Nu: Achieving Microsecond-Scale Resource Fungibility with Logical Processes

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Operational reality of today’s datacenter

- Users provision fixed-sized, coarse-grained instances.

Instance types (624)

Actions

Find resources by attribute or tag

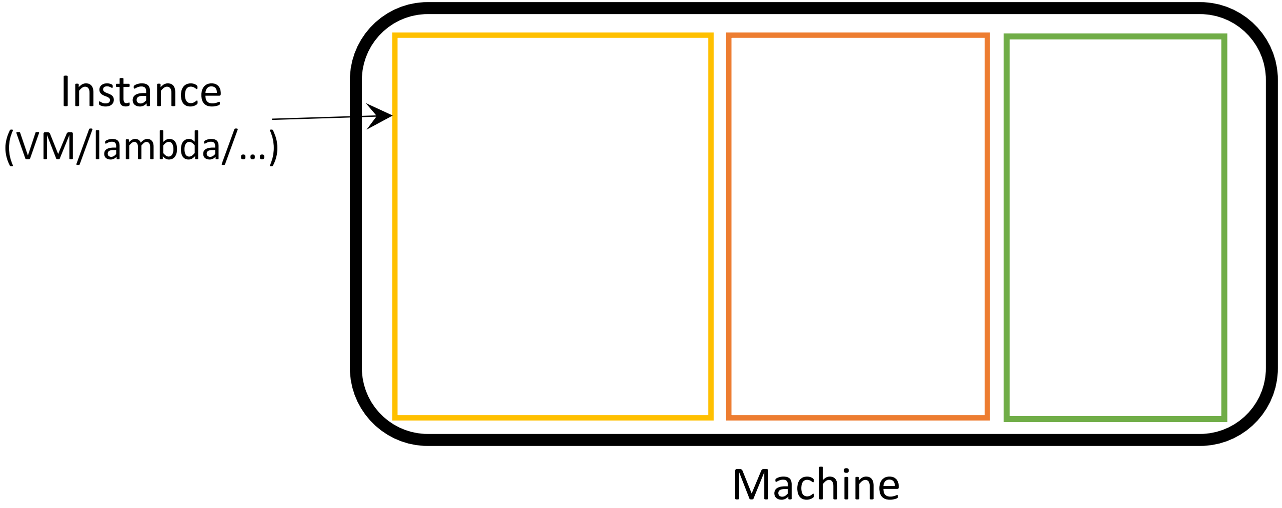
< 1 2 **3** 4 5 6 7 ... 13 >

Instance type	vCPUs	Architecture	Memory (GiB)	Storage (GB)	Storage type
d3.2xlarge	8	x86_64	64	11880	hdd
d3.4xlarge	16	x86_64	128	23760	hdd
d3.8xlarge	32	x86_64	256	47520	hdd
d3.xlarge	4	x86_64	32	5940	hdd
d3en.12xlarge	48	x86_64	192	335520	hdd

Operational reality of today's datacenter

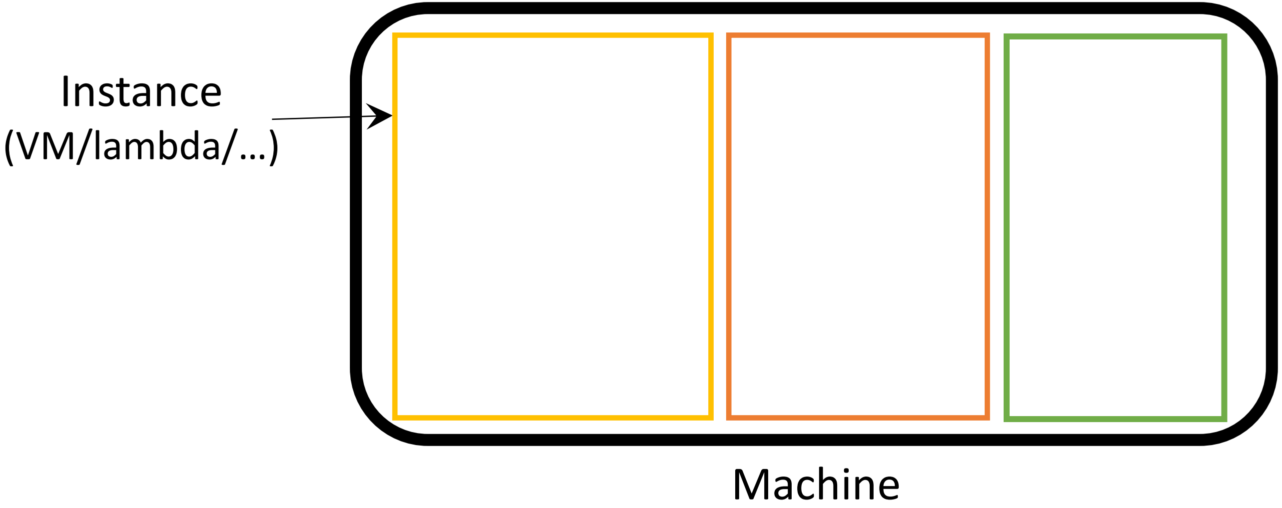
- Users provision fixed-sized, coarse-grained instances.

➢Operators bin-pack instances onto the available machines.



Inefficiency: resource overprovisioning

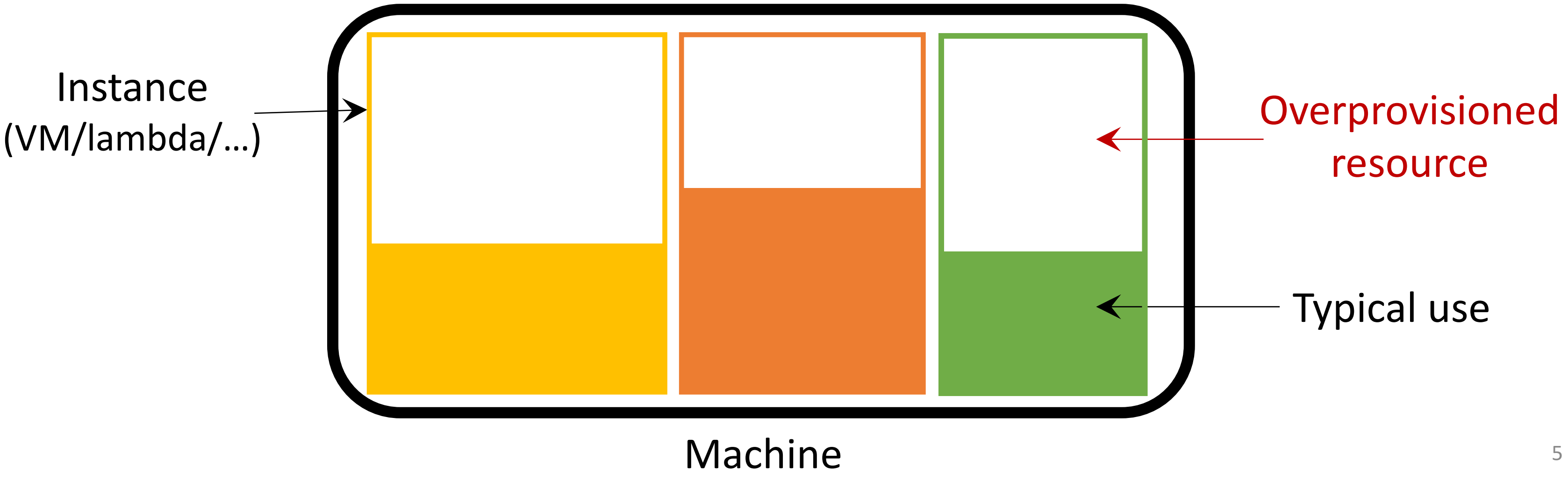
- Resource demands are often variable and hard to predict.



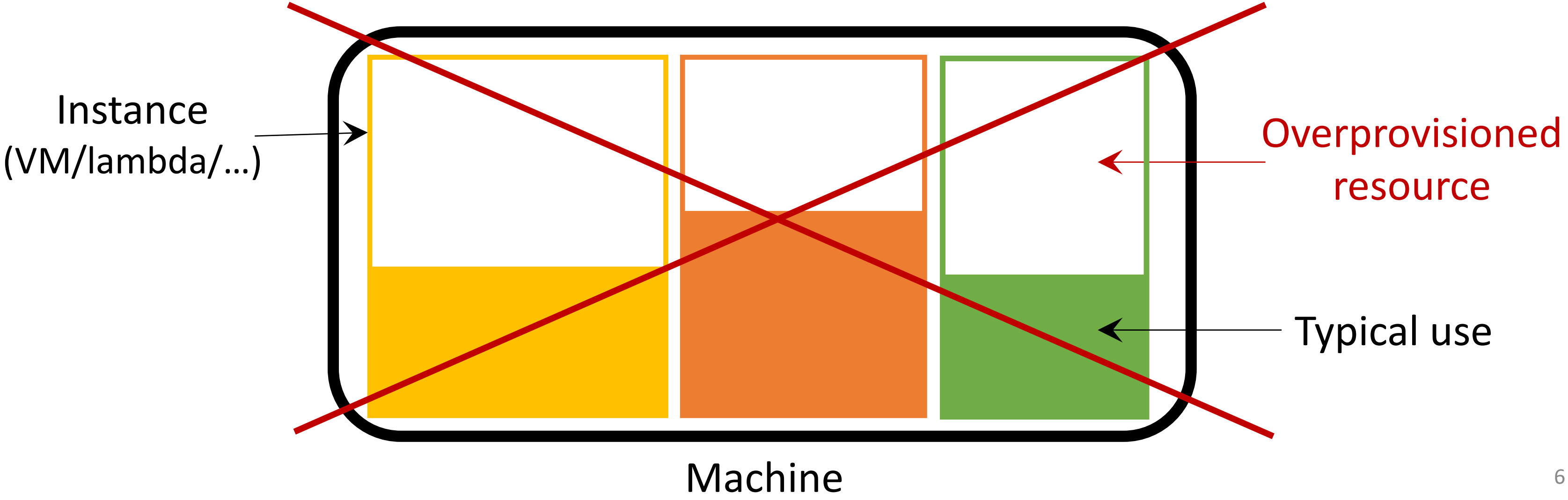
Inefficiency: resource overprovisioning

- Resource demands are often variable and hard to predict.

