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Demystifying container networking

35-44 minutes

Over the last year, at work I had multiple chances to debug how containers work. Recently we had to solve some networking problems a customer had with Kubernetes, and I decided I wanted to know more. Once the problem was solved, I spent more time on investigating what is actually going on under the hood. After seeing the wonderful Eric Chiang and Laurent Bernaille talks, and reading through the very informative posts by Lizzie Dixon and Julia Evans (that I really really recommend), I got enough information about how a container is created and managed. I'm going to rip off and mix some stuff from their awesome posts in the first part of mine.

What I missed in those talks was the networking part. How do containers talk to each other? In Bernaille's talk there is some information, but I after seeing the video I was still not convinced completely. I was especially interested about how Calico works, and for that I could find very little information.

To answer this kind of questions I will try to create containers from scratch, by using just standard Linux commands. I will also setup the networking to make them happily communicate, again from scratch. I like this approach because it gets low level enough to demystify things that look very complicated, while it's just a matter of spending some time to understand the basics.

This post is an extended version of a talk I gave internally at my company, trying to shed some light on the subject.

Prerequisites for a good understanding are some basic networking and Linux concepts:

- the OSI model, and in particular level 2 and 3;
- IP networking and the CIDR notation;
- NAT (Network Address Translation).

I will link the advanced topics as the post unfolds.

1 Containers from scratch

Rise your hand if you ever tried the magic of Docker at least once. You pull an image from the Internet, you run it and you are projected inside another OS, with different libraries and applications installed, and all of that in no time. But how magic is a container after all? Is it composed by very complicated tools? Is it a sort of virtual machine? In the first part of this post I'm going to create a container from scratch, by using only a Linux shell and standard Linux commands, to try to answer these questions.

1.1 Prepare the image

When you do a `docker pull` you are downloading a container image from the Internet. This image at its core is basically just a root filesystem. You can safely ignore the fact that it's composed by multiple stacked layers, because the end result is just a root filesystem.

So we can try to make our own, and for this post I decided to go with Alpine Linux, because it's small and it's different from my distribution.[1] Needless to say that for this to work you have to be running on Linux and with a fairly recent Kernel. I haven't checked the specific requirements, but if you updated your system in the last 5 years,[2] you're probably good to go.

Be powerful, be root. You'll save yourself a lot of `sudo` invocations and annoying "permission denied" messages:

```
sudo su
```

Download the mini root filesystem from the Alpine website and put it somewhere. Then extract it:

```
mkdir rootfs
cd rootfs
tar xf ../alpine-minirootfs-3.6.2-x86_64.tar.gz
```

if you look there, you'll see the root filesystem:

```
[root@mike-dell rootfs]# ls -l
total 64
drwxr-xr-x  2 root root 4096 Aug 13 16:22 bin
drwxr-xr-x  4 root root 4096 Jun 17 11:46 dev
drwxr-xr-x 15 root root 4096 Aug 13 16:26 etc
drwxr-xr-x  2 root root 4096 Jun 17 11:46 home
drwxr-xr-x  5 root root 4096 Aug 13 16:22 lib
drwxr-xr-x  5 root root 4096 Jun 17 11:46 media
drwxr-xr-x  2 root root 4096 Jun 17 11:46 mnt
dr-xr-xr-x  2 root root 4096 Jun 17 11:46 proc
drwx------  2 root root 4096 Aug 13 16:08 root
drwxr-xr-x  2 root root 4096 Jun 17 11:46 run
drwxr-xr-x  2 root root 4096 Jun 17 11:46 sbin
drwxr-xr-x  2 root root 4096 Jun 17 11:46 srv
drwxr-xr-x  2 root root 4096 Jun 17 11:46 sys
drwxrwxrwt  2 root root 4096 Jun 17 11:46 tmp
drwxr-xr-x  7 root root 4096 Jun 17 11:46 usr
drwxr-xr-x 13 root root 4096 Aug 13 16:22 var
```

1.2 chroot

Now let's try to `chroot` there. In this way we create a process and change its root directory to the one we just created:

```
chroot rootfs /bin/ash
export PATH=/bin:/usr/bin:/sbin
```

This will execute a shell inside the chroot environment. Side note: exporting a new `$PATH` (the second command) is wise, because otherwise you'd be carrying your host `$PATH` in the chroot, and this might not be correct there. So where are we exactly?

```
/ # cat /etc/os-release
NAME="Alpine Linux"
ID=alpine
VERSION_ID=3.6.2
PRETTY_NAME="Alpine Linux v3.6"
HOME_URL="http://alpinelinux.org"
BUG_REPORT_URL="http://bugs.alpinelinux.org"
```

Yes, in Alpine Linux. And you can't reach your host files anymore, because your root directory is now the one we just chroot-ed into.

Let's now install some useful packages. They'll come in handy for later:

```
apk add --no-cache python findmnt curl libcap bind-tools
```

Another thing we have to fix now is the `/proc` filesystem. If you look there you'll see that it's empty so any utility like `ps` won't work:

```
mount -t proc proc /proc
```

Now a question for you: Is this actually a container?

