not implement all Kubernetes scheduling primitives
  - E.g., affinity/anti-affinity aren't available
  - Avoids some performance pitfalls of the Kubernetes scheduling API

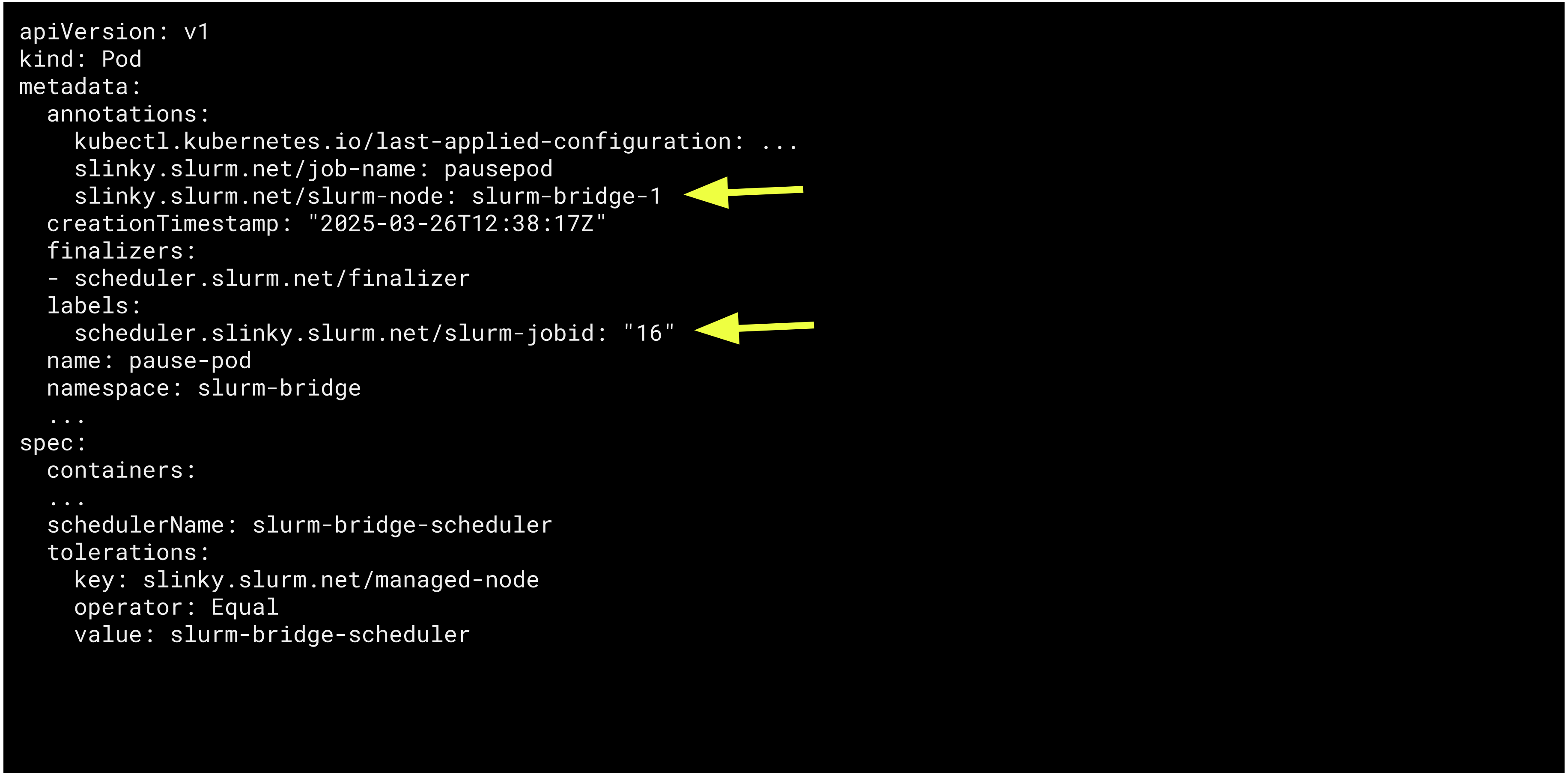

Slurm Bridge Scheduler Plugin
Slurm Bridge Workload Controller
Sort
PreFilter
Filter
Bind
Scheduling Cycle
Binding Cycle

