Google

Task Migration at Scale Using CRIU

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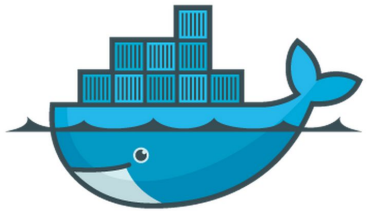
Who we are

Outside of Google, we've worked on open source **cluster management** and **containers**



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Who we are

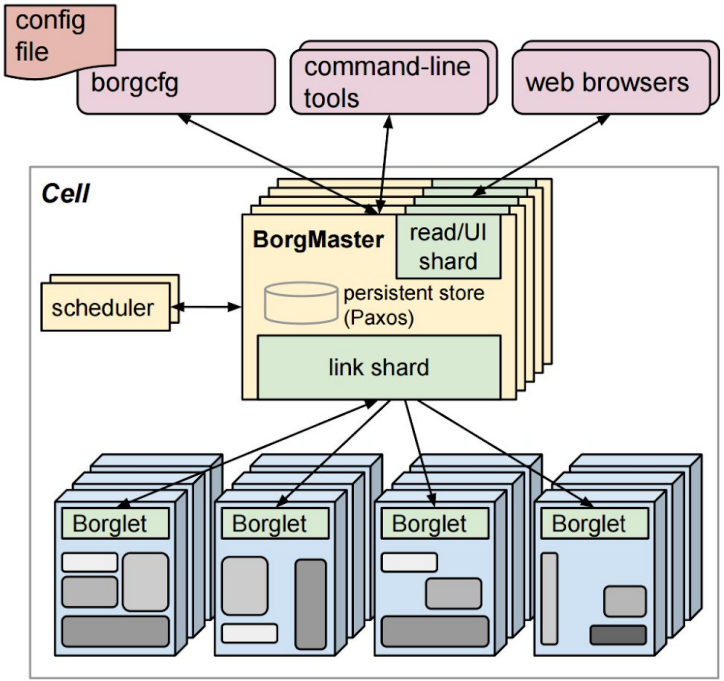
Inside Google: we're part of the **Borg** team

- Manages *all* compute jobs
- Runs on *every* server

What is Borg?

Google's cluster management system

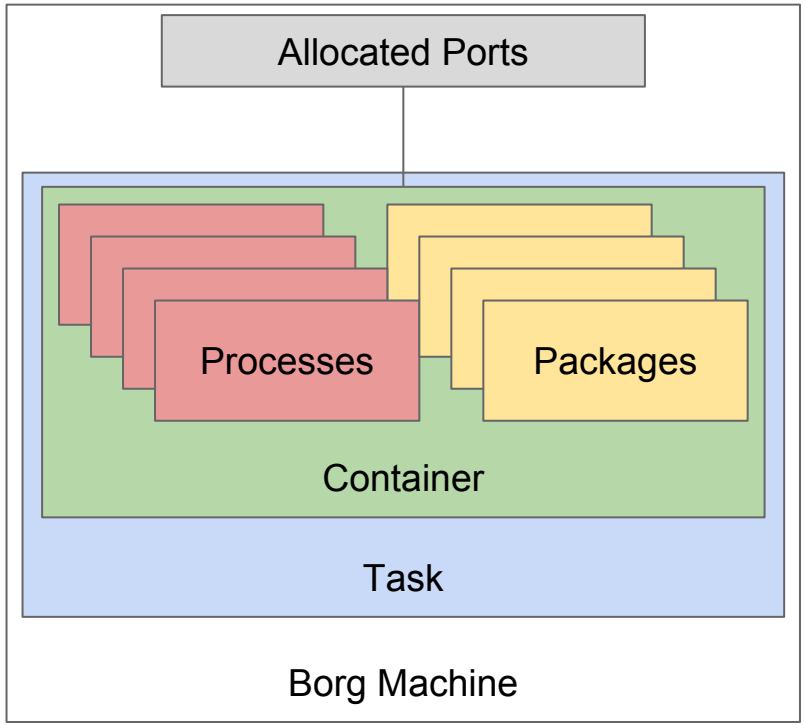
- **Borgmaster:** Cluster control and main API entrypoint
- **Borglet:** On-machine management daemon
- Suite of tools and UIs for managing jobs
- Many purpose-built platforms created on top of Borg
- Everything runs on Borg and everything runs in containers



Borg basics

Base compute primitive: **Task**

- A **priority** signals how quickly a task should schedule
- It's **appclass** describes a task as either serving (latency sensitive) or batch
- Static content/binaries provided by **packages**
- A **container** isolates a task's resources
  - Native Linux processes
  - Share an IP with the machine, ports are allocated for each task



Borg basics: evictions

When a task is **forcefully terminated** by Borg

- Typically receive a notification: 1-5min
- Our SLO allows for quite a few evictions
- Applications must handle them

Reasons for evictions

- **Preemption**: a higher priority task needs the resources
- Software **upgrades** (e.g.: kernel, firmware)
- Re-balancing for availability or performance

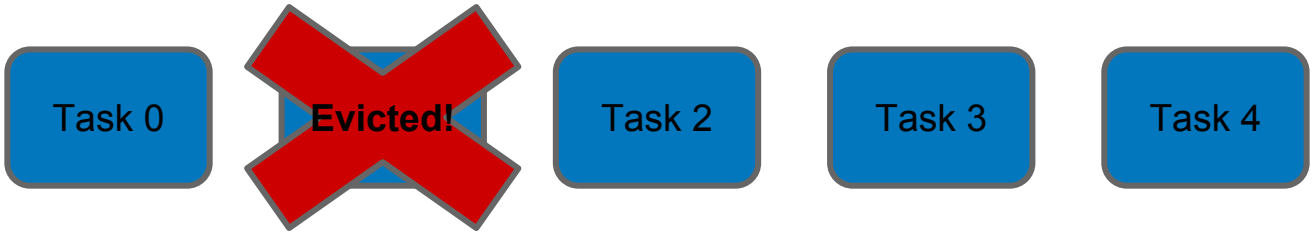
Evictions are impactful and hard to handle

Technical Complexity

- Handling evictions requires state management
  - How and what state to serialize and where to store it
- Application-specific and not very reusable

Lost Compute

- Batch jobs run at lower priorities and get preempted often
- Even platforms that handle them for users, don't do a great job



Compute is lost...