Sort-of, but the isolation is pretty poor. Take a look at `ps aux` from the "container":

```
/ # ps aux
PID   USER     TIME   COMMAND
    1 root       0:03 {systemd} /sbin/init
    2 root       0:00 [kthreadd]
    3 root       0:00 [kworker/0:0]
    4 root       0:00 [kworker/0:0H]
    6 root       0:00 [mm_percpu_wq]
    7 root       0:00 [ksoftirqd/0]
    8 root       0:01 [rcu_preempt]
    9 root       0:00 [rcu_sched]
   10 root       0:00 [rcu_bh]
   11 root       0:00 [migration/0]
   12 root       0:00 [watchdog/0]
   13 root       0:00 [cpuhp/0]
   14 root       0:00 [cpuhp/1]
   15 root       0:00 [watchdog/1]
   16 root       0:00 [migration/1]
```

```
   17 root       0:00 [ksoftirqd/1]
   19 root       0:00 [kworker/1:0H]
 ...
 2816 1170       0:00 top
```

oops… I can see all the processes of my host from here. An I can actually kill them:

```
killall top
```

Not only that. Look at the network:

```
/ # ip link
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN qlen 1000
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
3: wlan0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc fq_codel state UP
qlen 1000
    link/ether 40:49:0f:fe:c3:05 brd ff:ff:ff:ff:ff:ff
```

You can see my WiFi card for example. I could change the IP, take it down, etc. Not nice. The answer is then NO, this is not a container, because it's not isolated enough. This is just a process in a different root filesystem.

1.3 Namespaces

Linux has namespaces to the rescue. As `man 7 namespaces` says:

> A namespace wraps a global system resource in an abstraction that makes it appear to the processes within the namespace that they have their own isolated instance of the global resource. Changes to the global resource are visible to other processes that are members of the namespace, but are invisible to other processes. One use of namespaces is to implement containers.

or in other words: we take a resource like the list of processes in the machine, we make an isolated copy of it, give it to our process and make sure that any change there is not reflected to the root process list. This is the PID namespace. Is it hard to set up? Judge by yourself:

```
unshare -p -f chroot rootfs /usr/bin/env -i \
    HOME=/root \
    PATH=/bin:/usr/bin:/sbin:/usr/sbin \
    /bin/ash -l
```

With this command from the host, we create a new process (the `chroot` we used before) but we put it in a new PID namespace by prepending the `unshare -p` invocation. This command is nothing fancy, just a handy wrapper around the `unshare` Linux system call. The env command executed after the `chroot` makes sure that the environment is correctly filled, avoiding us to repeat the `export` command every time.

Let's take a look at the list of processes now, after we mount `/proc` again:

```
/ # mount -t proc proc /proc
/ # ps
PID   USER     TIME   COMMAND
    1 root       0:00 /bin/ash
    5 root       0:00 ps
```

Oh yes. Now our shell is actually PID 1. How weird is that? And yes, you won't be able to kill any host process.

From the host you can instead see the containerized process:

```
[root@mike-dell micheleb]# ps aux |grep /ash
root      8552  0.0  0.0   1540   952 pts/3    S+   20:06   0:00 /bin/ash
```

and kill it if you want to.

The PID is not the only namespace you can create, as you can imagine. The network for example is still the host one:

```
/bin # ip link
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN qlen 1000
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
3: wlan0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc fq_codel state UP
qlen 1000
    link/ether 40:49:0f:fe:c3:05 brd ff:ff:ff:ff:ff:ff
```

Let's isolate it then. It's just a matter of adding some flags to `unshare`:

```
unshare -pmn -f chroot rootfs /usr/bin/env -i \
```

```
    HOME=/root \
    PATH=/bin:/usr/bin:/sbin:/usr/sbin \
    /bin/ash -l
```

here we are isolating the PID, mount and network namespaces, all at once. And here is the result:

```
# / ip addr
1: lo: <LOOPBACK> mtu 65536 qdisc noop state DOWN qlen 1000
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
# / ping -c1 8.8.8.8
PING 8.8.8.8 (8.8.8.8): 56 data bytes
ping: sendto: Network unreachable
```

Pretty isolated I would say. Topic of the next section will be how to open a little hole in this isolation and get some containers to communicate somehow.

Before to move on I'd like to put a little disclaimer here. Even though I'm done with this section, it doesn't mean that with an `unshare` command you get a fully secure container. Don't go to your boss and say that you want to toss Docker and use shell scripts because it's the same thing.

What our container is still missing is, for example, resource isolation. We could crash the machine by creating a lot of processes, or slow it down by allocating a lot of memory. For this you need to use `cgroups`.[3] Then there's the problem you are still root inside the container, You are limited but you are still pretty powerful. You could for example change the system clock, reboot the machine, and other scary things. To control them you'd need to drop some capabilities.[4] I won't dig into these concepts in this post, because they don't affect the networking. All of that involves just simple Linux system calls and some magic in the `/proc` and `/sys/fs/cgroup/` filesystems.

I point you though to the excellent resources I linked at the beginning, especially Eric Chiang and Lizzie Dixon, if you are more curious. I could also write another post on that in the future.

