Nvshare

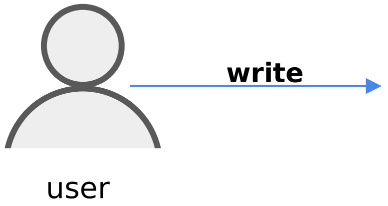
A Kubernetes Use Case

George Alexopoulos <giorgosalexo0@gmail.com>

Interactive environment

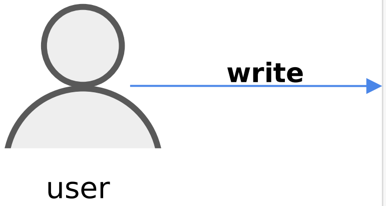
Interactive environment

Interactive environment



Interactive environment

Browser




```
In [ ]: # Initialize denominator
        k = 1

        # Initialize sum
        s = 0

        for i in range(1000000):

            # even index elements are positive
            if i % 2 == 0:
                s += 4/k
            else:
                # odd index elements are negative
                s -= 4/k

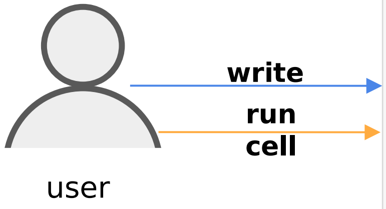
            # denominator is odd
            k += 2

        print("pi =",s)
```

```
In [ ]: print("Do something else.")
```

Interactive environment

Browse
r



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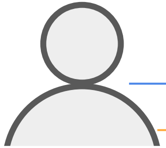
Interactive environment

Browser



user

write

run cell

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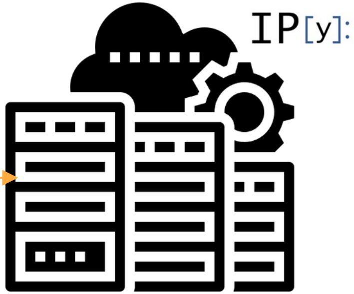
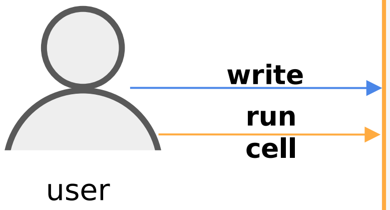
send cell code

backend-IPython



Interactive environment

Browser

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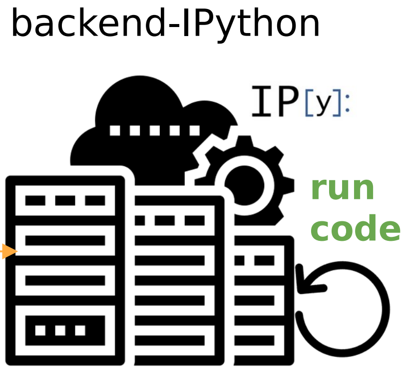
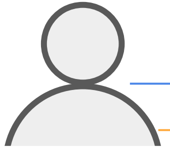


Interactive environment

Browser



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run cell

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print("Do something else.")
```

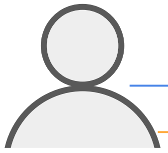
send cell code

receive result

backend-IPython

Interactive environment

Browse



write

run cell

user

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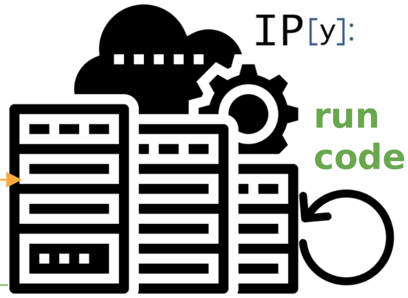
pi = 3.141591653589774З

In [ ]: print("Do something else.")
```

send cell code

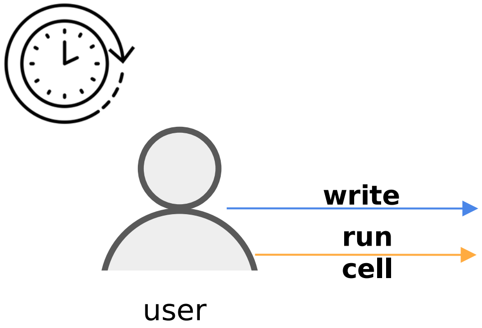
receive result

backend-IPython



Interactive environment

Browse

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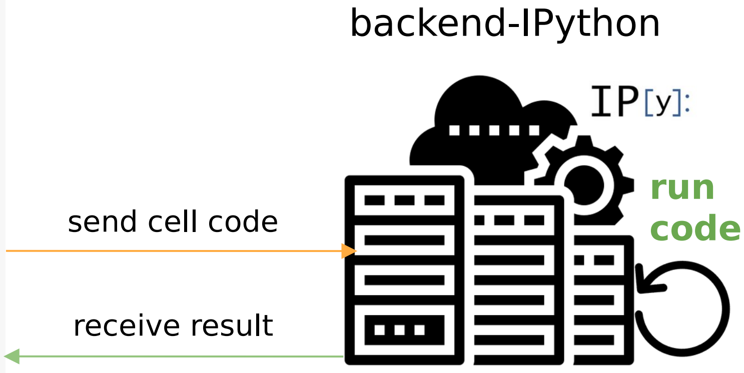
print("pi =",s)
```

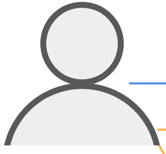
```
pi = 3.1415916535897743
```

```
In [ ]: print("Do something else.")
```



Interactive environment

Browse



user

write

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pi = 3.1415916535897743
```

run cell

In [ ]:

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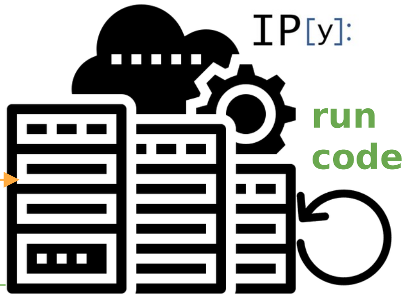
```

send cell code

receive result

backend-IPython



Interactive environment

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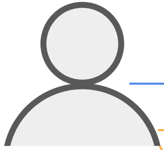
⋮



user

write

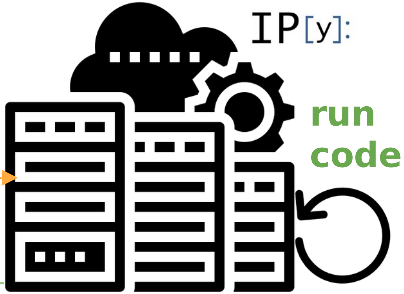
run cell

run cell

send cell code

receive result

backend-IPython



What is Kubeflow?

What is Kubeflow?

Kubeflow

What is Kubeflow?

Kubeflow =

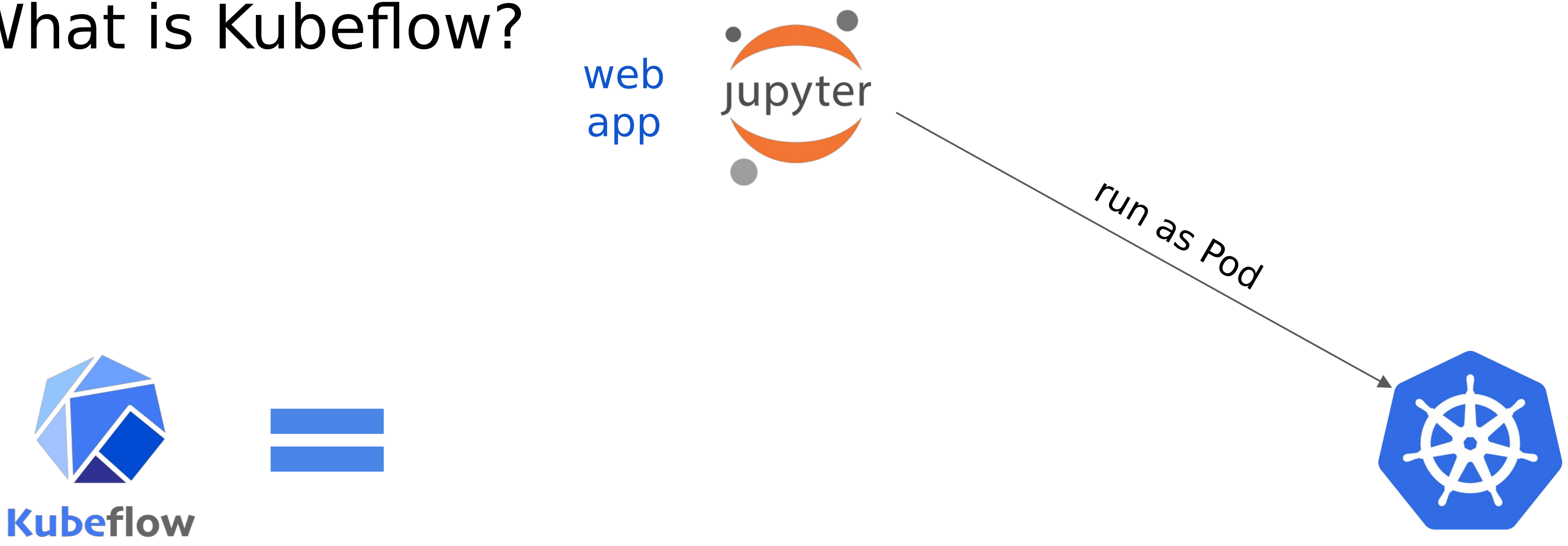
What is Kubeflow?

Kubeflow

What is Kubeflow?

web
app

What is Kubeflow?



What is Kubeflow?

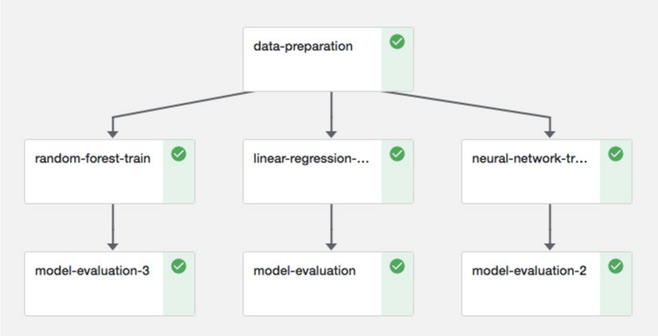
web
app

jupyter

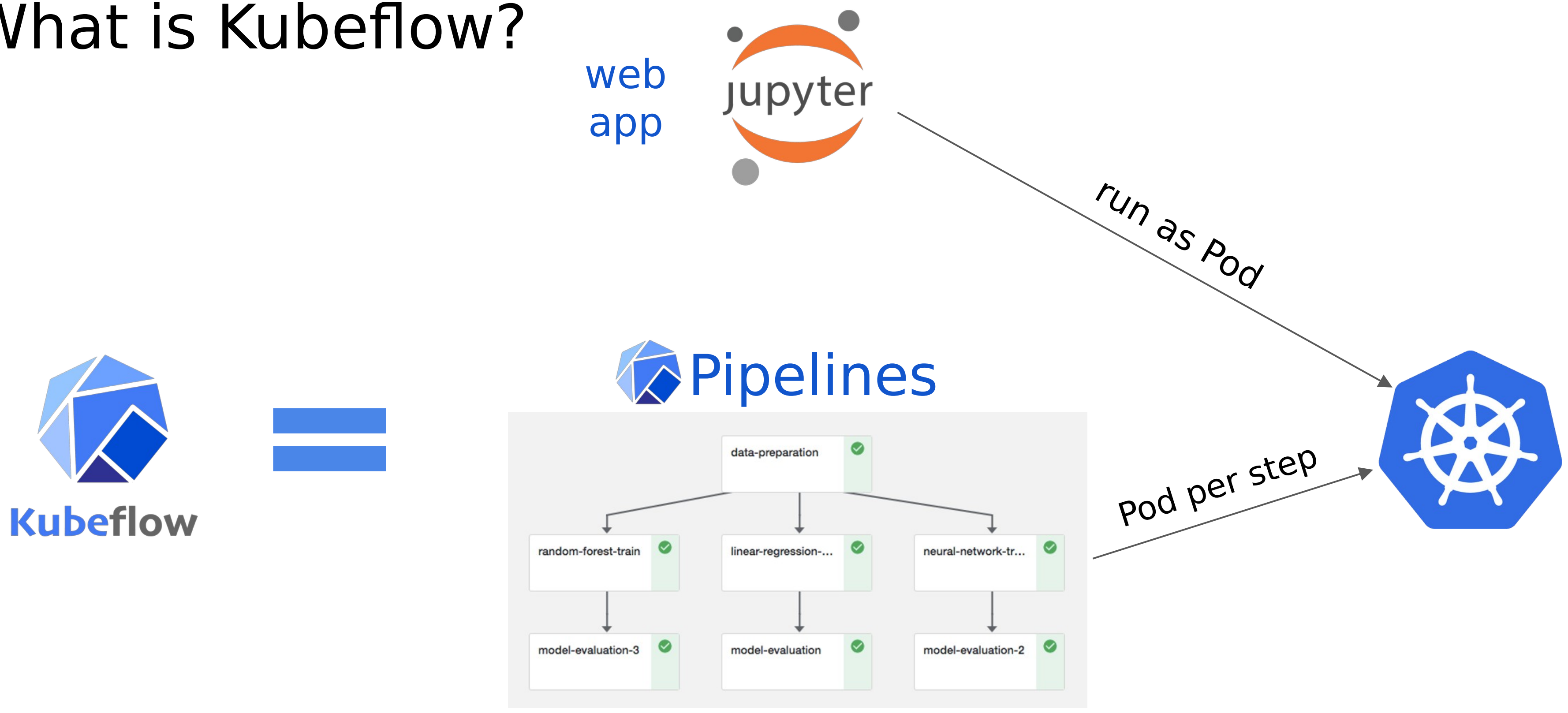
run as Pod

Kubeflow

Pipelines



What is Kubeflow?



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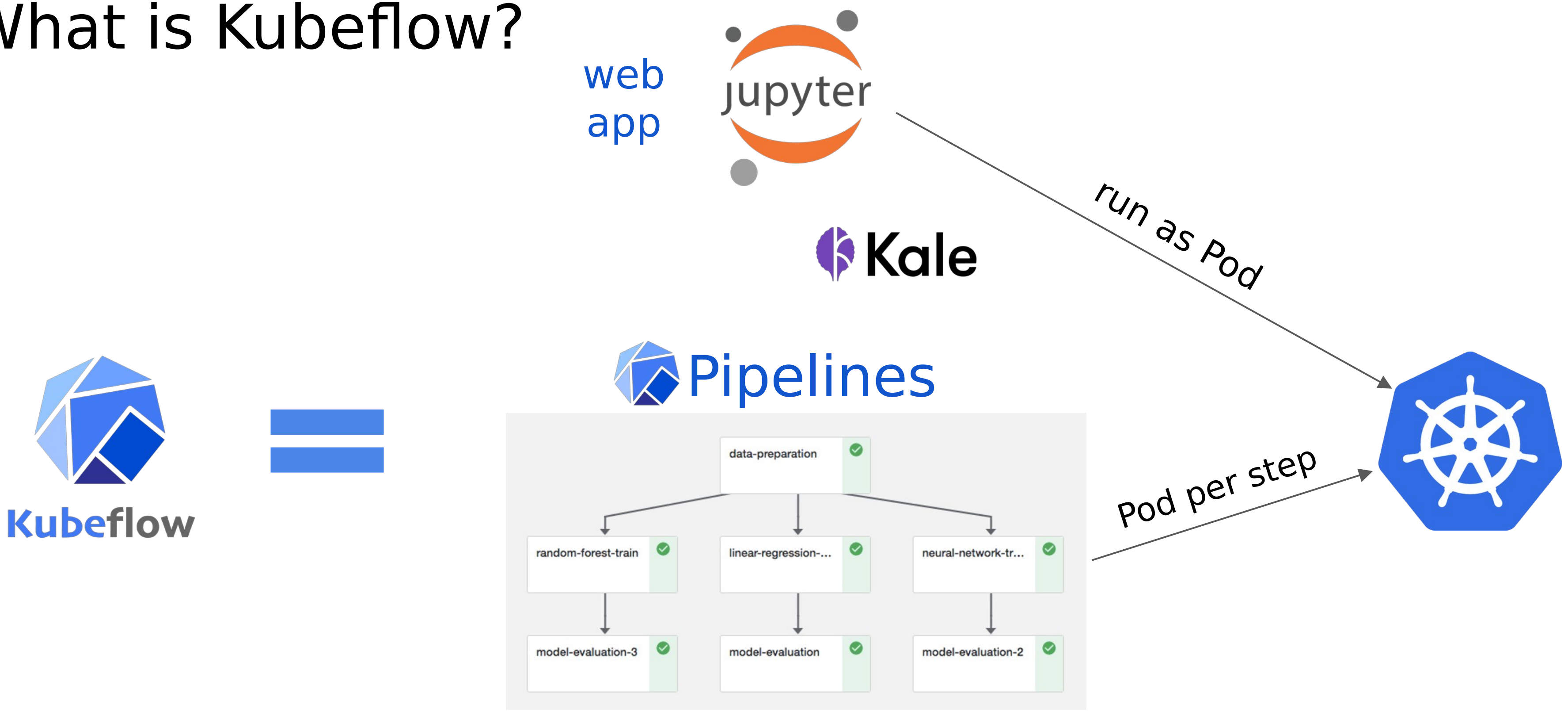

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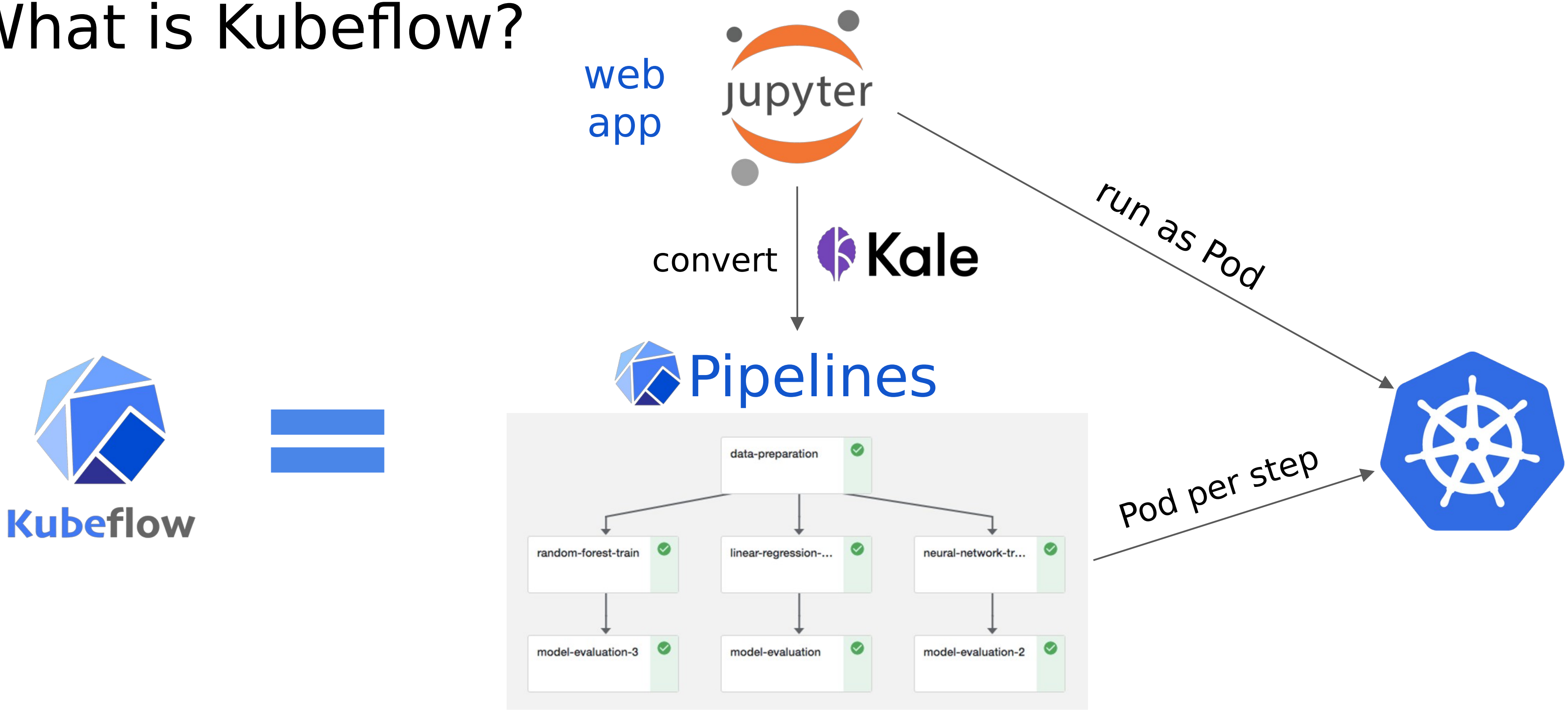

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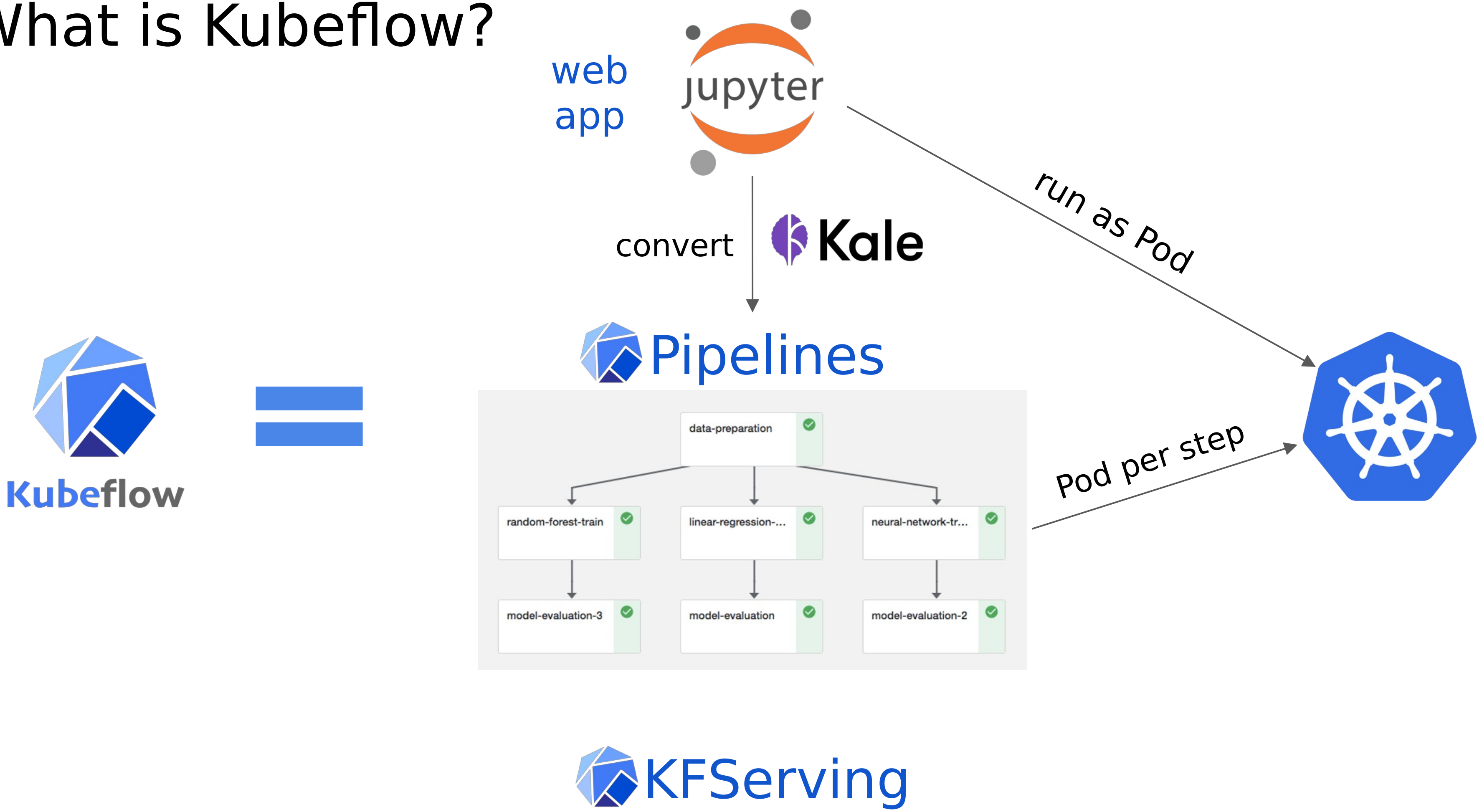

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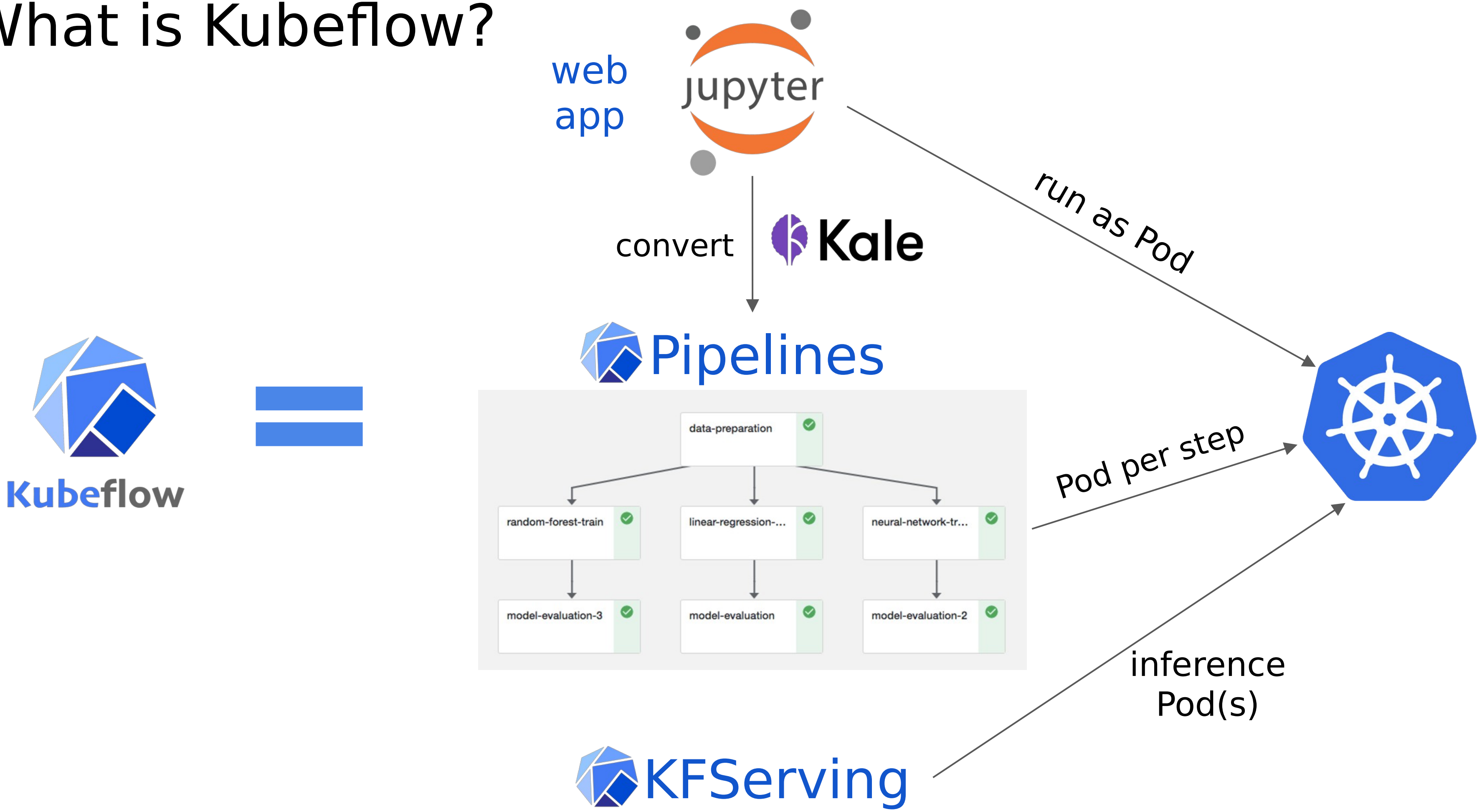

The Problem

The Problem

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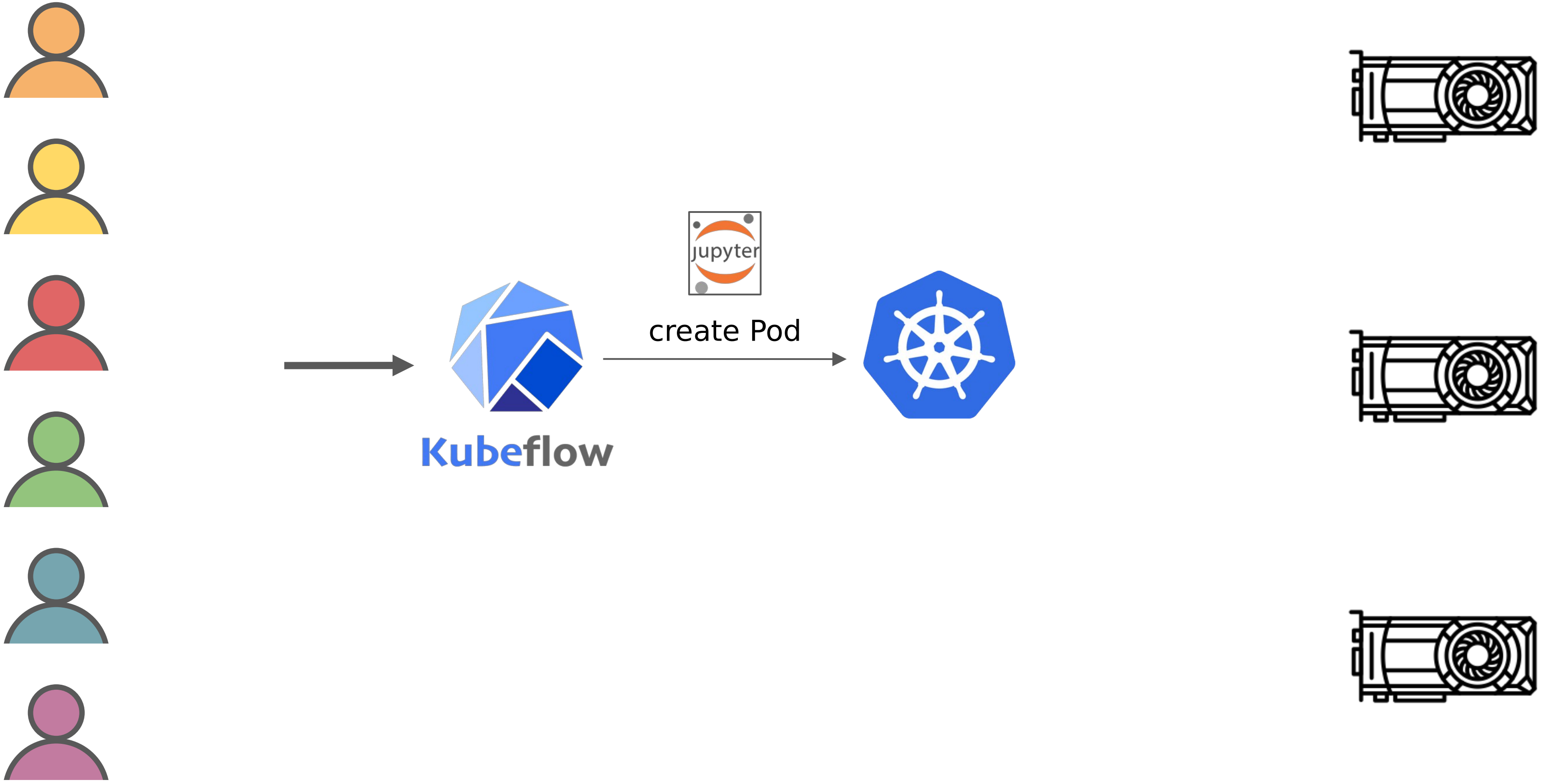

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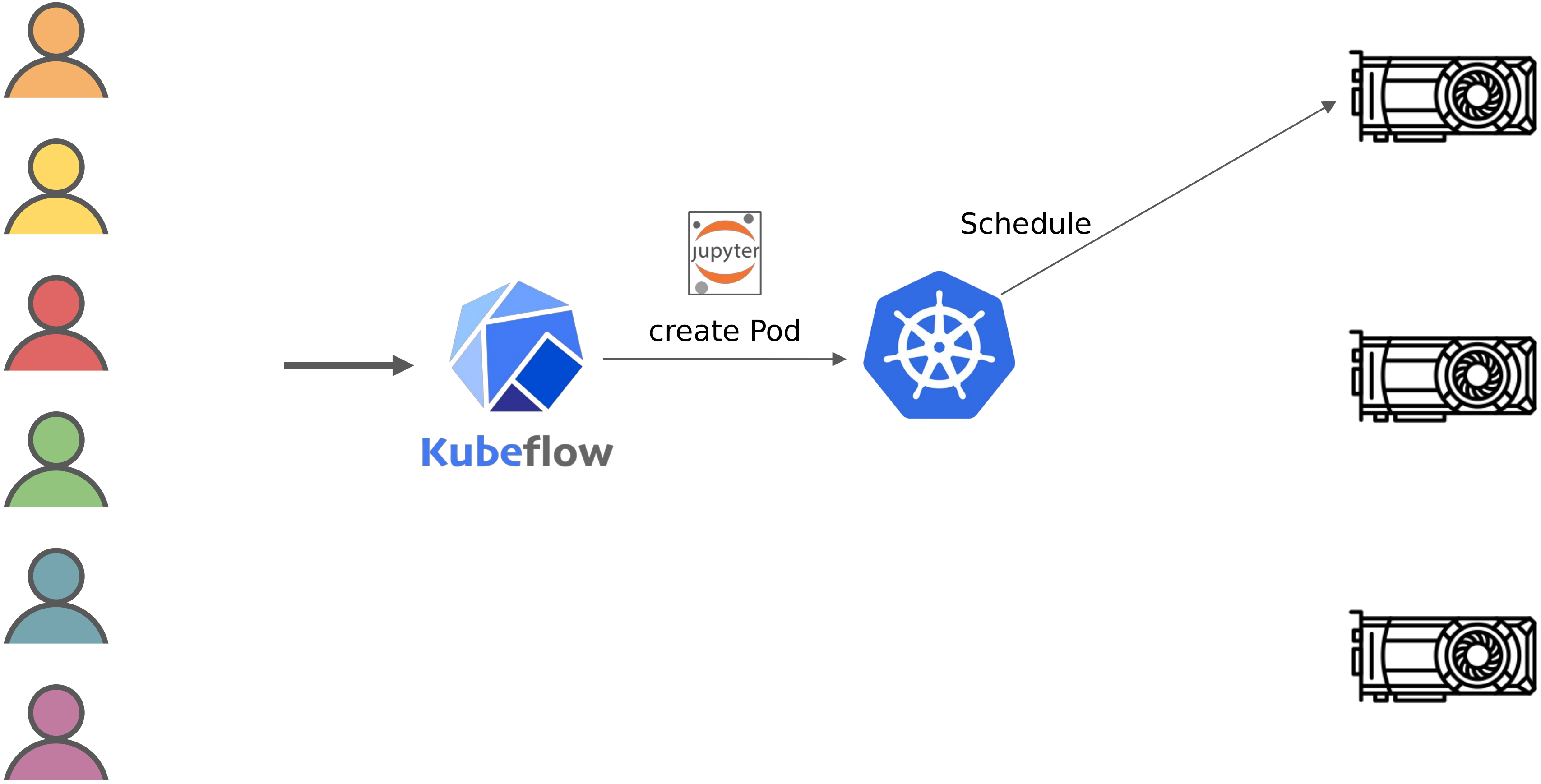

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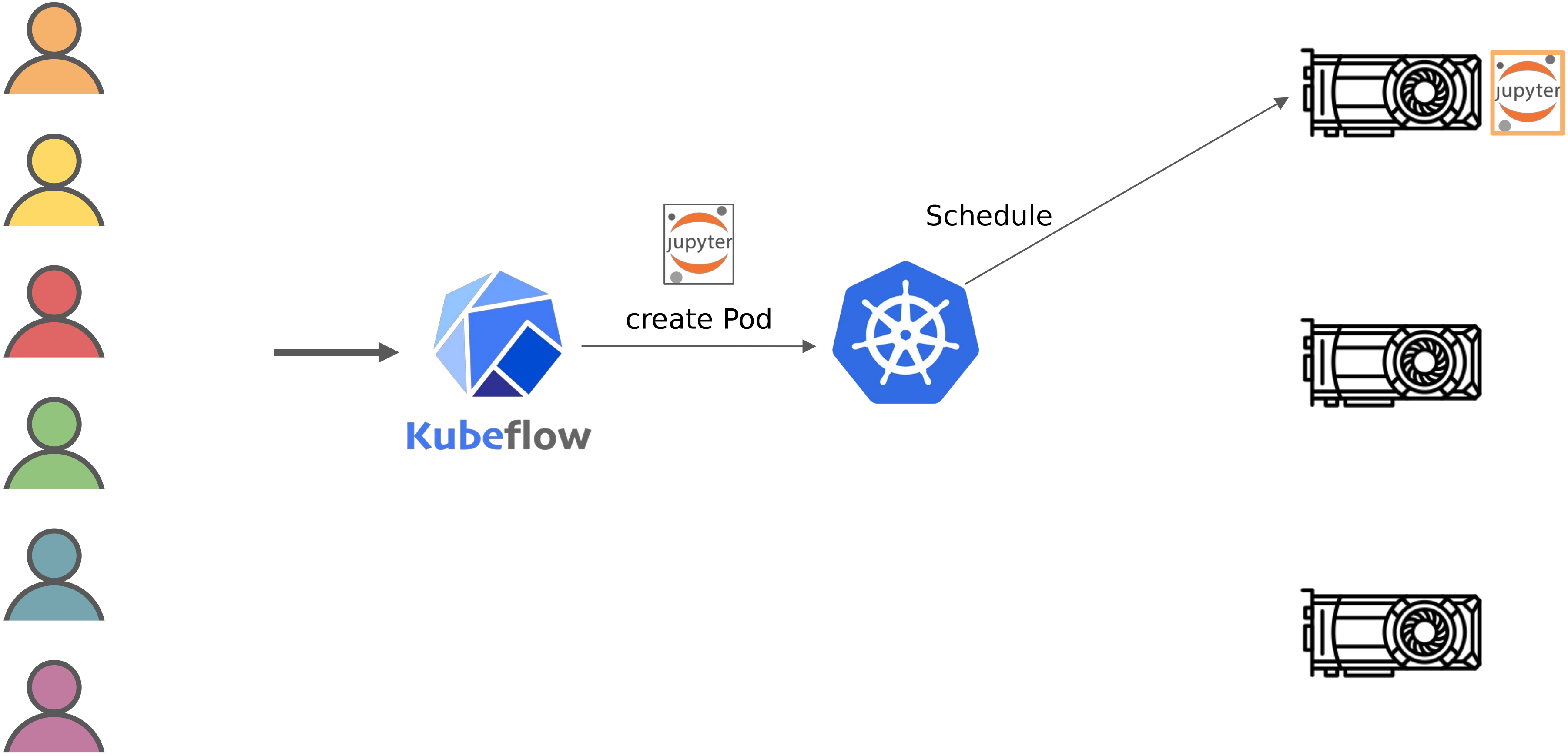

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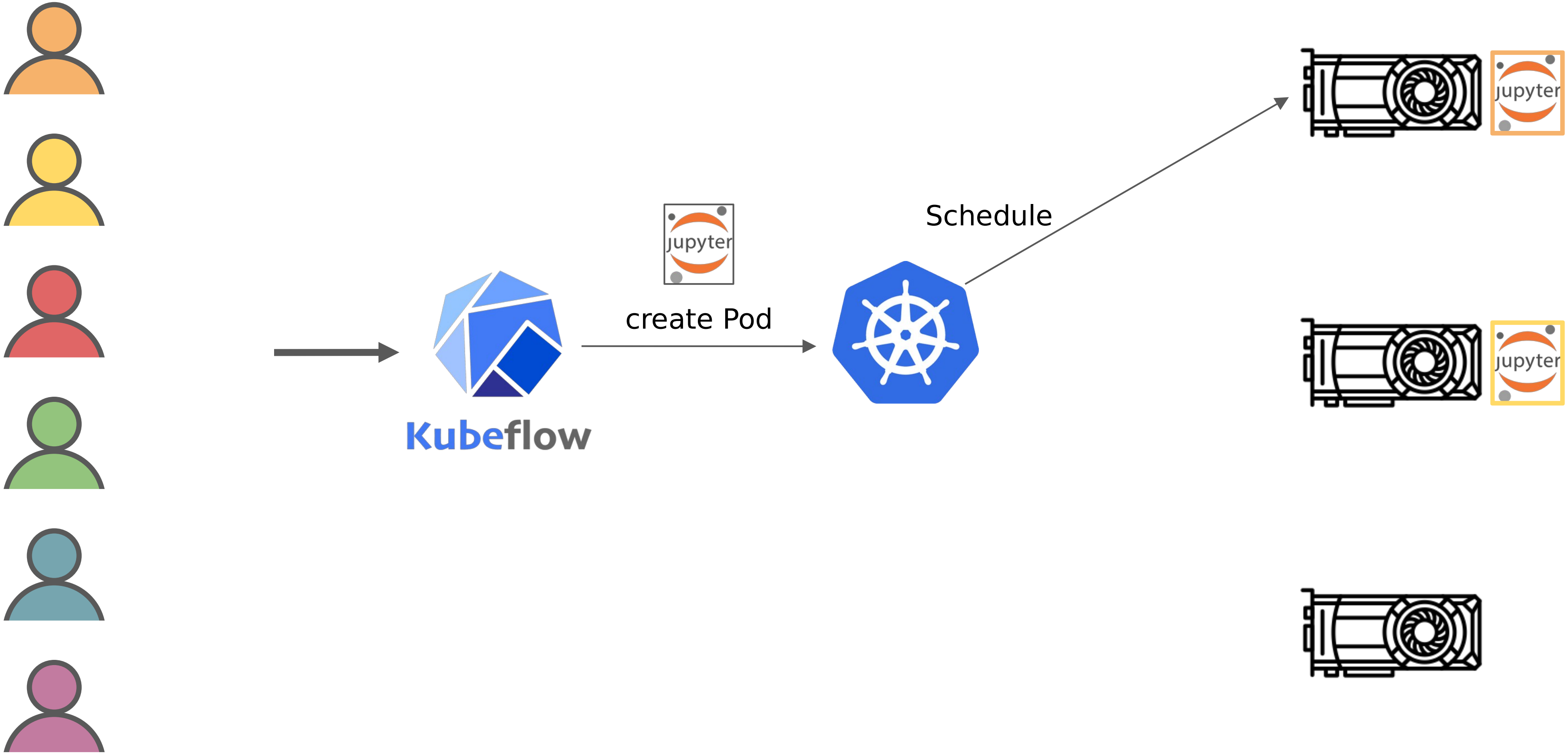
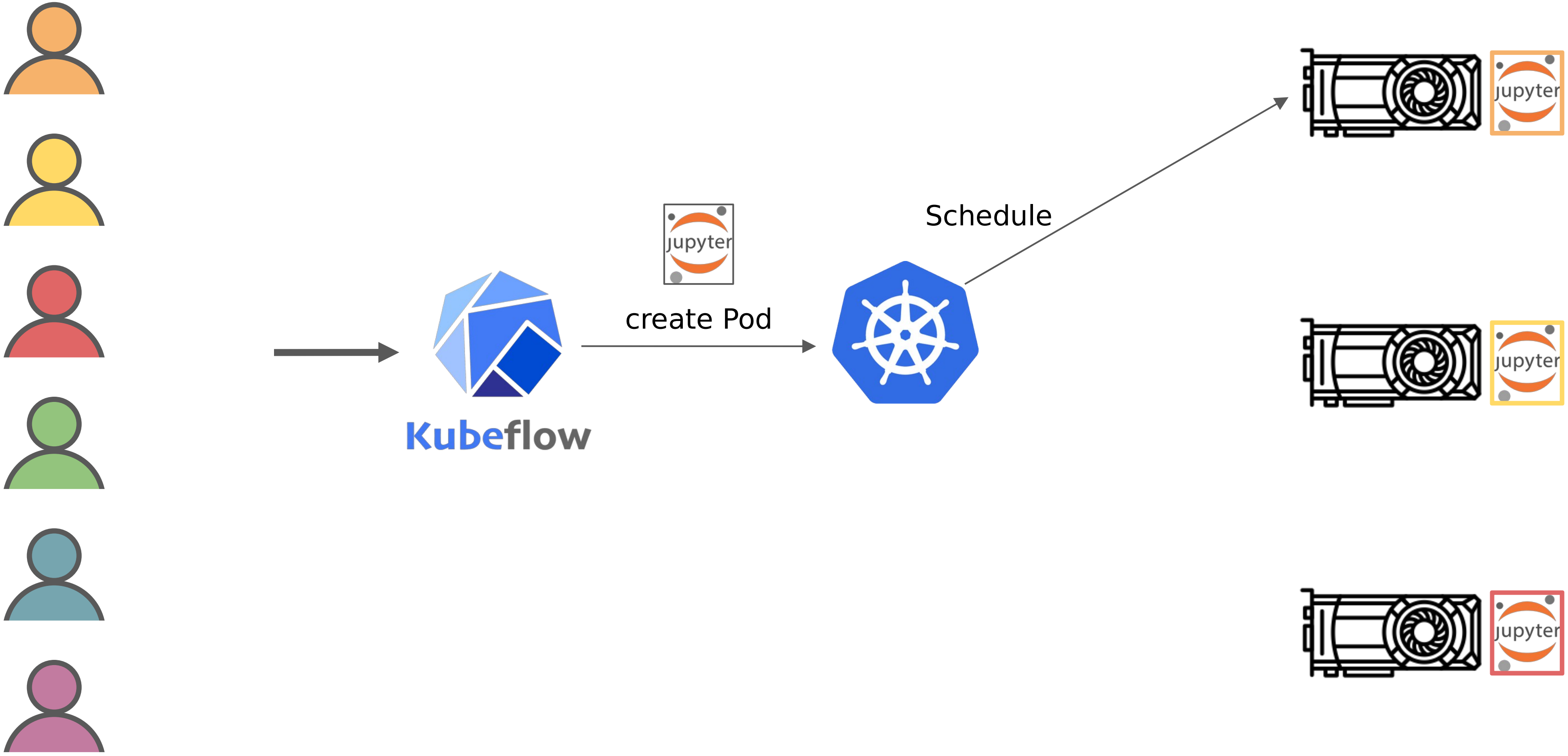
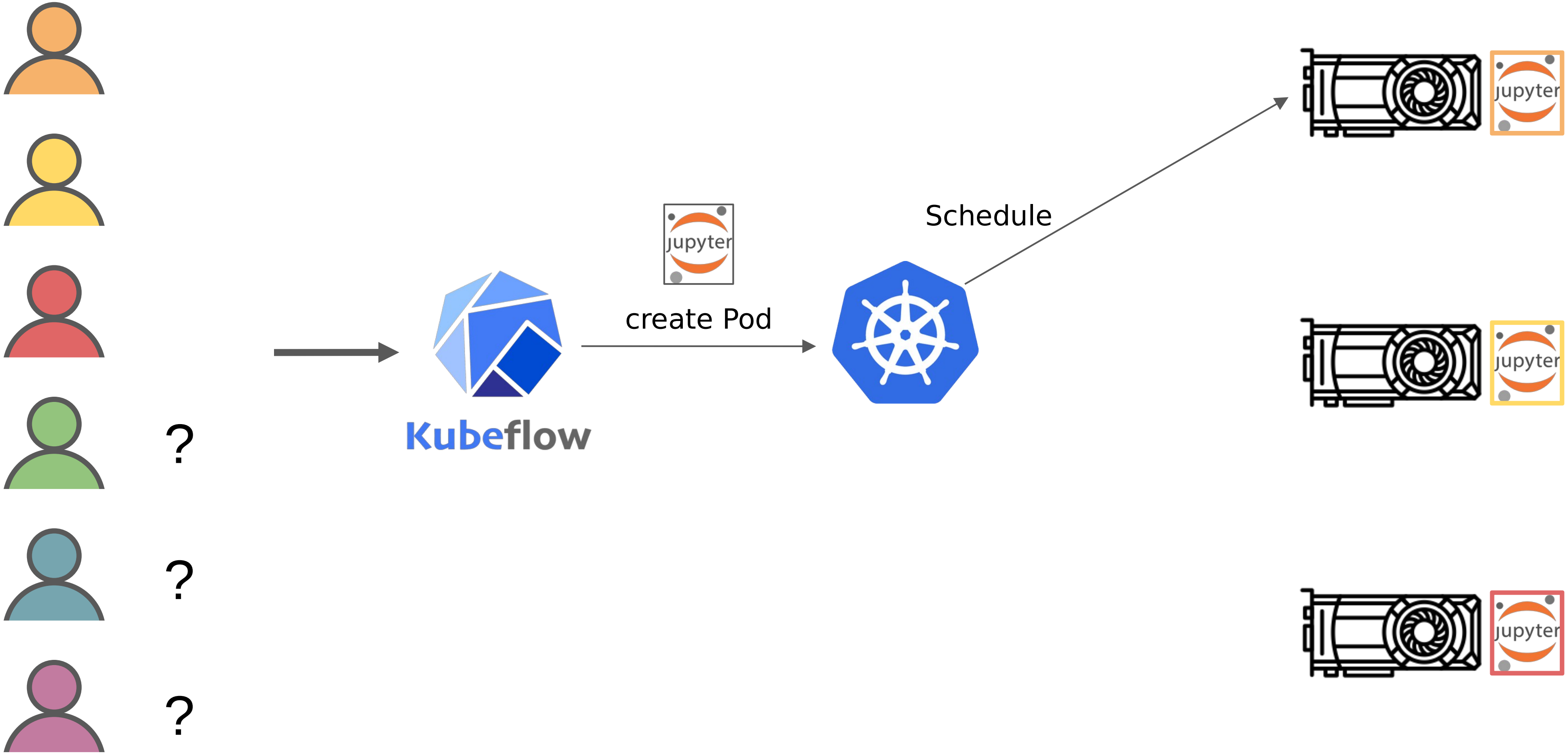


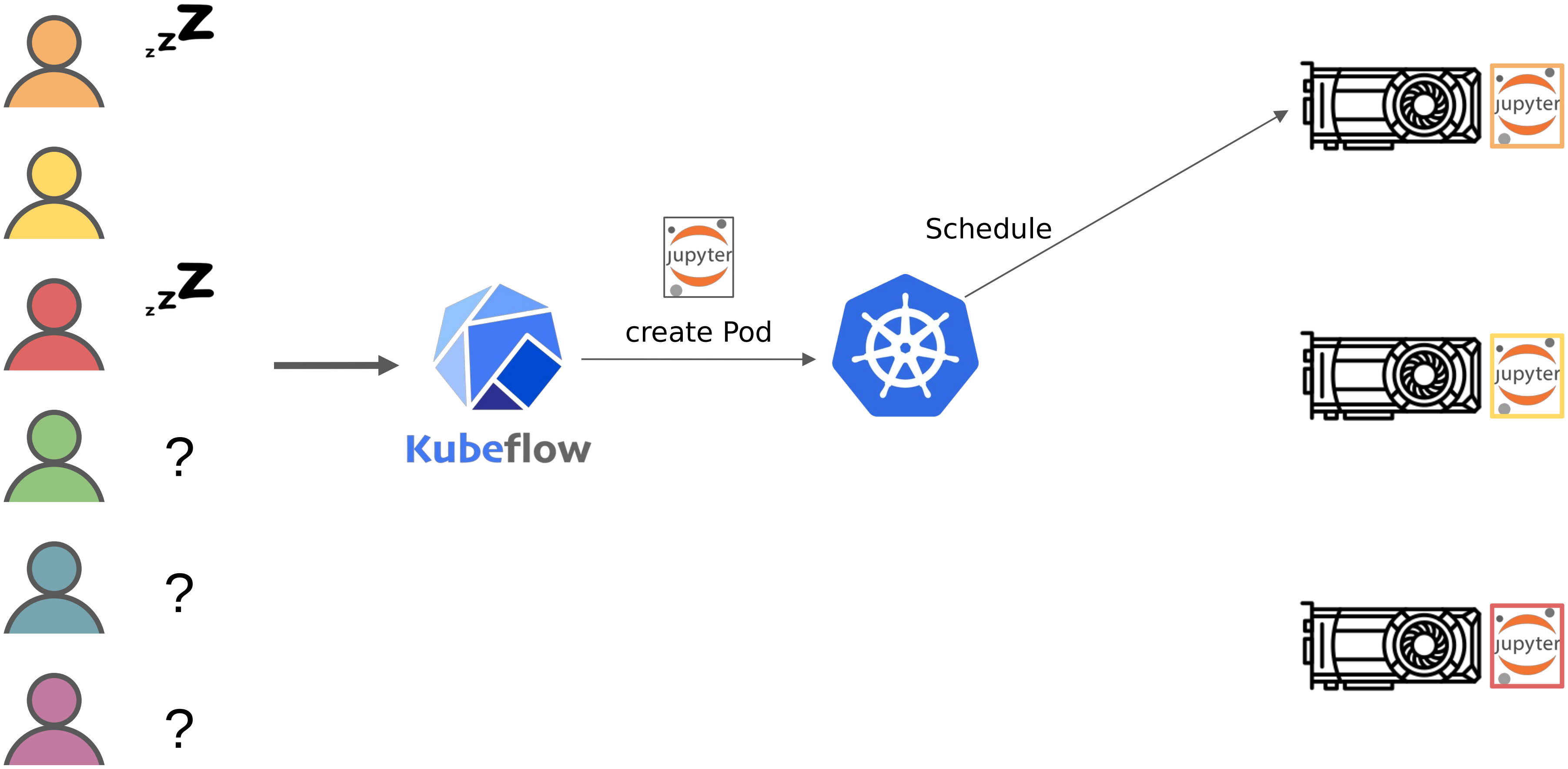
The Problem


jupyter
create Pod
Kubeflow
Schedule
jupyter
jupyter
jupyter

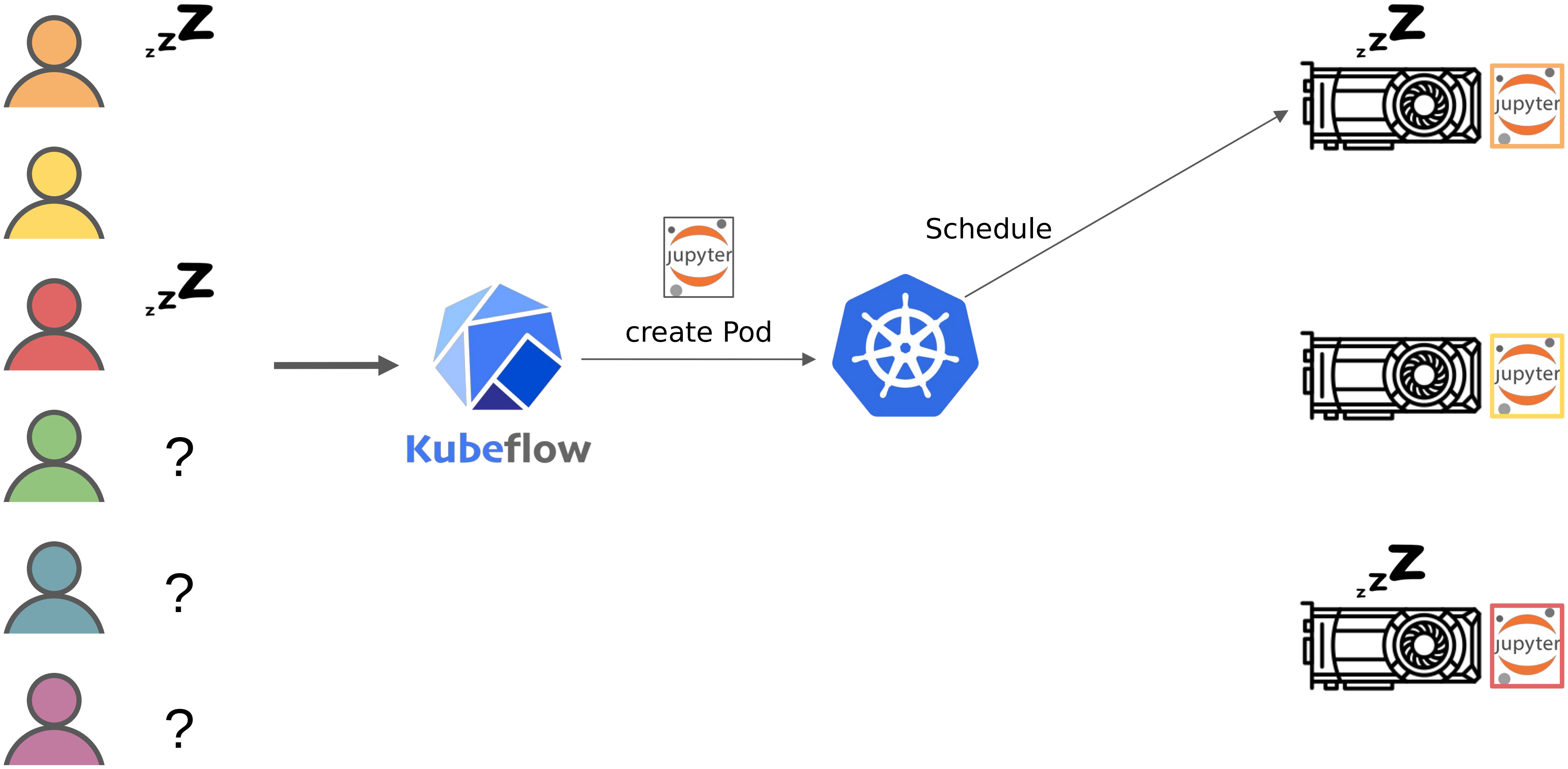
The Problem


?
?
?
Kubeflow
jupyter
create Pod
Schedule
jupyter
jupyter
jupyter

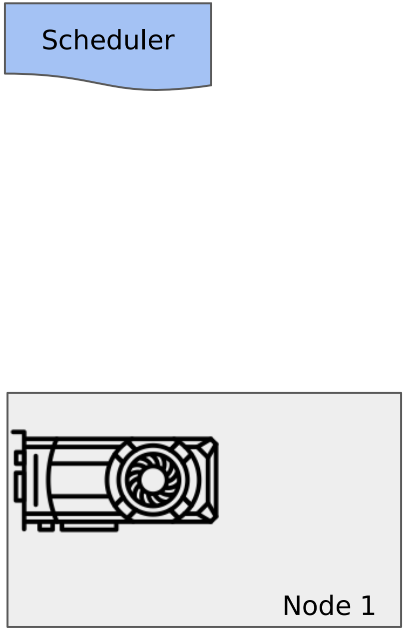
The Problem

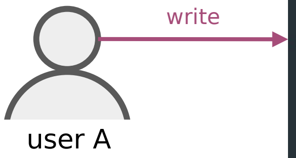

zzZ
zzZ
?
?
?
Kubeflow
jupyter
create Pod
Schedule
jupyter
jupyter
jupyter

The Problem



zzZ
zzZ
?
?
?
Kubeflow
jupyter
create Pod
Schedule
zzZ
jupyter
jupyter
zzZ
jupyter

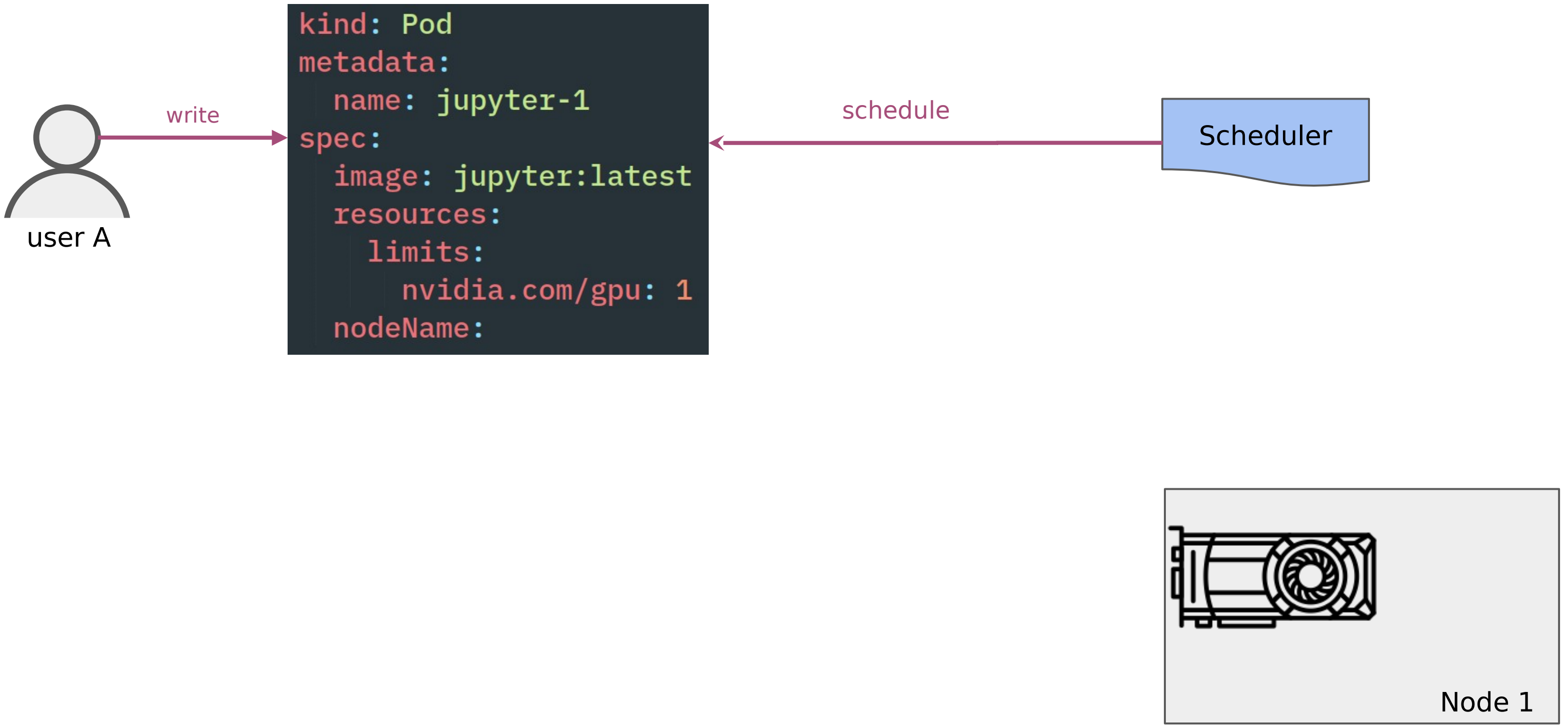

Scheduler
Node 1

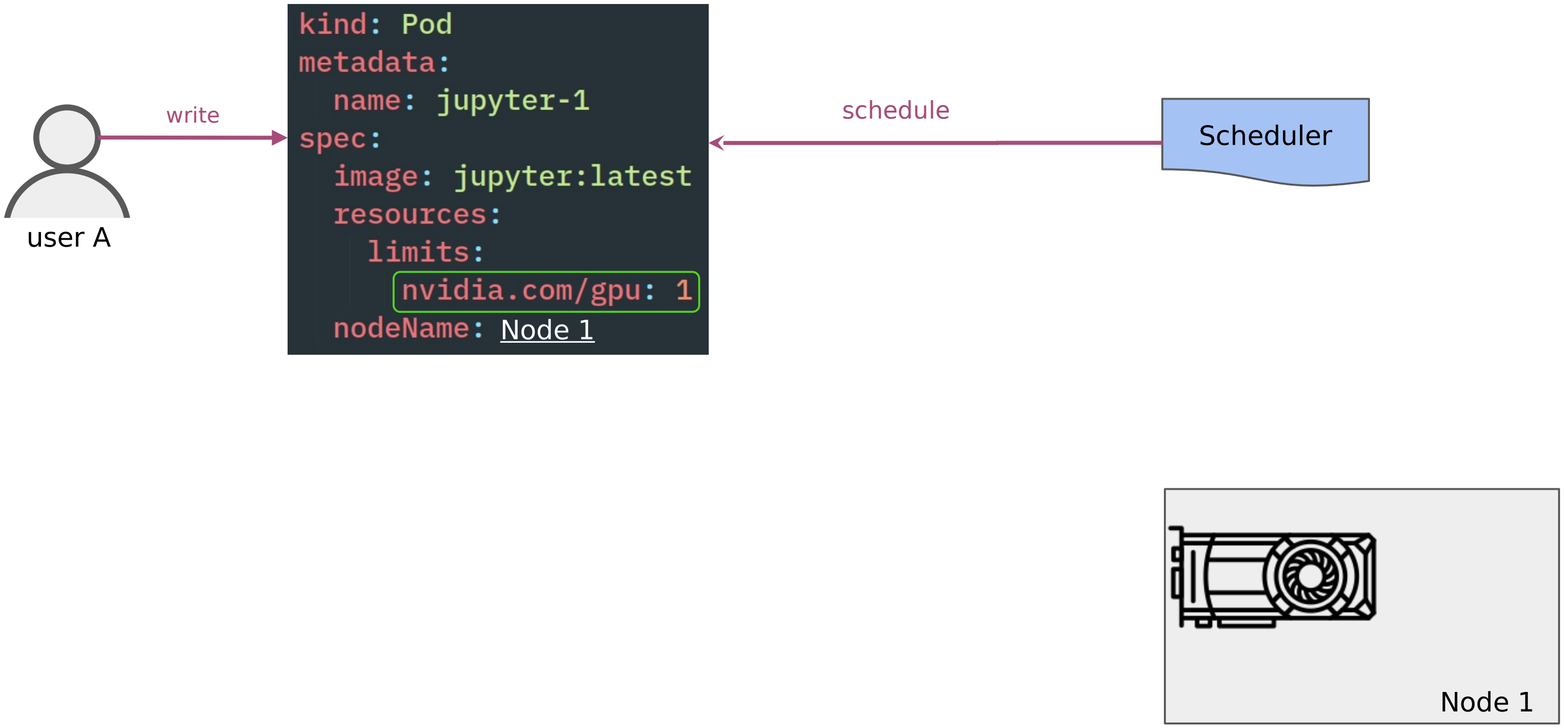



```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName:
```

Scheduler

Node 1


write
user A
kind: Pod
metadata:
name: jupyter-1
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName:
schedule
Scheduler
Node 1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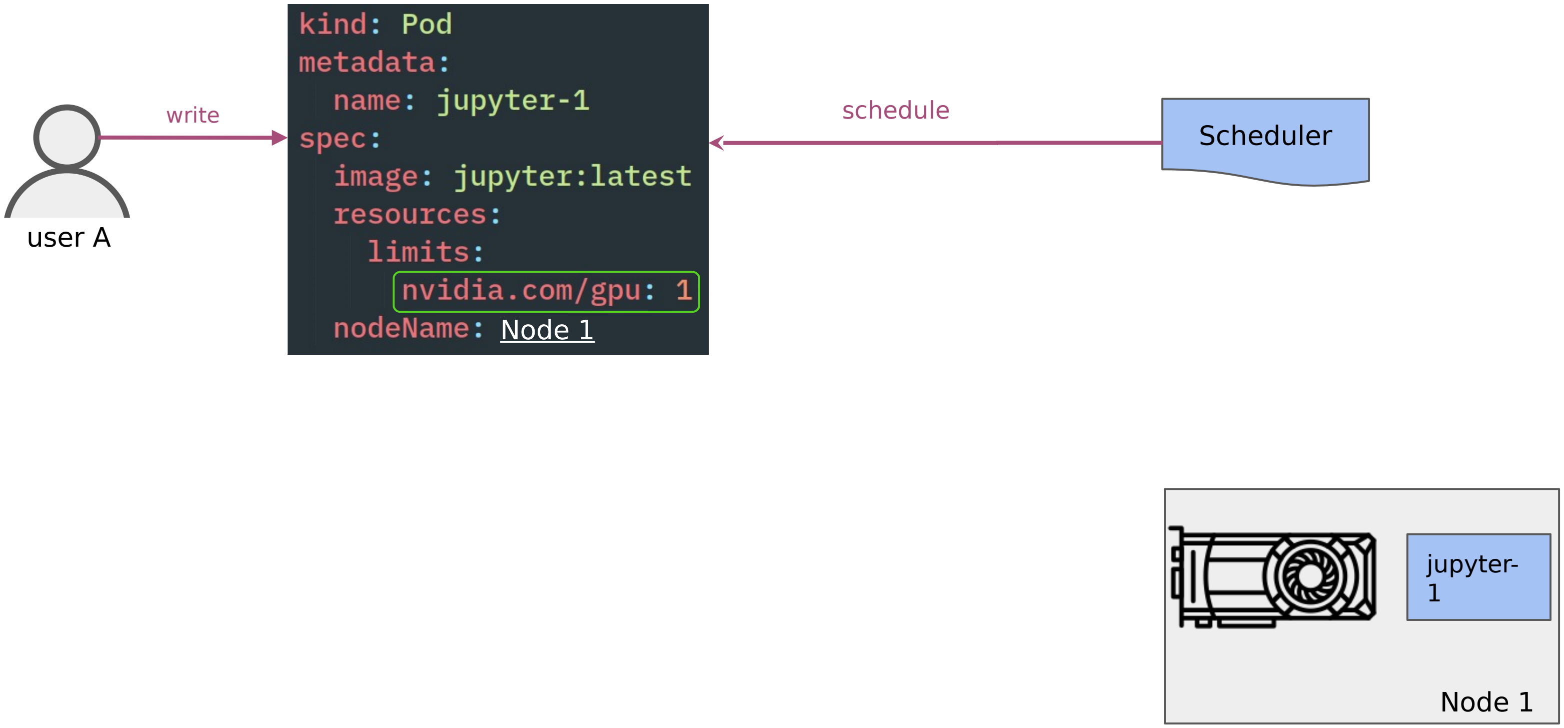
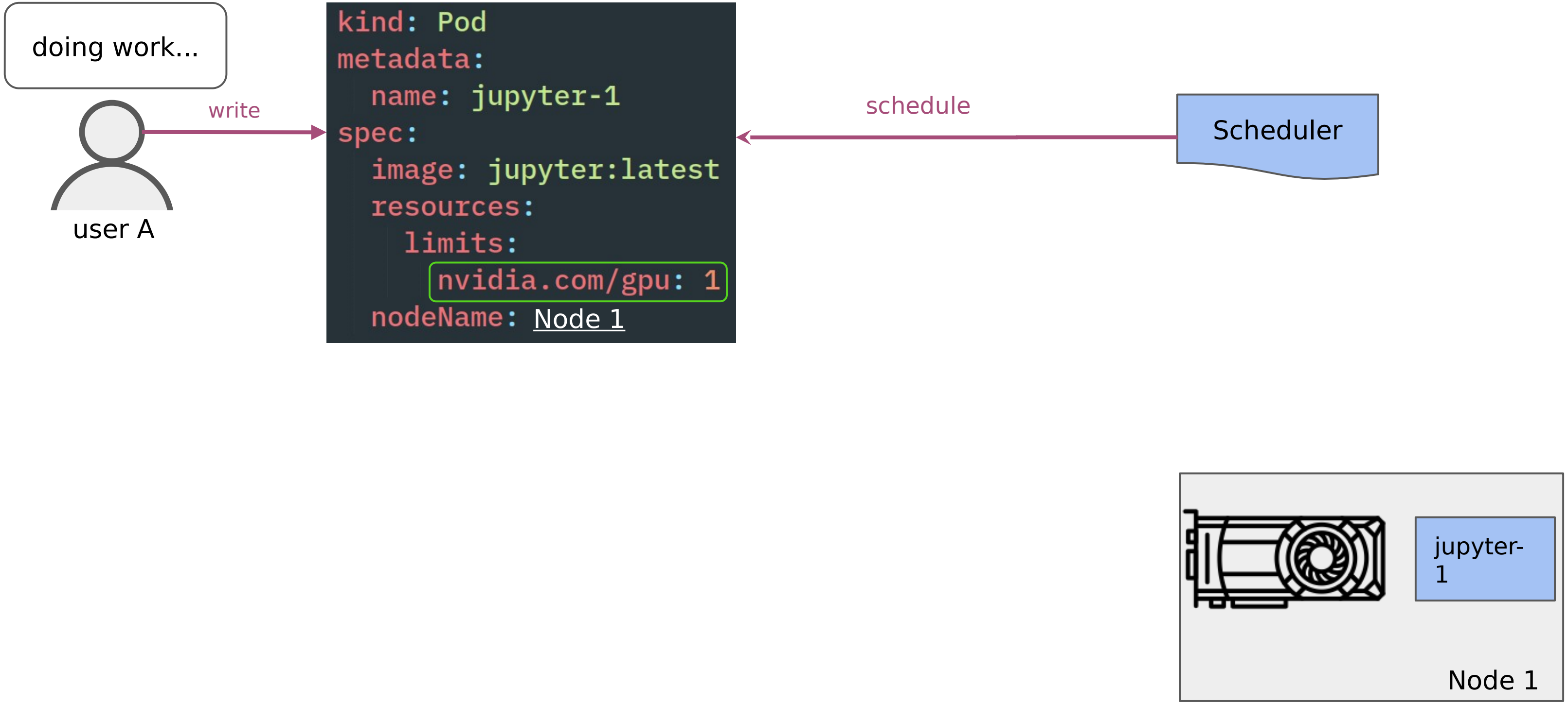
nodeName: Node 1
schedule
Scheduler
Node 1


write
user A
kind: Pod
metadata:
name: jupyter-1
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName: Node 1
schedule
Scheduler
jupyter-1
Node 1


doing work...
user A
write
kind: Pod
metadata:
name: jupyter-1
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName: Node 1
schedule
Scheduler
jupyter-1
Node 1

doing work...

user A

write

```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName: Node 1
```

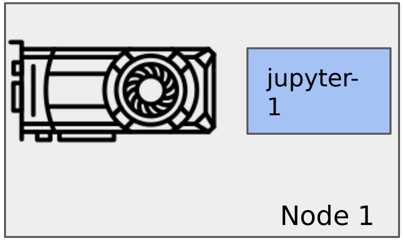
schedule

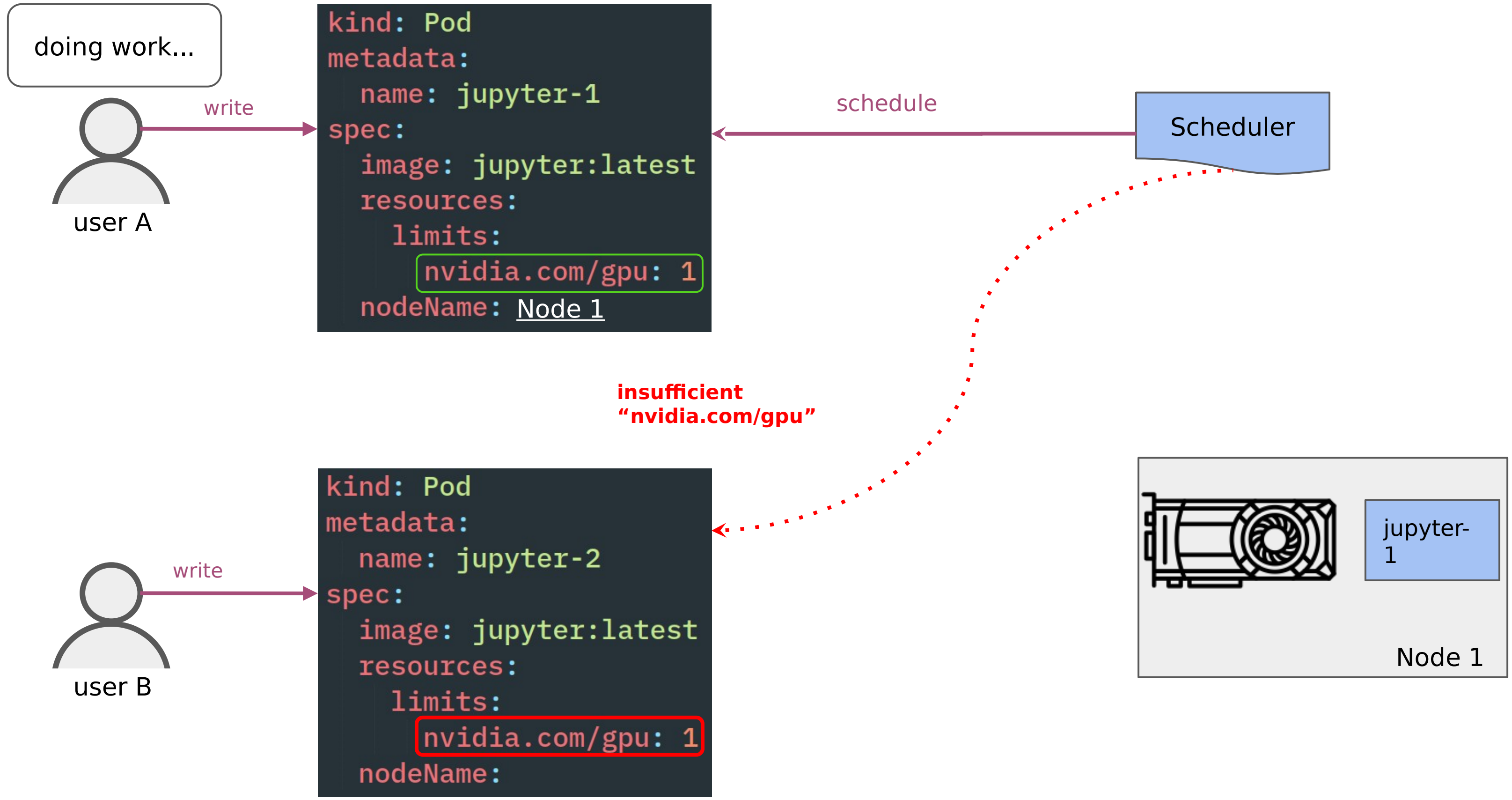
Scheduler

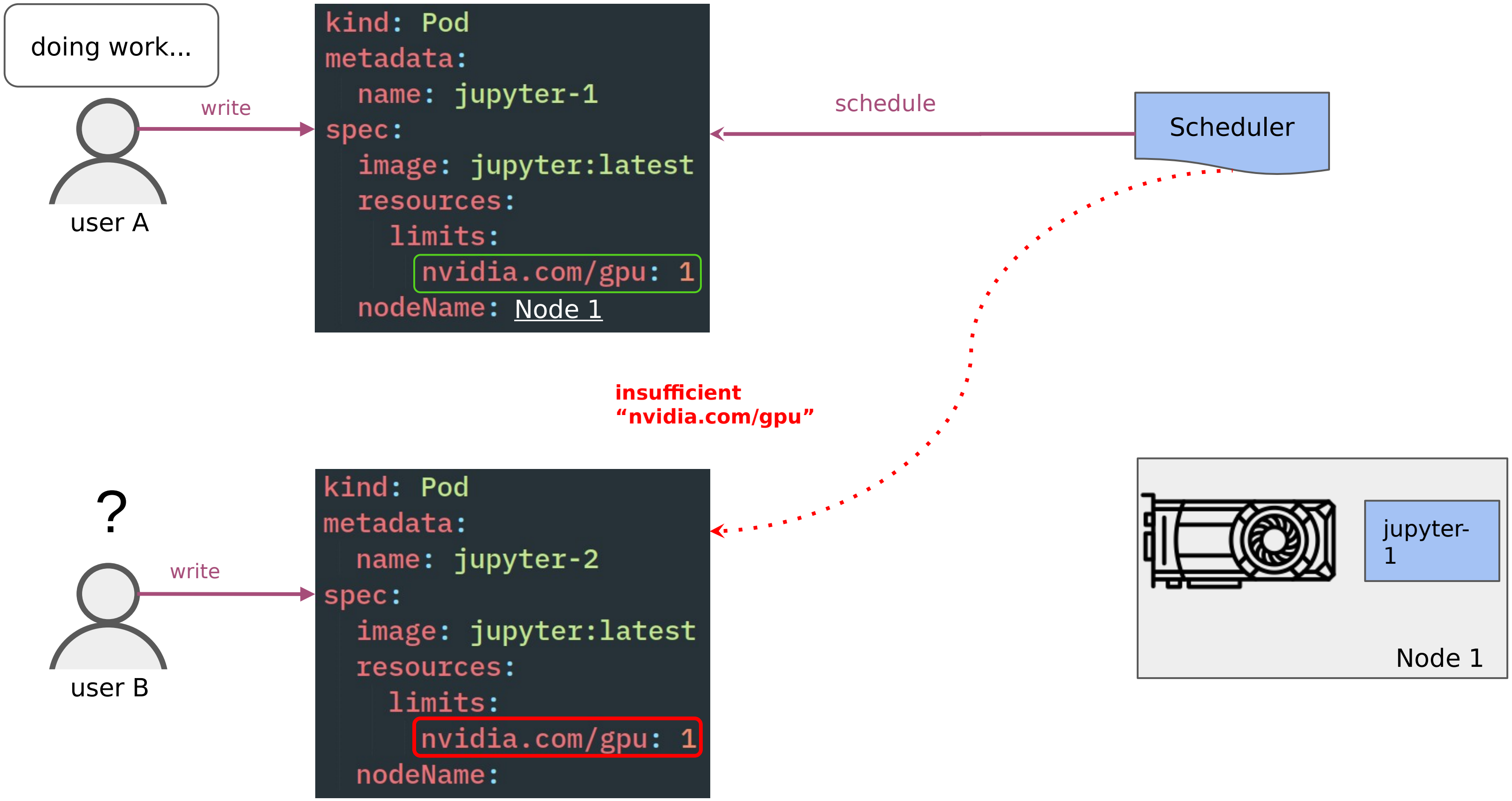
user B

write