Migrations to avoid evictions

Transparently replace evictions with migration

Native **task migration** offering in Borg

- Borg controls the eviction → always knows when to migrate
- Native management of state allows reuse for all workloads

Various possible mechanisms

- Checkpoint/restore
  - Pause application, transfer state, resume
  - Long blackout period, no brownout
- Live
  - Very short blackout, but with a longer brownout
  - Very low impact to applications

Challenges with task migration

Migrating network connections

Port collisions and port use

Storage migration is slow

Must virtualize machine-local resources

Linux process state hard to migrate

Challenges with task migration

~~Migrating network connections~~ Drop the connection, user handles reconnections

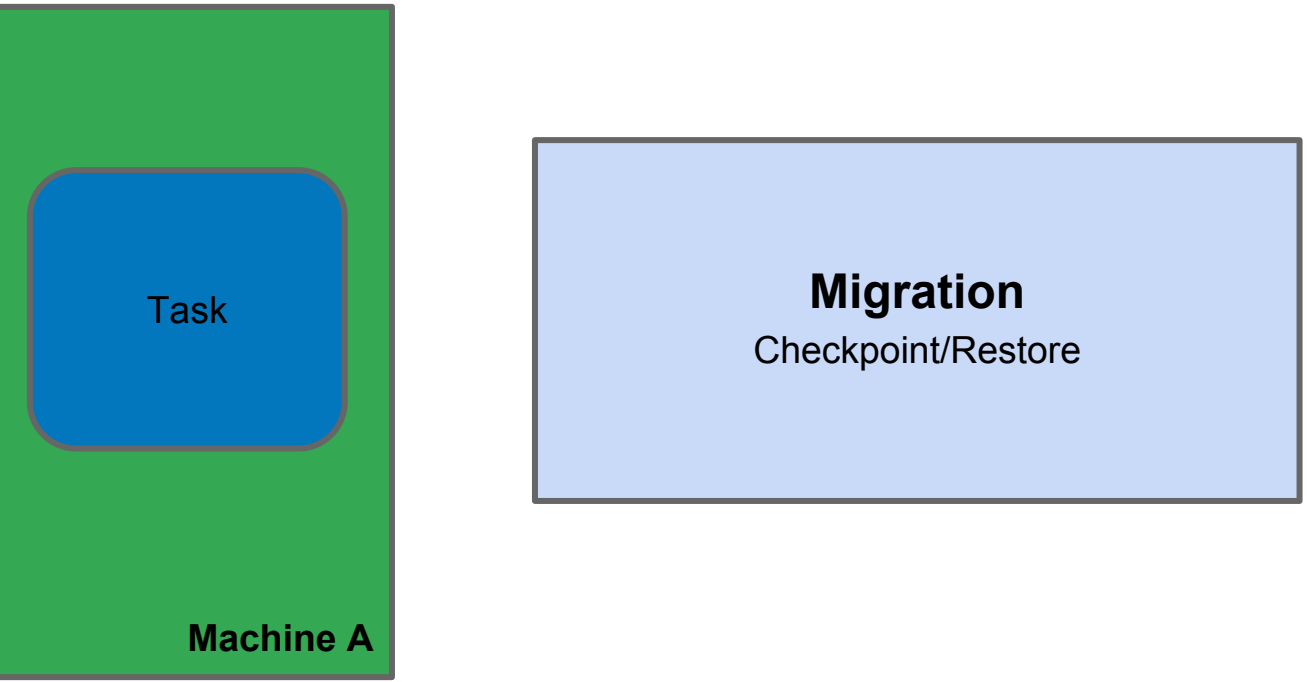
~~Port collisions and port use~~ NET namespaces and IPv6 per-container

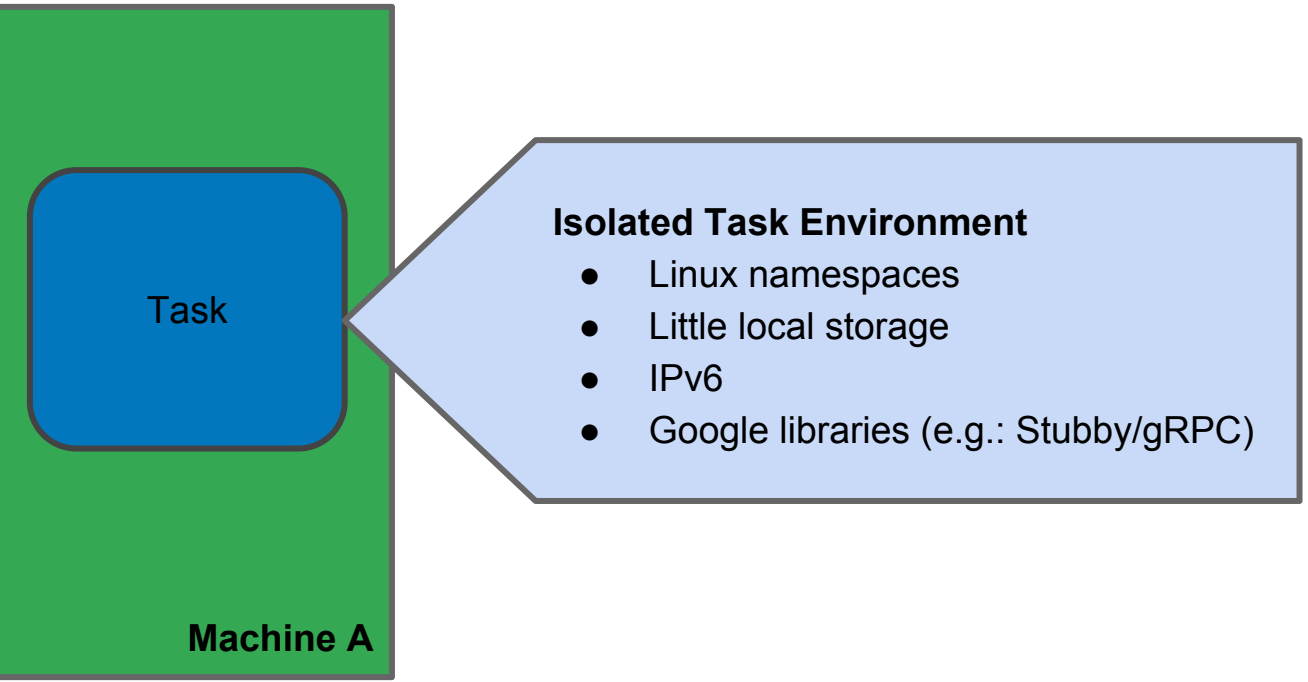
~~Storage migration is slow~~ Little to no local storage