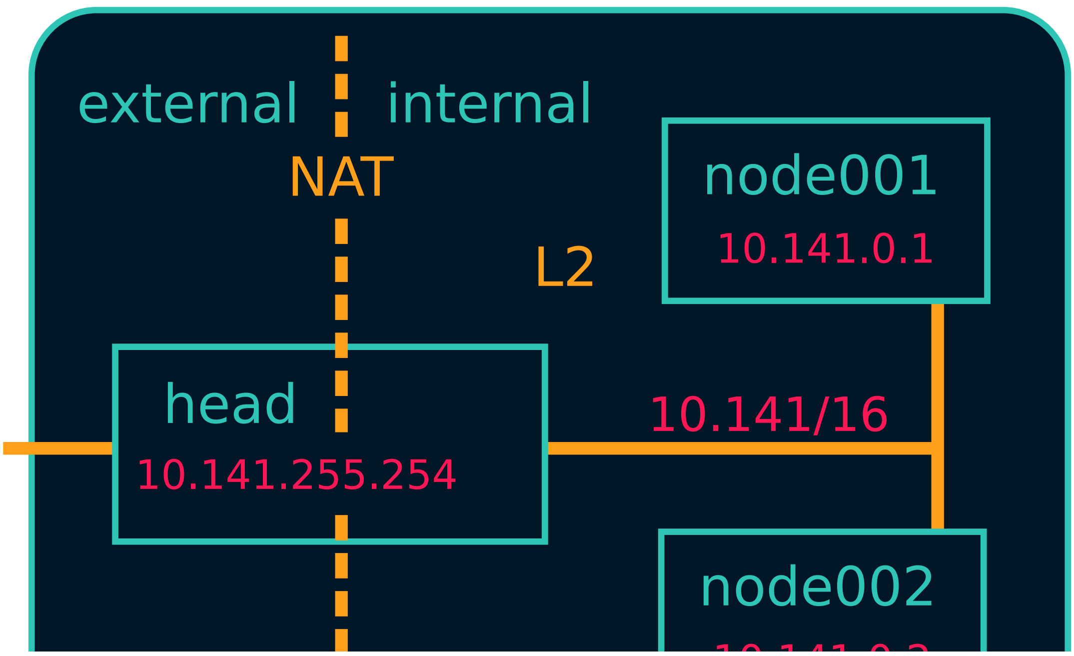
I hope I nevertheless convinced you that a container is nothing more than a highly configured Linux process. No virtualization and no crazy stuff is going on here. You could create a container today with just a plain Linux machine, by calling a bunch of Linux syscalls.

2 Networking from scratch

Goal of this section will be to break the isolation we put our container in, and make it communicate with:

- a container in the same host;
- a container in another host;
- the Internet.

I'm running this experiment in a three nodes cluster. The nodes communicate through a private network under 10.141/16. The head node has two network interfaces, so it's able to communicate with both the external and the internal network. The other two nodes have only one network interface and they can reach the external network by using the head node as gateway. The following schema should clarify the situation:



2.1 Communicate within the host

Right now our container is completely isolated. Let's try to at least ping the same host:

```
/# ping 10.141.0.1
PING 10.141.0.1 (10.141.0.1): 56 data bytes
ping: sendto: Network unreachable
```

It's not working, so the network is isolated. No matter what you do you won't be able to reach the outside, because the only interface you have there is the loopback (and it's also down).

```
/# ip link
1: lo: <LOOPBACK> mtu 65536 qdisc noop state DOWN qlen 1000
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
```

If you create another container on the same host, you can imagine they're not going to be able to communicate either.

How do we solve this problem? We use a veth pair, which stands for Virtual Ethernet pair. As the name suggests, a veth pair is a pair of virtual interfaces, that act as an Ethernet cable. Whatever comes into one end, goes to the other. Sounds useful? Yes, because we can move one end of the pair inside the container, and keep the other end in the host. So we are basically piercing a hole in the container to slide our little virtual wire in.

In another shell, same host, let's setup a `$CPID` variable to help us remember what is the container PID:[5]

```
CPID=$(ps -C ash -o pid= | tr -d ' ')
```

Let's create the veth pair with `iproute`:[6], move one end into the container and bring the host end up:

```
ip link add veth0 type veth peer name veth1
ip link set veth1 netns $CPID
ip link set dev veth0 up
```

If you take a look at the interfaces in the container now, you'll see something like:

```
/# ip l
1: lo: <LOOPBACK> mtu 65536 qdisc noop state DOWN qlen 1000
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
3: veth1@if4: <BROADCAST,MULTICAST,M-DOWN> mtu 1500 qdisc noop state DOWN qlen
1000
    link/ether 8e:7f:62:52:76:71 brd ff:ff:ff:ff:ff:ff
```

Cool! Everything is down, but we have a new interface. Let's also rename it to something less scary, like `eth0`. You'll feel more home in the container:

```
ip link set dev veth1 name eth0 address 8e:7f:62:52:76:71
```

where the address used is the MAC address shown by `ip link`, or `ip addr show dev veth1`.[7]