➢ Users have to overprovision resource for peak usage.

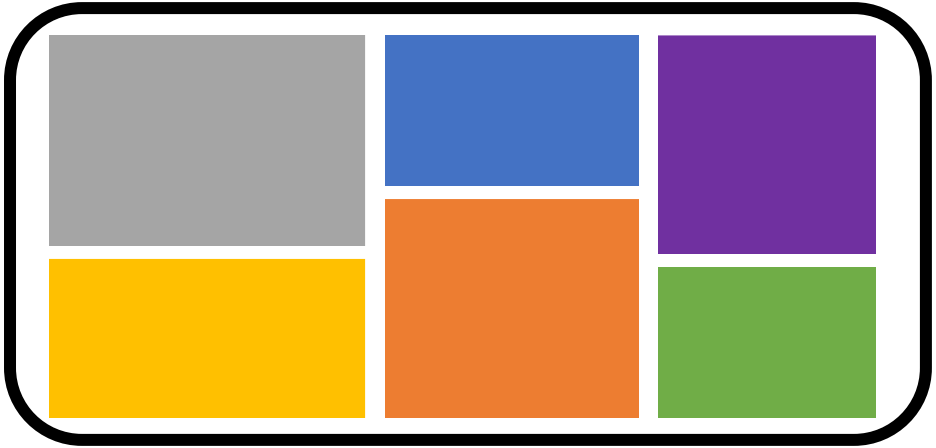


Can we avoid resource reservation?



Can we avoid resource reservation?

- Benefits: enables packing more apps.

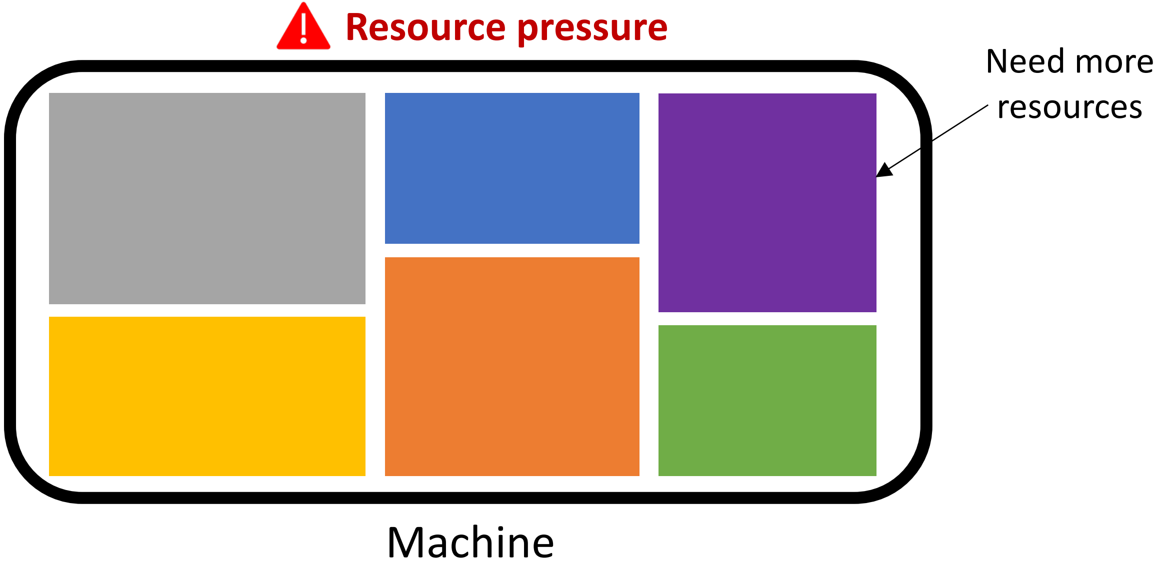


Machine

Can we avoid resource reservation?

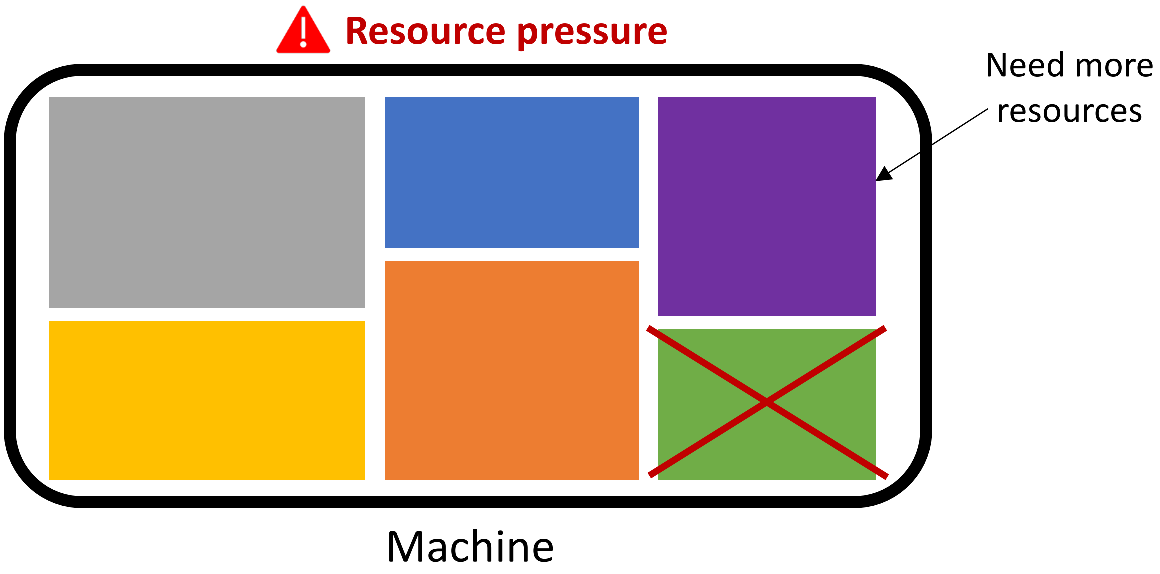
- Benefits: enables packing more apps.

➢ Problem: what if apps need more resource?



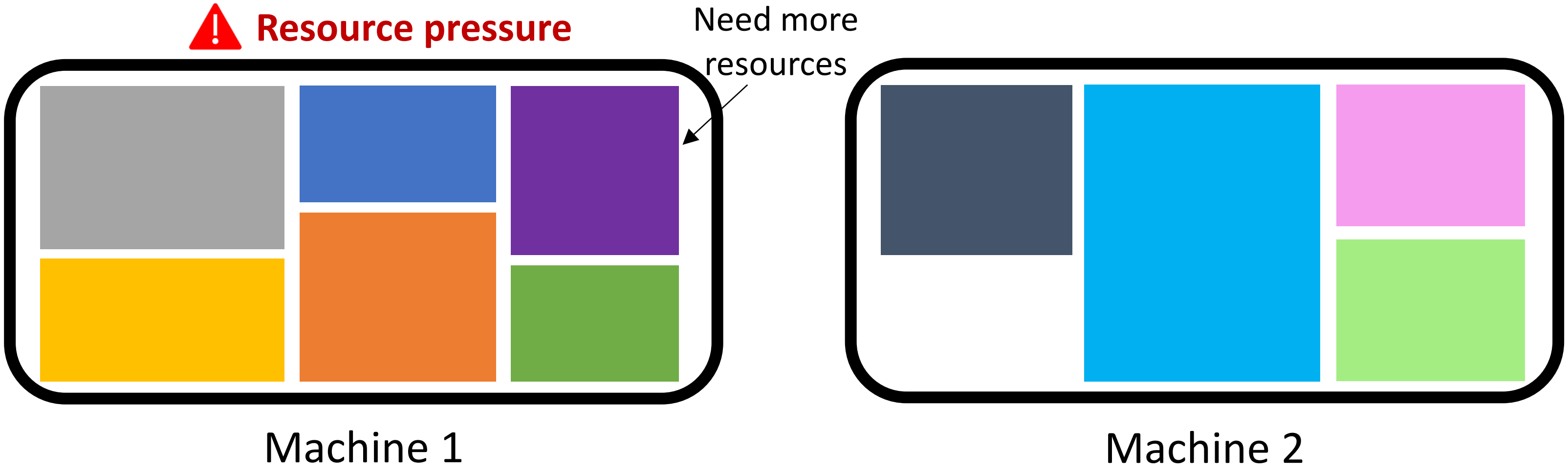
Strawman 1: kill applications

- Kill applications to make space.
- Unusable as it seriously disrupts victim's performance.



Strawman 2: migrate applications

- Migrate apps away from the overloaded machine.

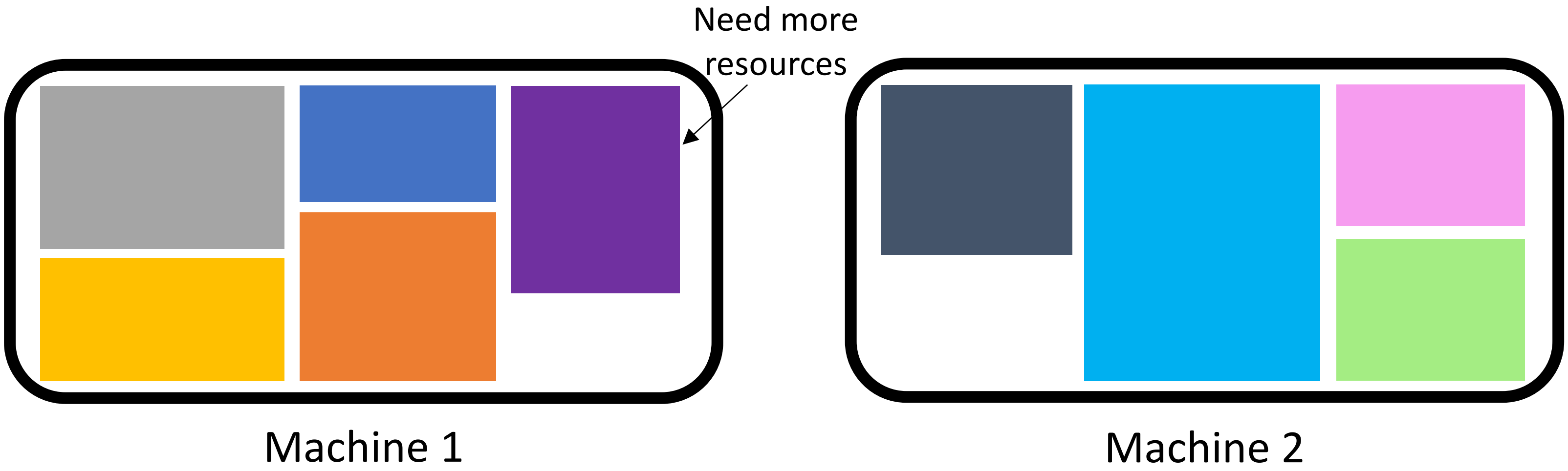


Strawman 2: migrate applications

- Migrate apps away from the overloaded machine.