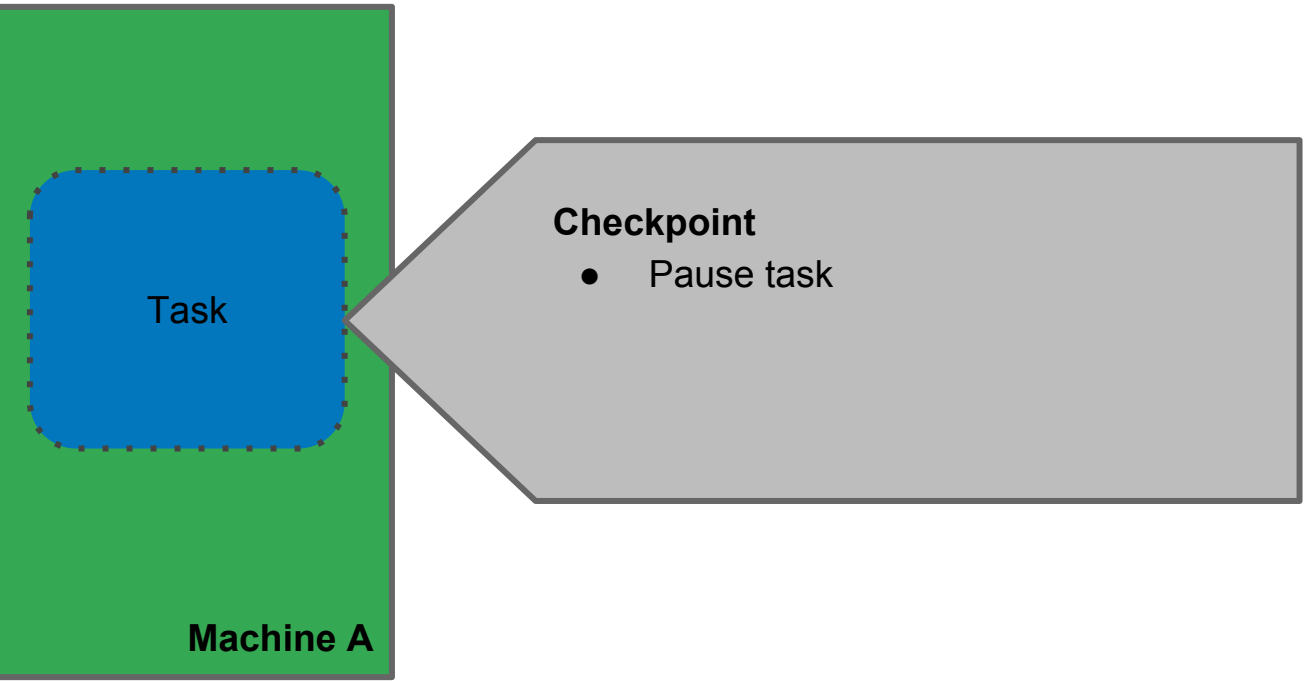
~~Must virtualize machine local resources~~ Linux namespaces

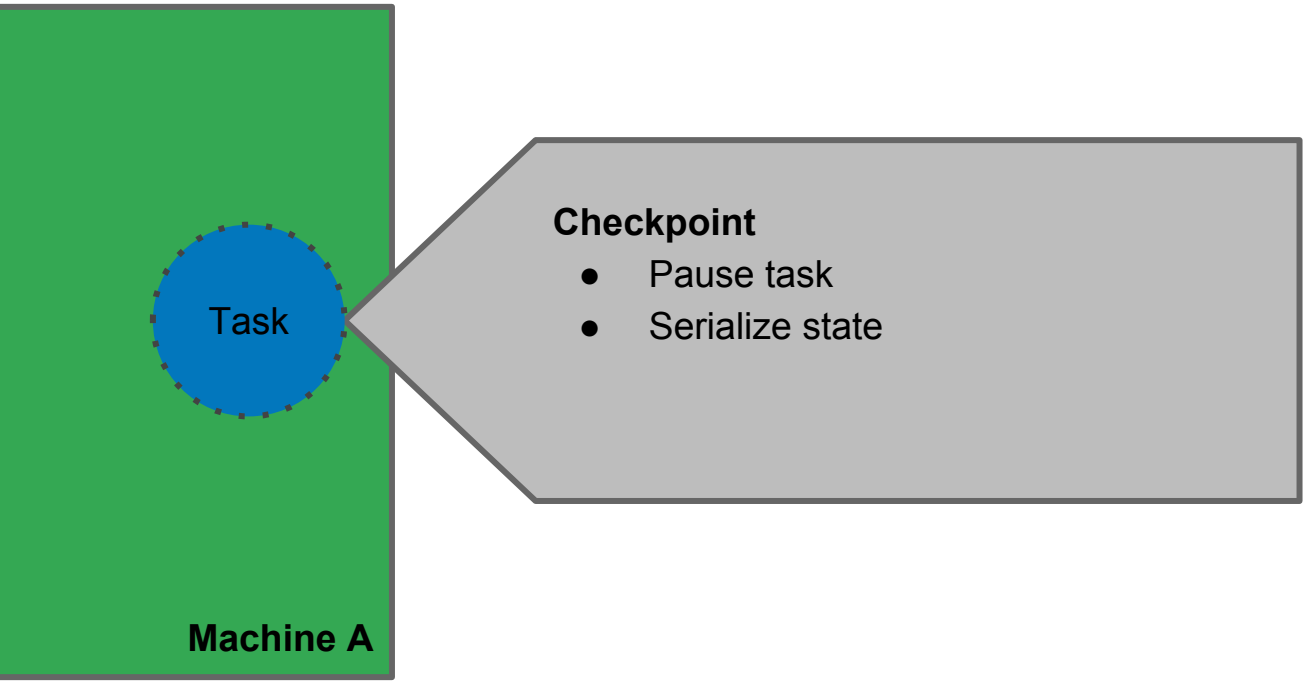
~~Linux process state hard to migrate~~ **CRIU!**

