Container's Anatomy

Namespaces, cgroups, and some filesystem magic

Who am I?

- Jérôme Petazzoni (@jpetazzo)
- French software engineer living in California
- I have built and scaled the dotCloud PaaS
  (almost 5 years ago, time flies!)
- I talk (too much) about containers
  (first time was maybe in February 2013, at SCALE in L.A.)
- Proud member of the House of Bash
  (when annoyed, we replace things with tiny shell scripts)

Outline

- What is a container?
  (high level and low level overviews)
- The building blocks
  (namespaces, cgroups, copy-on-write storage)
- Container runtimes
  (Docker, LXC, rkt, runC, systemd-nspawn...)
- Other containers
  (OpenVZ, Jails, Zones...)
- Hand-crafted, artisan-pick, house-blend containers
  (with demos!)

What is a container?

High level approach: it's a lightweight VM

- I can get a shell on it
  (through SSH or otherwise)
- It "feels" like a VM:
  - own process space
  - own network interface
  - can run stuff as root
  - can install packages
  - can run services
  - can mess up routing, `iptables` ...

Low level approach: it's chroot on steroids

- It's not quite like a VM:
  - uses the host kernel
  - can't boot a different OS
  - can't have its own modules
  - doesn't need `init` as PID 1
  - doesn't need syslogd, cron...
- It's just a bunch of processes visible on the host machine (contrast with VMs which are opaque)

How are they implemented?
Let's look in the kernel source!

- Go to LXR
- Look for "LXC" → zero result
- Look for "container" → 1000+ results
- Almost all of them are about data structures
  (or other unrelated concepts like "ACPI containers")
- There are some references to "our" containers,
  in documentation

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  in documentation
- ??? Are containers even in the kernel ???

Ancient archeology

Five years ago...

- When using the LXC tools (`lxc-start`, `lxc-stop` ...)
  you would often get weird messages mentioning
  `/cgroup/container_name/...`

- The `cgroup` pseudo filesystem has counters for CPU, RAM,
  I/O, and device access (`/dev/*`) but nothing about network

- I didn't find about "namespaces" by myself
  (maybe noticing `/proc/$PID/ns` would have helped;
  more on that later)

Modern archeology

Nowadays:

- Cgroups are often in `/sys/fs/cgroup`
- You quickly stumble on `nsenter`
  (which tips you off about namespaces)
- There is significantly more documentation everywhere

The building blocks

Control groups

Control groups

- Resource *metering* and *limiting*
  - memory
  - CPU
  - block I/O
  - network*
- Device node (`/dev/*`) access control