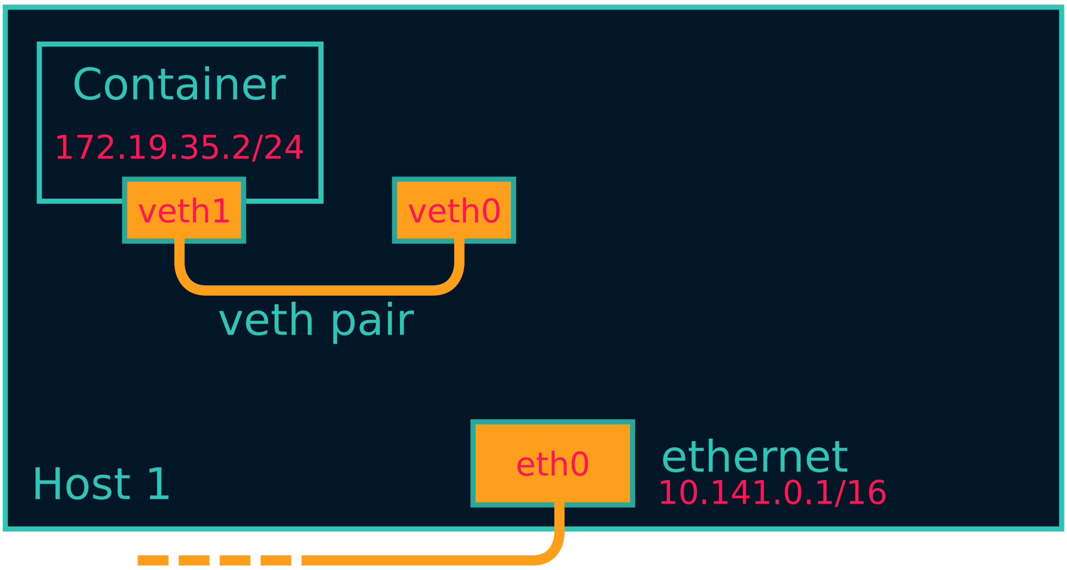
Now let's step back for a second. We have a container with this "cable" pointing out. What kind of IP should we give to the container? What kind of connectivity do we want to provide? The way we are going to set it up is the default Docker way: bridge networking. Containers on the same host live on the same network, but different than the host one. This means that we have to setup a virtual network where containers are able to talk to each other at level 2. This also means that we won't consume any physical IP address from the host network.

I choose the 172.19.35/24 subnet for the containers, since it doesn't conflict with the cluster private network (10.141/16).[8] This means that I have space for `2^8 - 2 = 254` containers in this machine.[9]

Now let's give the container an IP and bring it up, along with the loopback interface:

```
ip addr add dev eth0 172.19.35.2/24
ip link set eth0 up
ip link set lo up
```

And this is the current situation:



Now we want do to the very same thing with another container. So let's create it from the same root filesystem:

```
unshare -pmn -f chroot rootfs /usr/bin/env -i \
    HOME=/root \
    PATH=/bin:/usr/bin:/sbin:/usr/sbin \
    /bin/ash -l
mount -t proc proc /proc
```

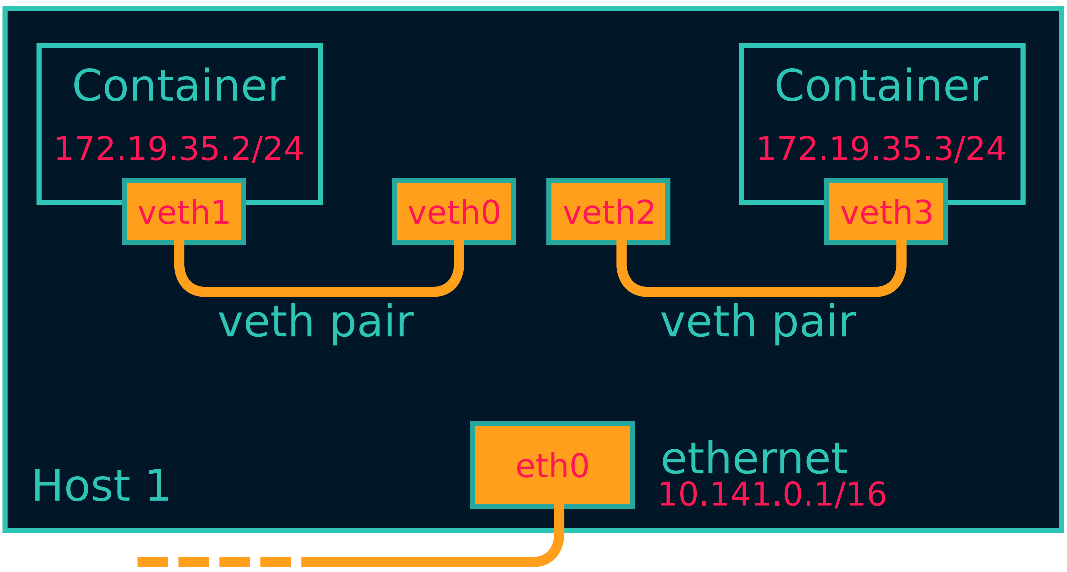
Then in the host we setup another `$CPID2` variable with the PID of this new container,[10] and then create another veth pair:

```
ip link add veth2 type veth peer name veth3
ip link set veth3 netns $CPID2
ip link set dev veth2 up
```