Migration Workflow

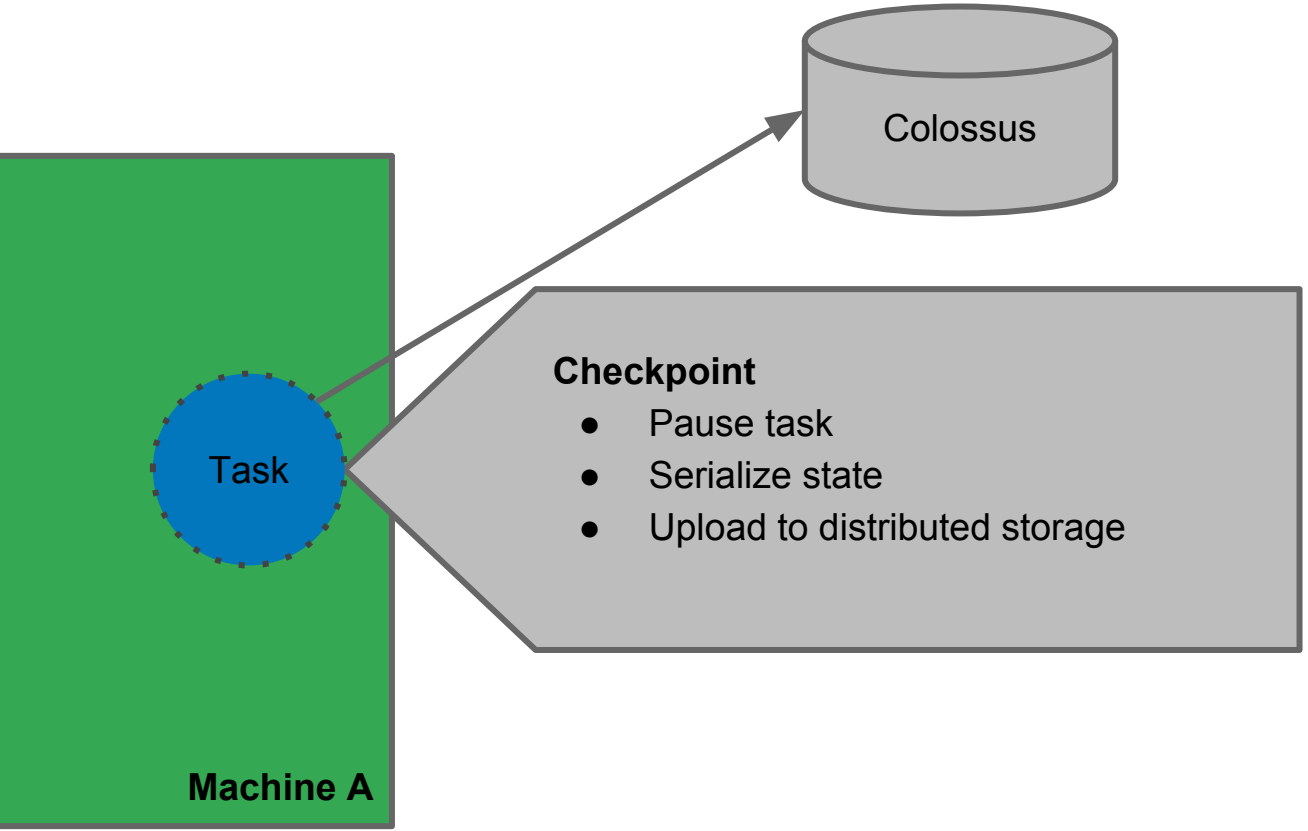

Task
Machine A
Migration
Checkpoint/Restore

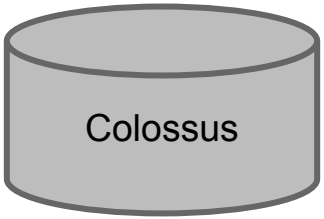

Task
Machine A
Isolated Task Environment
Linux namespaces
Little local storage
IPv6
Google libraries (e.g.: Stubby/gRPC)


Task
Machine A
Checkpoint
Pause task

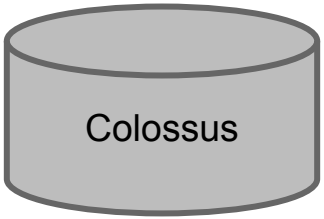

Task
Machine A
Checkpoint
Pause task
Serialize state


CRIU


Colossus
Checkpoint
Pause task
Serialize state
Upload to distributed storage
Task
Machine A