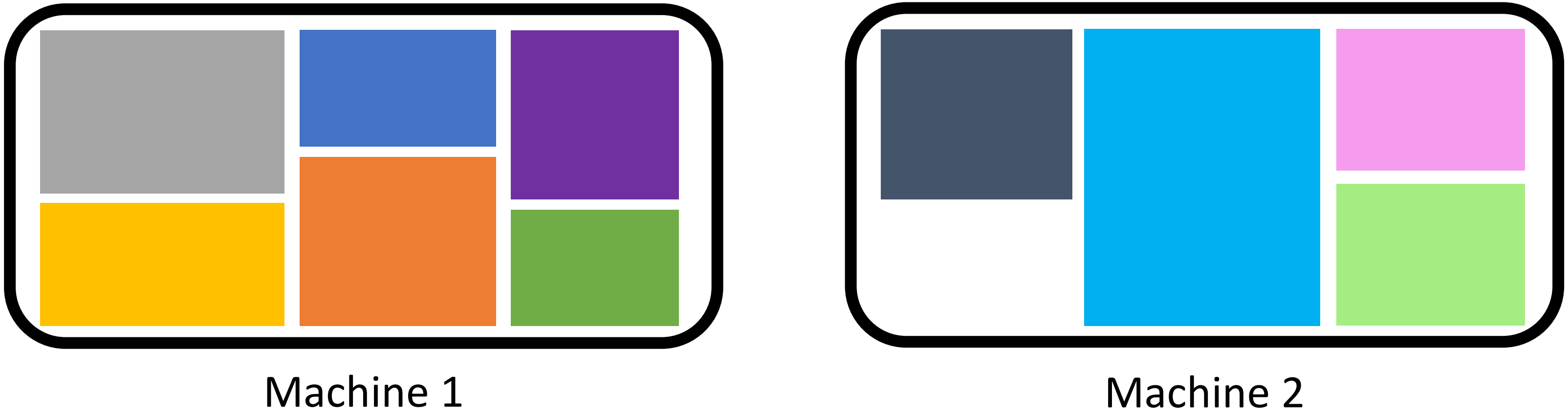
➢ Challenge: migration disrupts app's performance.

  -  E.g., takes seconds/minutes to migrate a VM.



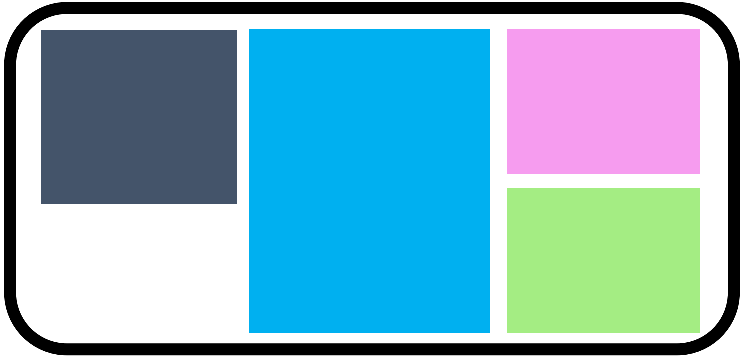
Design goal: achieving resource fungibility

- **Fungibility**: the ability to interchangeably use resources across machines w/o disruption.



Key Idea: fine-grained decomposition

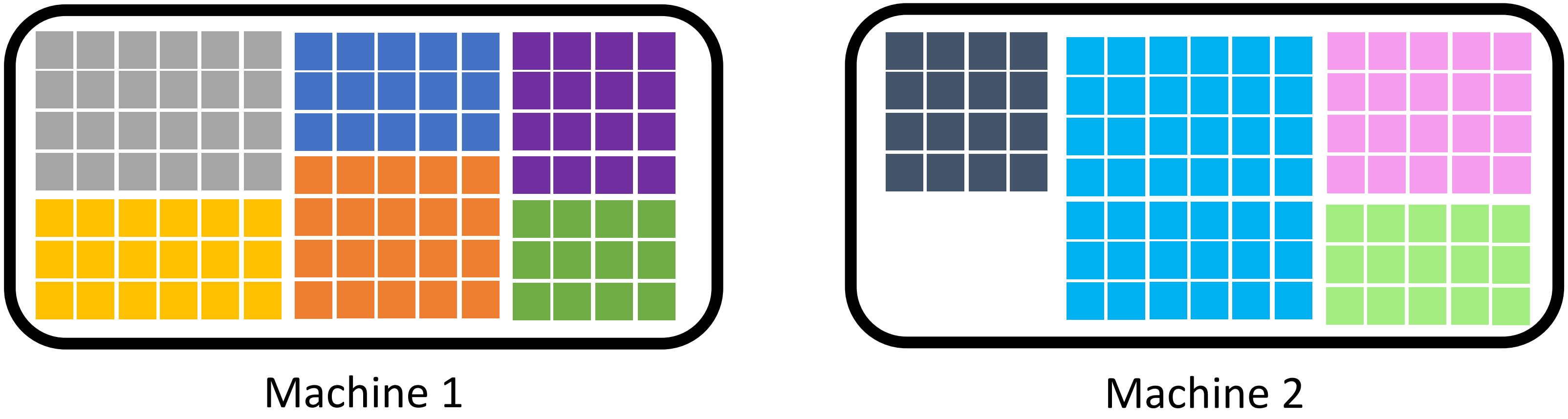
Machine 1



Machine 2

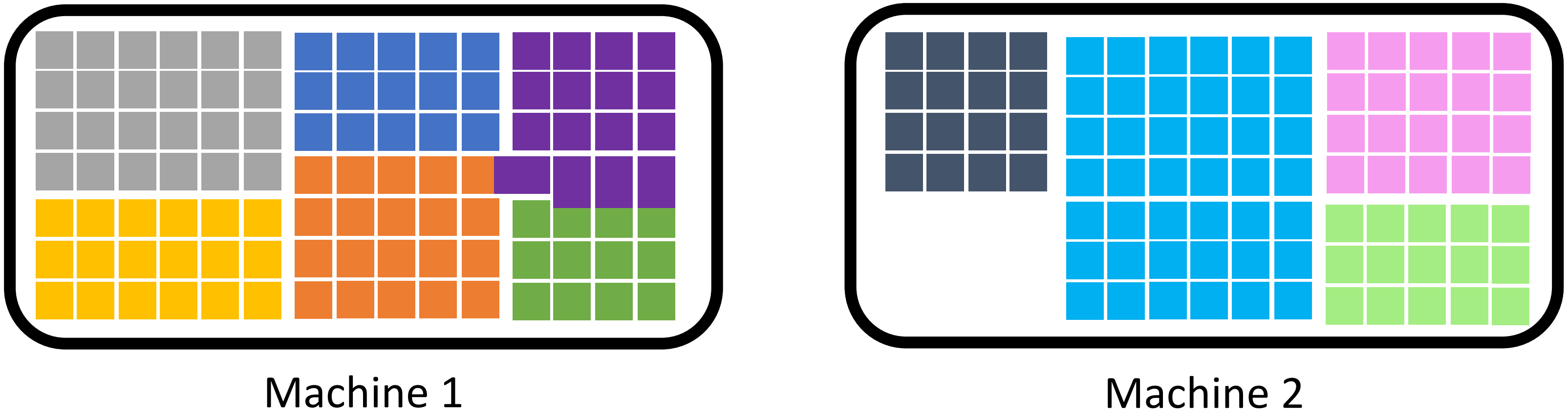
Key Idea: fine-grained decomposition

- Decompose apps into granular units.



Key Idea: fine-grained decomposition

- Decompose apps into granular units.
- Upon resource pressure, rapidly migrate units.
  - Only need to migrate the right amount of units.
  - ***~100 μs***/unit, orders of magnitude faster than migrating a VM.