Slurm Bridge
Demo Screenshots



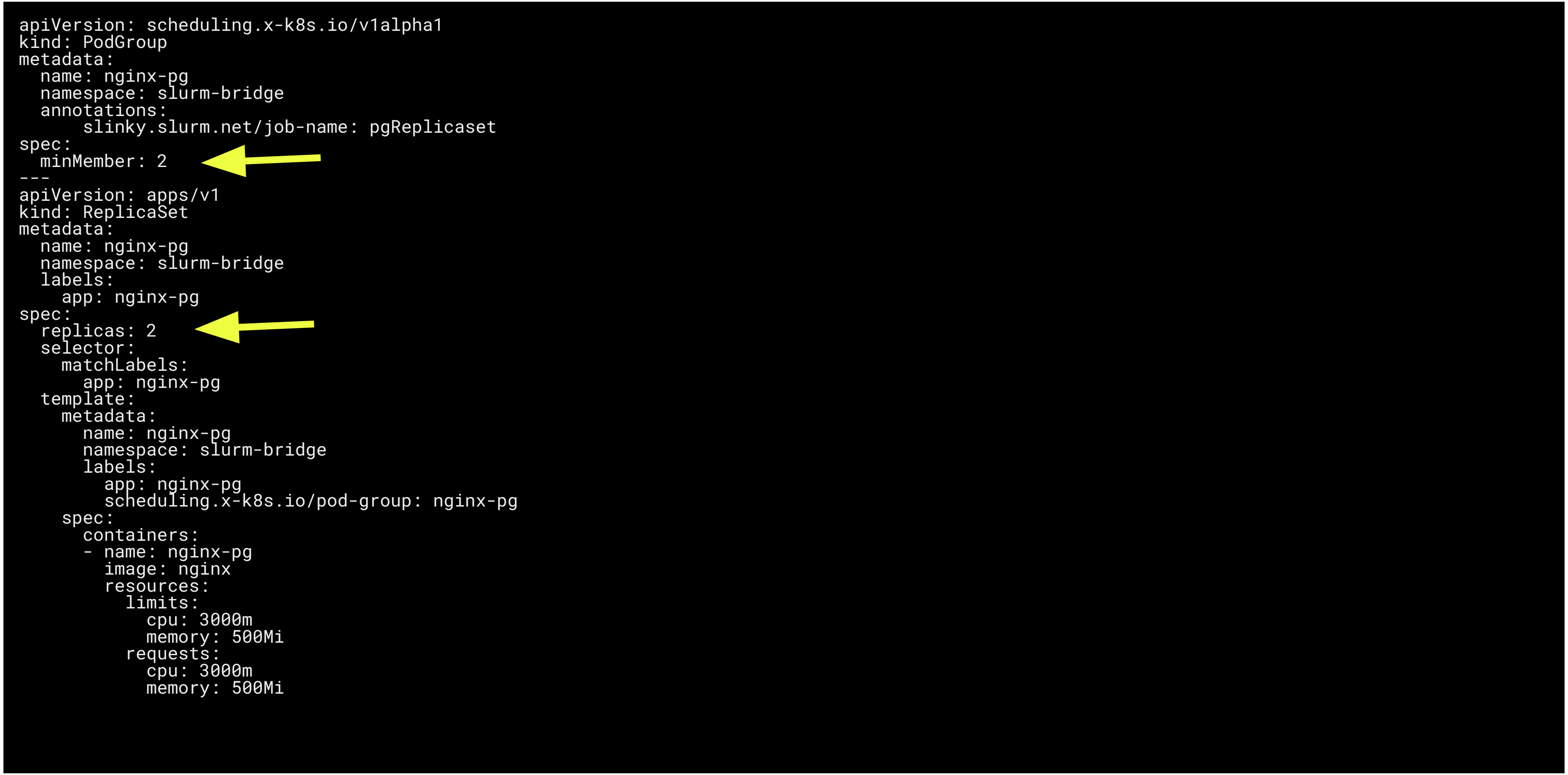
```
apiVersion: v1
kind: Pod
metadata:
  name: pause-pod
  namespace: slurm-bridge
  annotations:
    slinky.slurm.net/job-name: "pausepod"
spec:
  containers:
    - name: pause-pod
      image: registry.k8s.io/pause:3.6

$ kubectl apply -f pause-pod.yaml.debug
pod/pause-pod created

$ squeue
             JOBID PARTITION     NAME     USER ST       TIME  NODES NODELIST(REASON)
                16 slurm-bri pausepod    slurm  R       0:11      1 slurm-bridge-1

$ kubectl get pods -o wide -n slurm-bridge
NAME        READY   STATUS    RESTARTS   AGE   IP            NODE             NOMINATED NODE   READINESS GATES
pause-pod   1/1     Running   0          17s   10.244.2.12   slurm-bridge-1   <none>           <none>
```

Submission of a single-node pod. Scheduled immediately on the empty cluster, node placement communicated back to Bind()