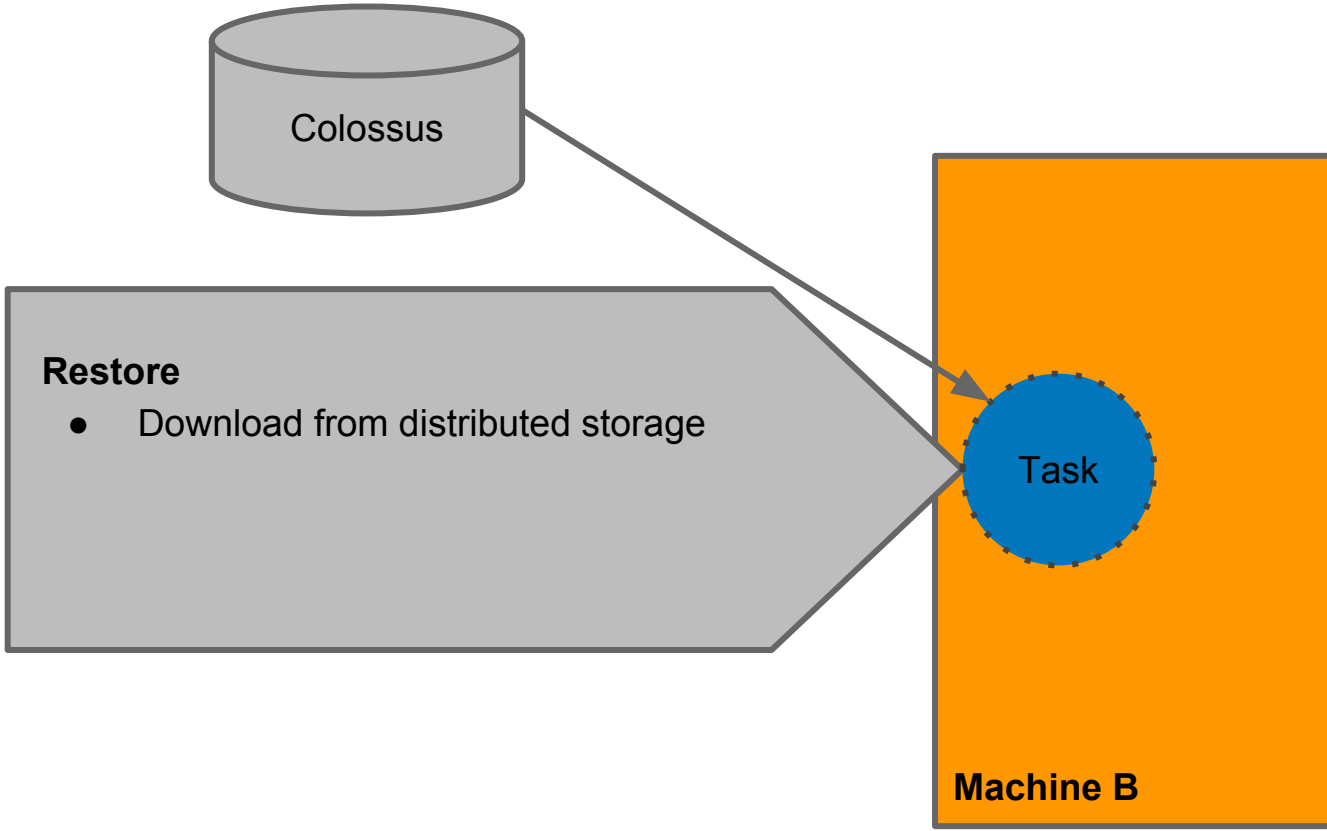
Machine A



Migration

- Borgmaster chooses new machine to schedule the task.