Challenges and design overview

Challenges	Nu's Design
Migration can disrupt app's performance	Decompose apps into small rapidly-migratable units

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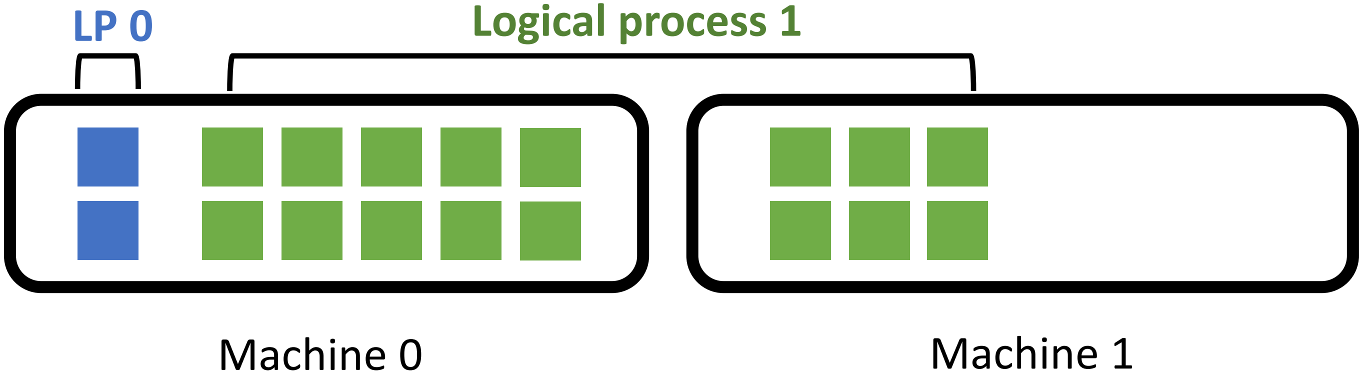
Challenges	Nu's Design
Migration can disrupt app's performance	Decompose apps into small rapidly-migratable units
Programming with small units is challenging	A familiar process-like programming model
Decomposition can increase the communication cost	An efficient locality-aware communication runtime

The logical process abstraction

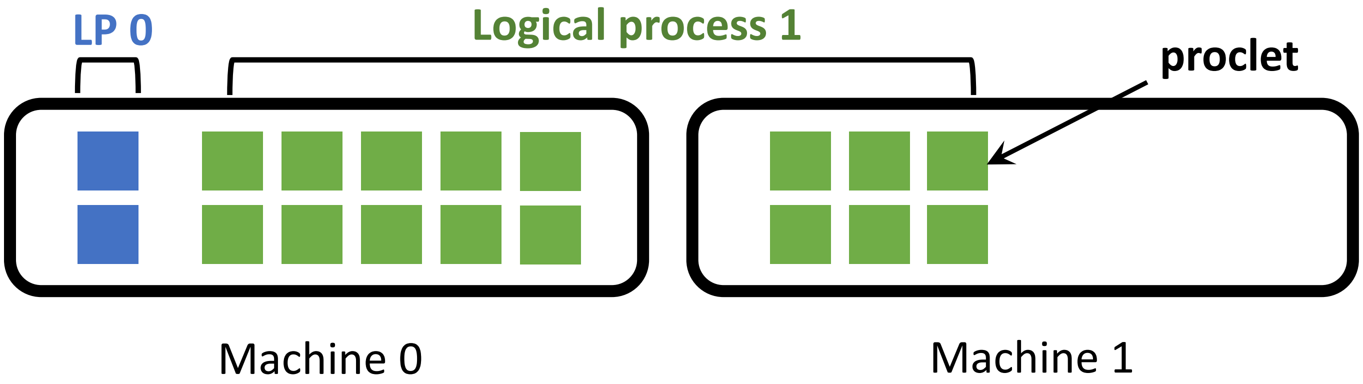
- Similar to the UNIX process, but can span across machines.



The logical process abstraction

- Similar to the UNIX process, but can span across machines.

➢ Consists of many smaller **proclets**.
  - An atomic unit of states and compute.
  - Can be independently migrated across machines.



Proclet communication

- Proclets communicate through message passing.
  - No memory sharing → avoids expensive cache coherency.

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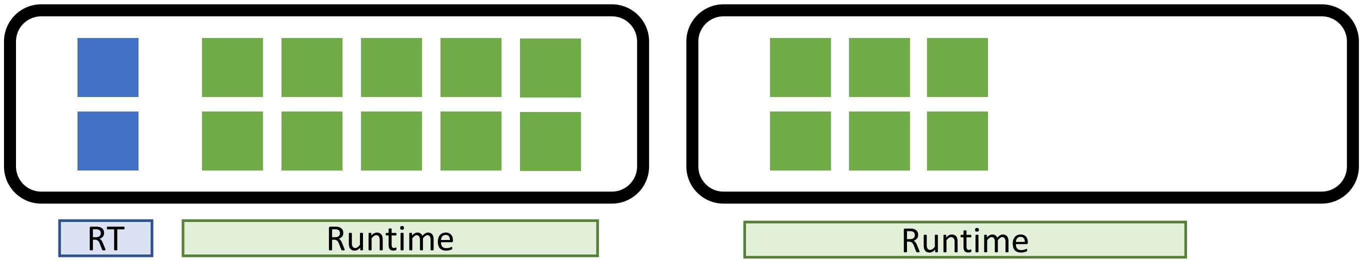
➢Runtime offers location transparency and optimizes performance.



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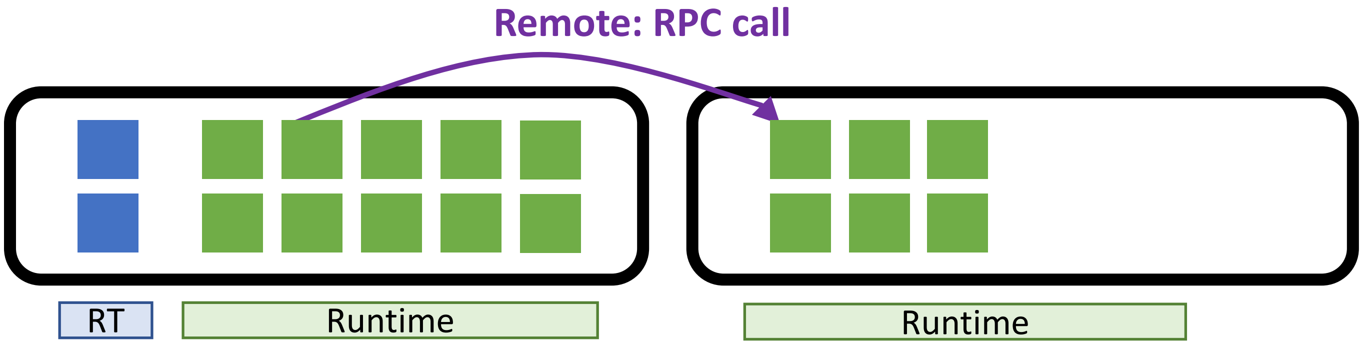

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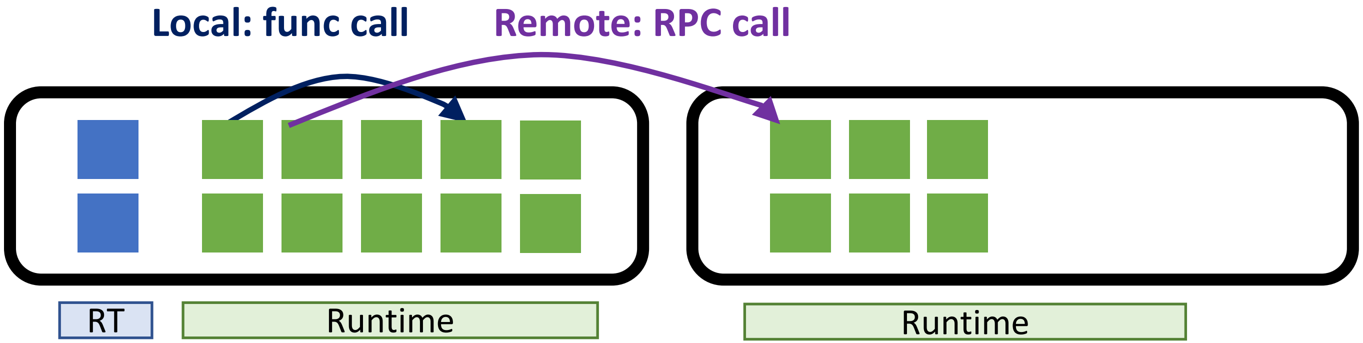
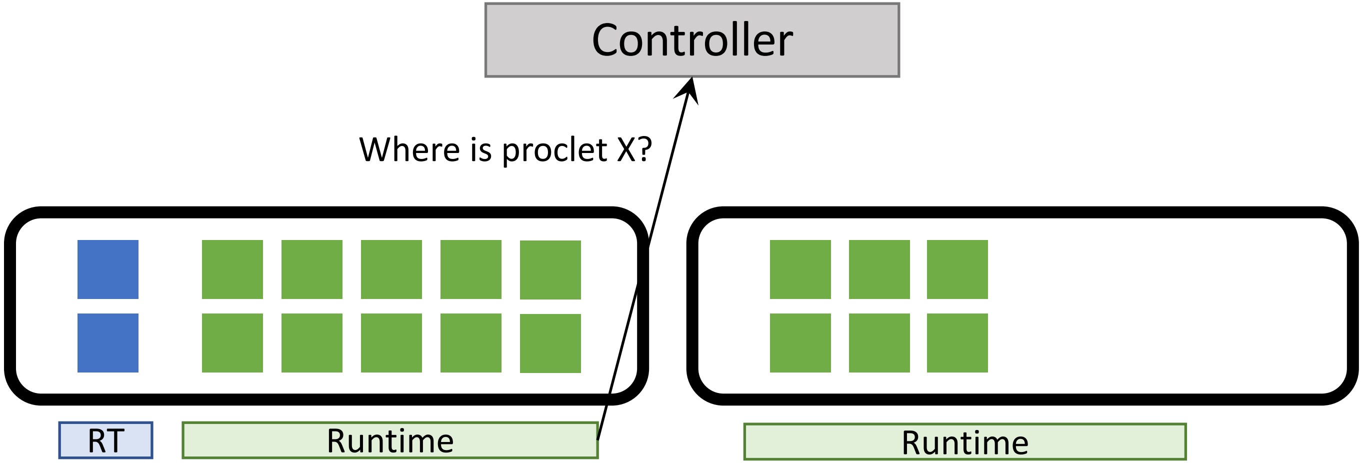


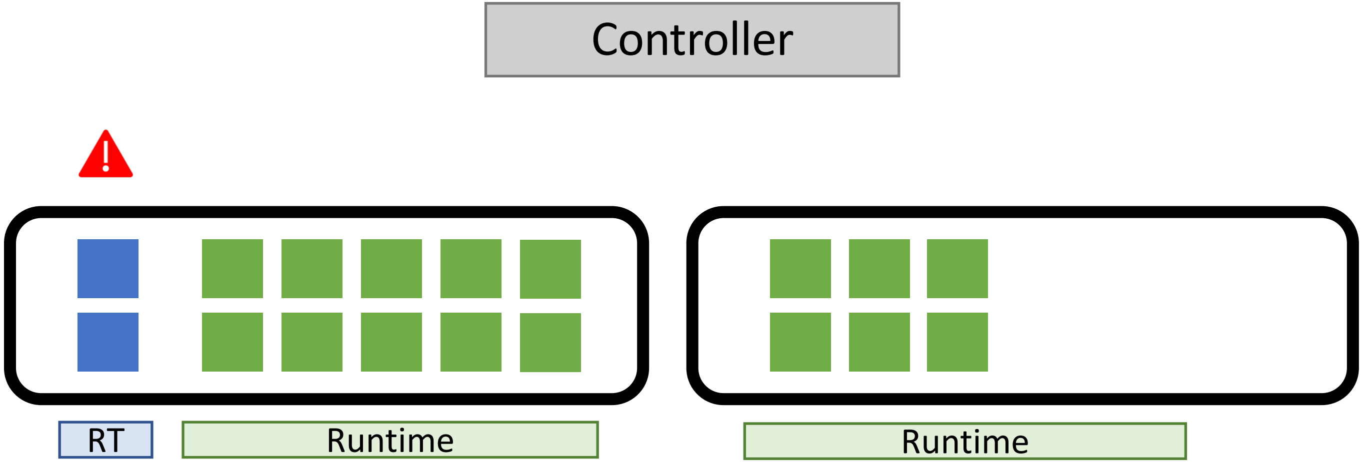
Centralized controller

- Tracks proclet locations and machine resources.
- Runtime caches location results to improve performance.