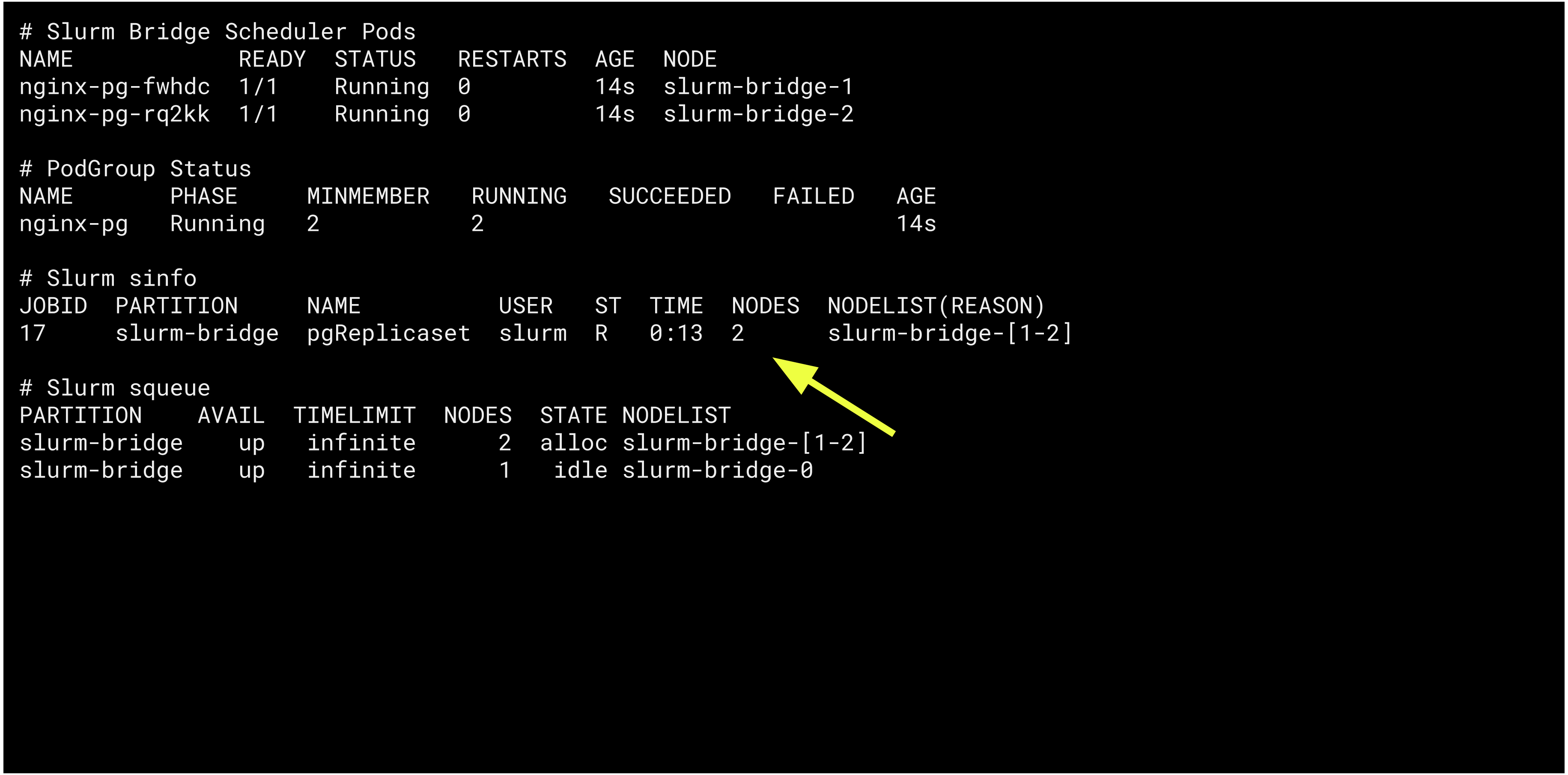
```
apiVersion: v1
kind: Pod
metadata:
  annotations:
    kubectl.kubernetes.io/last-applied-configuration: ...
    slinky.slurm.net/job-name: pausepod
    slinky.slurm.net/slurm-node: slurm-bridge-1
  creationTimestamp: "2025-03-26T12:38:17Z"
  finalizers:
  - scheduler.slurm.net/finalizer
  labels:
    scheduler.slinky.slurm.net/slurm-jobid: "16"
  name: pause-pod
  namespace: slurm-bridge
  ...
spec:
  containers:
  ...
  schedulerName: slurm-bridge-scheduler
  tolerations:
    key: slinky.slurm.net/managed-node
    operator: Equal
    value: slurm-bridge-scheduler
```

slurm-node annotation allows for flexible mapping between Slurm and Kubernetes names. Here they're equivalent.
Note the corresponding slurm-jobid label which is used to track status of the placeholder job.