Machine B

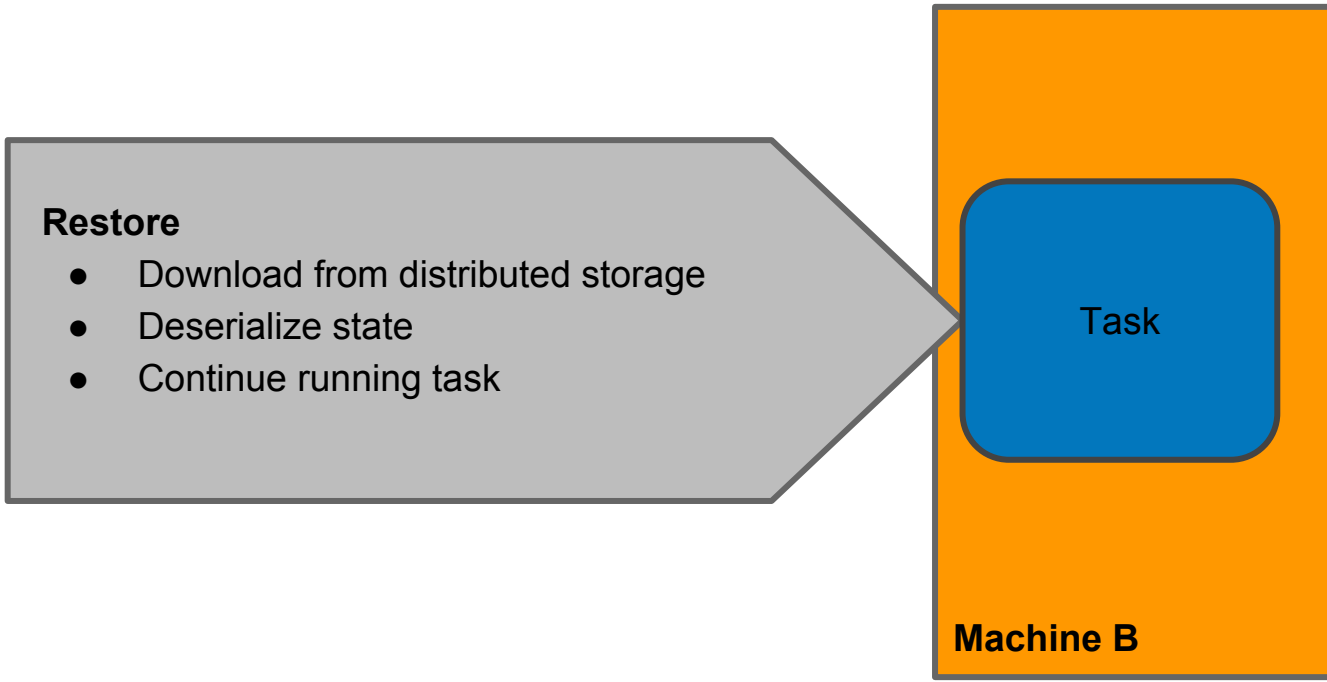

Colossus
Restore
● Download from distributed storage
Task
Machine B

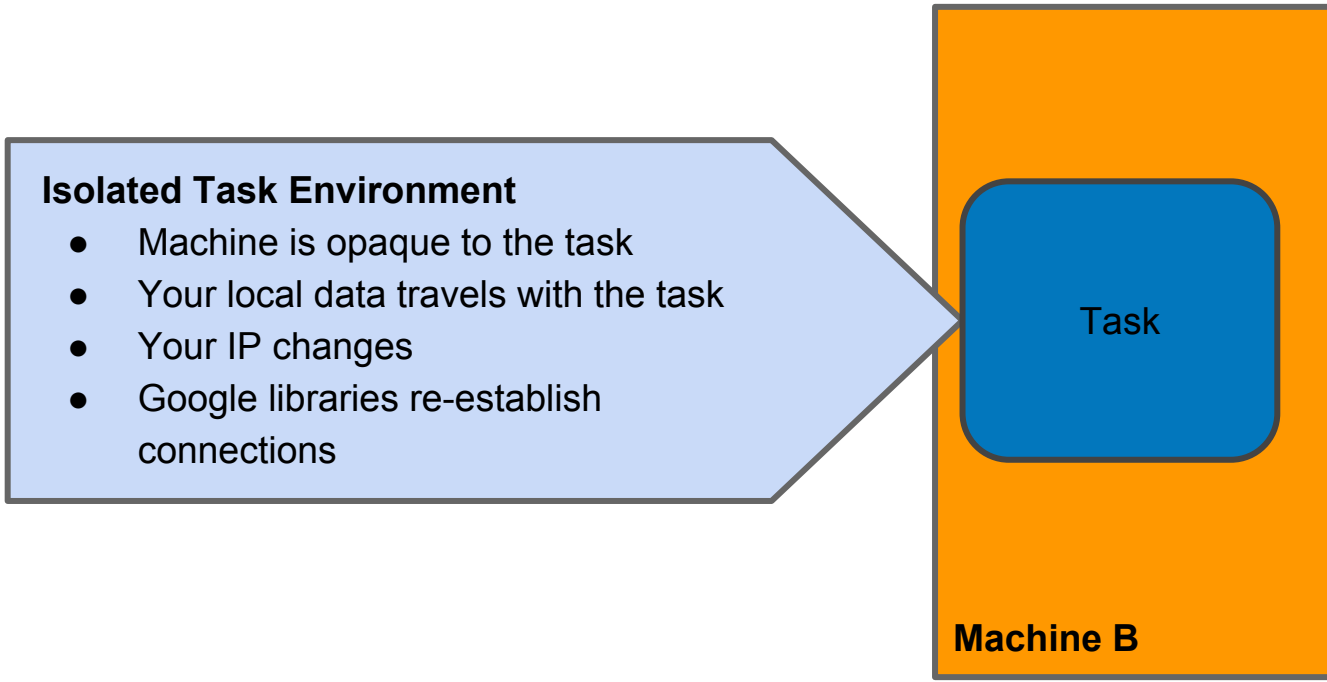
Restore

- Download from distributed storage
- Deserialize state

Task

Machine B


Restore
Download from distributed storage
Deserialize state
Continue running task
Task
Machine B


Isolated Task Environment
Machine is opaque to the task
Your local data travels with the task
Your IP changes
Google libraries re-establish connections
Task
Machine B

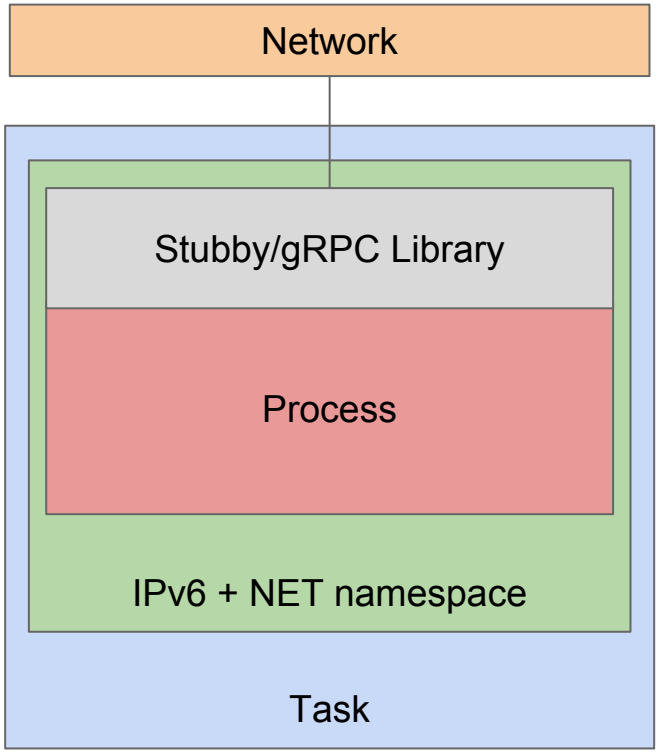
Networking

Networking @ Google

- Standardized RPC implementation: Stubby/gRPC
- Nearly all communication is RPC
- Unique IPv6 address per task
- BNS: Borg DNS, used by RPC layer

Task Migration

- Stubby/gRPC automatically reconnects
- Reconnect is transparent to users
- IP address changes, but this is rarely a problem