```yaml
kind: Pod
metadata:
  name: jupyter-2
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName:
```




doing work...
write
user A
kind: Pod
metadata:
name: jupyter-1
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName: Node 1
schedule
Scheduler
insufficient
“nvidia.com/gpu”
write
user B
kind: Pod
metadata:
name: jupyter-2
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName:
jupyter-
1
Node 1


doing work...
write
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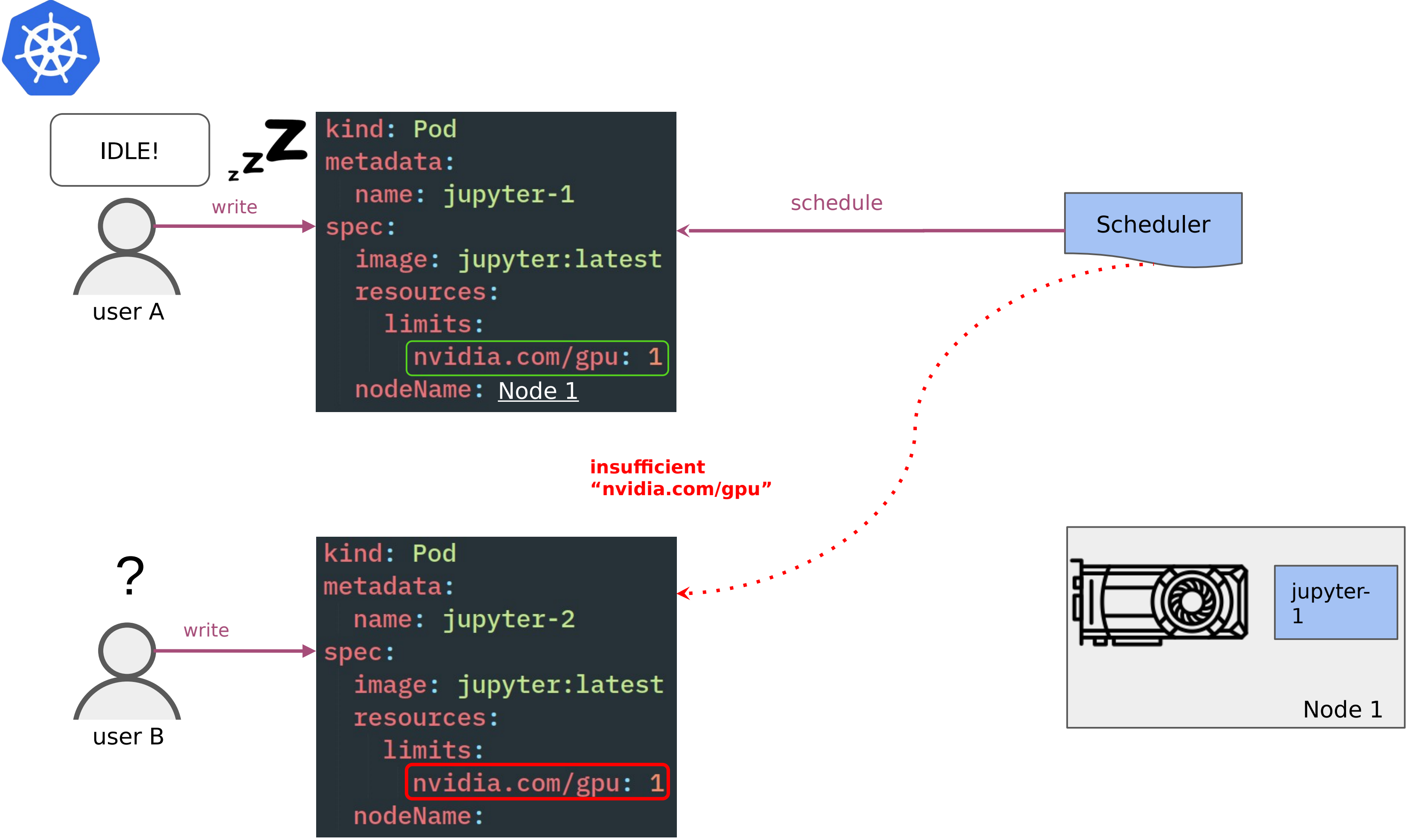
kind: Pod
metadata:
name: jupyter-1
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName: Node 1
schedule
Scheduler
insufficient
“nvidia.com/gpu”
?
write
user B
kind: Pod
metadata:
name: jupyter-2
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName:
jupyter-1
Node 1


IDLE!
zzZ
write
user A
kind: Pod
metadata:
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resources:
limits:
nvidia.com/gpu: 1
nodeName: Node 1
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Scheduler
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resources:
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nvidia.com/gpu: 1
nodeName:
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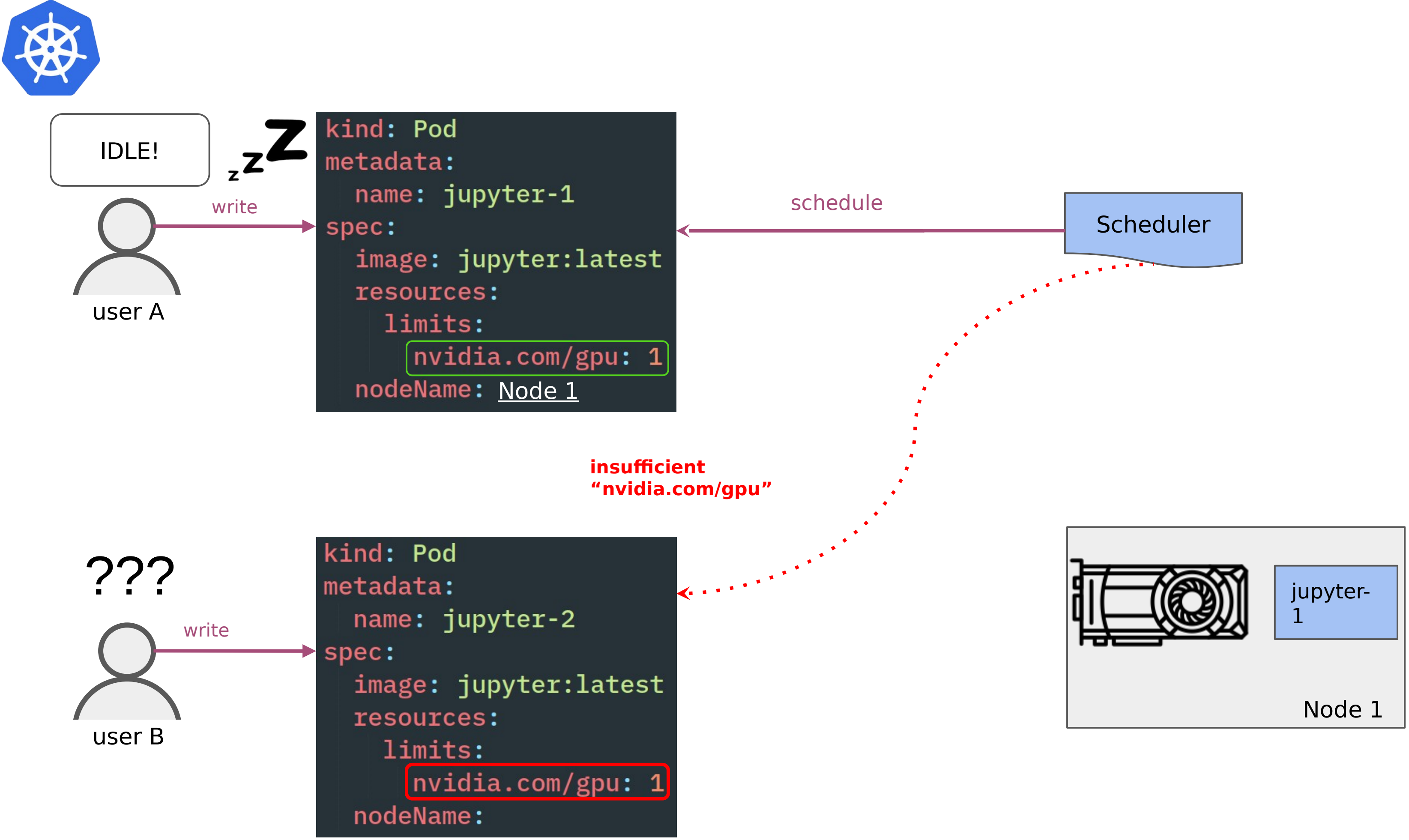
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metadata:
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image: jupyter:latest
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limits:
nvidia.com/gpu: 1
nodeName: Node 1
schedule
Scheduler
insufficient
“nvidia.com/gpu”
???
write
user B
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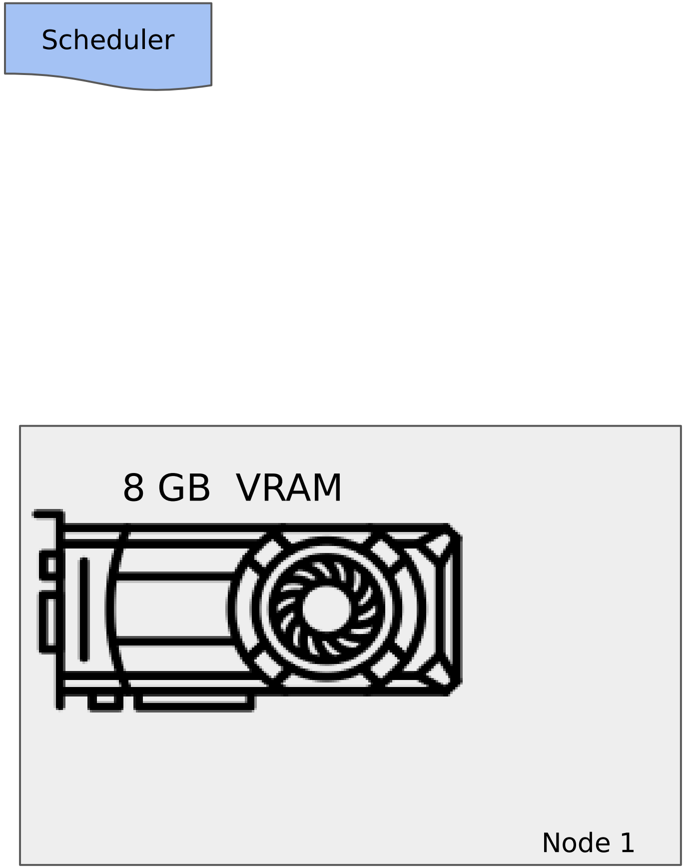
metadata:
name: jupyter-2
spec:
image: jupyter:latest
resources:
limits:
nvidia.com/gpu: 1
nodeName:
jupyter-
1
Node 1

Existing Approaches (Aliyun, Kubeshare)



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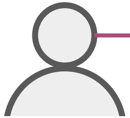


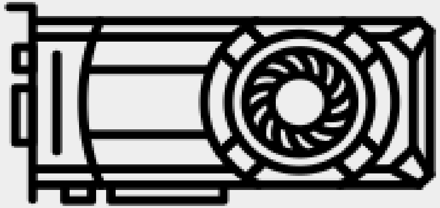
write

user
A

```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      aliyun.com/gpu-mem: 4
  nodeName:
```

Scheduler

8 GB VRAM



Node 1

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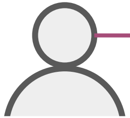

write

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metadata:
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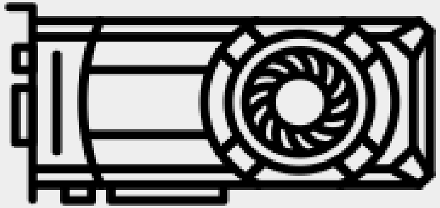
spec:
  image: jupyter:latest
  resources:
    limits:
      aliyun.com/gpu-mem: 4
  nodeName:
```

schedule

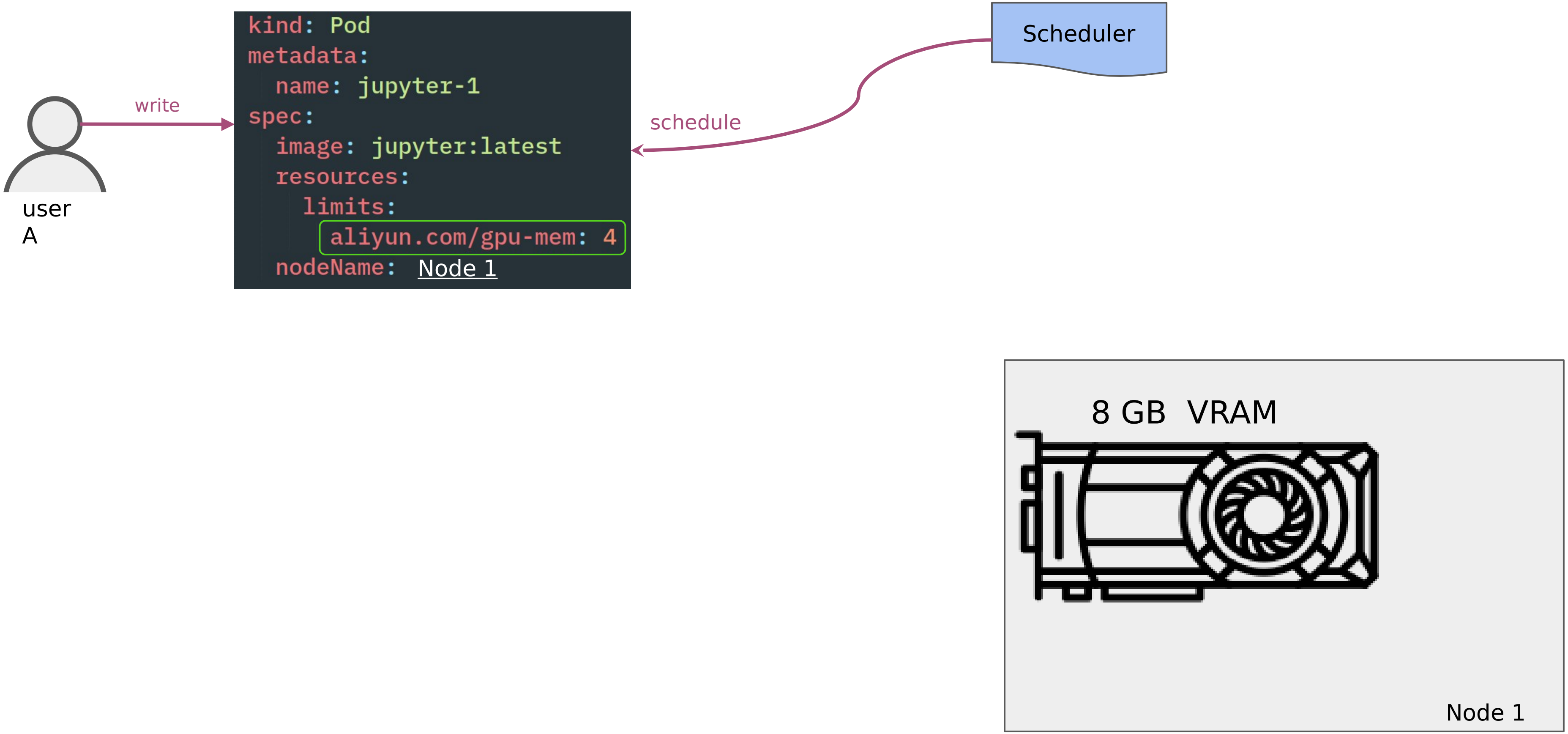
Scheduler

8 GB VRAM



Node 1

Existing Approaches (Aliyun, Kubeshare)



Existing Approaches (Aliyun, Kubeshare)

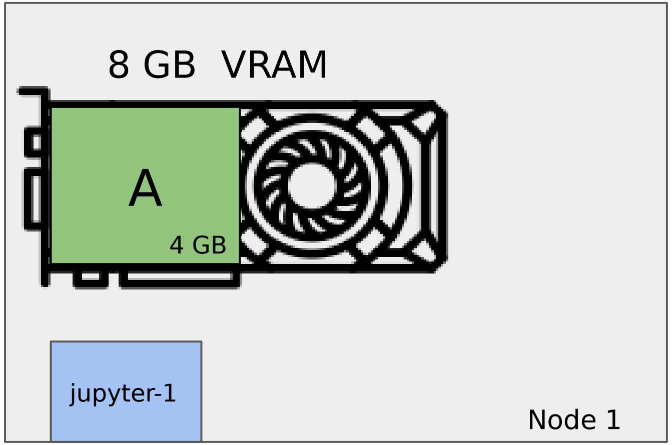
user A

write

```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      aliyun.com/gpu-mem: 4
  nodeName: Node 1
```

schedule

Scheduler



Existing Approaches (Aliyun, Kubeshare)

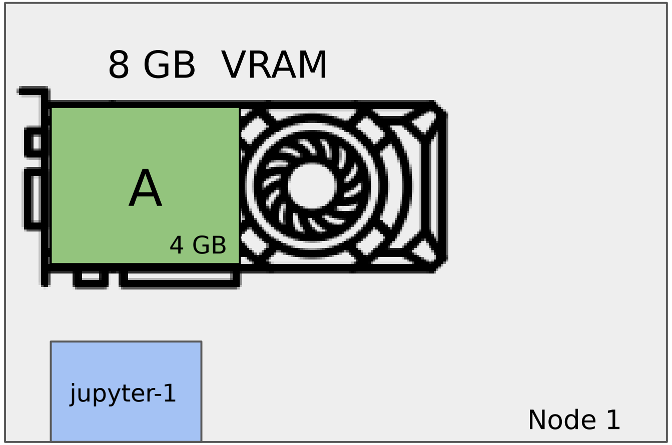
user A —write→

```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      aliyun.com/gpu-mem: 4
  nodeName: Node 1
```

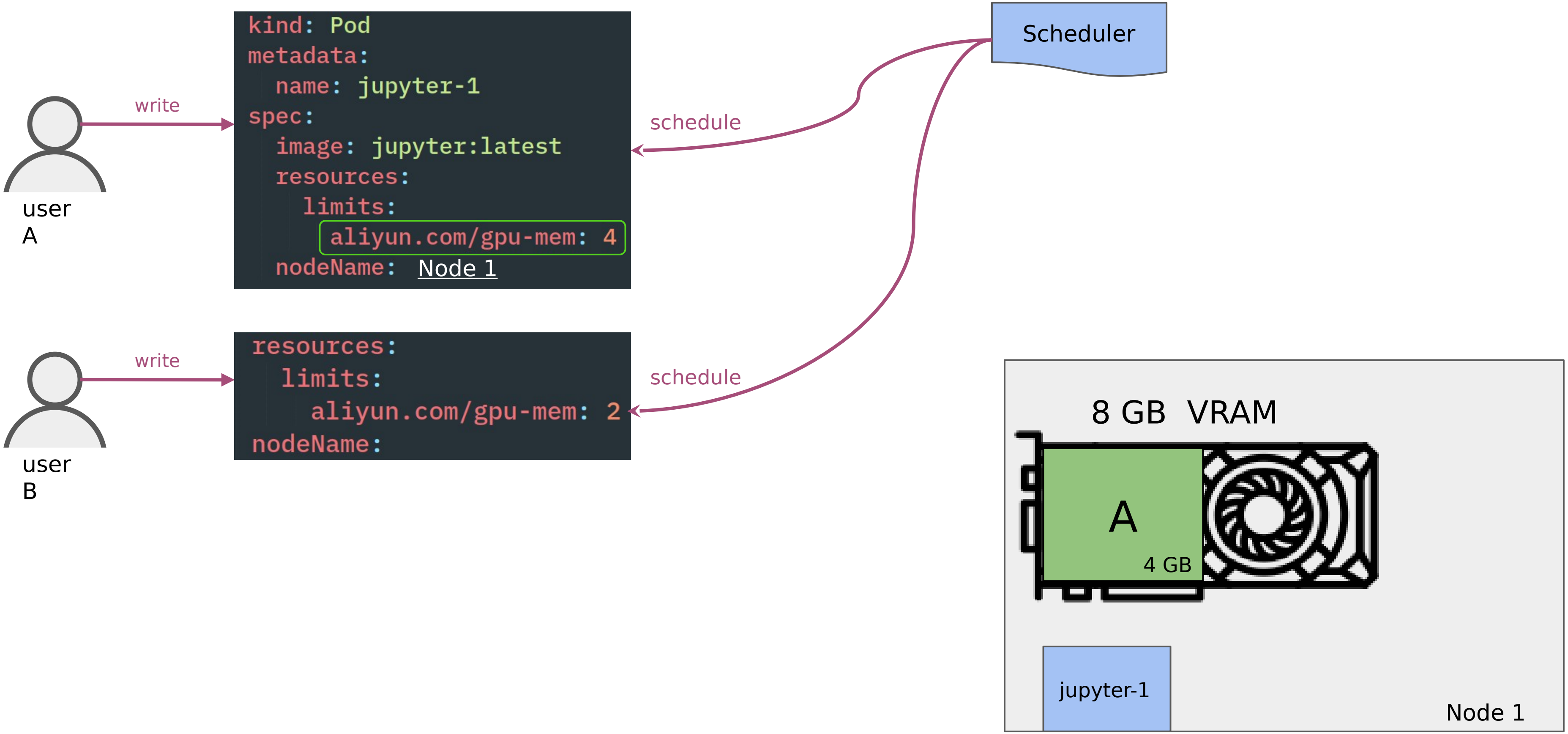
←schedule— Scheduler

user B —write→

```yaml
resources:
  limits:
    aliyun.com/gpu-mem: 2
nodeName:
```



Existing Approaches (Aliyun, Kubeshare)



Existing Approaches (Aliyun, Kubeshare)

Scheduler

user A — write

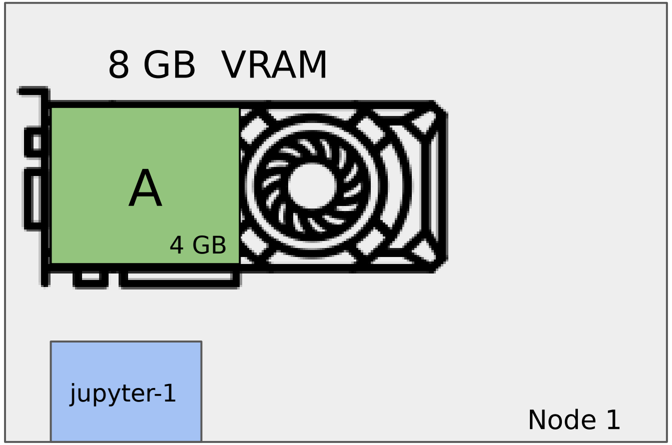
```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      aliyun.com/gpu-mem: 4
  nodeName: Node 1
```

schedule

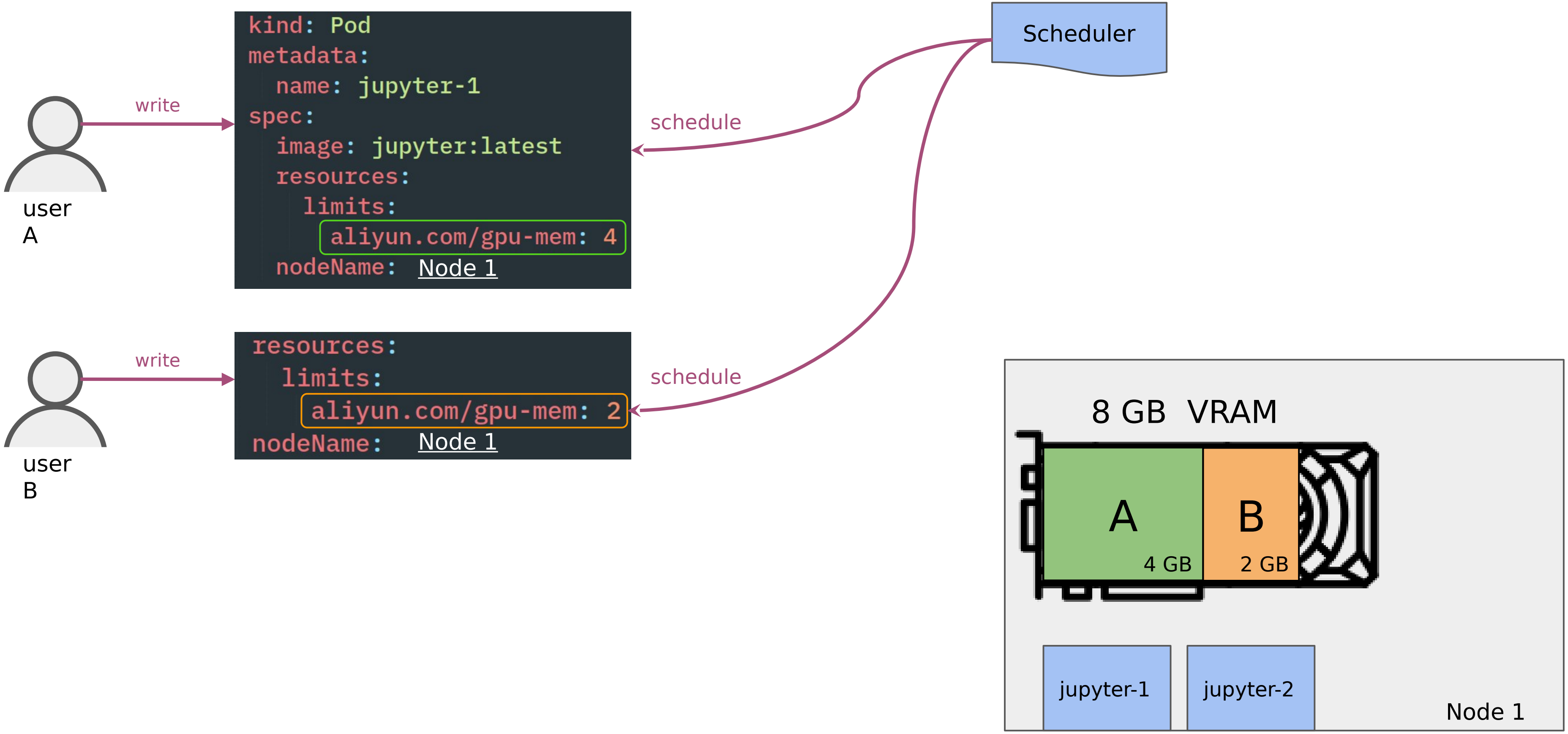
user B — write

```yaml
resources:
  limits:
    aliyun.com/gpu-mem: 2
nodeName: Node 1
```

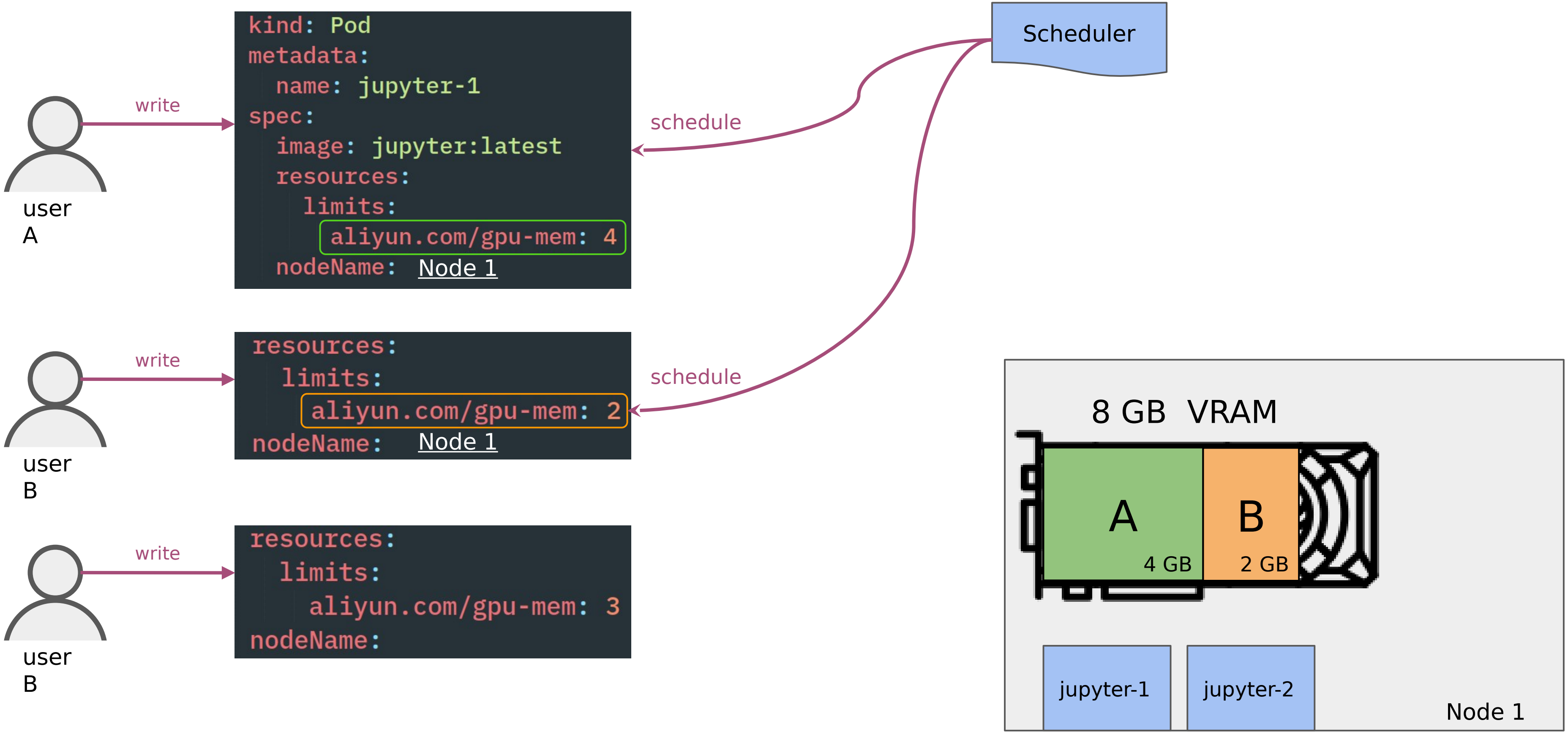
schedule



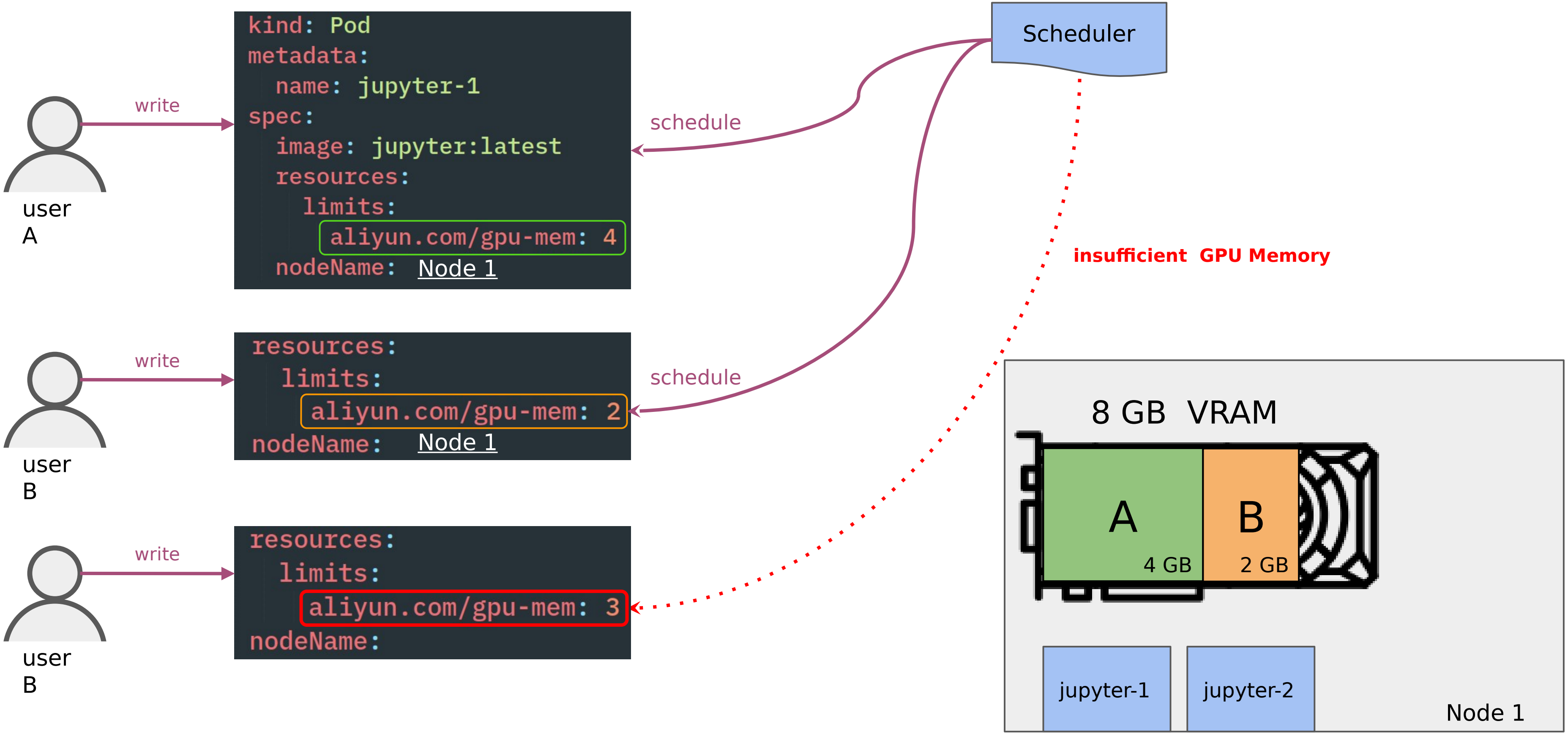
Existing Approaches (Aliyun, Kubeshare)



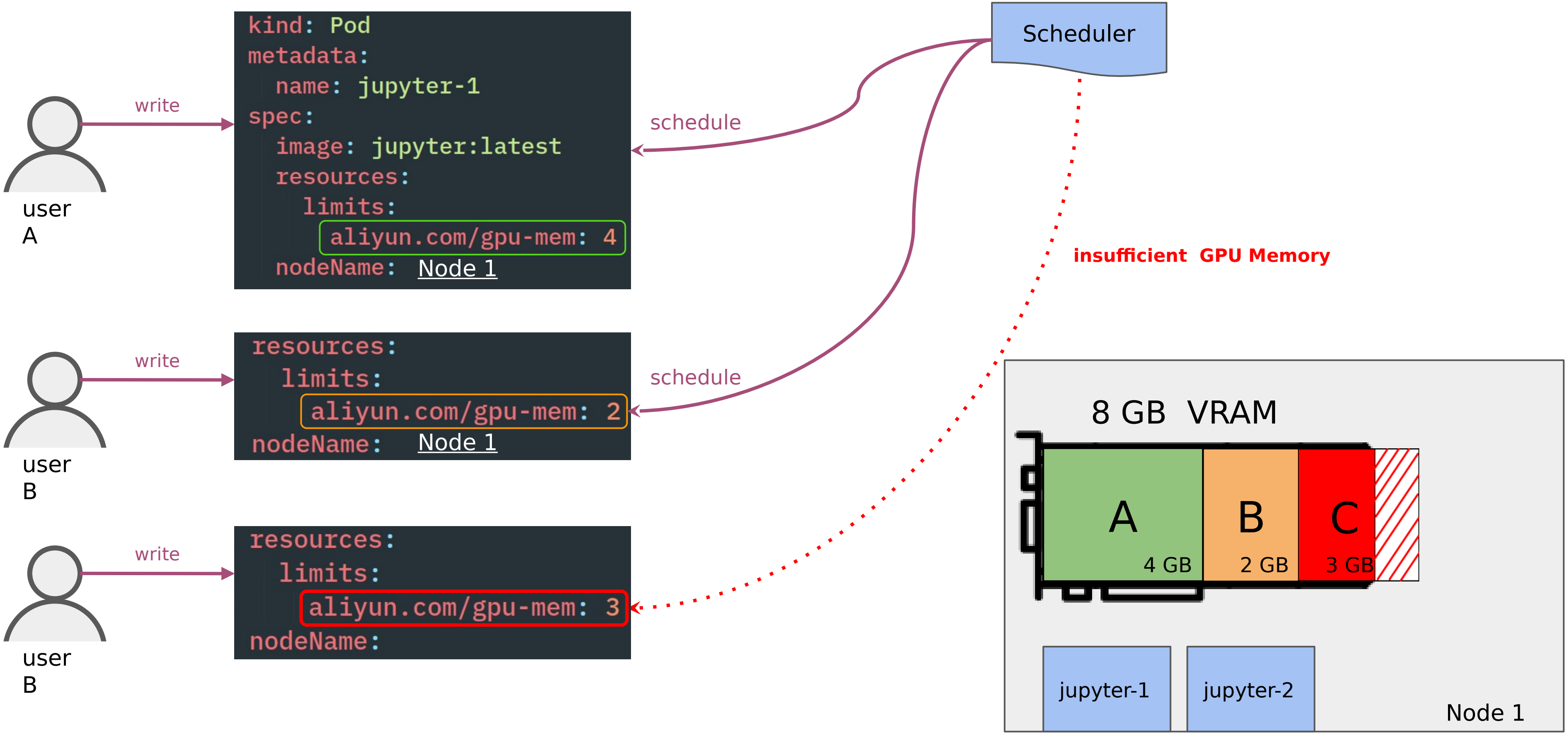
Existing Approaches (Aliyun, Kubeshare)



Existing Approaches (Aliyun, Kubeshare)

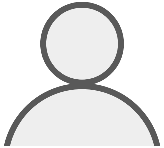


Existing Approaches (Aliyun, Kubeshare)



Key Idea

Key Idea



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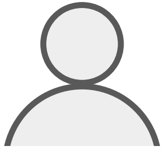
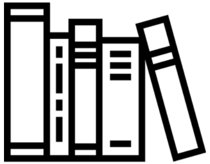
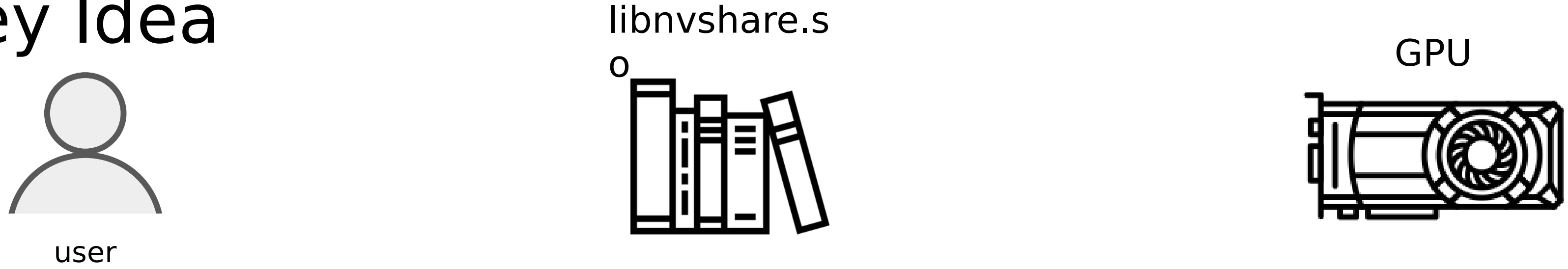


user

libnvshare.s
o



Key Idea



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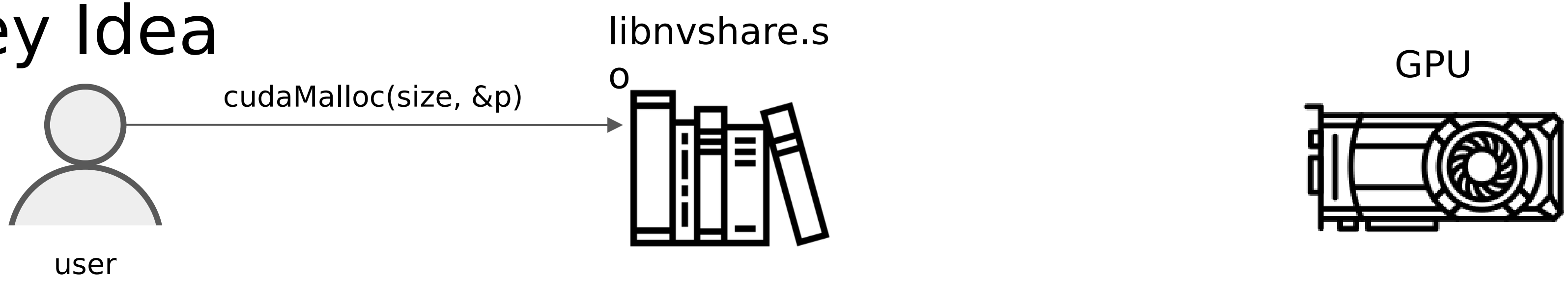
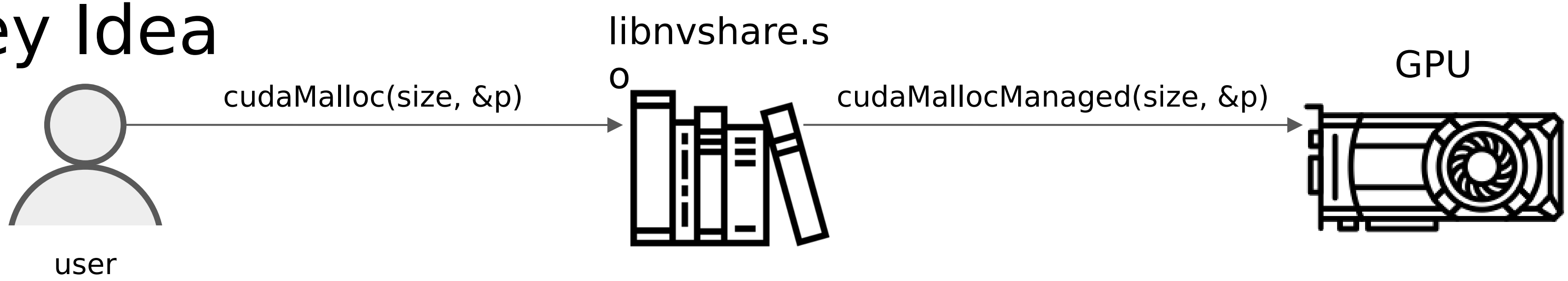


Key Idea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GPU
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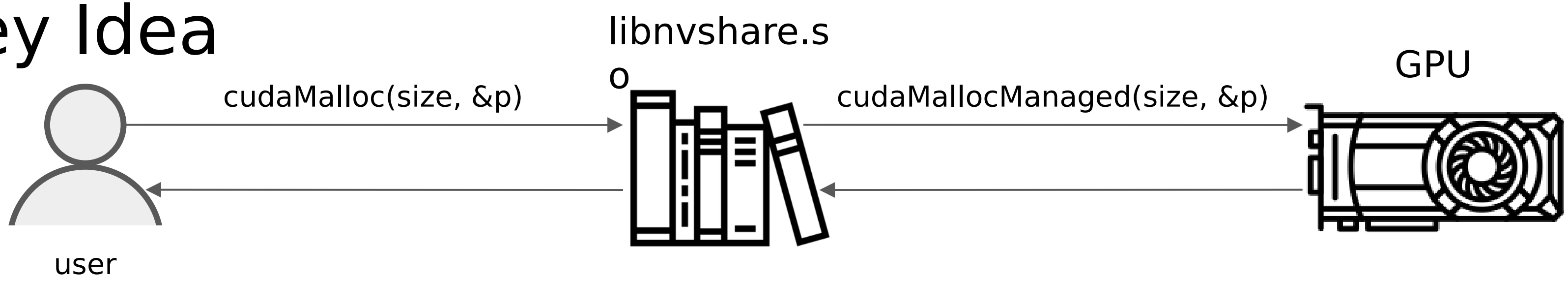
cudaMallocManaged(size, &p)
user

Key Idea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GPU
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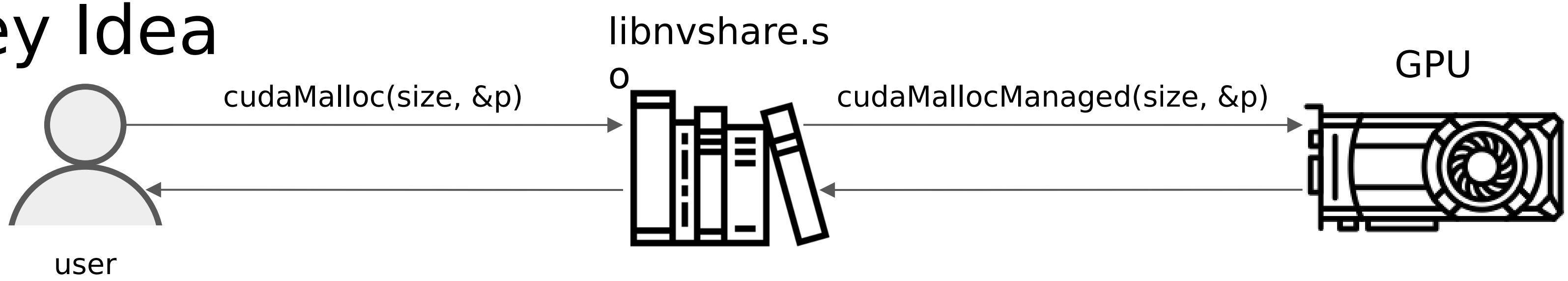
user

Key Idea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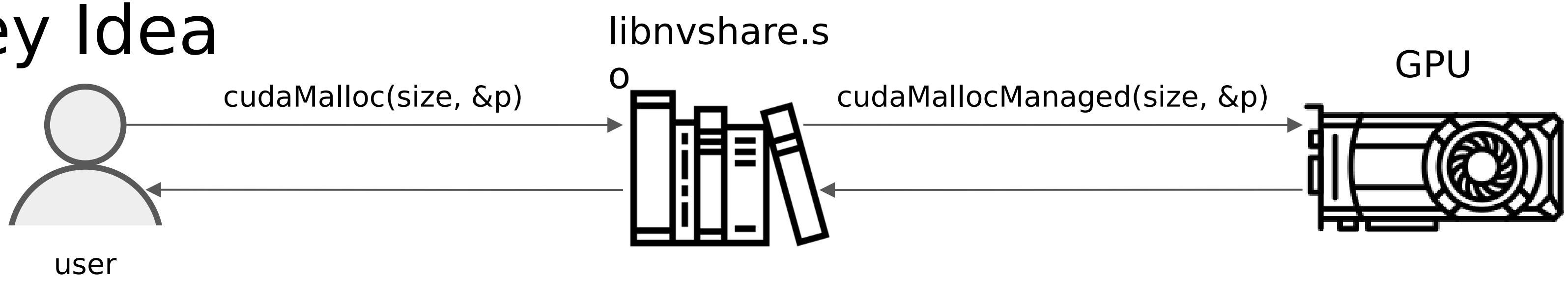
user

Key Idea



libnvshare.s
o
GPU
cudaMalloc(size, &p)
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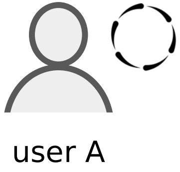
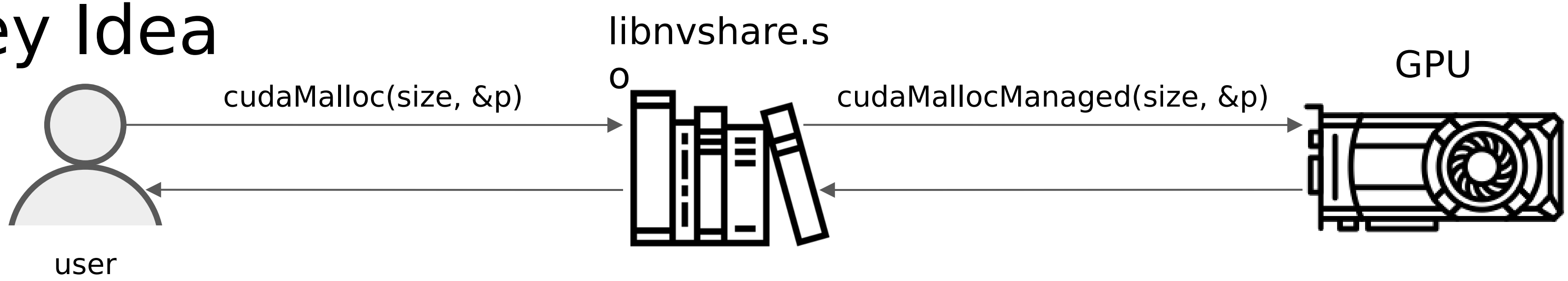
user



user A

Key Idea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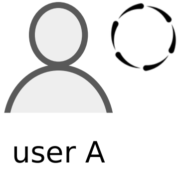
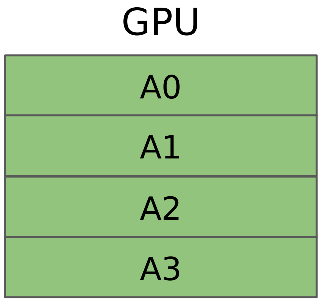

user A


GPU
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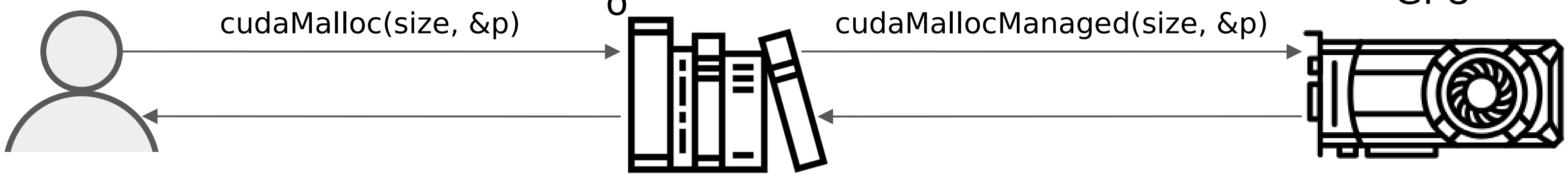
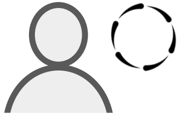
Key Idea





GPU

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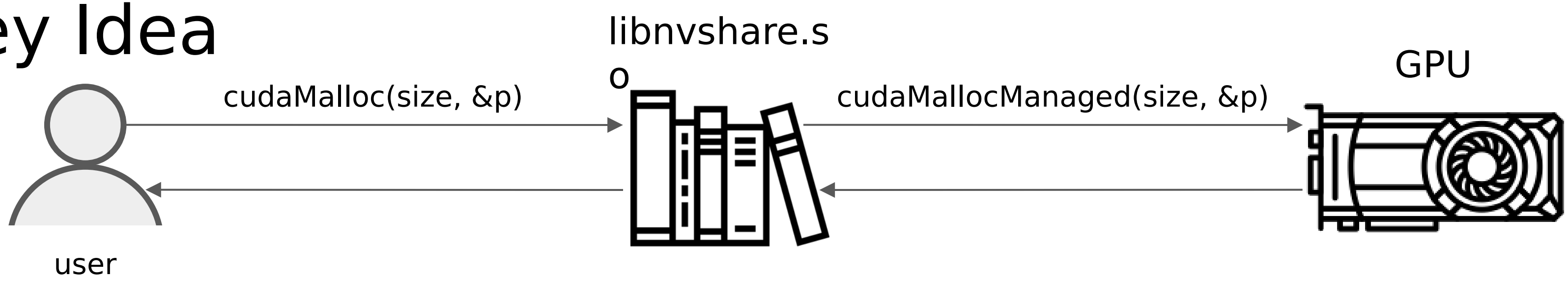
Key Idea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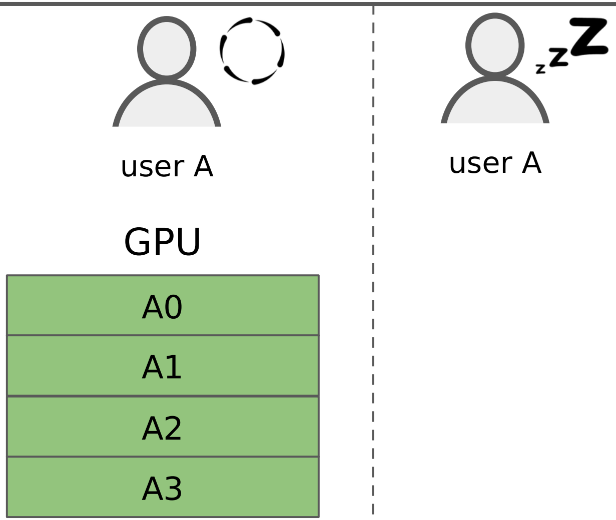
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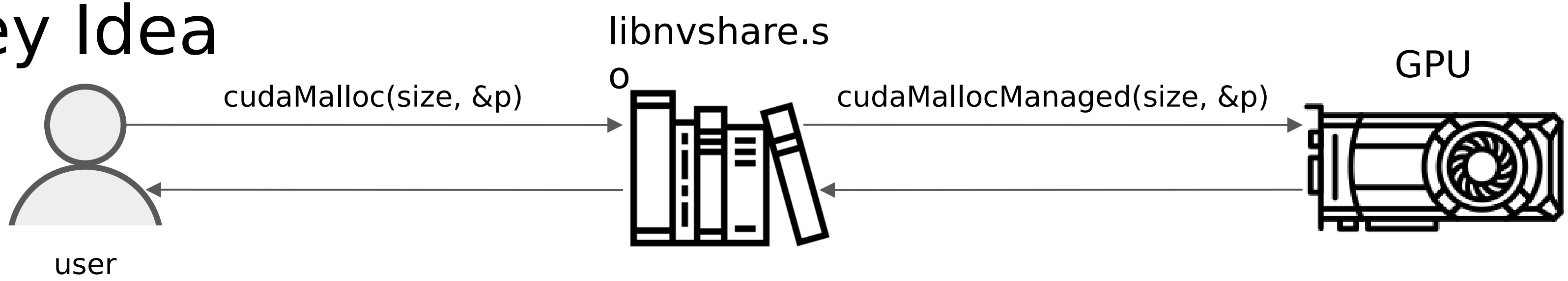
Key Idea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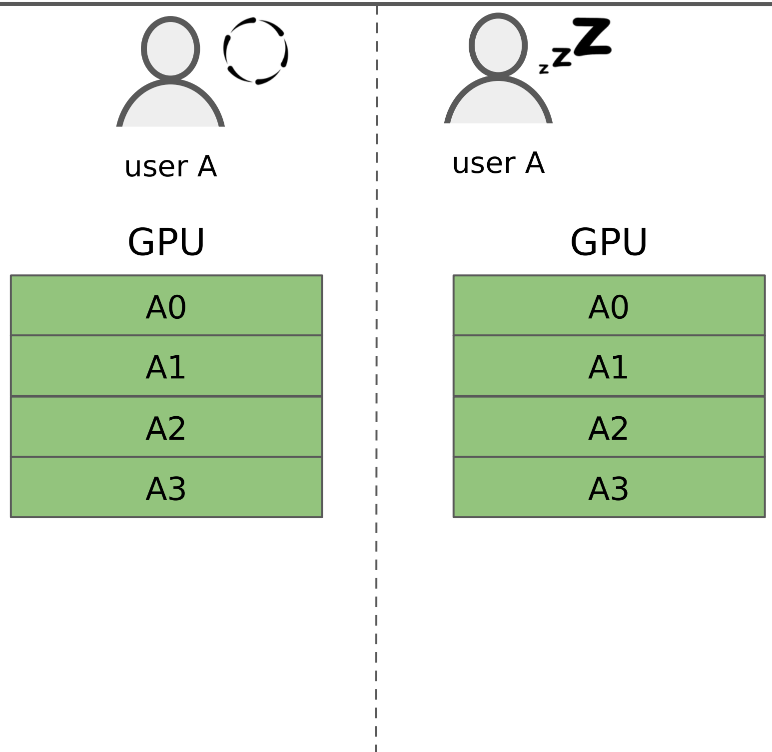
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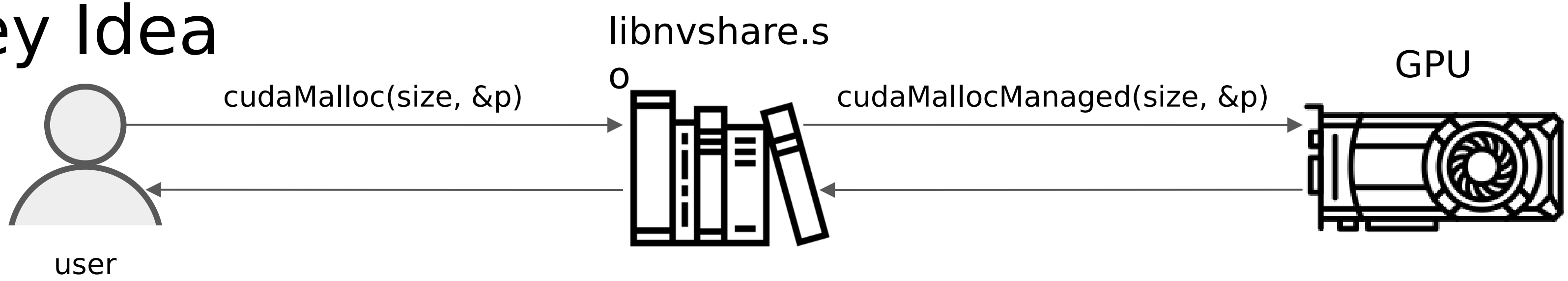
Key Idea



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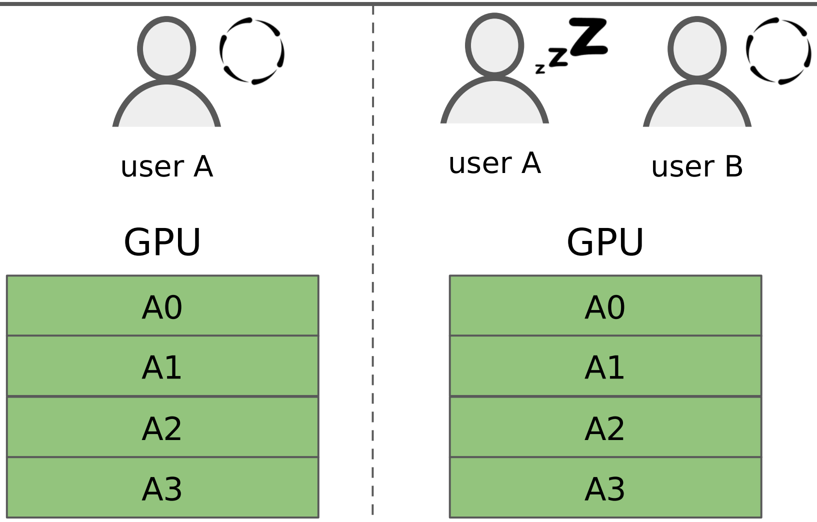

user A
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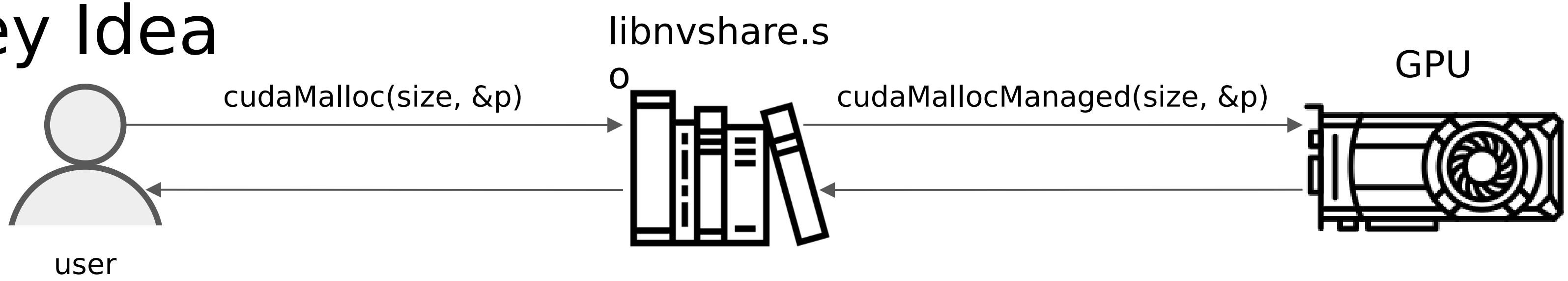
Key Idea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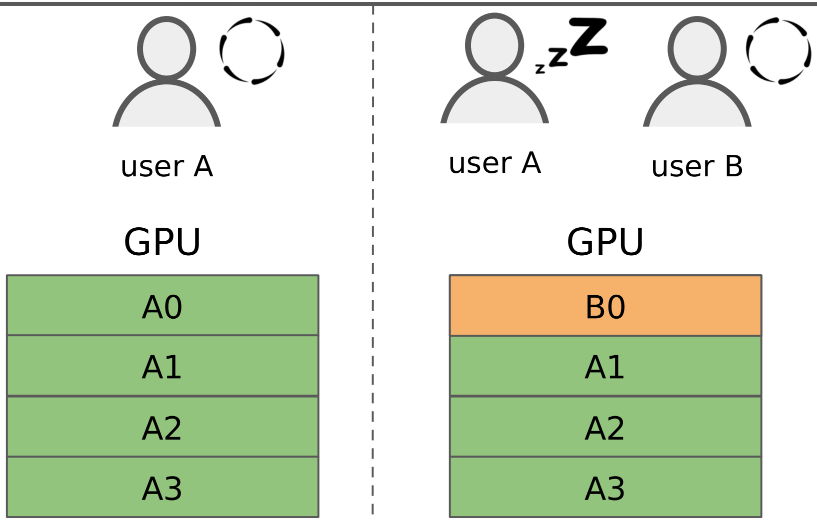
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A1
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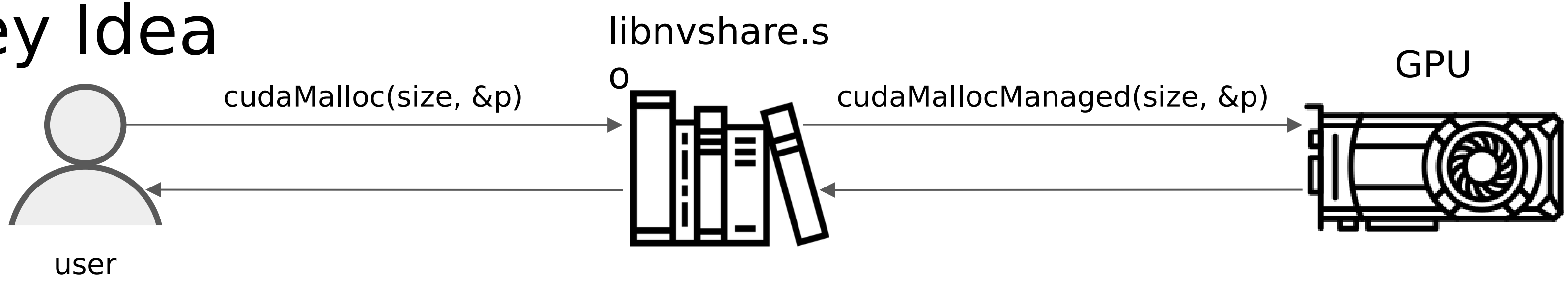
Key Idea



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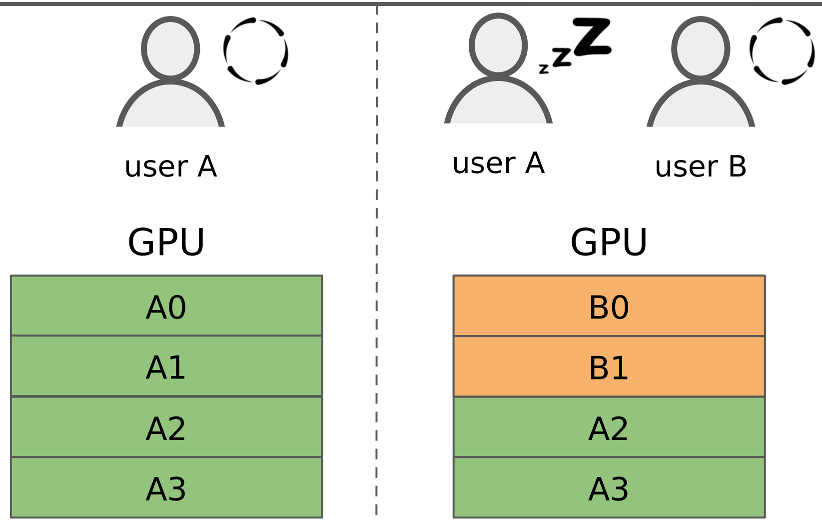

user A
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GPU
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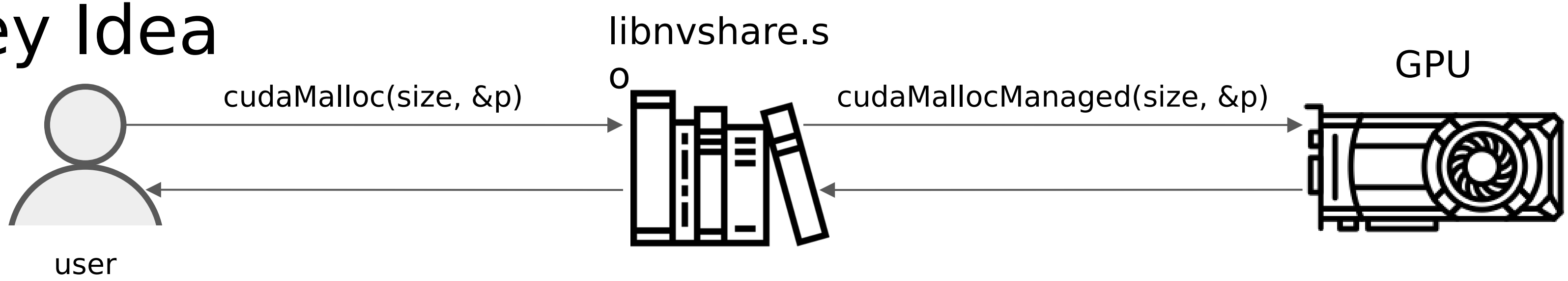
A3

Key Idea



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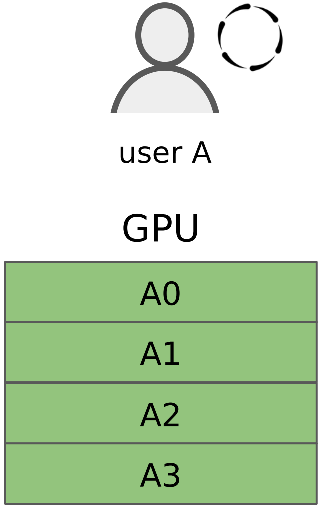

user A
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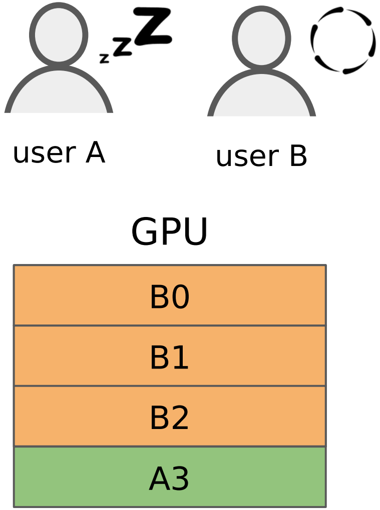

user A
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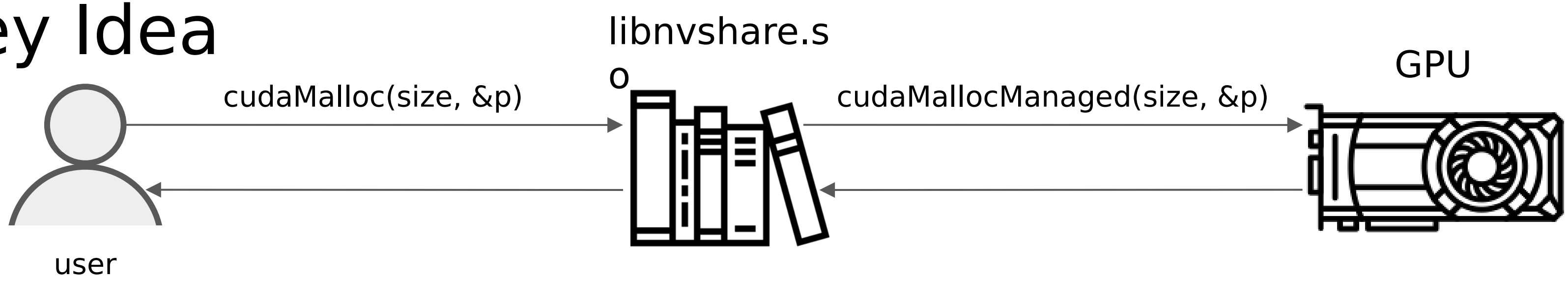
Key Idea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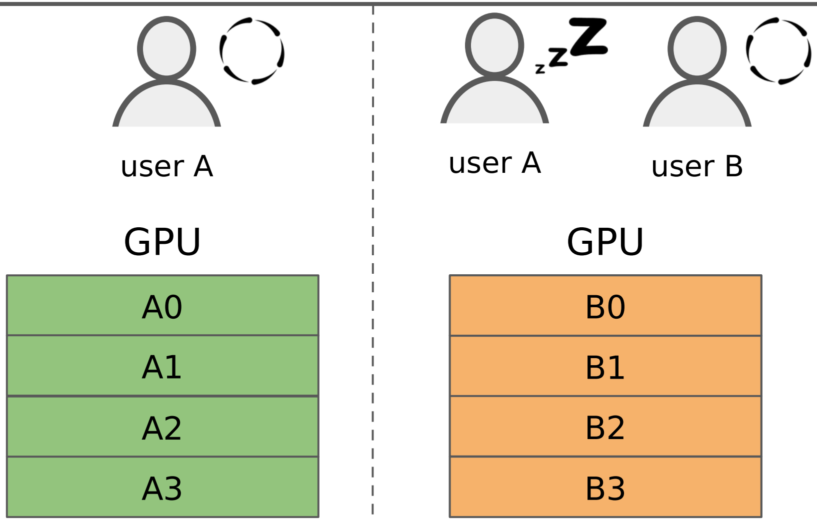
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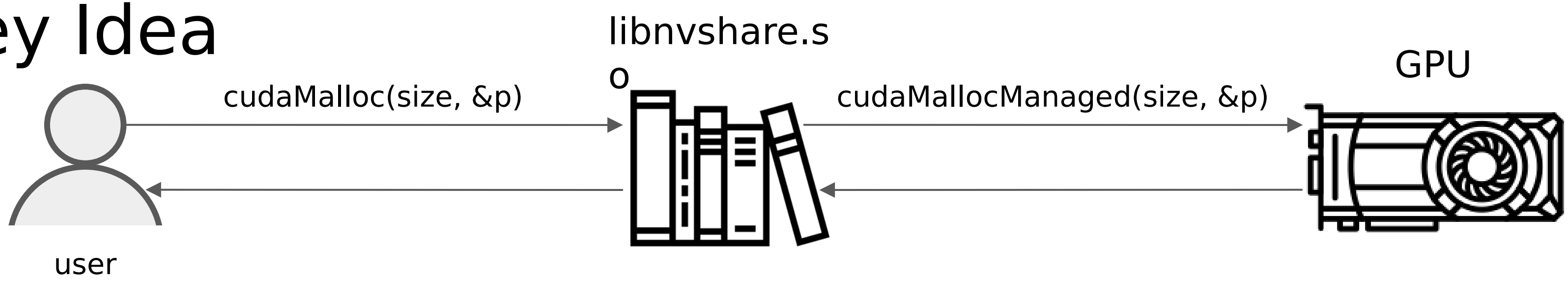
Key Idea



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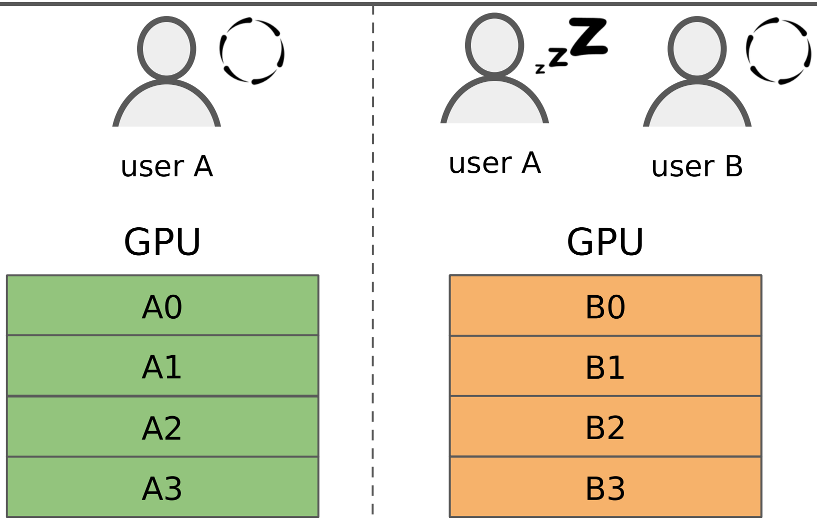

user A
user A
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GPU
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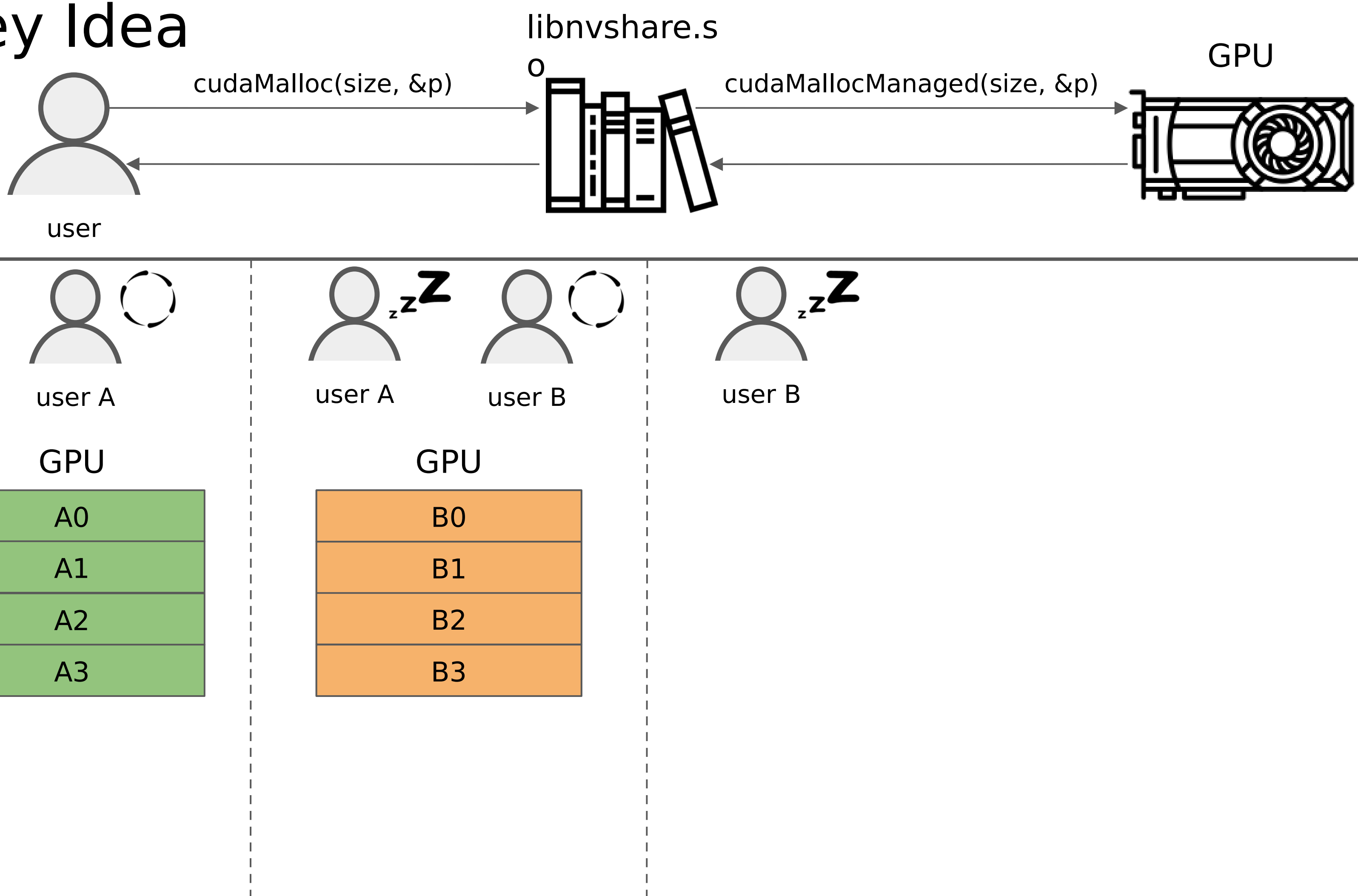
Key Idea



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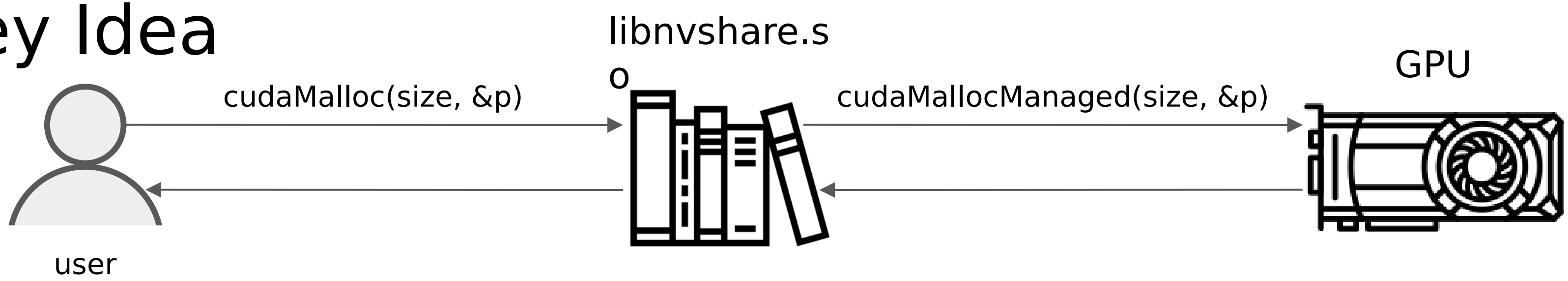
Key Idea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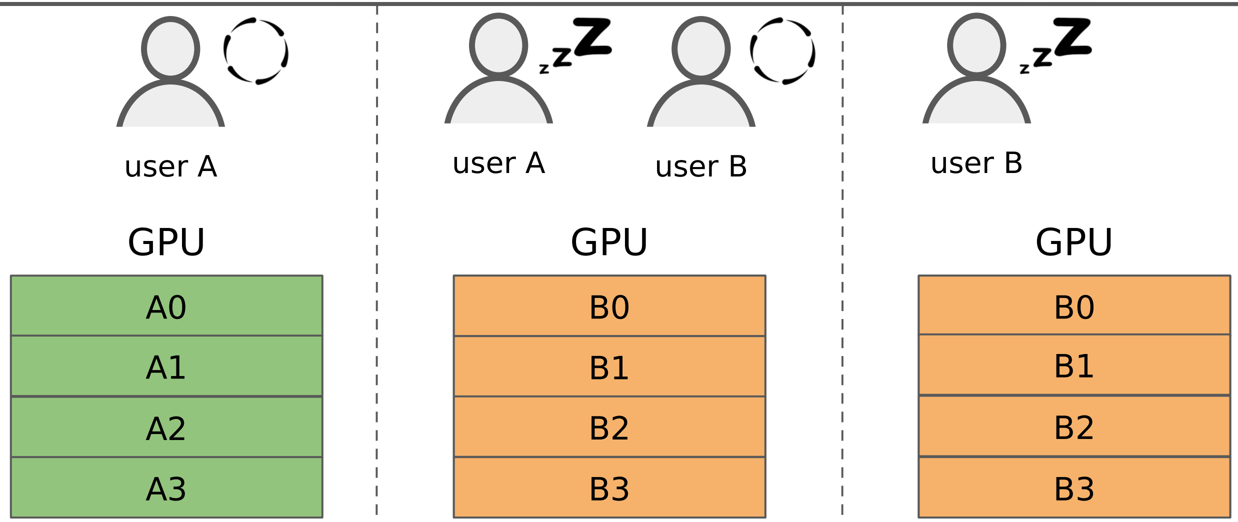
user A
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B1
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GPU
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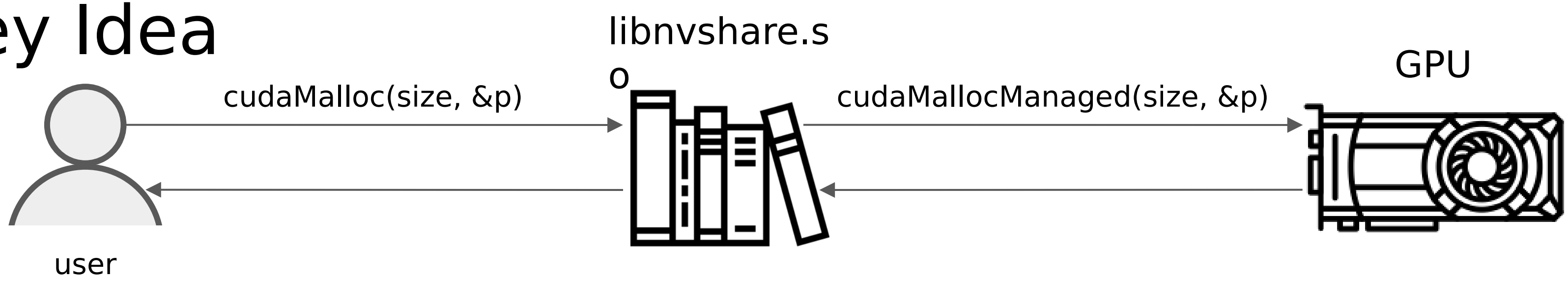
B2
B3