Then rename the interface in the container, give it an IP and bring it up as before:

```
ip link set dev lo up
MAC=$(ip addr show dev veth3 | grep 'link/ether' | tr -s ' ' | cut -d' ' -f3)
ip link set dev veth3 name eth0 address $MAC
ip addr add dev eth0 172.19.35.3/24
ip link set eth0 up
```

Note that I'm using another IP address in the 172.19.35/24 subnet. This is the situation right now:



What we need to do here is try to link those two veth pairs together, in a way that they can communicate at layer 2. Something like… a bridge! It will take care of linking together the two network segments. It works at level 2 like a switch (so it basically "talks Ethernet"), by "enslaving" existing interfaces. You add a bunch of interfaces into a bridge, and they will be communicating with each other thanks to the bridge.

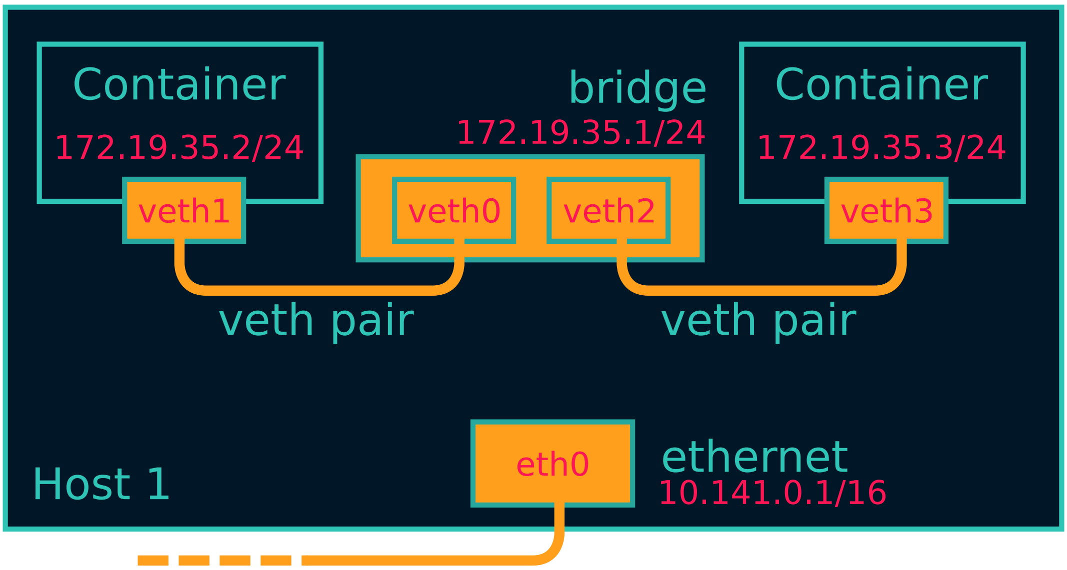
Let's create the bridge and put the two veth interfaces in it:

```
ip link add br0 type bridge
ip link set veth0 master br0
ip link set veth2 master br0
```

Now let's give the bridge an IP and bring it up:

```
ip addr add dev br0 172.19.35.1/24
ip link set br0 up
```

Now we have this topology in place:



As you can see, now the containers can ping each other:

```
/ # ping 172.19.35.3 -c1
PING 172.19.35.3 (172.19.35.3): 56 data bytes
64 bytes from 172.19.35.3: seq=0 ttl=64 time=0.046 ms

--- 172.19.35.3 ping statistics ---
1 packets transmitted, 1 packets received, 0% packet loss
round-trip min/avg/max = 0.046/0.046/0.046 ms
```

Let's check the ARP table[11] on the first container:

```
/ # ip neigh
172.19.35.3 dev eth0 lladdr c6:b3:e3:1d:97:7b used 40/35/10 probes 1 STALE
```

So this means that these two containers are on the same network, and can talk to each other at level 2. And here is indeed the ARP request going through:

```
[root@node001 ~]# tcpdump -i any host 172.19.35.3
22:55:37.858611 ARP, Request who-has 172.19.35.3 tell 172.19.35.2, length 28
22:55:37.858639 ARP, Reply 172.19.35.3 is-at c6:b3:e3:1d:97:7b (oui Unknown),
length 28
```

2.2 Reach the internet

If you try to reach the external network, or even the host IP, you'll see that it's still not working. That's because to reach a different network you need some kind of level 3 communication. The way Docker sets it up by default is with natting.[12] In this way, the 172.19.35/24 network will be invisible outside the host and mapped automatically into the host IP address, that in my case is 10.141.0.1 (which by the way is still a private IP, and will be natted by the head node into the public IP).