Proclet migration

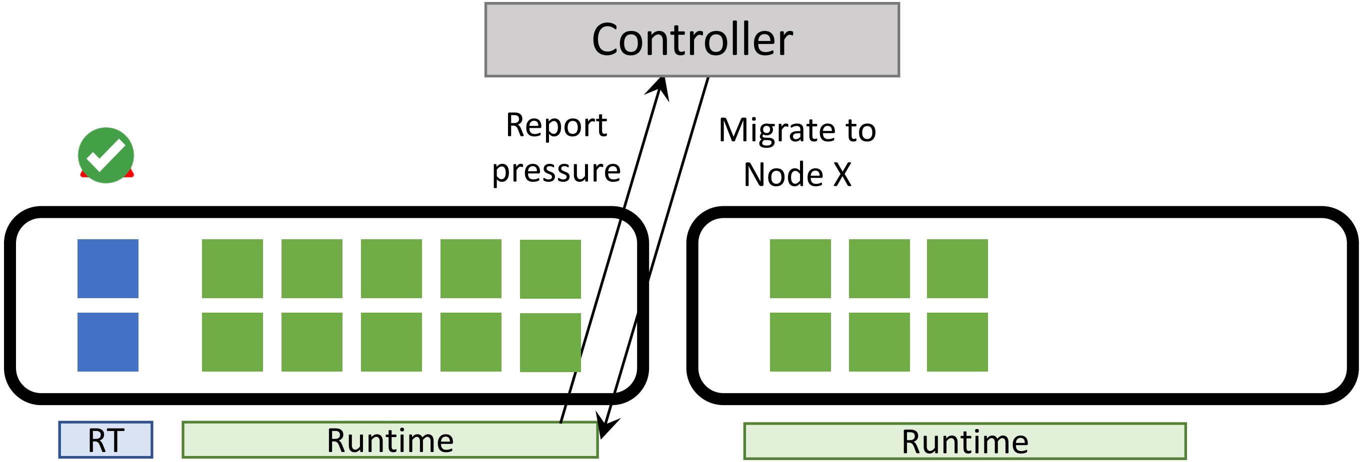
➢Runtime detects pressure and controller decides the new location.



Proclet migration

- Runtime detects pressure and controller decides the new location.

➢Rapidly migrate one proclet at a time.



Programming with Proclets

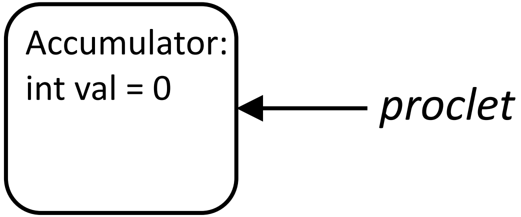
```
struct Accumulator {
    std::atomic<int> val_ = 0;
    void Add(int n) { val_ += n; }
    int Get() { return val; }
};
```

- Proclet class definition
  - Member variables are stored in proclet's heap
  - Public methods define the communication interface

Creating proclets

```
struct Accumulator {
    std::atomic<int> val_ = 0;
    void Add(int n) { val_ += n; }
    int Get() { return val; }
};
```

```
auto p = make_proclet<Accumulator>();
```

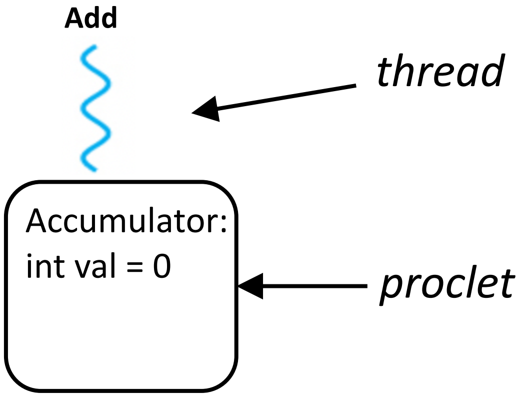


- Proclet smart pointer (like std::shared_ptr)
    - Can be passed as function arguments
    - Automatic lifetime management

Asynchronous Call

```
struct Accumulator {
    std::atomic<int> val_ = 0;
    void Add(int n) { val_ += n; }
    int Get() { return val; }
};

auto p = make_proclet<Accumulator>();
auto f0 = p.RunAsync(&Accumulator::Add, 1);
```



- Asynchronous call for latency hiding

Asynchronous Call

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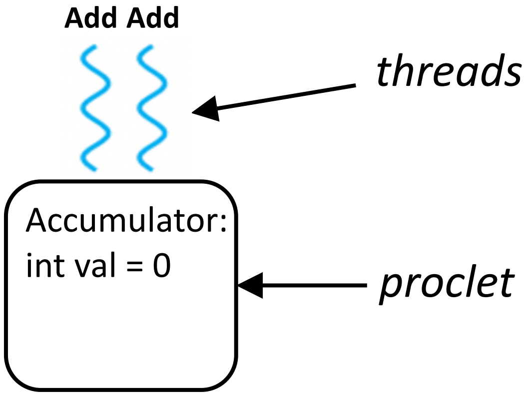
struct Accumulator {
    std::atomic<int> val_ = 0;
    void Add(int n) { val_ += n; }
    int Get() { return val; }
};
```

```
auto p = make_proclet<Accumulator>();
auto f0 = p.RunAsync(&Accumulator::Add, 1);
auto f1 = p.RunAsync(&Accumulator::Add, 1);
```



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Asynchronous Call

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struct Accumulator {
    std::atomic<int> val_ = 0;
    void Add(int n) { val_ += n; }
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};

auto p = make_proclet<Accumulator>();
auto f0 = p.RunAsync(&Accumulator::Add, 1);
auto f1 = p.RunAsync(&Accumulator::Add, 1);
f0.get(); f1.get();
```
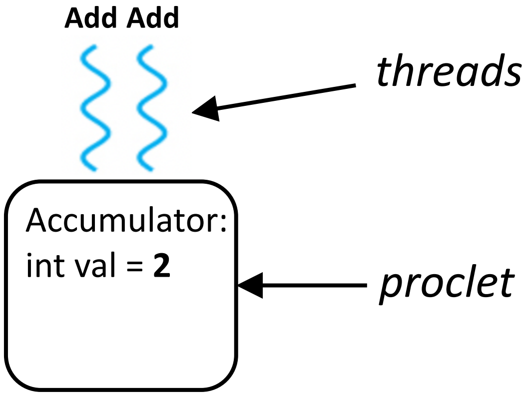
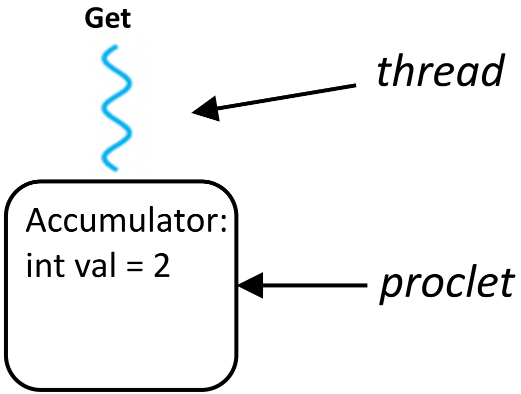



- Asynchronous call for latency hiding

Synchronous Call

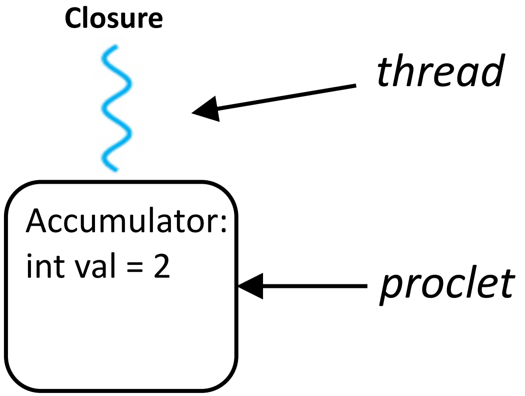
```
struct Accumulator {
    std::atomic<int> val_ = 0;
    void Add(int n) { val_ += n; }
    int Get() { return val; }
};


auto p = make_proclet<Accumulator>();
auto f0 = p.RunAsync(&Accumulator::Add, 1);
auto f1 = p.RunAsync(&Accumulator::Add, 1);
f0.get(); f1.get();
auto val = p.Run(&Accumulator::Get); // = 2
```



- ➢ Also supports simple synchronous call

Computation shipping

```
struct Accumulator {
    std::atomic<int> val_ = 0;
    void Add(int n) { val_ += n; }
    int Get() { return val; }
};

auto p = make_proclet<Accumulator>();
auto f0 = p.RunAsync(&Accumulator::Add, 1);
auto f1 = p.RunAsync(&Accumulator::Add, 1);
f0.get(); f1.get();
auto val = p.Run(&Accumulator::Get); // = 2
val = p.Run(+[](Accumulator &a) {
  a.Add(1); return a.Get(); }); // = 3
```