Key Idea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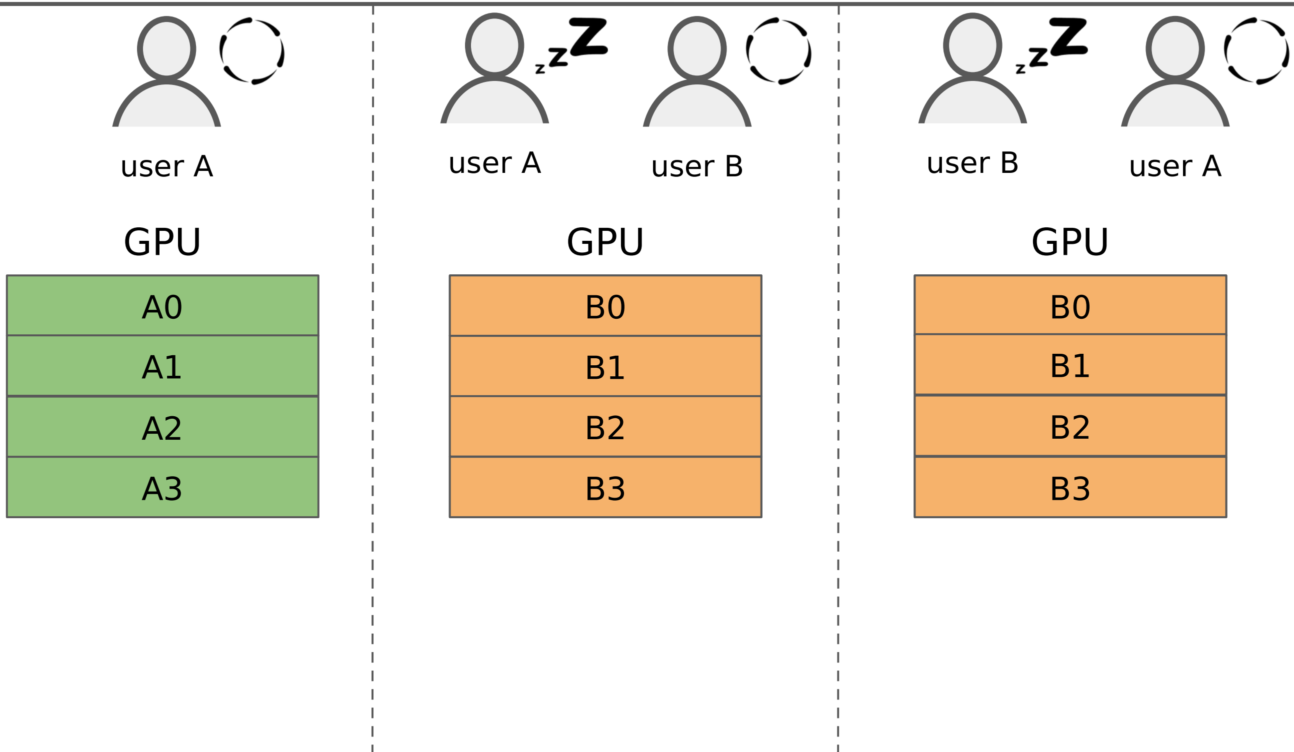
user A
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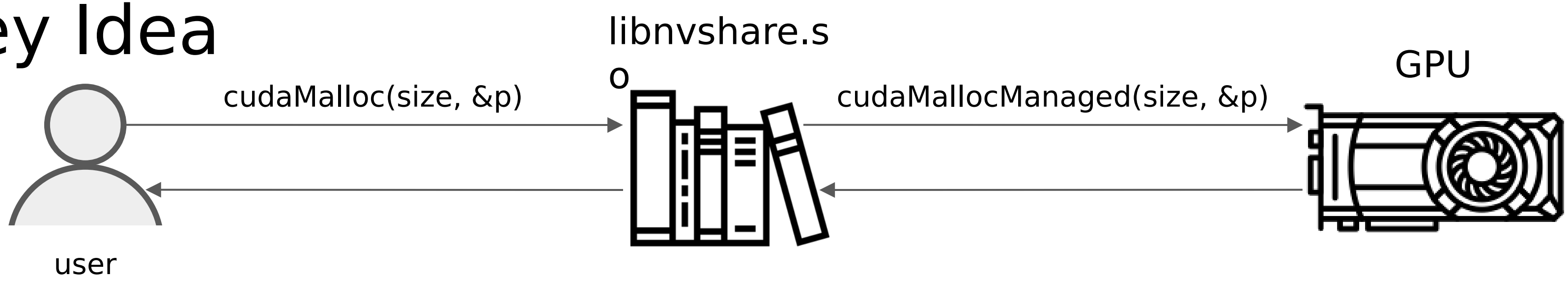
Key Idea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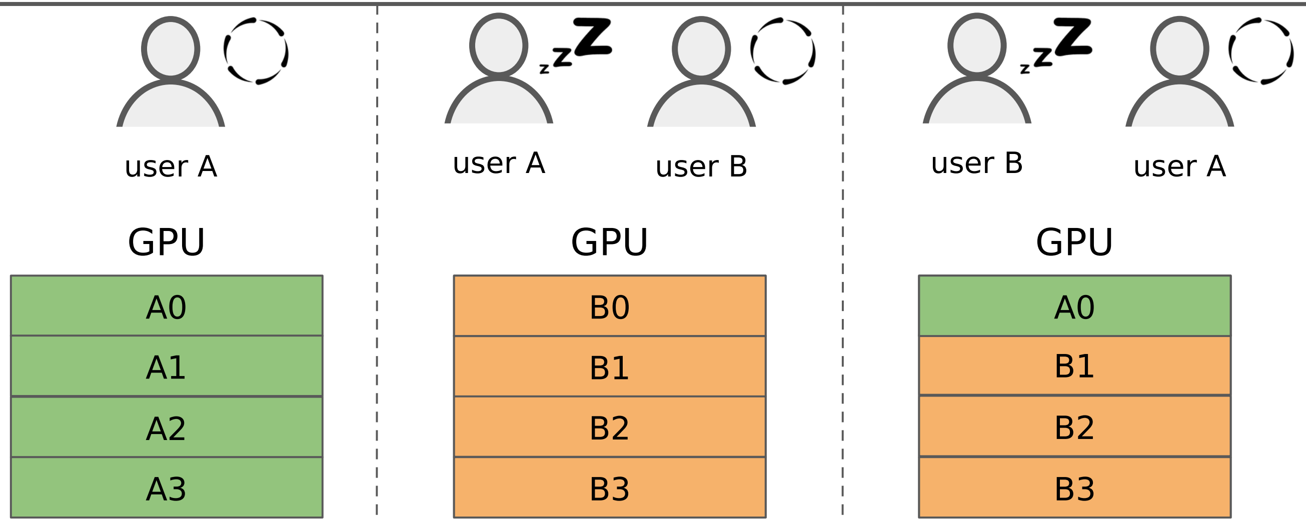
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GPU
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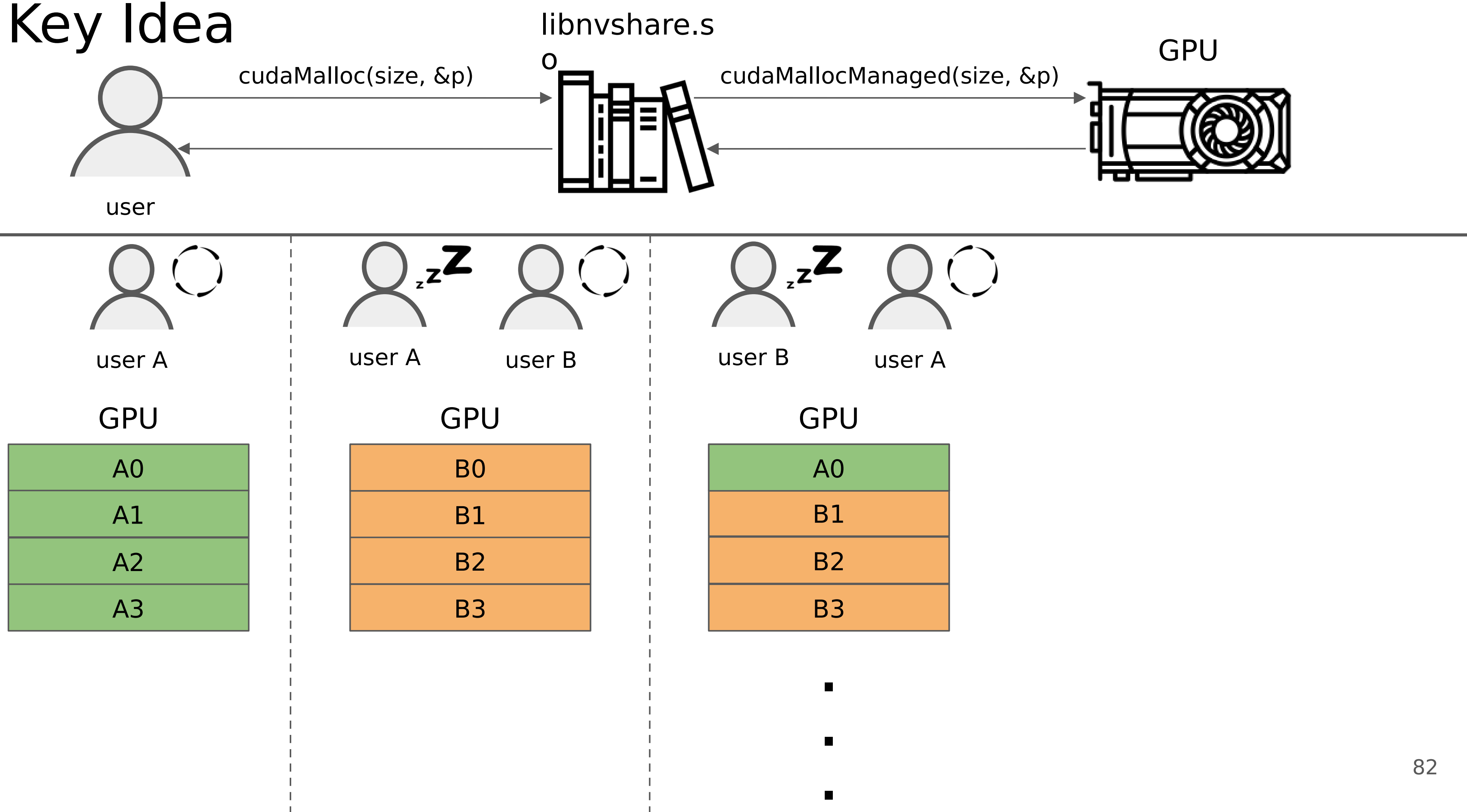
B3

Key Idea



libnvshare.so
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cudaMallocManaged(size, &p)
user
user A
user A
user B
user B
user A
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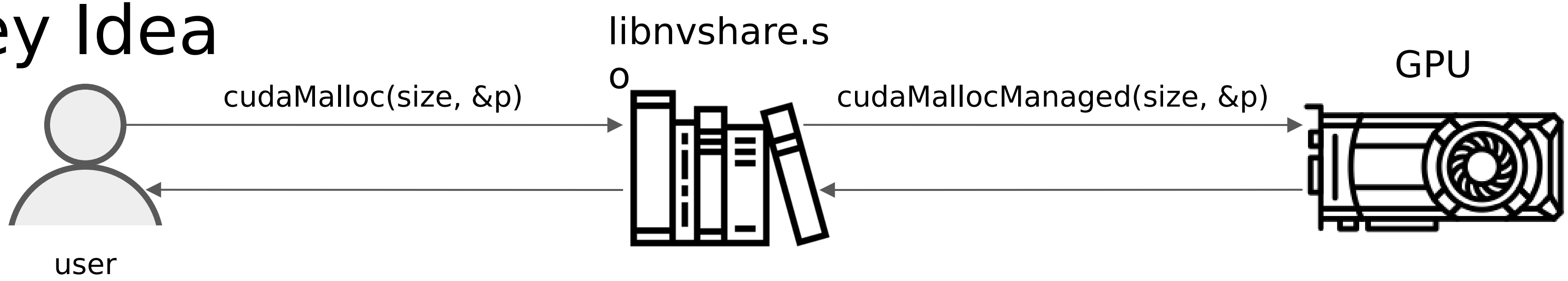
B3
GPU
A0
B1
B2
B3

Key Idea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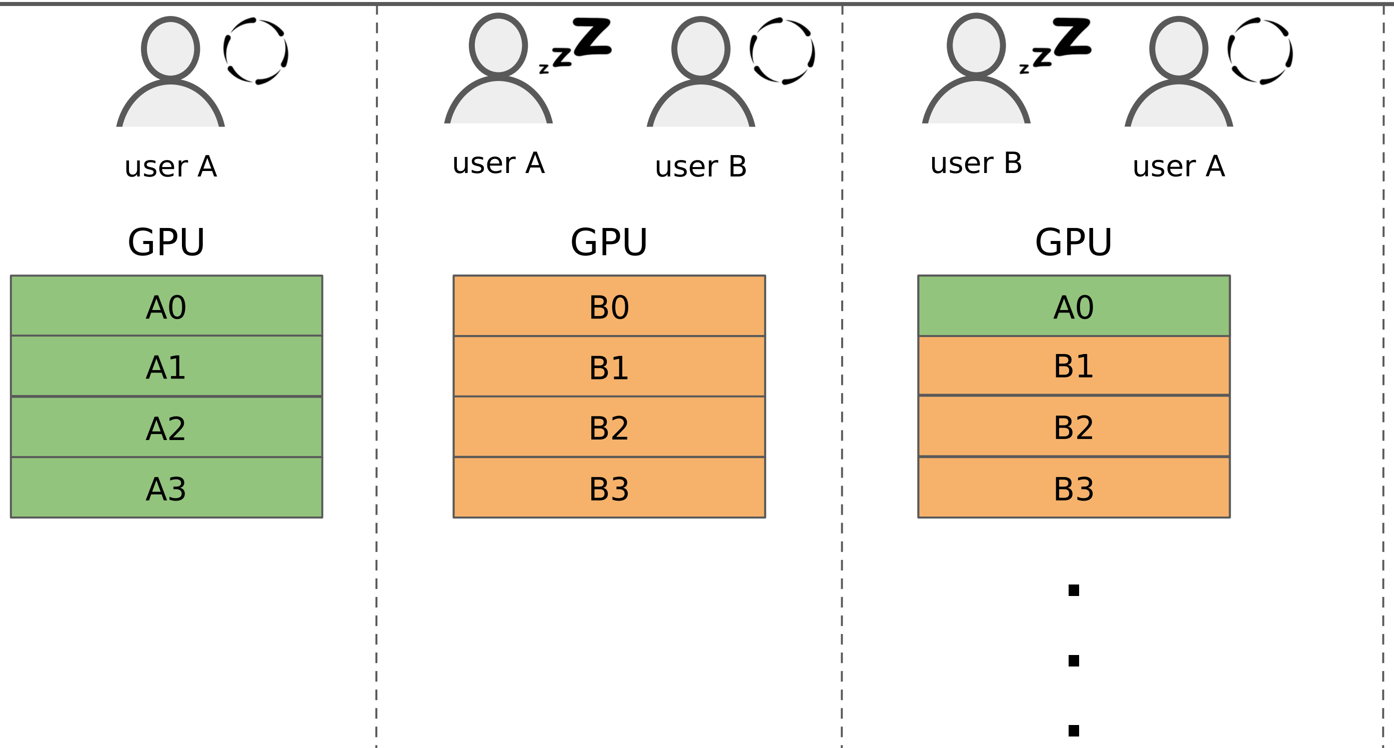
user A
GPU
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A1
A2
A3
user A
user B
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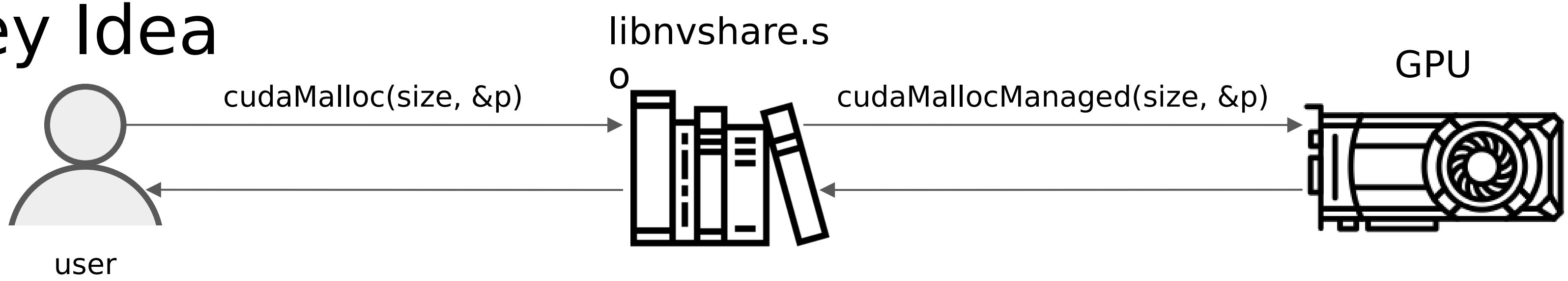
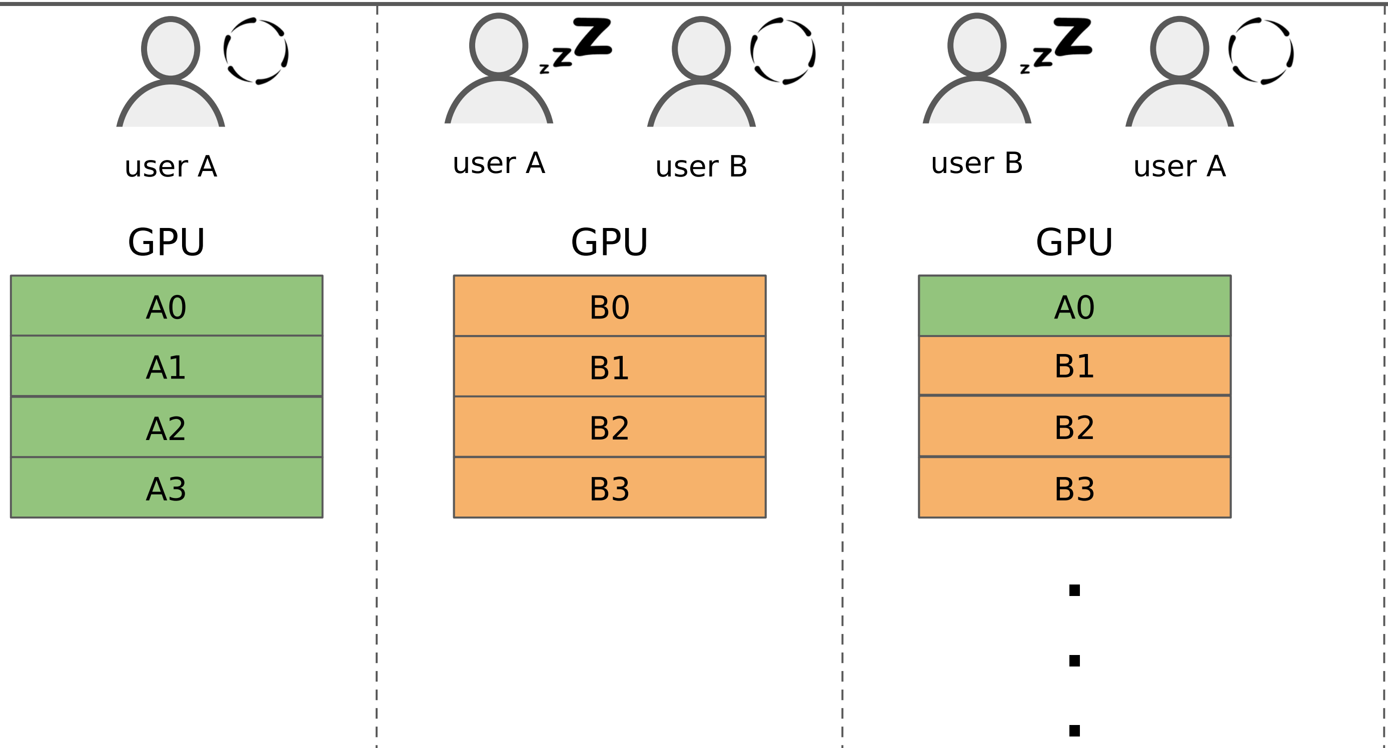
B0
B1
B2
B3
user B
user A
GPU
A0
B1
B2
B3

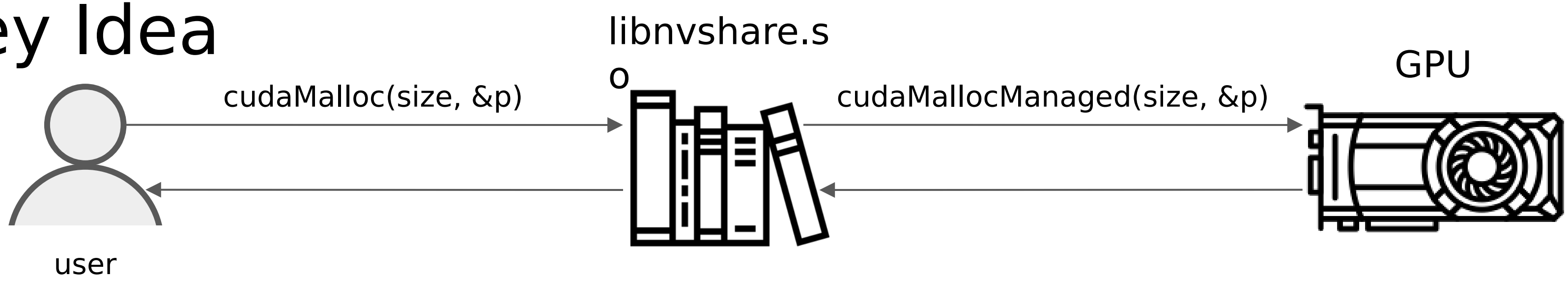
Key Idea

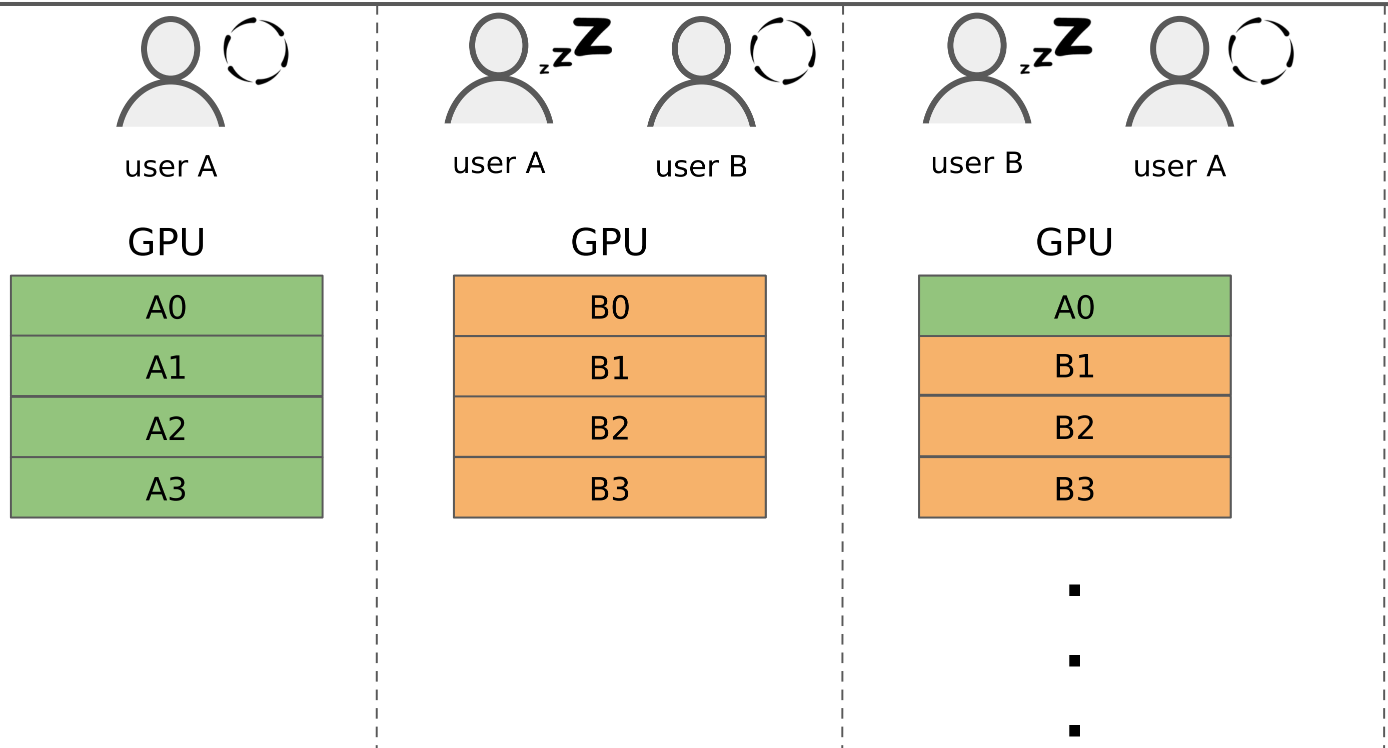




Result

Key Idea





Result

- # of co-located processes limited by system RAM

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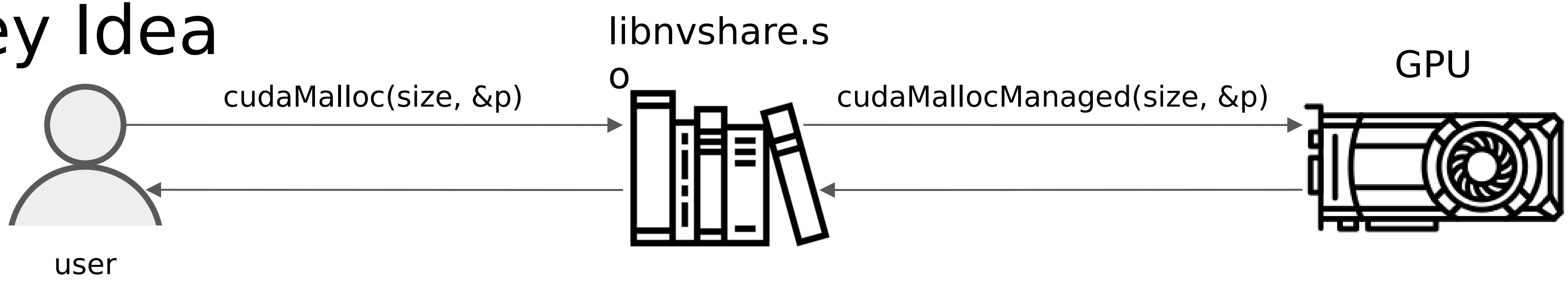
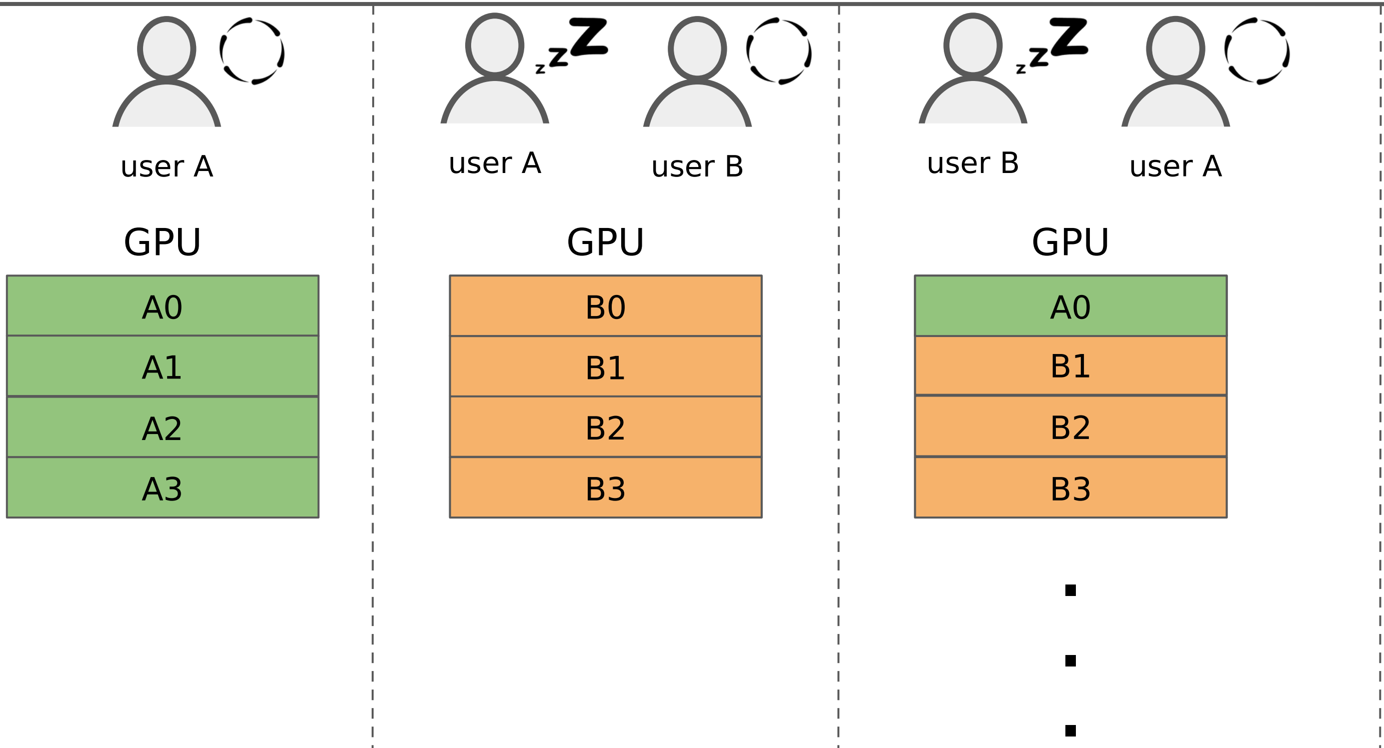
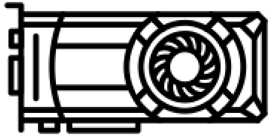


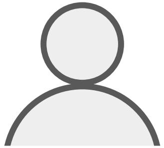


Result

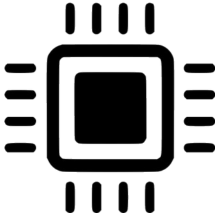
- # of co-located processes limited by system RAM
- each process can use the whole GPU memory

CUDA programming model





user



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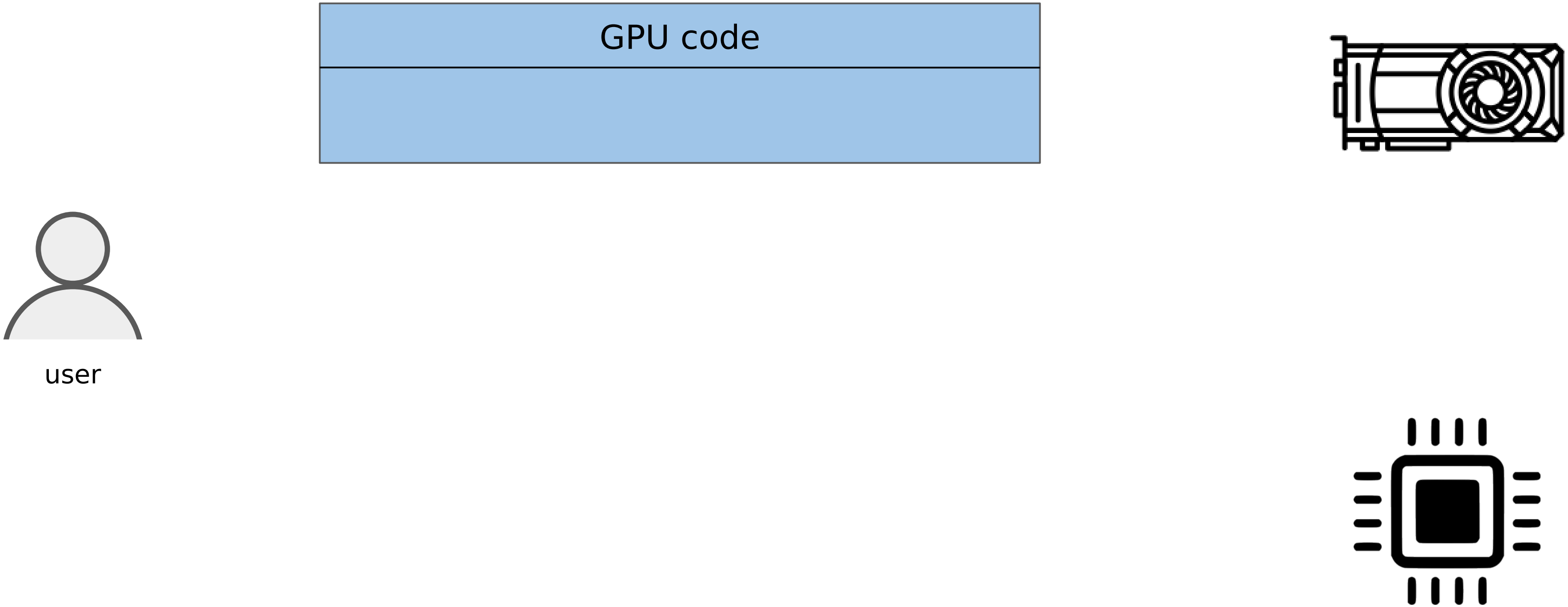

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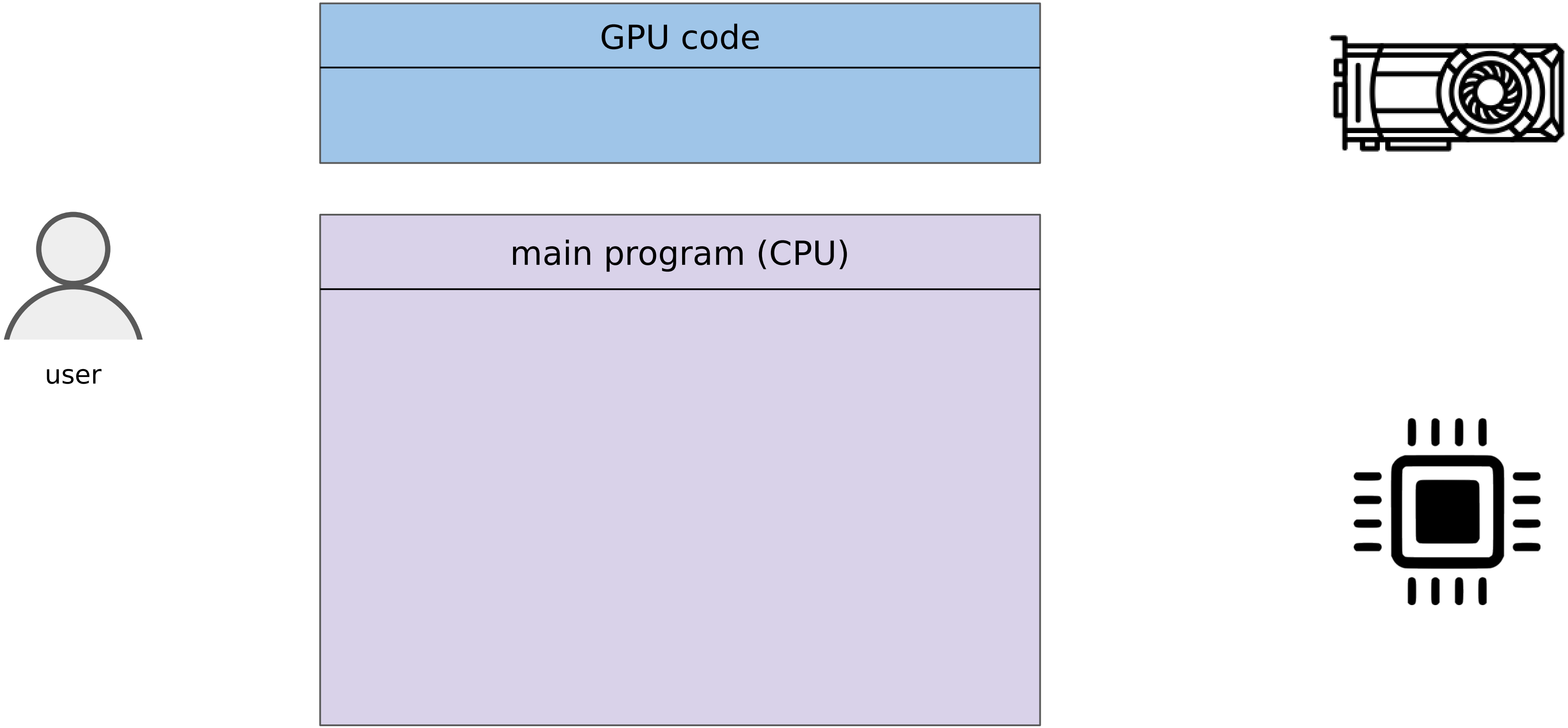
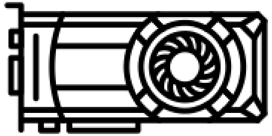


CUDA programming model

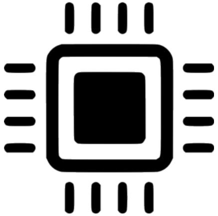
user

GPU code

```
__global__
void saxpy(int n, float a, float *x, float *y)
```



main program (CPU)



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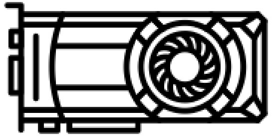
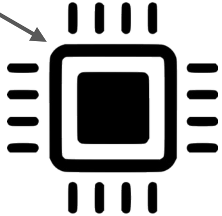


main program (CPU)

run



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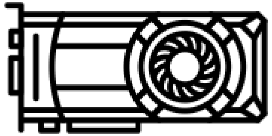

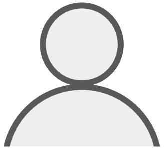

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```

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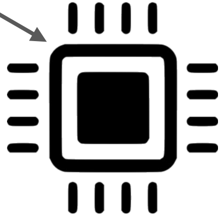

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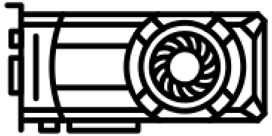

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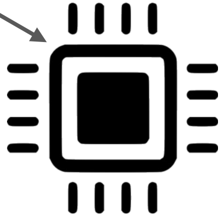

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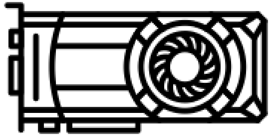

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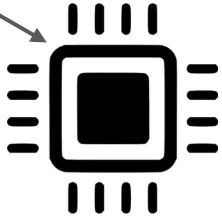
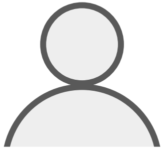


CUDA programming model



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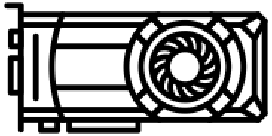

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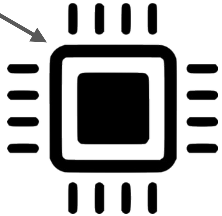
asynchronous!

run



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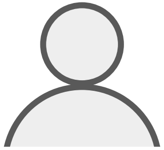

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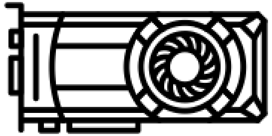

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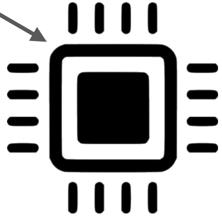
asynchronous!

```
cudaDeviceSynchronize();
```

run



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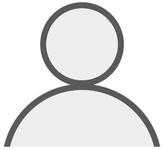

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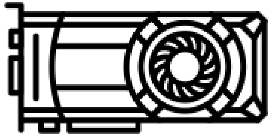

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```

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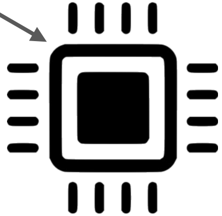
```

asynchronous!

```
cudaDeviceSynchronize();
```

4.
```
cudaMemcpy(DeviceToHost);
```

run



CUDA programming model

user

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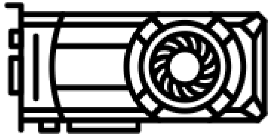

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saxpy<<<>>>();
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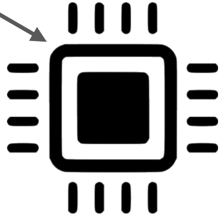
asynchronous!

```
cudaDeviceSynchronize();
```

4.
```
cudaMemcpy(DeviceToHost);
```

5.
```
cudaFree();
free();
```

run



CUDA multi-processing

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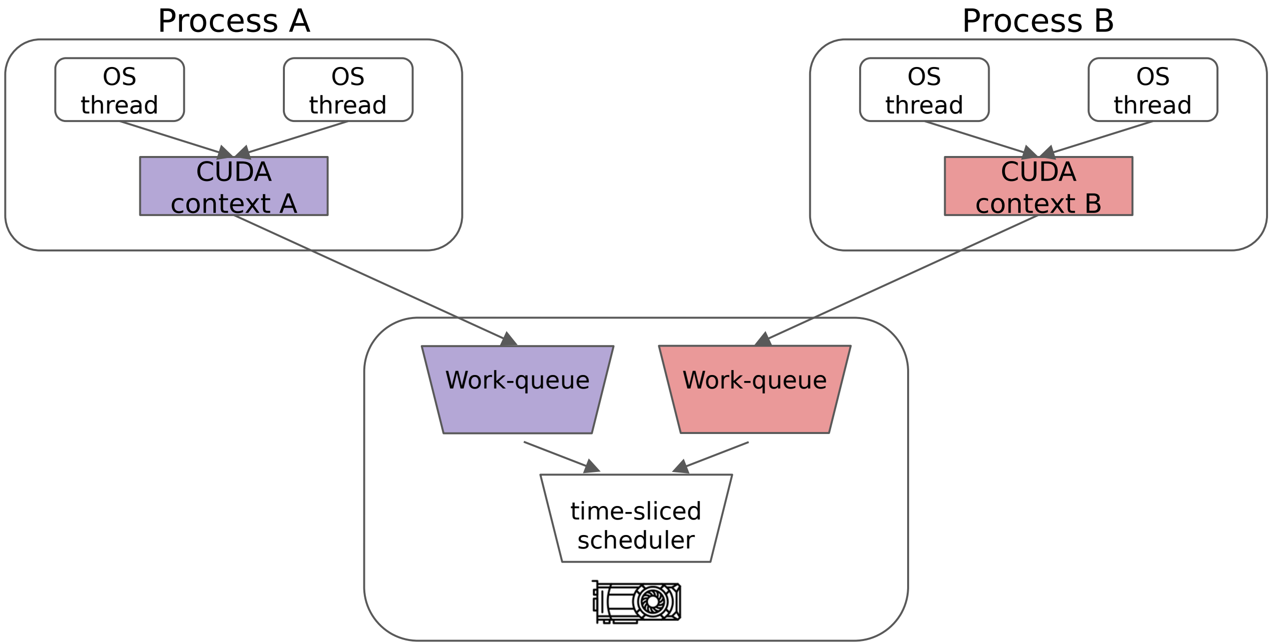

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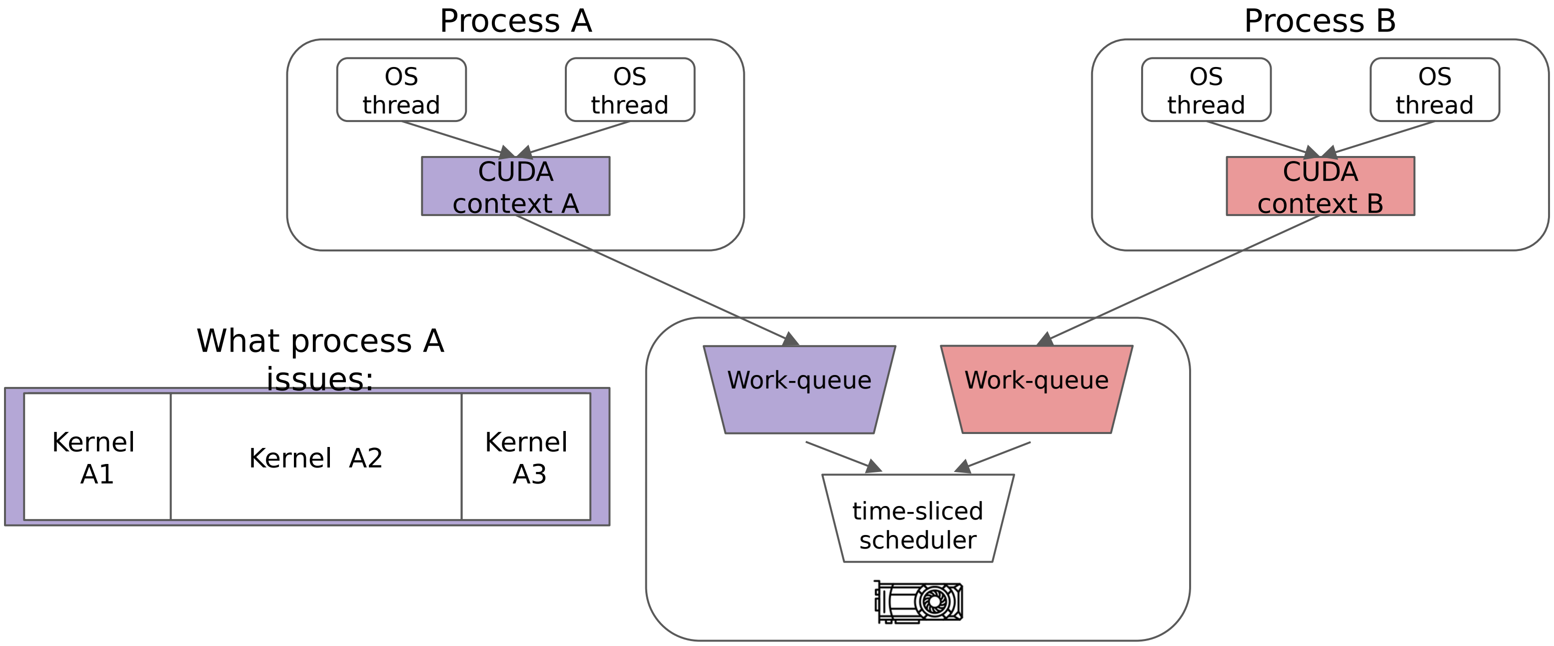

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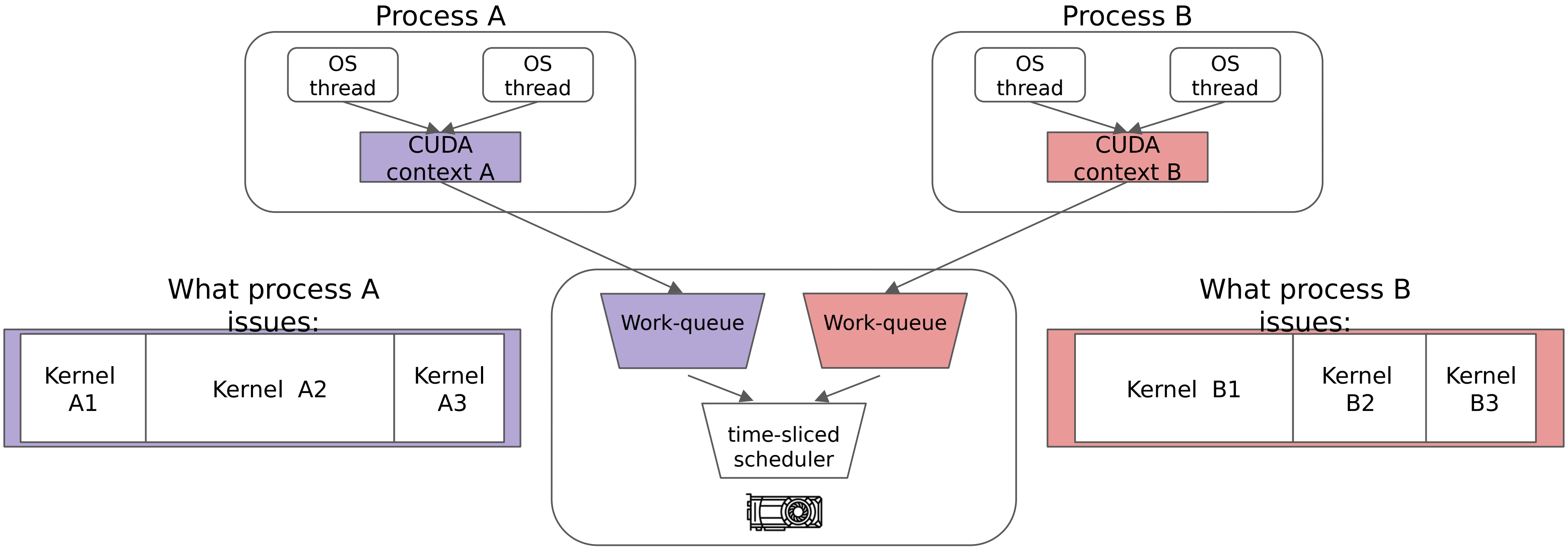

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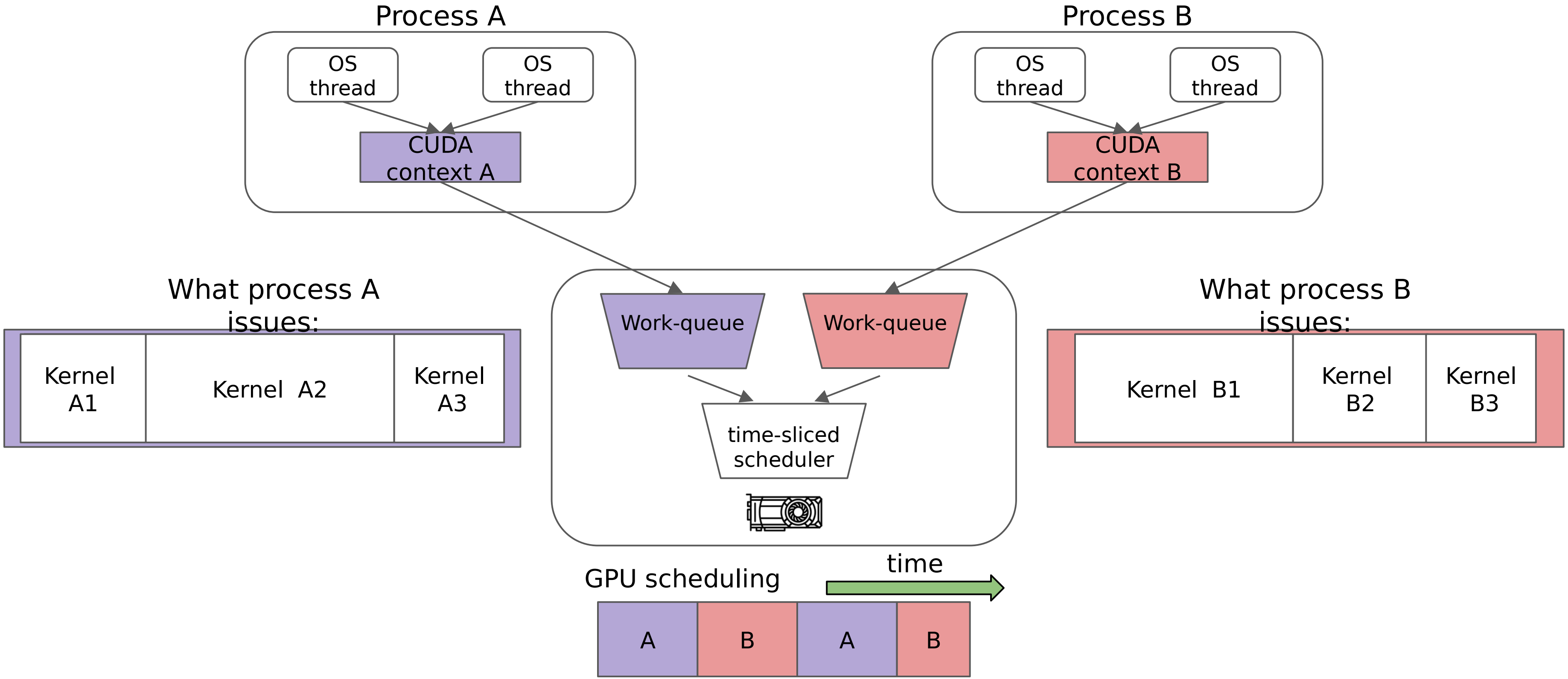

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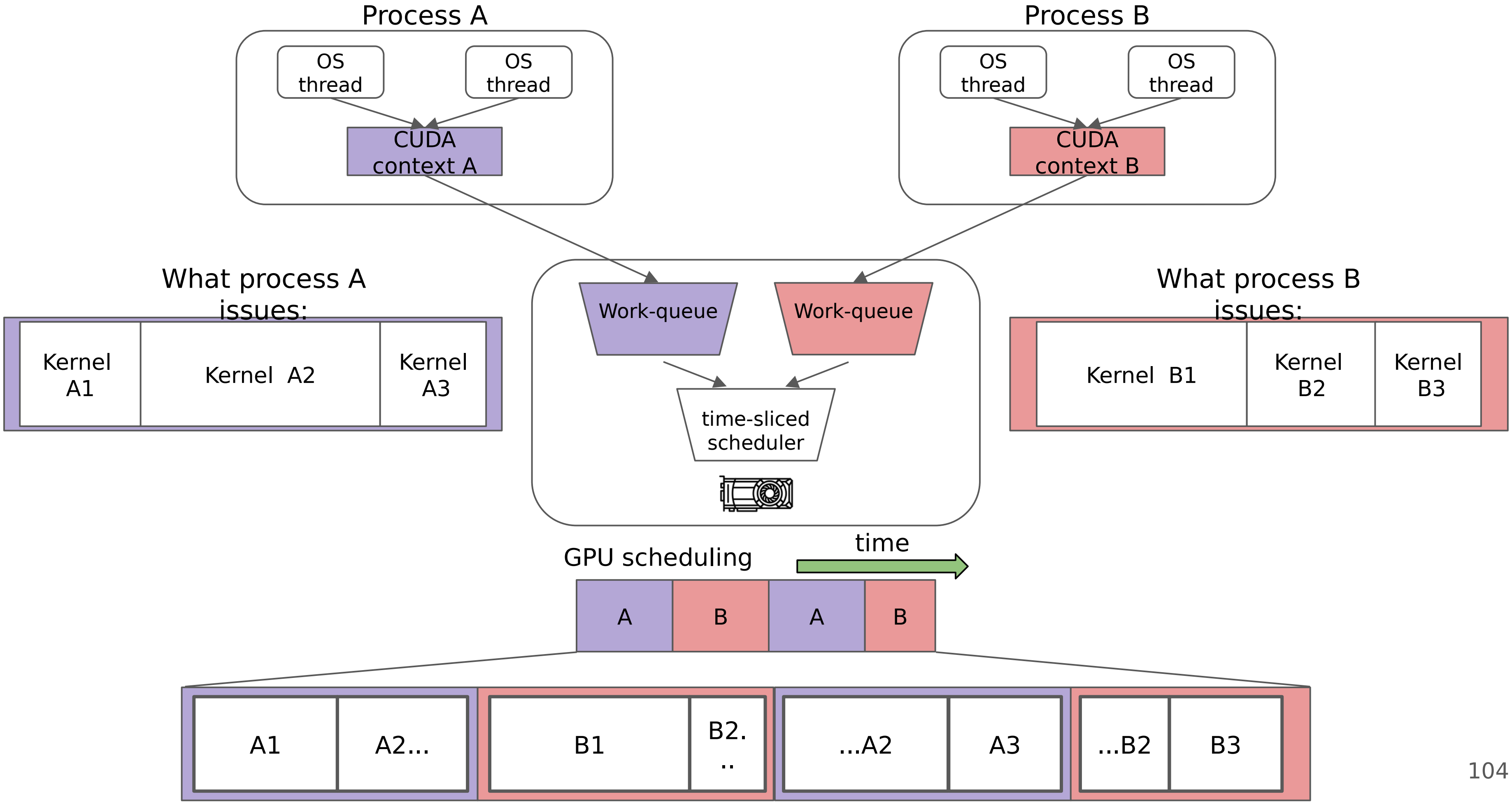
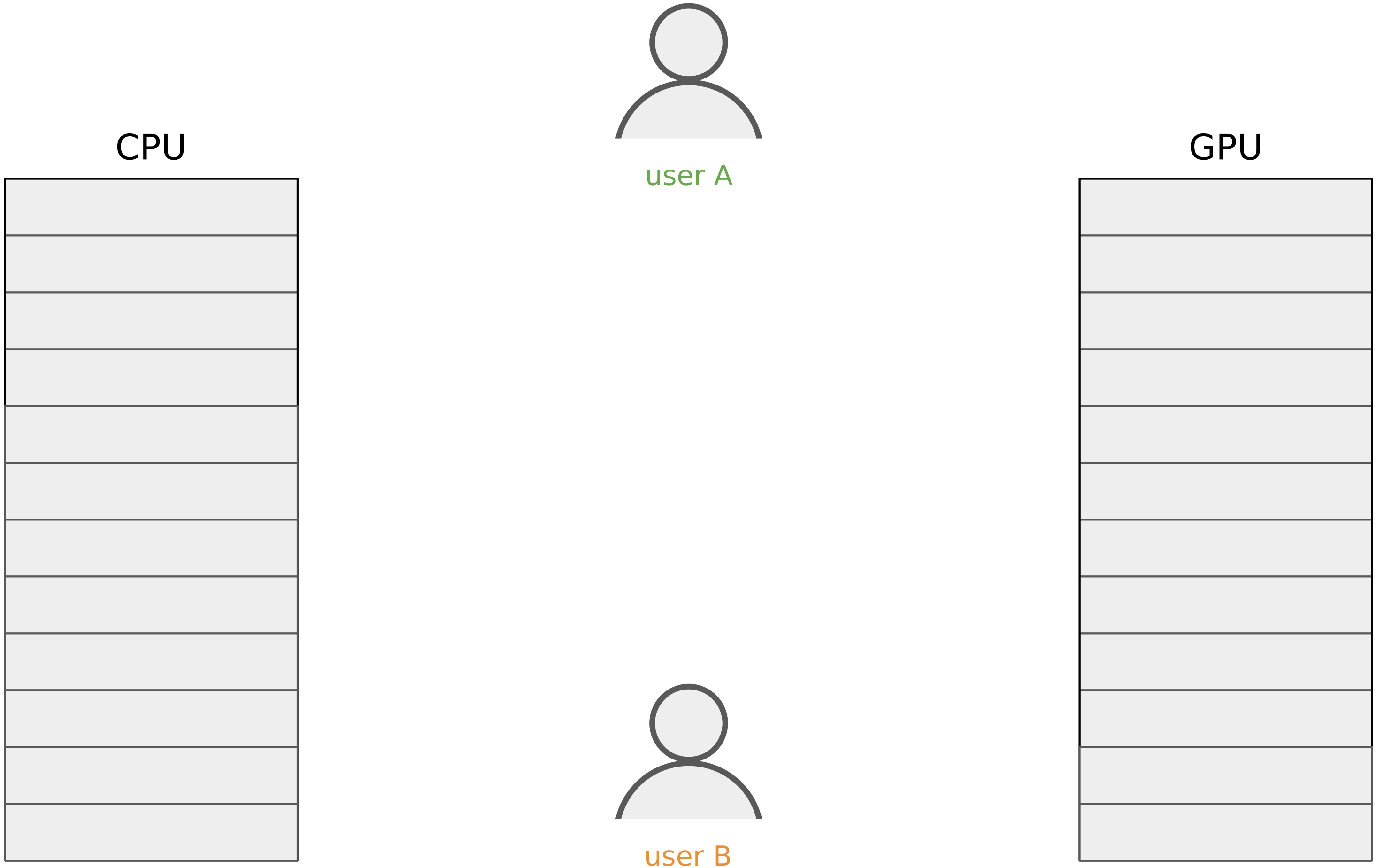


Default CUDA Memory Model



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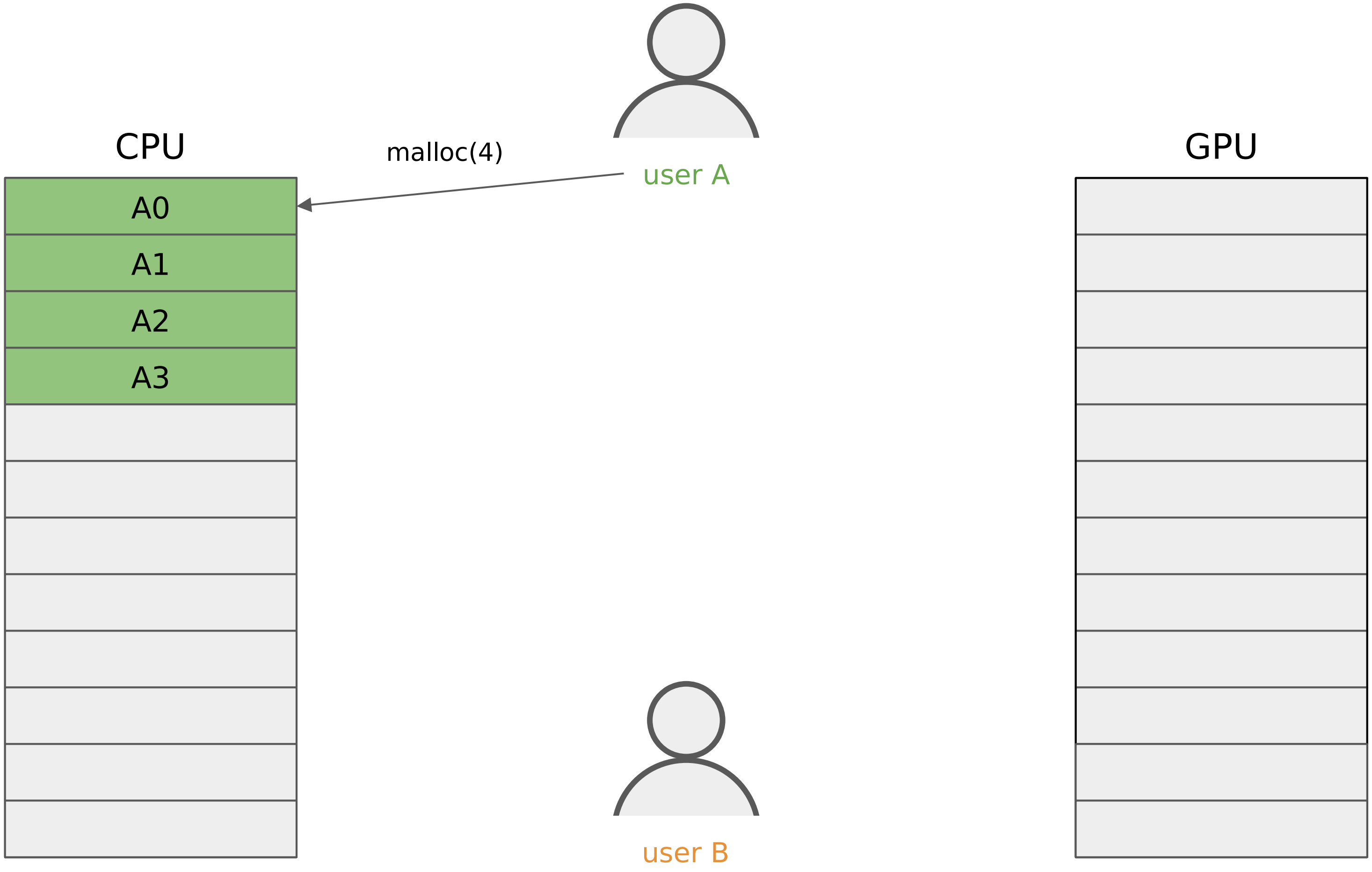

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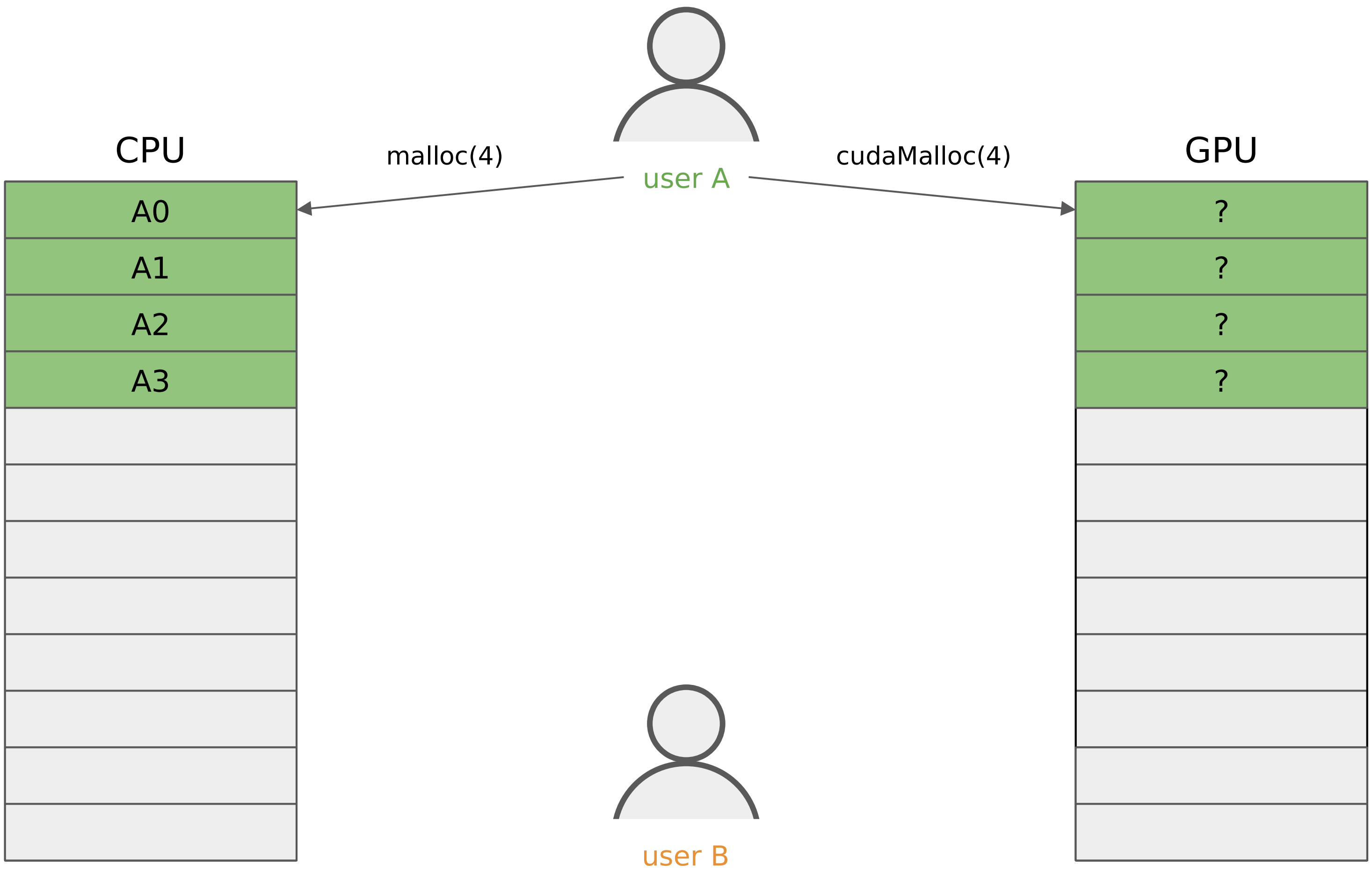

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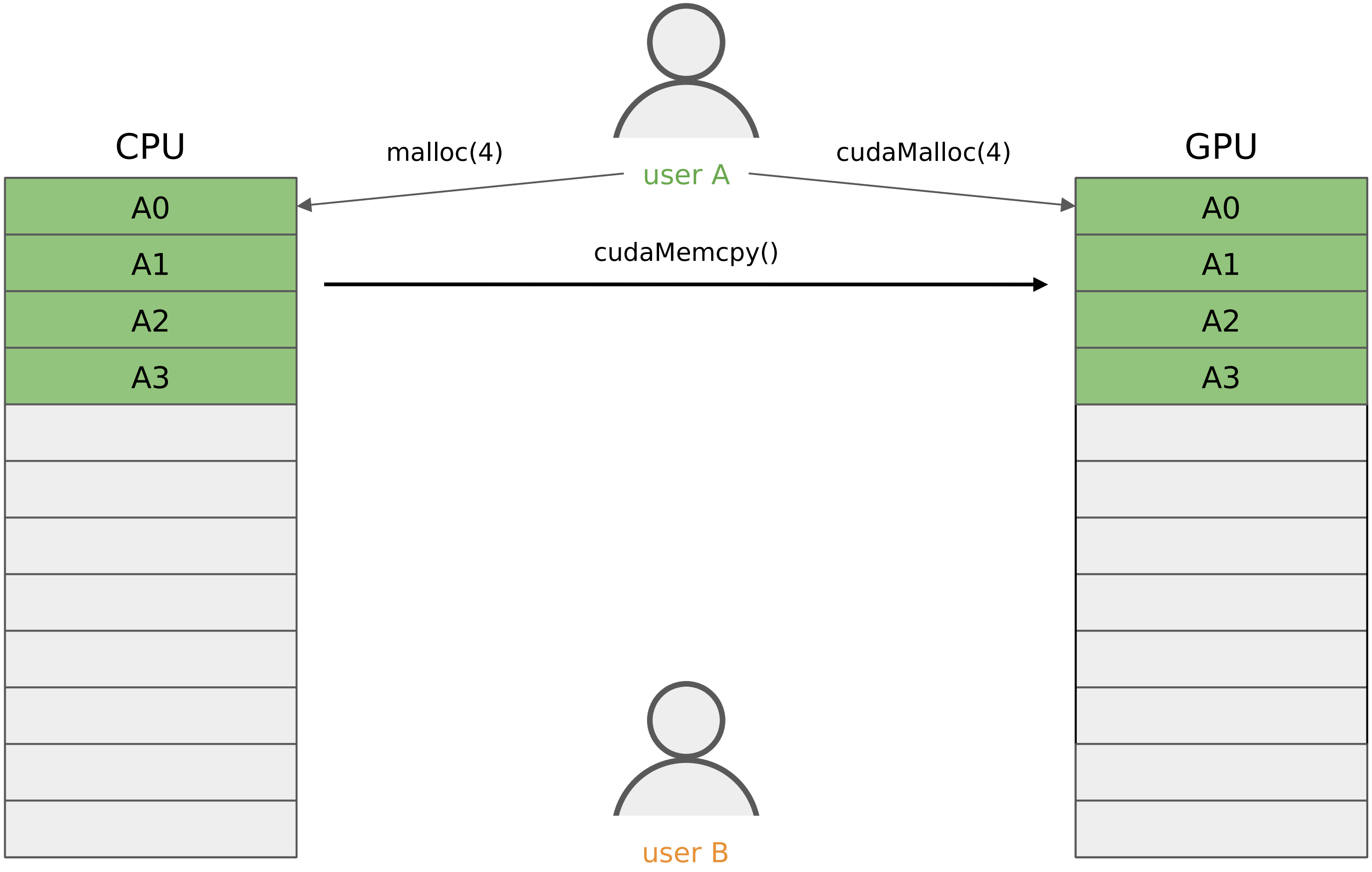

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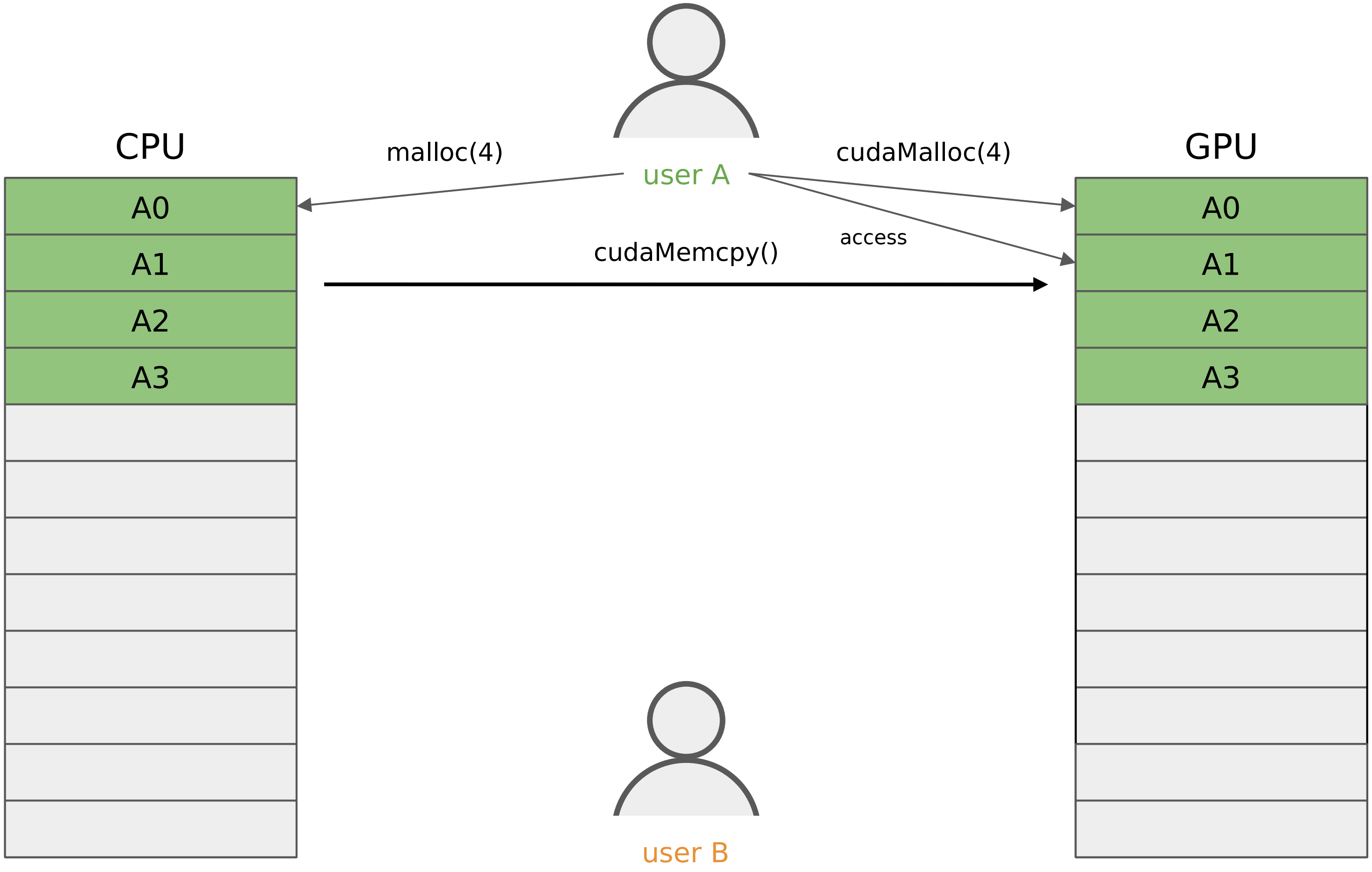

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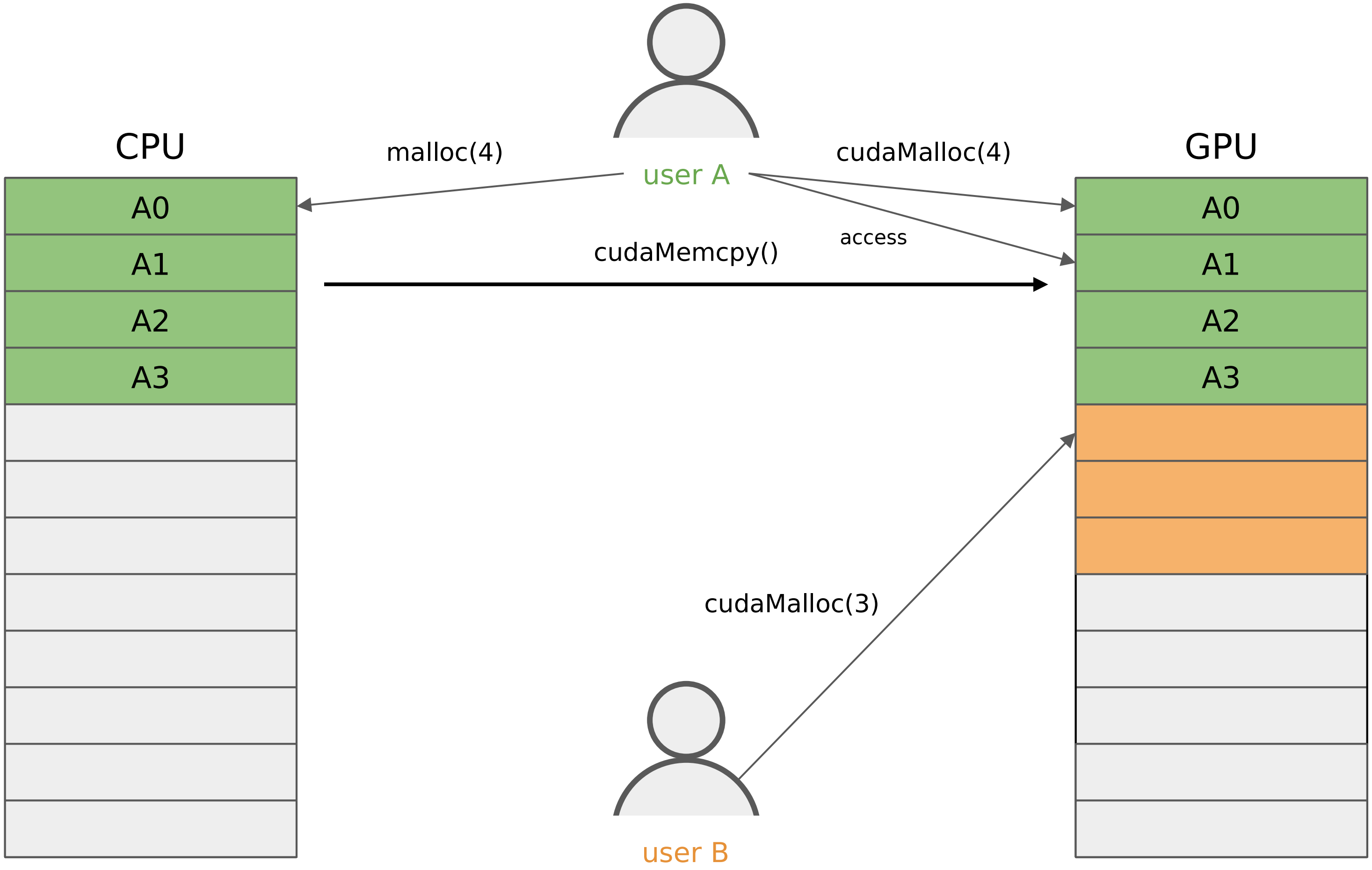

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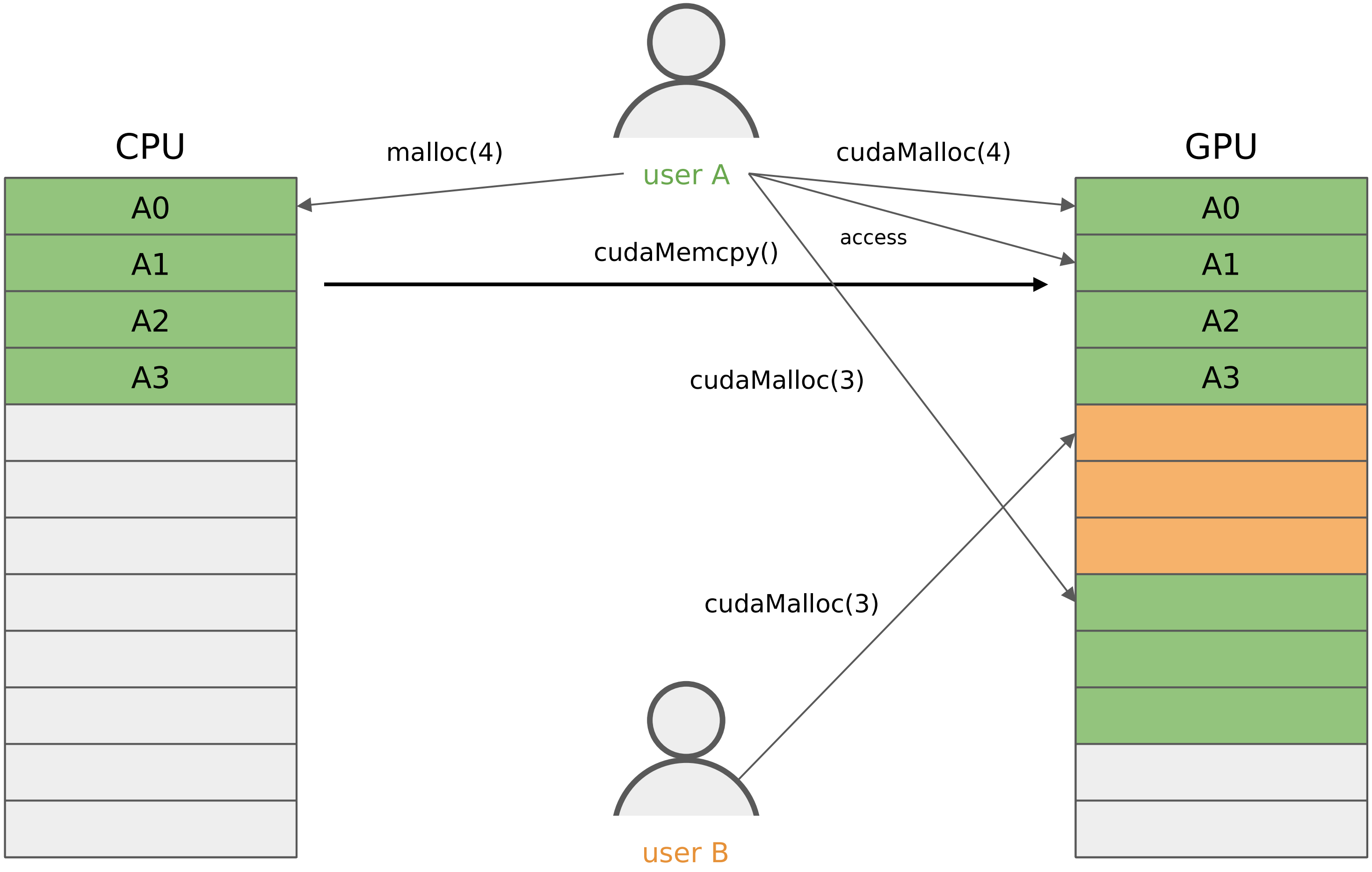

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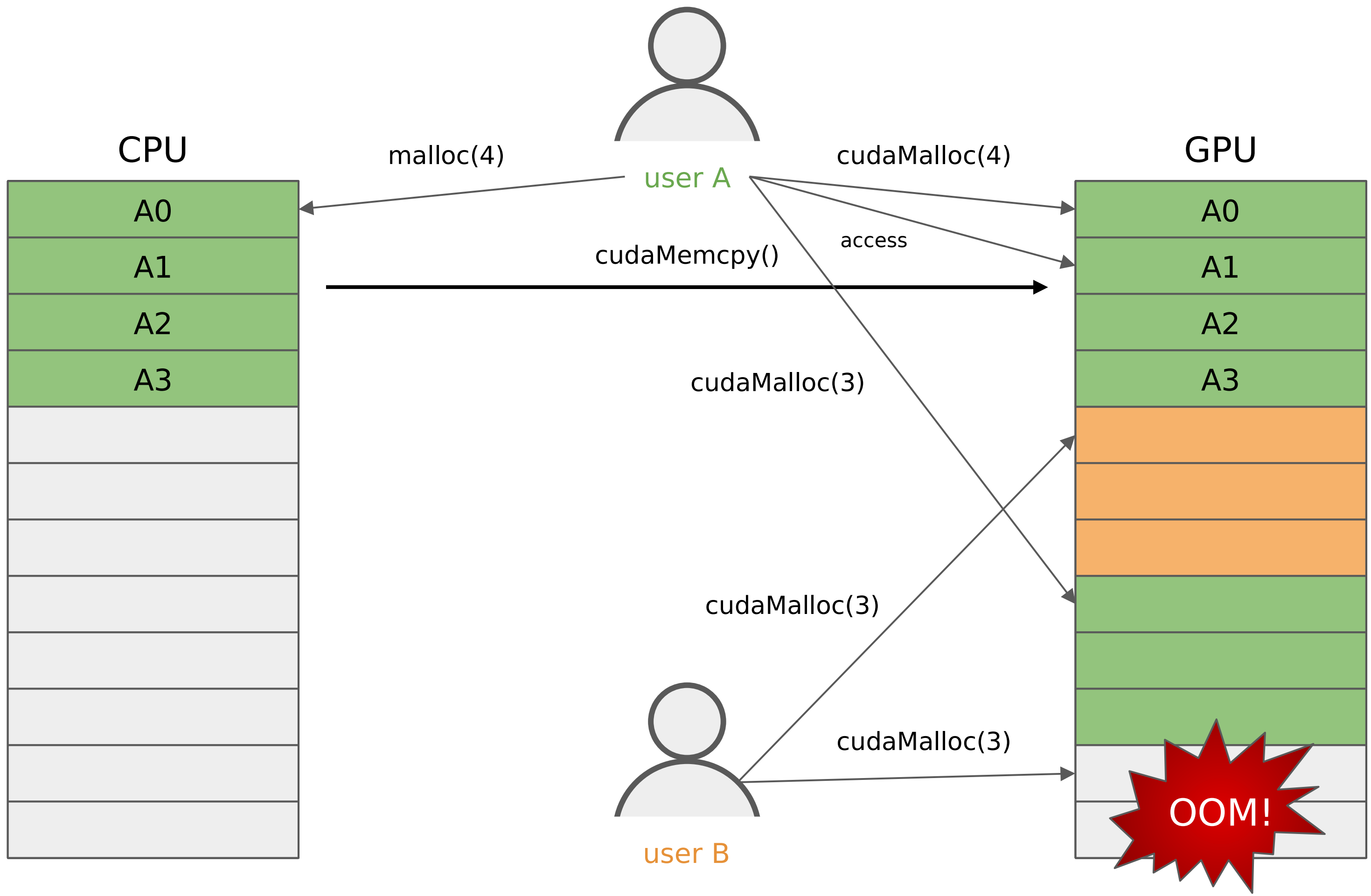
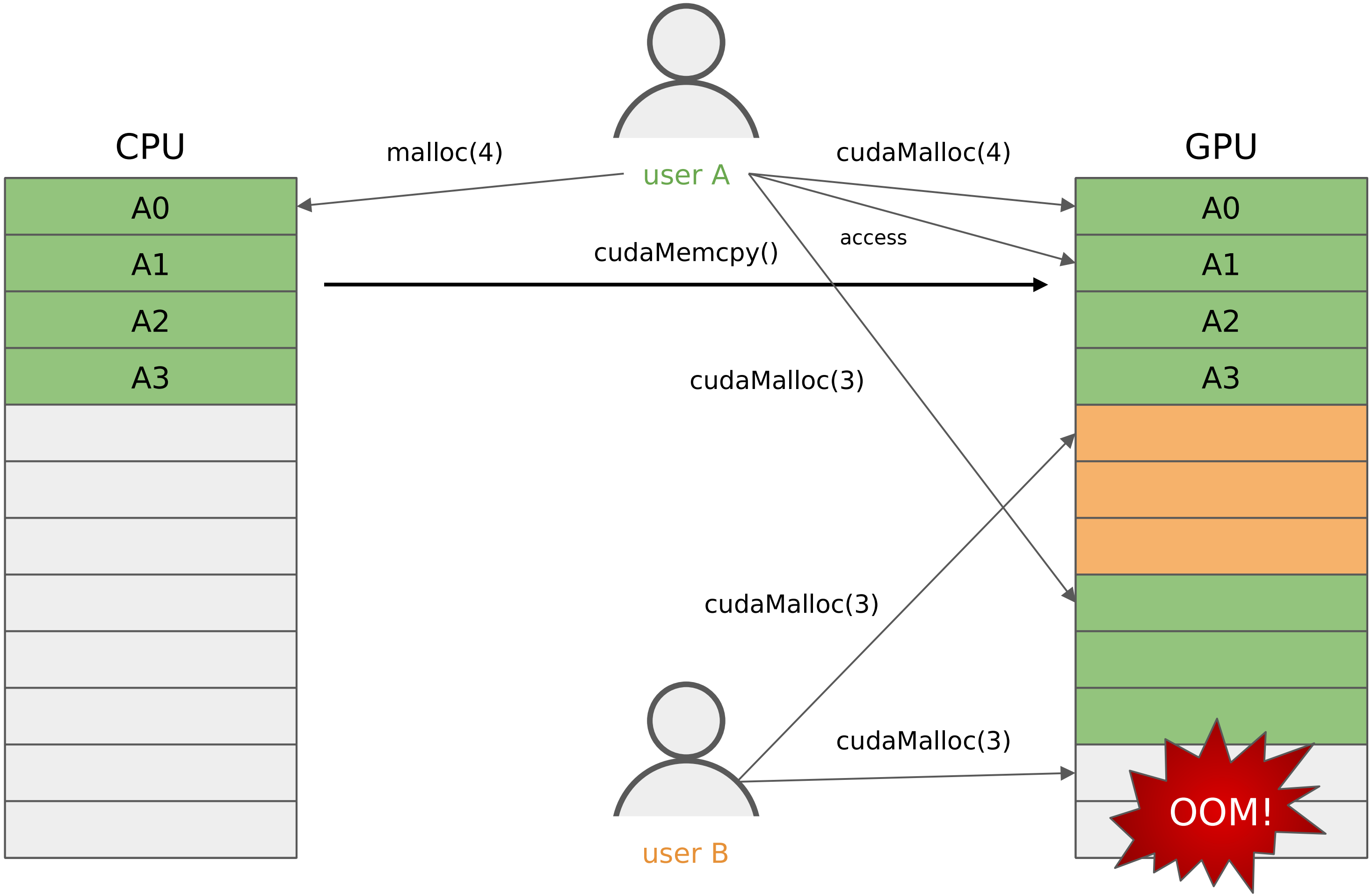


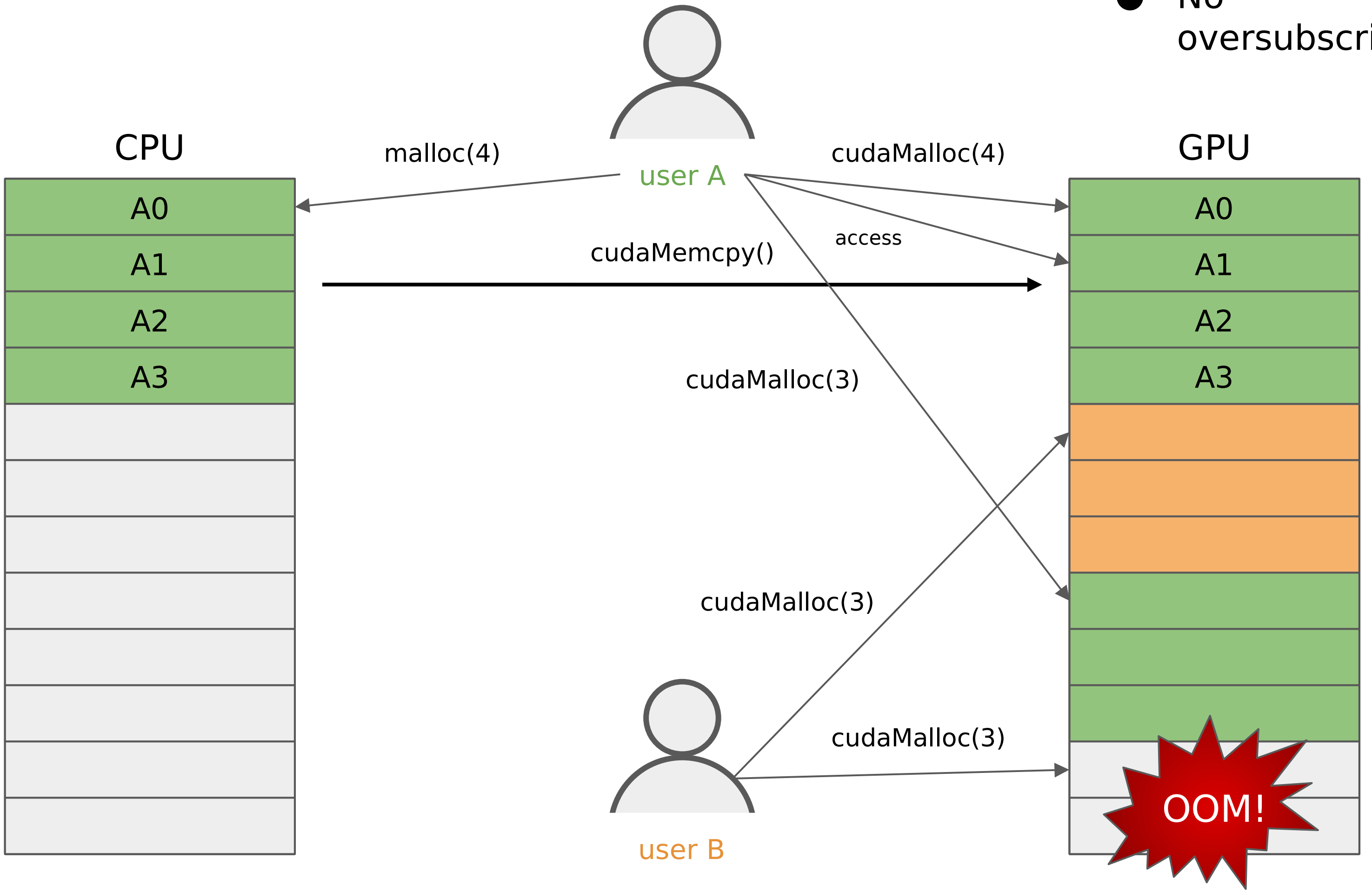
Default CUDA Memory Model

- FCFS



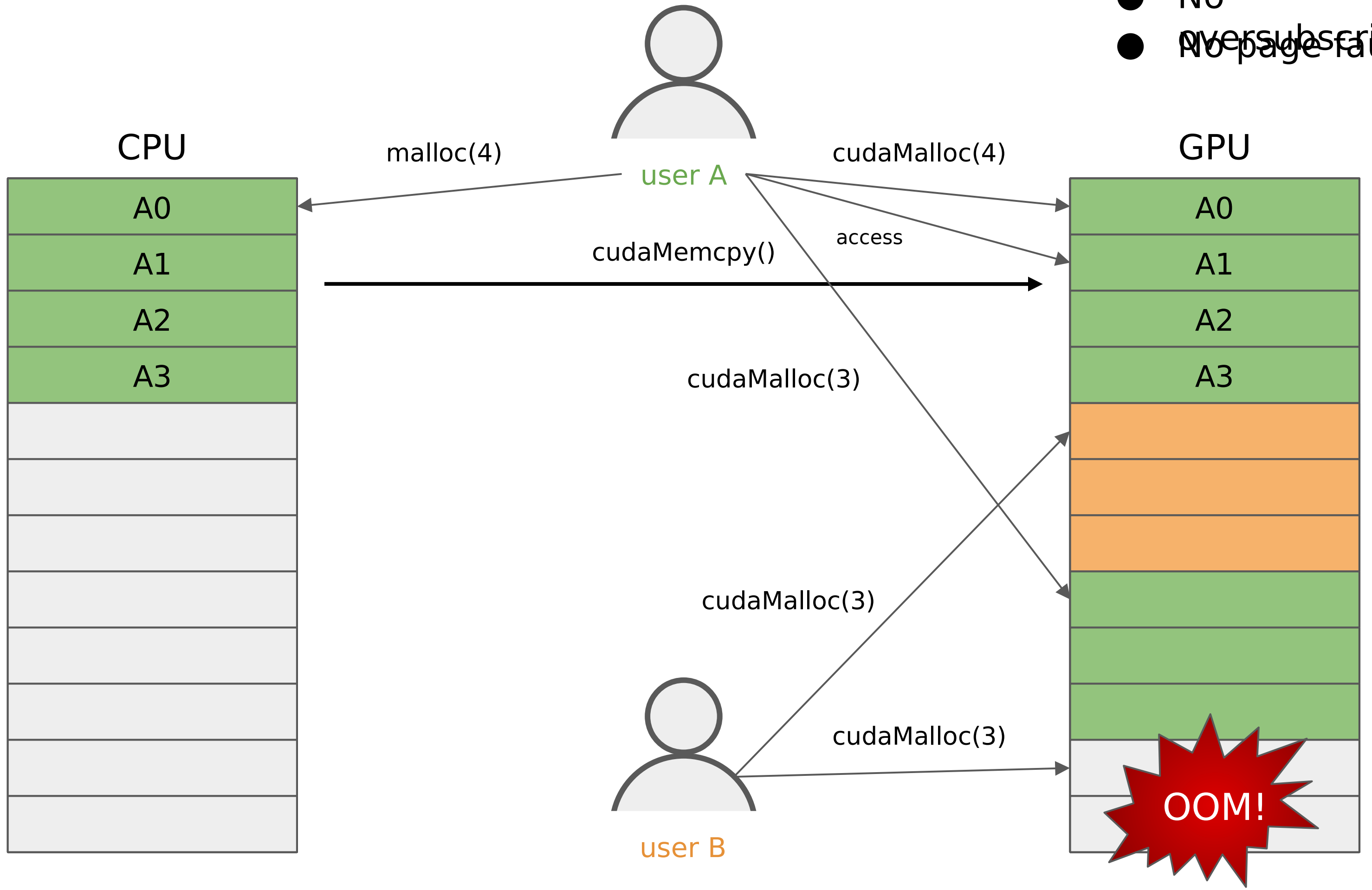
Default CUDA Memory Model

- FCFS
- No oversubscription



Default CUDA Memory Model

- FCFS
- No oversubscription
- No page faults



Controller Pattern

Used ***everywhere*** in Kubernetes

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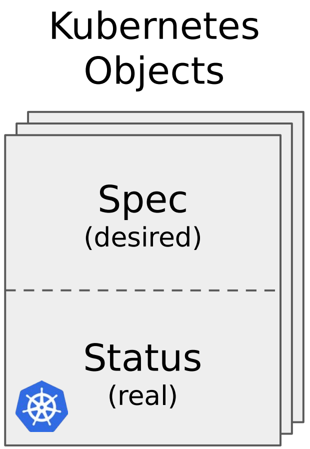

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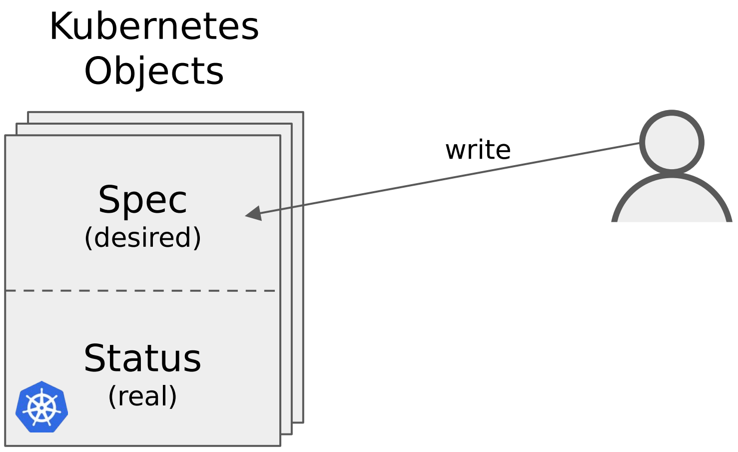

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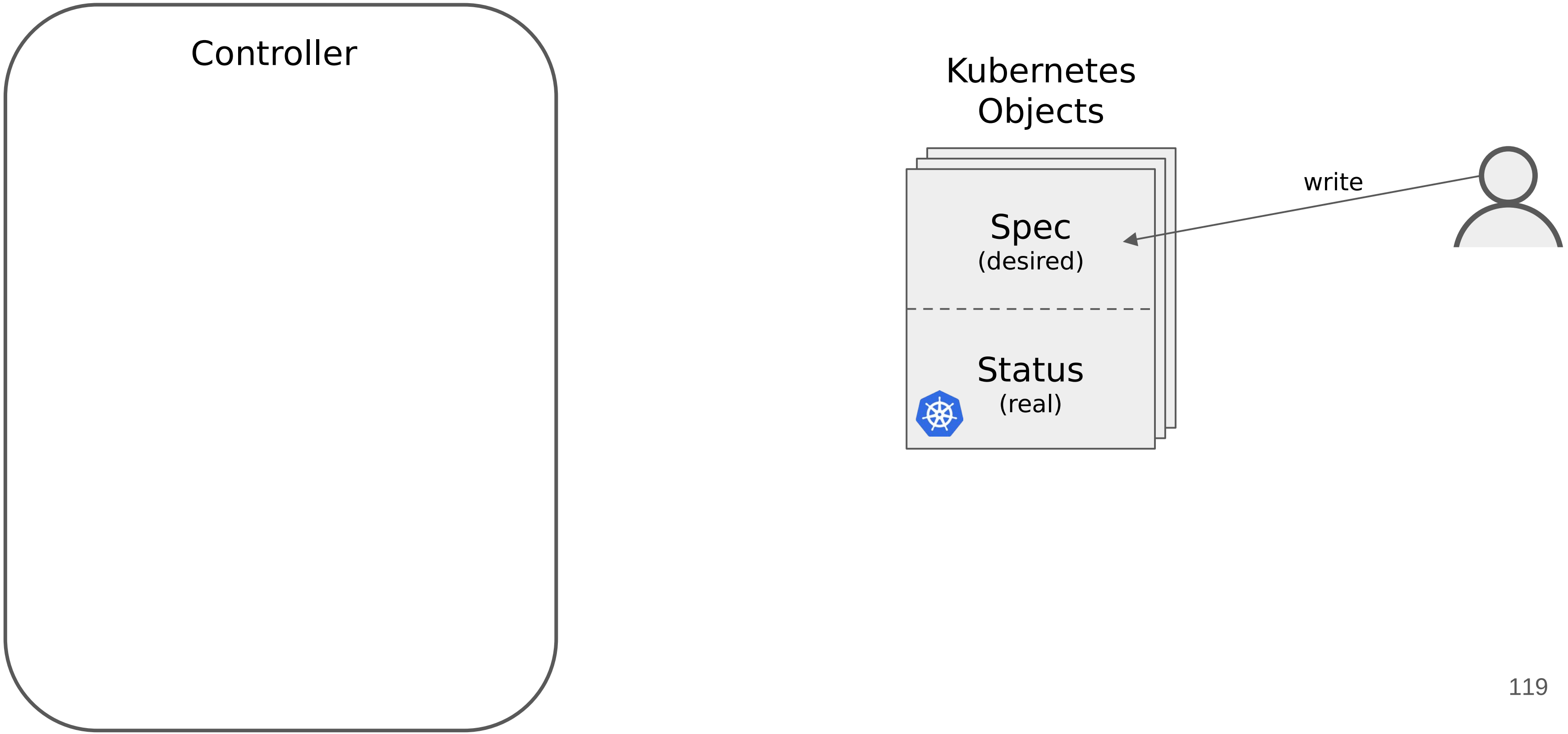

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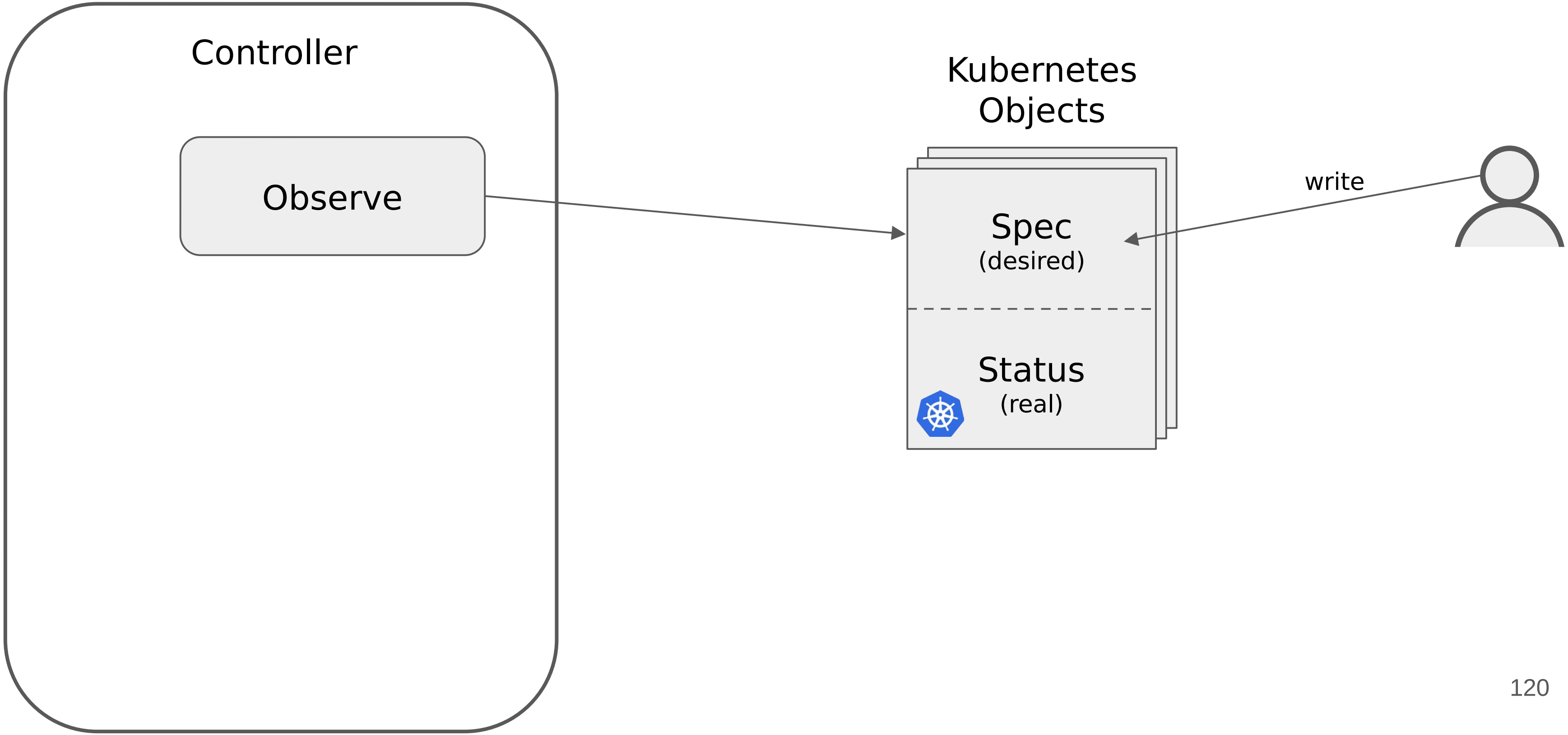

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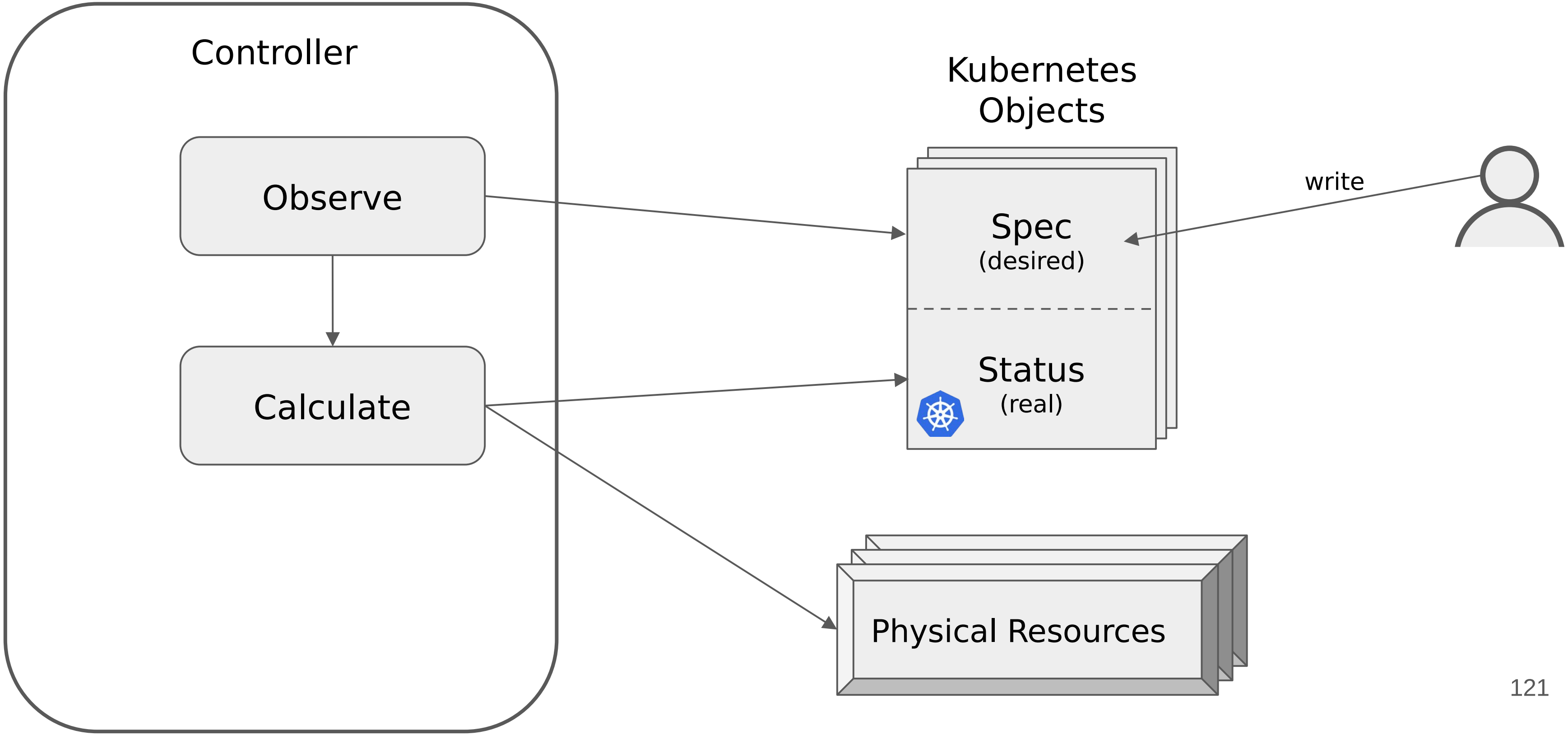

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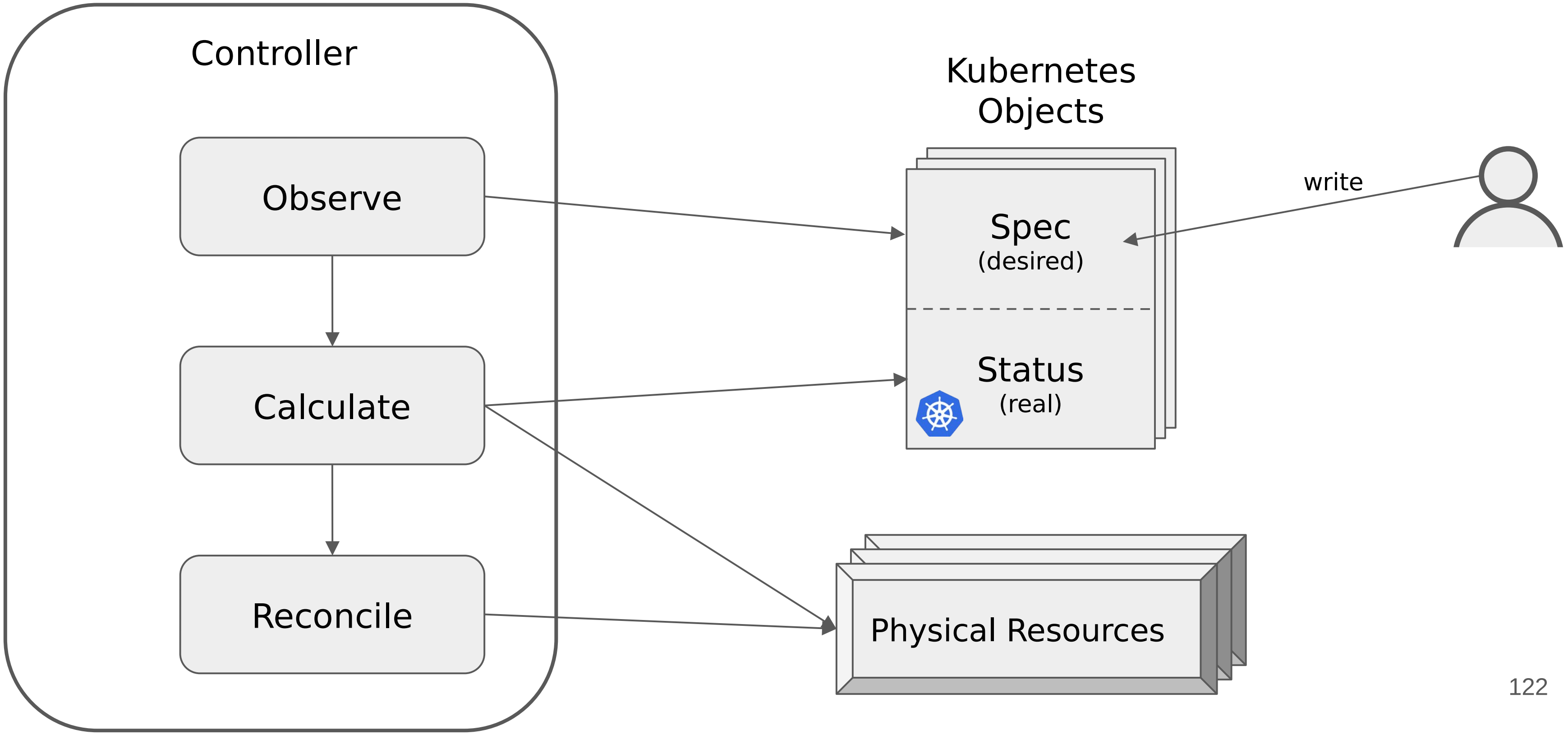

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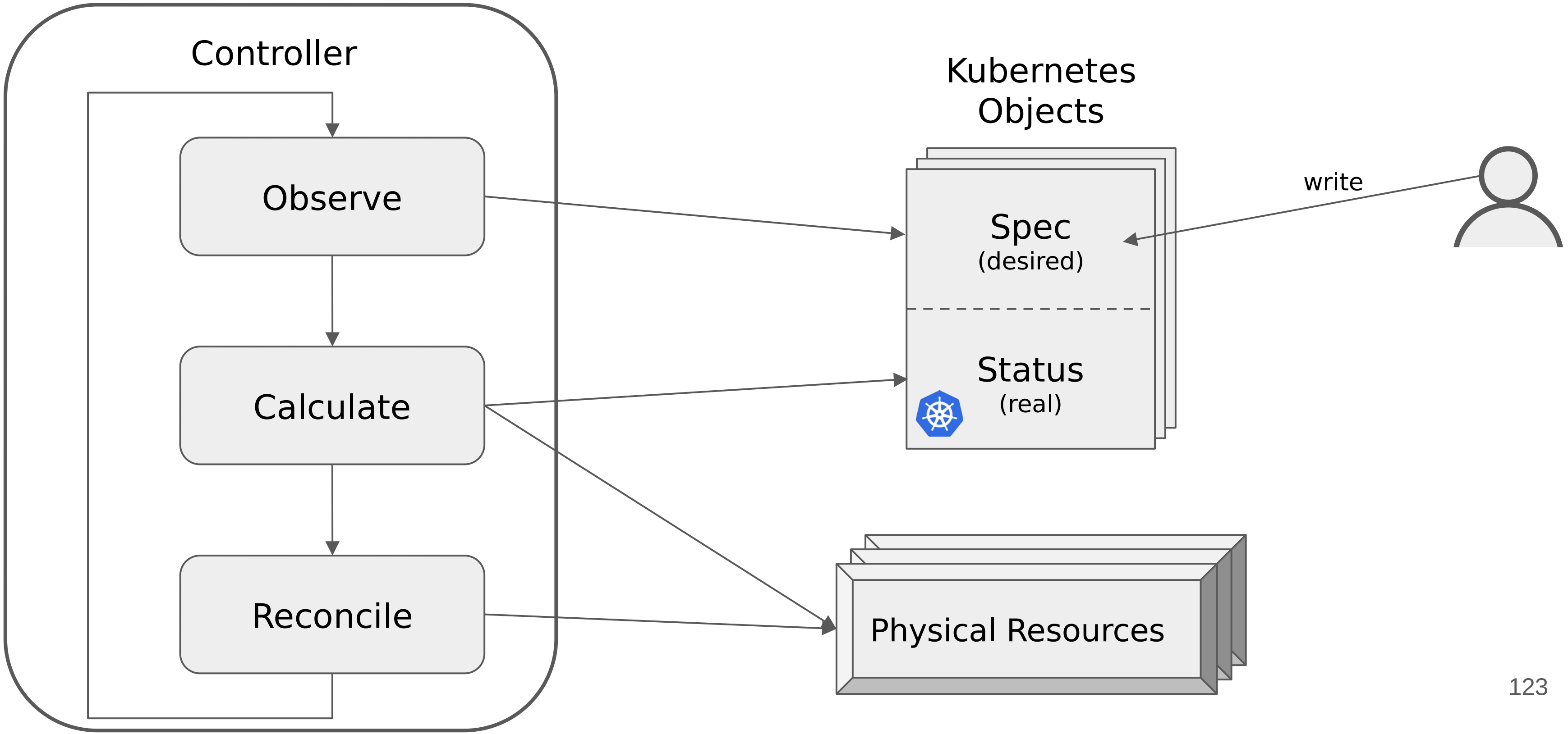
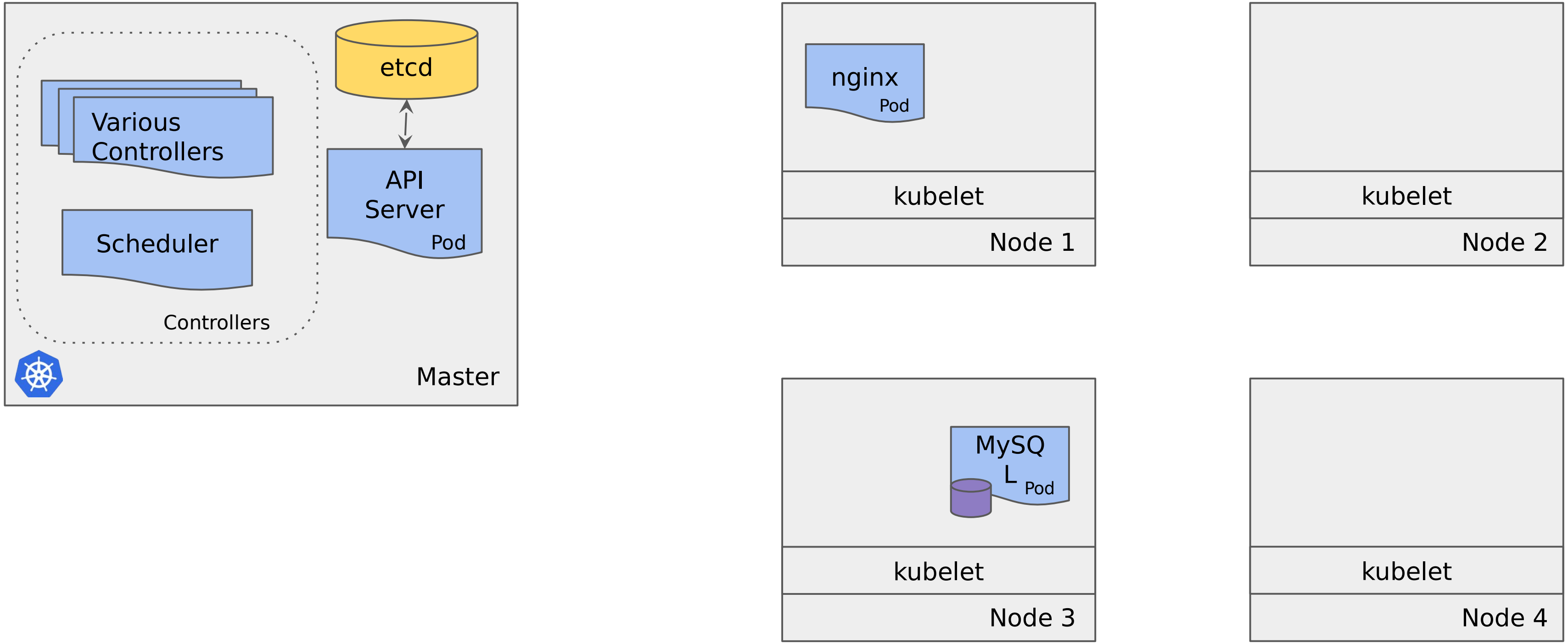


Kubernetes Scheduling



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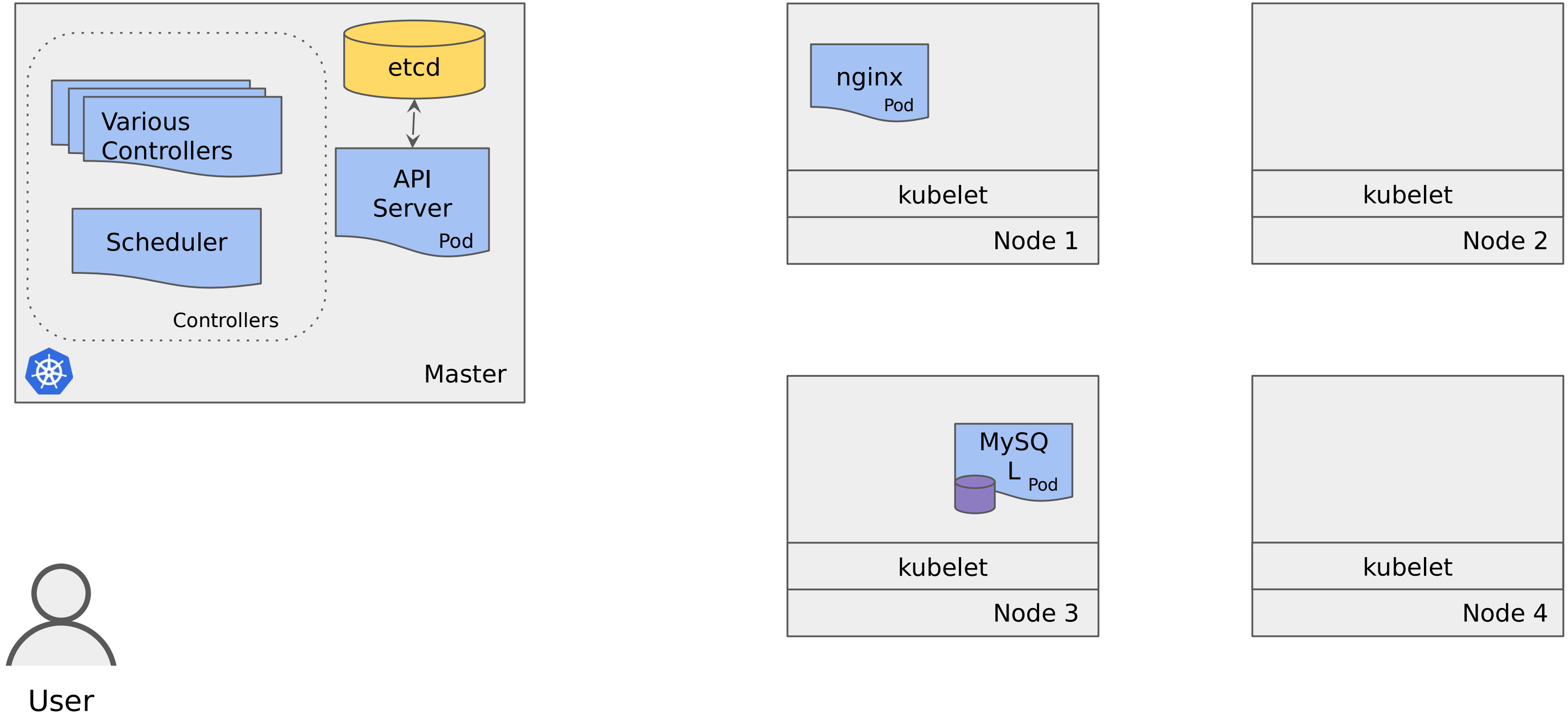

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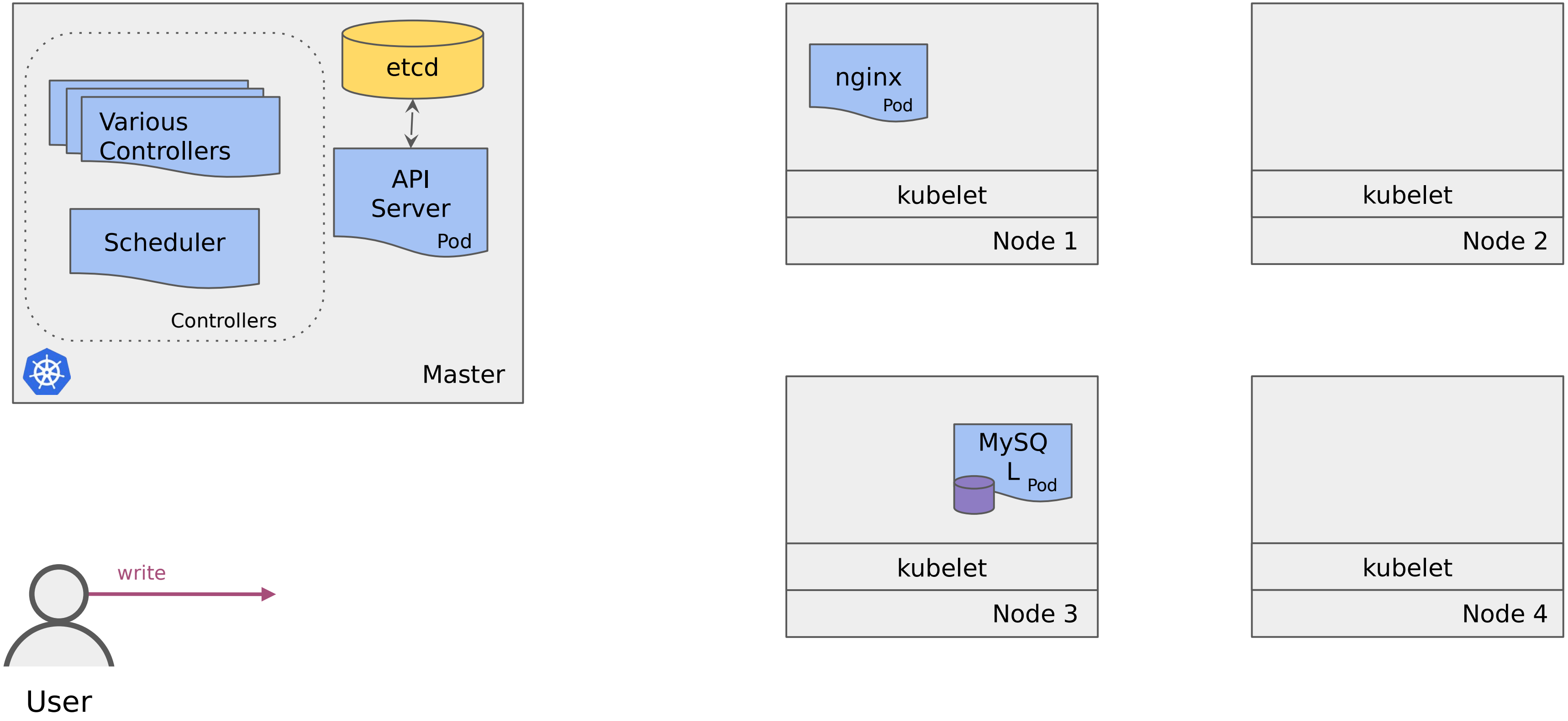

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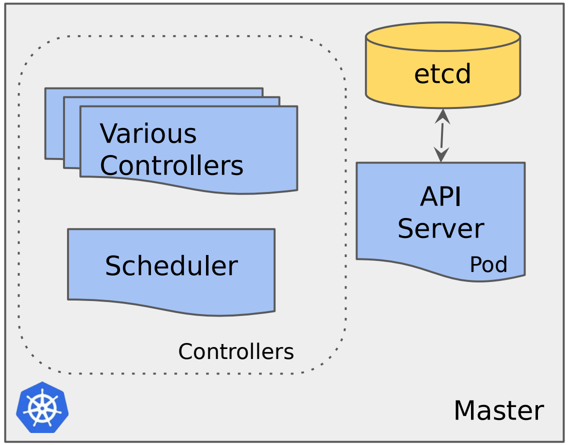

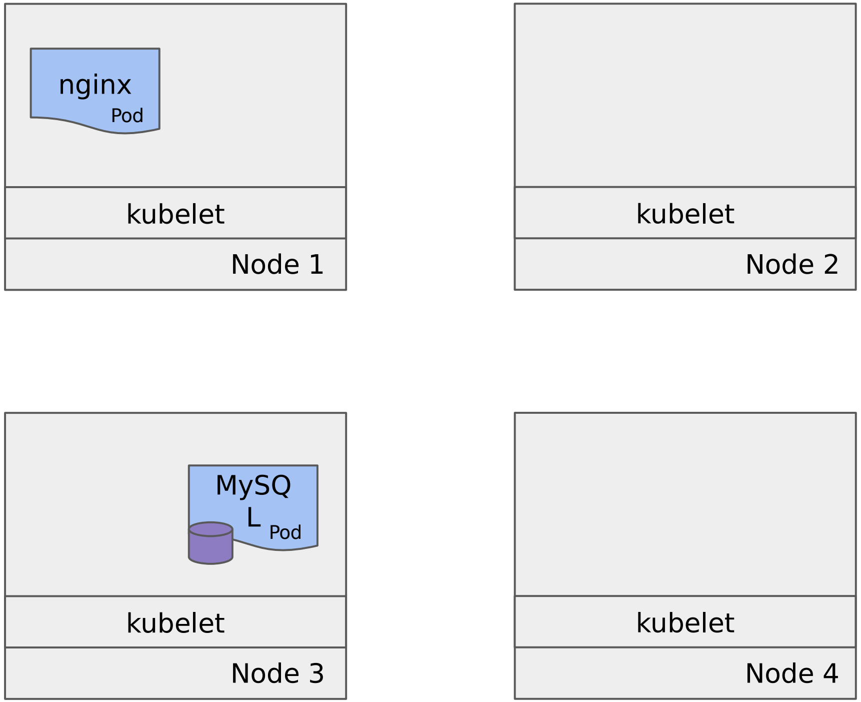