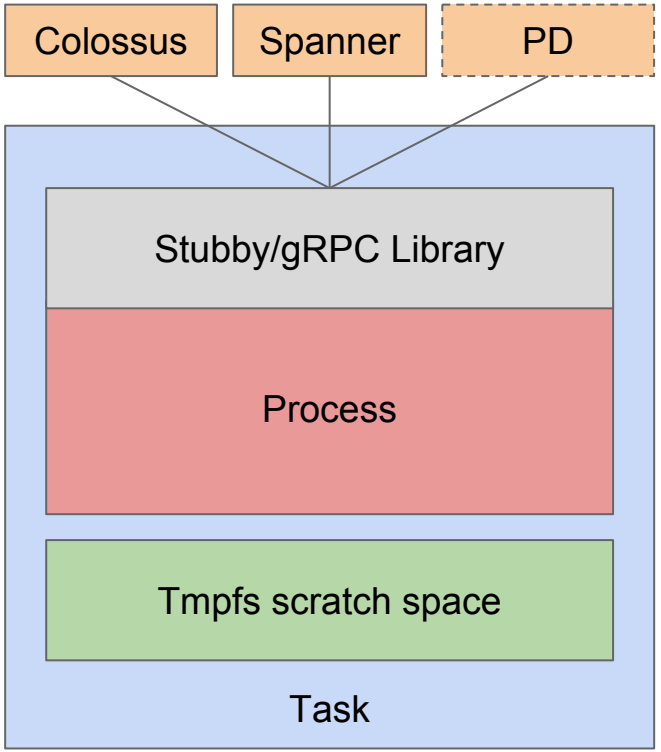
Storage

Storage @ Google: Minimized local storage

- Most tasks are **stateless**, few require local SSD/HDD
- Those that require state use our **remote storage stacks** (e.g.: Colossus, Spanner)
- Small local storage is offered via tmpfs

Task migration

- Lack of local storage greatly simplifies work
- Remote storage stacks use RPC and thus recover gracefully
- Small local storage is migrated with task



Task environment

Container

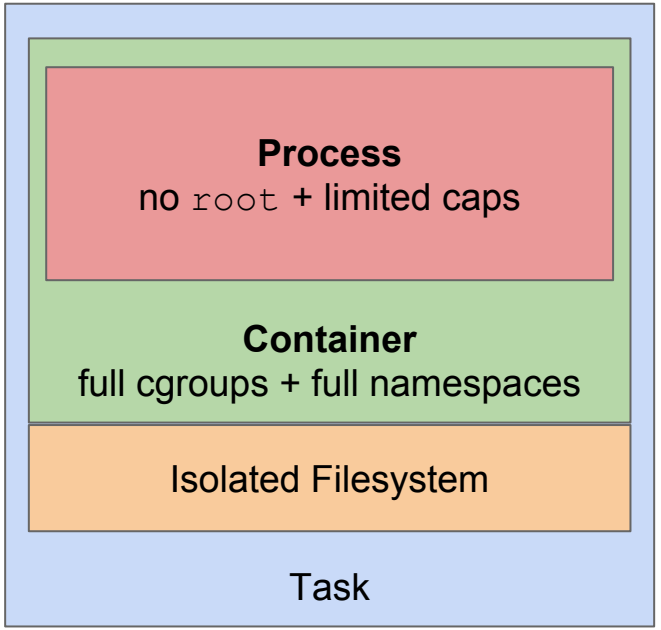
- Primarily used for resource isolation
- Full namespaces applied

Security

- Root is not mapped into user namespace
- Capabilities are strictly limited

Root filesystem

- Separate from the host machine’s
- Built and bundled by the task as a package



CRIU

Checkpoint/Restore in User Space

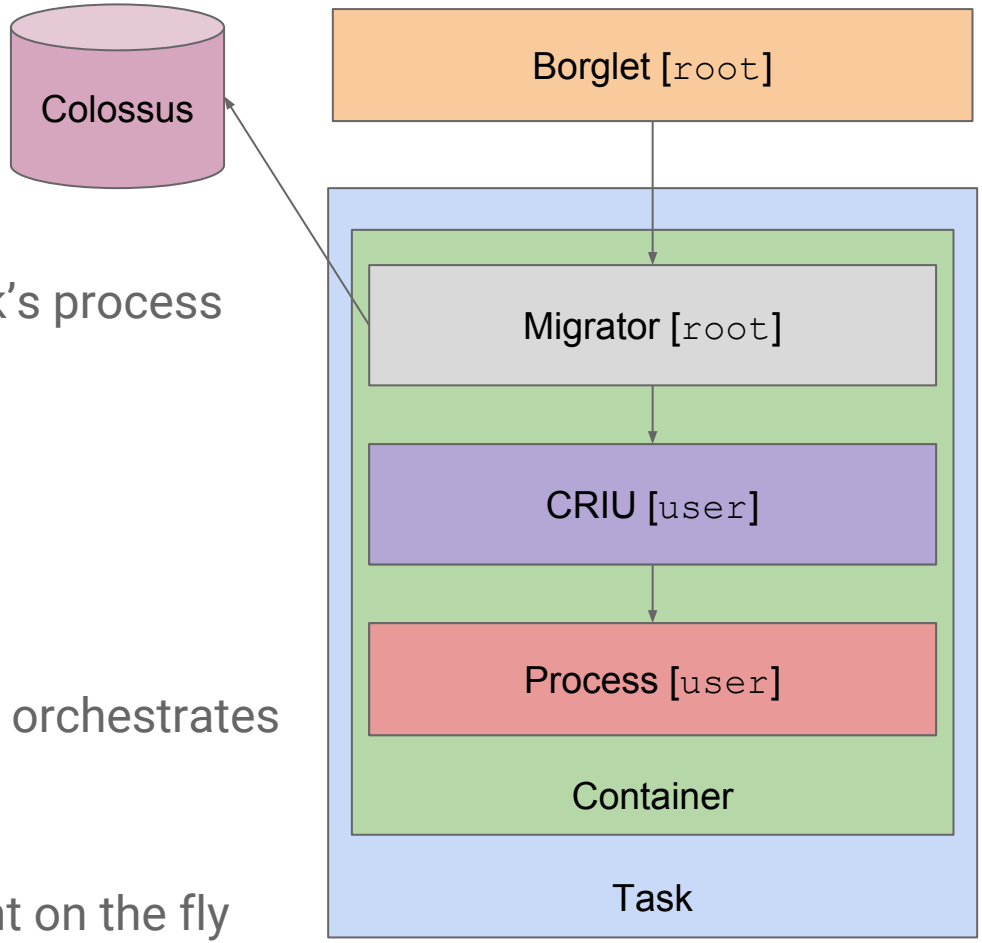
- Used to serialize/deserialize the task's process