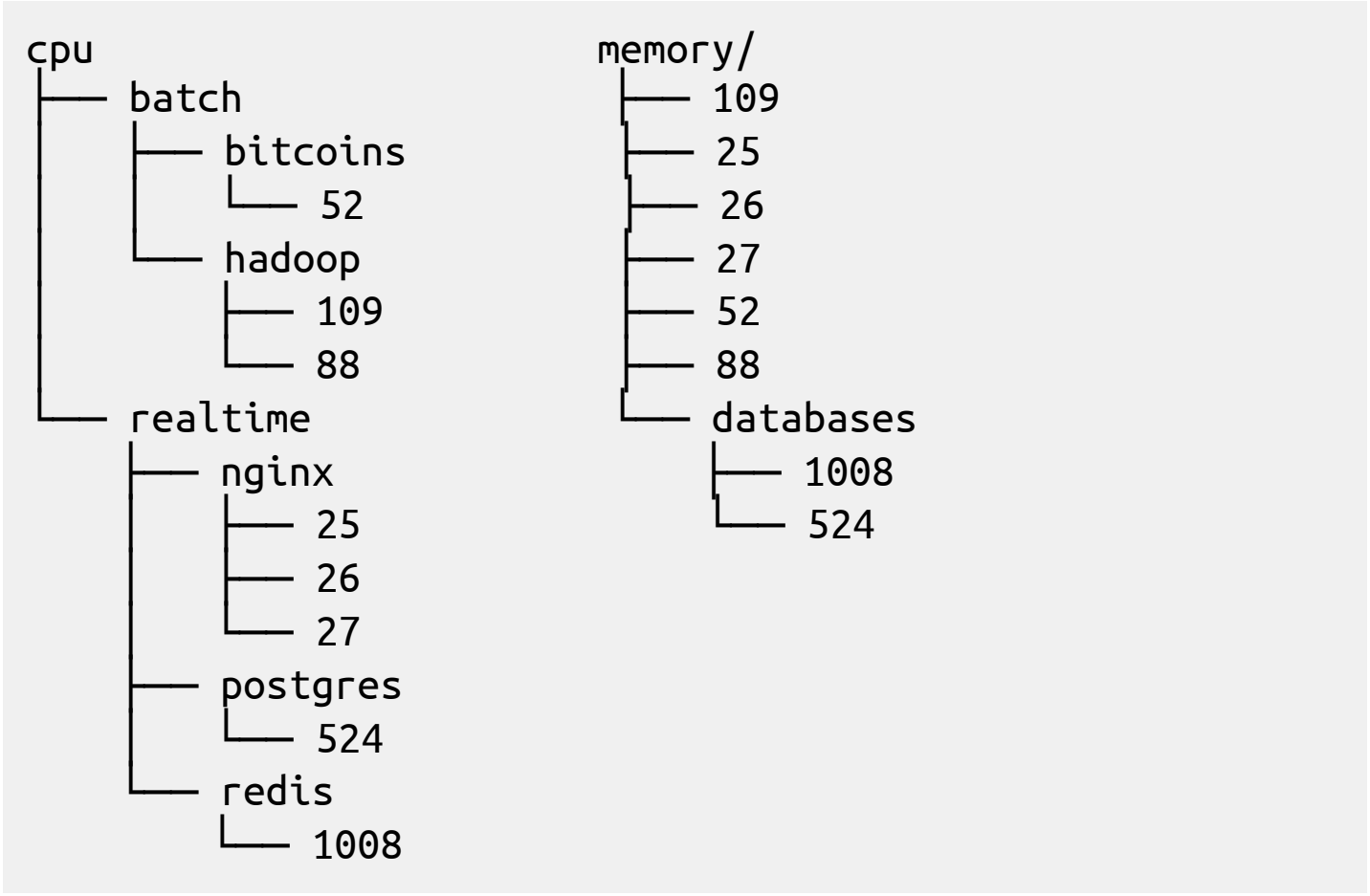
*With cooperation from iptables/tc; more on that later

Generalities

- Each subsystem (memory, CPU...) has a *hierarchy* (tree)
- Hierarchies are independent
  (the trees for e.g. memory and CPU can be different)
- Each process belongs to exactly 1 node in each hierarchy
  (think of each hierarchy as a different dimension or axis)
- Each hierarchy starts with 1 node (the root)
- All processes initially belong to the root of each hierarchy*
- Each node = group of processes
  (sharing the same resources)

*It's a bit more subtle; more on that later

Example


cpu
batch
bitcoins
52
hadoop
109
88
realtime
nginx
25
26
27
postgres
524
redis
1008
memory/
109
25
26
27
52
88
databases
1008
524

Memory cgroup: accounting

- Keeps track of pages used by each group:
  - file (read/write/mmap from block devices)
  - anonymous (stack, heap, anonymous mmap)
  - active (recently accessed)
  - inactive (candidate for eviction)
- Each page is "charged" to a group
- Pages can be shared across multiple groups
  (e.g. multiple processes reading from the same files)
- When pages are shared, the groups "split the bill"

Memory cgroup: limits

- Each group can have (optional) hard and soft limits
- Soft limits are not enforced
  (they influence reclaim under memory pressure)
- Hard limits will trigger a per-group OOM killer
- The OOM killer can be customized (oom-notifier);
  when the hard limit is exceeded:
  - freeze all processes in the group
  - notify user space (instead of going rampage)
  - we can kill processes, raise limits, migrate containers ...
  - when we're in the clear again, unfreeze the group
- Limits can be set for physical, kernel, total memory

Memory cgroup: tricky details

- Each time the kernel gives a page to a process,
  or takes it away, it updates the counters
- This adds some overhead
- Unfortunately, this cannot be enabled/disabled per process
  (it has to be done at boot time)
- Cost sharing means thata process leaving a group
  (e.g. because it terminates) can theoretically cause
  an out of memory condition