```yaml
kind: Pod
metadata:
  name: busybox
spec:
  image: busybox
  command: ['sh', '-c', 'sleep 1000']
  resources:
    requests:
      memory: "64Mi"
      cpu: "250m"
    limits:
      memory: "128Mi"
      cpu: "500m"
  nodeName:
```

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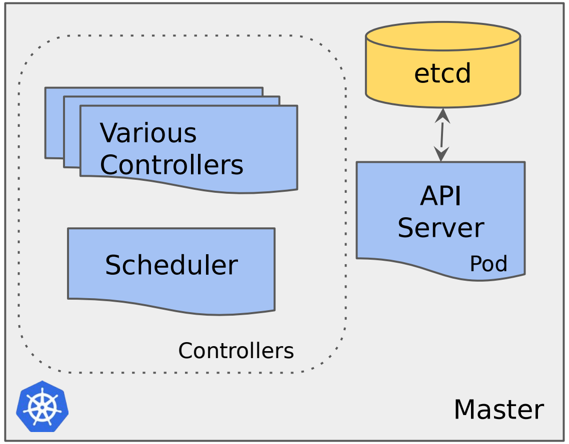

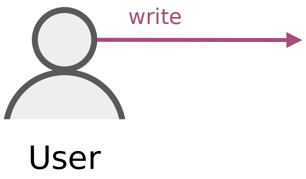


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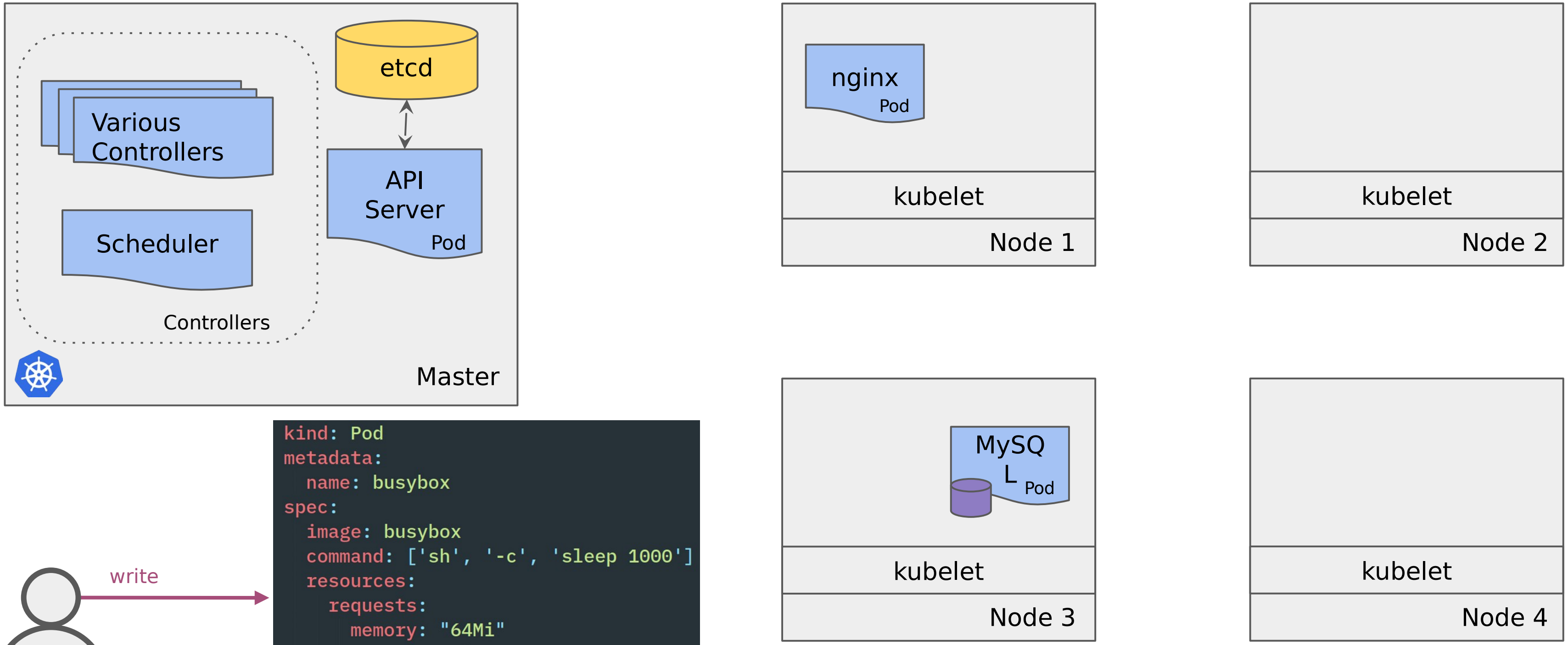


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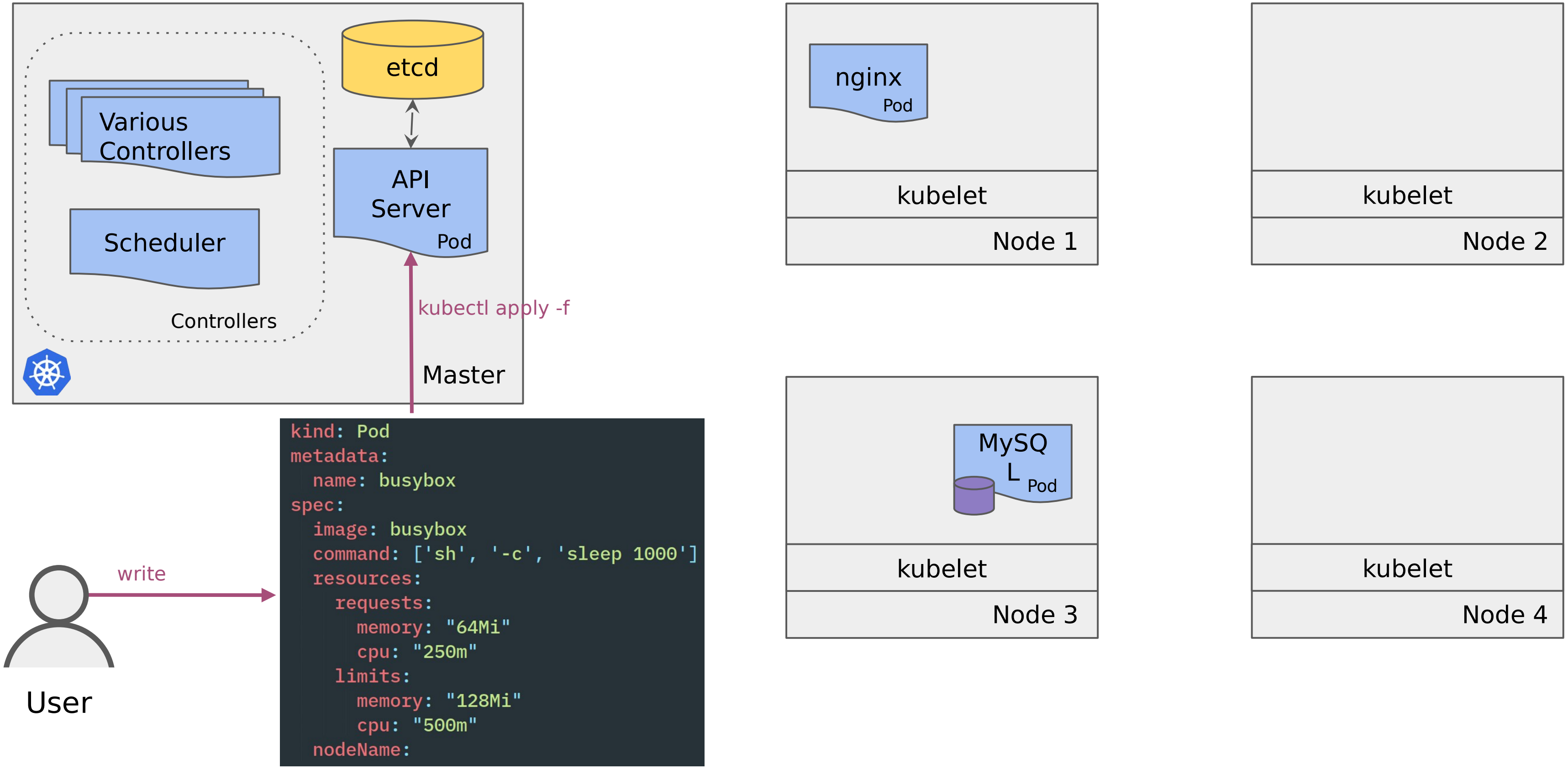
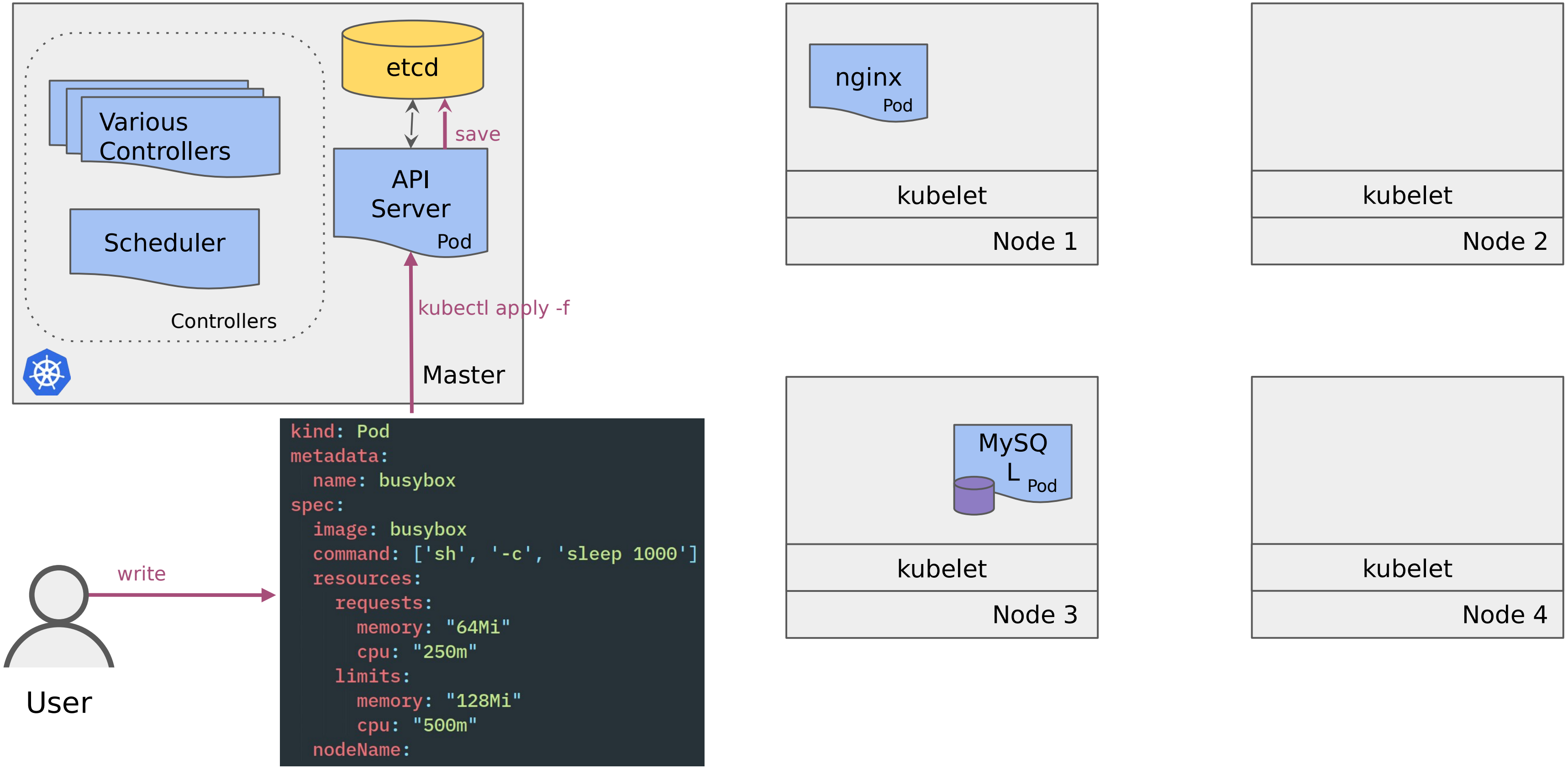
  name: busybox
spec:
  image: busybox
  command: ['sh', '-c', 'sleep 1000']
  resources:
    requests:
      memory: "64Mi"
      cpu: "250m"
    limits:
      memory: "128Mi"
      cpu: "500m"
  nodeName:
```

Kubernetes Scheduling



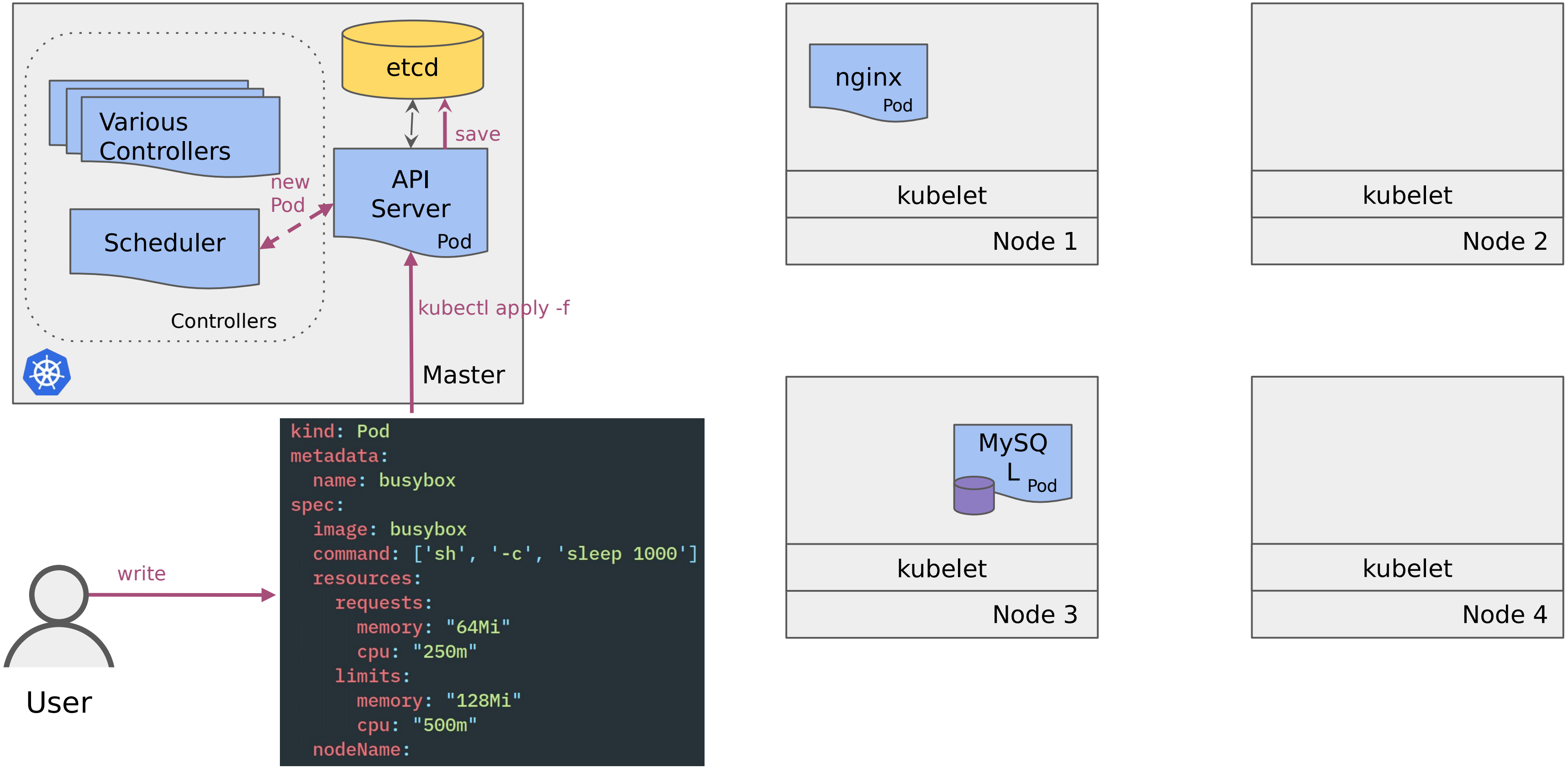

```yaml
kind: Pod
metadata:
  name: busybox
spec:
  image: busybox
  command: ['sh', '-c', 'sleep 1000']
  resources:
    requests:
      memory: "64Mi"
      cpu: "250m"
    limits:
      memory: "128Mi"
      cpu: "500m"
  nodeName:
```

Kubernetes Scheduling



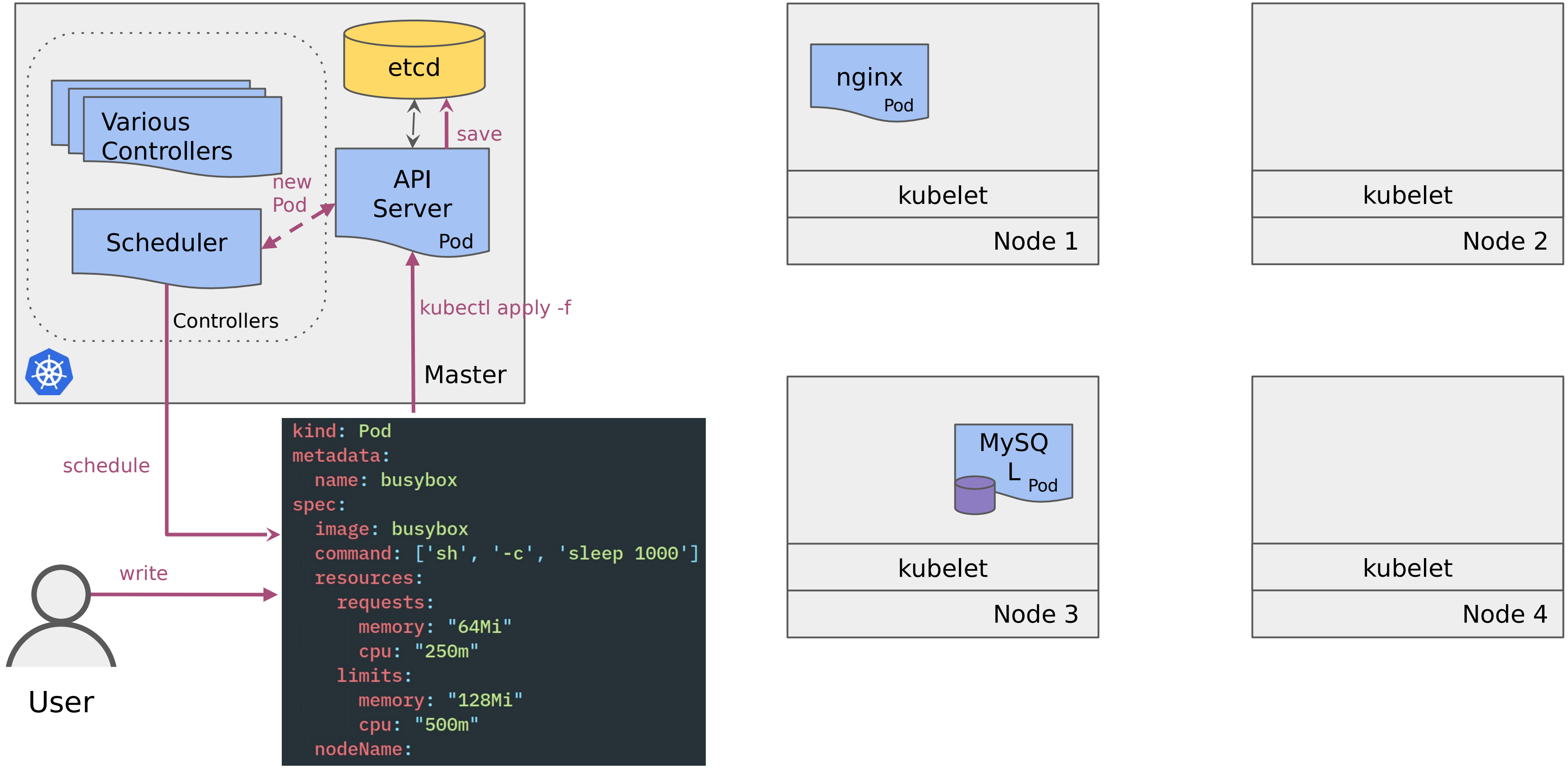

```yaml
kind: Pod
metadata:
  name: busybox
spec:
  image: busybox
  command: ['sh', '-c', 'sleep 1000']
  resources:
    requests:
      memory: "64Mi"
      cpu: "250m"
    limits:
      memory: "128Mi"
      cpu: "500m"
  nodeName:
```

Kubernetes Scheduling

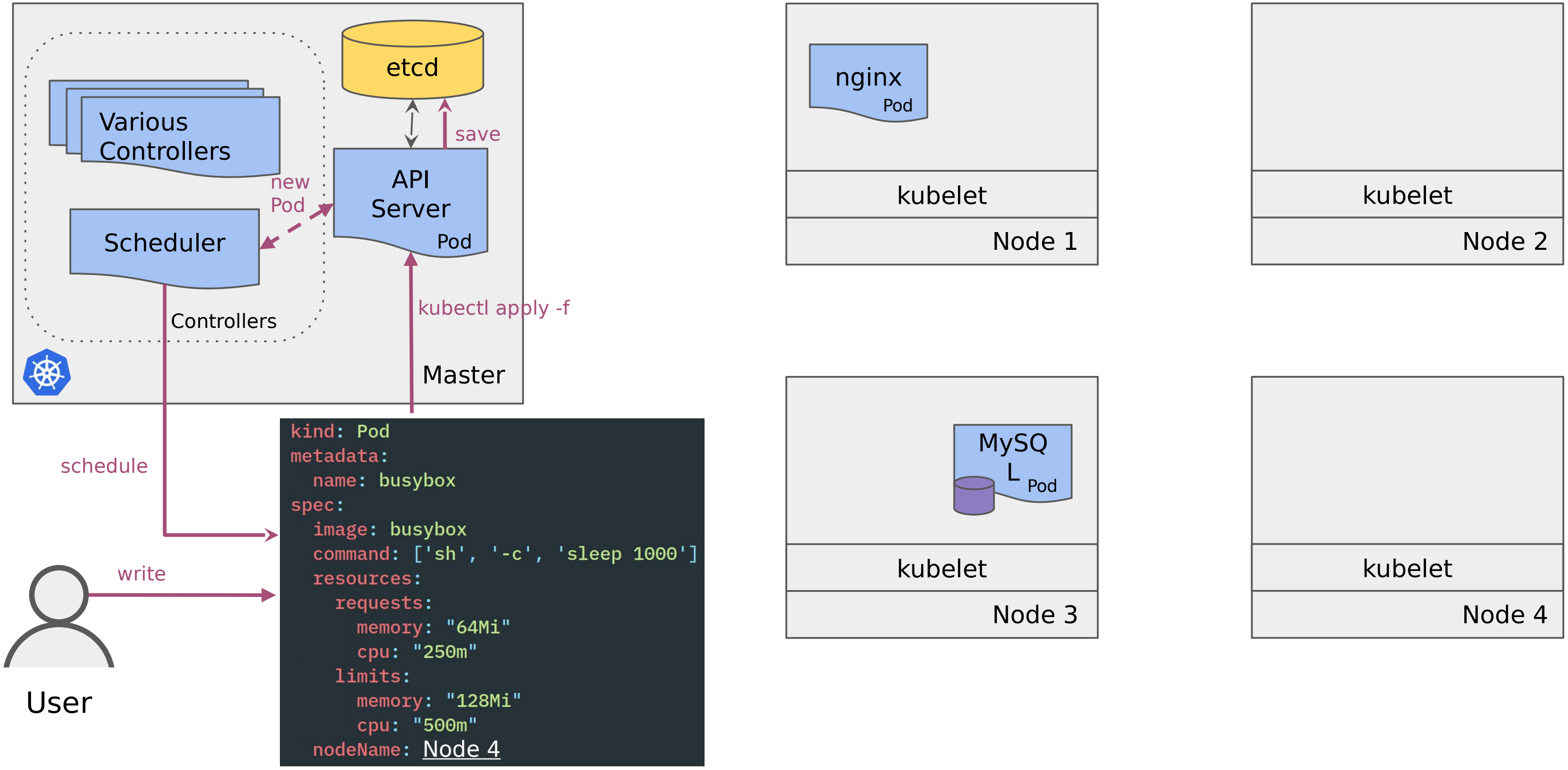



```yaml
kind: Pod
metadata:
  name: busybox
spec:
  image: busybox
  command: ['sh', '-c', 'sleep 1000']
  resources:
    requests:
      memory: "64Mi"
      cpu: "250m"
    limits:
      memory: "128Mi"
      cpu: "500m"
  nodeName:
```

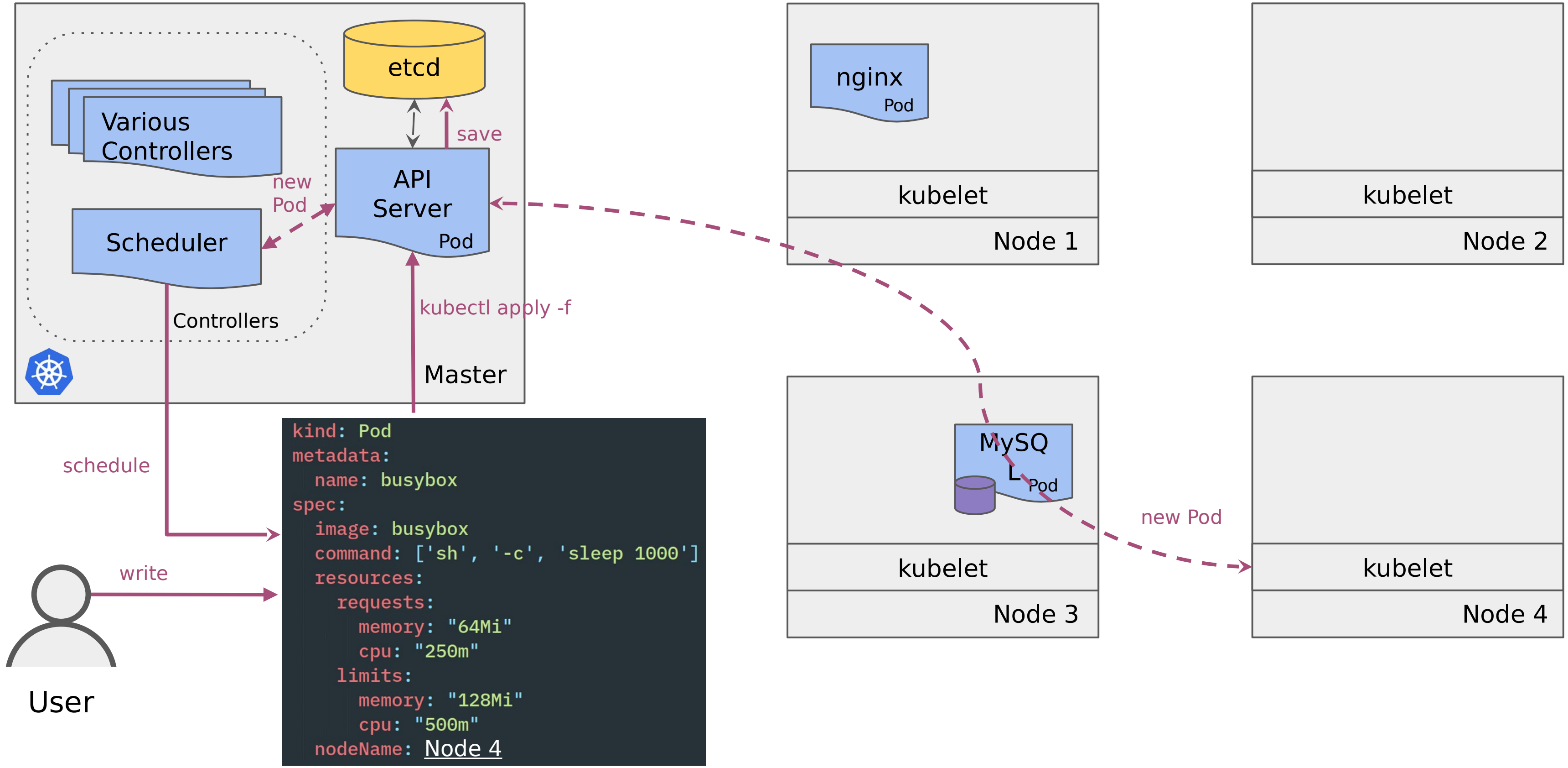
Kubernetes Scheduling



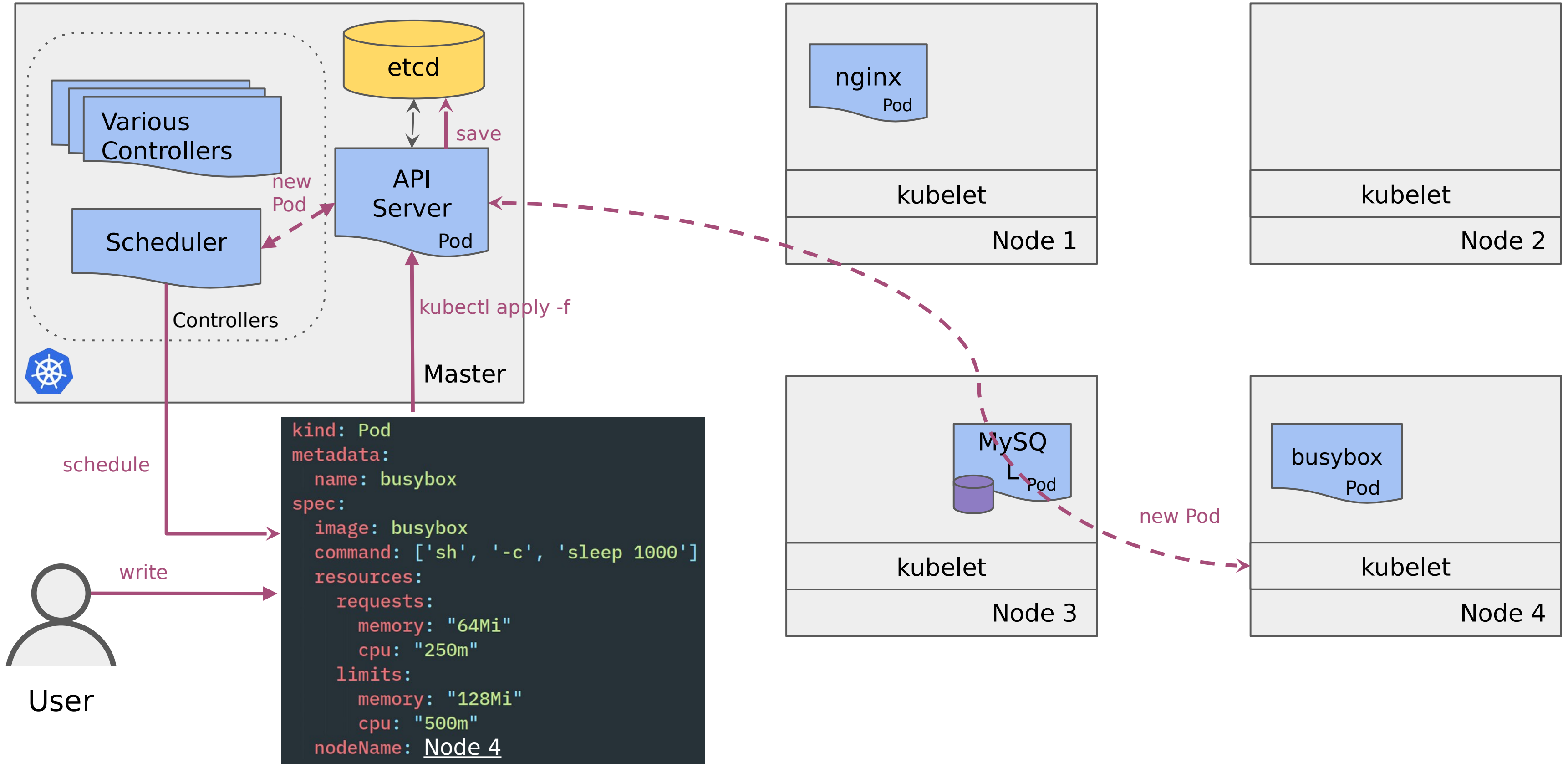
Kubernetes Scheduling



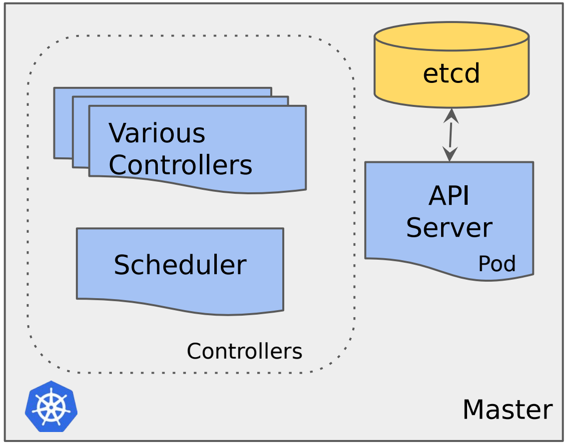
Kubernetes Scheduling

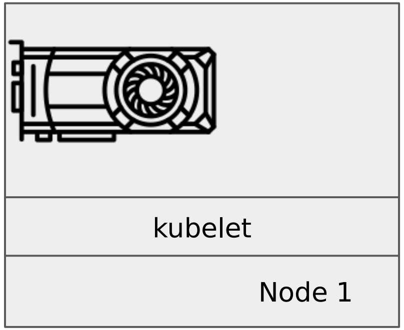


Kubernetes Scheduling

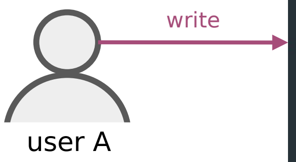


The Problem (once more)

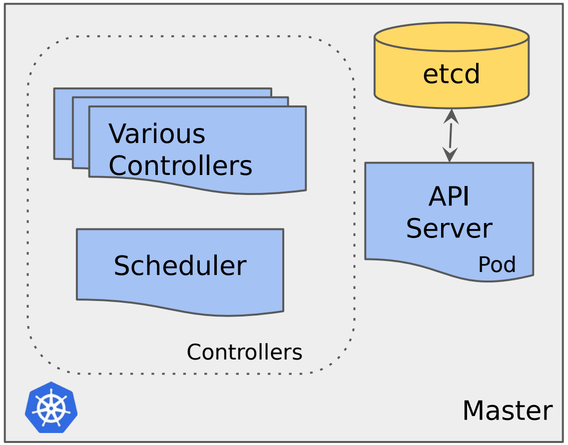


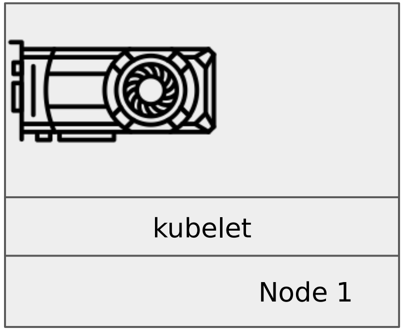


The Problem (once more)

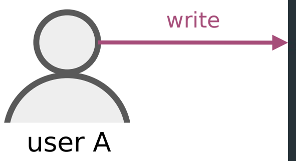



```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName:
```

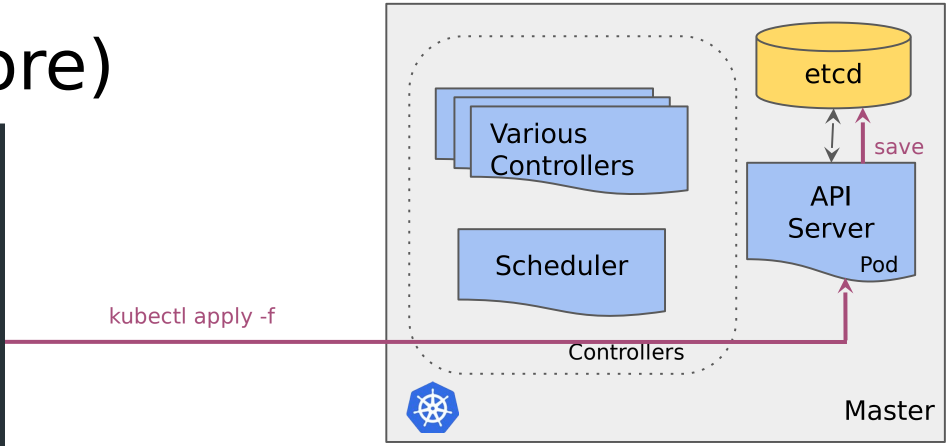


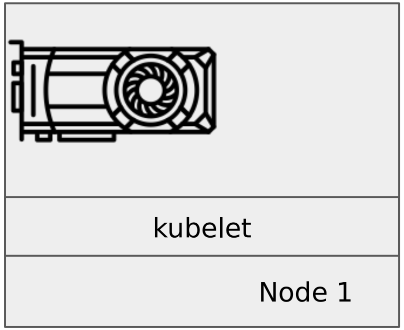


The Problem (once more)



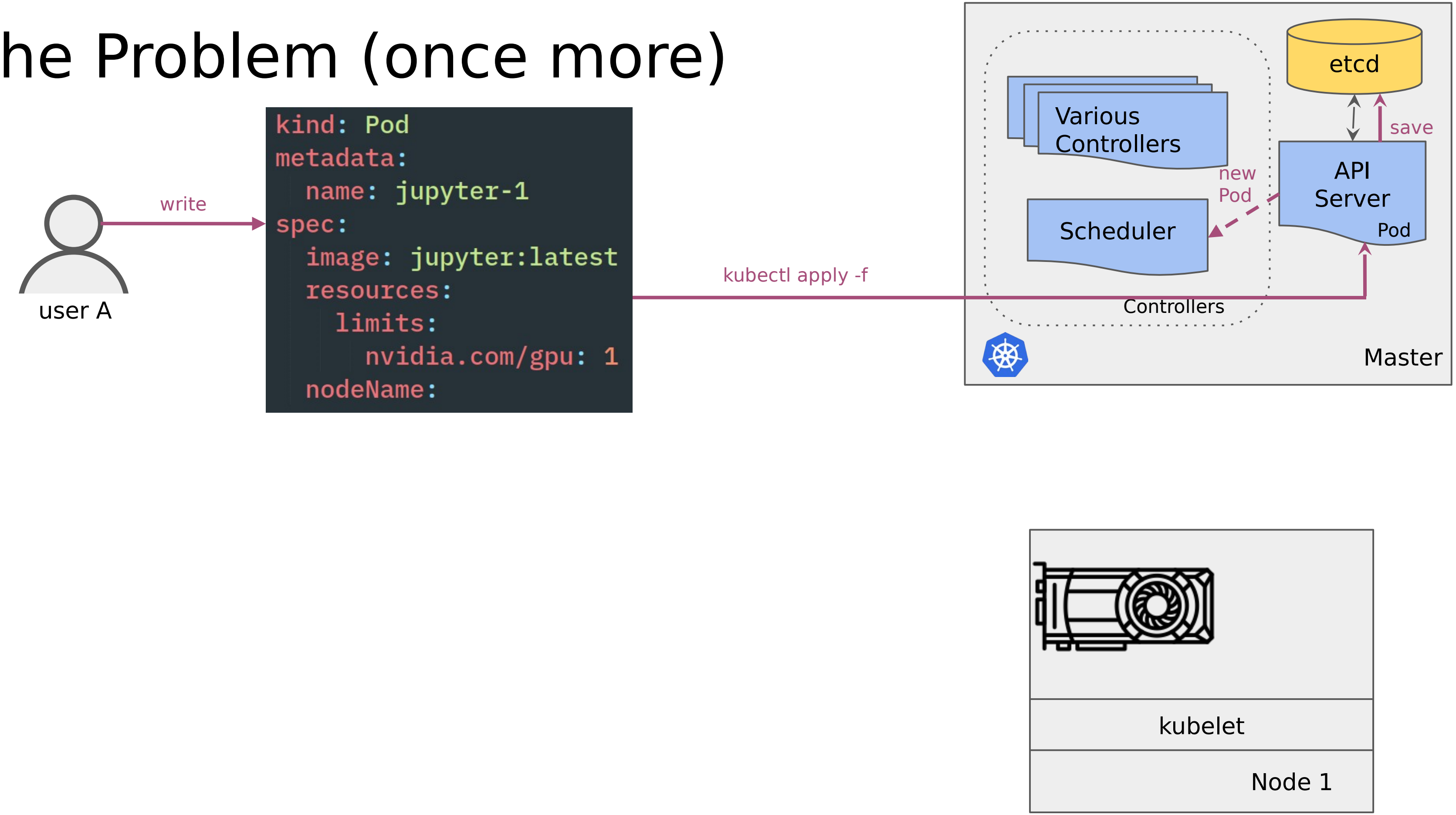

```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName:
```





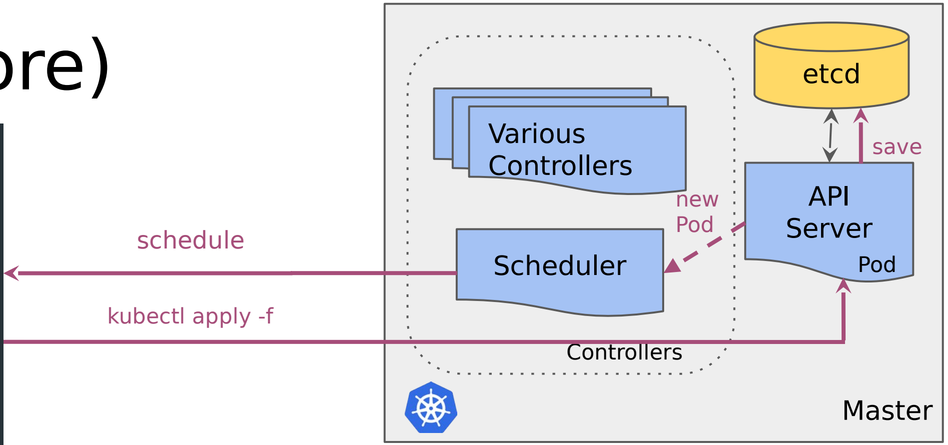
The Problem (once more)