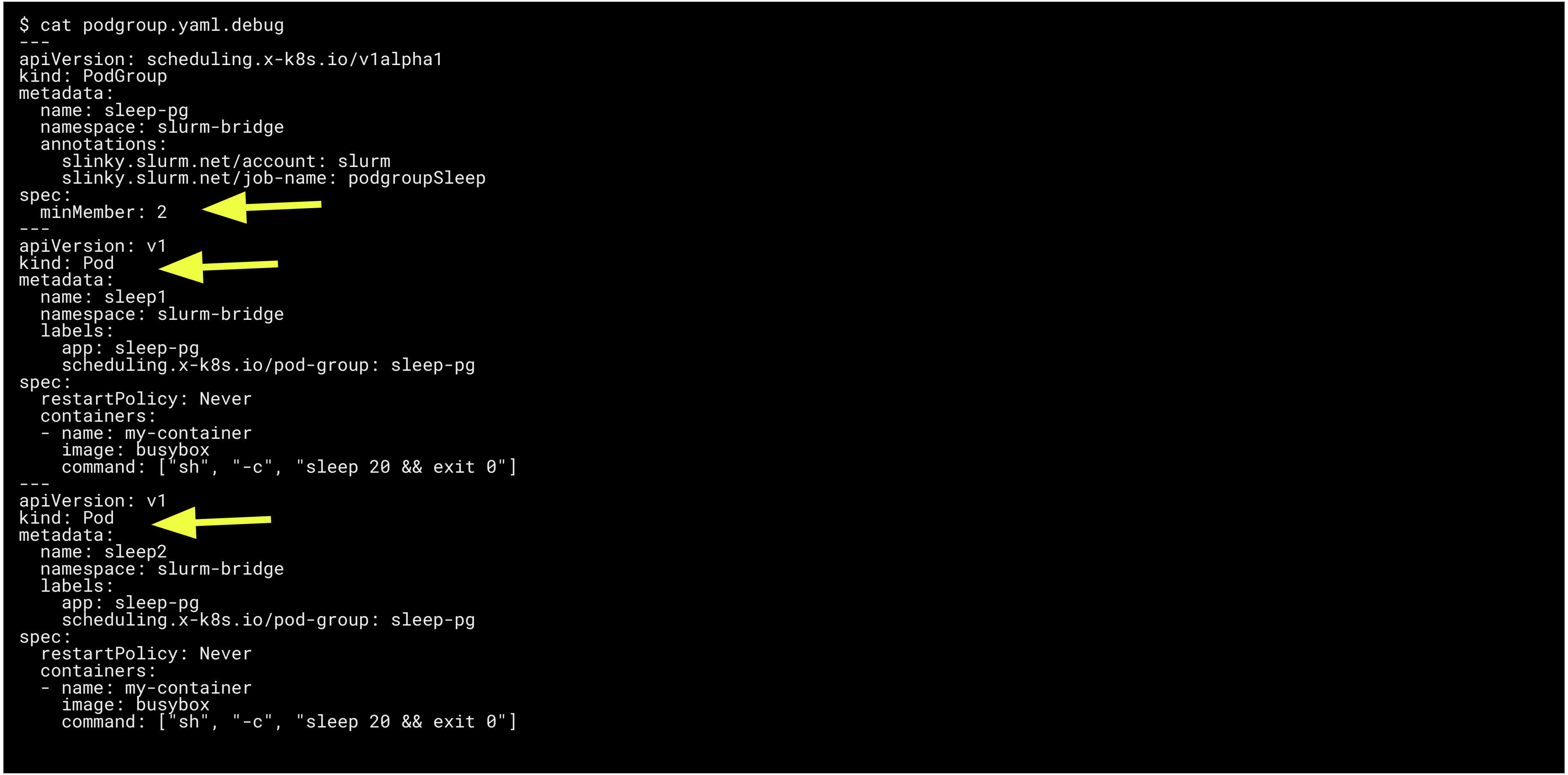
```
apiVersion: scheduling.x-k8s.io/v1alpha1
kind: PodGroup
metadata:
  name: nginx-pg
  namespace: slurm-bridge
  annotations:
      slinky.slurm.net/job-name: pgReplicaset
spec:
  minMember: 2
---
apiVersion: apps/v1
kind: ReplicaSet
metadata:
  name: nginx-pg
  namespace: slurm-bridge
  labels:
    app: nginx-pg
spec:
  replicas: 2
  selector:
    matchLabels:
      app: nginx-pg
  template:
    metadata:
      name: nginx-pg
      namespace: slurm-bridge
      labels:
        app: nginx-pg
        scheduling.x-k8s.io/pod-group: nginx-pg
    spec:
      containers:
      - name: nginx-pg
        image: nginx
        resources:
          limits:
            cpu: 3000m
            memory: 500Mi
          requests:
            cpu: 3000m
            memory: 500Mi
```

Multi-pod / multi-node workload controlled through replicas. Will be translated into a single placeholder job requiring 2 nodes.