Let's first enable IP forwarding, to allow the host to perform routing operations:

```
echo 1 > /proc/sys/net/ipv4/ip_forward
```

Then insert a NAT rule (also called IP masquerade) in the external interface:

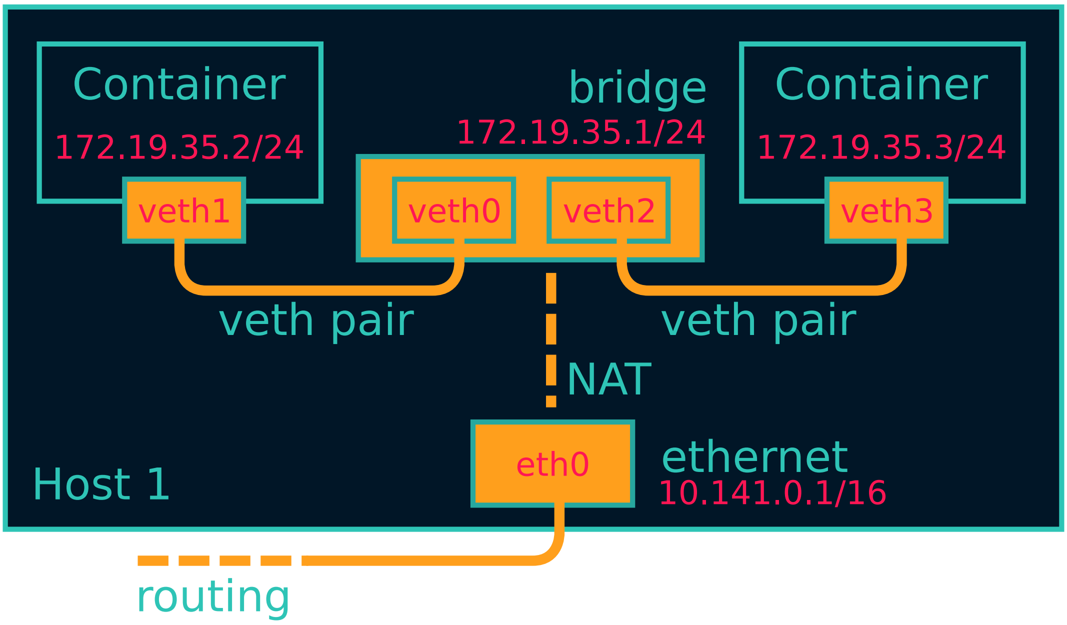
```
iptables -t nat -A POSTROUTING -o eth0 -j MASQUERADE
```

Then you need to set the default route in the container:

```
ip route add default via 172.19.35.1
```

In this way any packet with a destination on a different network will be sent through the gateway, which is the bridge. From there it will be natted by eth0, our physical interface, and then sent through the cluster fabric by using the physical IP as source.

This is now the situation:



If I ping Google's DNS from the container, I see this from the host:

```
[root@node001 ~]# tcpdump -i any host 8.8.8.8 -n
23:27:51.234333 IP 172.19.35.2 > 8.8.8.8: ICMP echo request, id 13824, seq 0,
length 64
23:27:51.234360 IP 10.141.0.1 > 8.8.8.8: ICMP echo request, id 13824, seq 0,
length 64
23:27:51.242230 IP 8.8.8.8 > 10.141.0.1: ICMP echo reply, id 13824, seq 0,
length 64
23:27:51.242251 IP 8.8.8.8 > 172.19.35.2: ICMP echo reply, id 13824, seq 0,
length 64
```

As you can see the packet comes from the container, is translated into the host IP (10.141.0.1) and then when it comes back, the destination is replaced with the container IP (172.19.35.2).

This is what I see from the head node, instead:

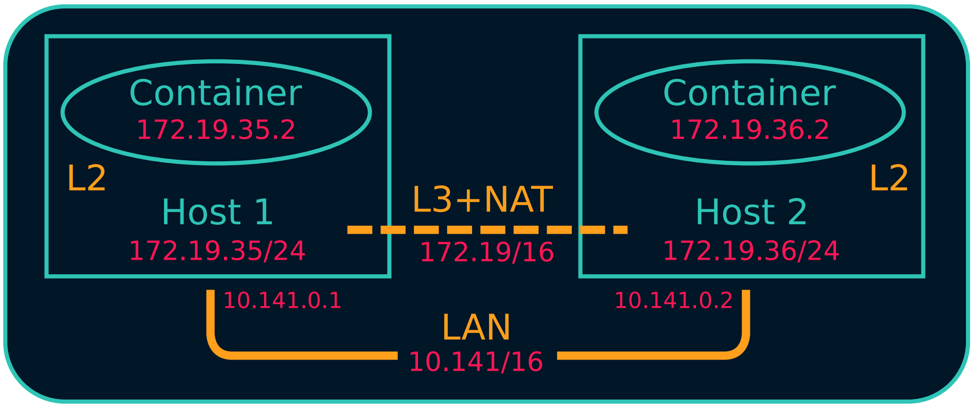
```
[root@head ~]# tcpdump -i any host 8.8.8.8 -n
23:25:20.209922 IP 10.141.0.1 > 8.8.8.8: ICMP echo request, id 13568, seq 0,
length 64
23:25:20.209943 IP 192.168.200.172 > 8.8.8.8: ICMP echo request, id 13568, seq
0, length 64
23:25:20.217286 IP 8.8.8.8 > 192.168.200.172: ICMP echo reply, id 13568, seq 0,
length 64
23:25:20.217310 IP 8.8.8.8 > 10.141.0.1: ICMP echo reply, id 13568, seq 0,
length 64
```

As you can see the packet comes from the node, it's forwarded through the head node public IP (192.168.200.172), and then comes back the other way around. NAT is also working here.