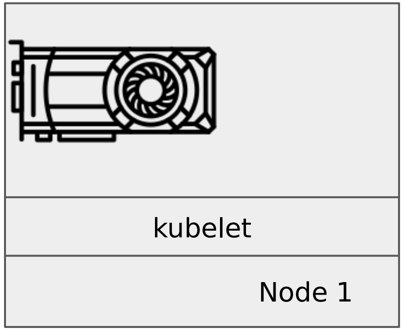
```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName:
```



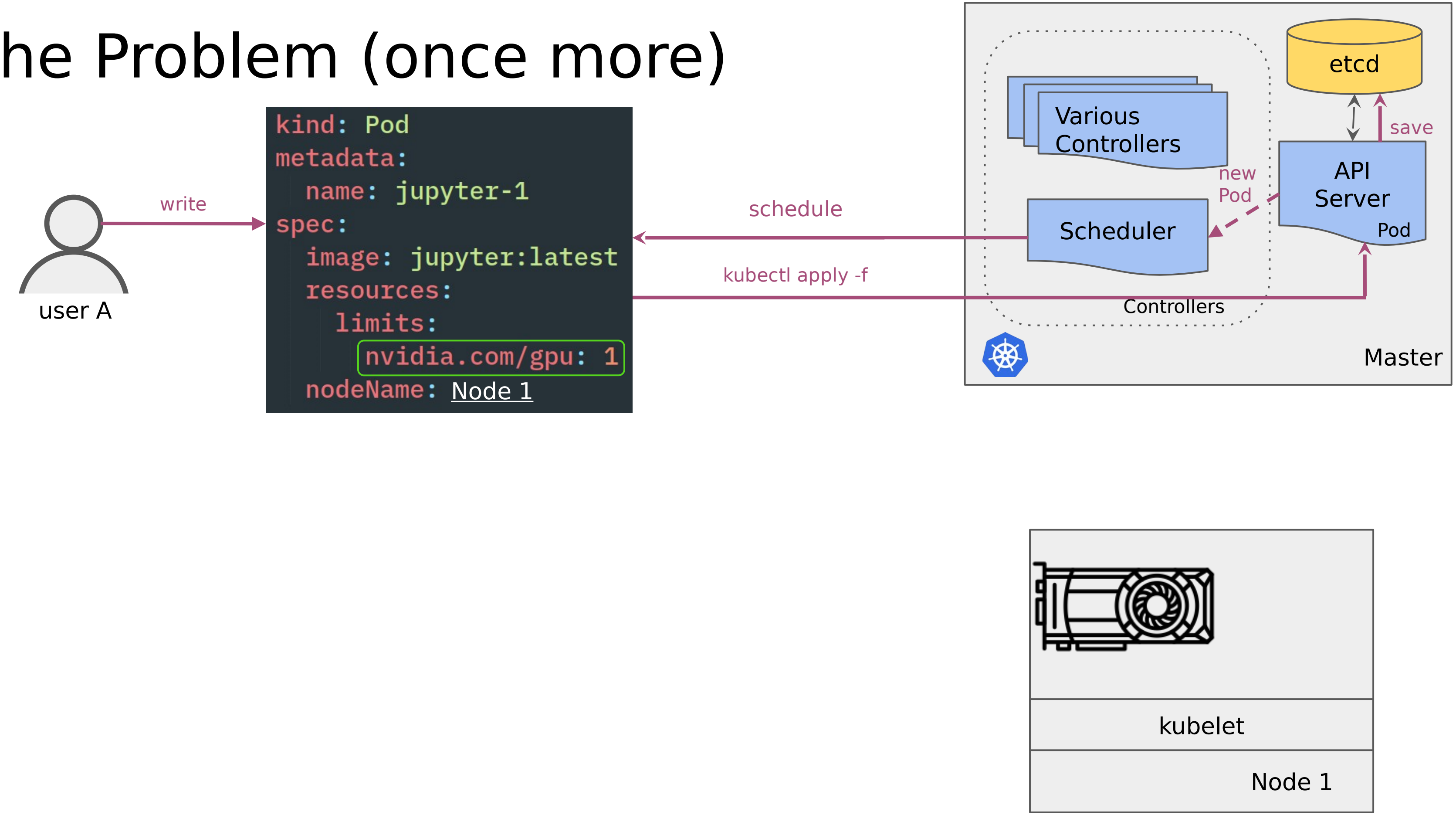
The Problem (once more)


```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName:
```

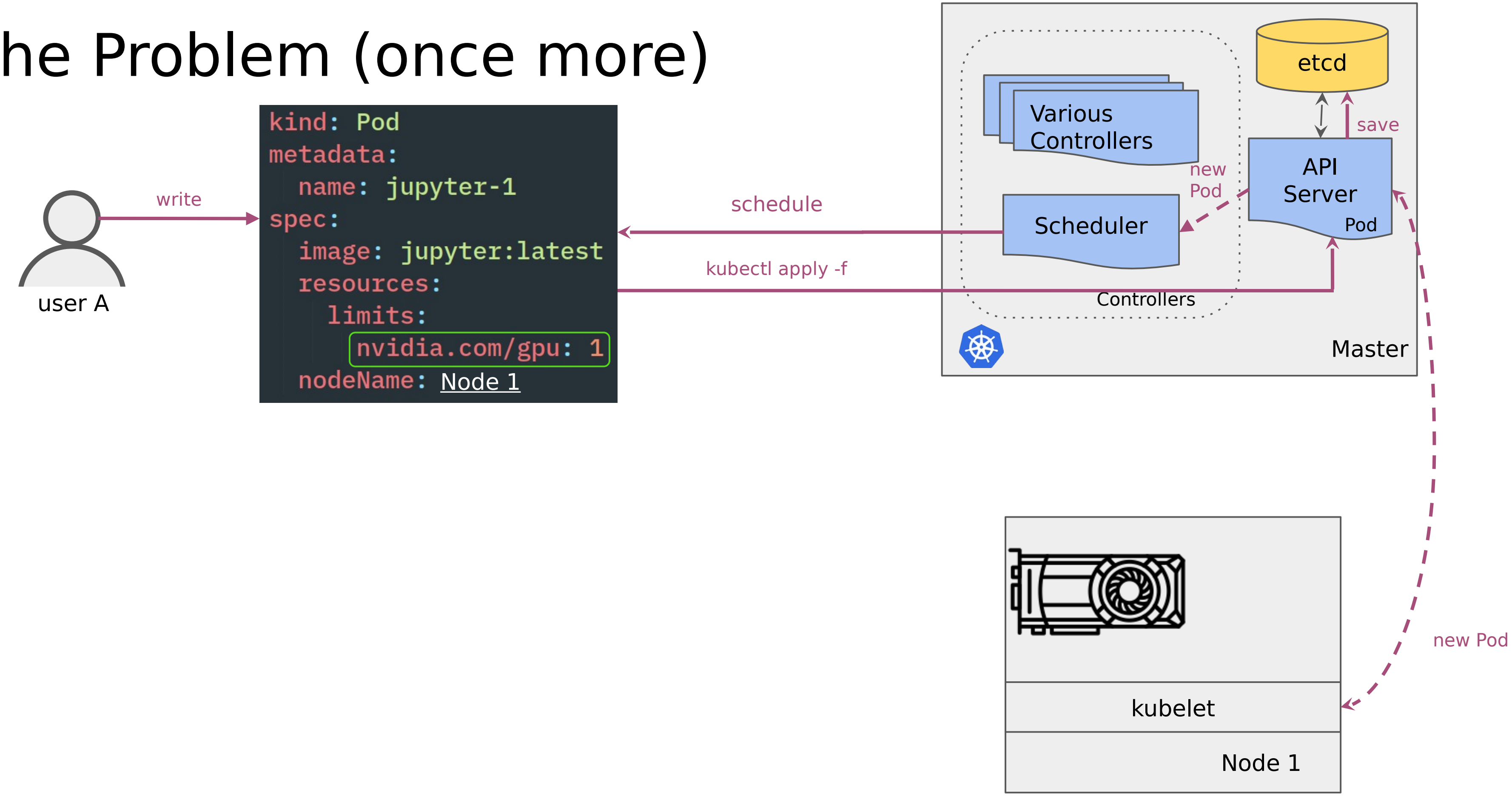




The Problem (once more)

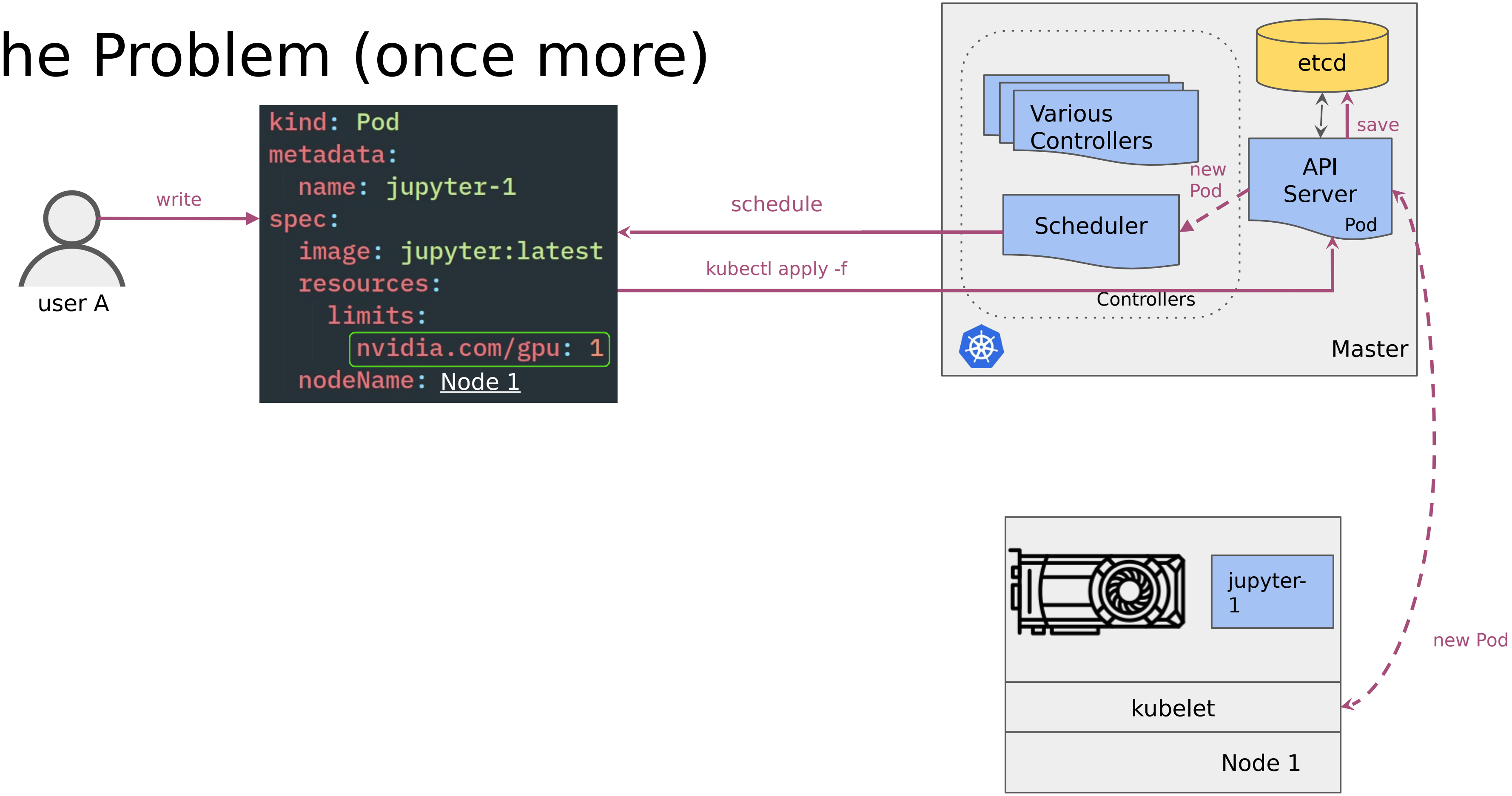


The Problem (once more)

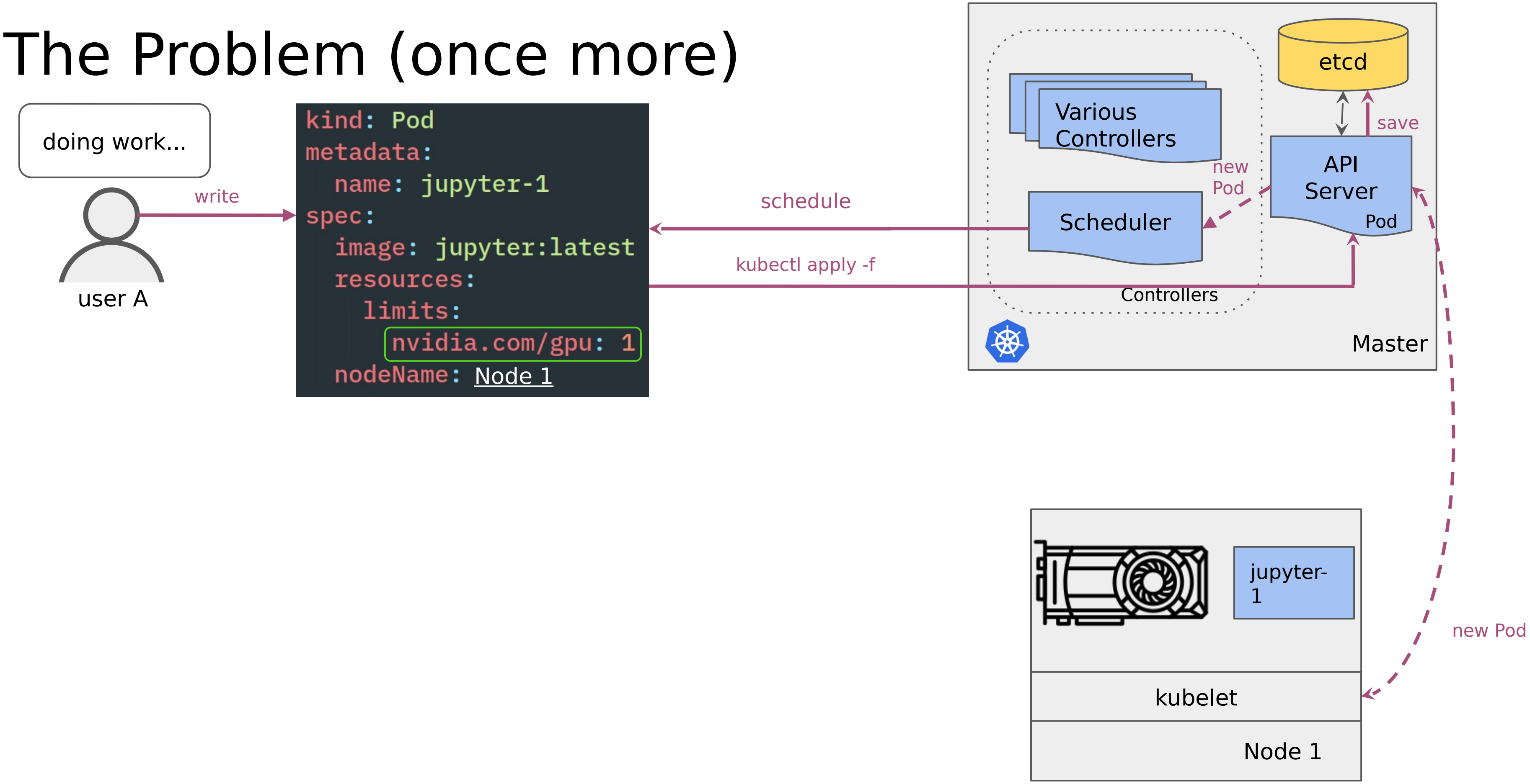


The Problem (once more)

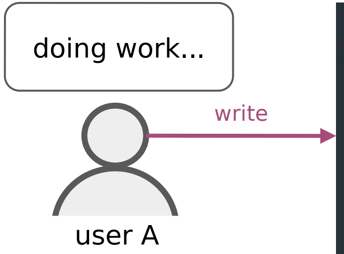
```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName: Node 1
```



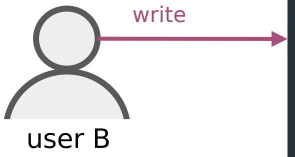
The Problem (once more)



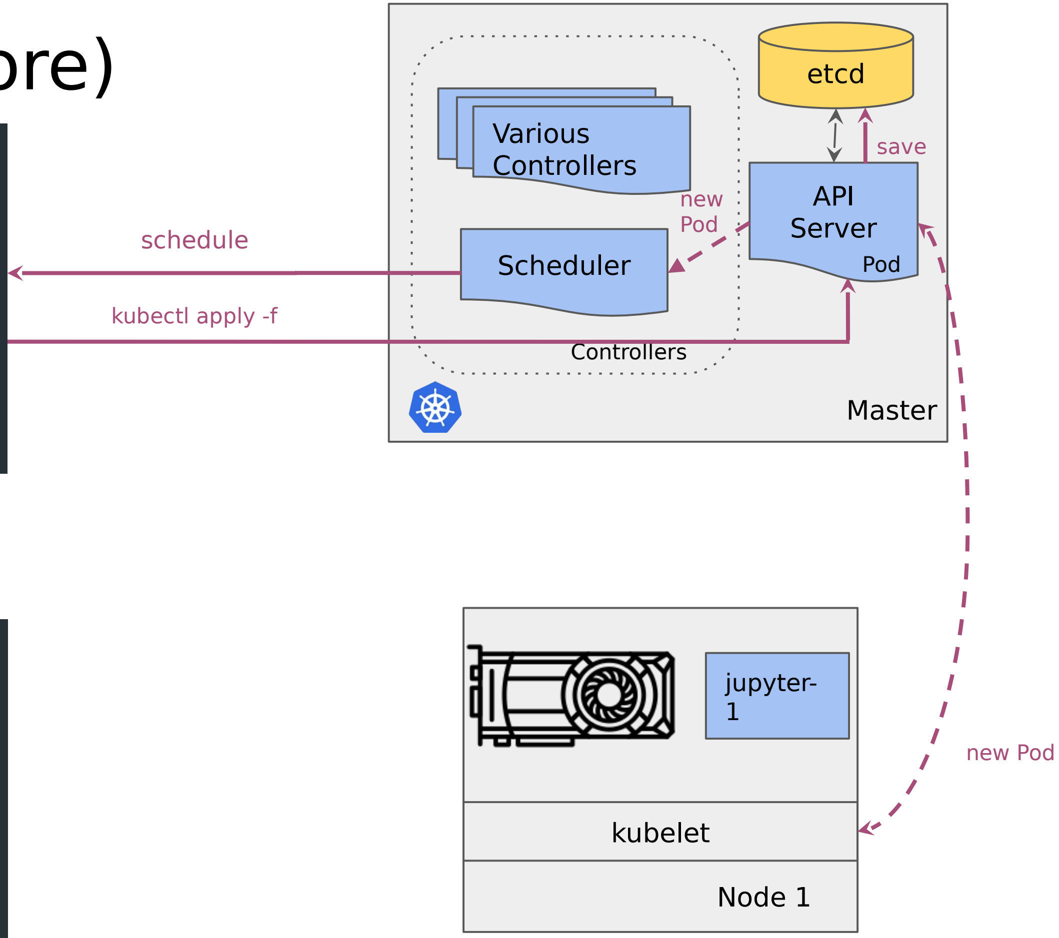
The Problem (once more)



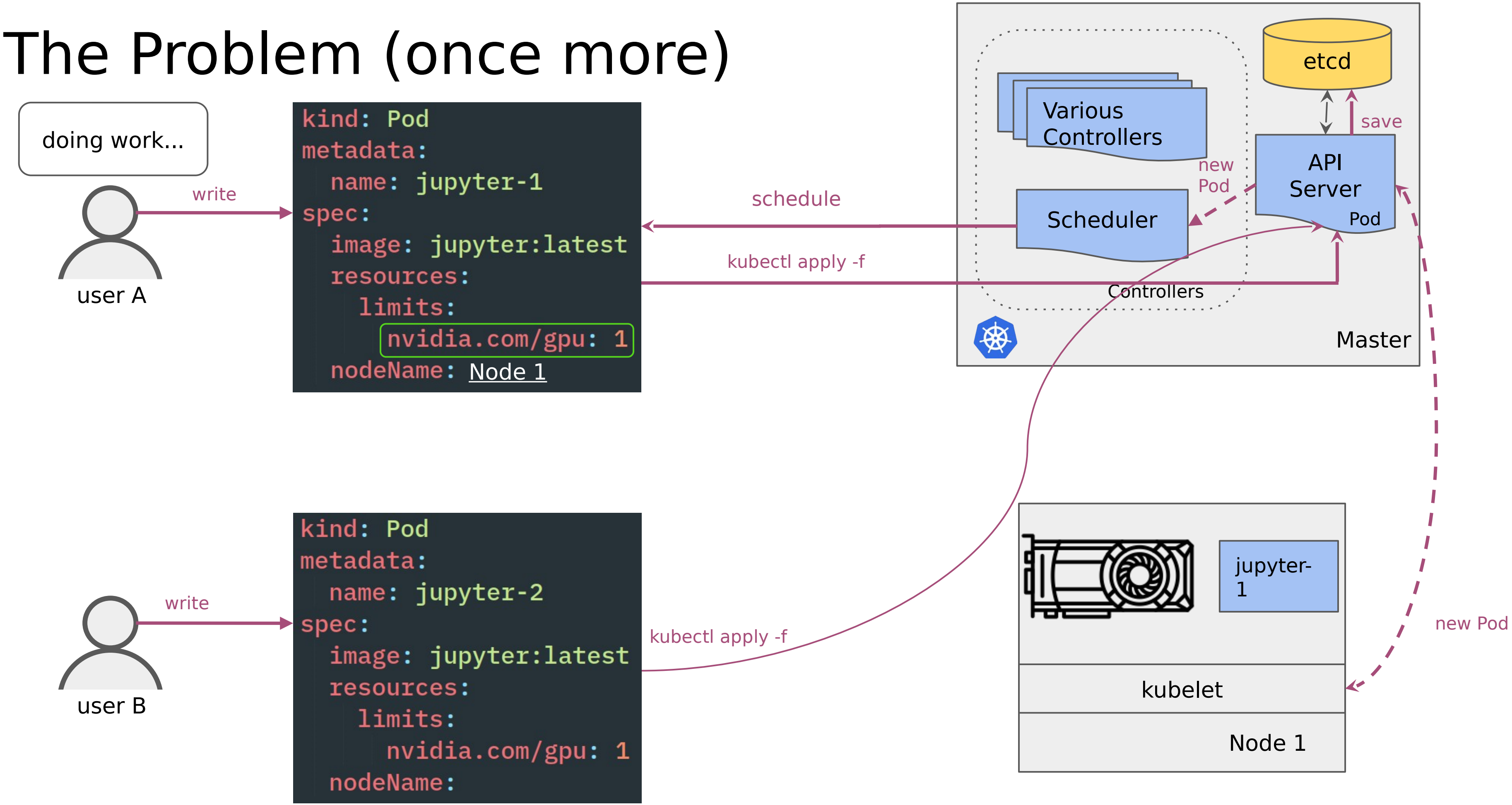

```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName: Node 1
```



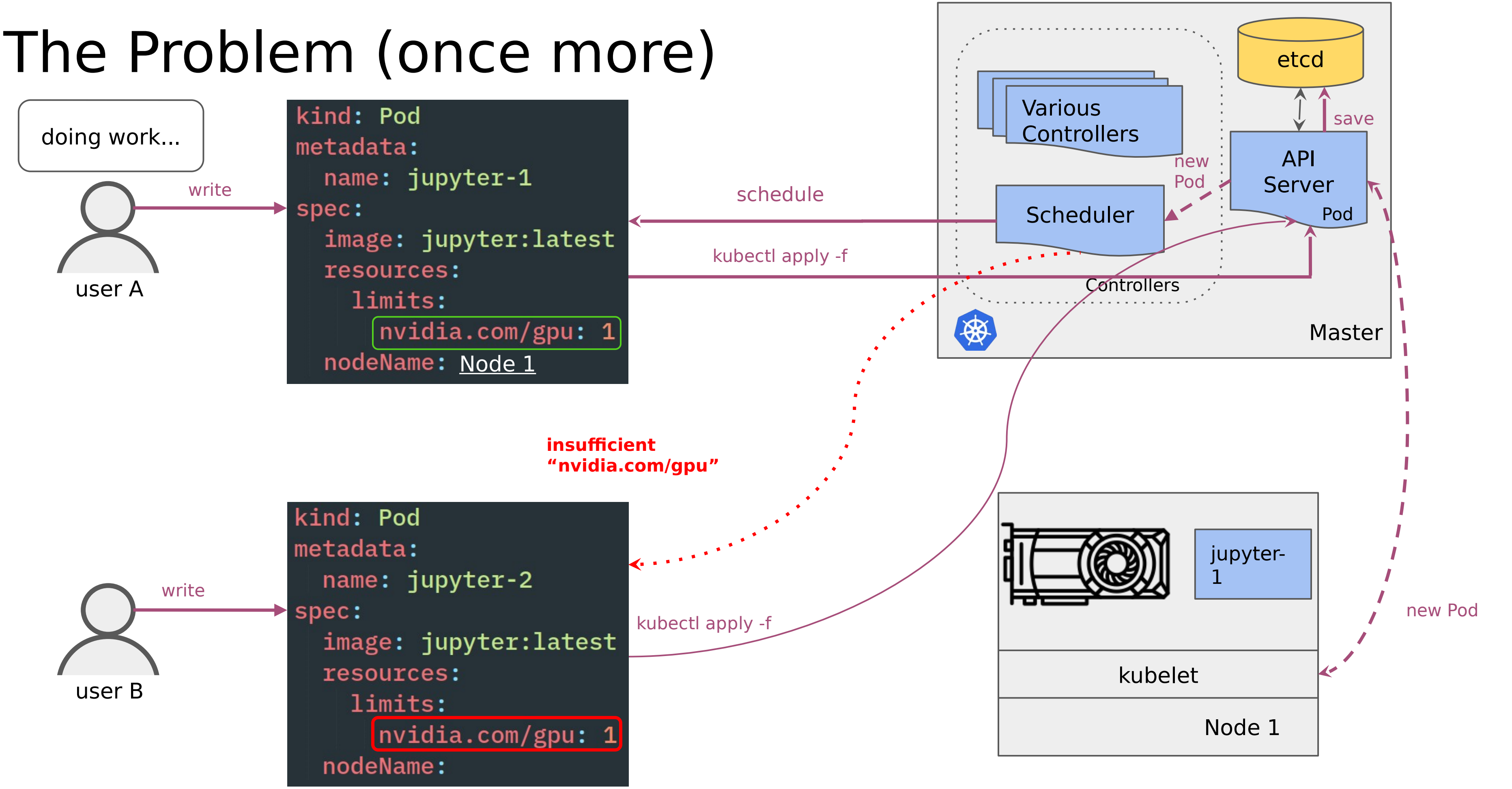

```yaml
kind: Pod
metadata:
  name: jupyter-2
spec:
  image: jupyter:latest
  resources:
    limits:
      nvidia.com/gpu: 1
  nodeName:
```



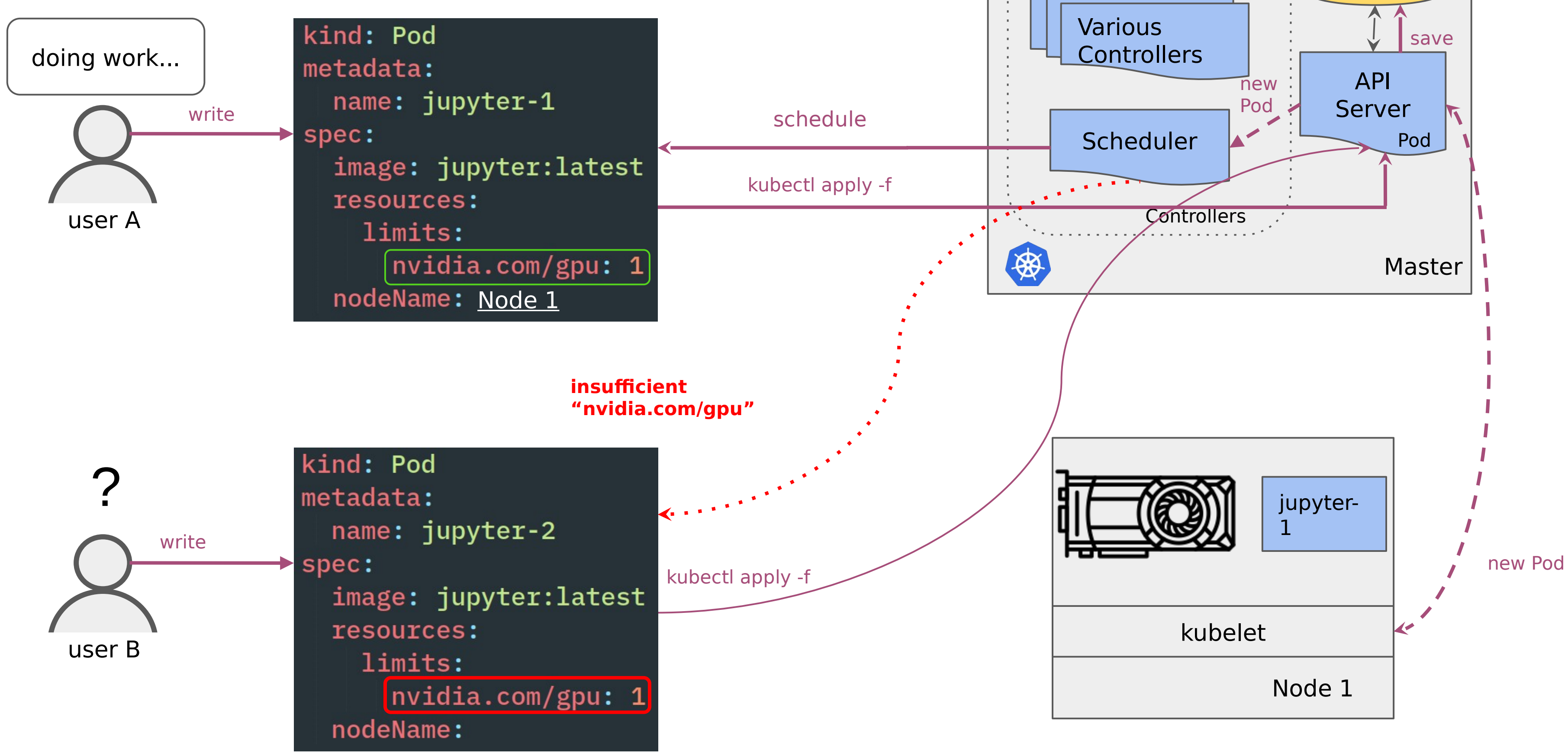
The Problem (once more)



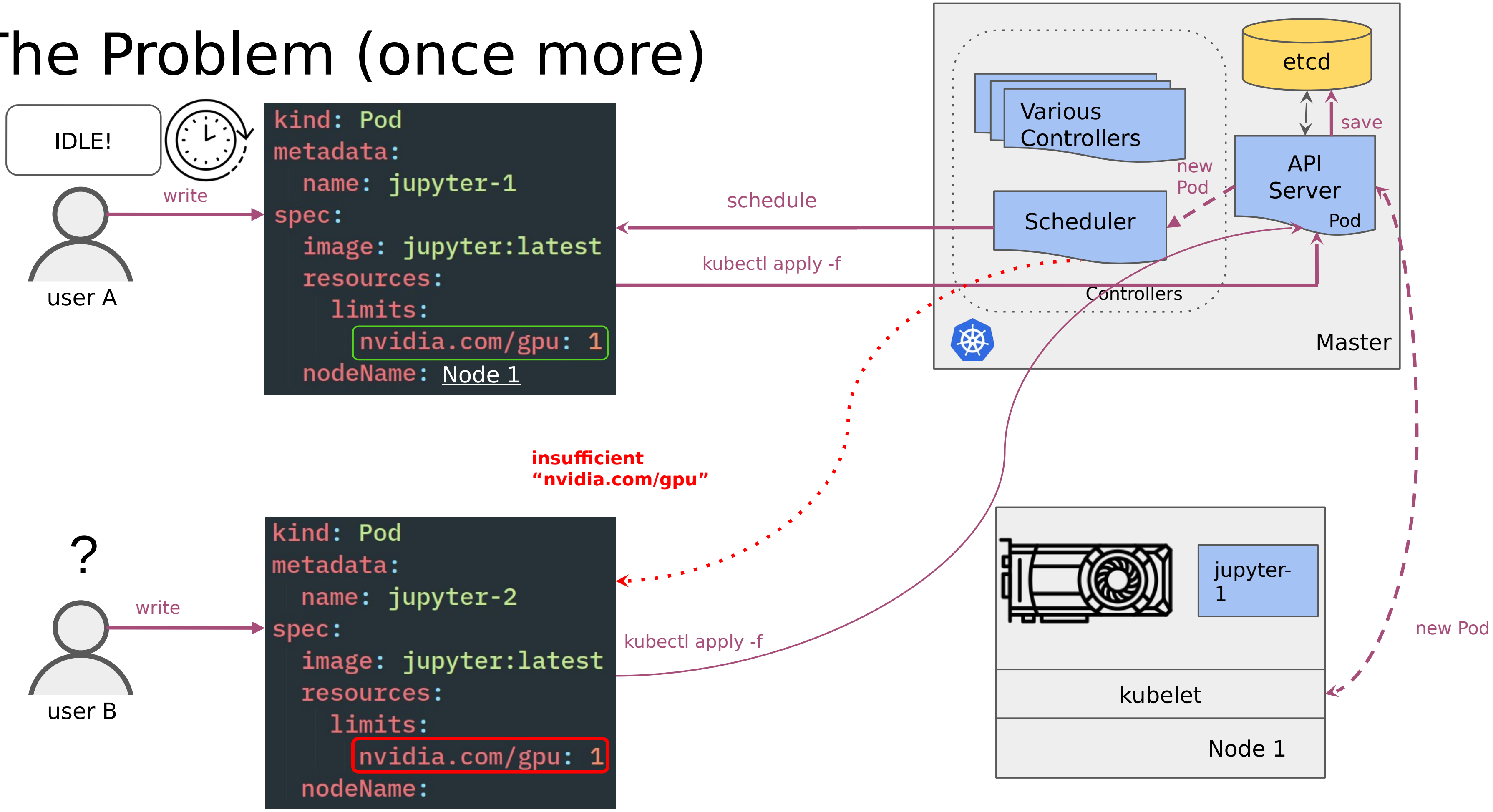
The Problem (once more)



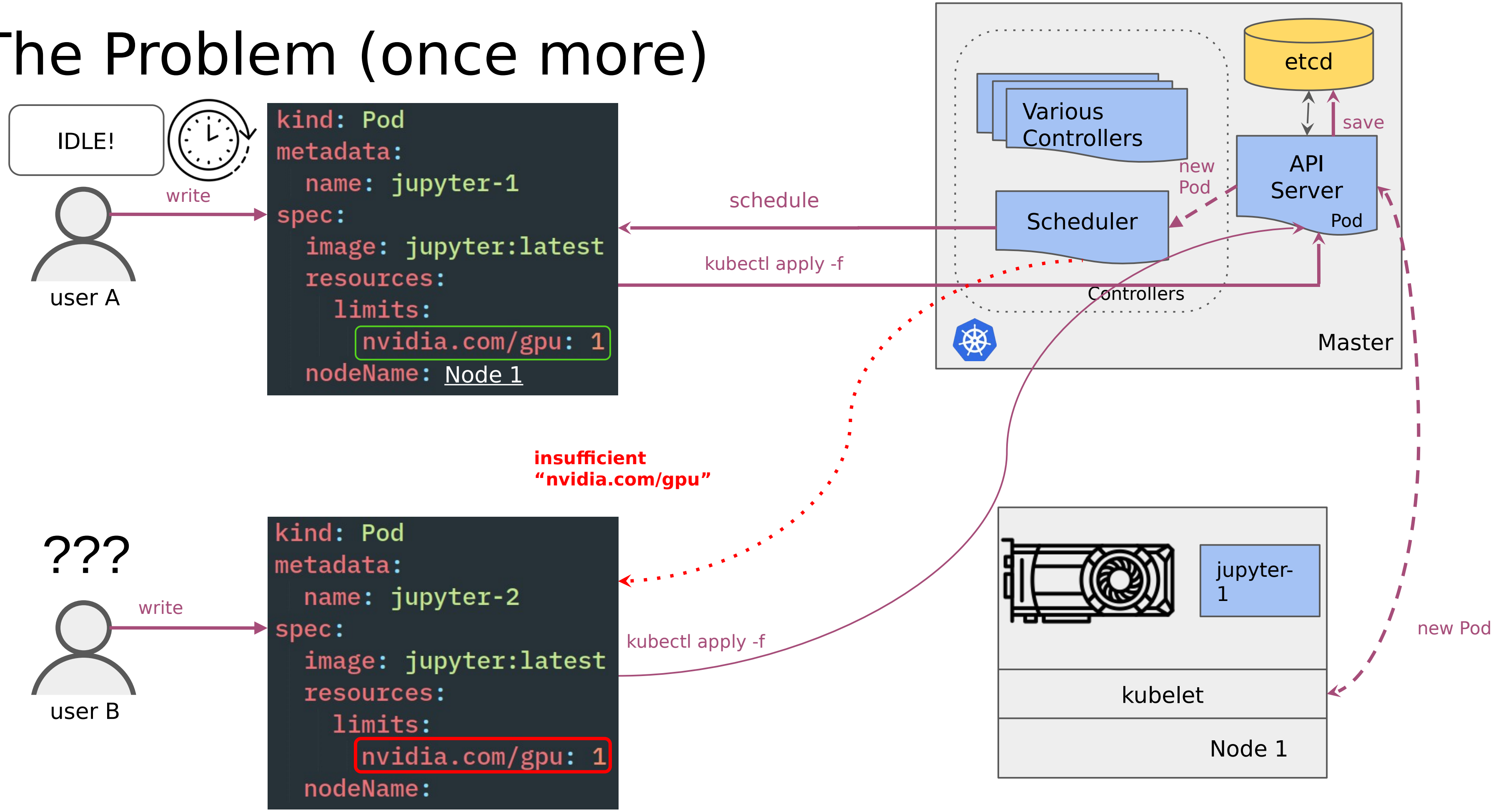
The Problem (once more)



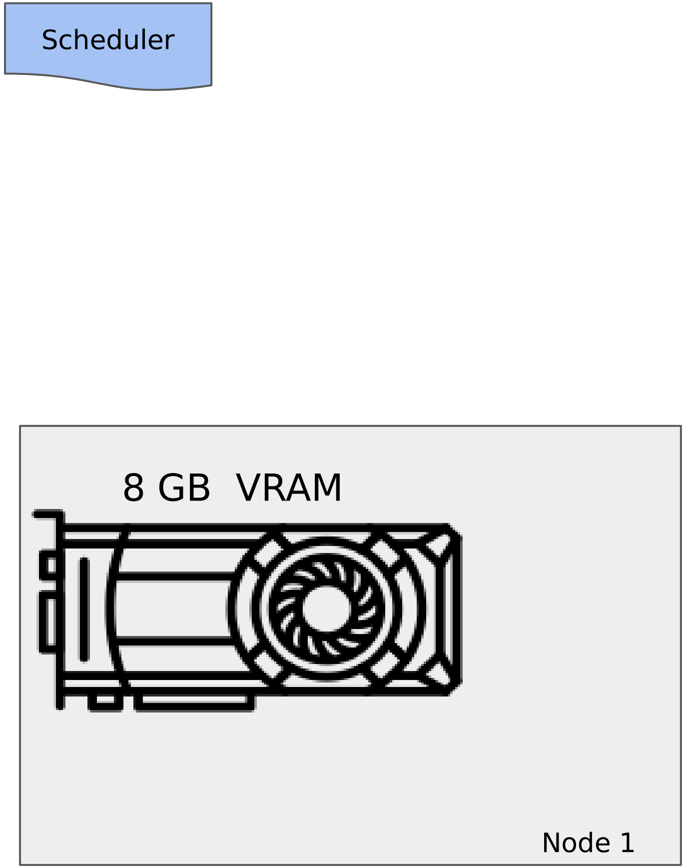
The Problem (once more)



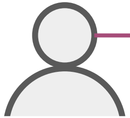
The Problem (once more)



Existing Approaches



Existing Approaches



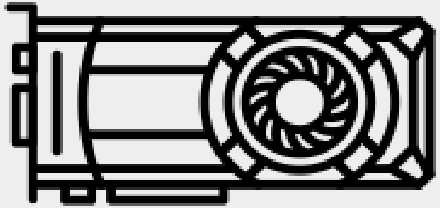
write

user
A

```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      aliyun.com/gpu-mem: 4
  nodeName:
```

Scheduler

8 GB VRAM



Node 1

Existing Approaches

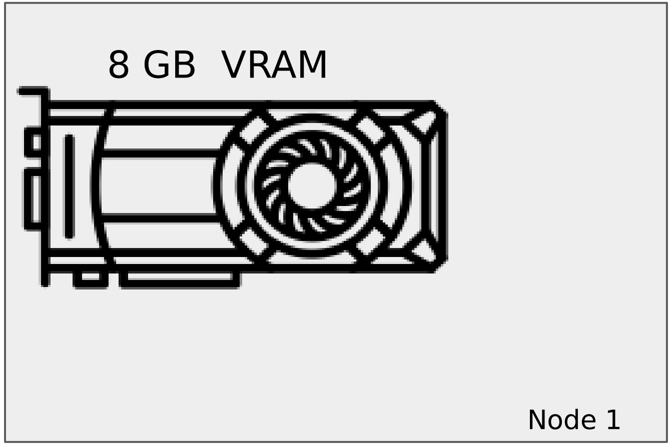
user A

write

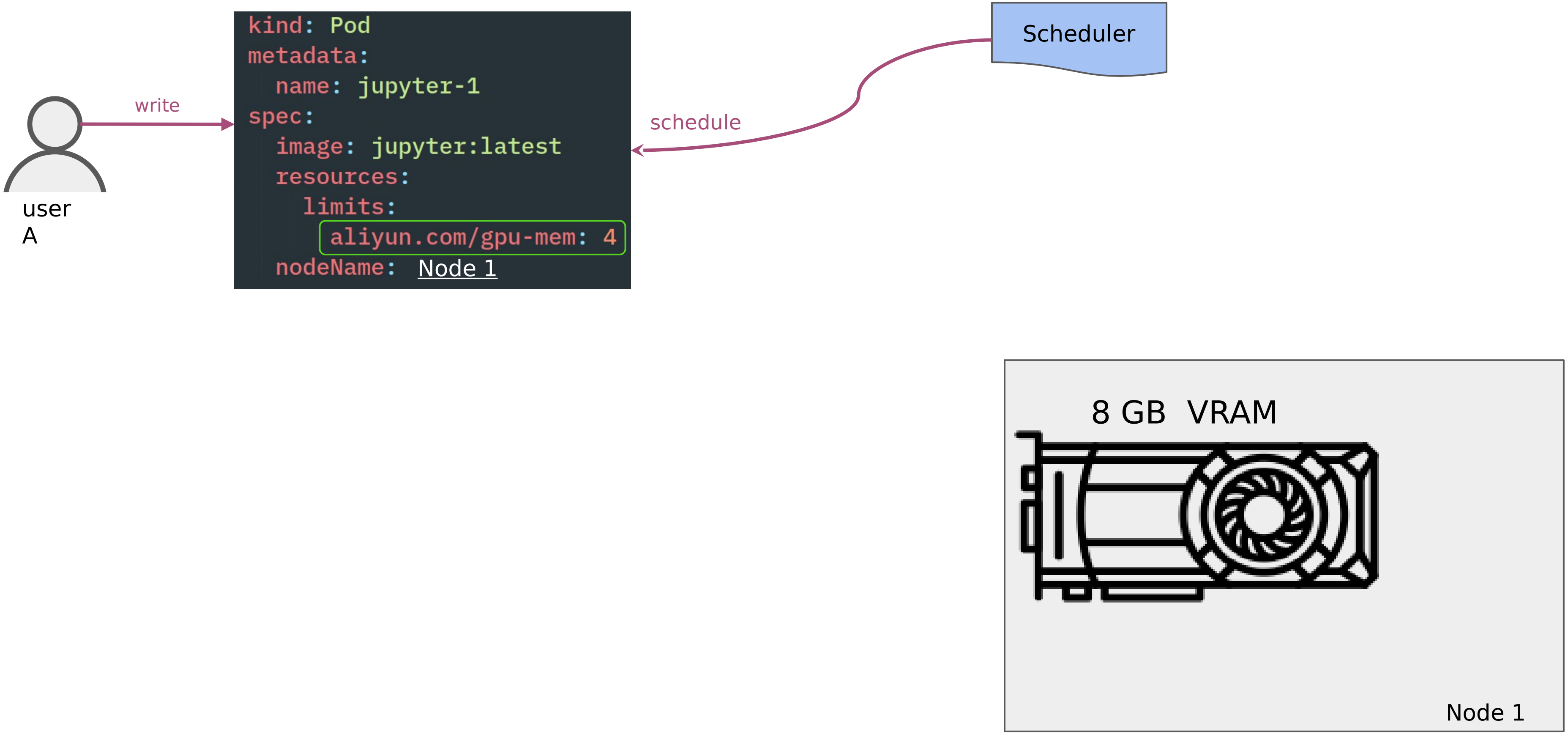
```yaml
kind: Pod
metadata:
  name: jupyter-1
spec:
  image: jupyter:latest
  resources:
    limits:
      aliyun.com/gpu-mem: 4
  nodeName:
```

schedule

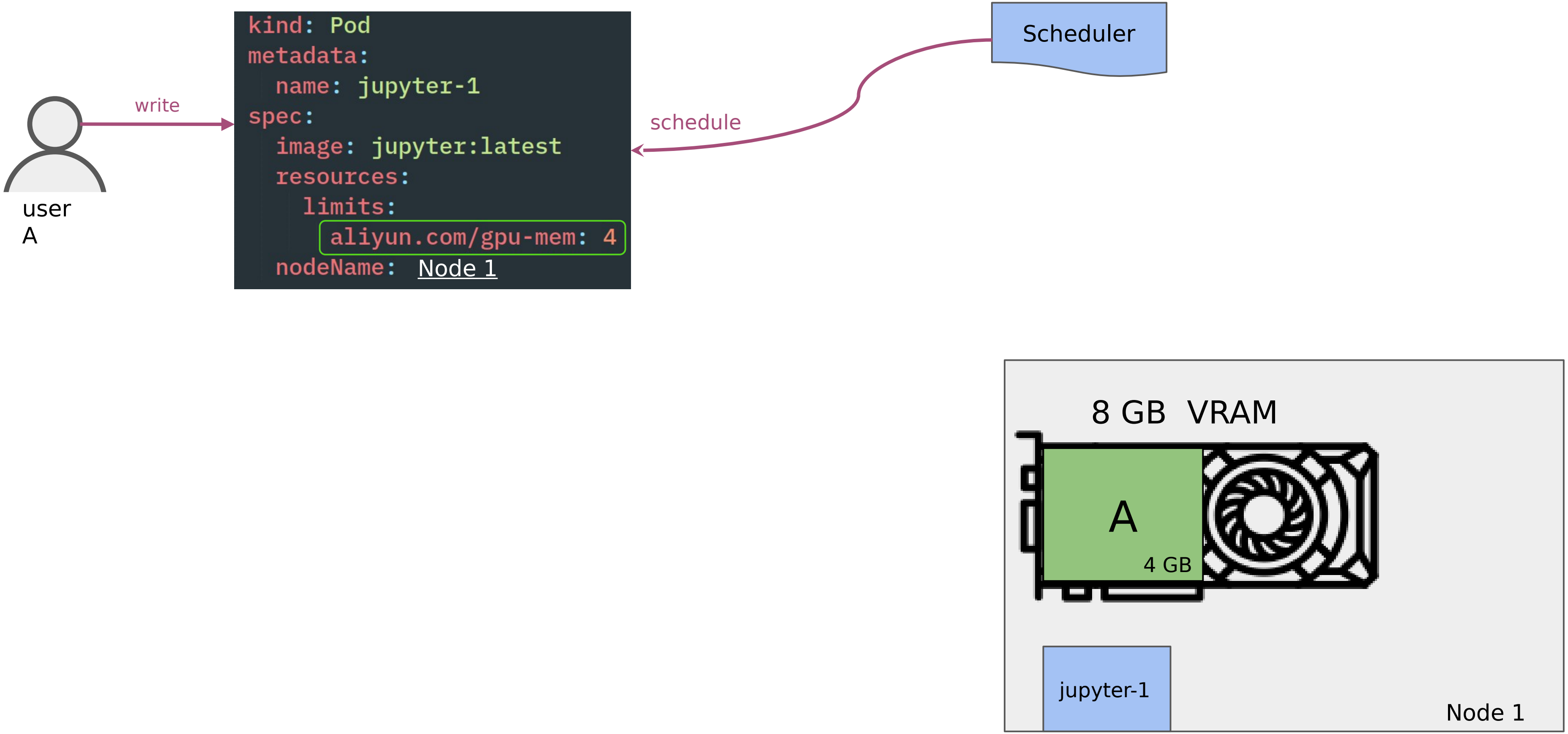
Scheduler



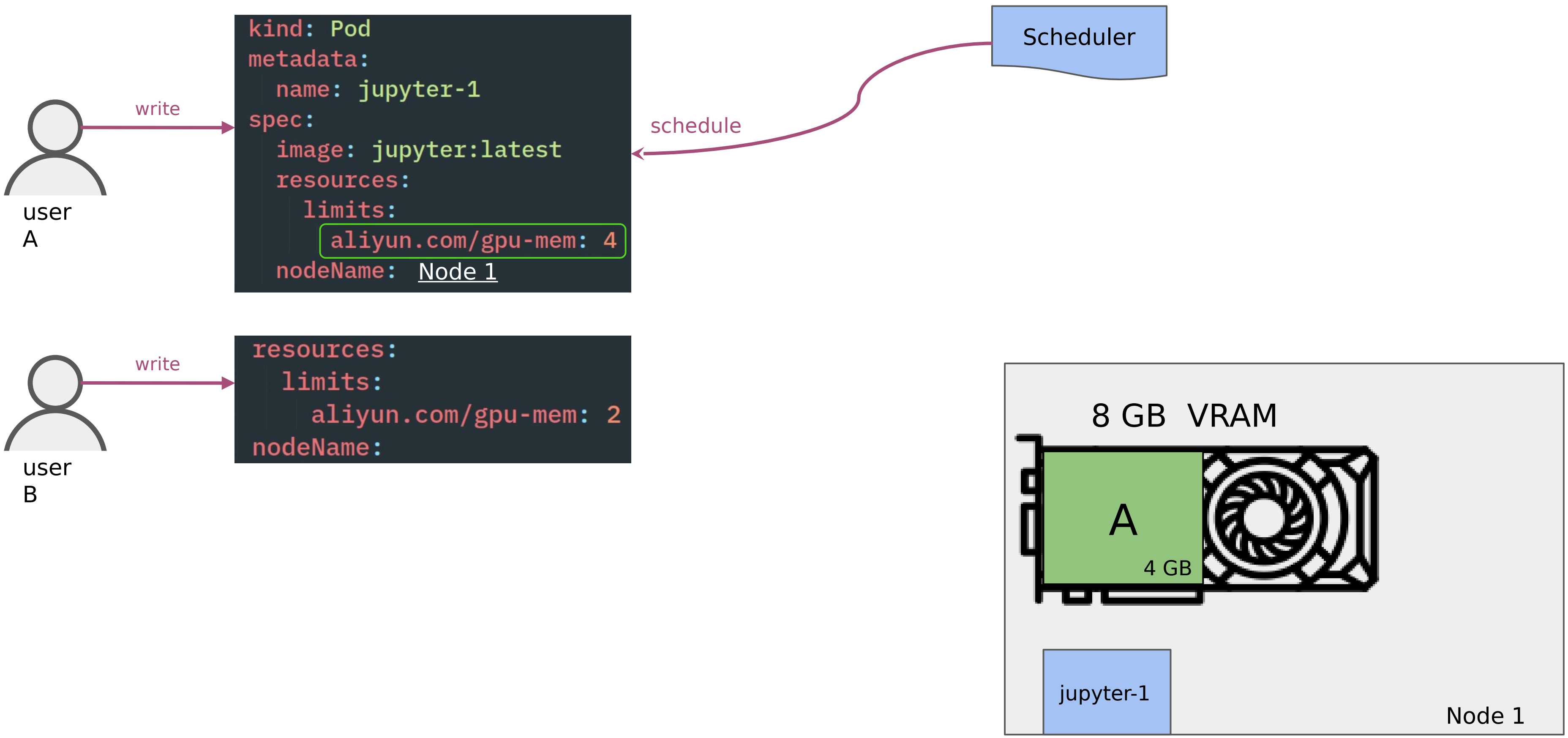
Existing Approaches



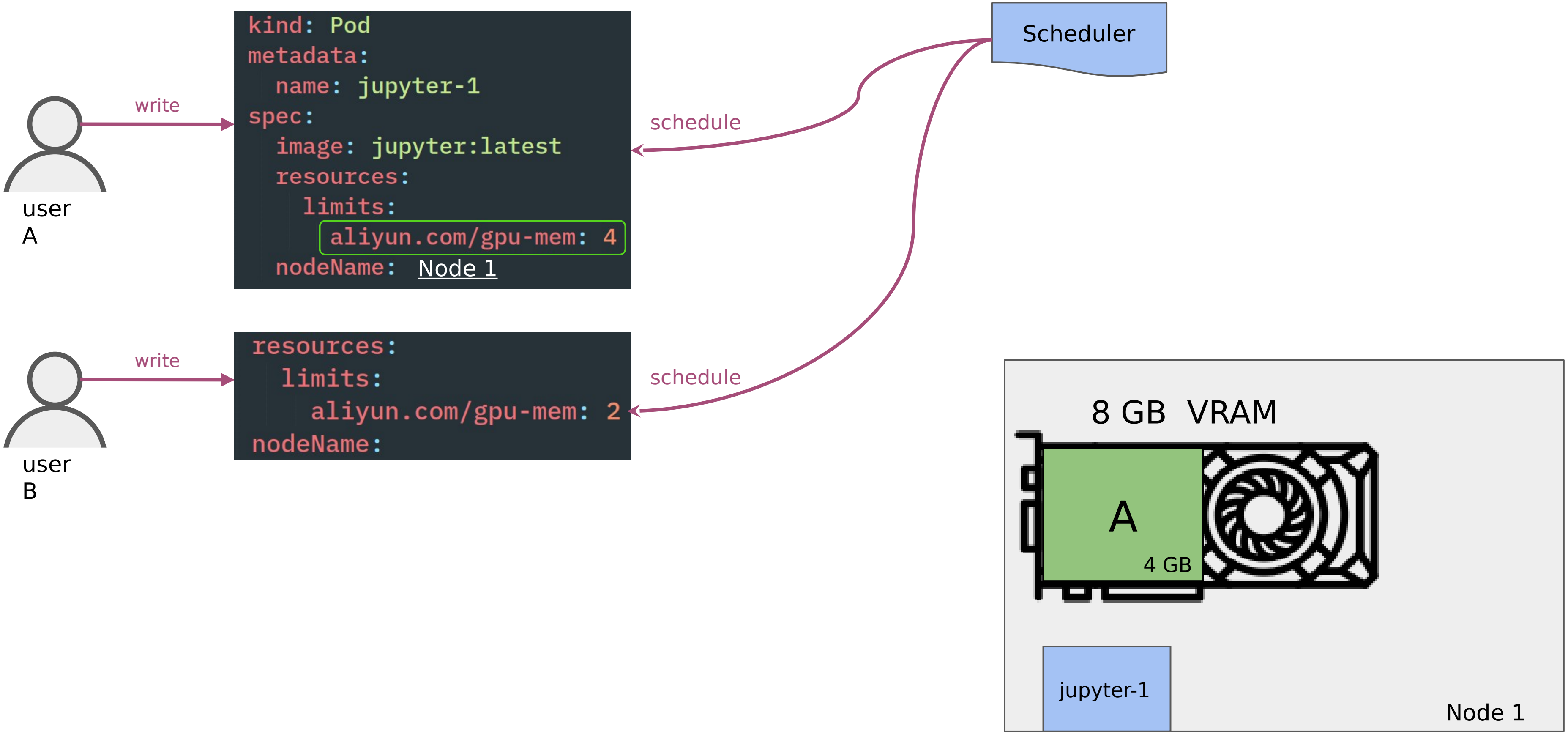
Existing Approaches



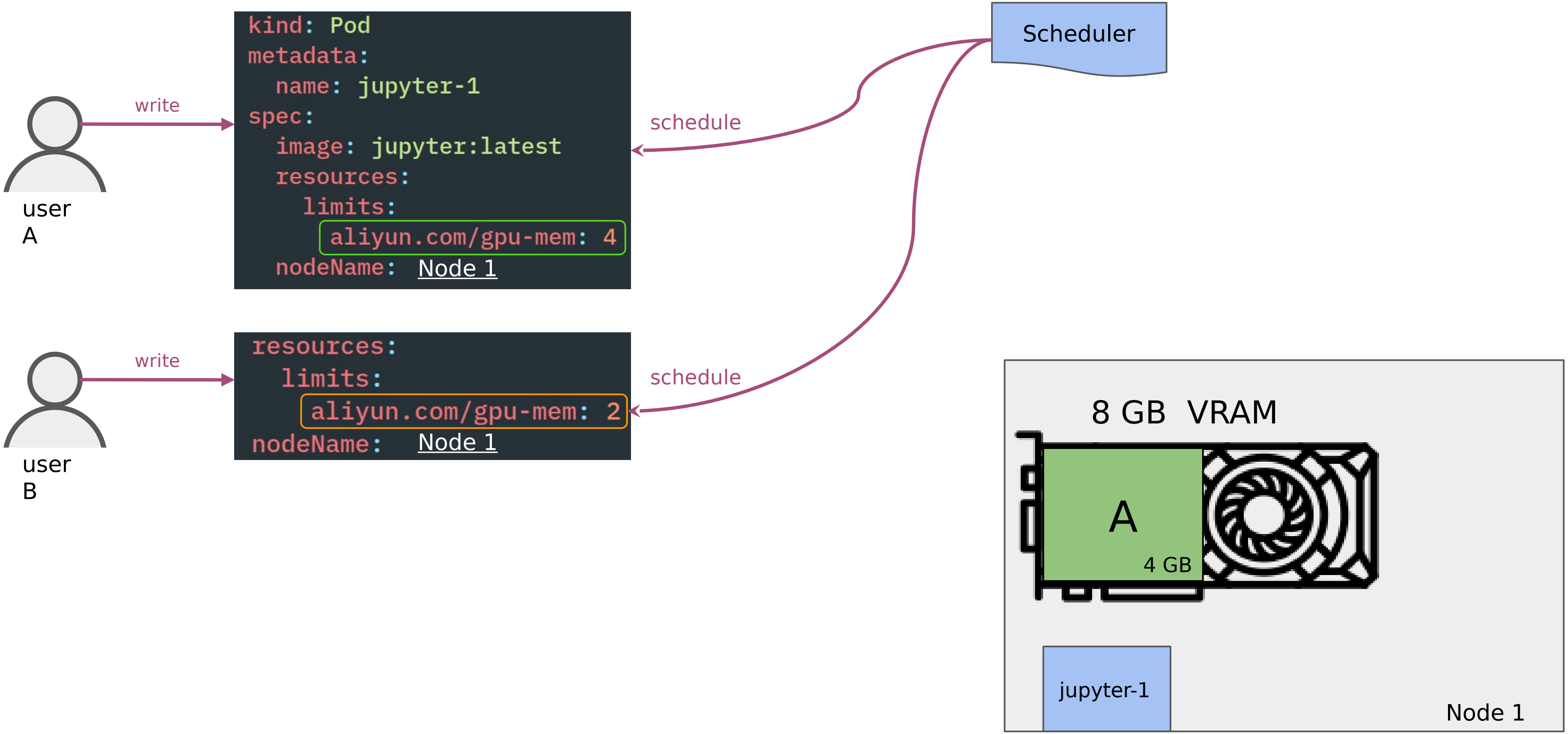
Existing Approaches



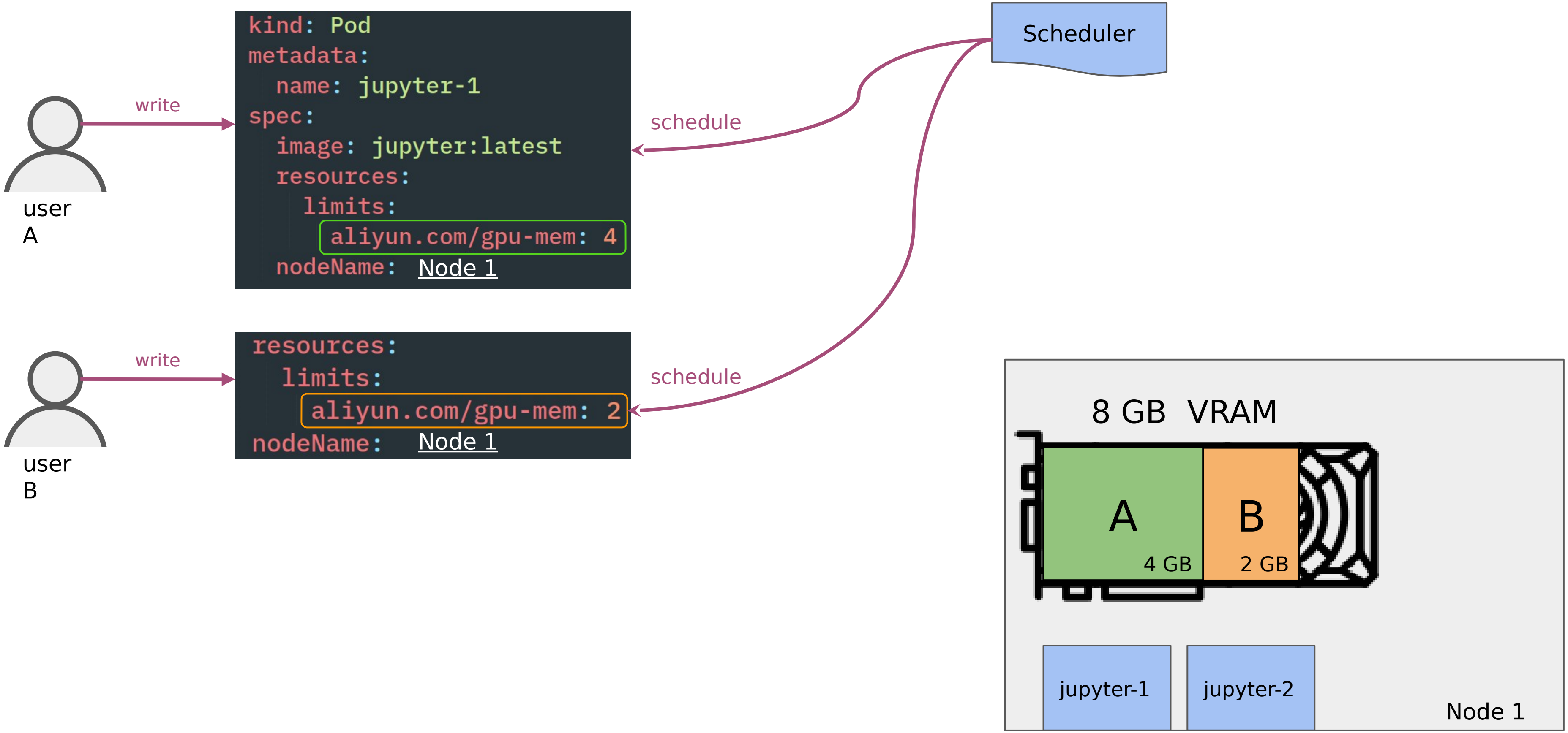
Existing Approaches



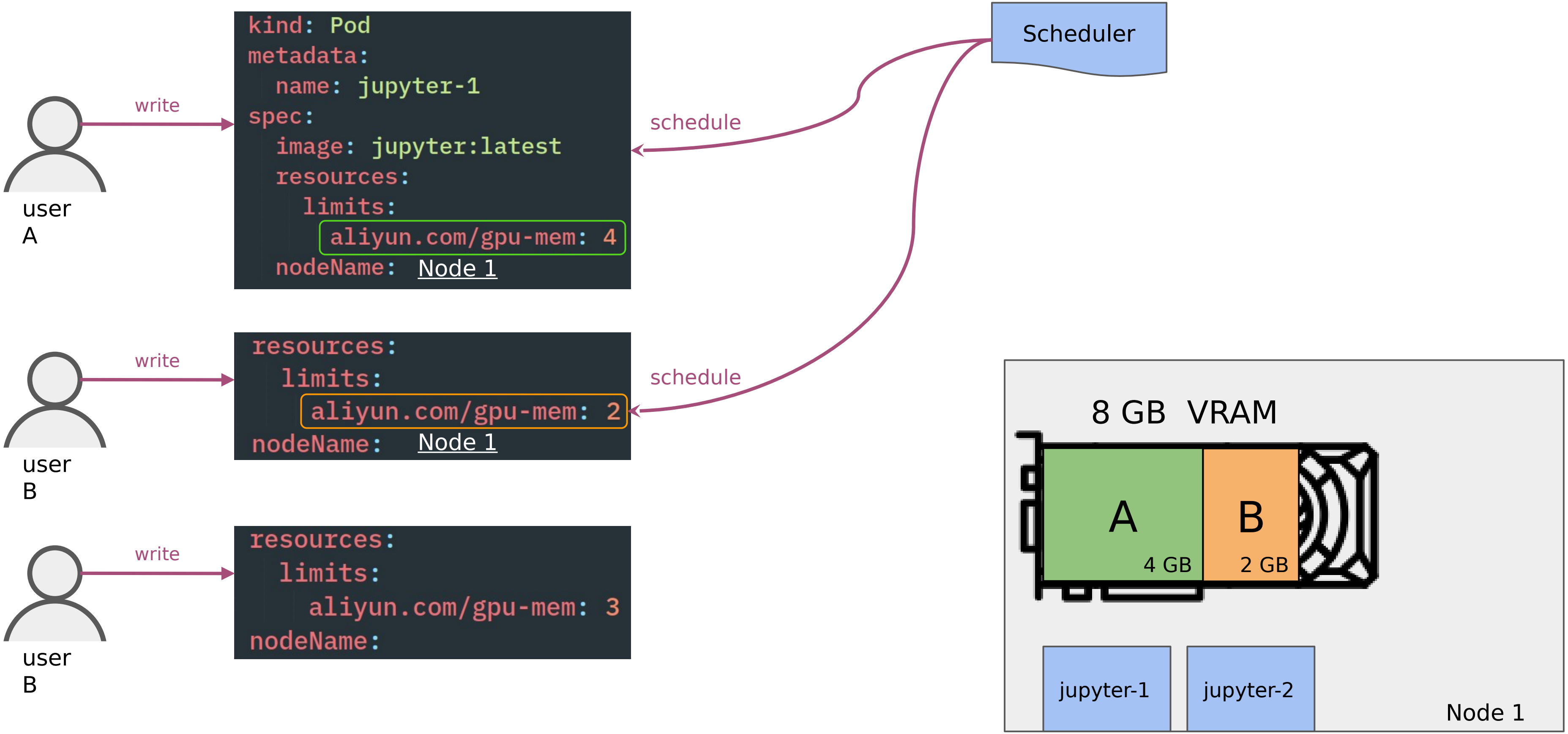
Existing Approaches



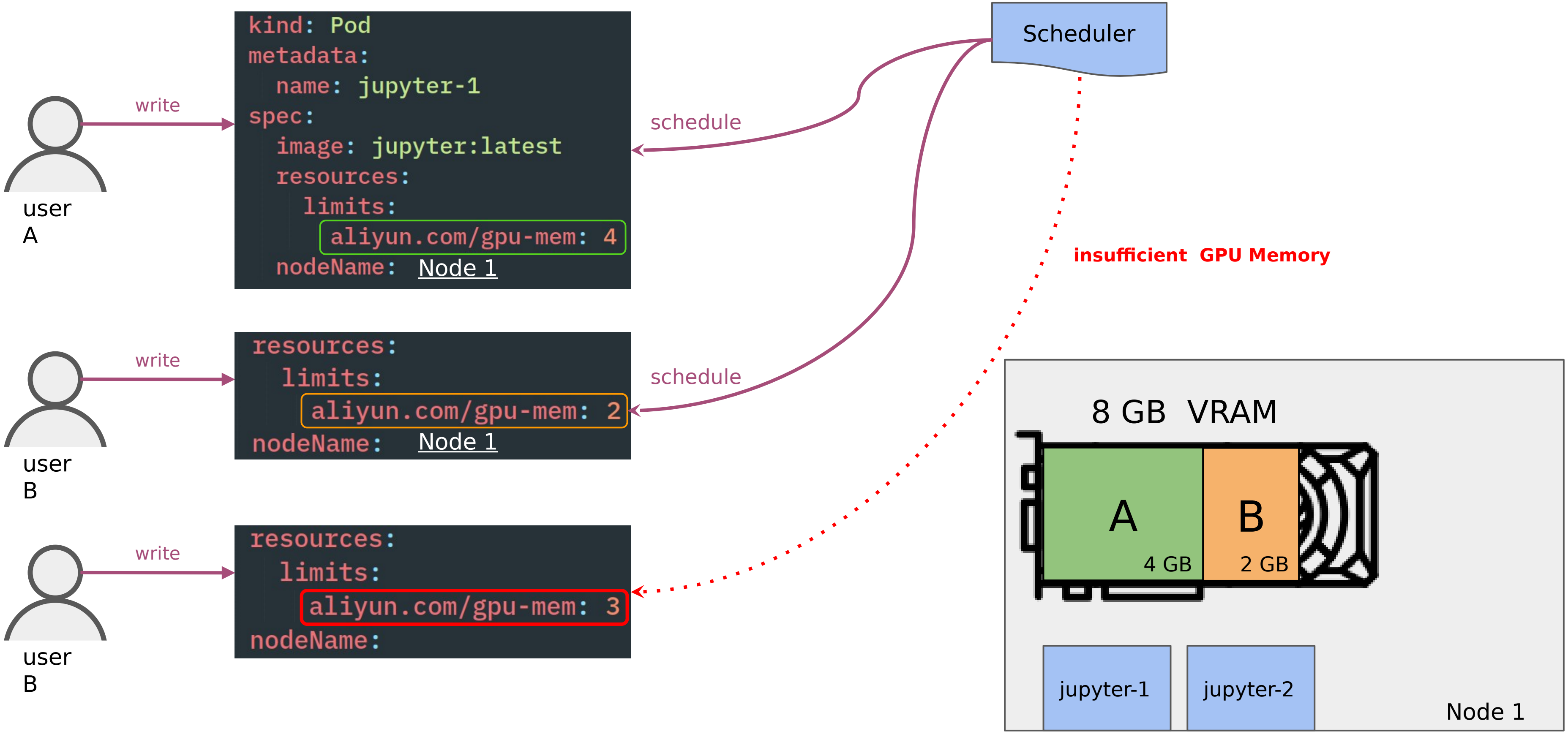
Existing Approaches



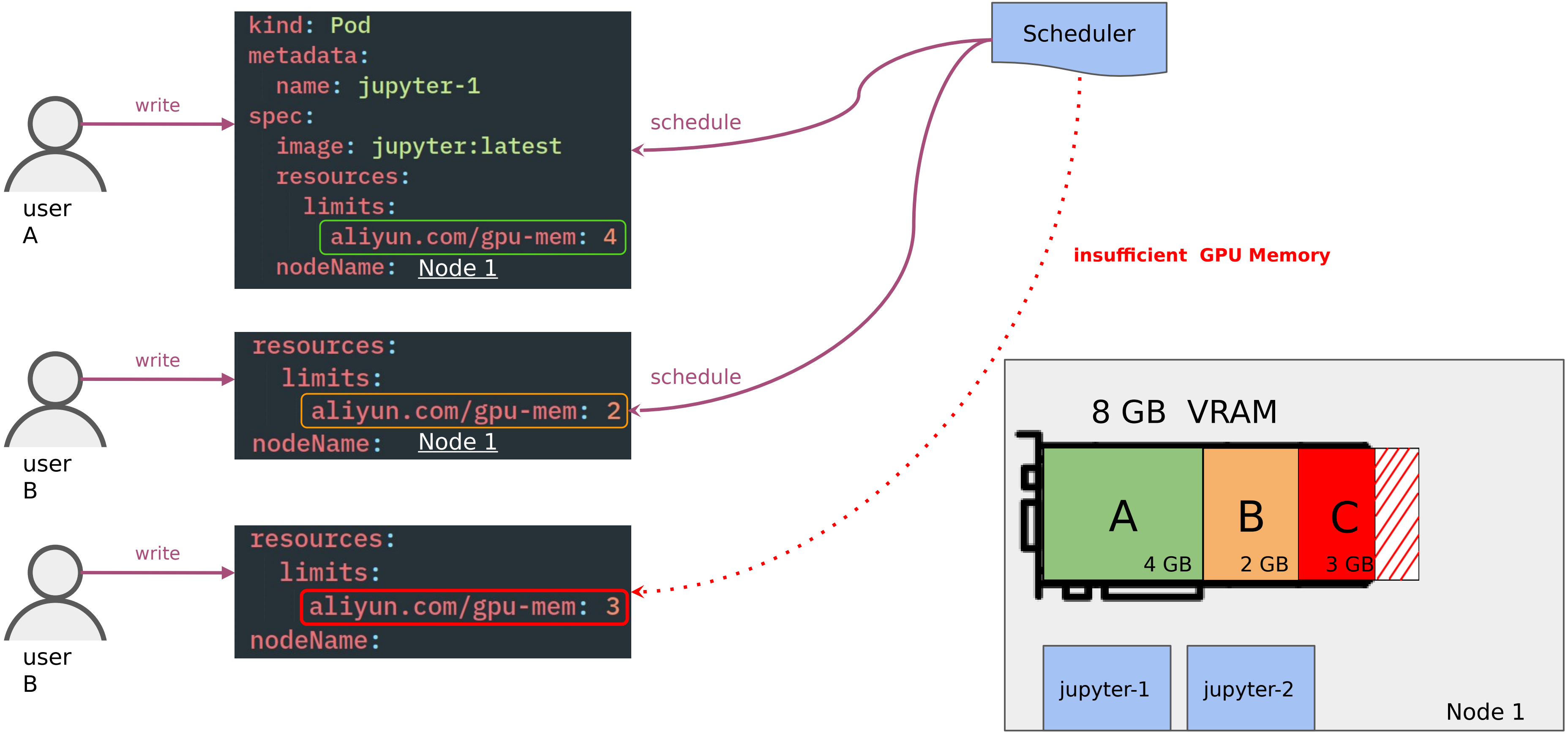
Existing Approaches



Existing Approaches



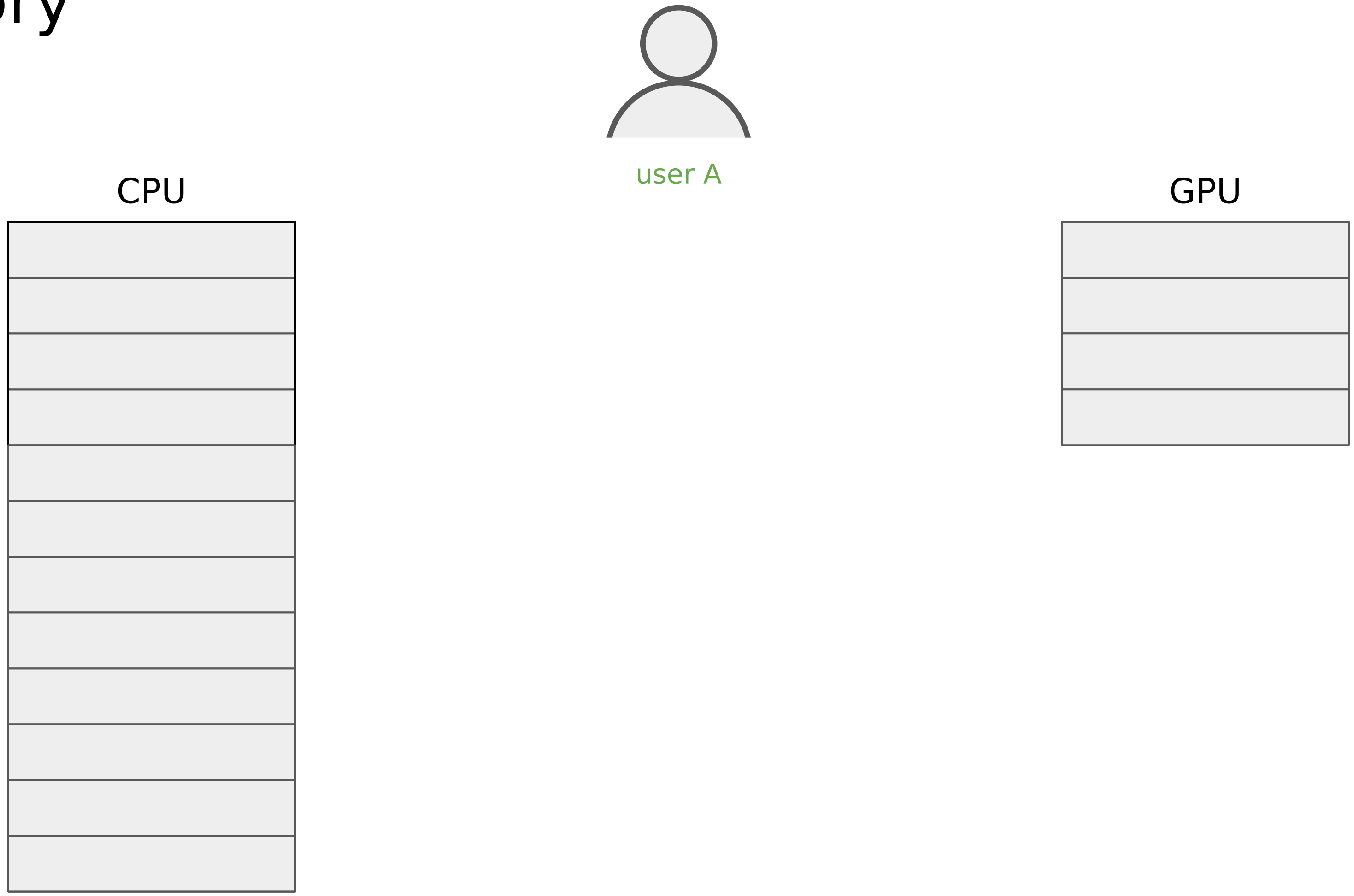
Existing Approaches



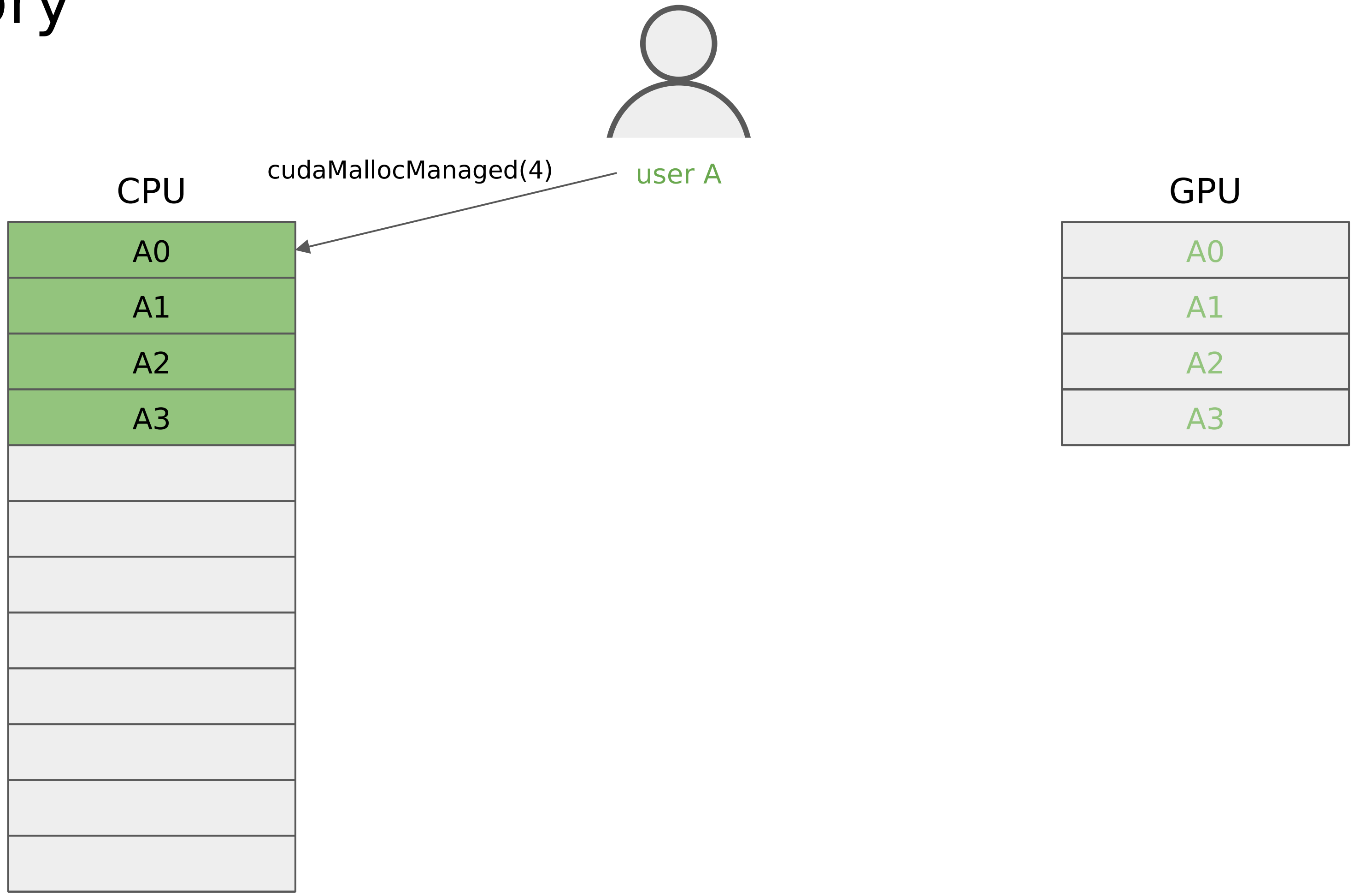
Existing Approaches

- Aliyun Scheduler Extender
  - GPUs no longer exclusively assigned to Pods
  - users specify GPU memory requests
  - uses GPU memory to bin pack Pods in Kubernetes
  - does not enforce memory limits (only used for scheduling)
- Kubeshare (HPDC '20)
  - similar to Aliyun w.r.t. the scheduling part
  - enforces GPU memory limits (assigns a memory slice to each process)
  - wraps CUDA API to keep track of how much memory each process allocates