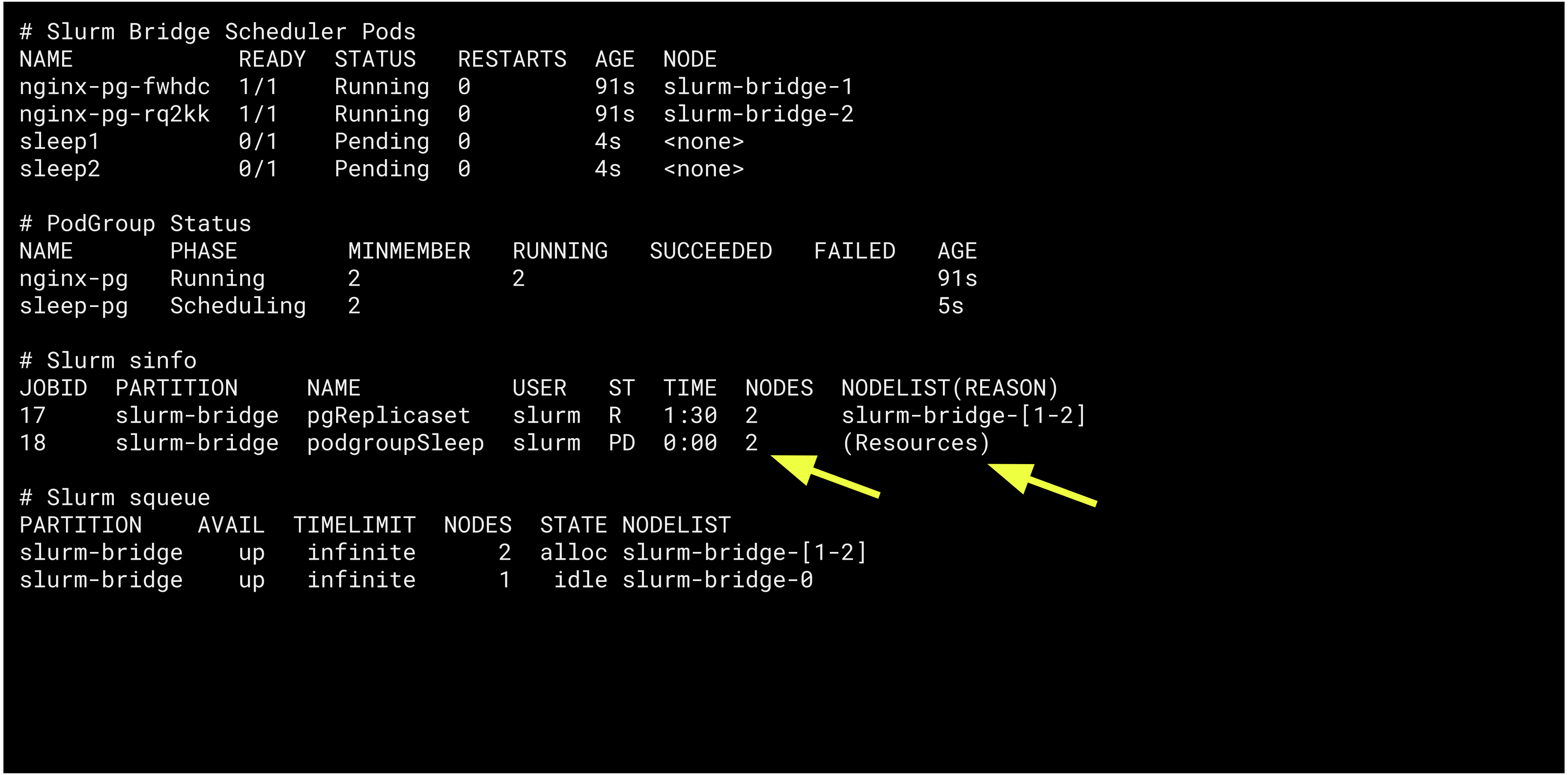
```
# Slurm Bridge Scheduler Pods
NAME              READY  STATUS   RESTARTS  AGE  NODE
nginx-pg-fwhdc  1/1    Running  0         14s  slurm-bridge-1
nginx-pg-rq2kk  1/1    Running  0         14s  slurm-bridge-2

# PodGroup Status
NAME       PHASE     MINMEMBER   RUNNING   SUCCEEDED   FAILED   AGE
nginx-pg   Running   2           2                              14s

# Slurm sinfo
JOBID  PARTITION     NAME           USER   ST  TIME  NODES  NODELIST(REASON)
17     slurm-bridge  pgReplicaset  slurm  R   0:13  2      slurm-bridge-[1-2]

# Slurm squeue
PARTITION    AVAIL  TIMELIMIT  NODES  STATE NODELIST
slurm-bridge    up   infinite      2  alloc slurm-bridge-[1-2]
slurm-bridge    up   infinite      1   idle slurm-bridge-0
```

Translated into 2 node job. Slurm natively understands multi-node workloads and efficiently schedules them.