2.3 Reach a remote container

Now from a container we are able to communicate with both another local container and with the externa network. The next step is to reach a container in another node, in the same physical private network (the 10.141/16 network the nodes sit in).

This is basically the plan:



The two nodes communicate through the physical private network 10.141/16. We want to assign a subnet to each node, so each will be able to host some containers. We have already assigned the 172.19.35/24 network to the first host. We can then assign another to the second, for example 172.19.36/24. I could have chosen any other IP range that doesn't conflict with the existing networks, but this one is especially handy, because both of them are part of a bigger 172.19/16 network. We can think of it as the containers' network, in which every host gets a slice (a /24 subnet). This means that we can assign `24 - 16 = 8` bits to different hosts, so maximum 255 nodes. Of course you can use different network sizes to accomodate your needs, but that's the way we are going to set it up here. NAT has been already setup in the first host, so we are going to do the same for the second one, and then add routing rules (layer 3) between the two hosts.

Let's go real quick over the second host, create a container, setup the networking there as we did for the first host:

```
unshare -pmn -f chroot rootfs /usr/bin/env -i \
    HOME=/root \
    PATH=/bin:/usr/bin:/sbin:/usr/sbin \
    /bin/ash -l
```

then in the host:

```
CPID=$(ps -C ash -o pid= | tr -d ' ')
ip link add veth0 type veth peer name veth1
ip link set veth1 netns $CPID
ip link set dev veth0 up
ip link add br0 type bridge
ip link set veth0 master br0
ip addr add dev br0 172.19.36.1/24
ip link set br0 up
echo 1 > /proc/sys/net/ipv4/ip_forward
iptables -t nat -A POSTROUTING -o eth0 -j MASQUERADE
```

Note that I used the 172.19.36.1/24 IP for the bridge. Then in the container:

```
ip link set dev lo up
MAC=$(ip addr show dev veth1 | grep 'link/ether' | tr -s ' ' | cut -d' ' -f3)
ip link set dev veth1 name eth0 address $MAC
ip addr add dev eth0 172.19.36.2/24
ip link set eth0 up
ip route add default via 172.19.36.1
```

and again I use 172.19.36/24 here. Now the container is able to talk to the Internet, as the other one. But, is the first container able to reach this new container?

Try to think about it.

Then try to do it. No, it doesn't work, but why? The answer is in the routing table of the first host:

```
[root@node001 ~]# ip r
default via 10.141.255.254 dev eth0
10.141.0.0/16 dev eth0  proto kernel  scope link  src 10.141.0.1
```

```
172.19.35.0/24 dev br0  proto kernel  scope link  src 172.19.35.1
```

There is a default gateway pointing to the head node, and two "scope link" ranges, for networks reachable at level 2 (unsurprisingly there are the 10.141/16 physical network, and the 172.19.35/24 network for the local containers). As you can see there's no rule for 172.19.36/24. This means the packet will go through the default gateway, and from there it will try to go outside, because the head node doesn't know anything about this IP either.

What we should do is add a routing rule to the node table, telling that any packet for 172.19.36/24 should be forwarded to the second host, listening at 10.141.0.2:

```
ip route add 172.19.36.0/24 via 10.141.0.2 src 10.141.0.1
```

The same goes for the other host, but in reverse:

```
ip route add 172.19.35.0/24 via 10.141.0.1 src 10.141.0.2
```

And now, both containers are able to talk to each other. If you want to show something fancy, you could run NGINX in one container, and `curl` the beautiful default page from the other.

Hooray!

3 Bonus: Calico

What I showed in the last section is basically how Docker sets up its bridge networking. The routing rules to make the containers see each other come from me. What Docker Swarm and other networking solutions for Docker use instead is usually overlay networking, like VXLAN. VXLAN encapsulate layer 2 Ethernet frames within layer 3 UDP packets. This provides layer 2 visibility to containers across hosts. I didn't show this approach because the routing rules were simpler, and also because I prefer the Calico approach, that I will present in this section.

Some of you may already know Kubernetes. It's the most popular (any my favorite) container orchestrator. What it basically does is providing declarative APIs to manage containers. Restarts upon failures, replicas' scaling, upgrading, ingress, and many other things can be managed automatically by Kubernetes. For all this magic to happen, Kubernetes imposes some restrictions on the underlying infrastructure. Here is the section about the networking model:

- all containers can communicate with all other containers without NAT
- all nodes can communicate with all containers (and vice-versa) without NAT
- the IP that a container sees itself as is the same IP that others see it as.