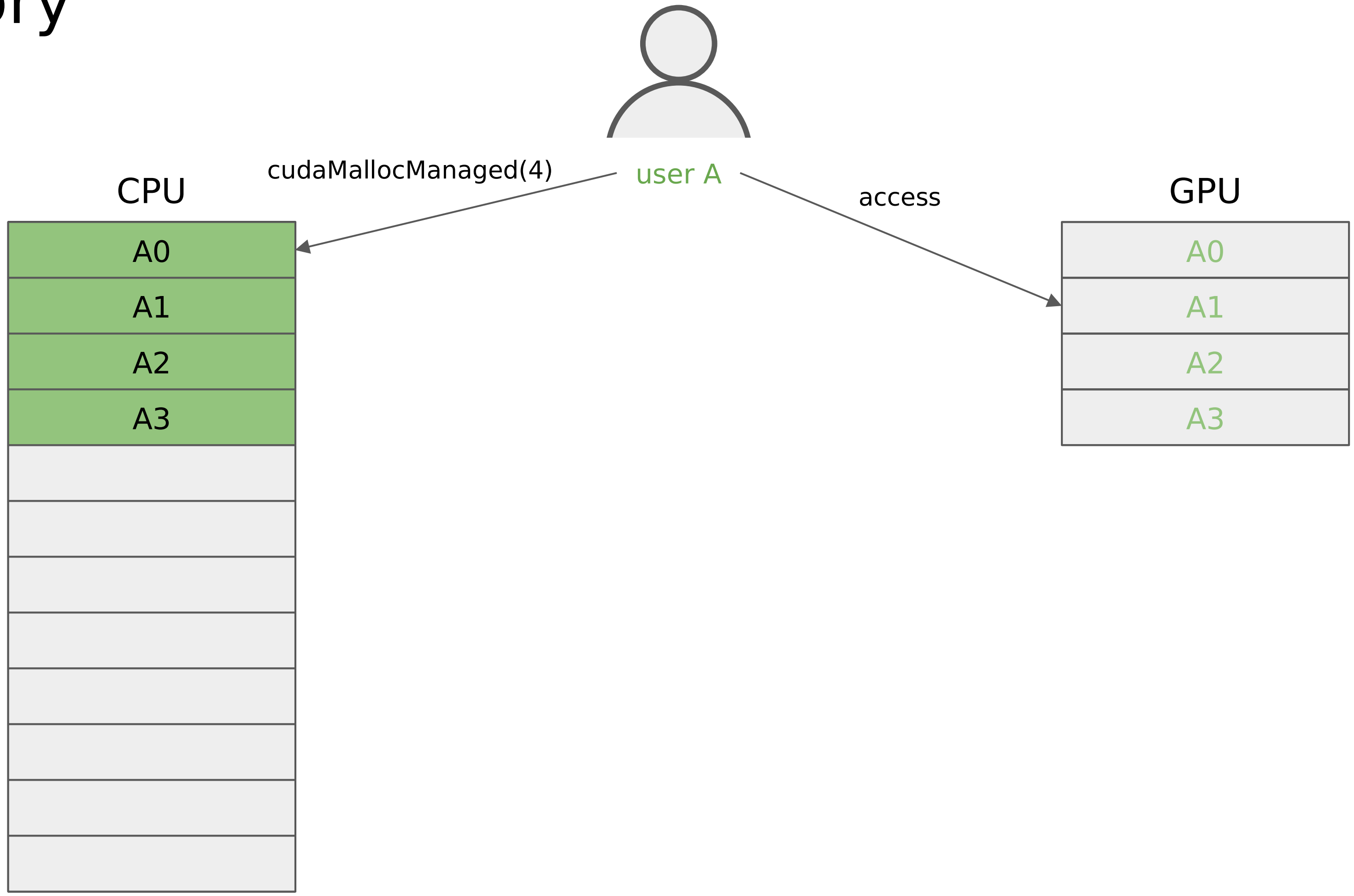
Memory



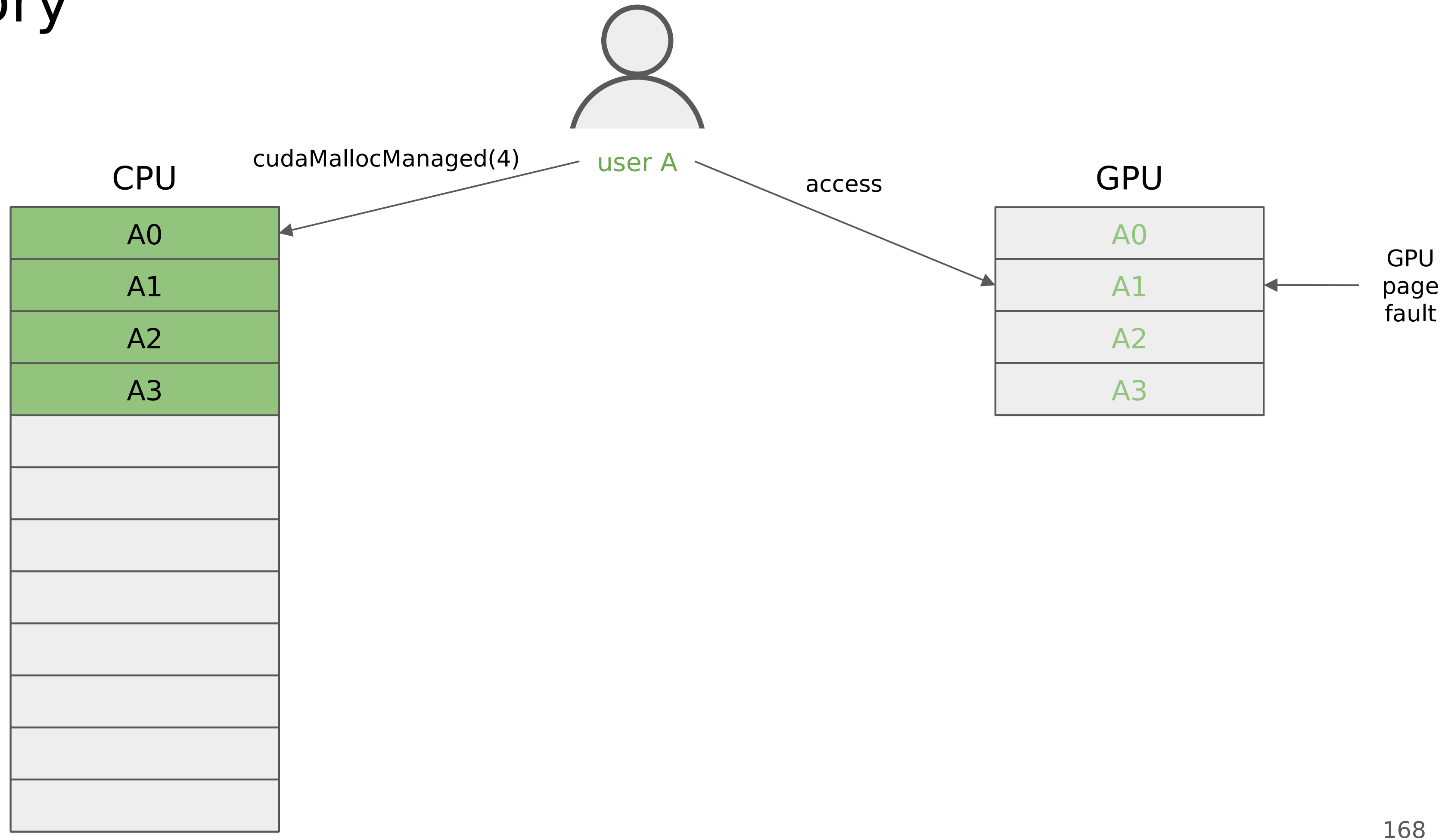
Memory



Memory

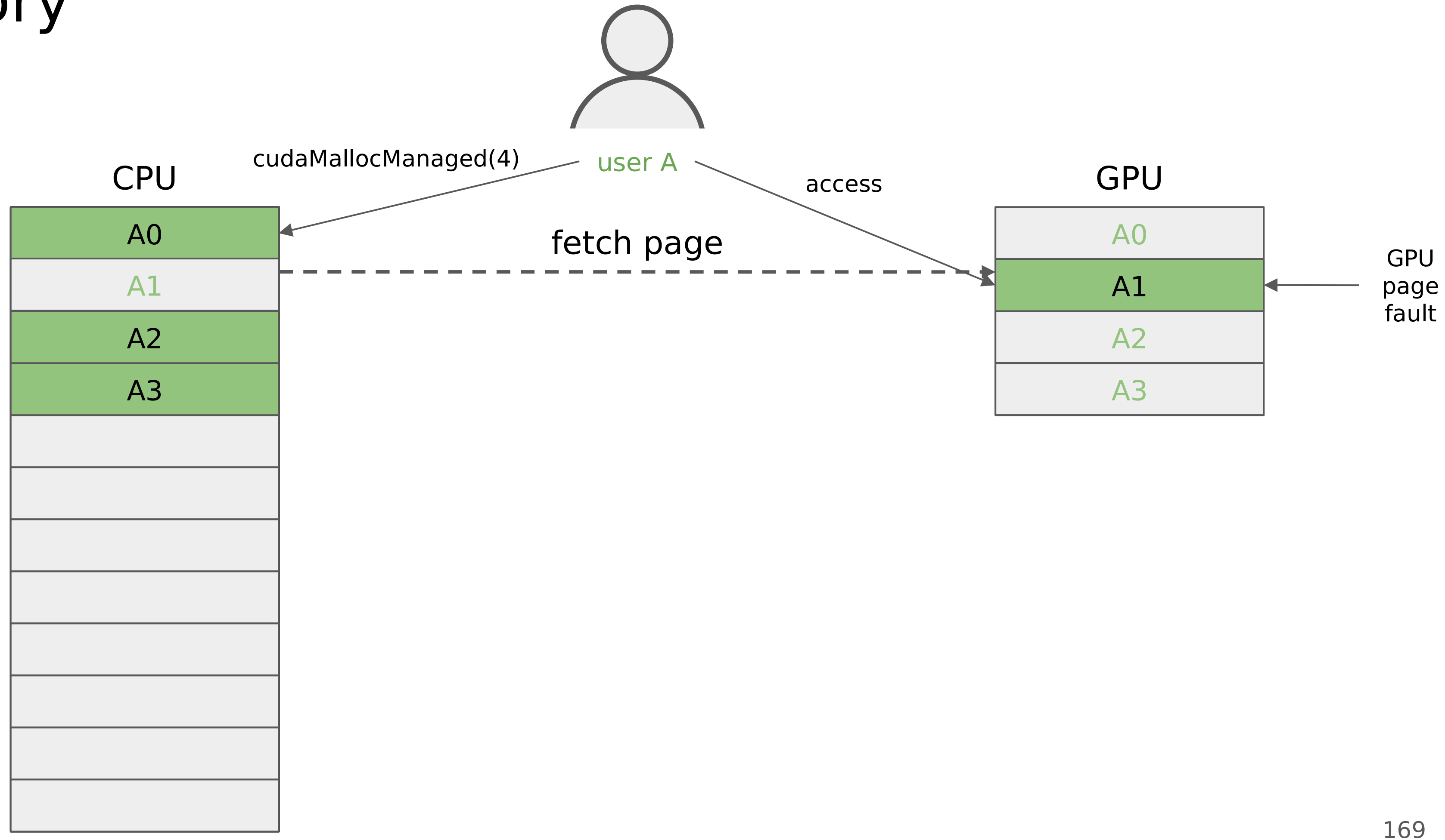

user A
cudaMallocManaged(4)
access
CPU
A0
A1
A2
A3
GPU
A0
A1
A2
A3

Memory



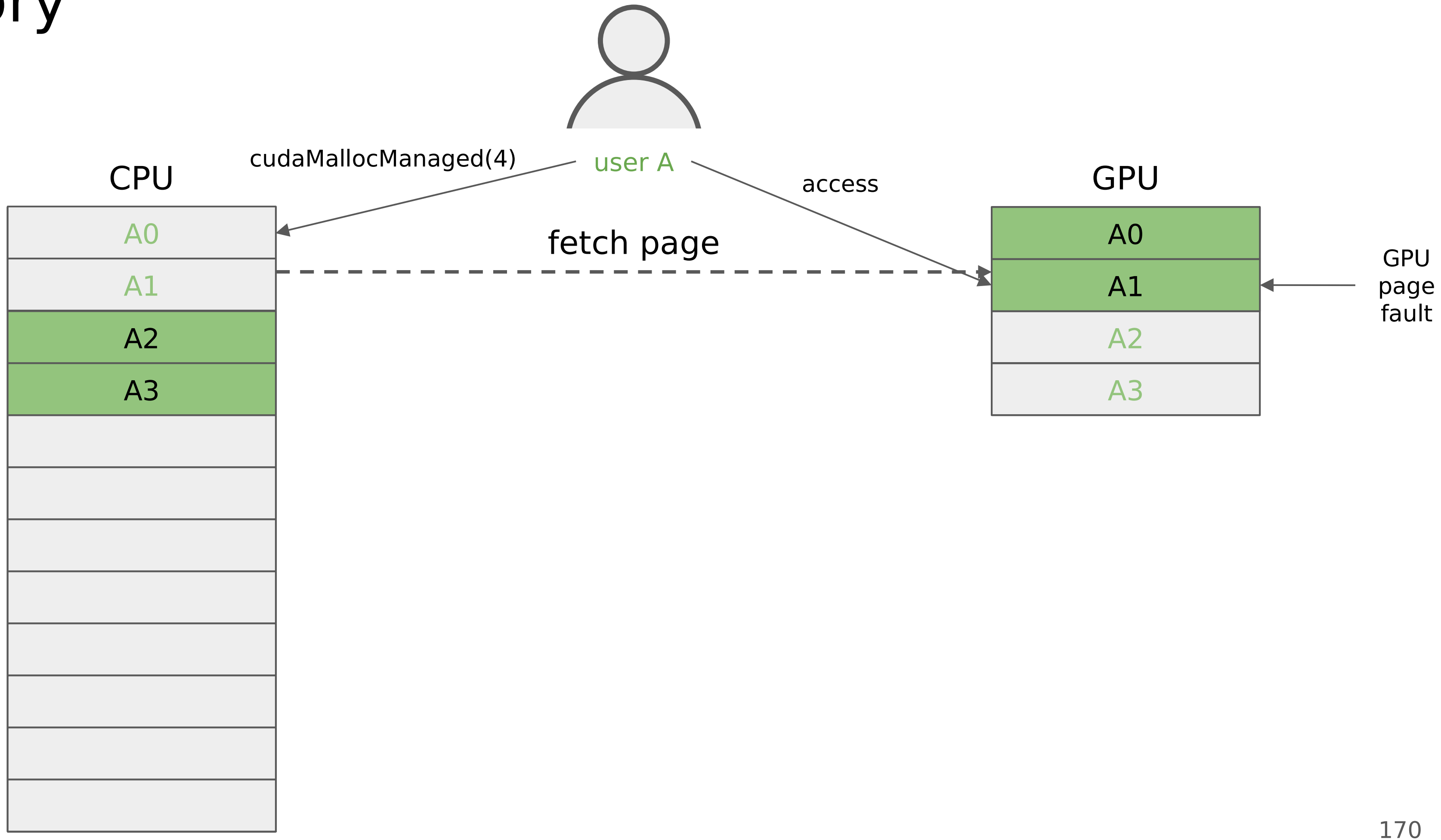
user A
cudaMallocManaged(4)
access
CPU
A0
A1
A2
A3
GPU
A0
A1
A2
A3
GPU
page
fault

Memory

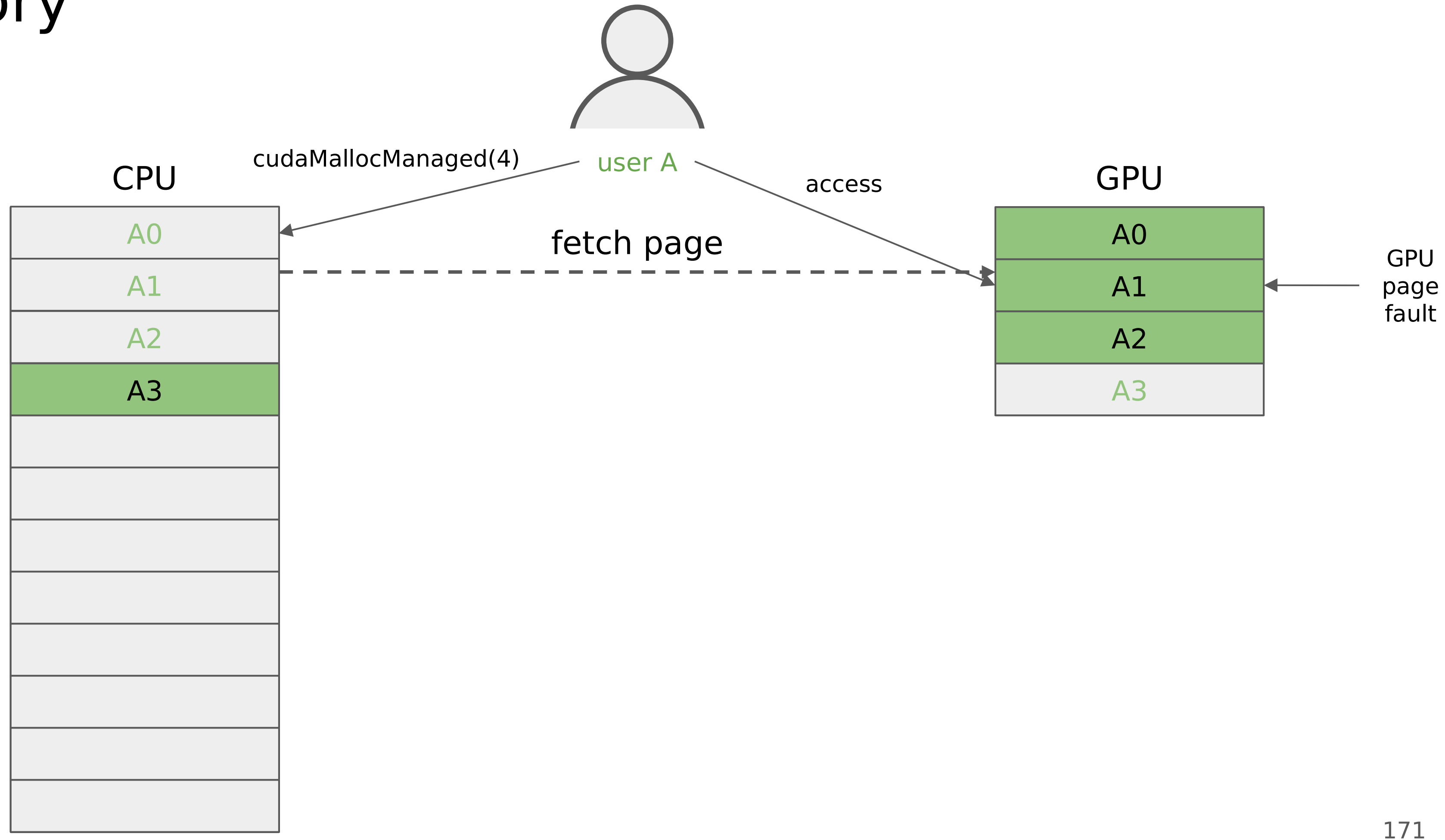


user A
cudaMallocManaged(4)
access
CPU
GPU
A0
A1
A2
A3
fetch page
A0
A1
A2
A3
GPU
page
fault

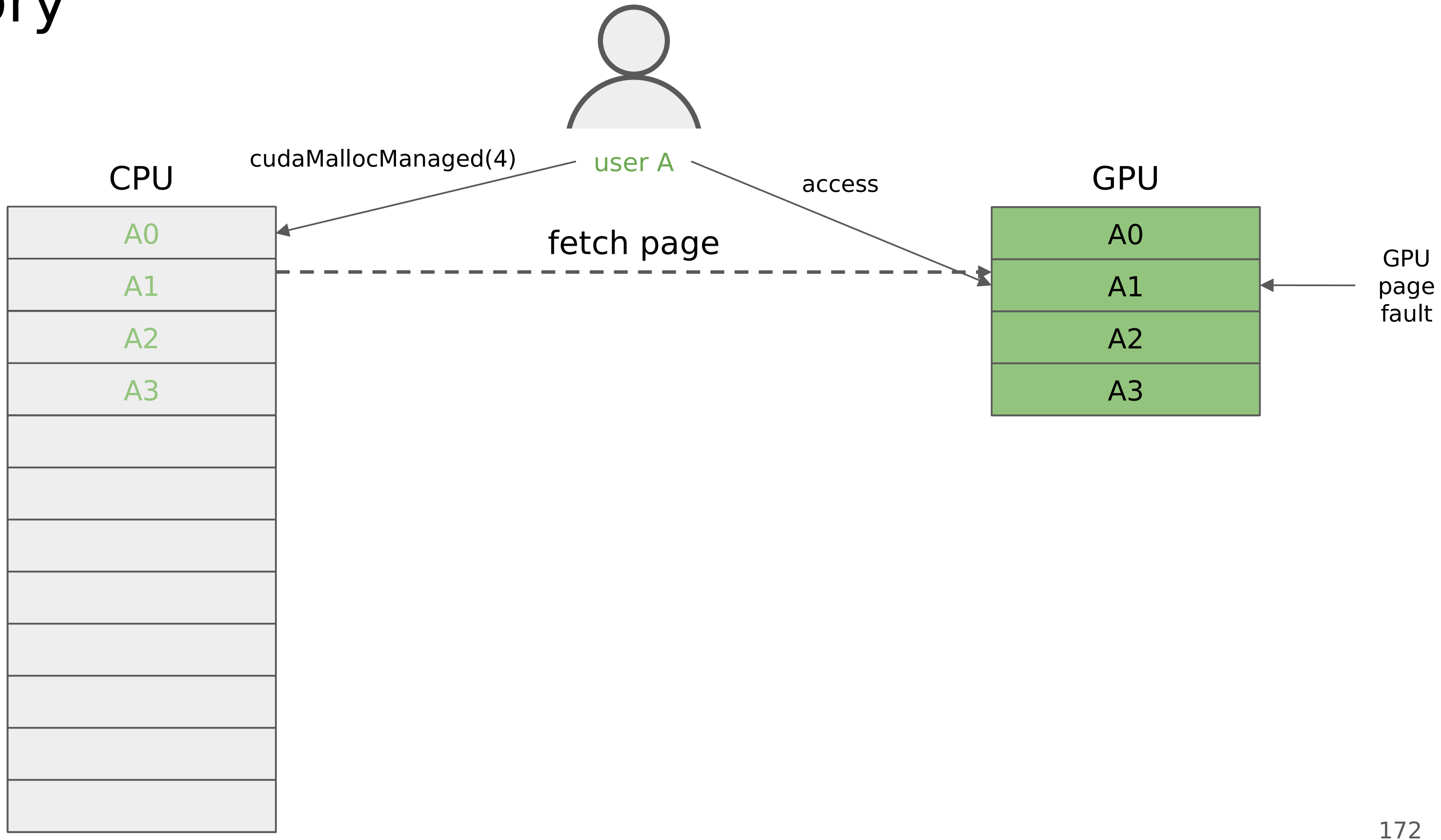
Memory


user A
cudaMallocManaged(4)
access
CPU
GPU
fetch page
A0
A1
A2
A3
A0
A1
A2
A3
GPU page fault

Memory

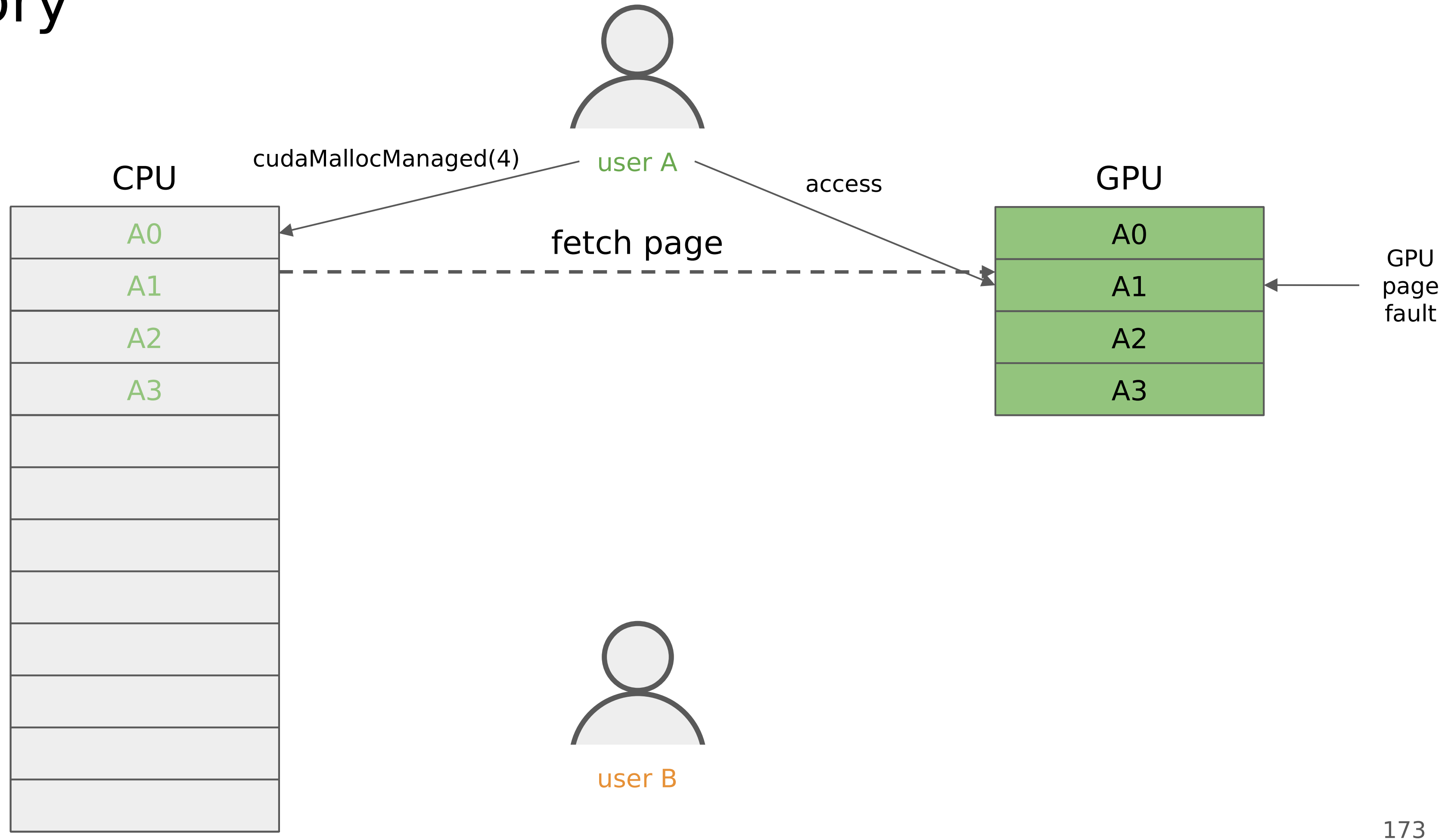

user A
cudaMallocManaged(4)
access
CPU
GPU
A0
A1
A2
A3
fetch page
A0
A1
A2
A3
GPU
page
fault

Memory



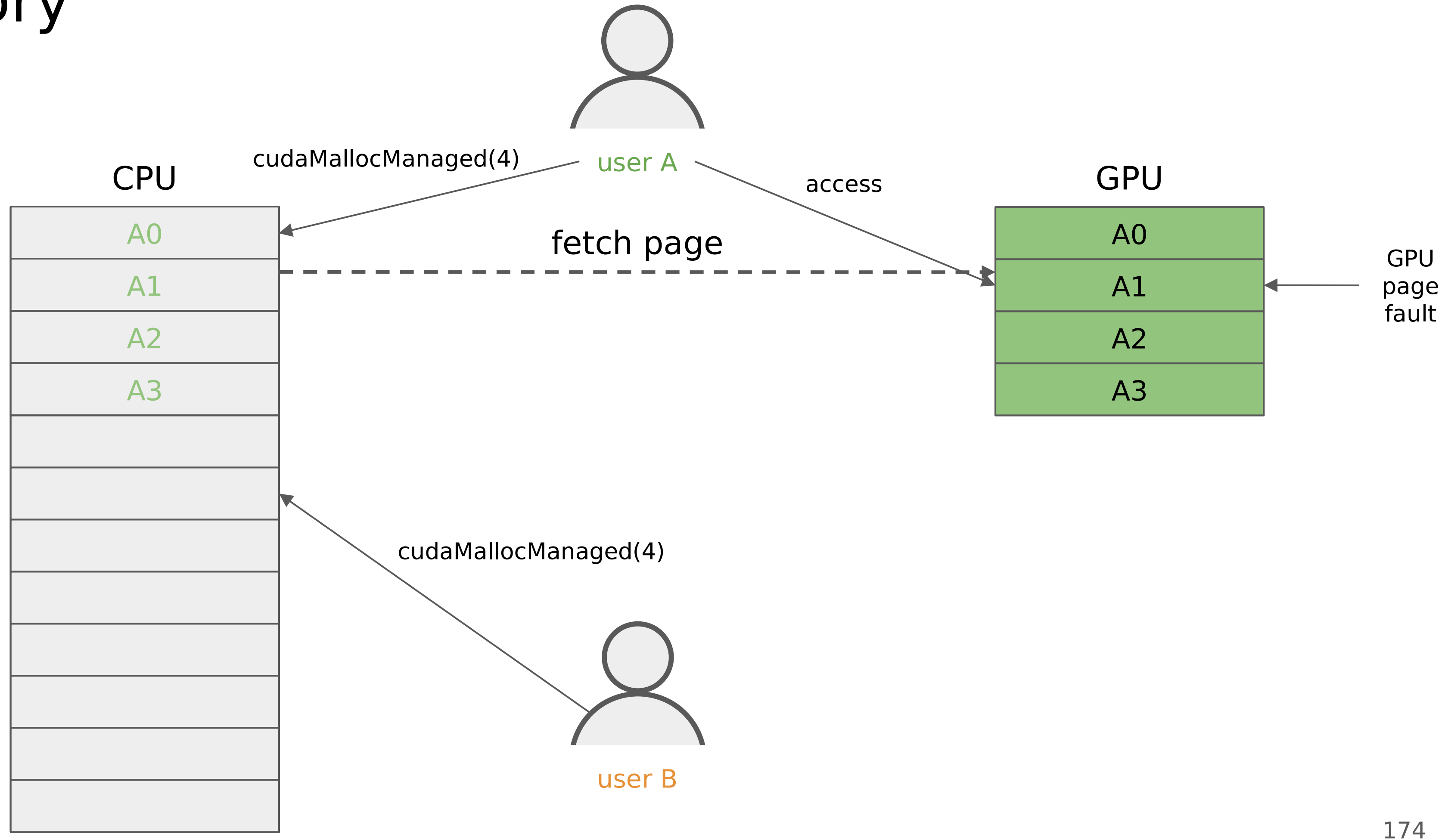
user A
cudaMallocManaged(4)
access
CPU
GPU
A0
A1
A2
A3
fetch page
A0
A1
A2
A3
GPU
page
fault

Memory



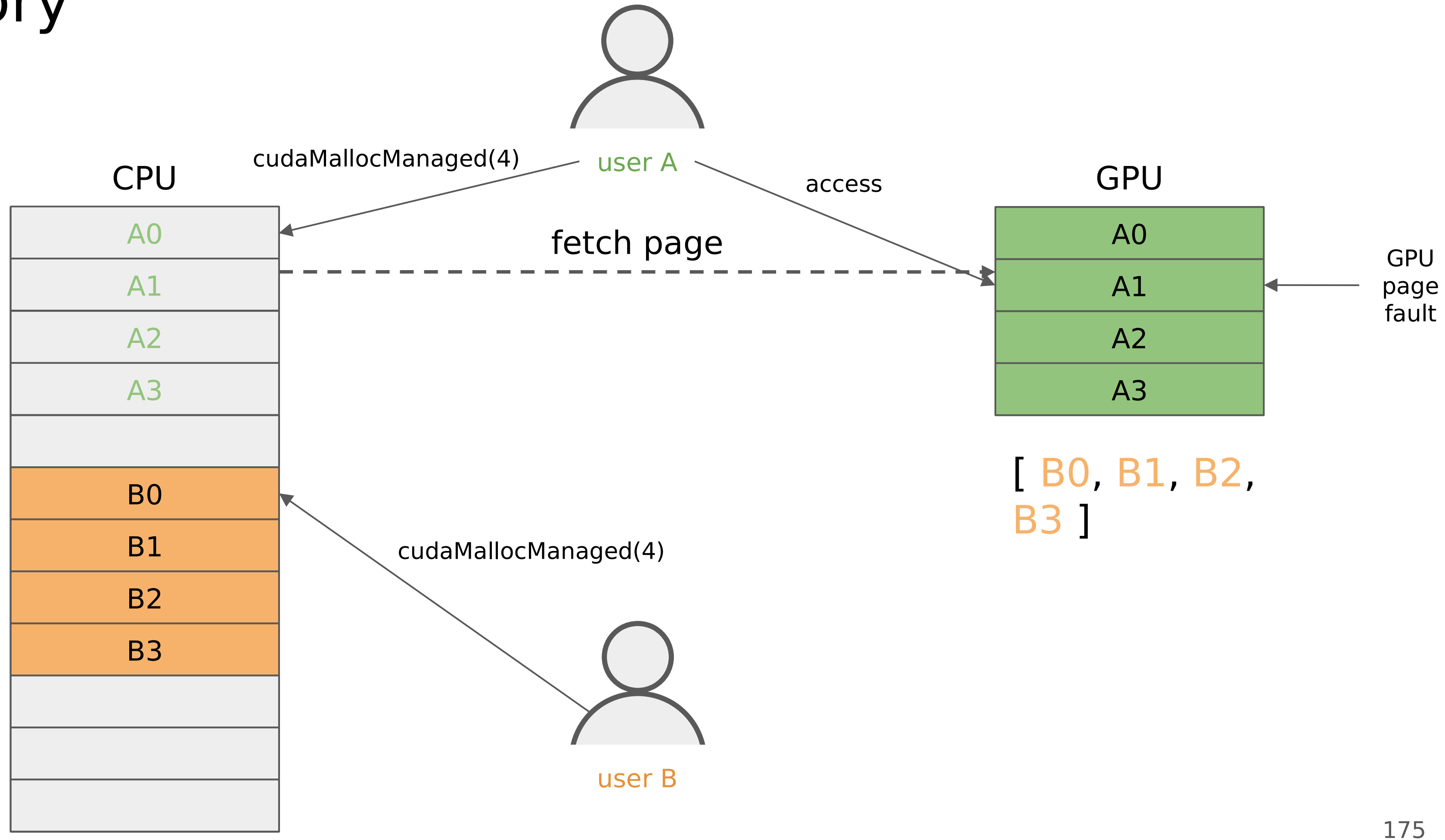
user A
cudaMallocManaged(4)
access
CPU
GPU
A0
A1
A2
A3
fetch page
A0
A1
A2
A3
GPU
page
fault
user B

Memory



user A
cudaMallocManaged(4)
access
CPU
GPU
A0
A1
A2
A3
fetch page
A0
A1
A2
A3
GPU page fault
cudaMallocManaged(4)
user B

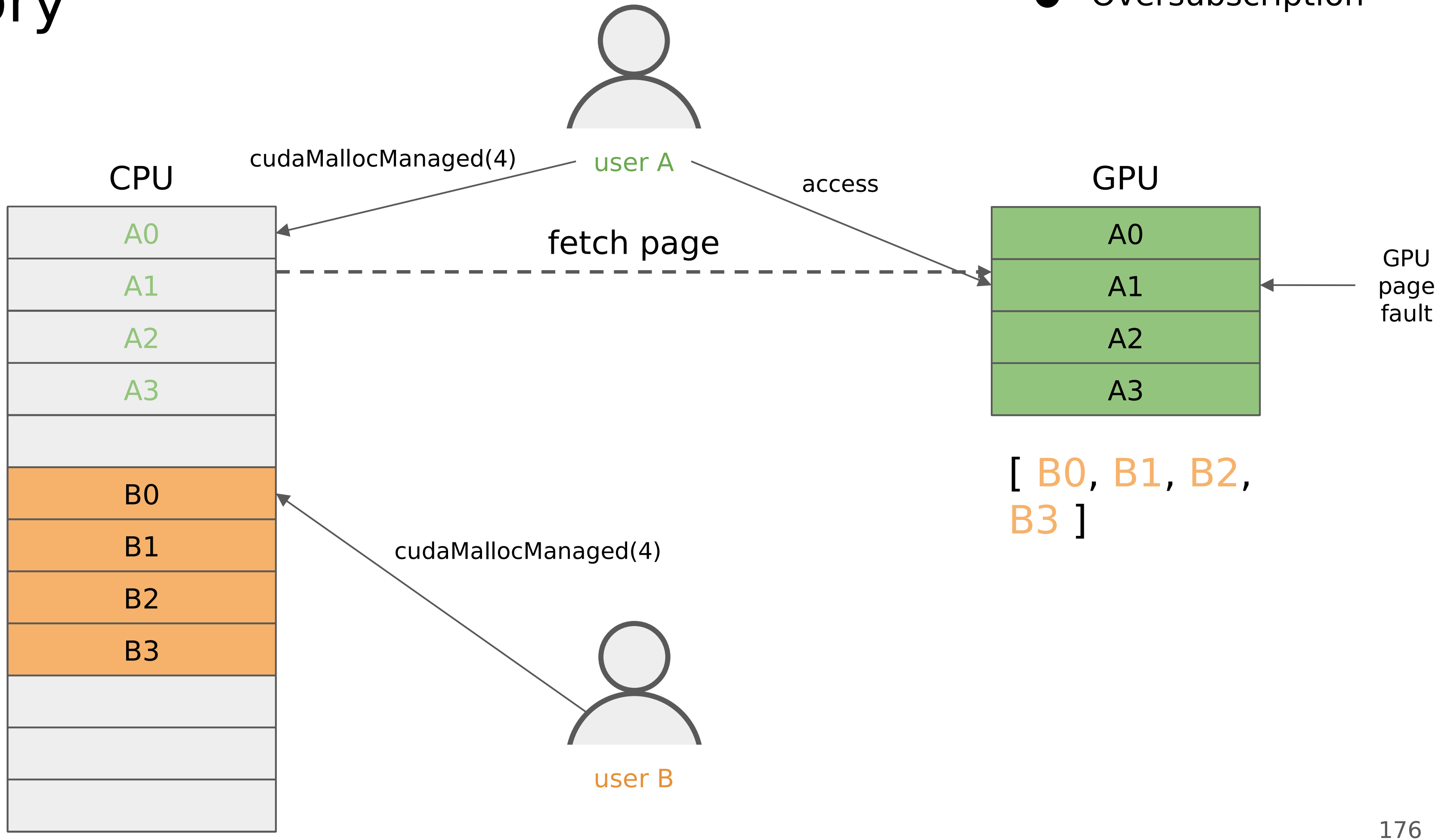
Memory



CPU
cudaMallocManaged(4)
user A
access
GPU
A0
A1
A2
A3
fetch page
A0
A1
A2
A3
GPU page fault
B0
B1
B2
B3
[B0, B1, B2, B3]
cudaMallocManaged(4)
user B

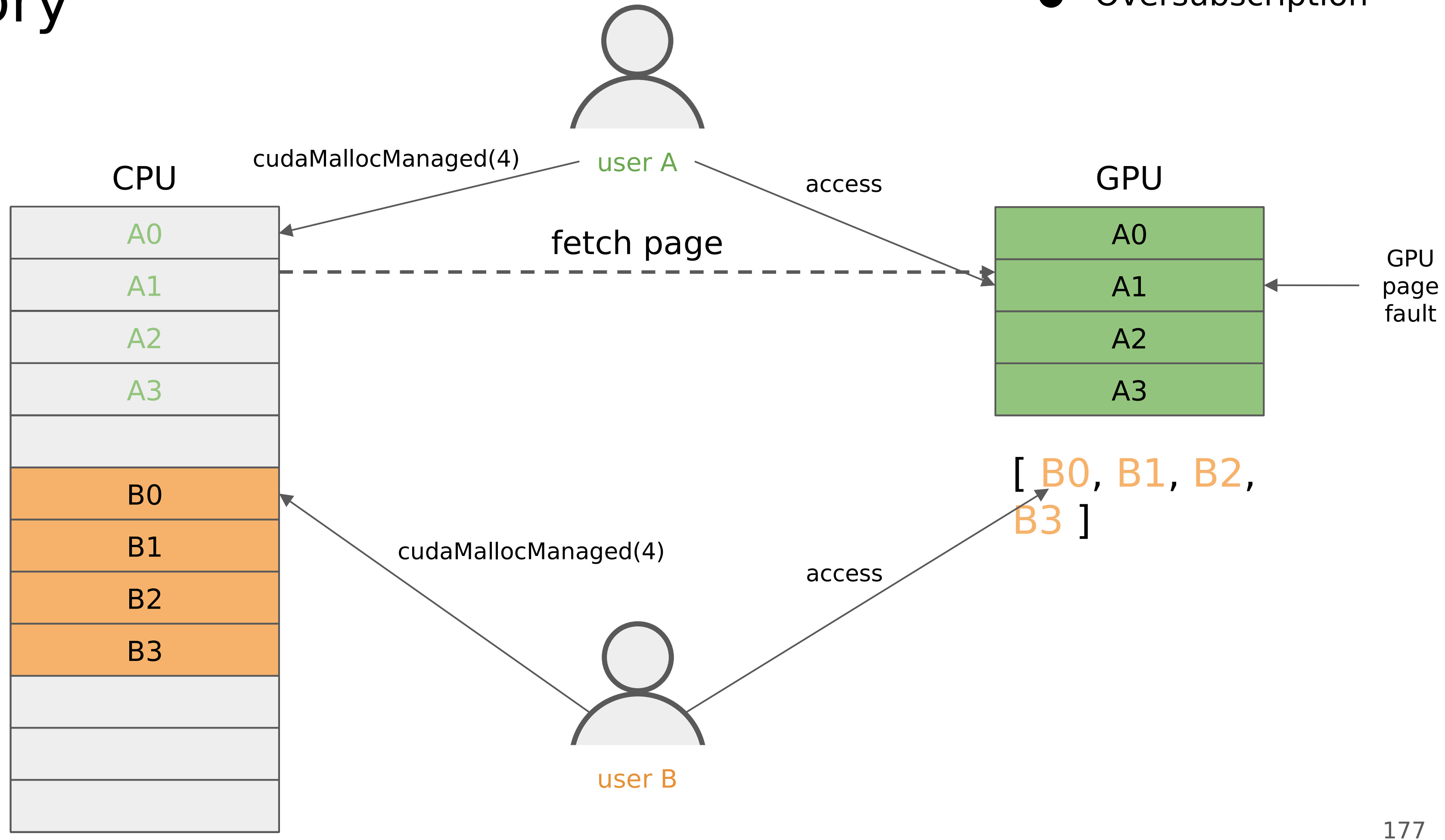
Memory

- Oversubscription



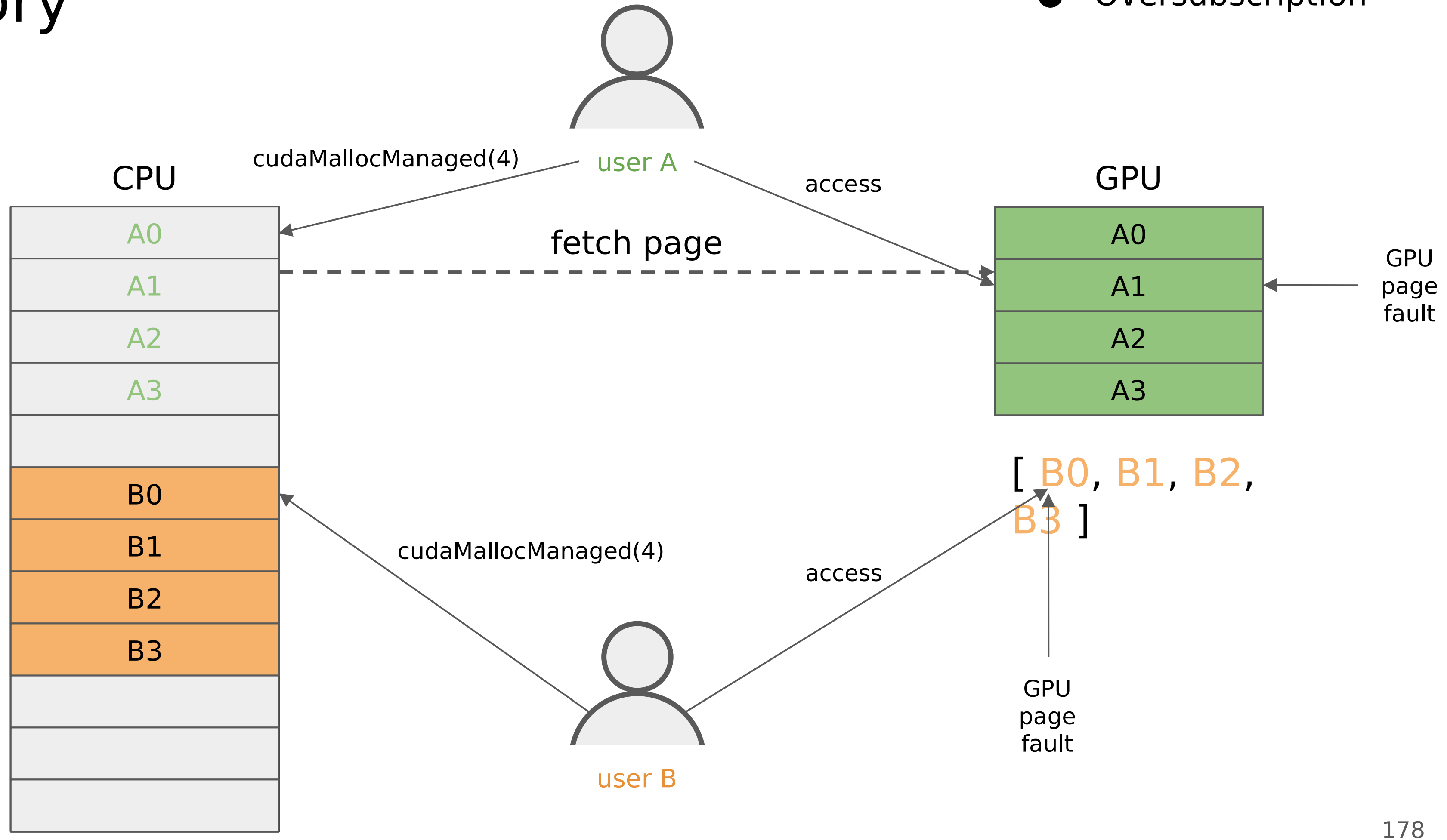
Memory

- Oversubscription



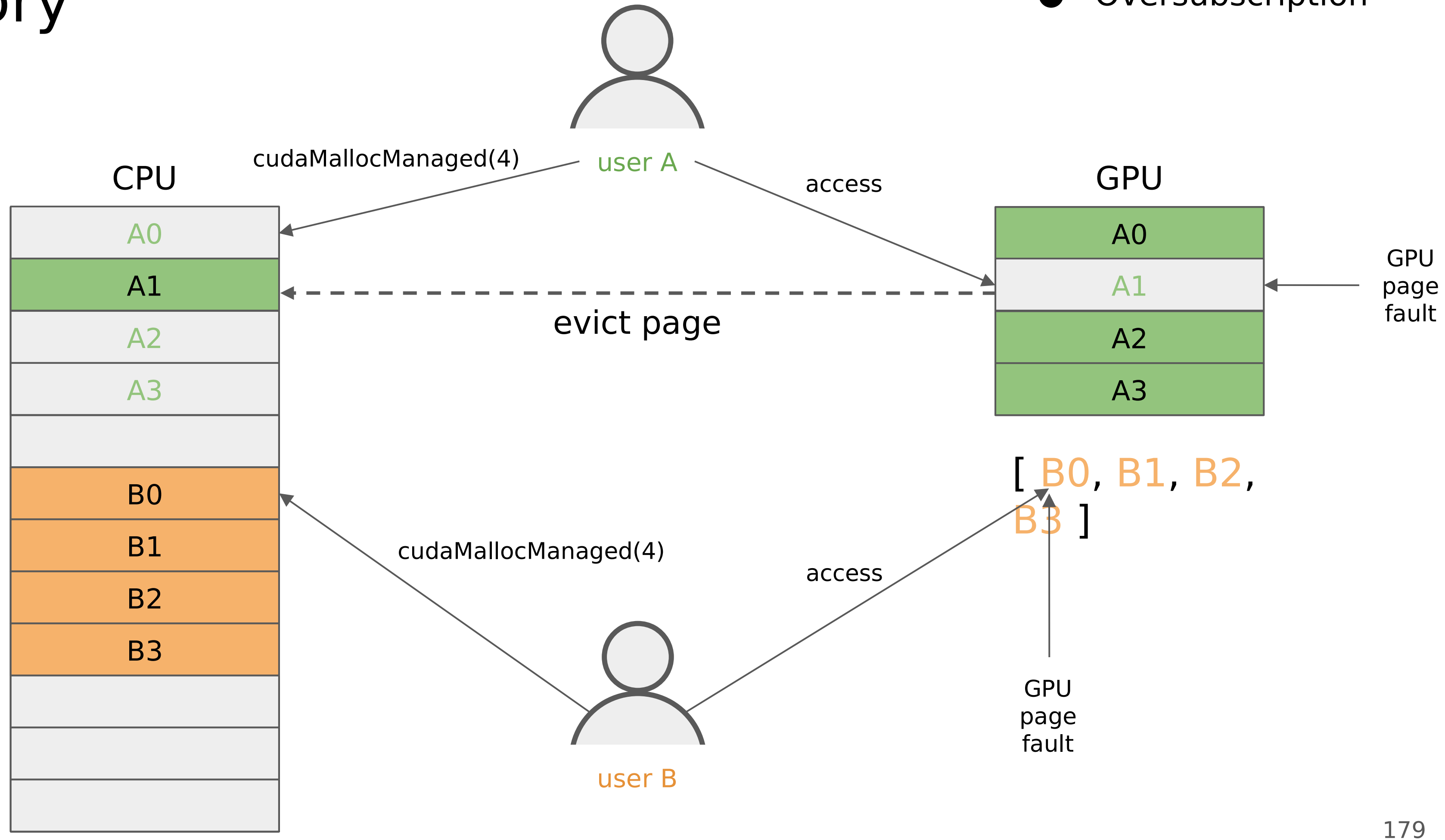
Memory

- Oversubscription



Memory

- Oversubscription



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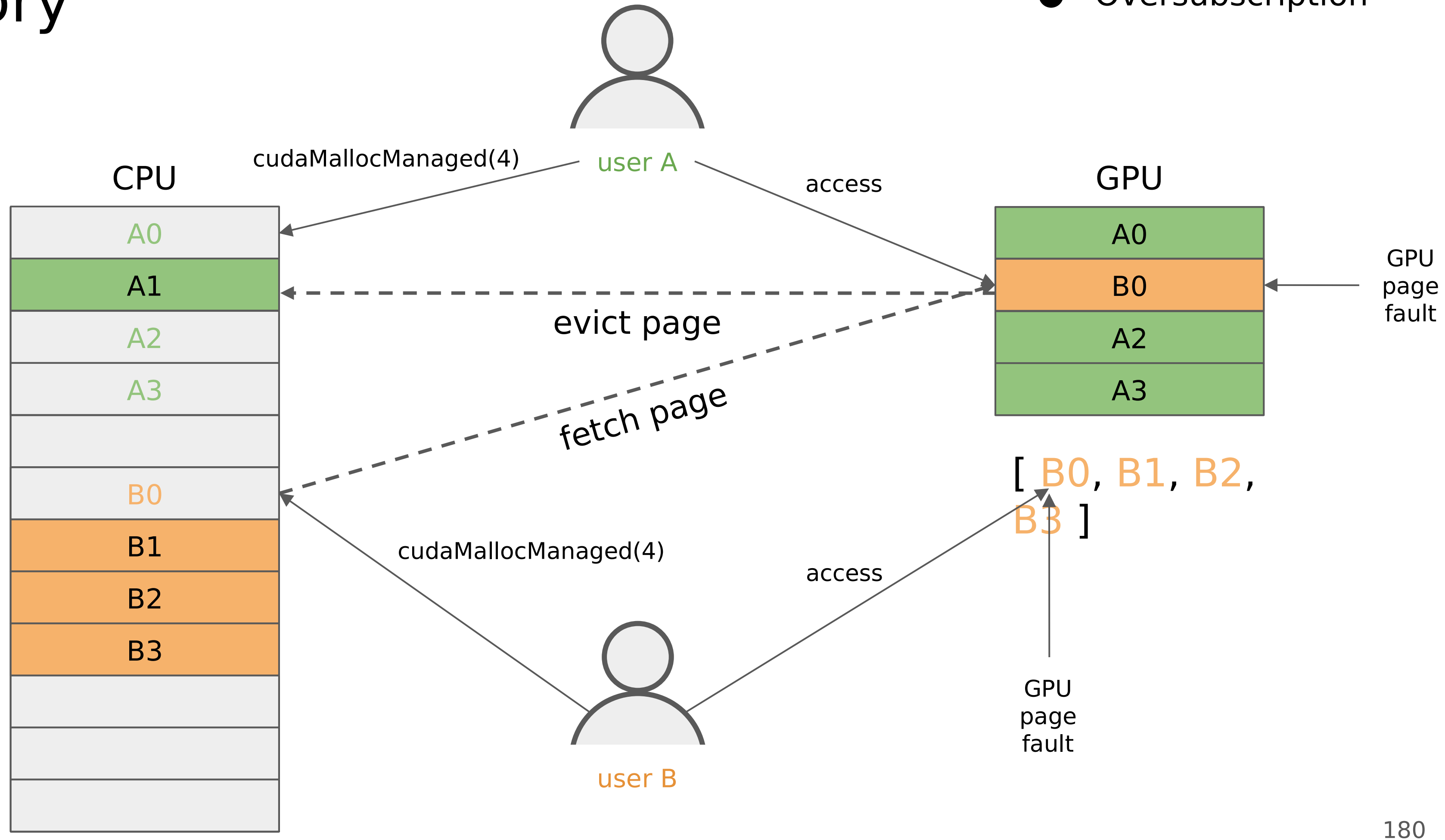
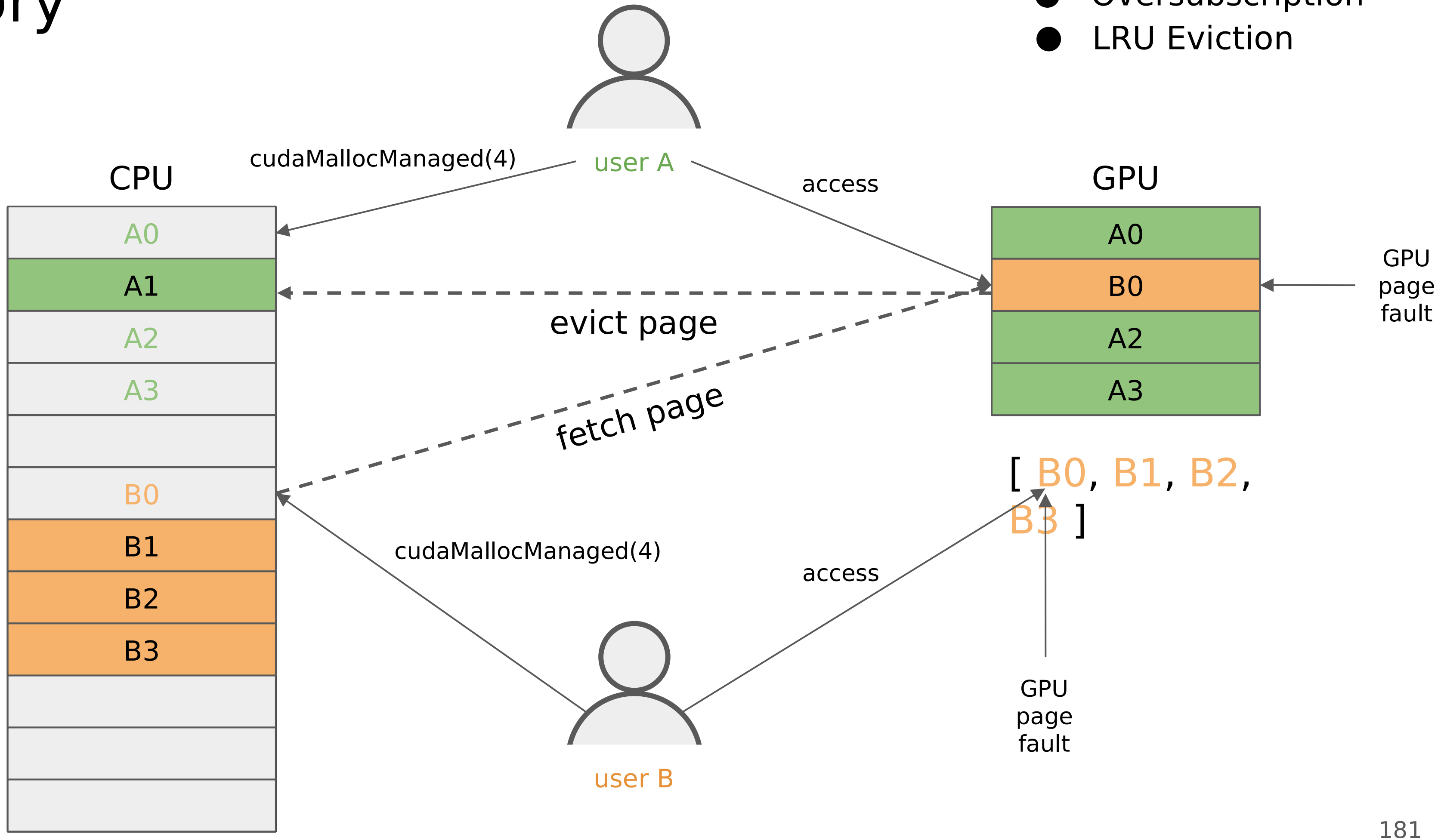


Memory

- Oversubscription
- LRU Eviction



Function wrappers

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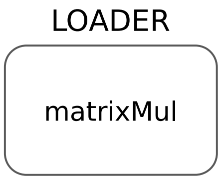

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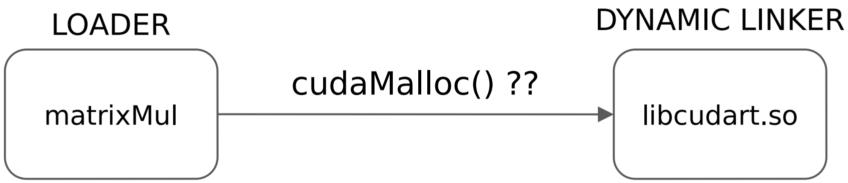

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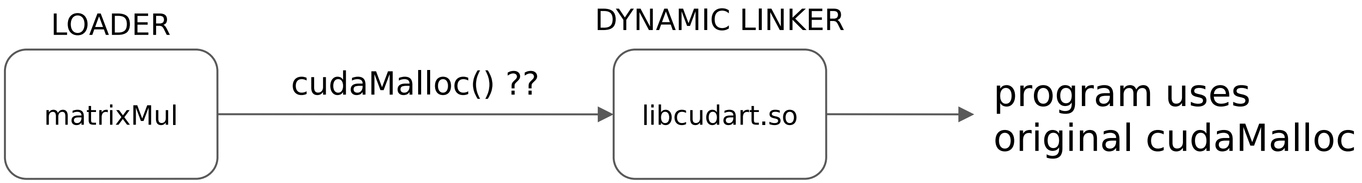

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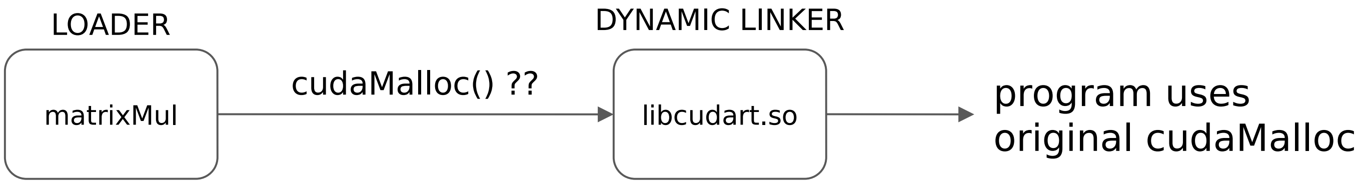

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our custom version

Normally:

LOADER

matrixMul

cudaMalloc() ??

DYNAMIC LINKER

libcudart.so

program uses original cudaMalloc

LD_PRELOAD=libnvshare.so

Function wrappers

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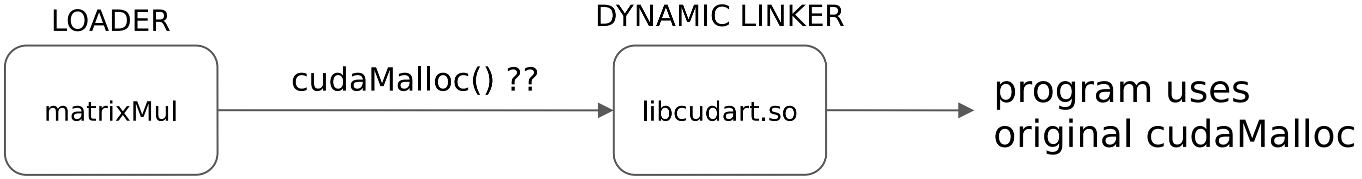
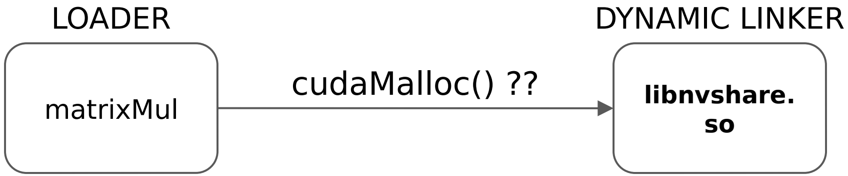


LD_PRELOAD=libnvshare.so



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Normally:

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- which can **internally** call the original

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- which can **internally** call the original
- … if we will it

Key Idea

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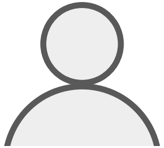

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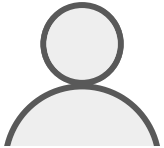
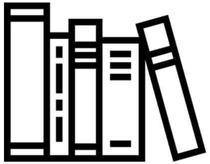


user

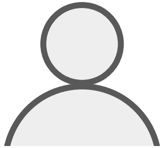
libnvshare.so



Key Idea

libnvshare.so

GPU



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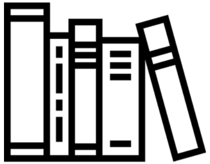

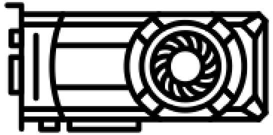

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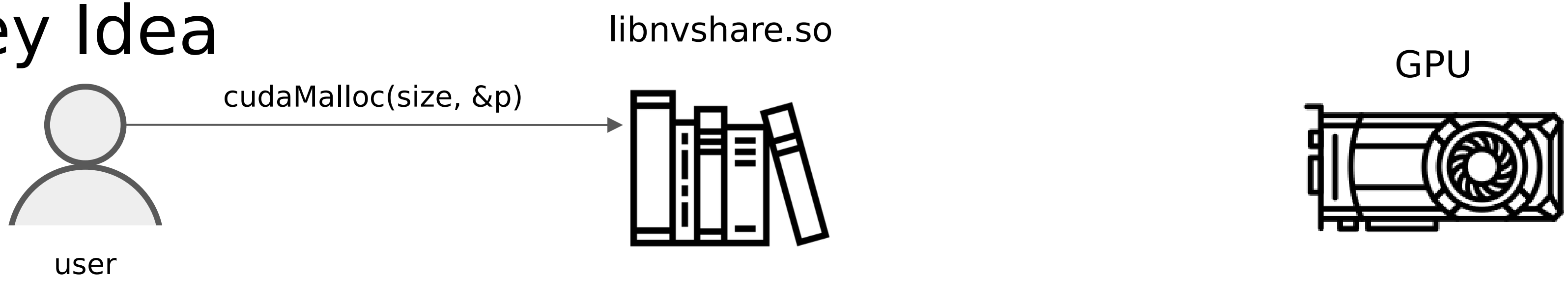

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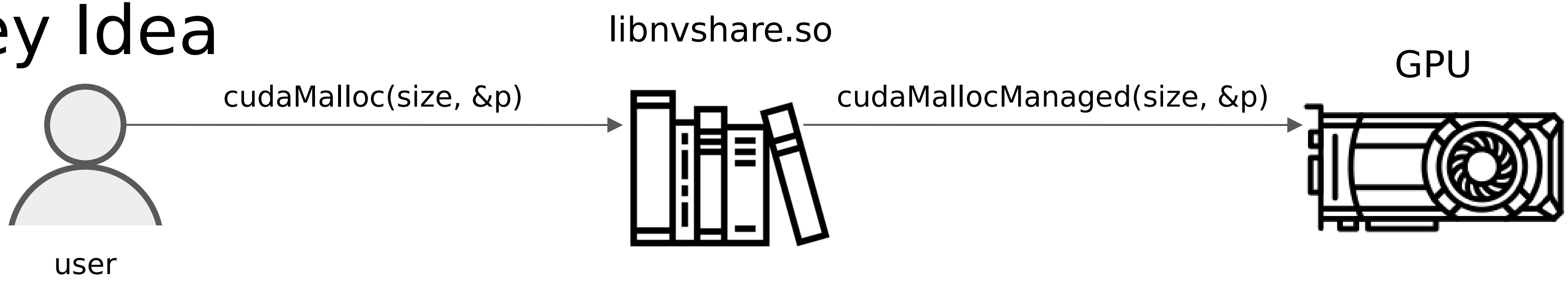
libnvshare.so
GPU
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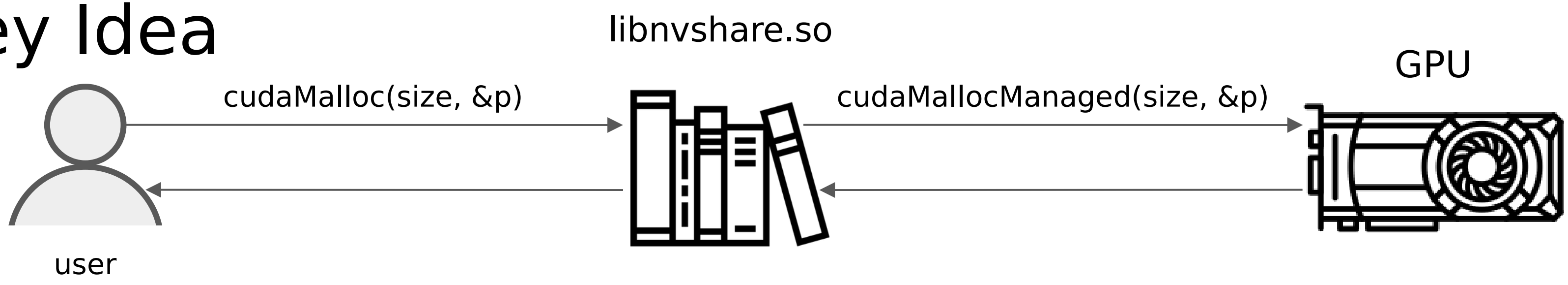
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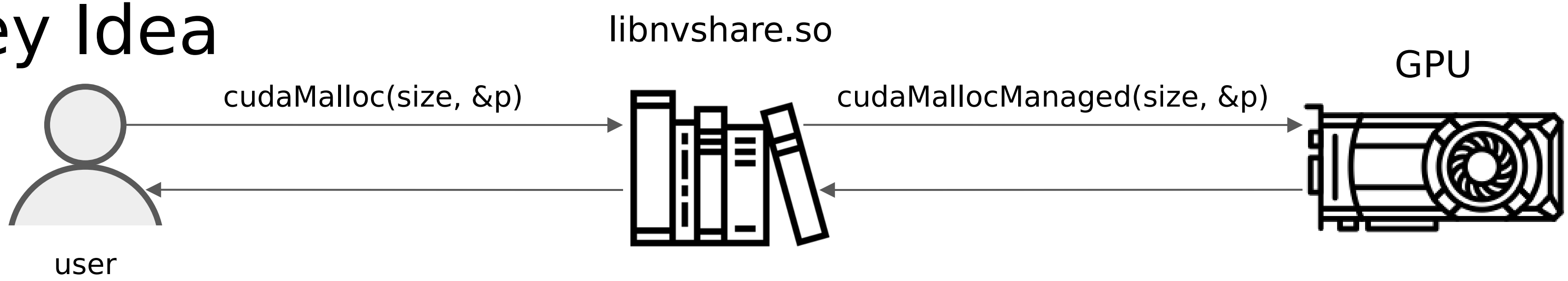

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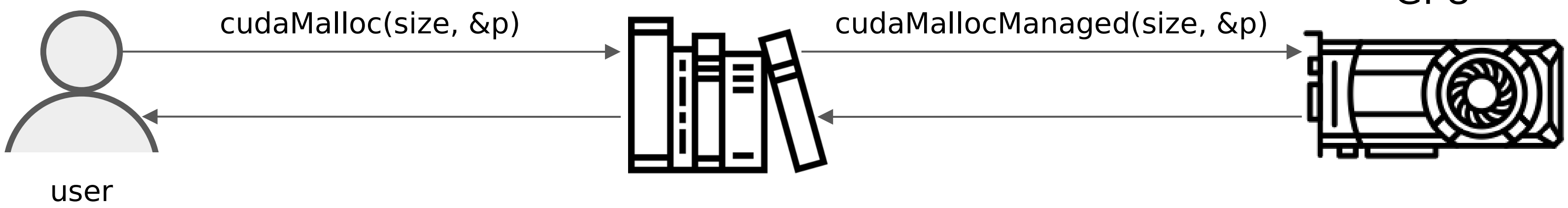
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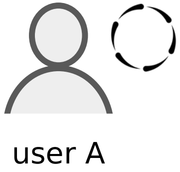
user A

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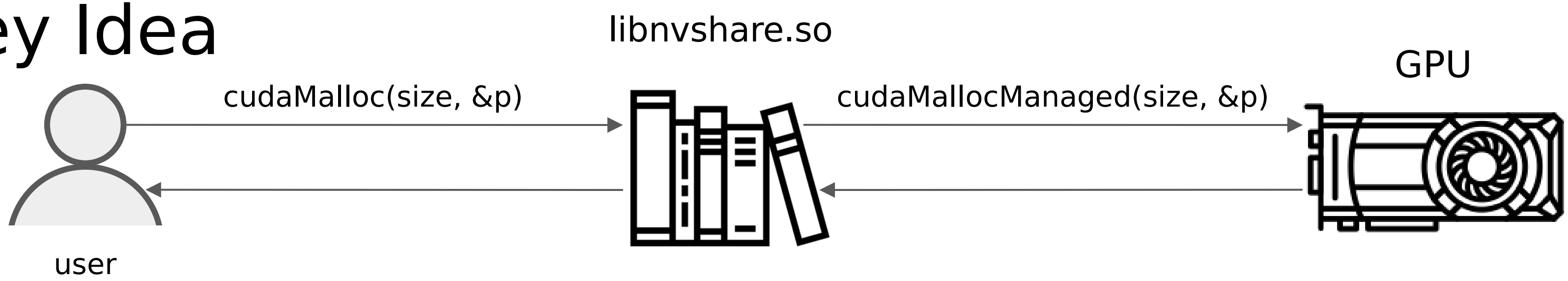

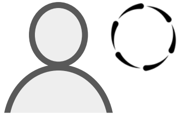

user A

GPU

A0
A1
A2
A3

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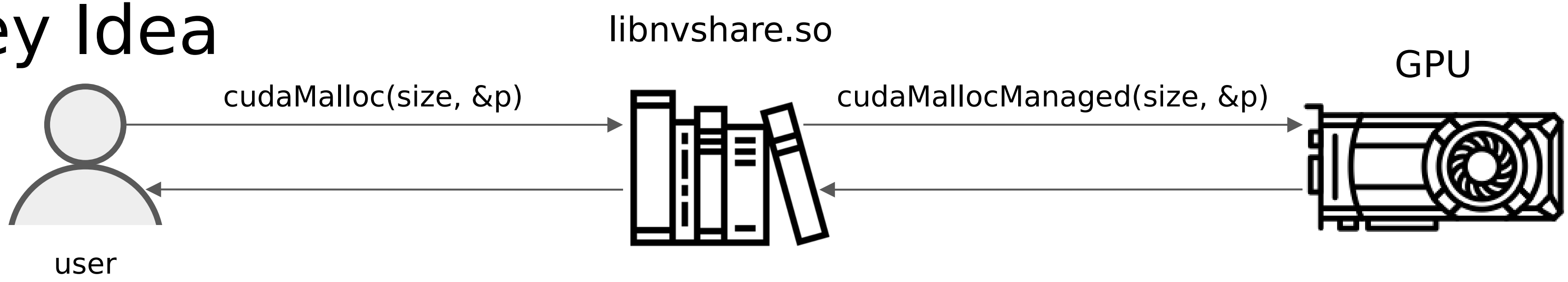

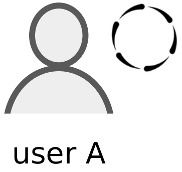

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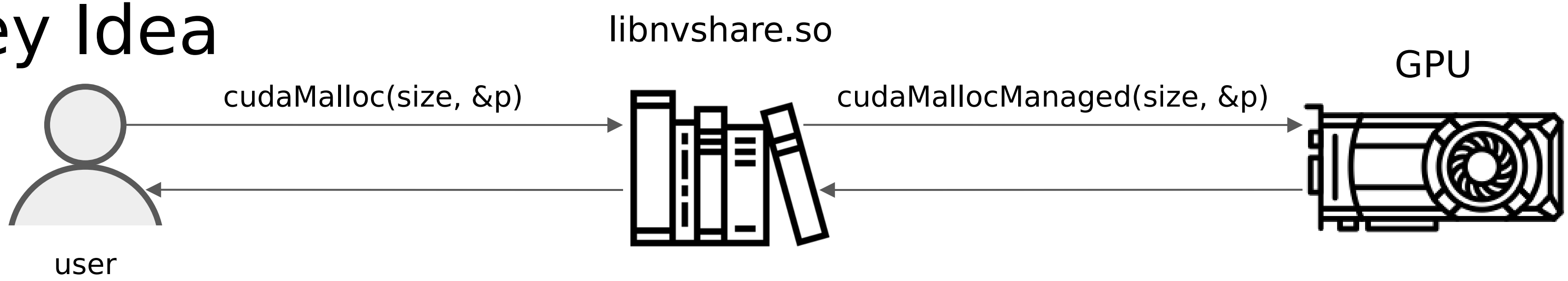

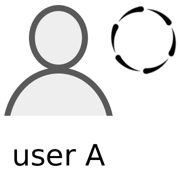

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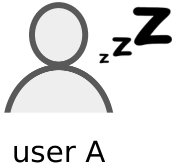

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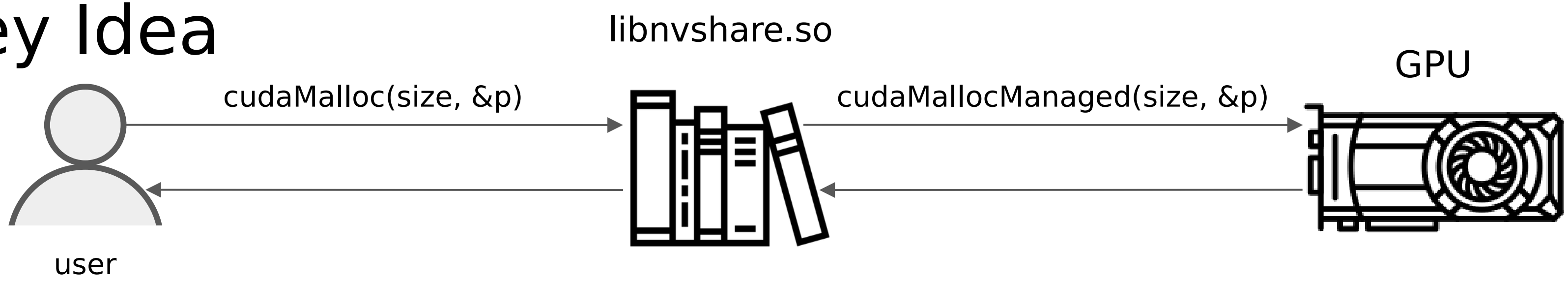
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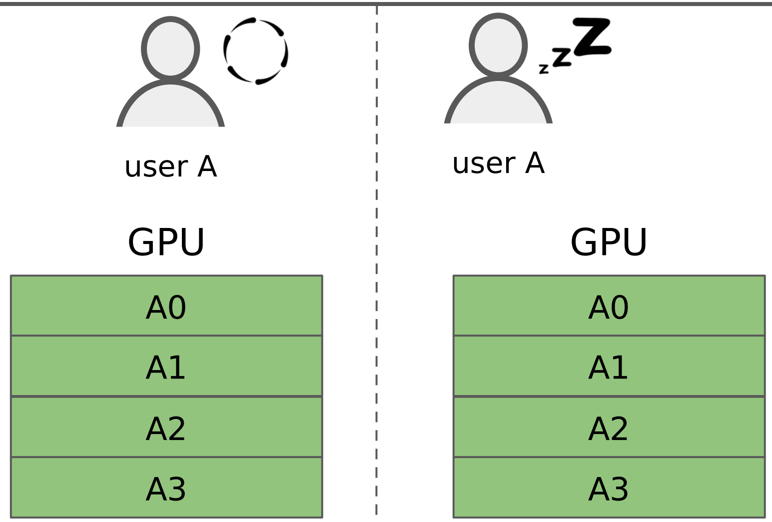
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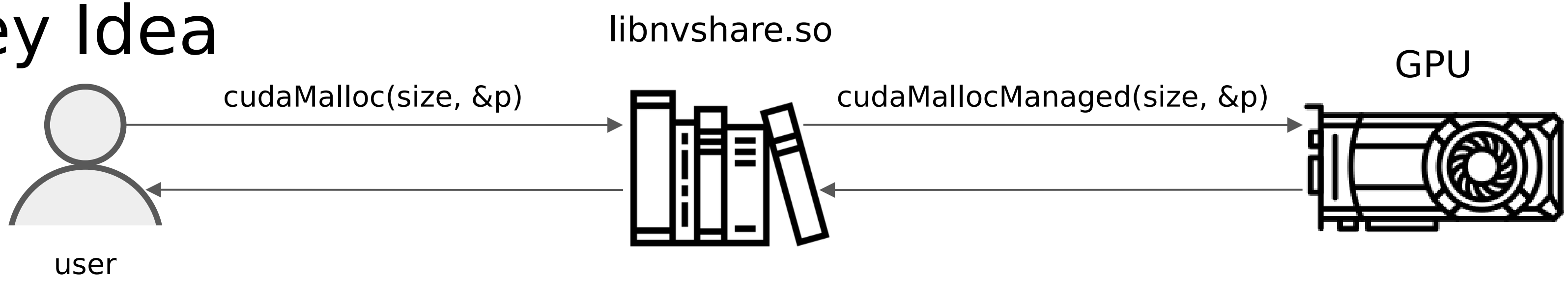

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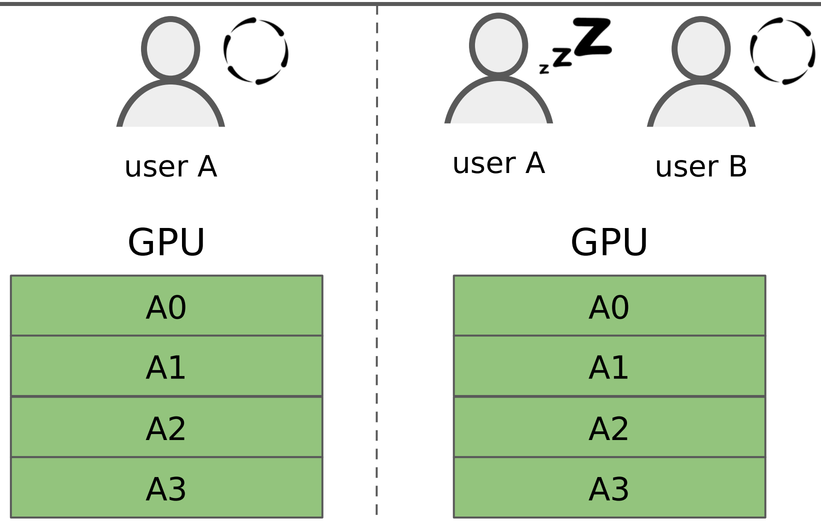

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user B
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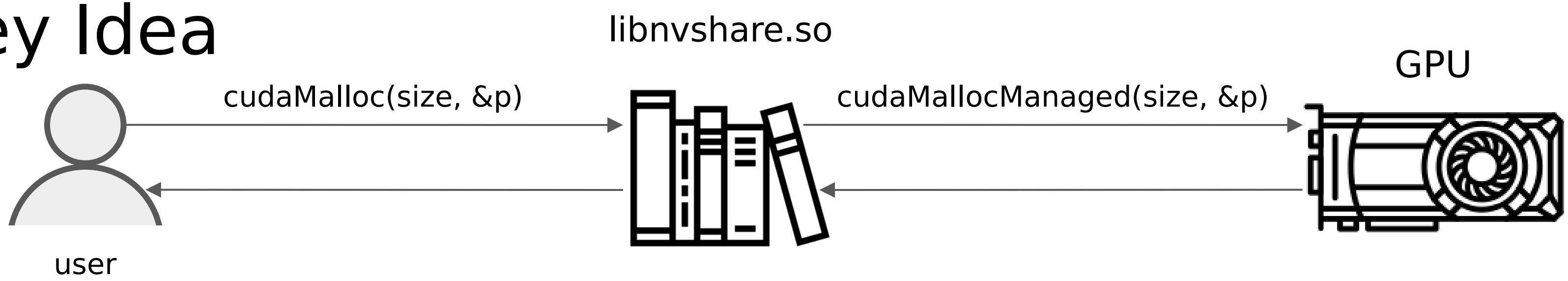
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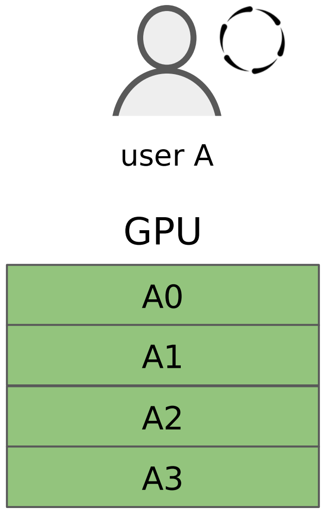
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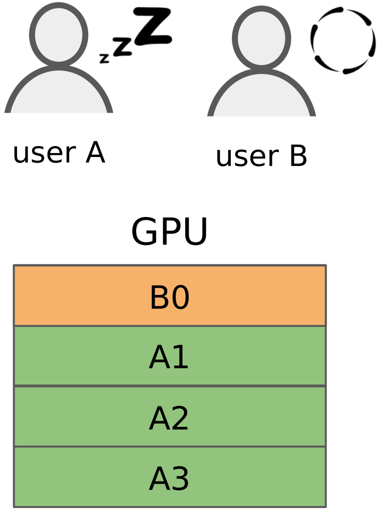
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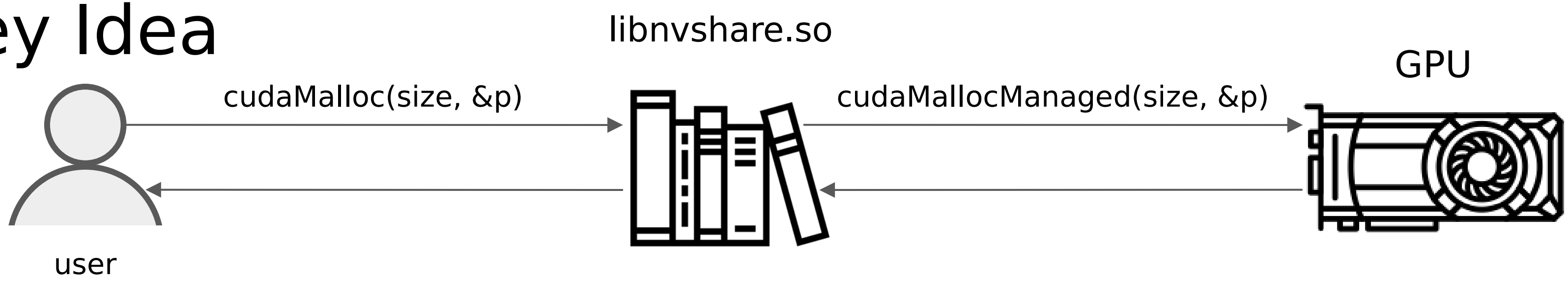