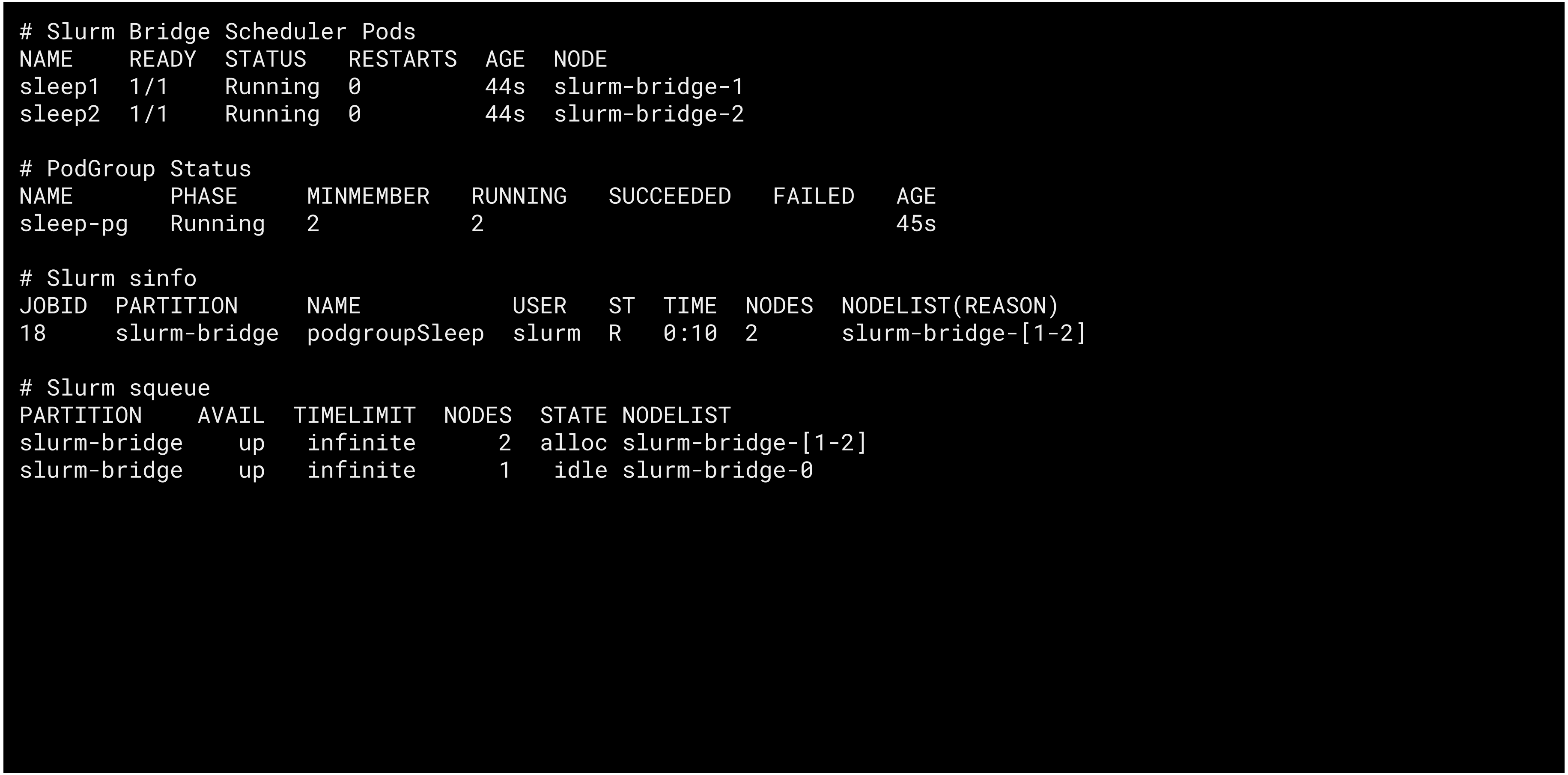
```
$ cat podgroup.yaml.debug
---
apiVersion: scheduling.x-k8s.io/v1alpha1
kind: PodGroup
metadata:
  name: sleep-pg
  namespace: slurm-bridge
  annotations:
    slinky.slurm.net/account: slurm
    slinky.slurm.net/job-name: podgroupSleep
spec:
  minMember: 2
---
apiVersion: v1
kind: Pod
metadata:
  name: sleep1
  namespace: slurm-bridge
  labels:
    app: sleep-pg
    scheduling.x-k8s.io/pod-group: sleep-pg
spec:
  restartPolicy: Never
  containers:
  - name: my-container
    image: busybox
    command: ["sh", "-c", "sleep 20 && exit 0"]
---
apiVersion: v1
kind: Pod
metadata:
  name: sleep2
  namespace: slurm-bridge
  labels:
    app: sleep-pg
    scheduling.x-k8s.io/pod-group: sleep-pg
spec:
  restartPolicy: Never
  containers:
  - name: my-container
    image: busybox
    command: ["sh", "-c", "sleep 20 && exit 0"]
```