➢ Ships a closure with very low overhead

More details in the paper

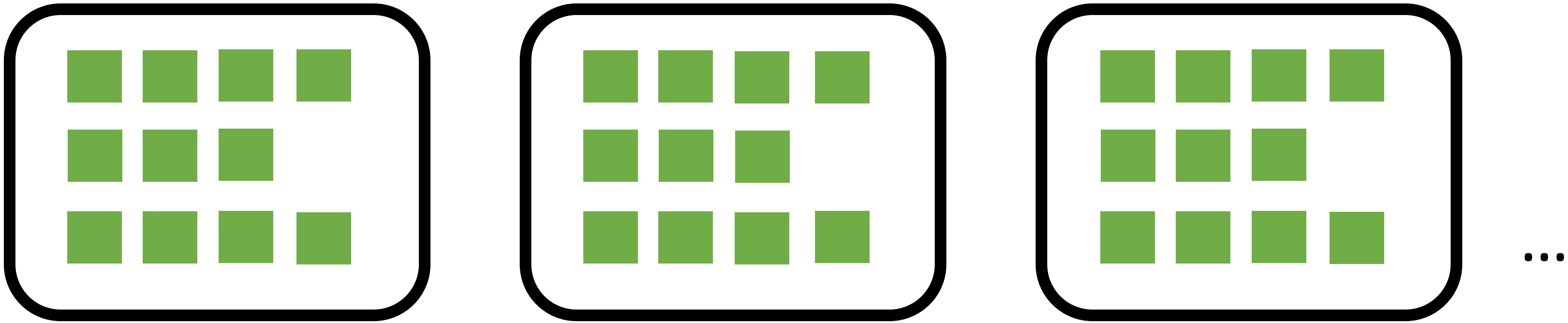
- Fault tolerance and proclet replication.
- Security and threat model.
- Placement and migration policy.
- Migration and RPC optimizations.

Evaluation

- Setup: 32 machines in a rack connected with 100GbE
- Applications:
  - Social network microservices (from DeathStarBench).
  - Key-value store.
  - Phoenix (a C++ MapReduce framework)
- Focus on answering followings:
  - Can we reconcile tensions between utilization and performance?
  - How fast can we migrate proclets across machines?

Able to achieve high utilization w/o disruption?

- Initially run the social network app across all 32 nodes.

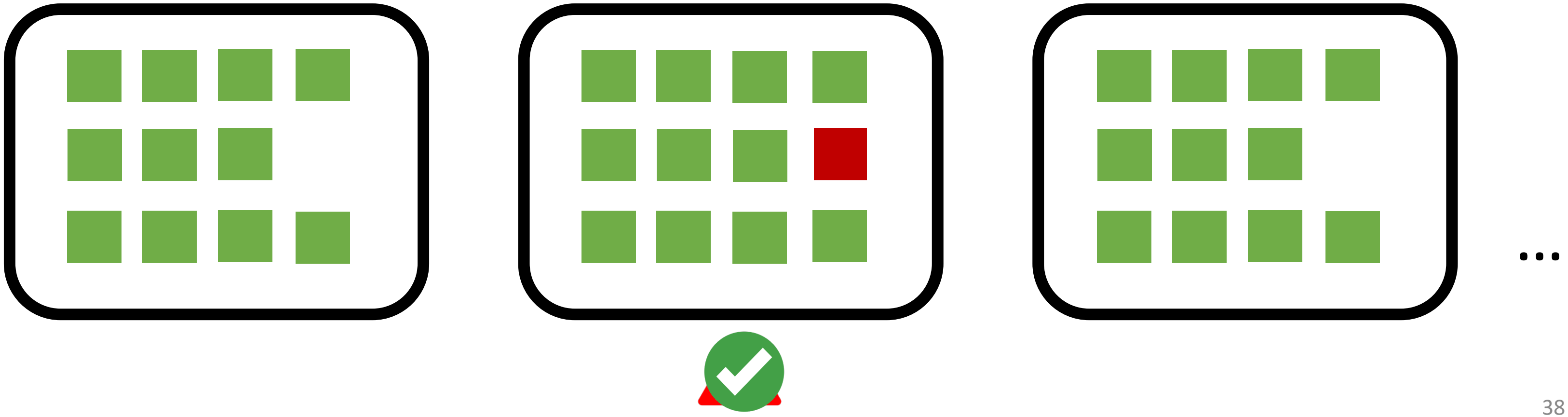


Able to achieve high utilization w/o disruption?

- Initially run the social network app across all 32 nodes.

➢ Then launch the memory antagonist at one node.

  - Allocates memory as fast as possible, around 7 GB/s.



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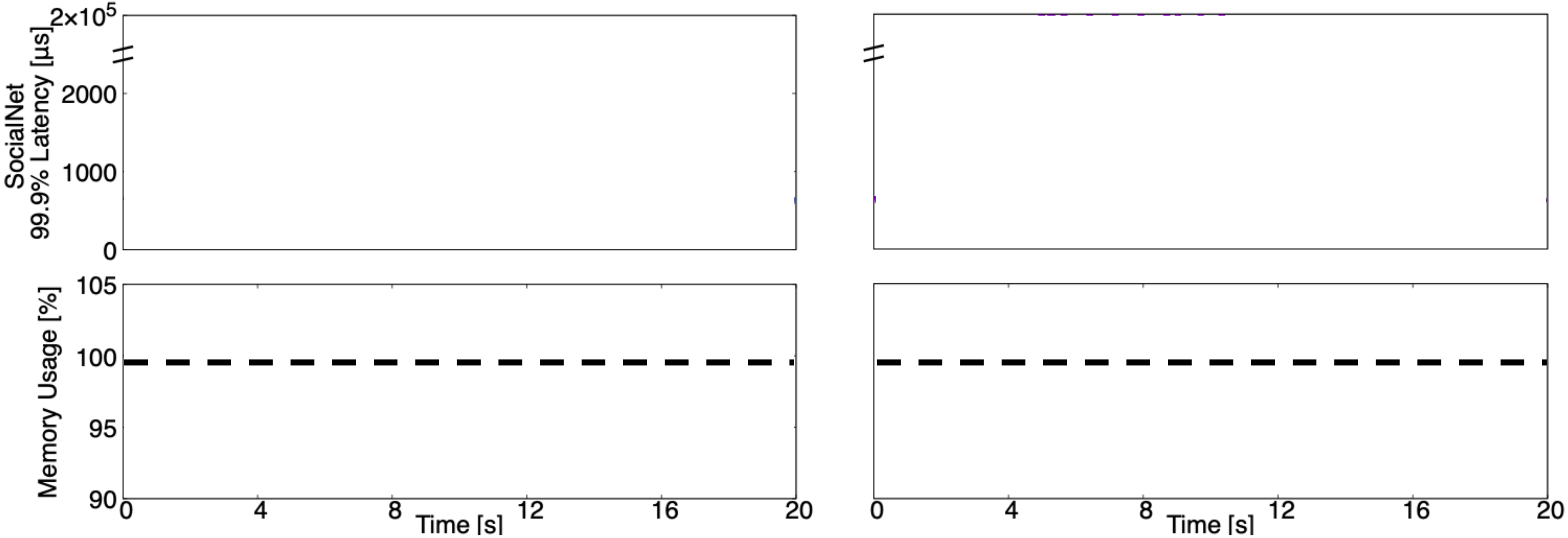
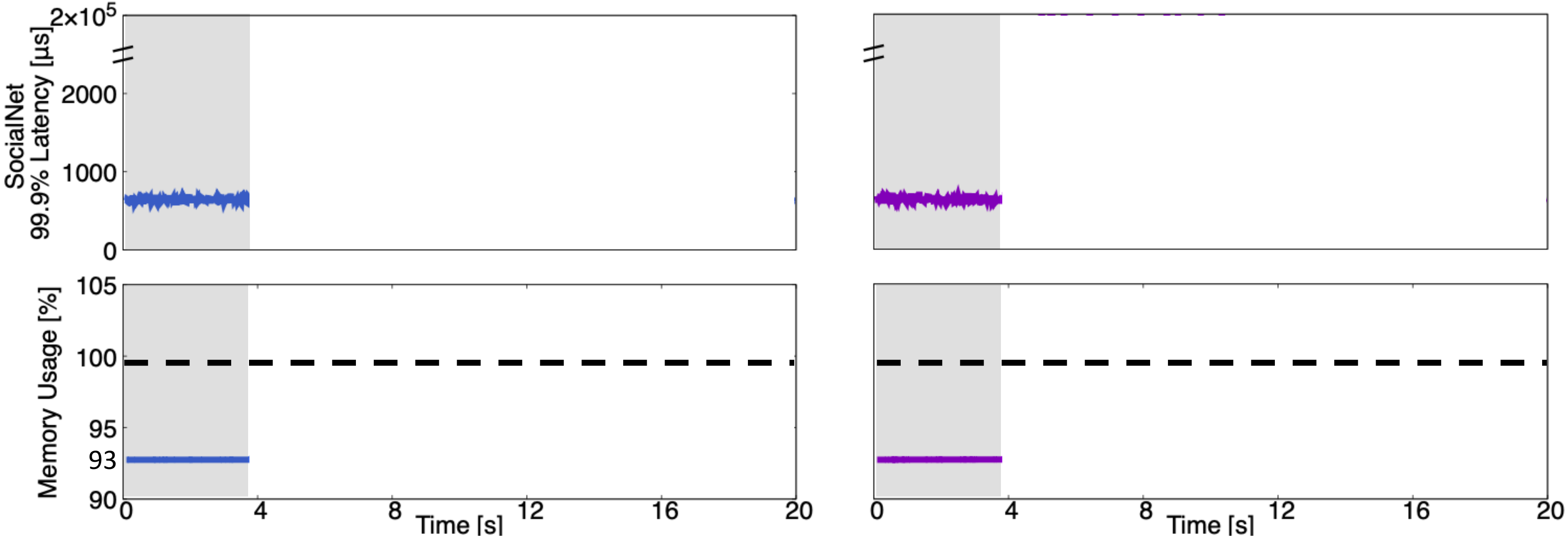


Nu

MigrOS [ATC'21]

(container live migration)

Able to achieve high utilization w/o disruption?