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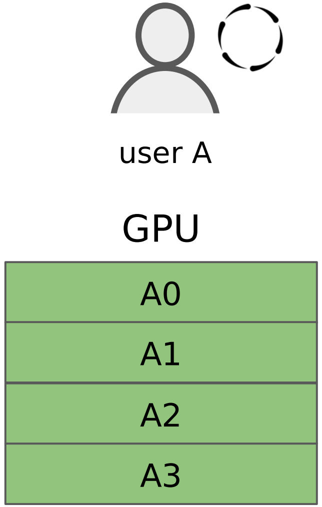

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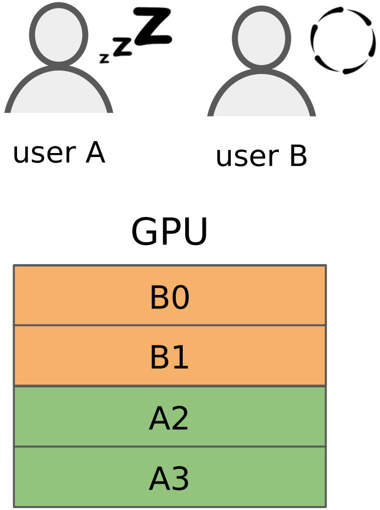

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B0
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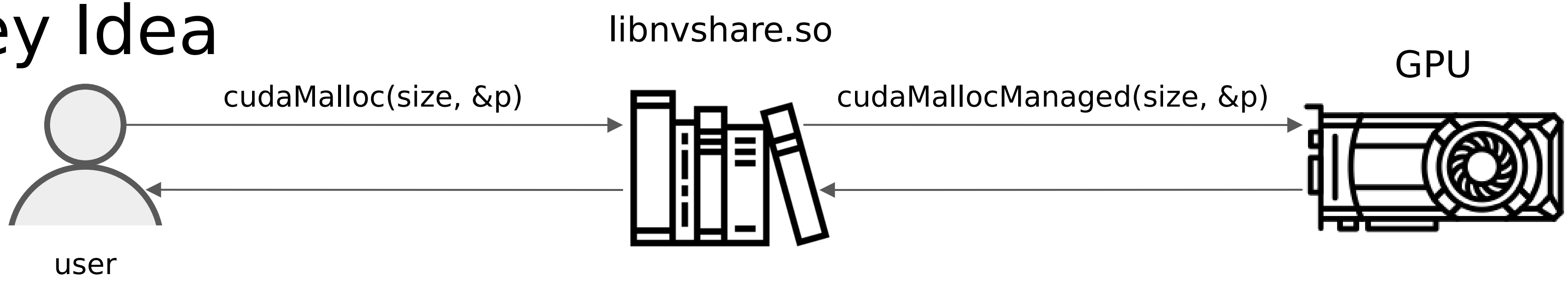
A3

Key Idea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GPU
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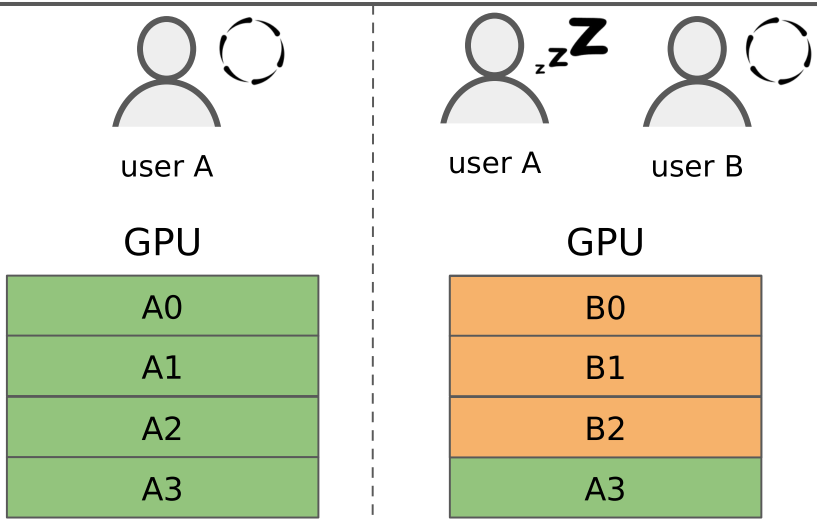
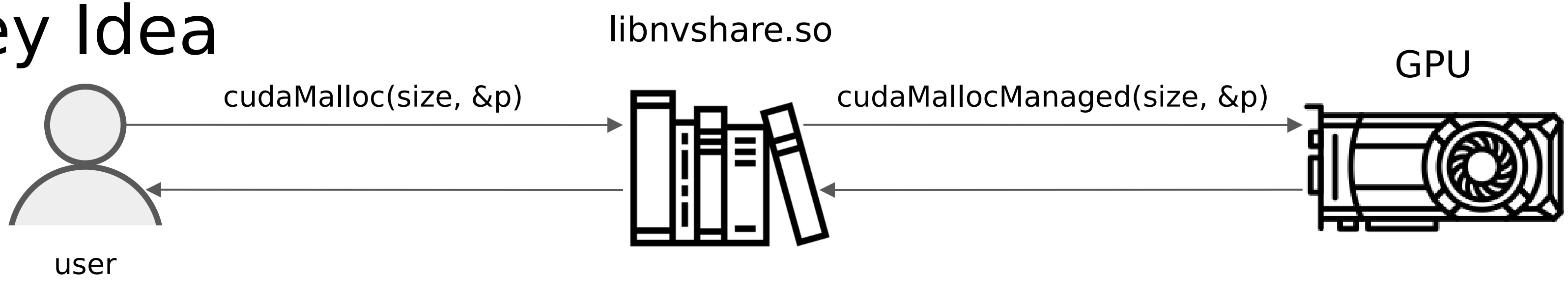
cudaMallocManaged(size, &p)
user


user A
GPU
A0
A1
A2
A3
user A
user B
GPU
B0
B1
B2
A3

Key Idea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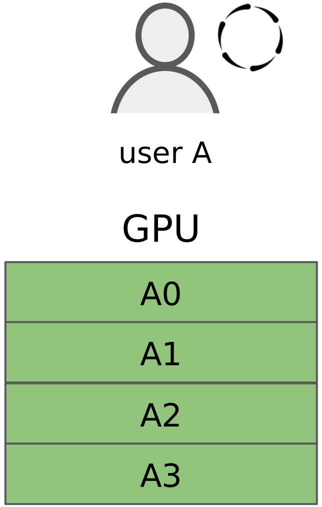
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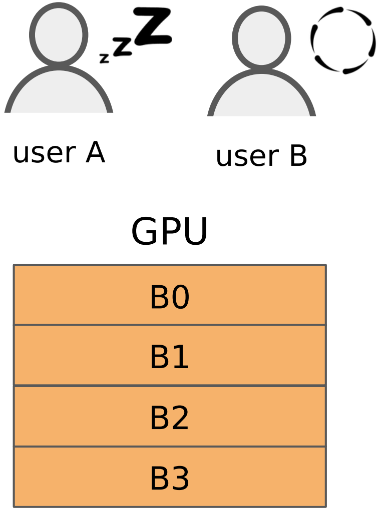
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user B
GPU
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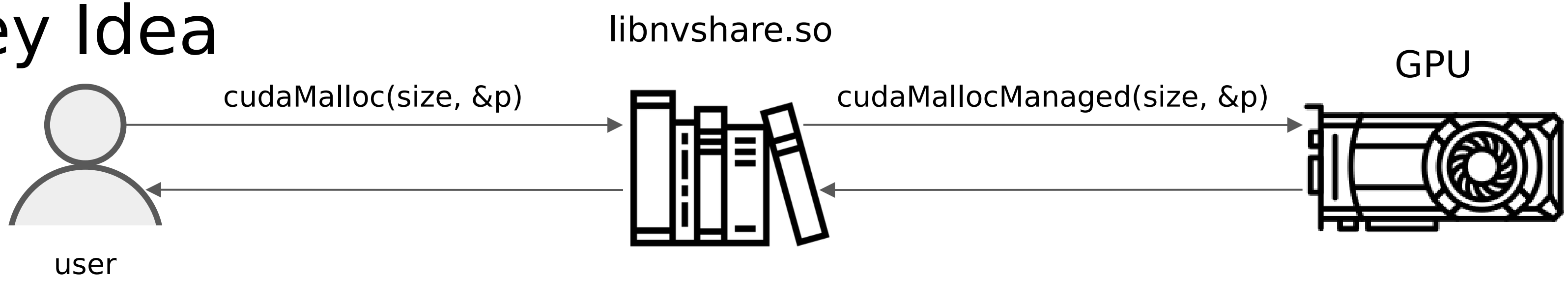
B1
B2
B3

Key Idea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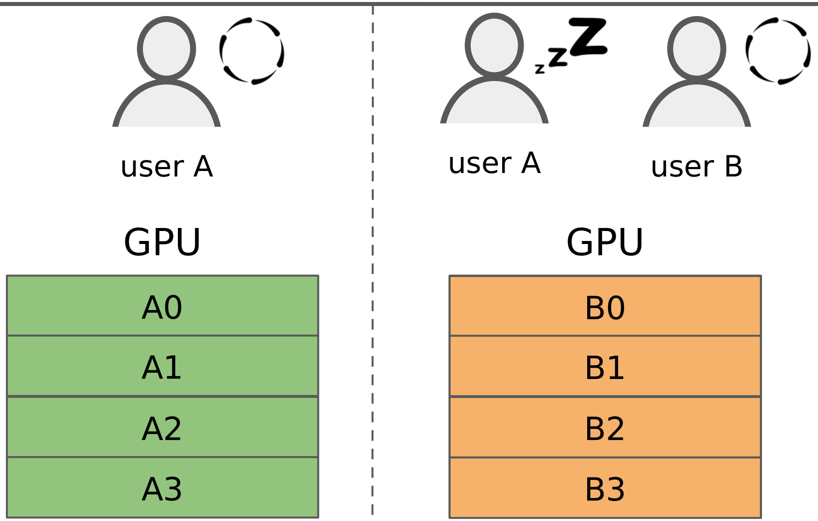
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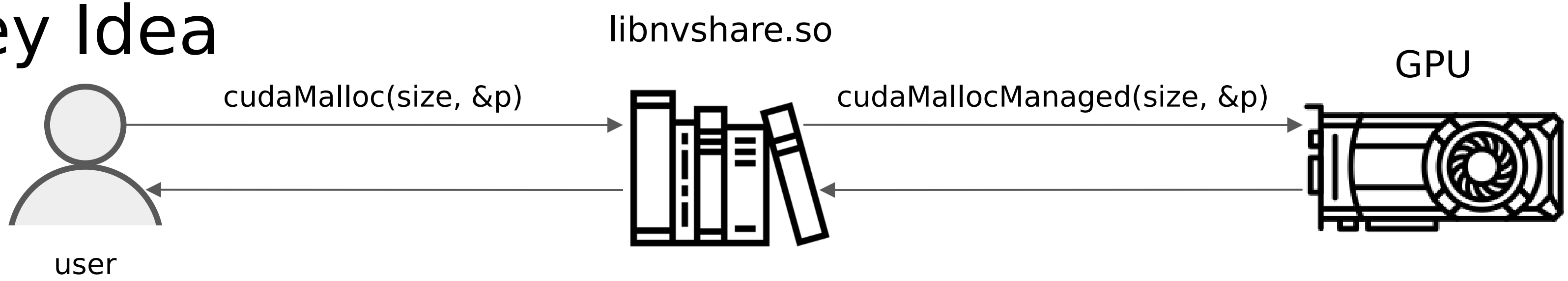
A1
A2
A3
user A
user B
GPU
B0
B1
B2
B3

Key Idea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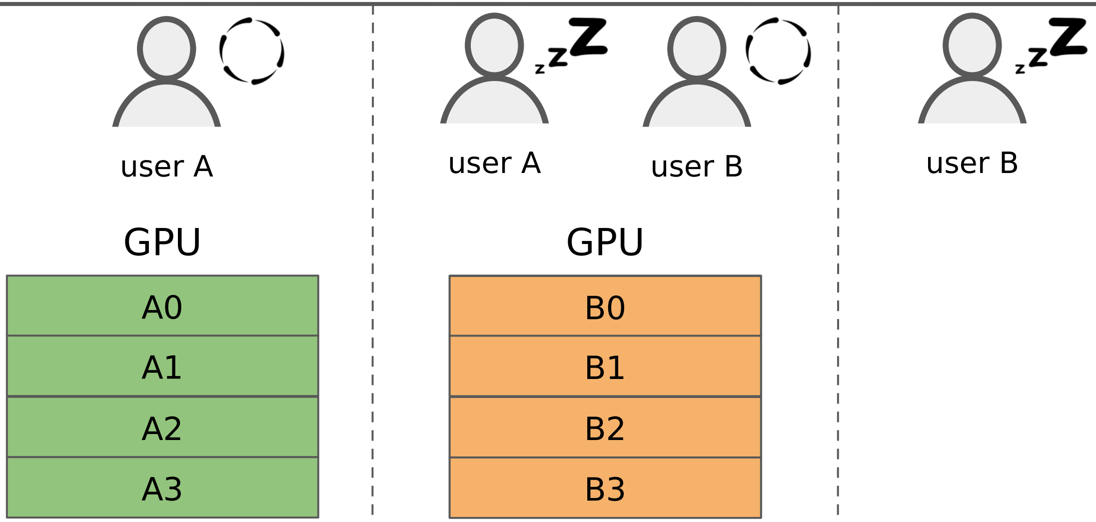
user A
user A
user B
user B
GPU
A0
A1
A2
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GPU
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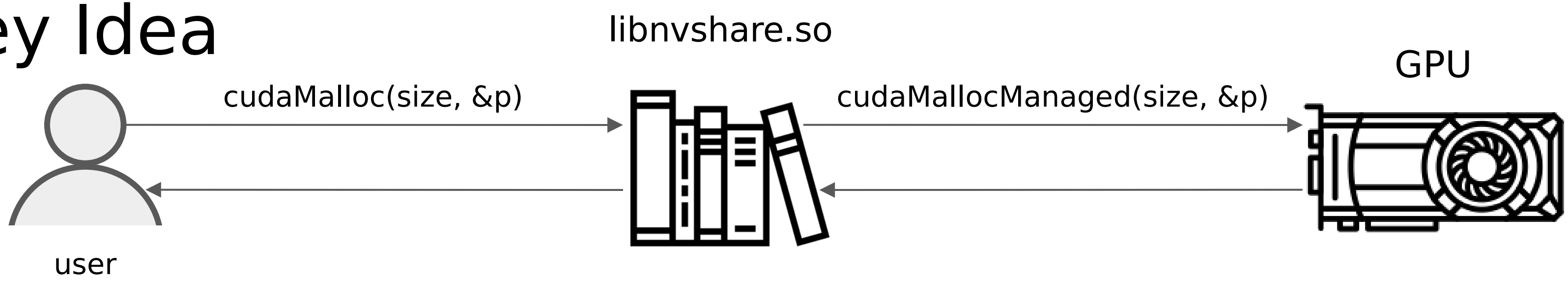
Key Idea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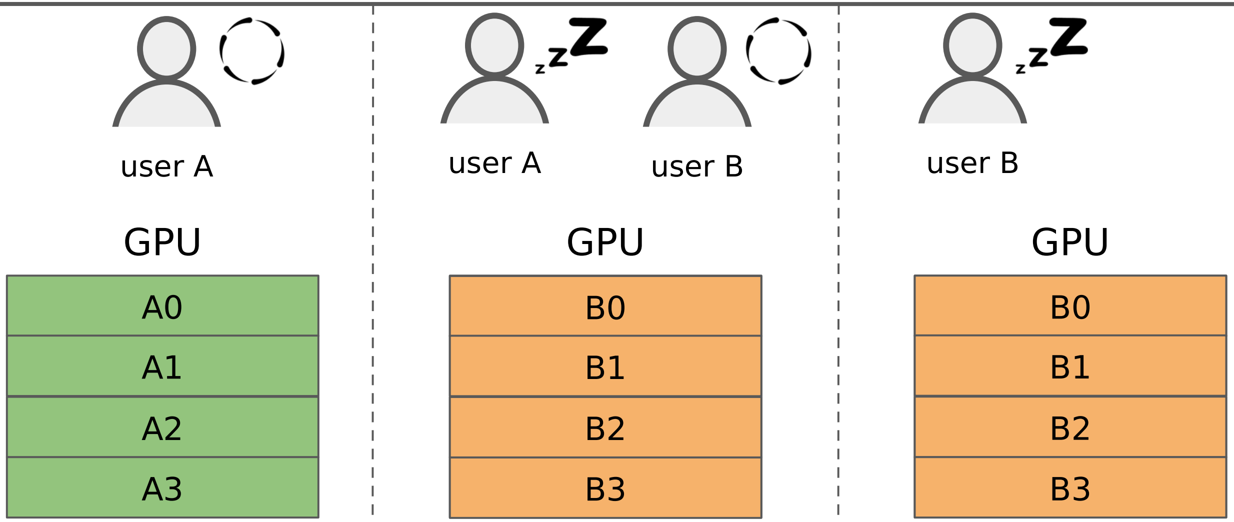
user A
user A
user B
user B
GPU
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A3
GPU
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GPU
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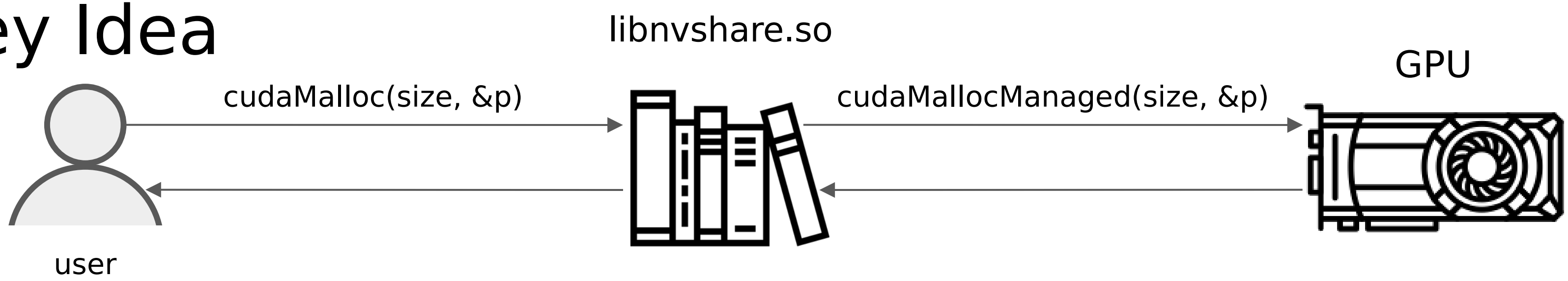
Key Idea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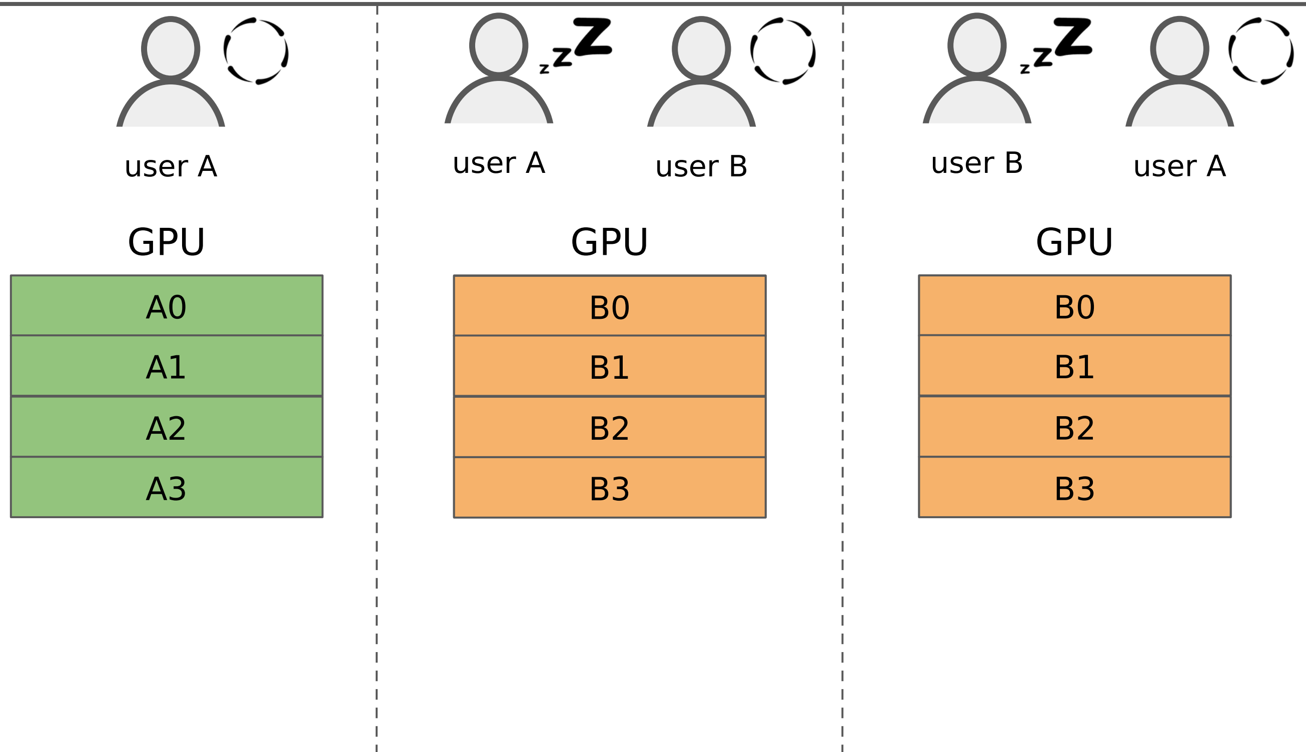
user


user A
GPU
A0
A1
A2
A3
user A
user B
GPU
B0
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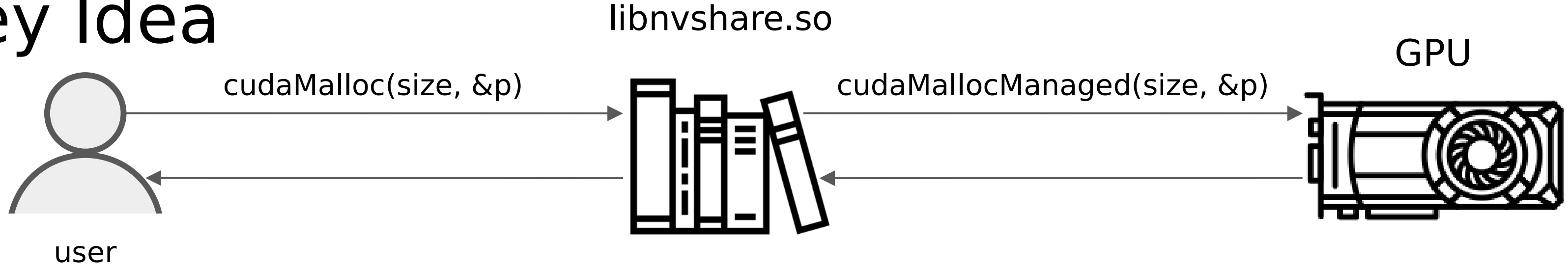
B2
B3
user B
user A
GPU
B0
B1
B2
B3

Key Idea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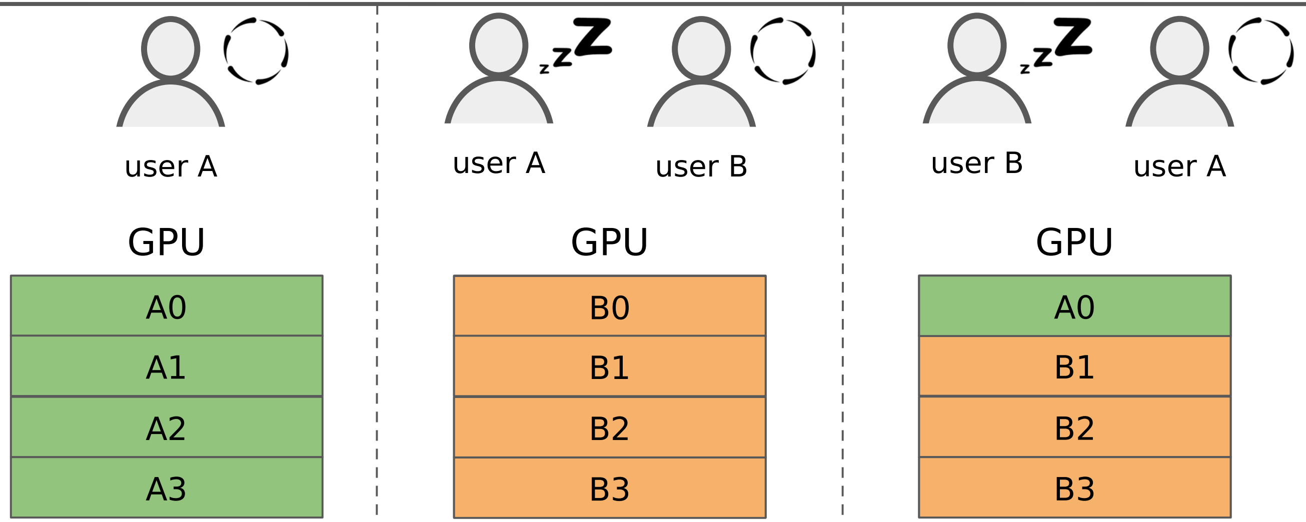
user


user A
GPU
A0
A1
A2
A3
user A
user B
GPU
B0
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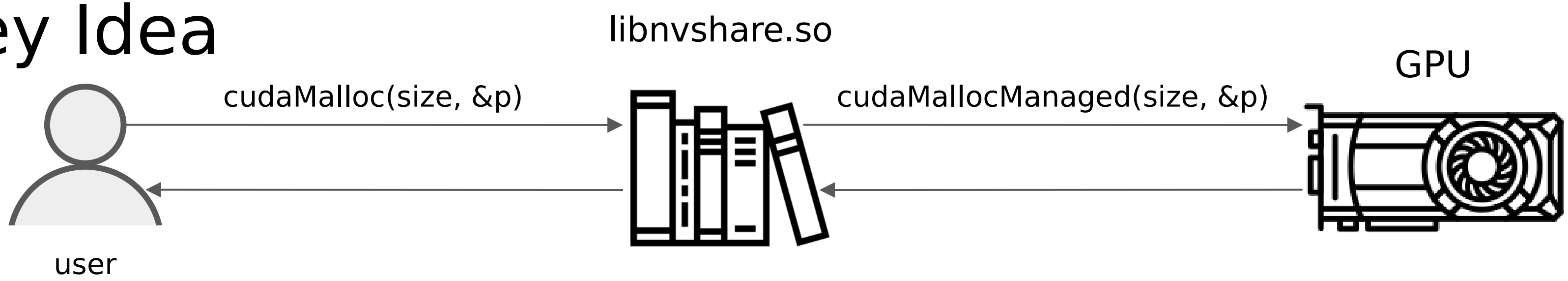
B2
B3
user B
user A
GPU
A0
B1
B2
B3

Key Idea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cudaMalloc(size, &p)
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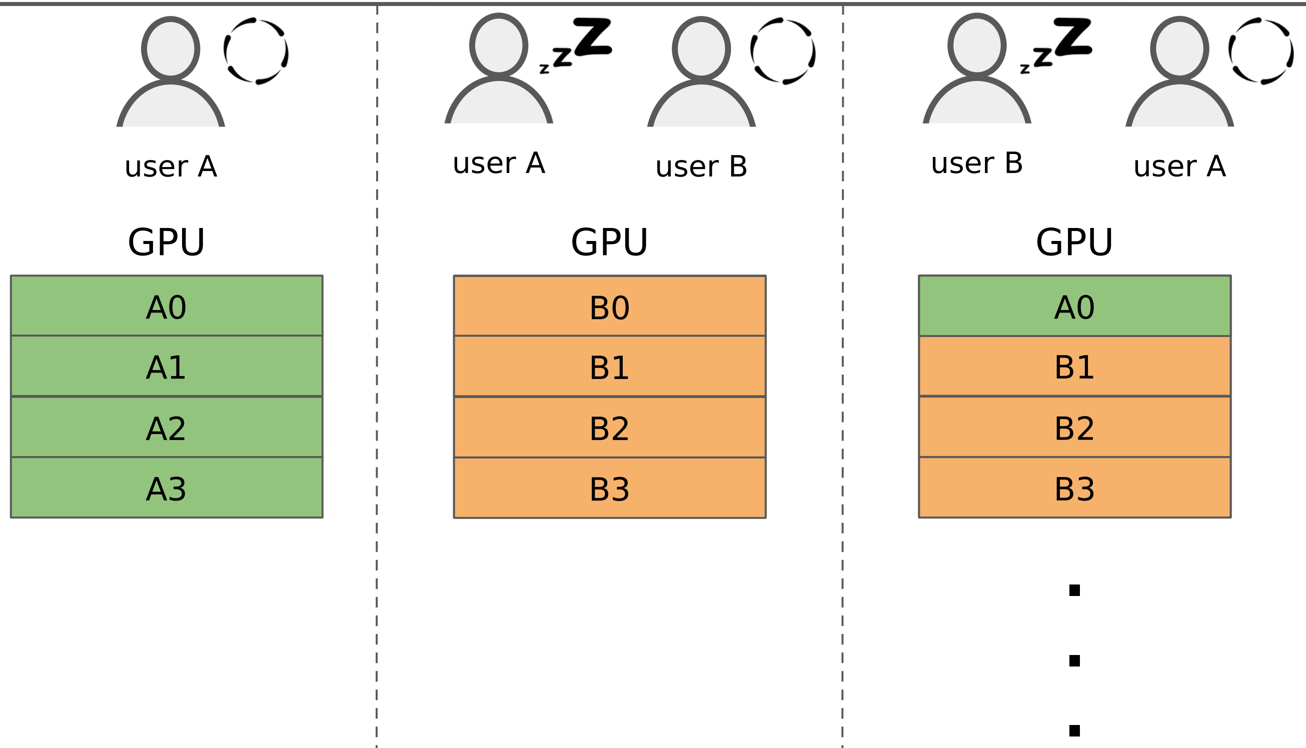
GPU
user


user A
GPU
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A3
user A
user B
GPU
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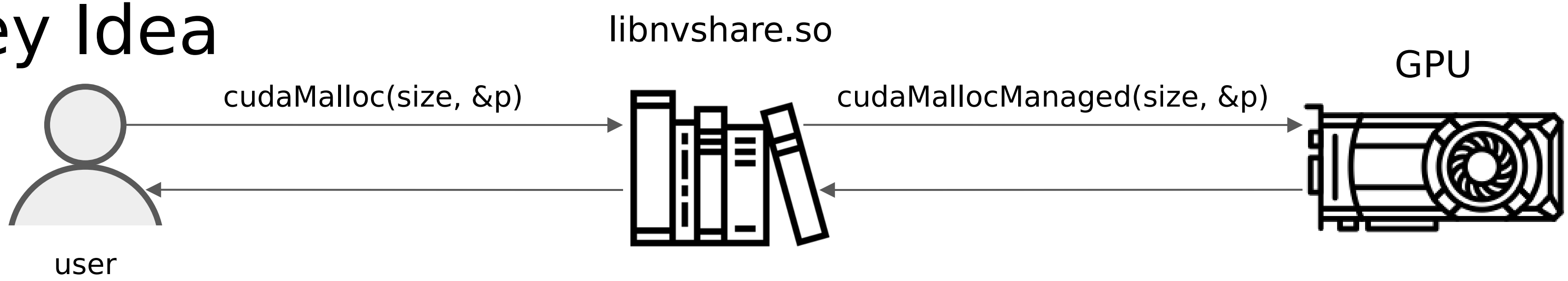
B1
B2
B3
user B
user A
GPU
A0
B1
B2
B3

Key Idea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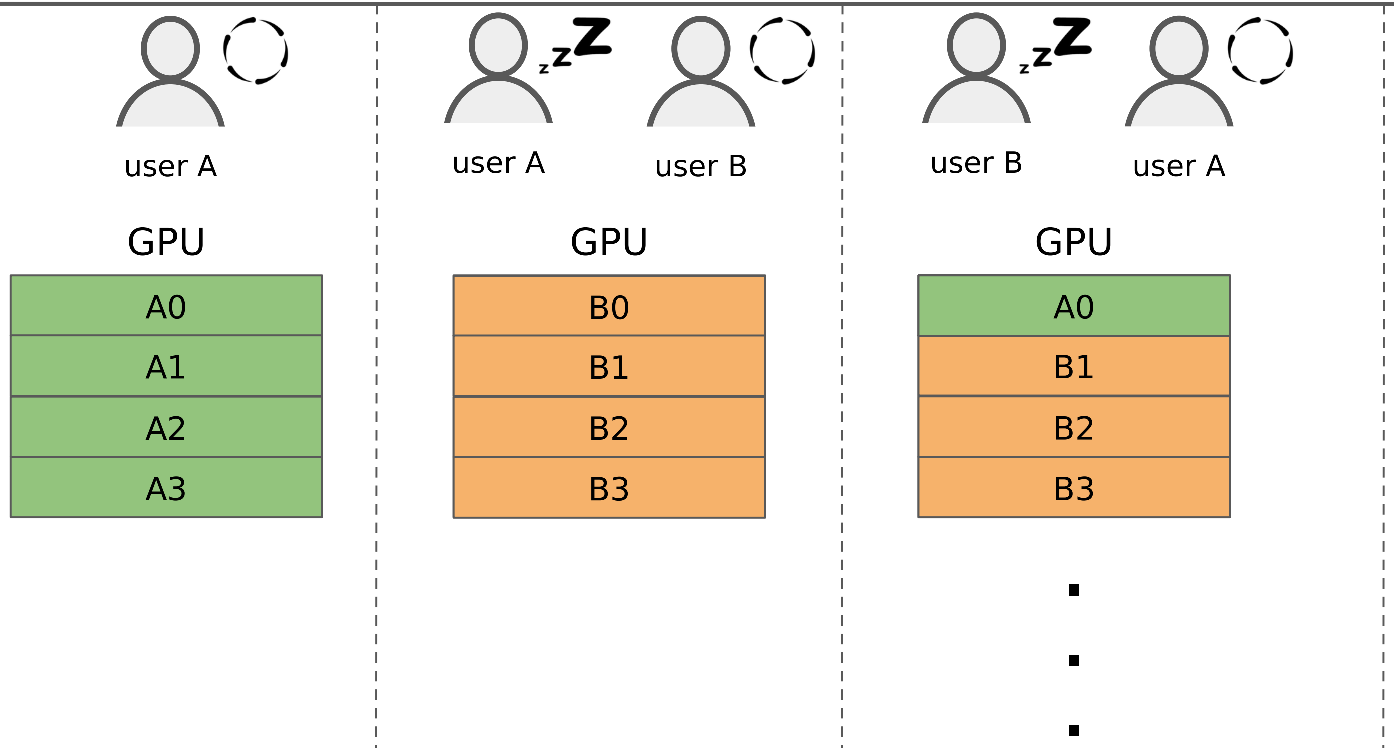
user


user A
user A
user B
user B
user A
GPU
A0
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GPU
B0
B1
B2
B3
GPU
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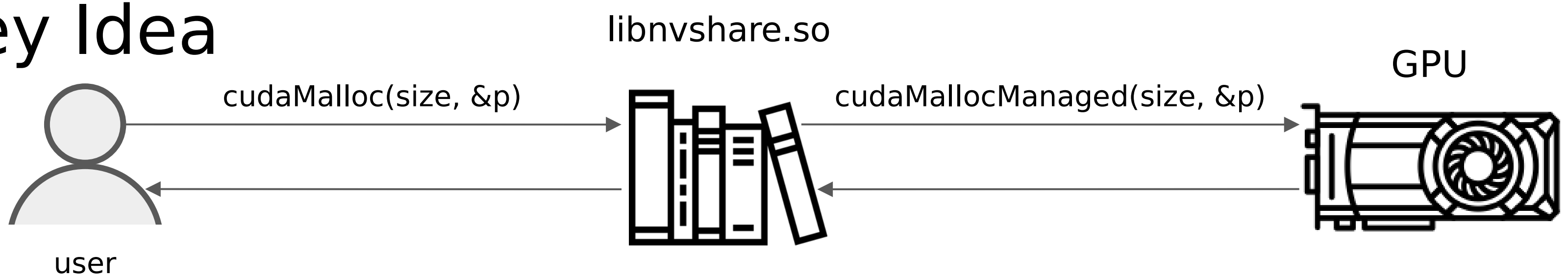
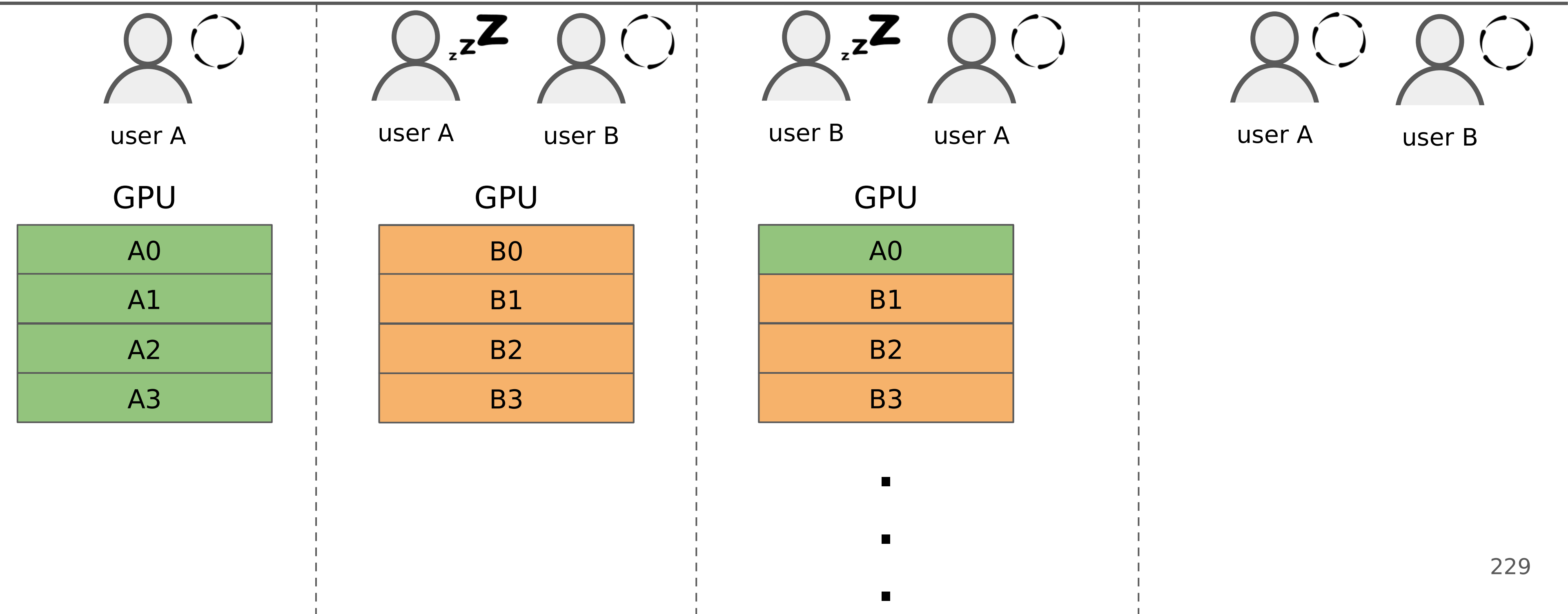
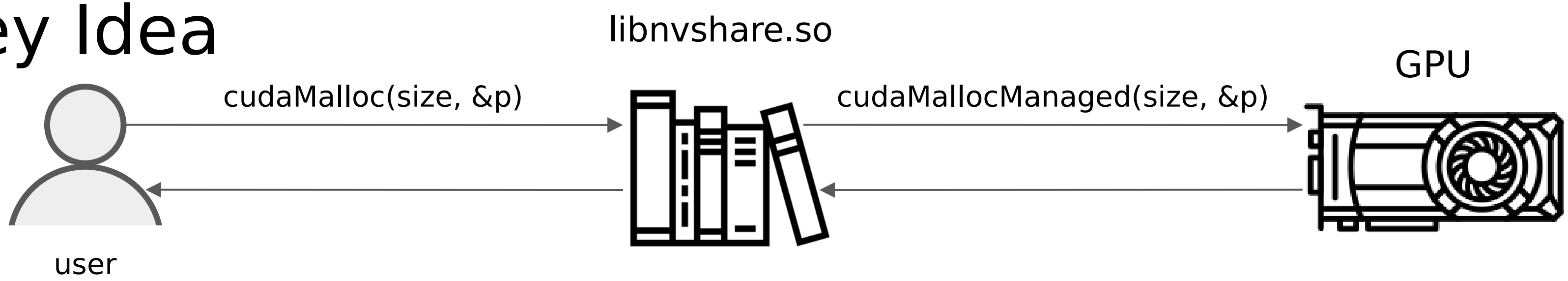
B1
B2
B3

Key Idea


libnvshare.so
GPU
cudaMalloc(size, &p)
cudaMallocManaged(size, &p)
user


user A
user A
user B
user B
user A
user A
user B
GPU
A0
A1
A2
A3
GPU
B0
B1
B2
B3
GPU
A0
B1
B2
B3

Key Idea


libnvshare.so
GPU
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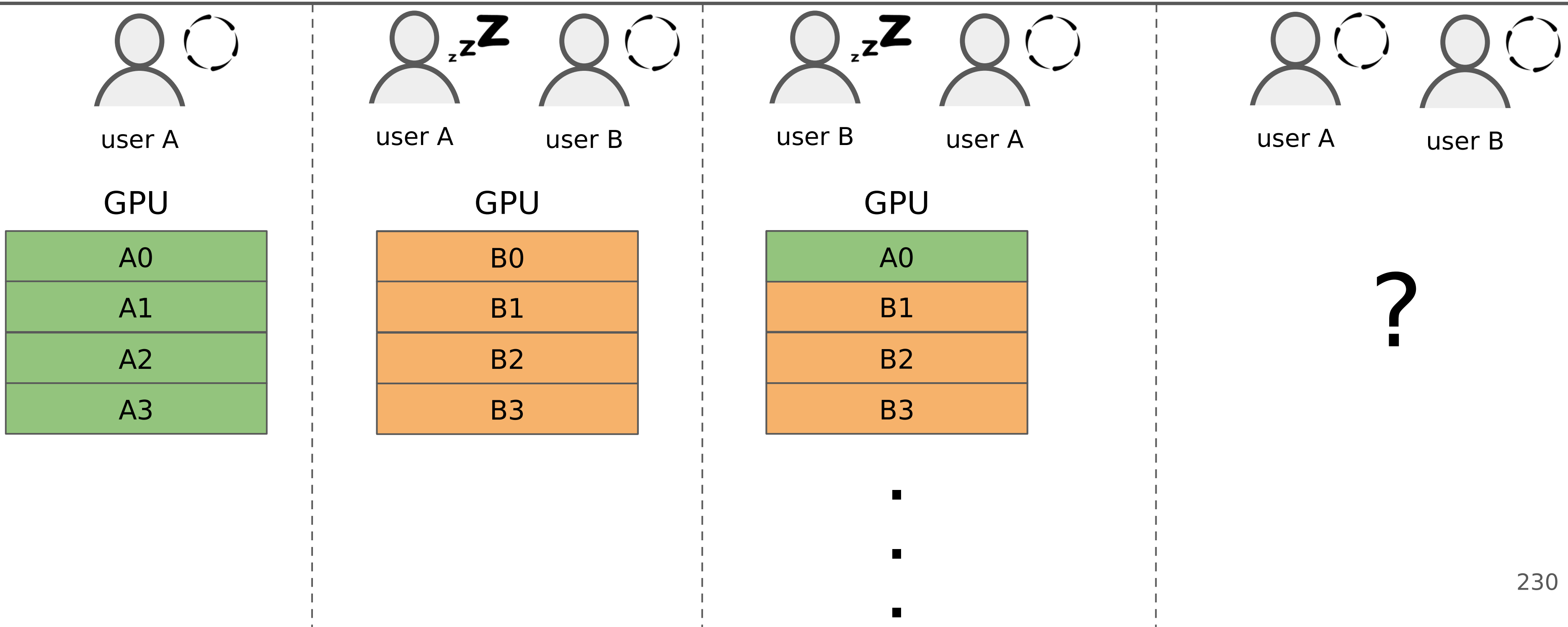
user


user A
user A
user B
user B
user A
user A
user B
GPU
A0
A1
A2
A3
GPU
B0
B1
B2
B3
GPU
A0
B1
B2
B3
?

When GPU bursts overlap

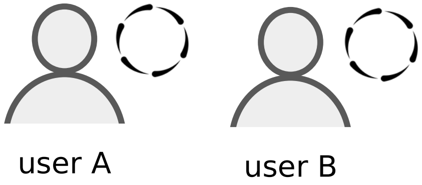
When GPU bursts overlap

When GPU bursts overlap

Sometimes

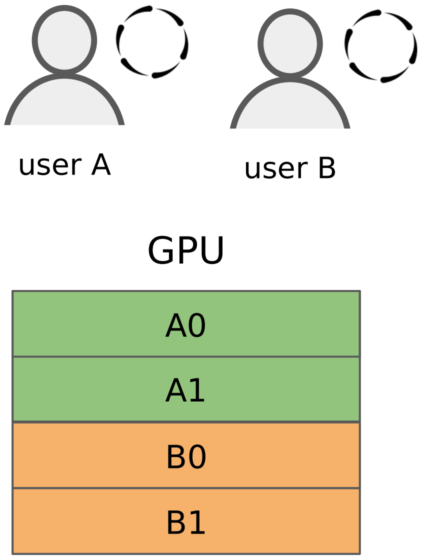
When GPU bursts overlap

Sometimes



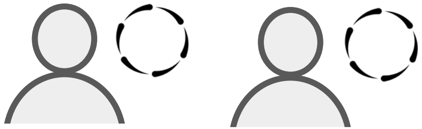
When GPU bursts overlap

Sometimes



When GPU bursts overlap

Sometimes



user A user B

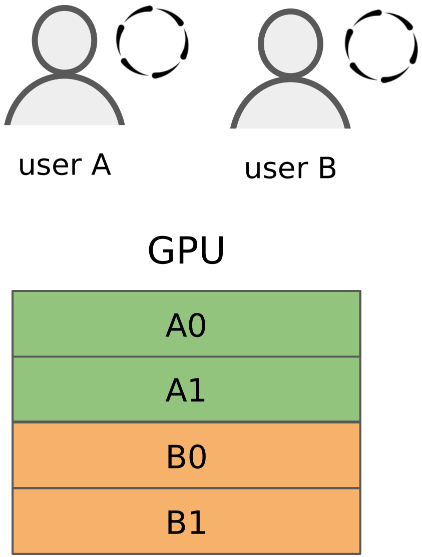
GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

When GPU bursts overlap

Sometimes

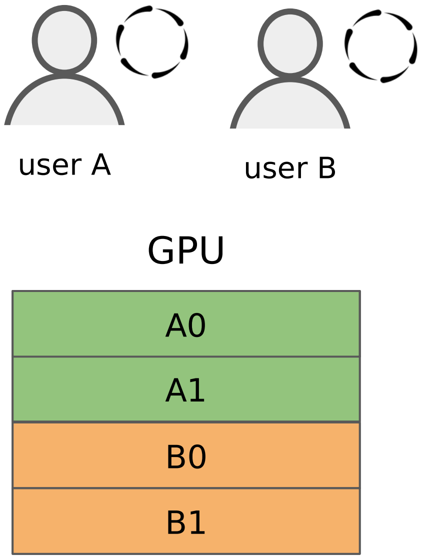


$\Sigma wss_i <$ GPU memory

No page faults

When GPU bursts overlap

Sometimes

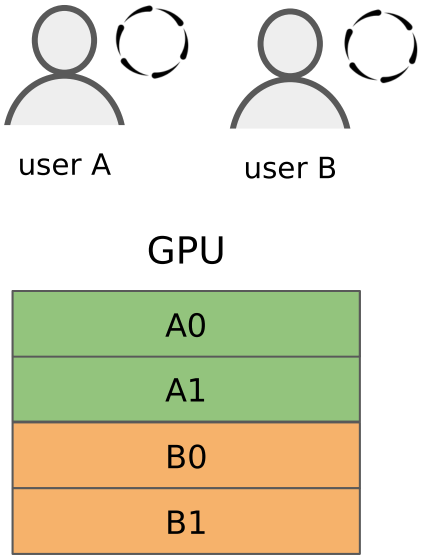


$\Sigma Wss_i <$ GPU memory

No page faults

When GPU bursts overlap

Sometimes | Other times

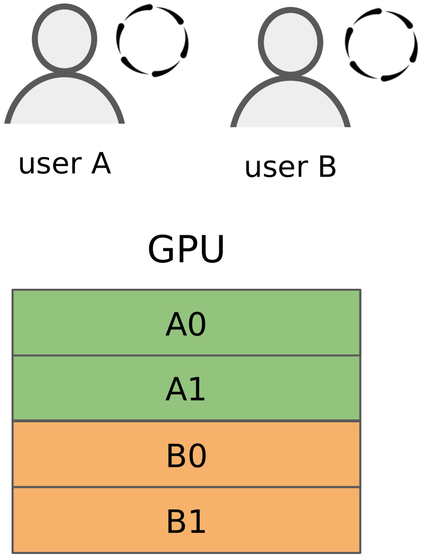


$\Sigma Wss_i <$ GPU memory

No page faults

When GPU bursts overlap

Sometimes | **Other times**



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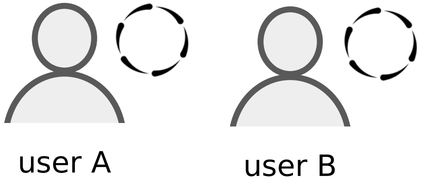
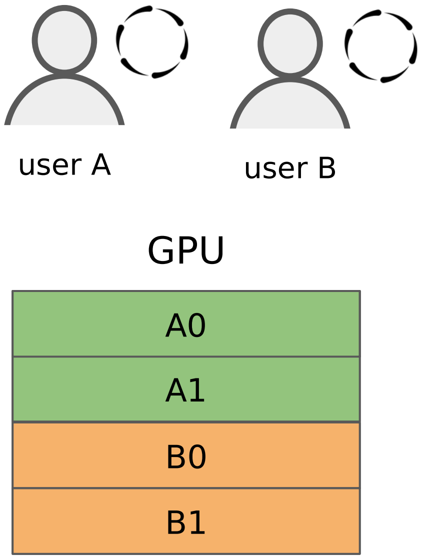
No page faults



When GPU bursts overlap

Sometimes	Other times



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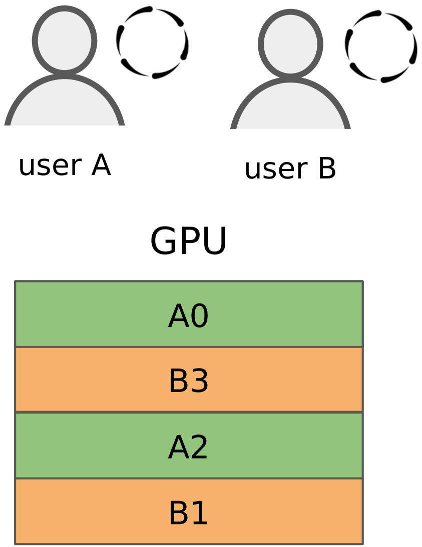
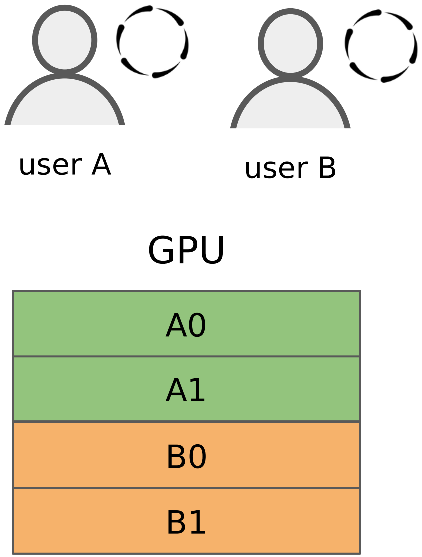
No page faults



When GPU bursts overlap

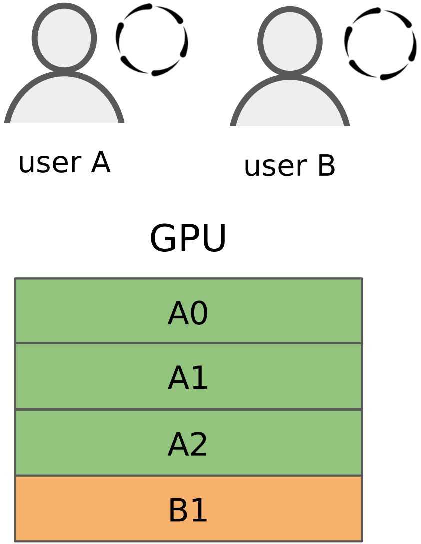
Sometimes



$\Sigma \text{Wss}_i <$ GPU memory

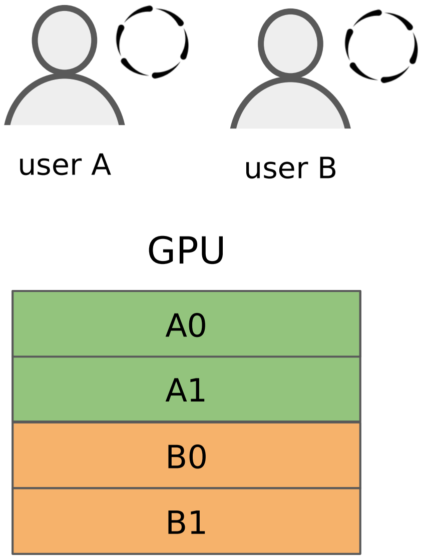
No page faults

Other times



When GPU bursts overlap

Sometimes



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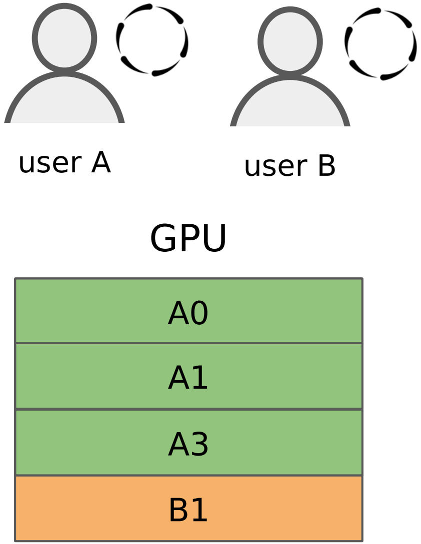
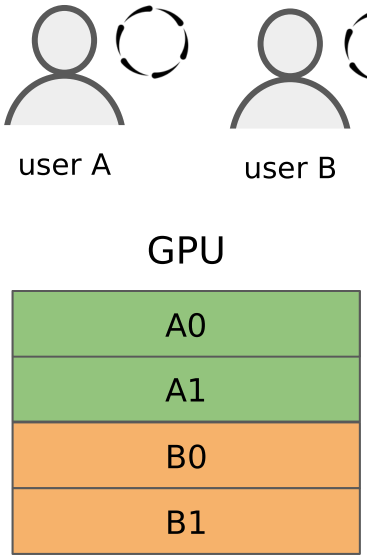
No page faults

Other times



When GPU bursts overlap

Sometimes



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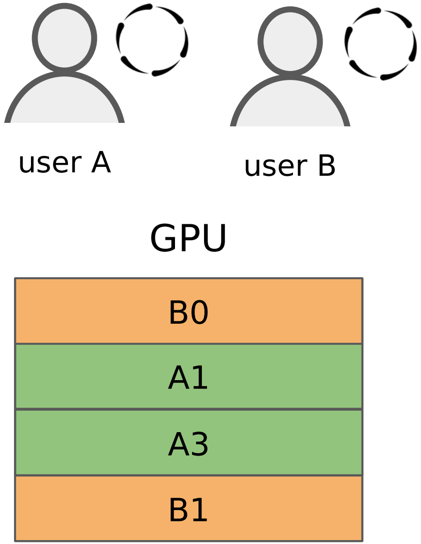
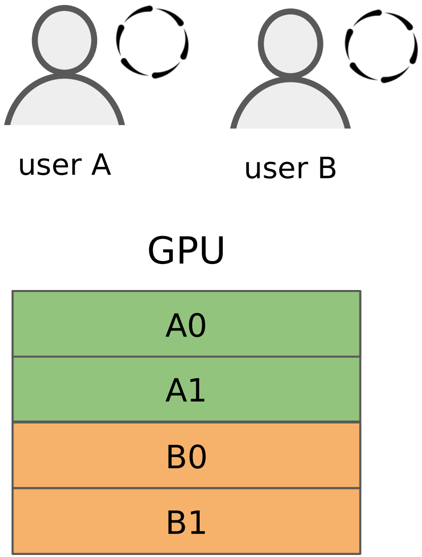
No page faults

Other times



When GPU bursts overlap

Sometimes



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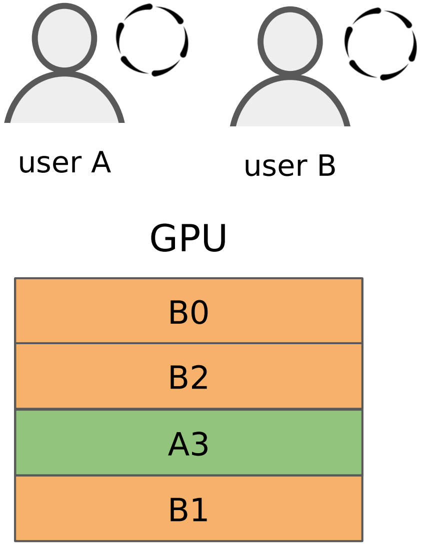
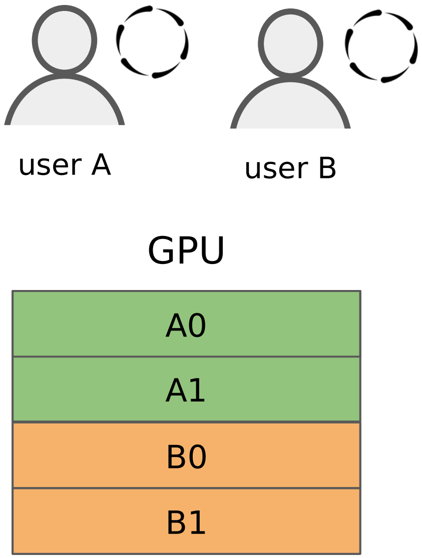
No page faults

Other times



When GPU bursts overlap

Sometimes



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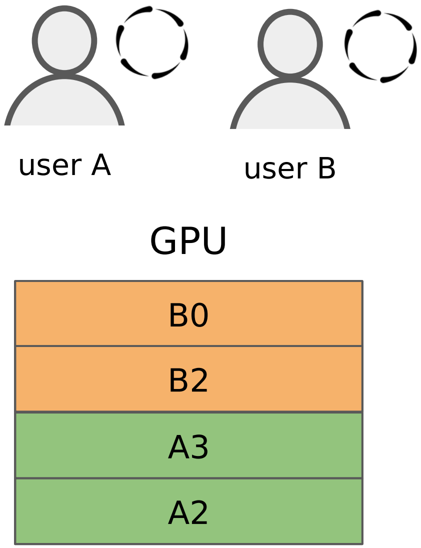
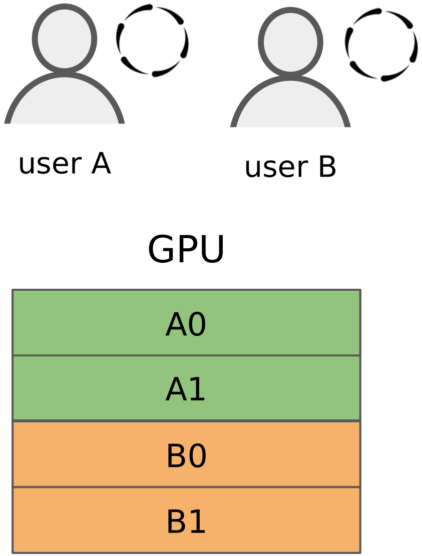
No page faults

Other times



When GPU bursts overlap

Sometimes



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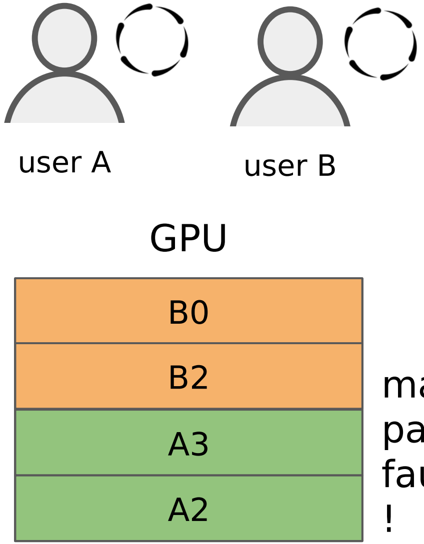
No page faults

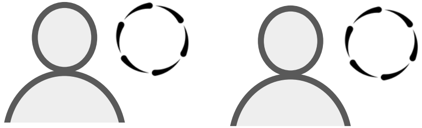
Other times



many page faults !

When GPU bursts overlap

Sometimes	Other times



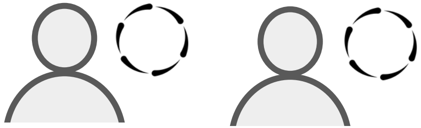
user A user B

GPU

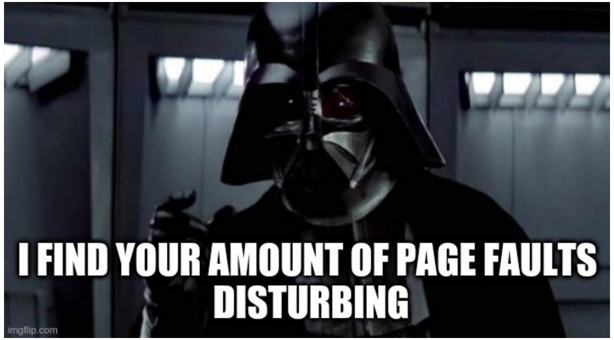
A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

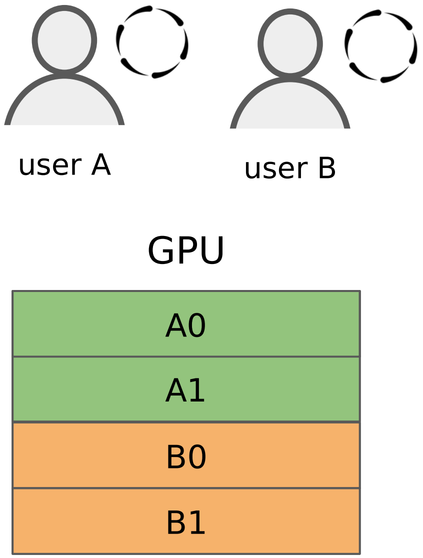


user A user B



When GPU bursts overlap

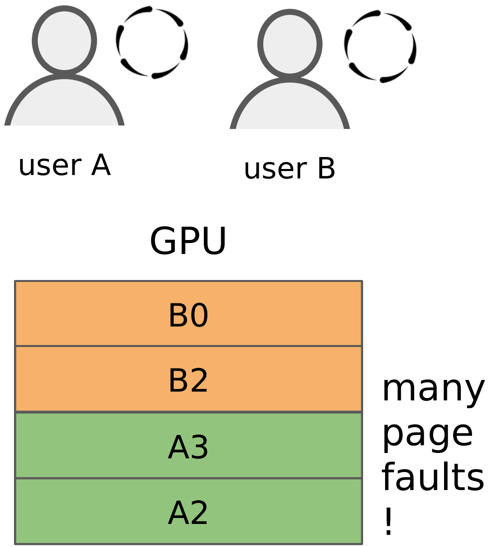
Sometimes



$\Sigma Wss_i <$ GPU memory

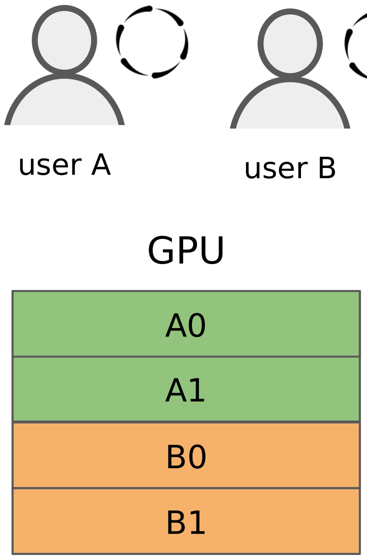
No page faults

Other times



When GPU bursts overlap

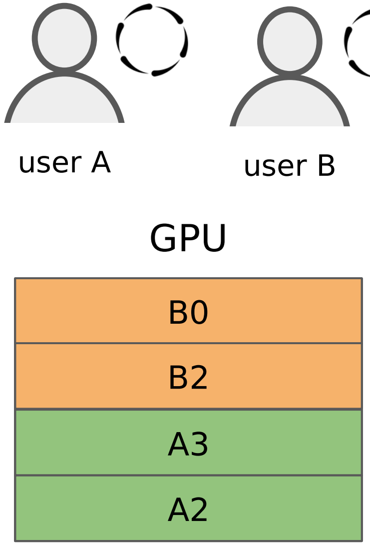
Sometimes



$\Sigma Wss_i <$ GPU memory

No page faults

Other times

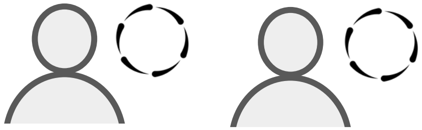


many page faults !

$\Sigma Wss_i >$ GPU memory

When GPU bursts overlap

Sometimes



user A

user B

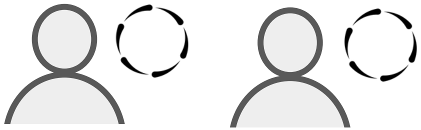
GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times



user A

user B

GPU

B0
B2
A3
A2

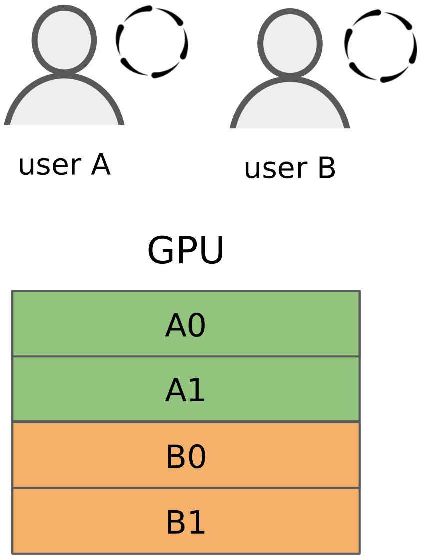
many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

When GPU bursts overlap

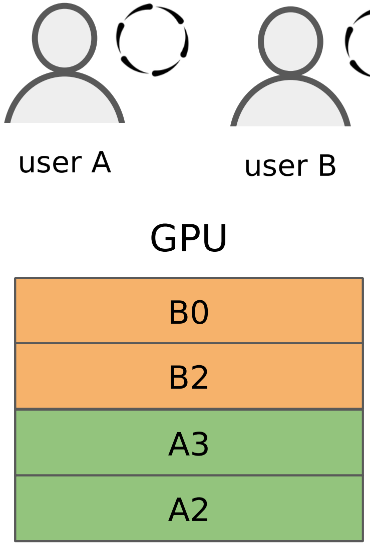
Sometimes



$\Sigma Wss_i <$ GPU memory

No page faults

Other times



many page faults !

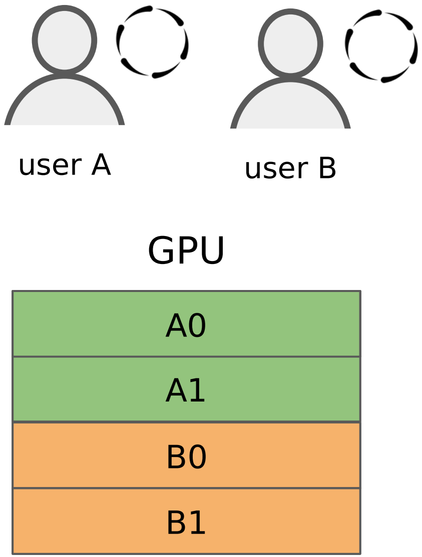
$\Sigma Wss_i >$ GPU memory

Thrashing!

When GPU bursts overlap

Sometimes	Other times	Solution

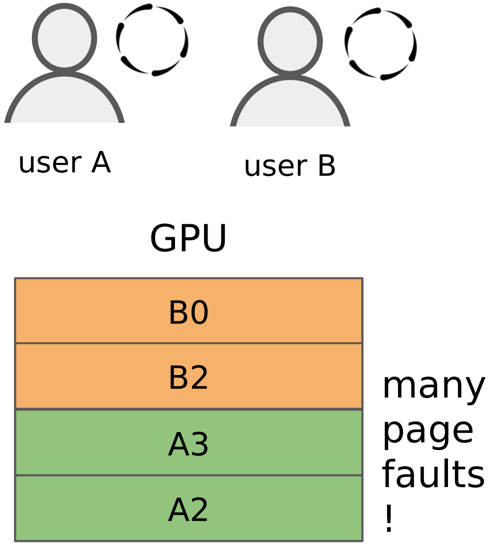
Sometimes



$\Sigma Wss_i < \text{GPU memory}$

No page faults

Other times



$\Sigma Wss_i > \text{GPU memory}$

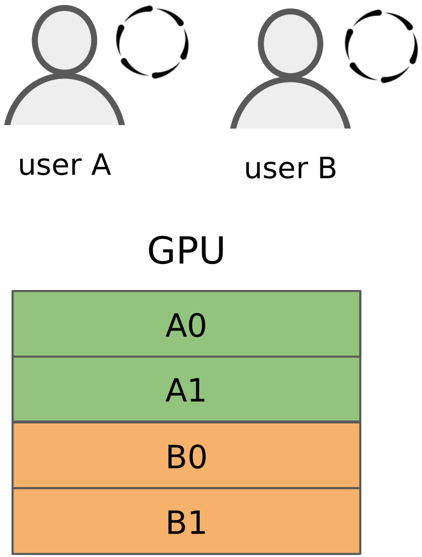
Thrashing!

Solution

When GPU bursts overlap

Sometimes	Other times	Solution

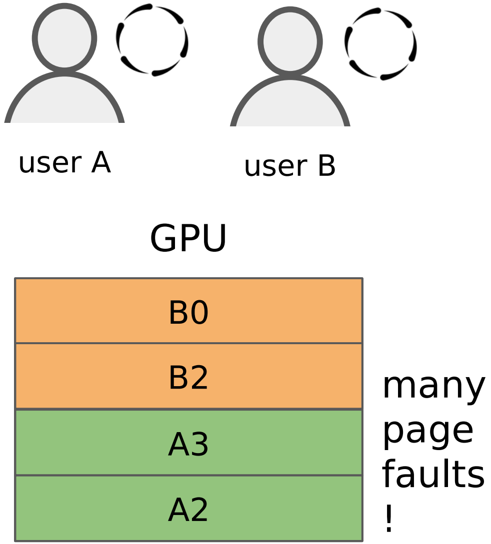
Sometimes



$\Sigma Wss_i <$ GPU memory

No page faults

Other times

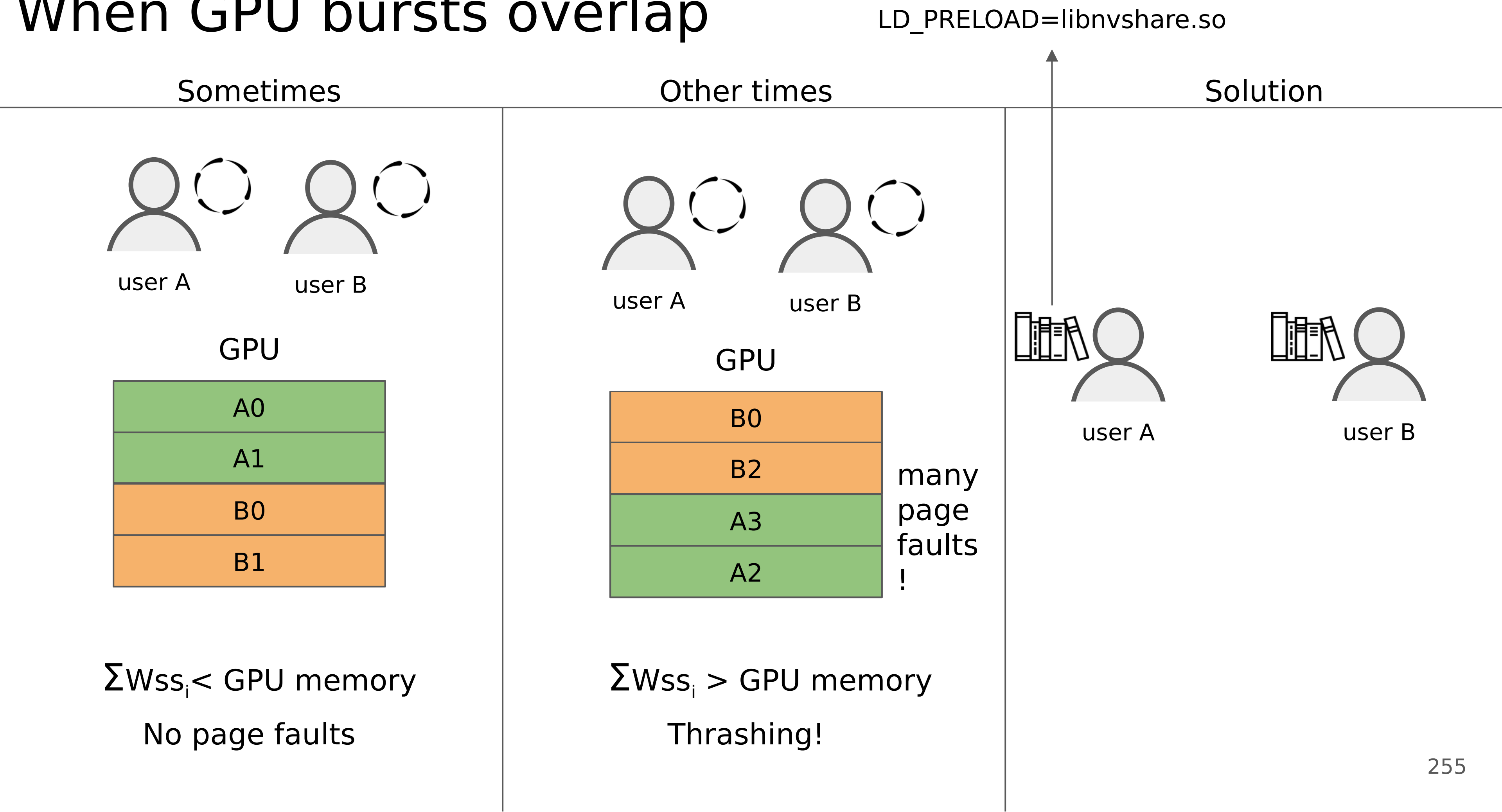


$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

When GPU bursts overlap



When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes

user A

user B

GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times

user A

user B

GPU

B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

user A

user B

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes

user A

user B

GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times

user A

user B

GPU

B0
B2
A3
A2

many page faults !

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Thrashing!

Solution

user A

user B

When GPU bursts overlap

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B0
B2
A3
A2

many page faults !

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Thrashing!

Solution

user A

user B

GPU

B0
B2
A3
A2

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GPU

B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

user A

user B

GPU

B0
B2
A3
A2

- pause only GPU computations

When GPU bursts overlap

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Sometimes

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B1

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No page faults

Other times

user A

user B

GPU

B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

GO

user A

user B

GPU

B0
B2
A3
A2

- pause only GPU computations

When GPU bursts overlap

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B1

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A3
A2

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A2

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B2
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A2

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A1
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GPU

B0
B2
A3
A2

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GPU

B0
B2
A3
A2

many page faults !

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Thrashing!

Solution

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user B

GPU

A0
A1
A3
A2

- pause only GPU computations

When GPU bursts overlap

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GPU

A0
A1
B0
B1

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No page faults

Other times

user A user B

GPU

B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

GO

WAIT

user A user B

GPU

A0
A1
A3
A2

- pause only GPU computations

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes

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GPU

A0
A1
B0
B1

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No page faults

Other times

user A   user B

GPU

B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

GO

WAIT

user A   user B

GPU

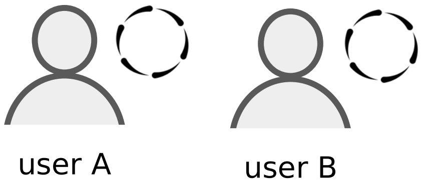
A0
A1
A3
A2

- pause only GPU computations

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes



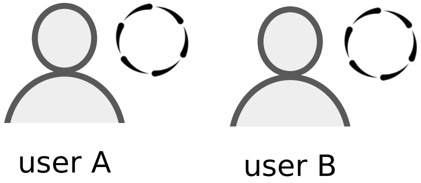
GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times



GPU

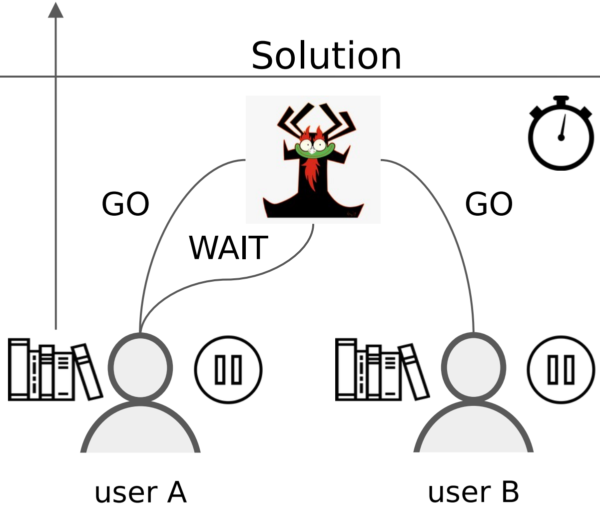
B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution



GPU

A0
A1
A3
A2

- pause only GPU computations

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

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user B

GPU

A0
A1
B0
B1

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No page faults

Other times

user A

user B

GPU

B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

GO

WAIT

GO

user A

user B

GPU

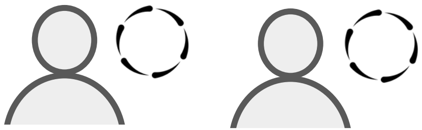
A0
A1
A3
A2

- pause only GPU computations

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes



user A user B

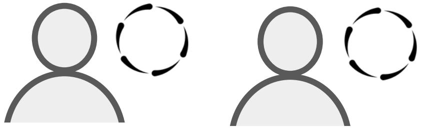
GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times



user A user B

GPU

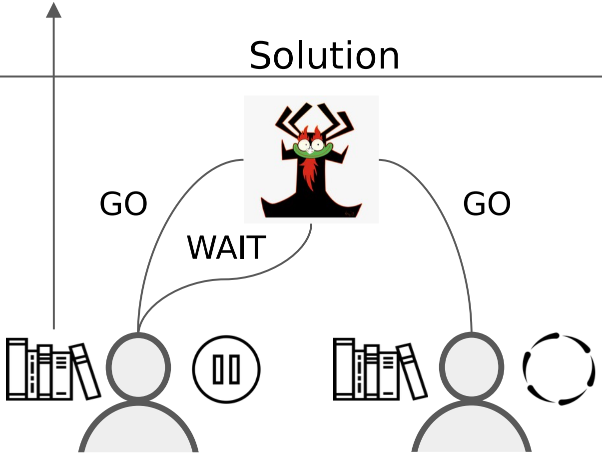
B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution



user A user B

GPU

A0
A1
B0
A2

- pause only GPU computations

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes

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GPU

A0
A1
B0
B1

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No page faults

Other times

user A user B

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B0
B2
A3
A2

many page faults !

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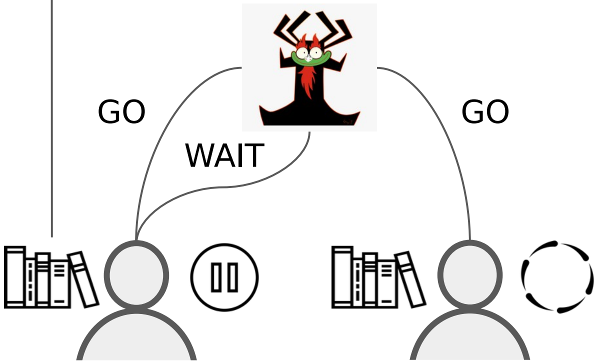

user A user B

GPU

A0
A1
B0
B1

- pause only GPU computations

When GPU bursts overlap

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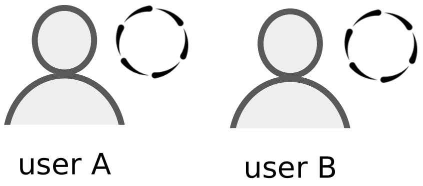


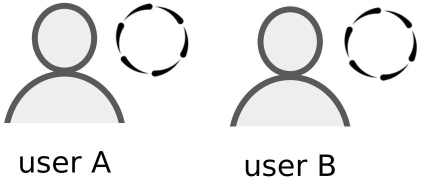
GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times



GPU

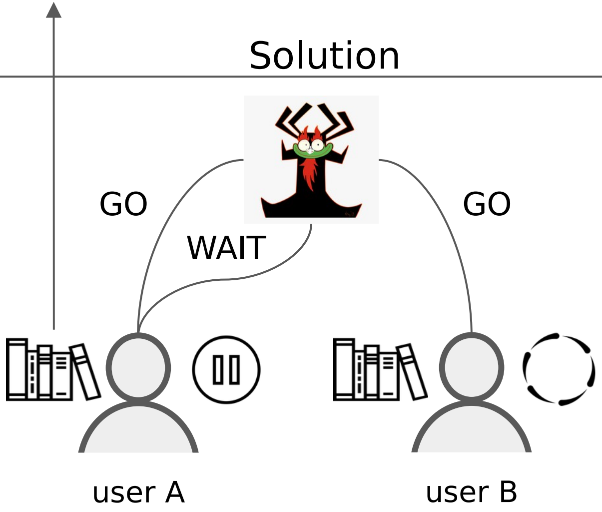
B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution



GPU

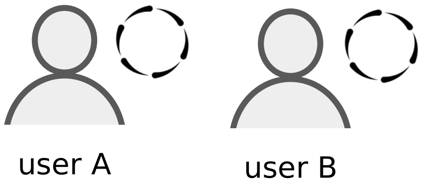
B2
A1
B0
B1

- pause only GPU computations

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes



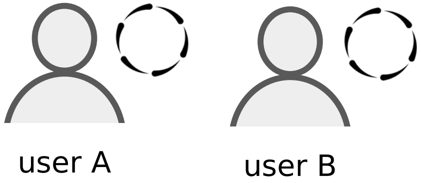
GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times



GPU

B0
B2
A3
A2

many page faults !