Security and isolation

- Run inside a task's container
- Run with minimal privileges

The Migrator

- Injected into task during a migration, orchestrates the migration
- Manages execution of CRIU
- Encrypts and compresses checkpoint on the fly
  - Pretends to be a CRIU pageserver



In practice today

Migrations take **1-2min** and succeed **90%+** of the time

Where the time goes

- Checkpoint/restore is relatively fast for well-behaved tasks
- Writing/reading to remote storage dominates checkpoint/restore
- Scheduling delays are also a large source of latency

Causes of failures

- Timeouts from high task resource usage (e.g.: threads, memory)
- Different host environments
- Misc failures in serialization (e.g.: unsupported features)

Users

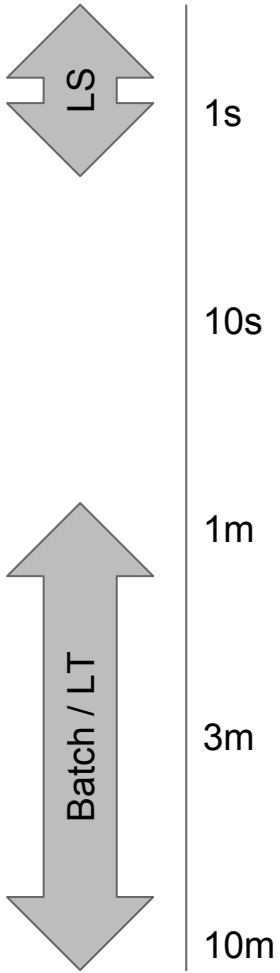
Works well for **batch** jobs

- Latency tolerant, longer-running, and lower priority
- Some are highly sharded and see many evictions
- Long pipelines suffer when some parts are evicted

User feedback

- They love it! Super **simple to adopt**
- Desire for advanced features
  - Migration notifications
  - User-controlled pause/resume

Not a great offering for latency-sensitive jobs



Adoption challenges

Handling connection failures

- In theory: users are taught to expect failures
- In practice: users don’t handle failures well
  - Expect them not to occur and reset their state when they do

Isolating task environment

- Users make assumptions about the underlying host
  - Services are available via localhost
  - Expecting host:port to work
- Users don’t expect the underlying host to change at runtime
  - Certain features detected at startup and never refreshed (e.g.: kernel, CPU, location)

Experience with CRIU

In one word? **AMAZING!**

- Mostly worked out of the box with few changes
- Reliability and performance have been great in production
- Community has been helpful and quick to fix issues

Our changes

- Performance improvements for checkpoint/restore
- Increasing/improving some limitations (see next slide)
- Most patches sent upstream

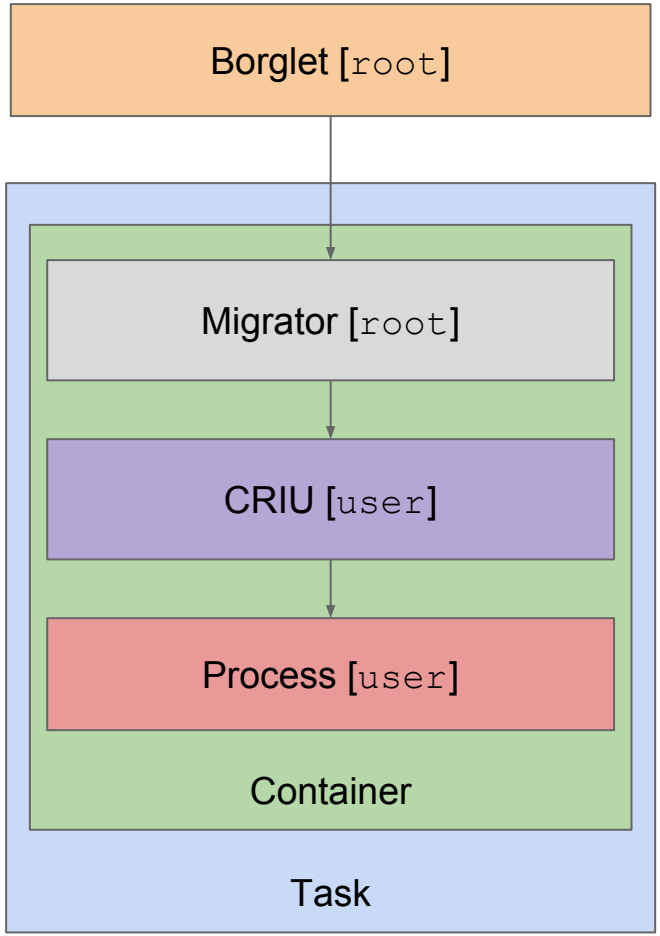
CRIU security

CRIU suggested to run as root

- Security auditing found a series of bugs
- A malicious task can hijack a CRIU process

Recommendation

- Run CRIU as the task's user
- Run in user namespace without root mapped in
- Trim privileges to minimal set



What could do with improvements

Performance

- Some expensive operations remain, some have kernel limitations
  - e.g.: `waitpid` on all threads is $O(n^2)$

Security

- Reducing need for root and elevated capabilities
- Not well tested in this setup

Misc

- Contributing patches back is a bit hard

What could do with improvements

Live migration

- Parts of incremental restore are very, very difficult
- Lots of work ahead to do the type of brownout used in VM live migration today

Handling time

- Hard to abstract away many of the time HW counters
- Time namespaces to the rescue?

Future work

Increasing adoption internally

- Reduce lost compute and simplify user tasks
- Targeting on-by-default for large batch workloads

Machine-to-machine migration

- Skip the distributed storage of the checkpoint
- Reduces migration times to ~30s

Live migration

- Able to address latency sensitive workloads
- Will require some work in our stack and in CRIU

Questions?

Native task migration offering in Borg

- Reduces compute lost to evictions
- Simplifies task handling of preemptions
- Addresses most batch workloads
- Serving workloads need live migration

CRIU

- Works amazingly well out of the box
- Security an area of investment
- We are excited about and look forward to live migration!

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