Second multi-node workload, this time with the pods explicitly enumerated.



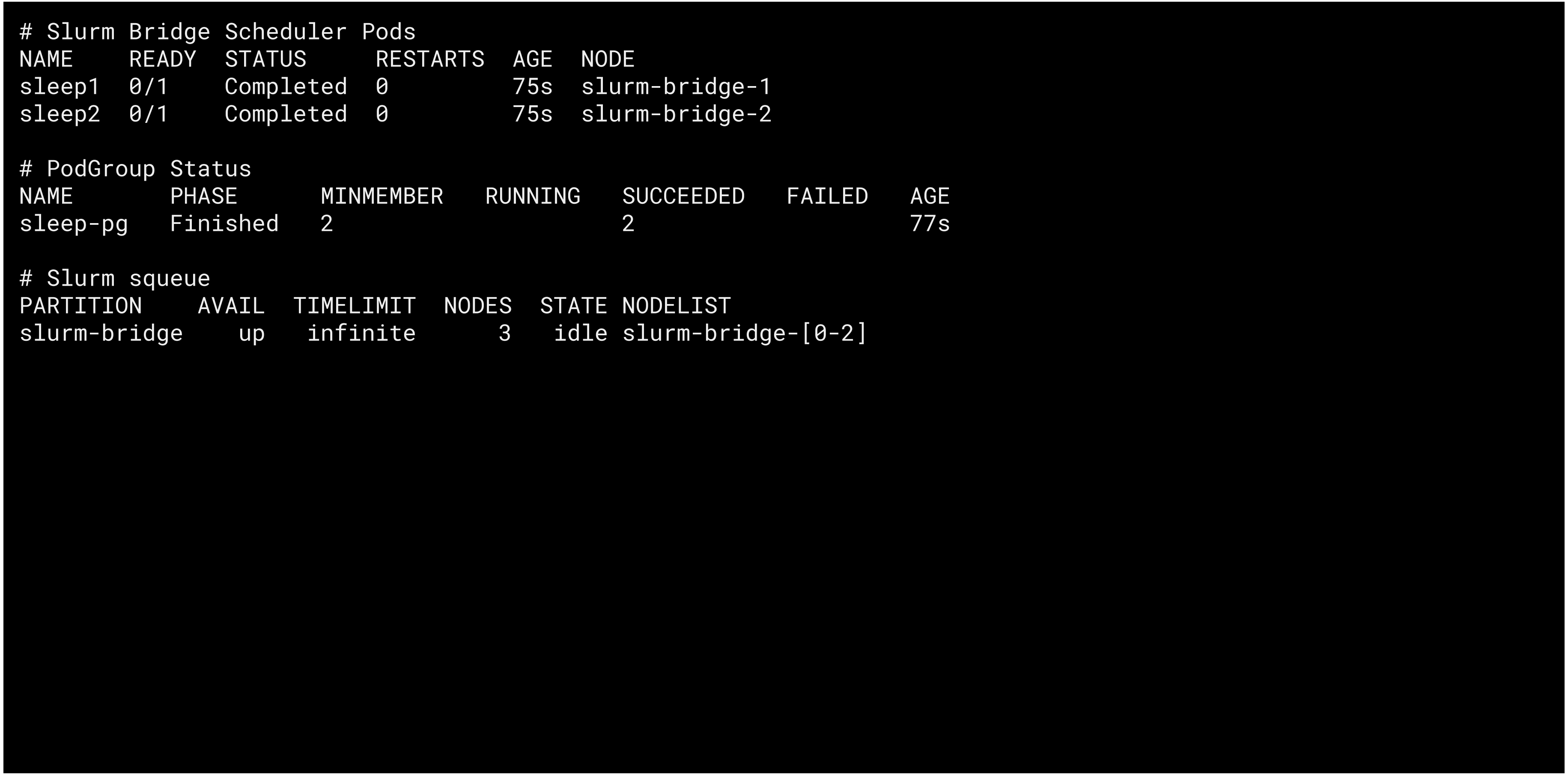
```
# Slurm Bridge Scheduler Pods
NAME             READY  STATUS   RESTARTS  AGE  NODE
nginx-pg-fwhdc   1/1    Running  0         91s  slurm-bridge-1
nginx-pg-rq2kk   1/1    Running  0         91s  slurm-bridge-2
sleep1           0/1    Pending  0         4s   <none>
sleep2           0/1    Pending  0         4s   <none>

# PodGroup Status
NAME        PHASE         MINMEMBER   RUNNING   SUCCEEDED   FAILED   AGE
nginx-pg    Running       2           2                              91s
sleep-pg    Scheduling    2                                          5s

# Slurm sinfo
JOBID  PARTITION     NAME           USER   ST  TIME  NODES  NODELIST(REASON)
17     slurm-bridge  pgReplicaset   slurm  R   1:30  2      slurm-bridge-[1-2]
18     slurm-bridge  podgroupSleep  slurm  PD  0:00  2      (Resources)

# Slurm squeue
PARTITION    AVAIL  TIMELIMIT  NODES  STATE NODELIST
slurm-bridge    up   infinite      2  alloc slurm-bridge-[1-2]
slurm-bridge    up   infinite      1   idle slurm-bridge-0
```