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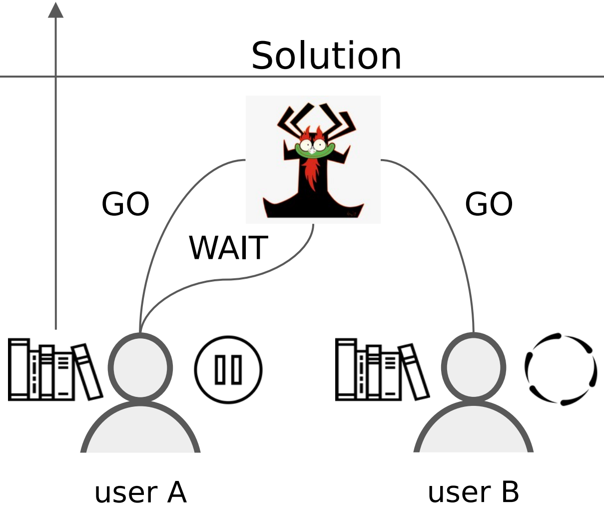
Thrashing!

Solution



GPU

B2
B3
B0
B1

- pause only GPU computations

When GPU bursts overlap

LD_PRELOAD=libnvshare.so

Sometimes

user A

user B

GPU

A0
A1
B0
B1

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No page faults

Other times

user A

user B

GPU

B0
B2
A3
A2

many page faults !

$\Sigma Wss_i >$ GPU memory

Thrashing!

Solution

GO

WAIT

GO

user A

user B

GPU

B2
B3
B0
B1

- pause only GPU computations

When GPU bursts overlap

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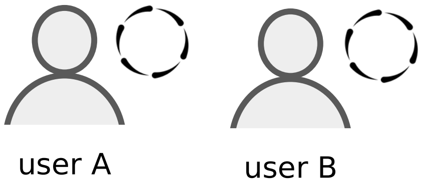
Sometimes



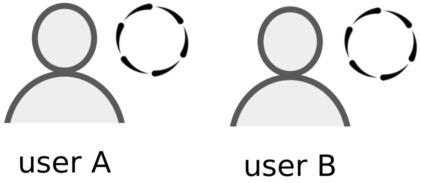
GPU

A0
A1
B0
B1

$\Sigma Wss_i <$ GPU memory

No page faults

Other times



GPU

B0
B2
A3
A2

many page faults !

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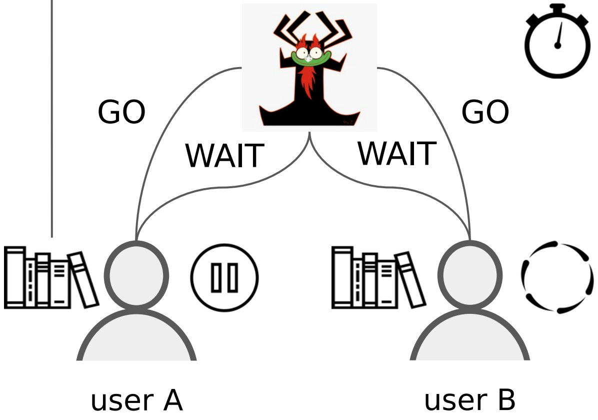
Thrashing!

Solution



GPU

B2
B3
B0
B1

- pause only GPU computations

Anti-thrashing idea

Anti-thrashing idea

- WSS > GPU Memory

Anti-thrashing idea

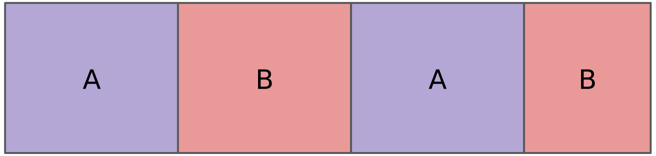
- WSS > GPU Memory

Default case:

Anti-thrashing idea

- WSS > GPU Memory

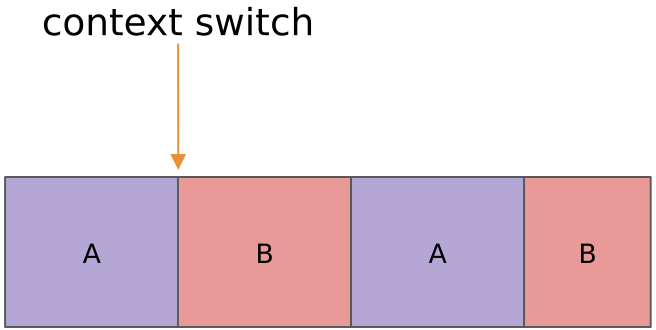
Default case:



Anti-thrashing idea

- WSS > GPU Memory

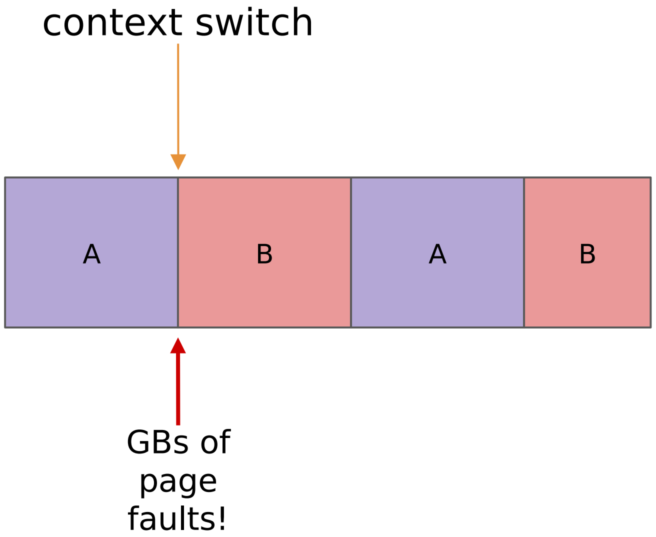
<u>Default case:</u>



Anti-thrashing idea

- WSS > GPU Memory

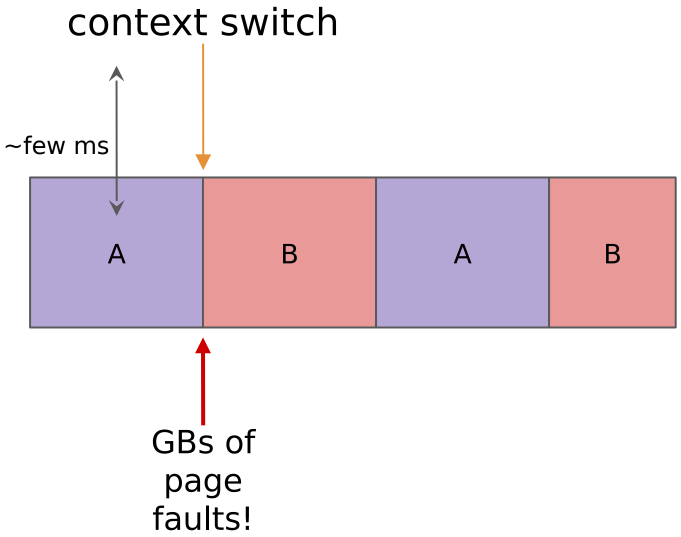
Default case:



Anti-thrashing idea

- WSS > GPU Memory

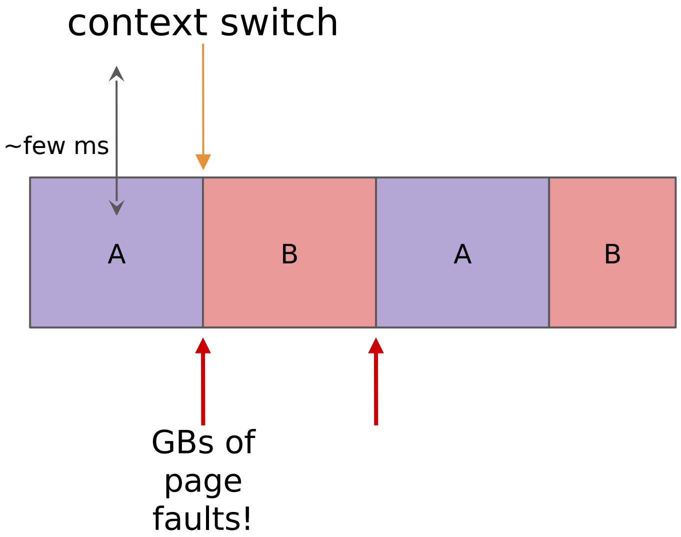
<u>Default case:</u>



Anti-thrashing idea

- WSS > GPU Memory

Default case:



Anti-thrashing idea

- WSS > GPU Memory

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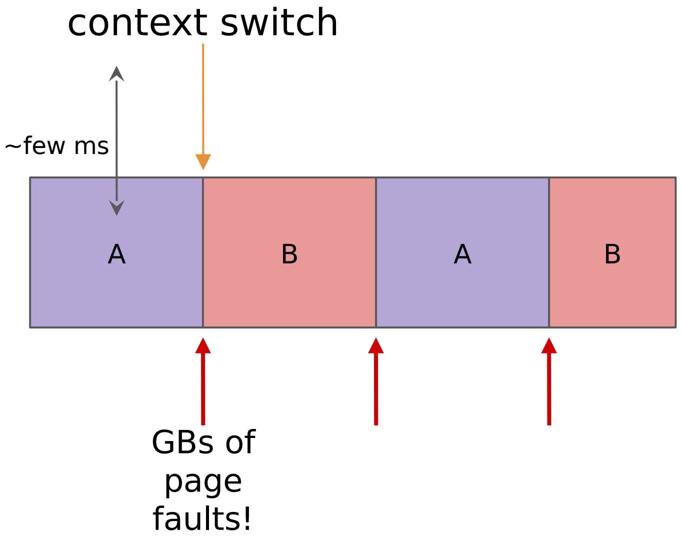
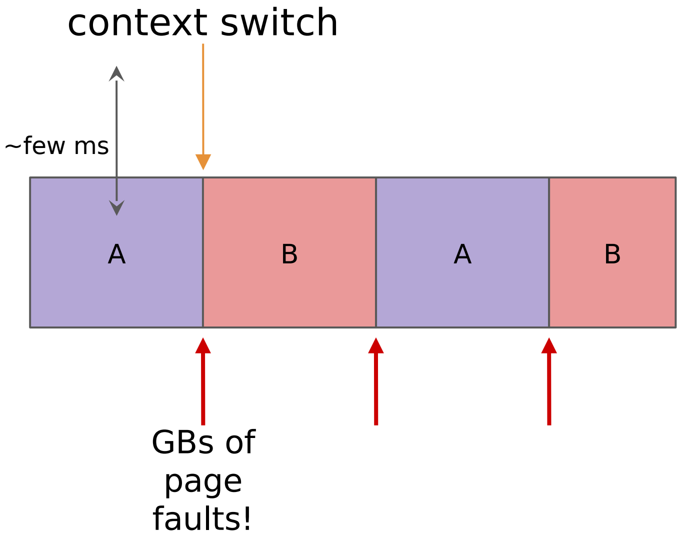


Anti-thrashing idea

- WSS > GPU Memory

<u>Default case:</u>

- memory swaps happen too frequently



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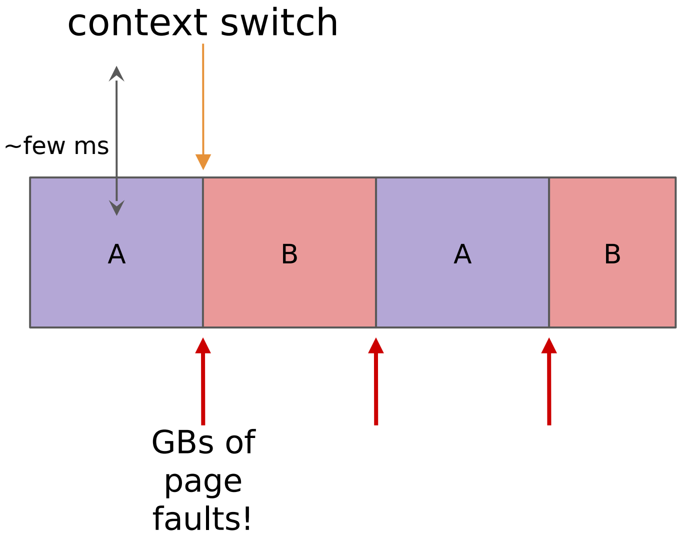

Anti-thrashing idea

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Default case:

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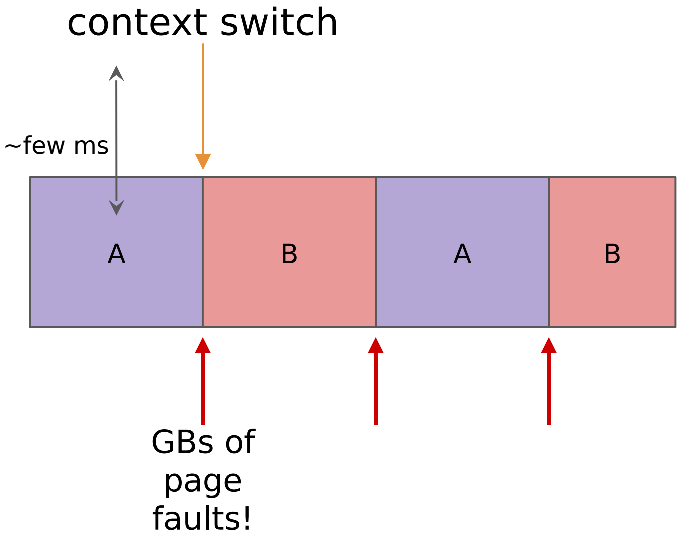

anti-thrashing mechanism:

Anti-thrashing idea

- WSS > GPU Memory

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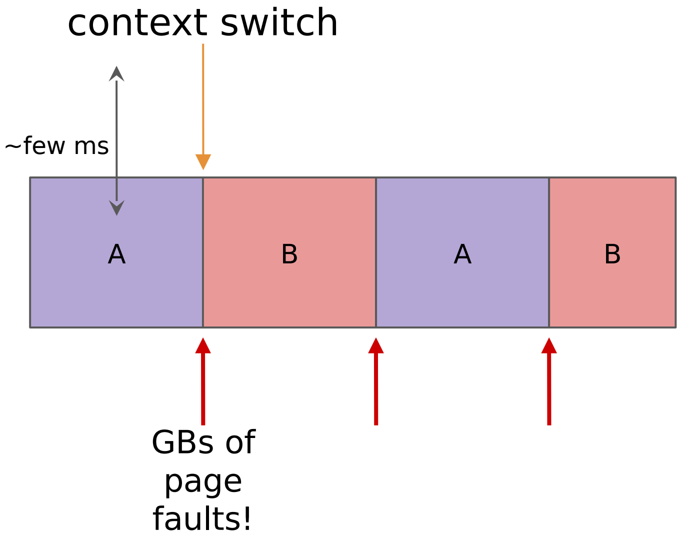
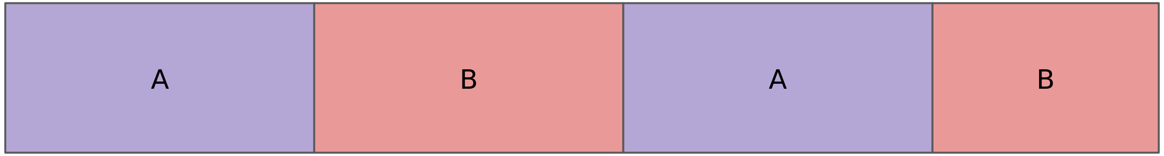
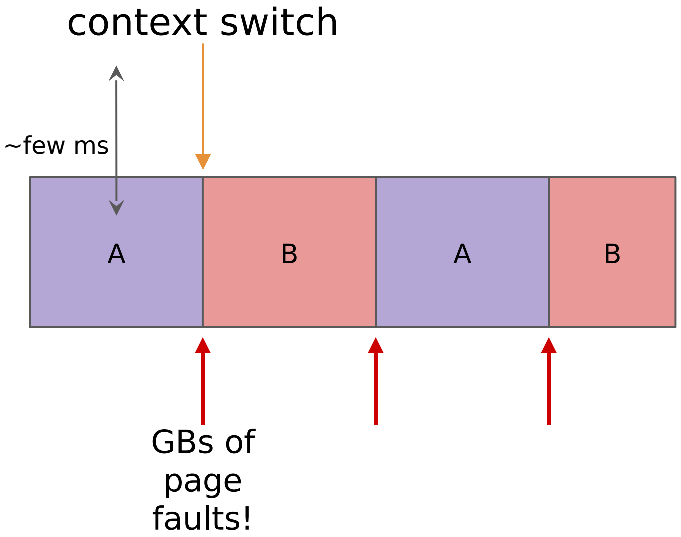


<u>anti-thrashing mechanism:</u>



Anti-thrashing idea

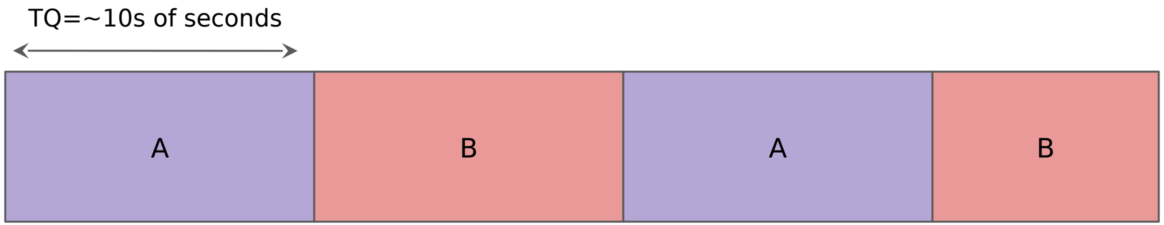
- WSS > GPU Memory



Default case:

- memory swaps happen too frequently
- Thrashing!

anti-thrashing mechanism:



Anti-thrashing idea

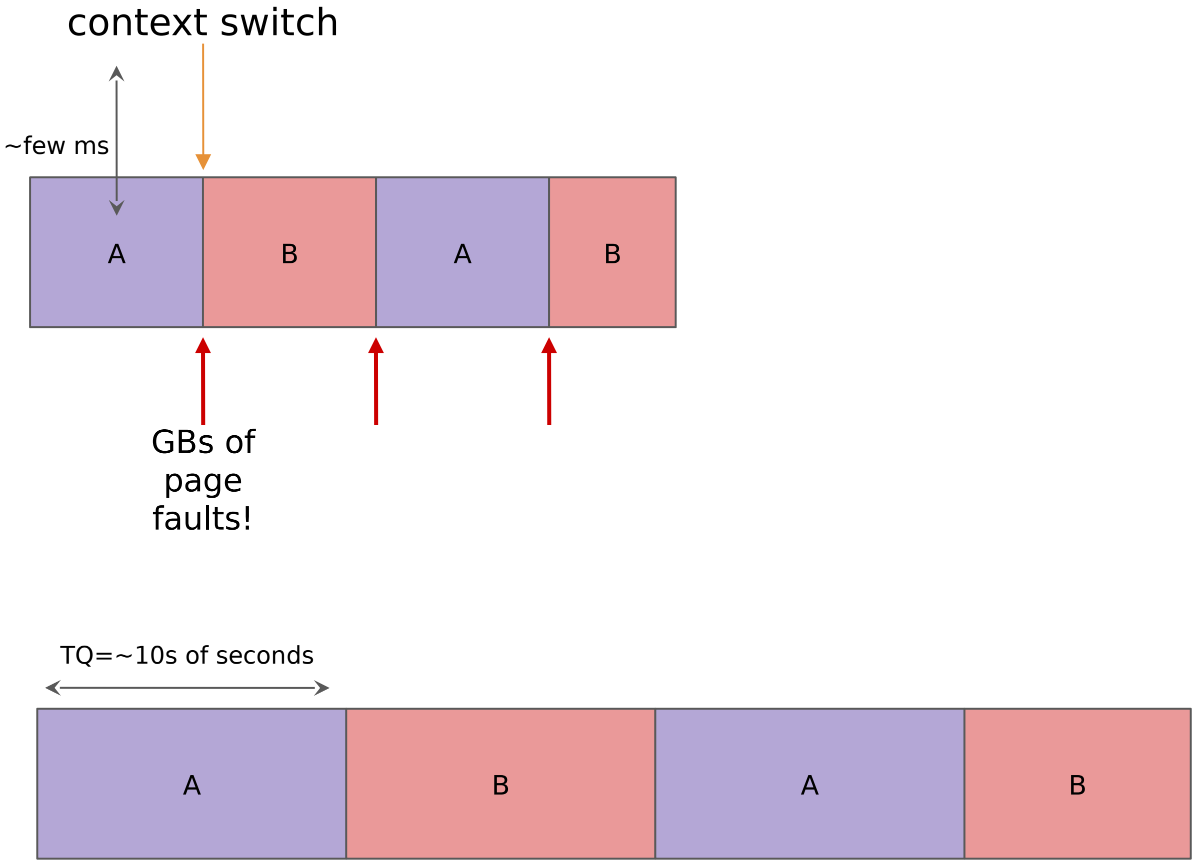
- WSS > GPU Memory

Default case:

- memory swaps happen too frequently
- Thrashing!

anti-thrashing mechanism:

- orders of magnitude fewer memory swaps

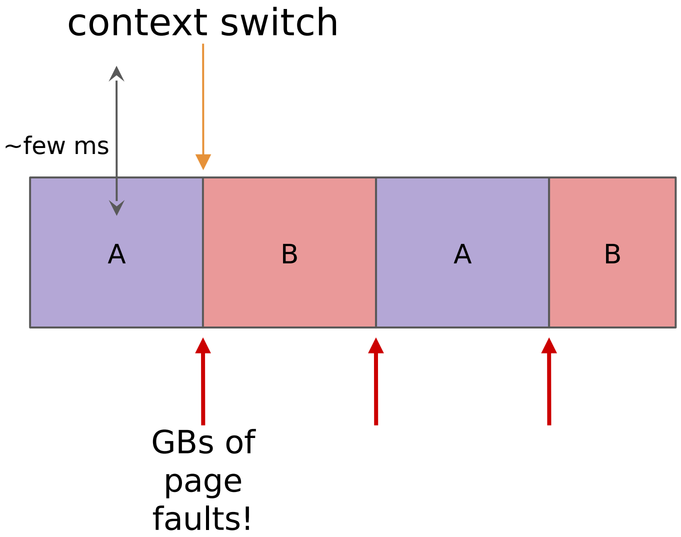


Anti-thrashing idea

- WSS > GPU Memory

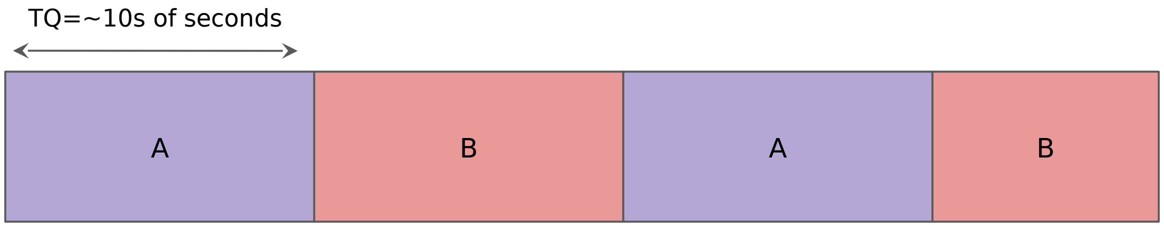
Default case:

- memory swaps happen too frequently
- Thrashing!



anti-thrashing mechanism:

- orders of magnitude fewer memory swaps
- Cooperative Scheduling

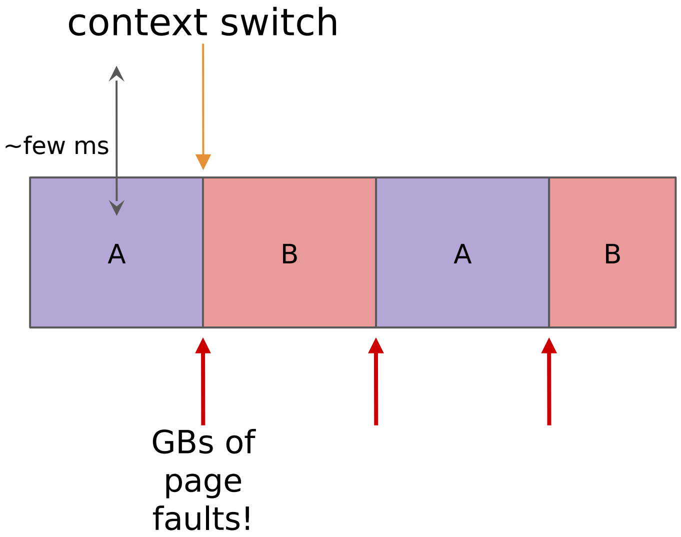


Anti-thrashing idea

- WSS > GPU Memory

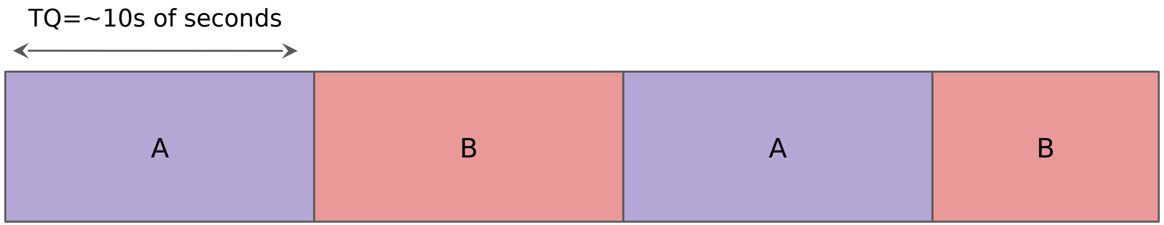
Default case:

- memory swaps happen too frequently
- Thrashing!



anti-thrashing mechanism:

- orders of magnitude fewer memory swaps
- Cooperative Scheduling
- No Thrashing!



Demo

Evaluation

Evaluation

- 16-core CPU (Intel Xeon 2.3 GHz - Haswell), 104 GB of RAM and an NVIDIA Tesla P100 GPU (16 GB).

Evaluation

- 16-core CPU (Intel Xeon 2.3 GHz - Haswell), 104 GB of RAM and an NVIDIA Tesla P100 GPU (16 GB).

- non-interactive (conventional) tasks

Evaluation

- 16-core CPU (Intel Xeon 2.3 GHz - Haswell), 104 GB of RAM and an NVIDIA Tesla P100 GPU (16 GB).
- non-interactive (conventional) tasks
- measure **T**otal **C**ompletion **T**ime

Evaluation

- 16-core CPU (Intel Xeon 2.3 GHz - Haswell), 104 GB of RAM and an NVIDIA Tesla P100 GPU (16 GB).
- non-interactive (conventional) tasks
- measure **T**otal **C**ompletion **T**ime

Programs

Name	Working Set Size	GPU/CPU ratio
small_90	7.2 GB	90/10
small_50	7.2 GB	50/50
big_90	15.3 GB	90/10
big_50	15.3 GB	50/50

Evaluation

- 16-core CPU (Intel Xeon 2.3 GHz - Haswell), 104 GB of RAM and an NVIDIA Tesla P100 GPU (16 GB).
- non-interactive (conventional) tasks
- measure **T**otal **C**ompletion **T**ime

Programs

Name	**Working Set Size**	**GPU/CPU ratio**
small_90	7.2 GB	90/10
small_50	7.2 GB	50/50
big_90	15.3 GB	90/10
big_50	15.3 GB	50/50

Evaluation

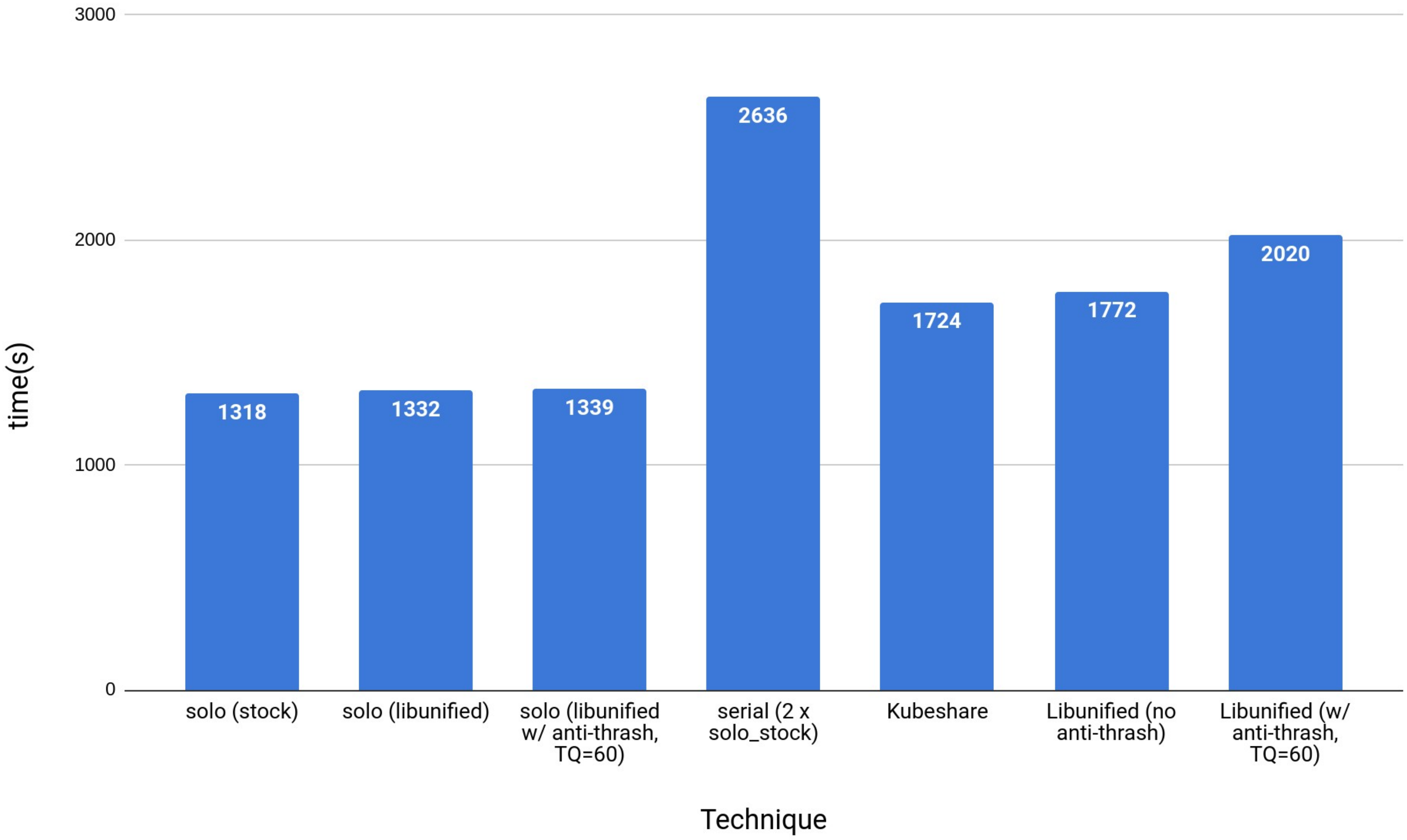
- 16-core CPU (Intel Xeon 2.3 GHz - Haswell), 104 GB of RAM and an NVIDIA Tesla P100 GPU (16 GB).
- non-interactive (conventional) tasks
- measure **T**otal **C**ompletion **T**ime

Programs

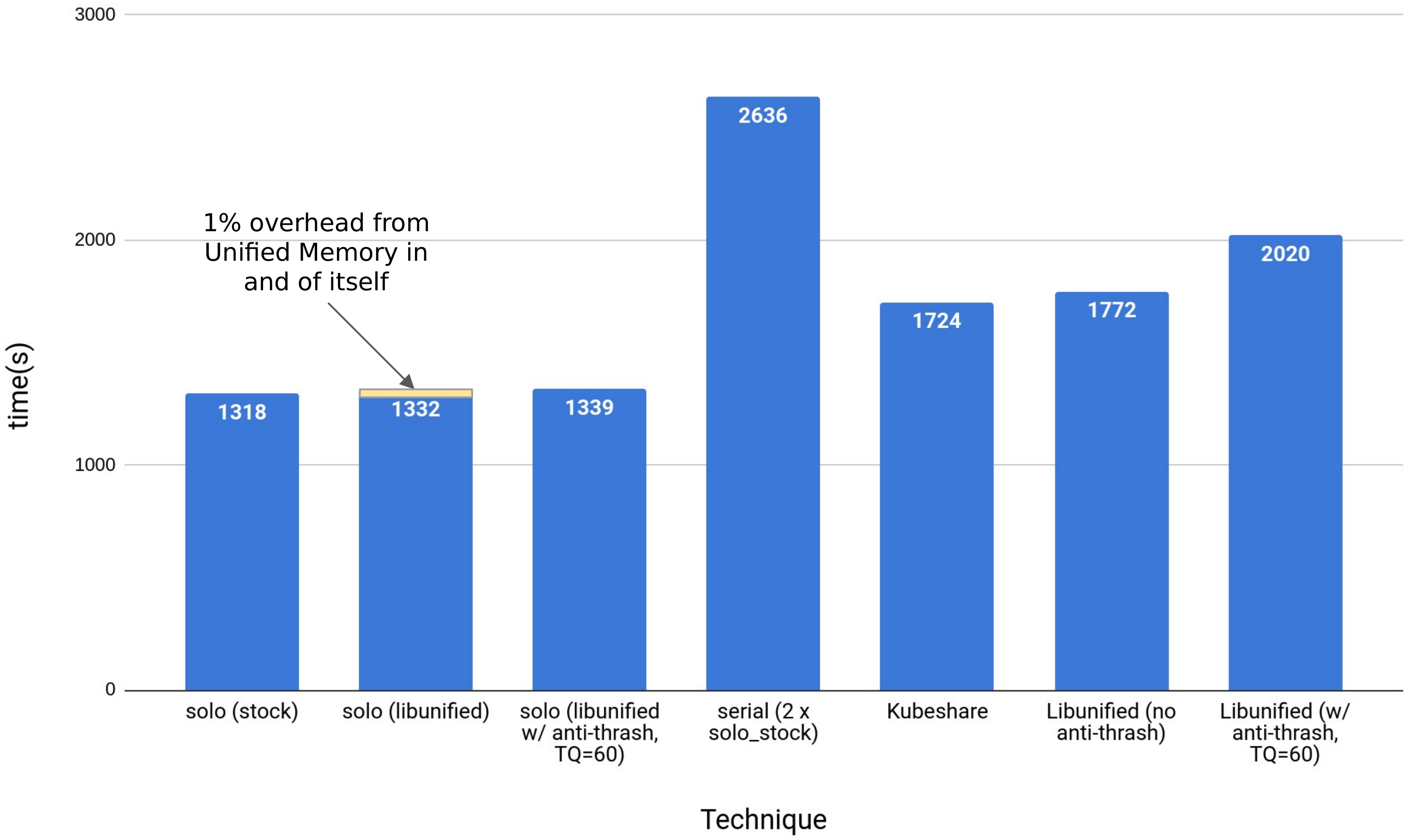
Name	Working Set Size	GPU/CPU ratio
small_90	7.2 GB	90/10
small_50	7.2 GB	50/50
big_90	15.3 GB	90/10
big_50	15.3 GB	50/50

- Running 2 x big_{50,90} in parallel causes **thrashing**!

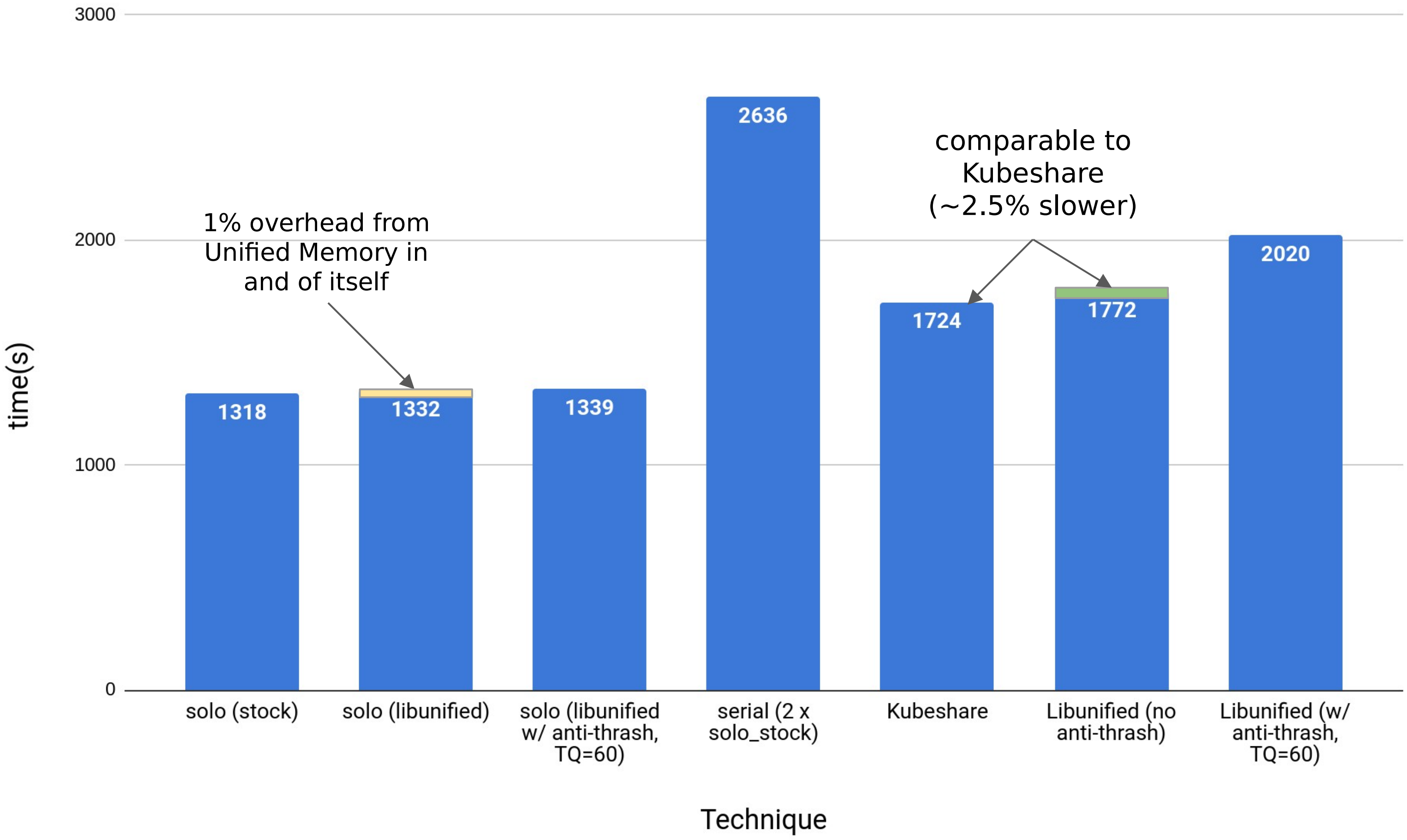
Results for small_50



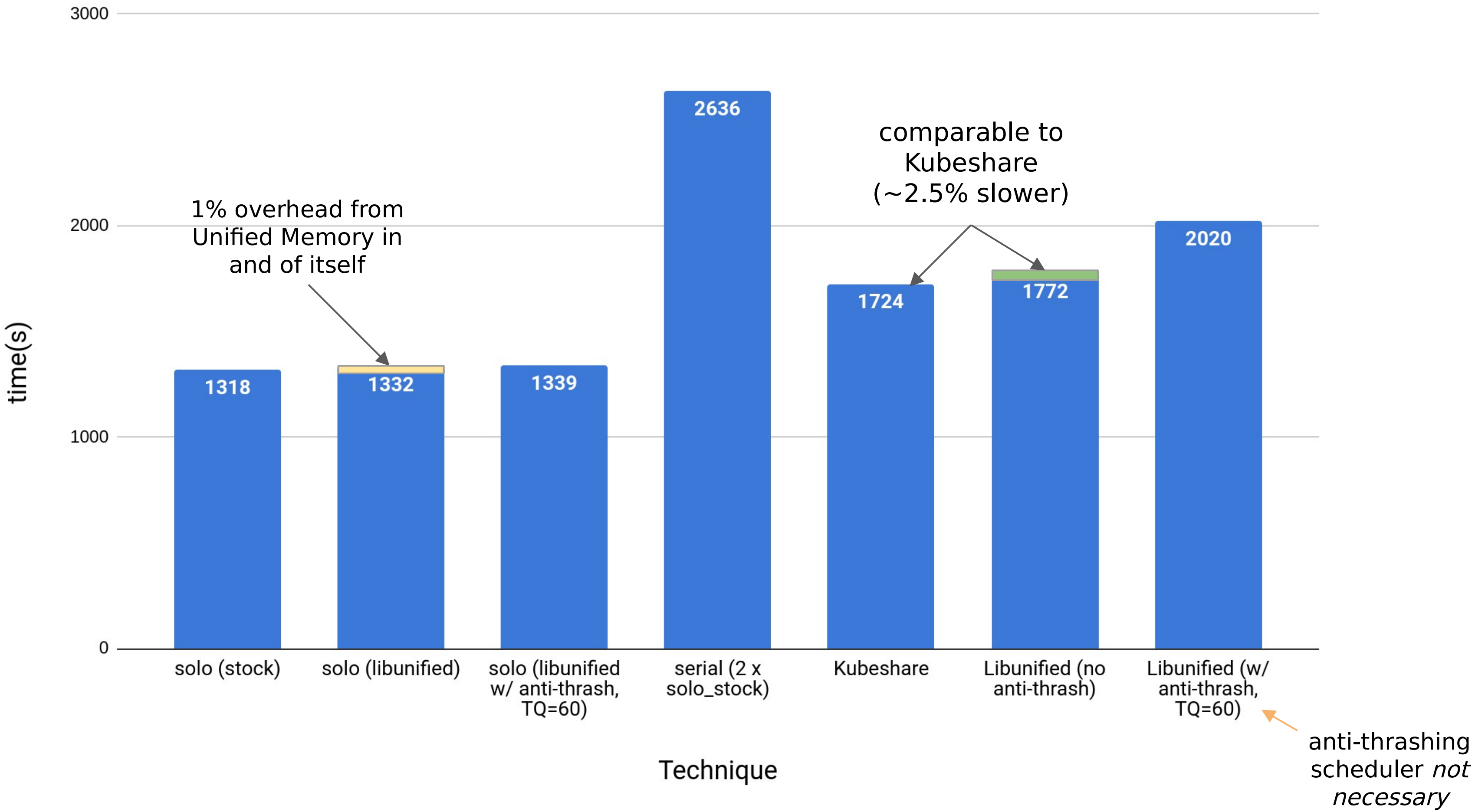
Results for small_50



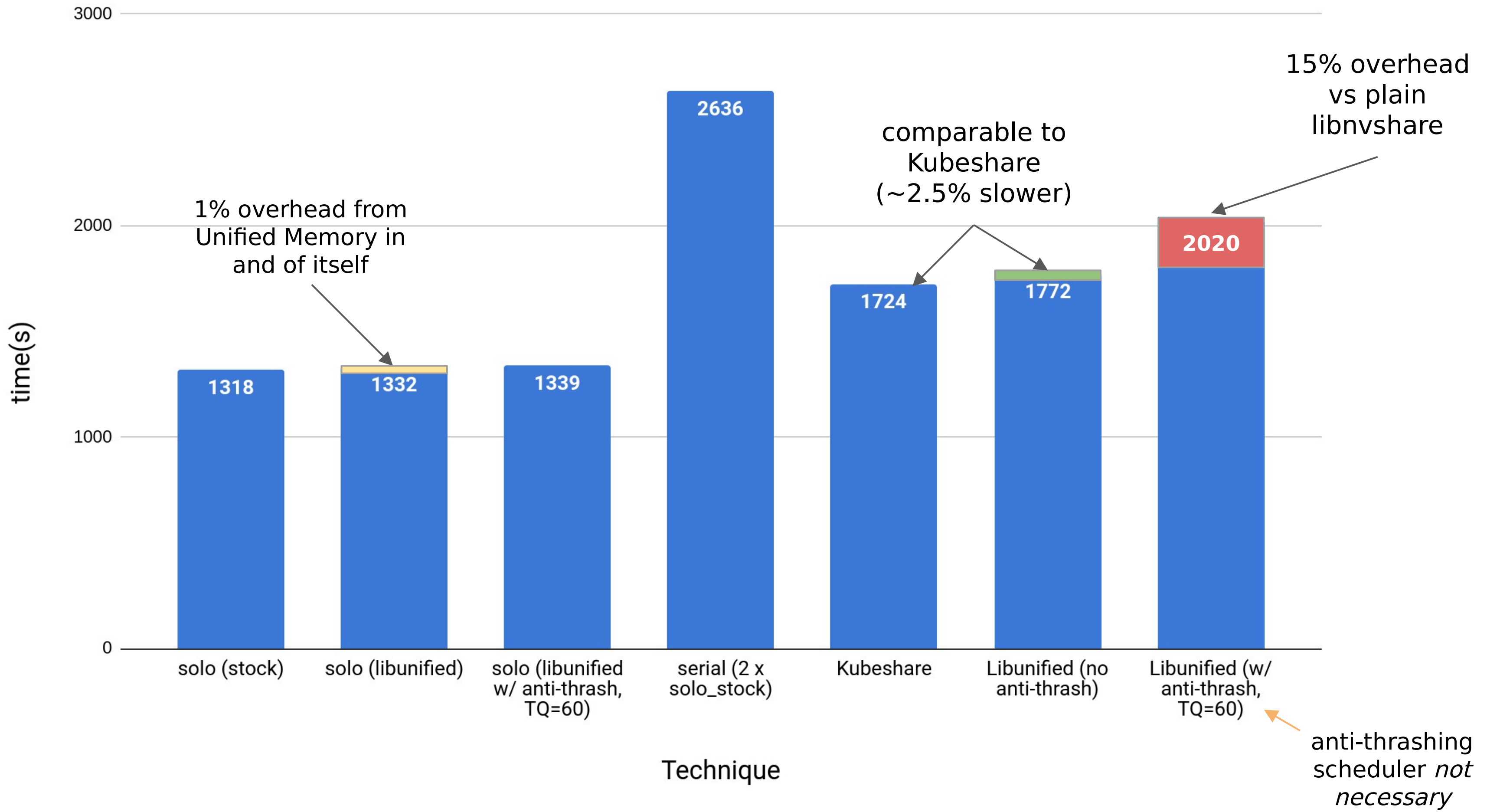
Results for small_50



Results for small_50



Results for small_50



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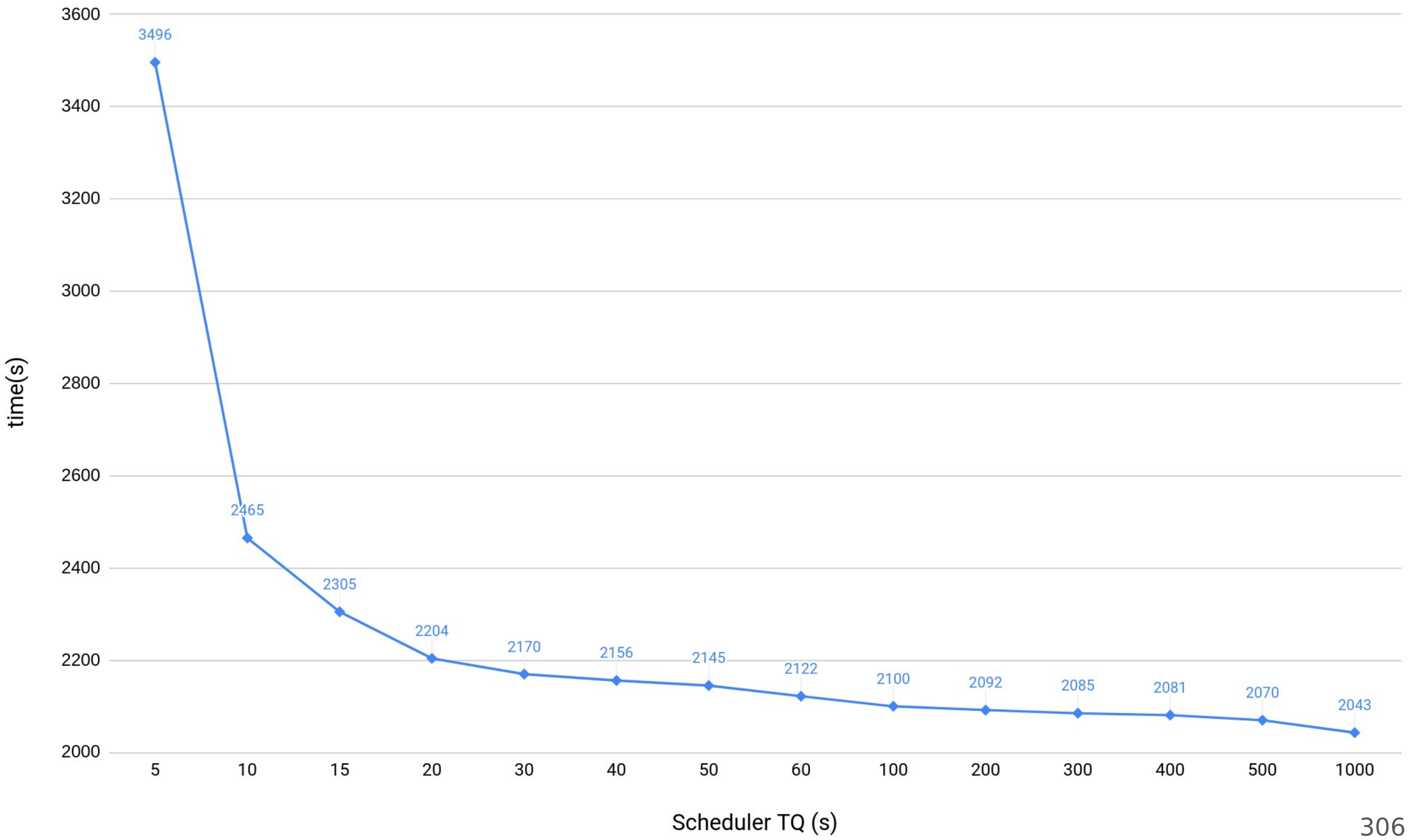
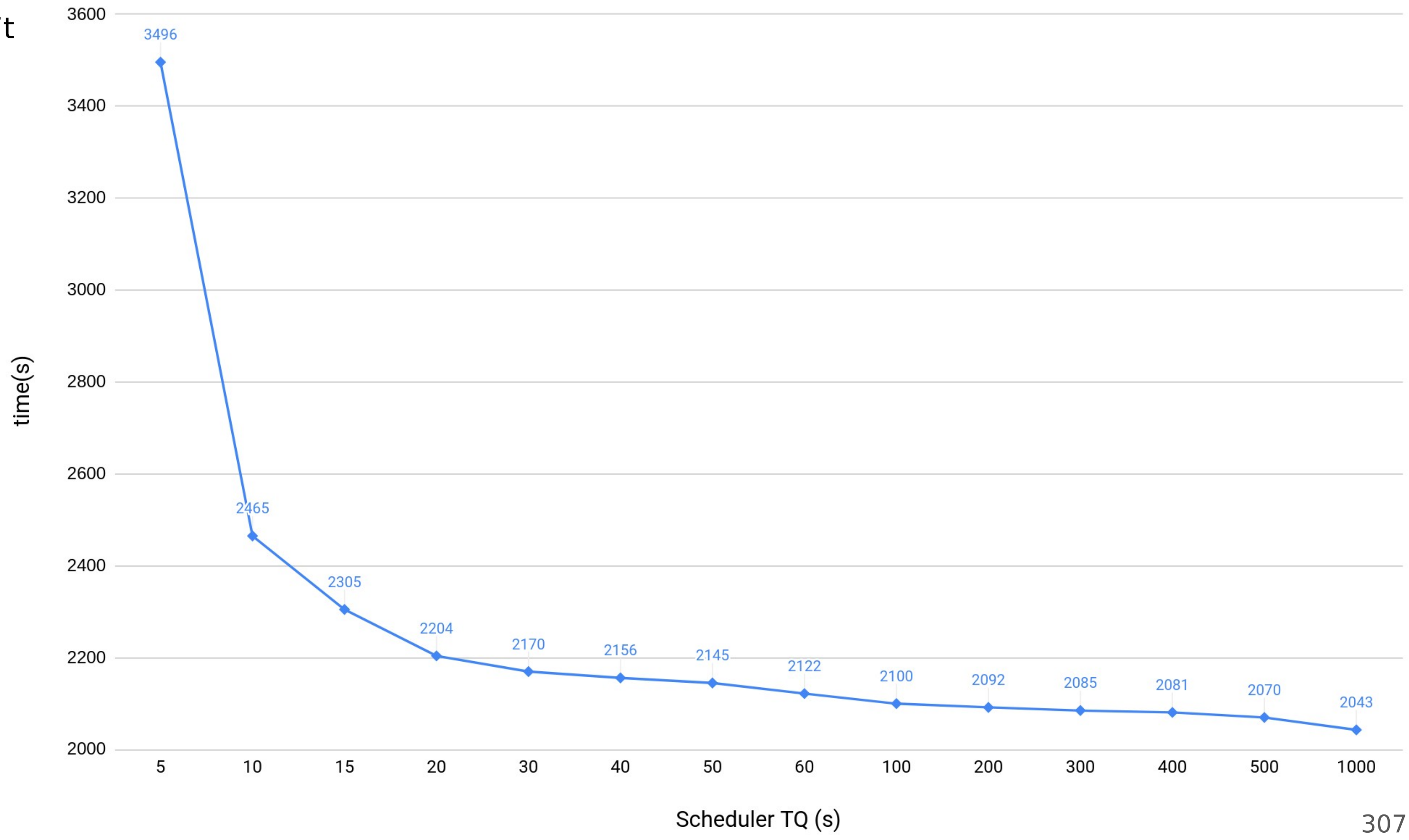


Results for big_50

- Kubeshare can't run 2 x big !



Results for big_50

T(libnvshare, no anti-thrash) = 11757 s

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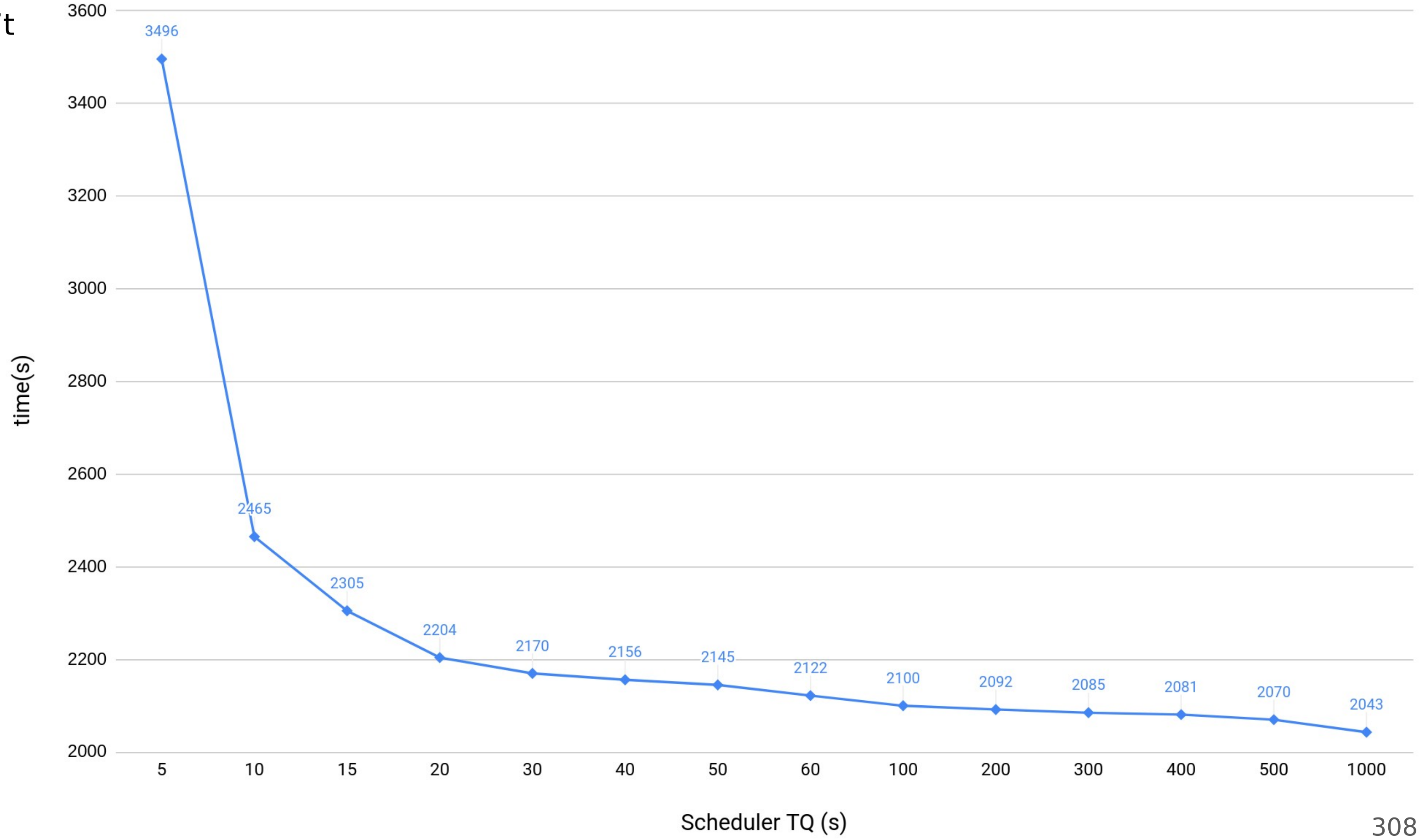

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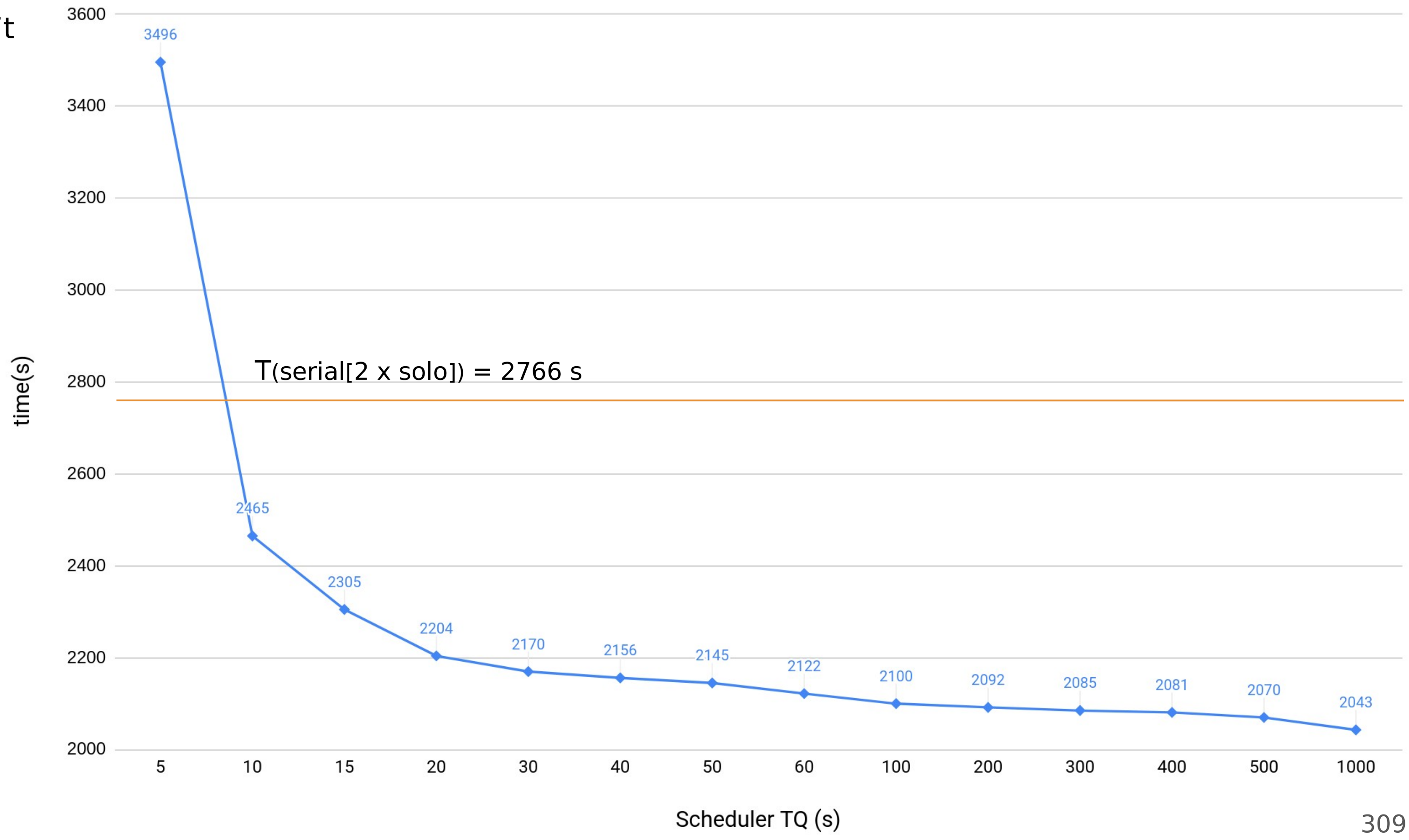

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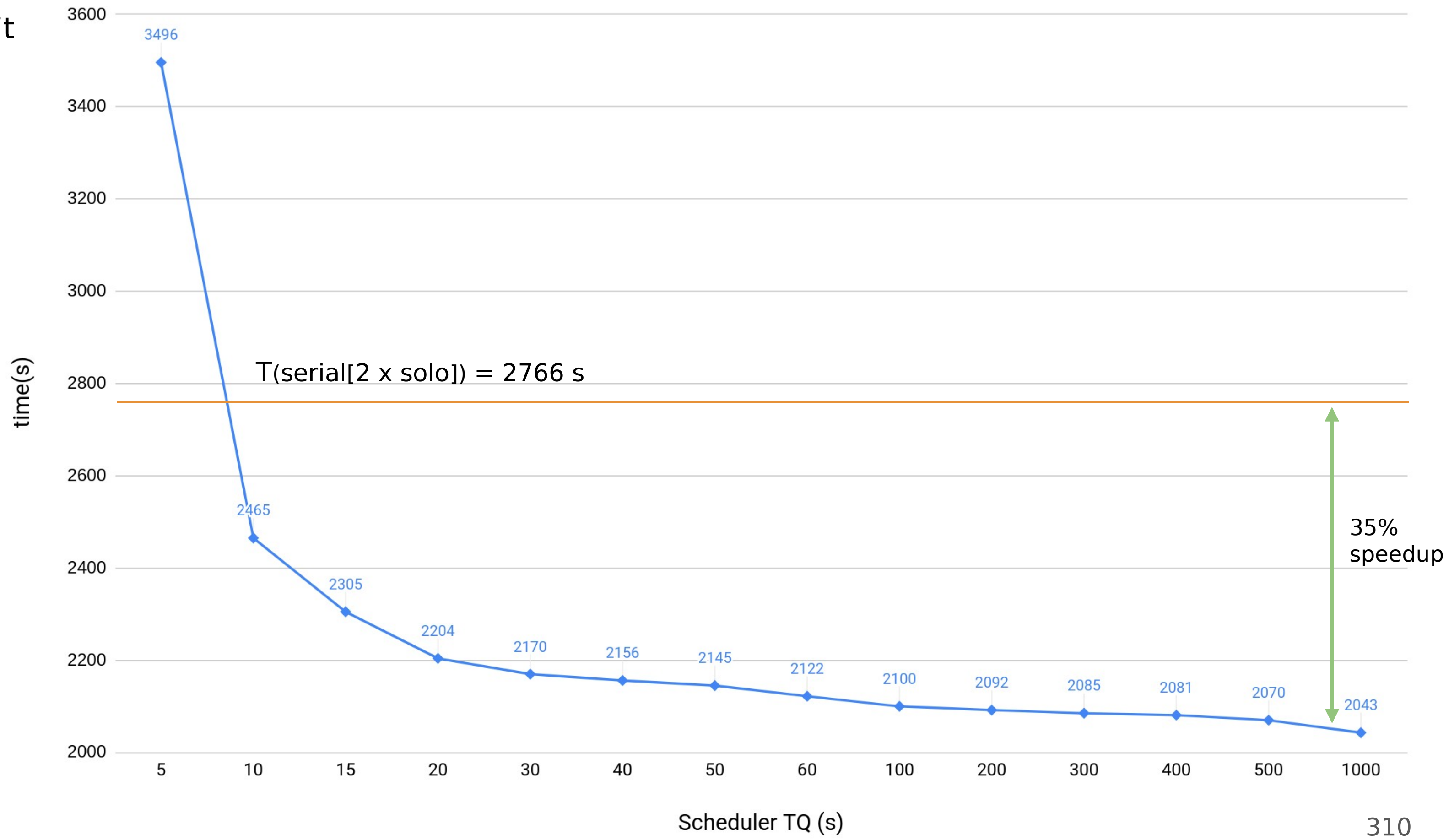

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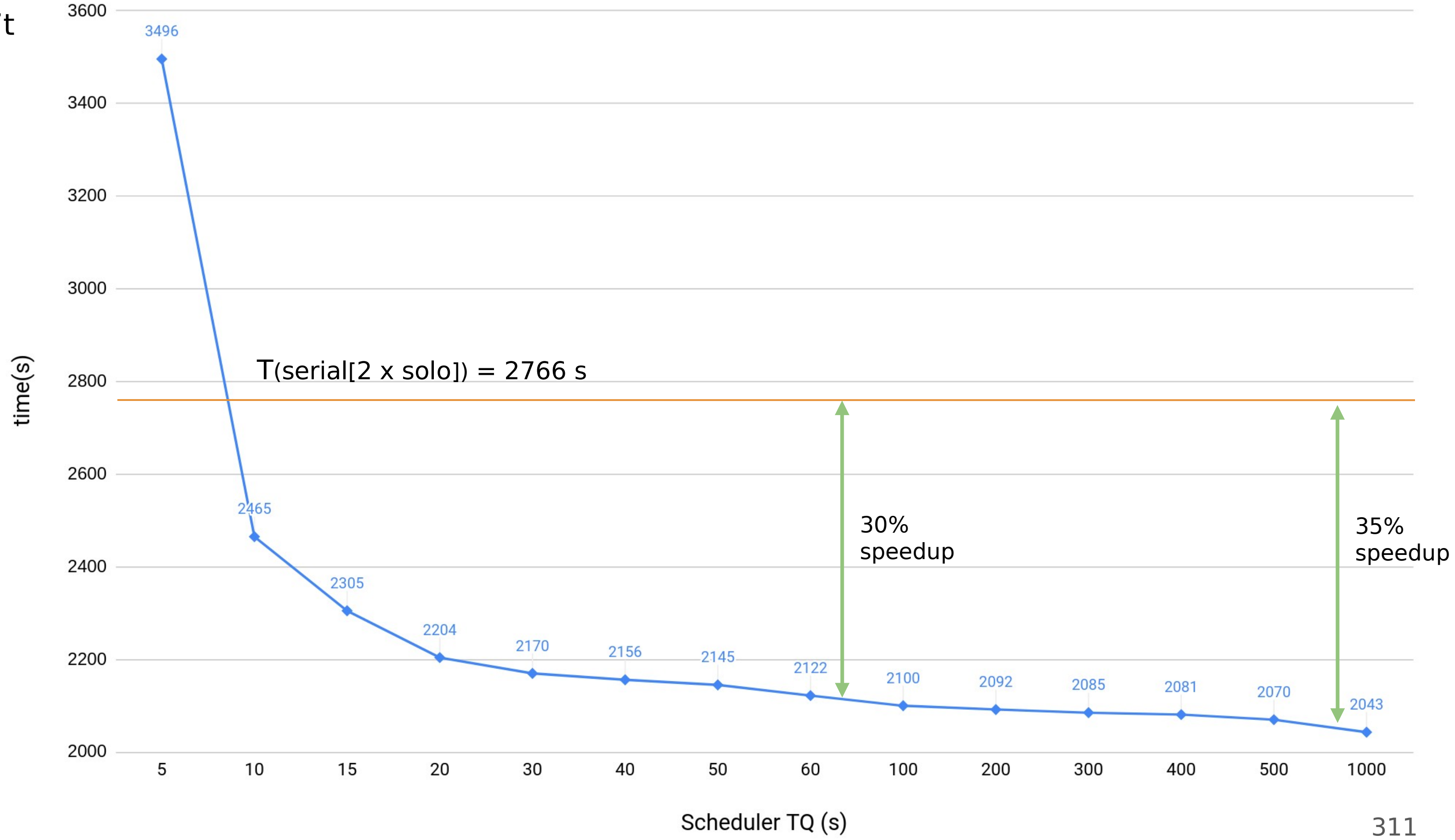

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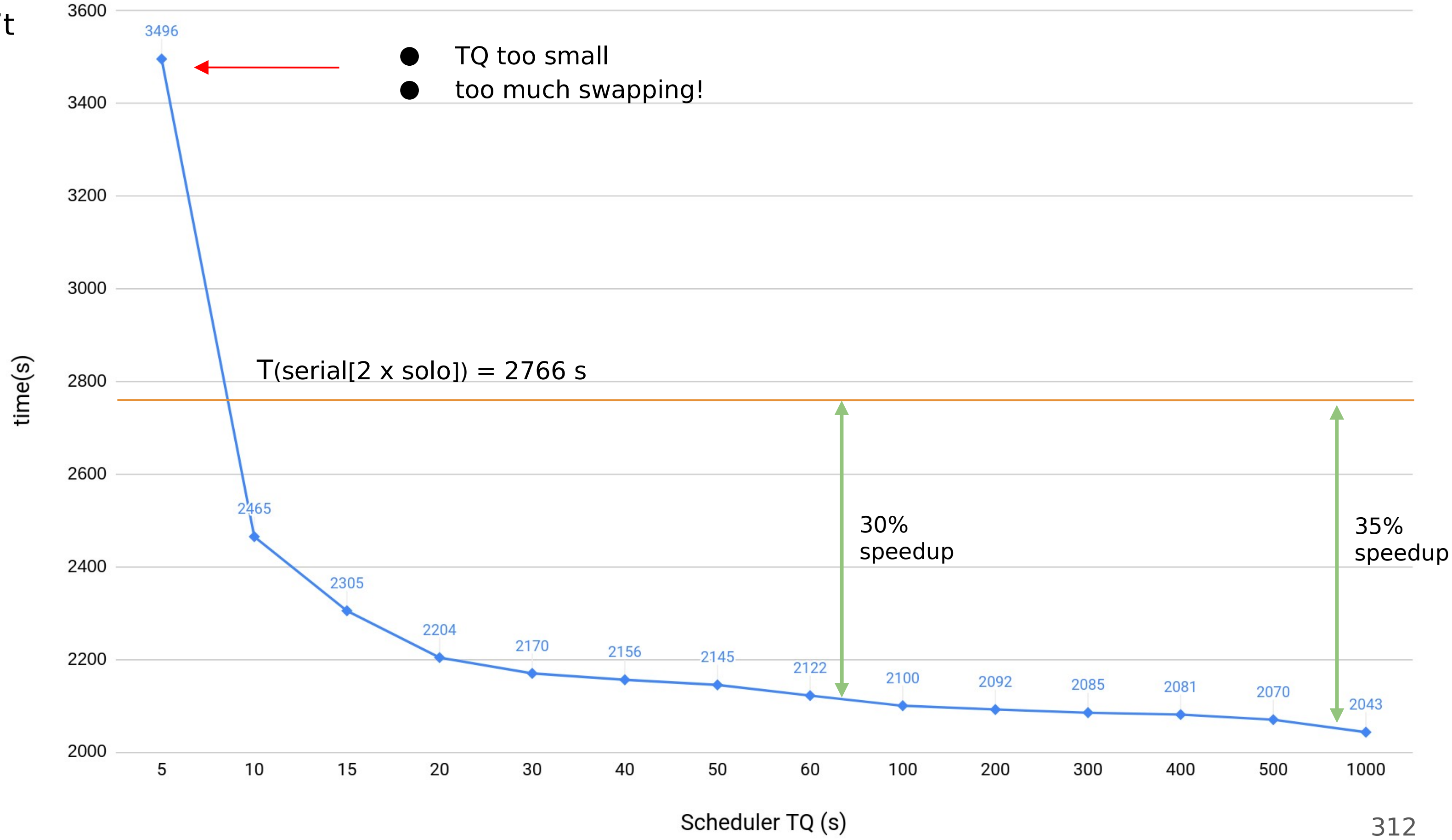

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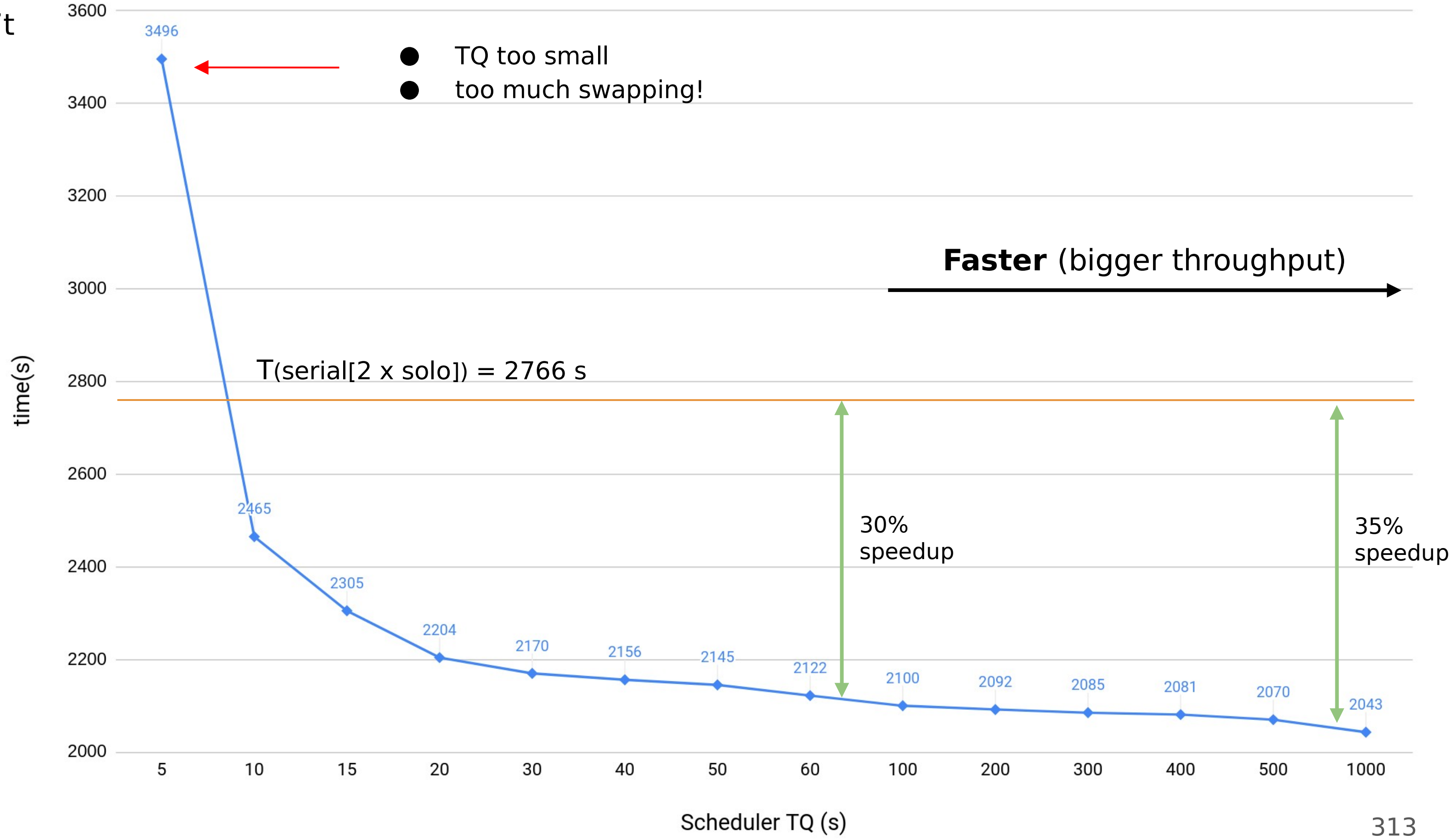

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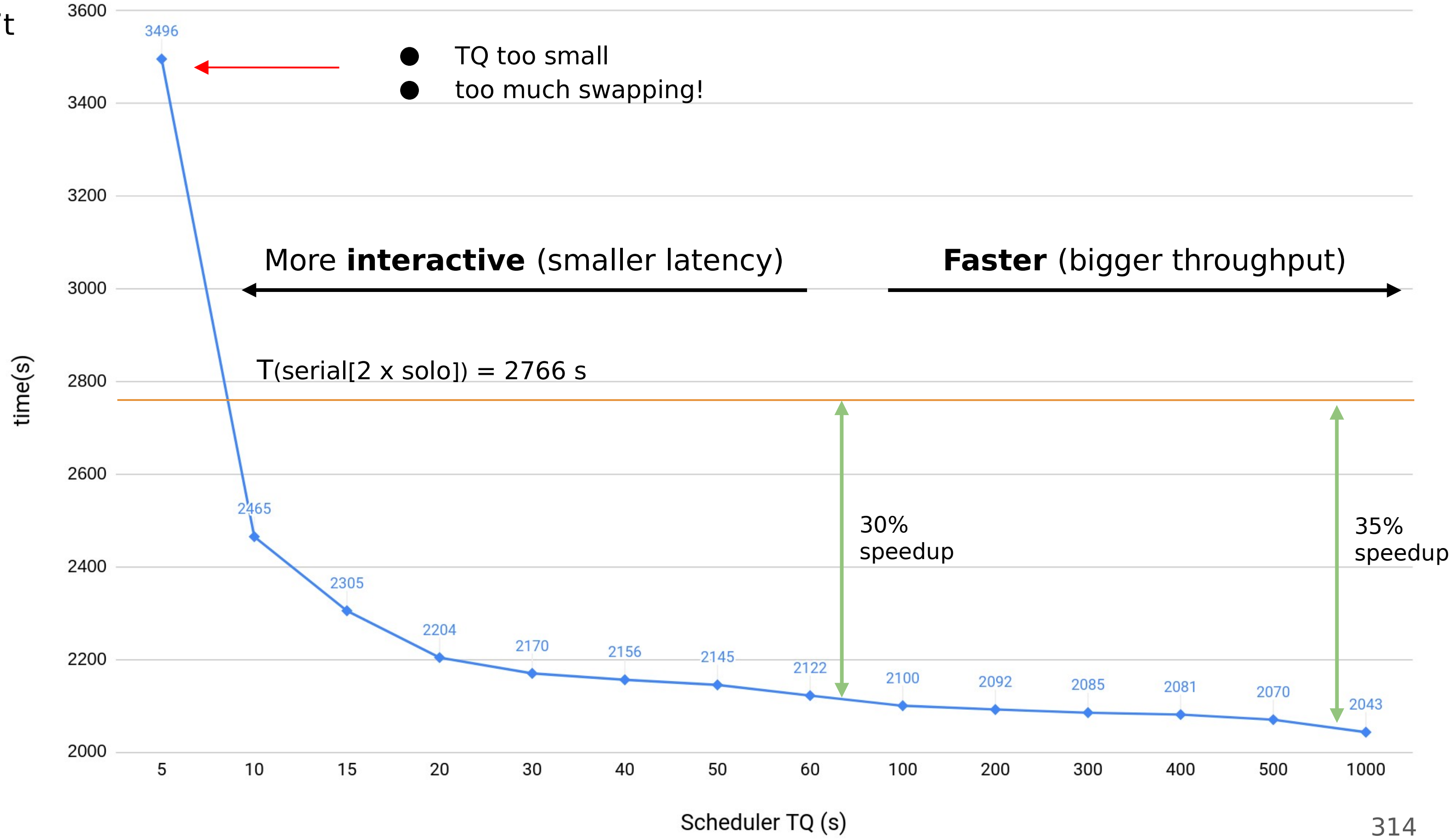

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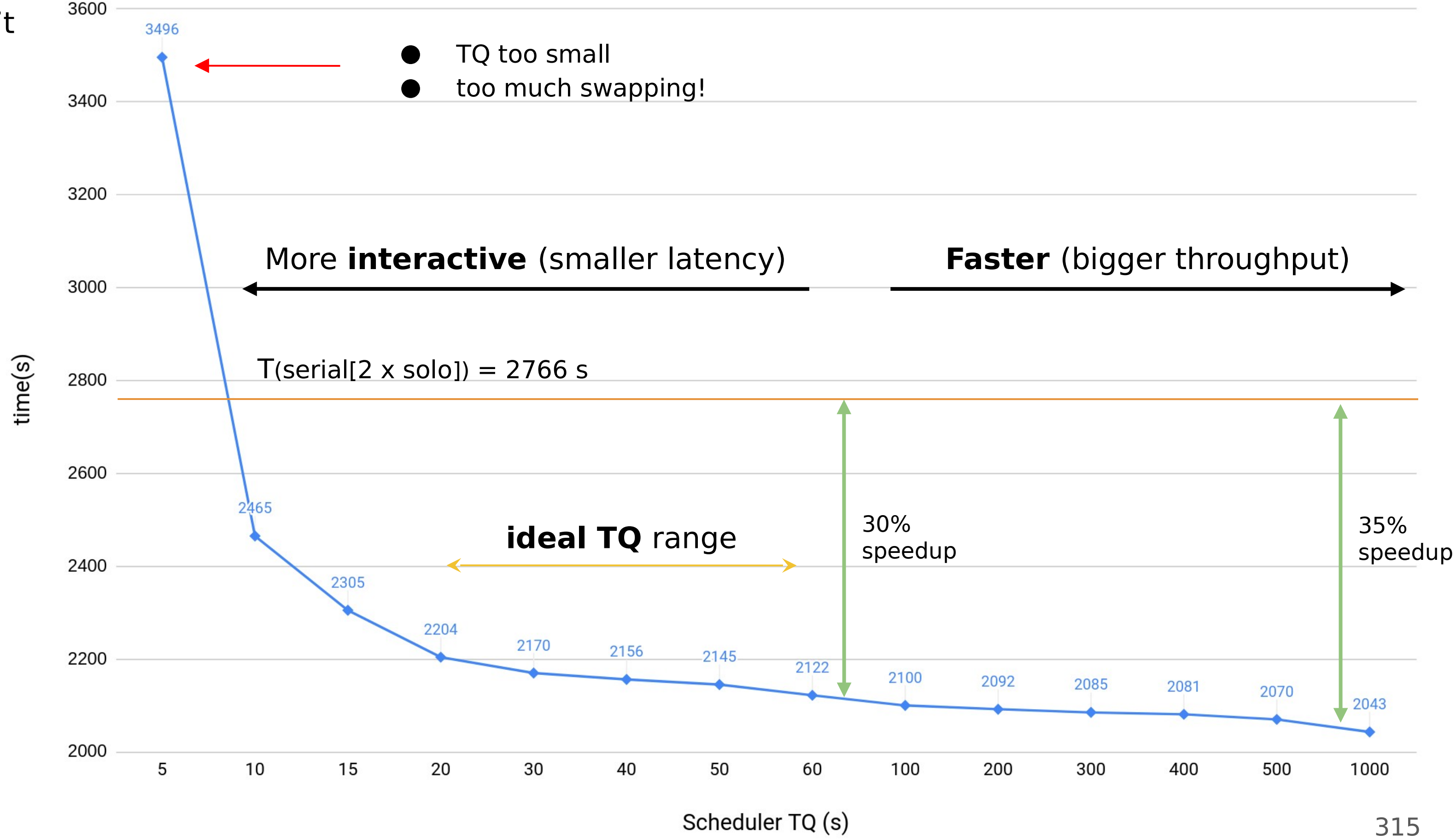

A new state of the art

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- # of co-located processes limited by system RAM
- each process can use the whole GPU memory
- GPU utilization increases even for non-interactive jobs
- No code changes to user programs
- Sensible default policies:
  - anti-thrashing scheduler **always on**
  - default TQ = 20 sec

Future Work

- Deploy to production environments
- Support multiple GPUs per node
- Create heuristics (e.g. PCIe traffic) to automatically enable/disable the anti-thrashing mechanism
- Publish our work

- Later on: Intra-node job migration from one GPU to another
- Later on: Inter-node GPU job migration (Checkpoint-restart)

Thank you!

Questions?