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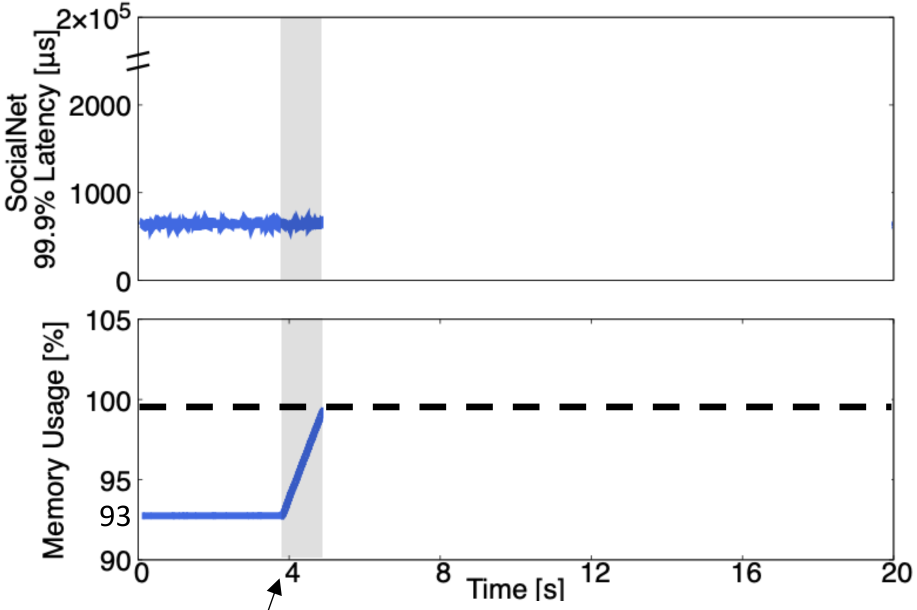
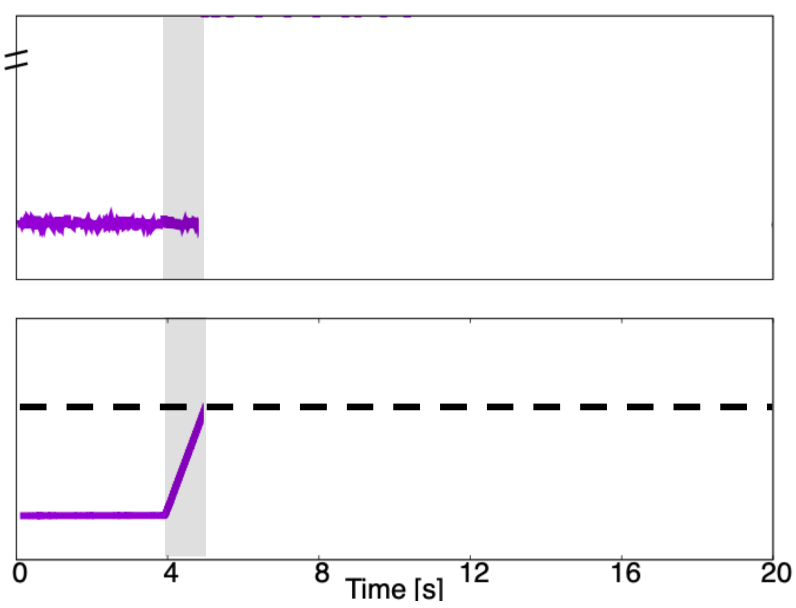


Antagonist starts

Nu



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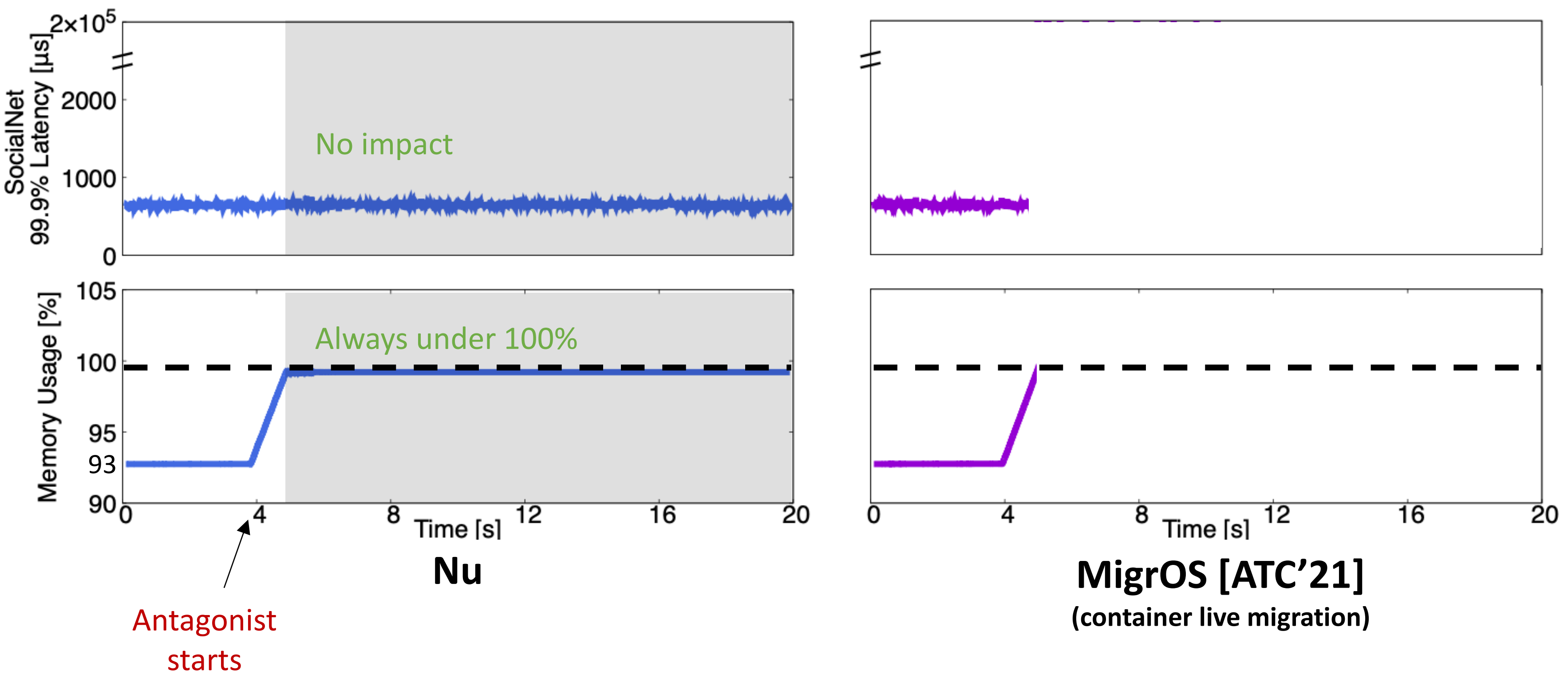

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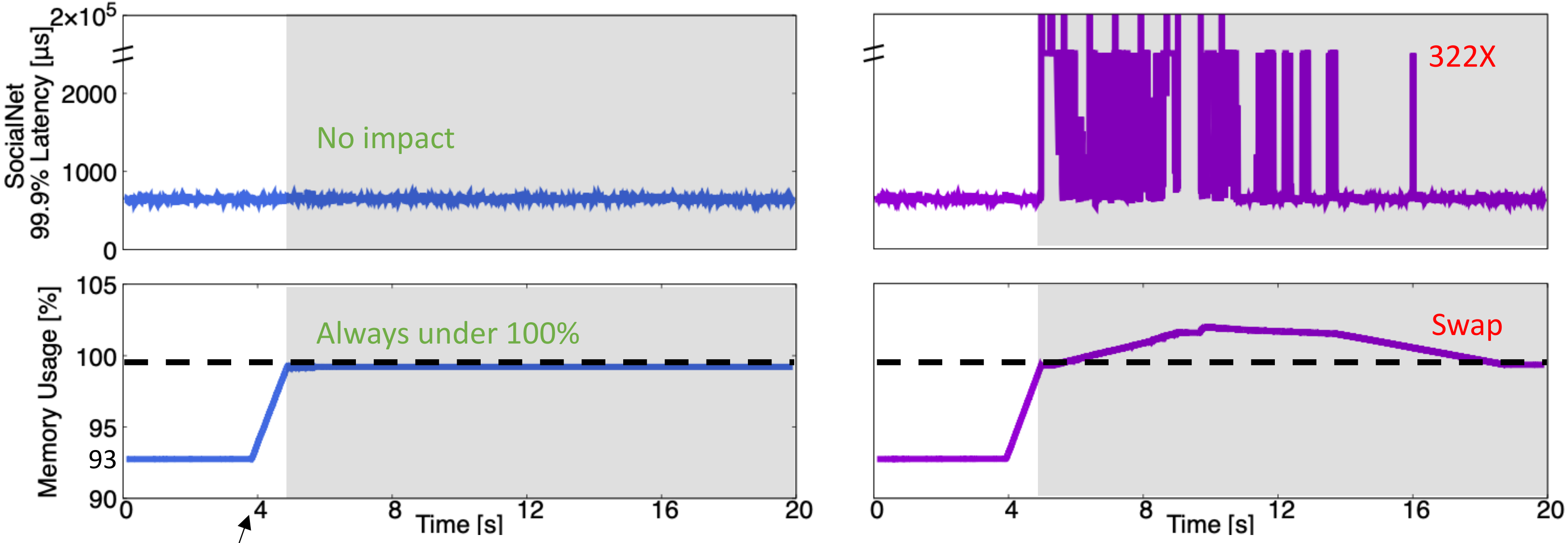