Note that this second workload is pending - insufficient nodes available. Slurm will schedule this once resources are available.



```
# Slurm Bridge Scheduler Pods
NAME    READY  STATUS    RESTARTS  AGE  NODE
sleep1  1/1    Running  0         44s  slurm-bridge-1
sleep2  1/1    Running  0         44s  slurm-bridge-2

# PodGroup Status
NAME       PHASE     MINMEMBER   RUNNING   SUCCEEDED   FAILED   AGE
sleep-pg   Running   2           2                              45s

# Slurm sinfo
JOBID  PARTITION     NAME           USER   ST  TIME  NODES  NODELIST(REASON)
18     slurm-bridge  podgroupSleep  slurm  R   0:10  2      slurm-bridge-[1-2]

# Slurm squeue
PARTITION    AVAIL  TIMELIMIT  NODES  STATE NODELIST
slurm-bridge    up   infinite      2  alloc slurm-bridge-[1-2]
slurm-bridge    up   infinite      1   idle slurm-bridge-0
```

First workload completed, second workload is now running.



```
# Slurm Bridge Scheduler Pods
NAME    READY  STATUS     RESTARTS  AGE  NODE
sleep1  0/1    Completed  0         75s  slurm-bridge-1
sleep2  0/1    Completed  0         75s  slurm-bridge-2

# PodGroup Status
NAME       PHASE      MINMEMBER   RUNNING   SUCCEEDED   FAILED   AGE
sleep-pg   Finished   2                     2                    77s

# Slurm squeue
PARTITION    AVAIL  TIMELIMIT  NODES  STATE NODELIST
slurm-bridge    up   infinite      3   idle slurm-bridge-[0-2]
```

Everything complete. Workload controller has ensured system state is kept in sync. Pods can be deleted, or placeholder jobs cancelled or timed out, and will reconcile system state between the two.

Future Work

Future Work

- Further refinement, documentation, and testing of the Slurm Operator
- Work with the Kubernetes community to be able to handle fine-grained control and understanding of native resources
    - "DRA-for-Cores"
    - Publish CPU affinity mapping for other DRA devices
- Allow for Slurm to operate as a pure Kubernetes scheduler
    - Remove requirement for slurmd daemon on nodes managed by the Slurm Bridge
        - Requires new "external" node status within Slurm to indicate Slur's own resource management layer is disabled
    - Requires extension to the Slurm Workload Controller to automatically create "external" nodes within Slurm
- Investigation into better coordination with Autoscaler

CPU affinity - HPC requirements

- HPC workloads have a broad range of ways to model their internal application layouts
- HPC workload managers evolved to support a huge range of options
- Subset of these allocation options:
    - number-of-tasks, number-of-nodes, number-of-tasks-per-node
    - cpus, cpus-per-gpu, cpus-per-node, cpus-per-task
    - gpus, gpus-per-node, gpus-per-task, gpus-per-socket
    - sockets-per-node, threads-per-core
    - gpu-to-cpu-pinning

CPU resource management

- CPU resource management
    - Significant functional gap compared to Slurm's native resource management
    - CPU affinity has significant performance impacts on most workloads
        - Managed by through the Linux cpuset cgroup controller
            - Kubernetes lacks centralized planning for CPUs
                - Delegated to the runtime
                    - But precludes effective backfill scheduling
    - Discussing different models with the device management wg and others
        - May publish a POC DRA driver for CPUs while discussing whether something should be pushed into core Kubernetes

Questions?

Thank You

https://github.com/SlinkyProject

SCHEDMD

The Slurm Company