Cpu cgroup

- Keeps track of user/system CPU time
- Keeps track of usage per CPU
- Allows to set weights
- Can't set CPU limits
  - OK, let's say you give N%
  - then the CPU throttles to a lower clock speed
  - now what?
  - same if you give a time slot
  - instructions? their exec speed varies wildly
  - ¯_ツ_/¯

Cpuset cgroup

- Pin groups to specific CPU(s)
- Reserve CPUs for specific apps
- Avoid processes bouncing between CPUs
- Also relevant for NUMA systems
- Provides extra dials and knobs
  (per zone memory pressure, process migration costs...)

Blkio cgroup

- Keeps track of I/Os for each group
  - per block device
  - read vs write
  - sync vs async
- Set throttle (limits) for each group
  - per block device
  - read vs write
  - ops vs bytes
- Set relative weights for each group

Full disclosure: this used to be clunky for async operations, and I haven't tested it in ages. ☹

Net_cls and net_prio cgroup

- Automatically set traffic class or priority,
  for traffic generated by processes in the group
- Only works for egress traffic
- Net_cls will assign traffic to a class
  (that has to be matched with tc/iptables,
  otherwise traffic just flows normally)
- Net_prio will assign traffic to a priority
  (priorities are used by queuing disciplines)

Devices cgroup

- Controls what the group can do on device nodes
- Permissions include read/write/mknod
- Typical use:
  - allow `/dev/{tty,zero,random,null}` ...
  - deny everything else
- A few interesting nodes:
  - `/dev/net/tun` (network interface manipulation)
  - `/dev/fuse` (filesystems in user space)
  - `/dev/kvm` (VMs in containers, yay inception!)
  - `/dev/dri` (GPU)

Subtleties

- PID 1 is placed at the root of each hierarchy
- When a process is created, it is placed in the same groups as its parent
- Groups are materialized by one (or multiple) pseudo-fs (typically mounted in `/sys/fs/cgroup`)
- Groups are created by `mkdir` in the pseudo-fs
- To move a process:

```
echo $PID > /sys/fs/cgroup/.../tasks
```

- The cgroup wars: systemd vs cgmanager vs ...

Namespaces

Namespaces

- Provide processes with their own view of the system
- Cgroups = limits how much you can use;
  namespaces = limits what you can see (and therefore use)
- Multiple namespaces:
  - pid
  - net
  - mnt
  - uts
  - ipc
  - user
- Each process is in one namespace of each type

Pid namespace

- Processes within a PID namespace only see processes in the same PID namespace
- Each PID namespace has its own numbering (starting at 1)
- When PID 1 goes away, the whole namespace is killed
- Those namespaces can be nested
- A process ends up having multiple PIDs (one per namespace in which its nested)

Net namespace: in theory

- Processes within a given network namespace get their own private network stack, including:
  - network interfaces (including `lo`)
  - routing table**s**
  - iptables rules
  - sockets (`ss`, `netstat`)
- You can move a network interface from a netns to another

```
ip link set dev eth0 netns PID
```

Net namespace: in practice

- Typical use-case:
  - use `veth` pairs
    (two virtual interfaces acting as a cross-over cable)
  - `eth0` in container network namespace
  - paired with `vethXXX` in host network namespace
  - all the `vethXXX` are bridged together
    (Docker calls the bridge `docker0`)
- But also: the magic of `--net container`
  - shared `localhost` (and more!)

Mnt namespace

- Processes can have their own root fs (à la chroot)
- Processes can also have "private" mounts
  - `/tmp` (scoped per user, per service...)
  - Masking of `/proc`, `/sys`
  - NFS auto-mounts (why not?)
- Mounts can be totally private, or shared
- No easy way to pass along a mount
  from a namespace to another ☹

Uts namespace

- gethostname / sethostname
- 'nuff said!

lpc namespace

Ipc namespace

- Does anybody knows about IPC?

Ipc namespace

- Does anybody knows about IPC?
- Does anybody *cares* about IPC?

Ipc namespace

- Does anybody knows about IPC?
- Does anybody *cares* about IPC?
- Allows a process (or group of processes) to have own:
  - IPC semaphores
  - IPC message queues
  - IPC shared memory

  ... without risk of conflict with other instances.