Antagonist starts

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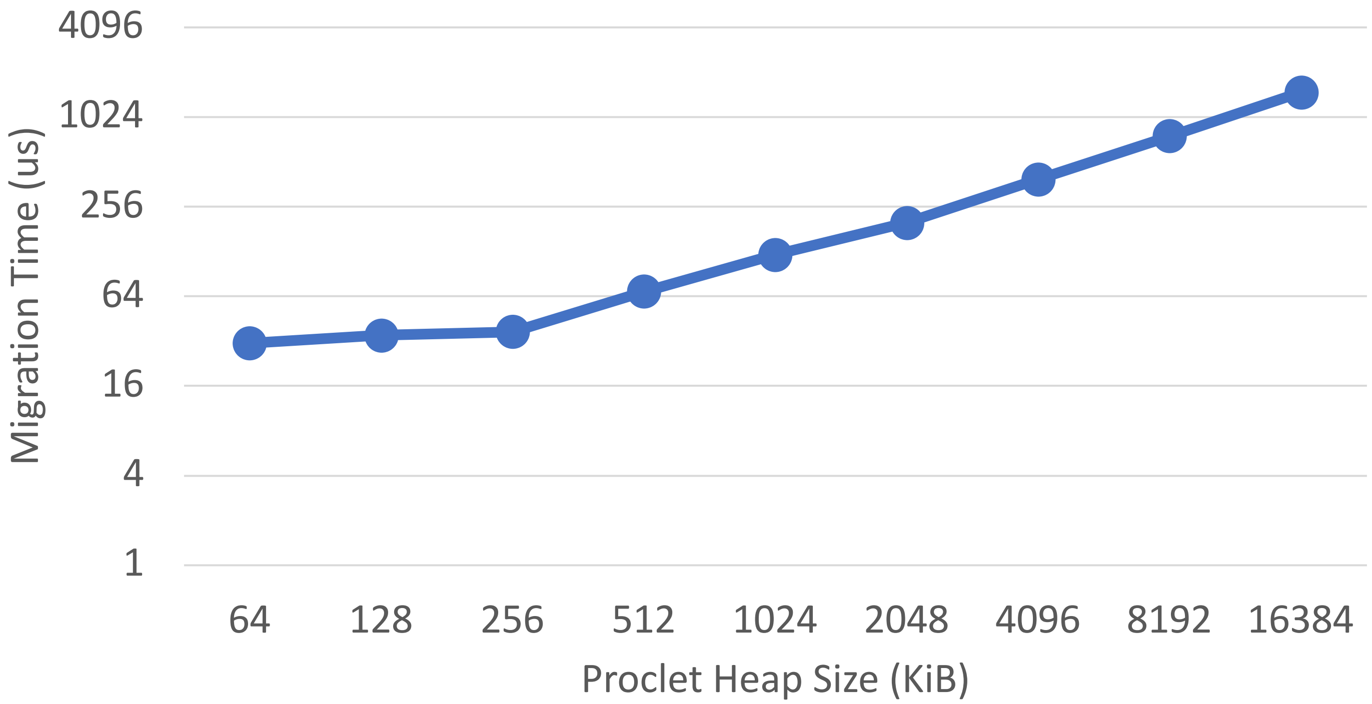
How fast can we migrate proclets?



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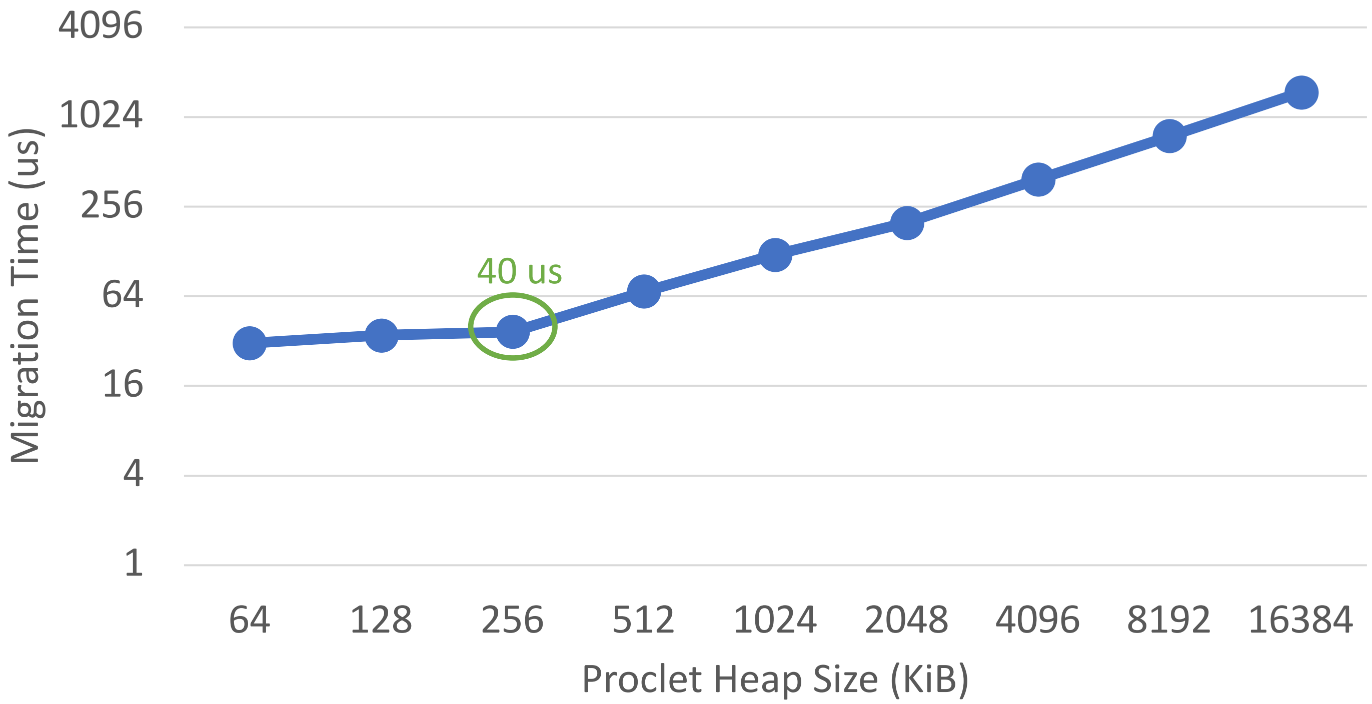

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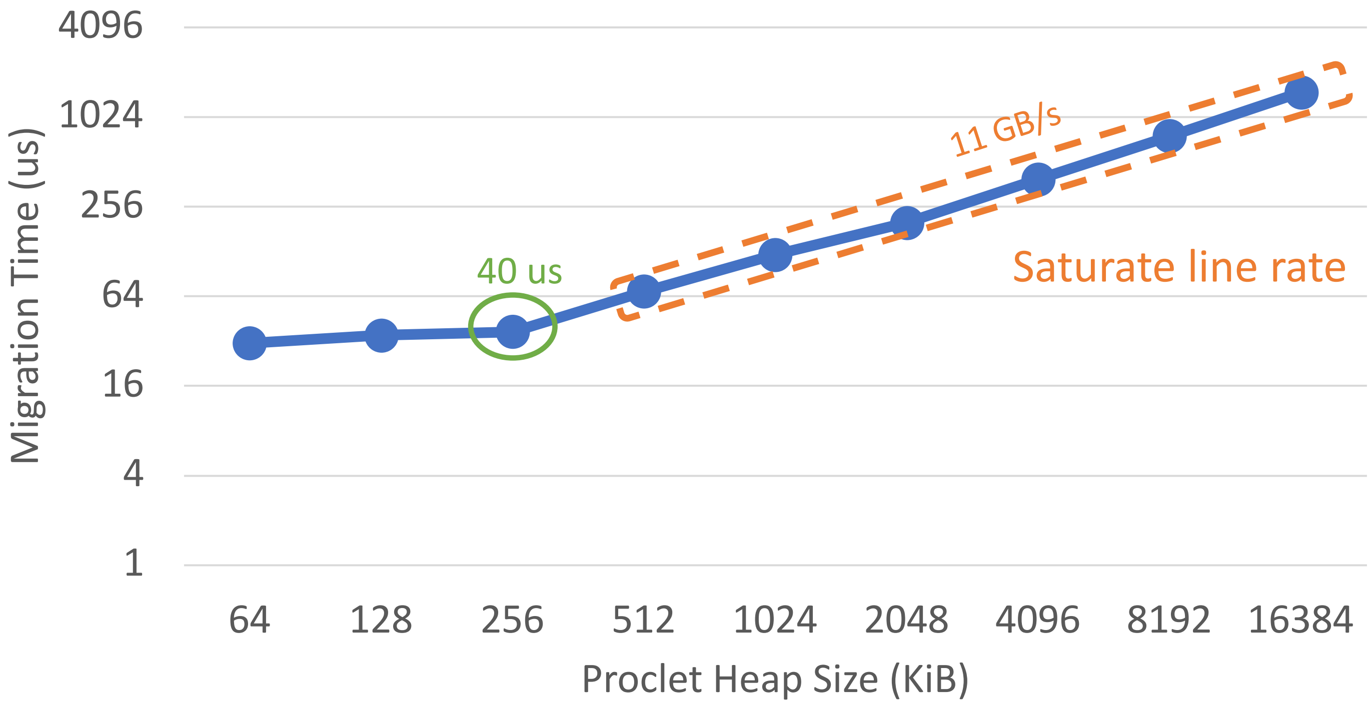

More results in the paper

- Other applications: KV store, Phoenix.
- React quickly to CPU pressure as well.
- Scale linearly with the number of machines.
- Match/exceed the performance of existing implementations.

Related Work

- Other migration systems.
  - VM/container/process live migration: MigrOS [ATC’ 21]
- Other programming models.
  - Distributed objects: Orca [OOPSLA’ 93]
  - Serverless: Boki [SOSP’ 21]
  - Actor: Ray [OSDI’ 18].
- Other options for fungibility.
  - Resource disaggregation: LegoOS [OSDI’ 18]
  - Load balancing: Slicer [OSDI’ 16]

Conclusion

- Resource overprovisioning impacts datacenter utilization.
- Nu's logical process avoids overprovisioning through fungibility.
- Key ideas: 1) decompose apps into granular proclets.
  2) rapidly migrate proclets upon pressure.
- Nu achieves high utilization without performance disruption.
- Code is available at https://github.com/Nu-NSDI23/Nu.