User namespace

- Allows to map UID/GID; e.g.:
  - UID 0→1999 in container C1 is mapped to UID 10000→11999 on host
  - UID 0→1999 in container C2 is mapped to UID 12000→13999 on host
  - etc.
- Avoids extra configuration in containers
- UID 0 (`root`) can be squashed to a non-privileged user
- Security improvement

But: devil is in the details

Namespace manipulation

- Namespaces are created with the `clone()` system call
  (i.e. with extra flags when creating a new process)
- Namespaces are materialized by pseudo-files in
  `/proc/<pid>/ns`
- When the last process of a namespace exits, it is destroyed
  (but can be preserved by bind-mounting the pseudo-file)
- It is possible to "enter" a namespace with `setns()`
  (exposed by the `nsenter` wrapper in `util-linux`)

Copy-on-write

Copy-on-write storage

- Create a new container instantly
  (instead of copying its whole filesystem)
- Storage keeps track of what has changed
- Many options available
  - AUFS, overlay (file level)
  - device mapper thinp (block level)
  - BTRFS, ZFS (FS level)
- Considerably reduces footprint and "boot" times

See also: Deep dive into Docker storage drivers

Other details

Orthogonality

- All those things can be used independently
- Use a few cgroups if you just need resource isolation
- Simulate a network of routers with network namespaces
- Put the debugger in a container's namespaces,
  but not its cgroups (to not use its resource quotas)
- Setup a network interface in an isolated environment,
  then move it to another
- etc.

One word about overhead

- Even when you don't run containers ...
  ... you are in a container
- Your host processes still execute in the root namespaces and cgroups
- Remember: there are three kind of lies

One word about overhead

- Even when you don't run containers ...
  ... you are in a container
- Your host processes still execute in the root namespaces and cgroups
- Remember: there are three kind of lies
- Lies, damn lies, and benchmarks

Some missing bits

- Capabilities
  - break down "root / non-root" into fine-grained rights
  - allow to keep root, but without the dangerous bits
  - however: `CAP_SYS_ADMIN` remains a big catchall
- SELinux / AppArmor ...
  - containers that actually contain
  - deserve a whole talk on their own

Container runtimes

LXC

- Set of userland tools
- A container is a directory in `/var/lib/lxc`
- Small config file + root filesystem
- Early versions had no support for CoW
- Early versions had no support to move images around
- Requires significant amount of elbow grease
  (easy for sysadmins/ops, hard for devs)

systemd-nspawn

From its manpage:

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```
#define INDEX_HOST "index.do" /* the URL we get the data from */ "cker.io"
#define HEADER_TOKEN "X-Do" /* the HTTP header for the auth token */ "cker-Token:"
#define HEADER_REGISTRY "X-Do" /*the HTTP header for the registry */ "cker-Endpoints:"
```

Docker Engine

- Daemon controlled by REST(ish) API
- First versions shelled out to LXC,
  now uses its own `libcontainer` runtime
- Manages containers, images, builds, and more
- Some people think it does too many things

rkt, runC

- Back to the basics!
- Focus on container execution
  (no API, no image management, no build, etc.)
- They implement different specifications:
  - rkt implements appc (App Container)
  - runC implements OCP (Open Container Project),
    leverages Docker's libcontainer

Which one is best?

- They *all* use the same kernel features
- Performance will be exactly the same
- Look at:
  - features
  - design
  - ecosystem

Other containers

OpenVZ

- Also Linux
- Older, but battle-tested
  (e.g. Travis CI gives you root in OpenVZ)
- Tons of neat features too
  - ploop (efficient block device for containers)
  - checkpoint/restore, live migration
  - venet (~more efficient veth)
- Still developed

Jails / Zones

- FreeBSD / Solaris
- Coarser granularity than namespaces and cgroups
- Strong emphasis on security
- Great for hosting providers
- Not so much for developers
  (where's the equivalent of `docker run -ti ubuntu`?)

Note: Solaris branded zones can run Linux binaries

Build your own

FOR EDUCATIONAL
PURPOSES ONLY


root@dockerhost:~#

Thanks!
Questions?

@jpetazzo
@docker