As the documentation says:

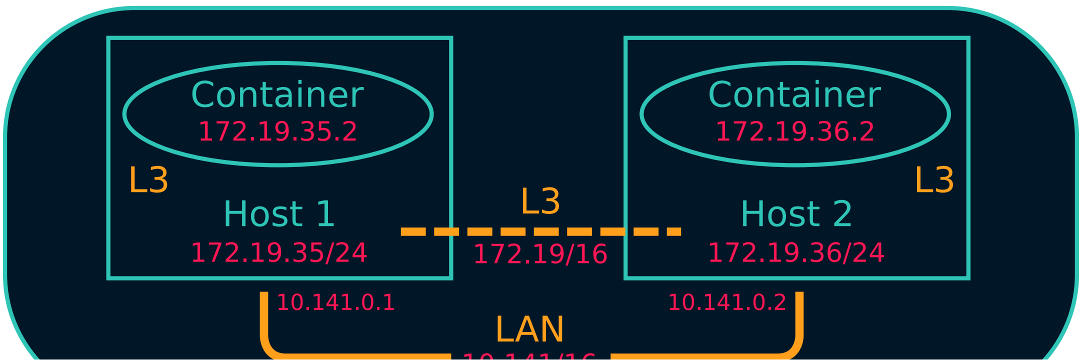
> Coordinating ports across multiple developers is very difficult to do at scale and exposes users to cluster-level issues outside of their control. Dynamic port allocation brings a lot of complications to the system - every application has to take ports as flags, the API servers have to know how to insert dynamic port numbers into configuration blocks, services have to know how to find each other, etc. Rather than deal with this, Kubernetes takes a different approach.

The solution we used in the previous section does not satisfy these requirements. In our case the source IP is rewritten by NAT, so the destination container sees only the host IP.

There are a number of projects that satisfy the Kubernetes requirements, and among them I really like Project Calico, so I'm going to reproduce its setup here, again the hard way, just Linux commands.

The Calico's solution is to use layer 3 networking all the way up to the containers. No Docker bridges, no NAT, just pure routing rules and iptables. Interestingly enough, the way Calico distributes the routing rules is through BGP,[13] which is the same way the Internet works.

The end result we're going to aim at is this:



Looks familiar? Yes, it's almost the same as the one I used in the previous section. We're going to use the same IP ranges: the host networking under 10.141/16, and we're going to setup a 172.19/16 network for the containers. As before, every host gets a /24 subnet. The difference is in the way the packets are routed. With Calico everything goes at layer 3, so on the wire you'll see packets coming from a 172.19/16 address and going to a 172.19/16 address because, as I said before, no natting or overlays are used.

3.1 Setup the host network

Without further ado, let's create our container on the first host:

```
unshare -pmn -f chroot rootfs /usr/bin/env -i \
    HOME=/root \
    PATH=/bin:/usr/bin:/sbin:/usr/sbin \
    /bin/ash -l
```

Then, let's create our veth pair, and move one end into the container:

```
CPID=$(ps -C ash -o pid= | tr -d ' ')
ip link add veth0 type veth peer name veth1
ip link set veth1 netns $CPID
ip link set dev veth0 up
```

Let's now give the container an IP address:

```
ip link set dev lo up
MAC=$(ip addr show dev veth1 | grep 'link/ether' | tr -s ' ' | cut -d' ' -f3)
ip link set dev veth1 name eth0 address $MAC
ip addr add dev eth0 172.19.35.2/32
ip link set eth0 up
```

Have you noted anything strange? I'm using a /32 address for the container IP. This means that whenever I send a packet, even for a container living on the same host, it will need to go through level 3. This allows to get rid of the bridge, and also makes sure that the container doesn't try (and fail) to reach another at level 2, by sending useless ARP requests.

Now on the host we need to enable ARP proxy for the veth interface.

```
echo 1 > /proc/sys/net/ipv4/conf/veth0/rp_filter
echo 1 > /proc/sys/net/ipv4/conf/veth0/route_localnet
echo 1 >/proc/sys/net/ipv4/conf/veth0/proxy_arp
echo 0 >/proc/sys/net/ipv4/neigh/veth0/proxy_delay
echo 1 >/proc/sys/net/ipv4/conf/veth0/forwarding
```

What this does is basically replying to ARP requests with its own MAC address. In this way, when the container looks for the link local address, veth0 will say: "it's me!", replying with it's own MAC address, and the packet will be sent there at layer 2.[14]

We also need to enable IP forwarding on the host's physical interface, to allow routing:

```
echo 1 >/proc/sys/net/ipv4/conf/eth0/forwarding
```

And inside the container we have to add a couple of routing rules:

```
ip r add 169.254.1.1 dev eth0  scope link
ip r add default via 169.254.1.1 dev eth0
```

Here we use a local link address, so we don't have to manage the IP of the other pair of the veth. We can assign the same address to all the veths, since the address is valid only within the link, so no routing will be performed by the kernel. We've also added a default route, that says to use that IP for any address outside of the local range. But since our local range is a /32, no IP is local. So, what we are saying to the kernel in the end is: "any time we want to reach something outside the container, just put it on the eth0 link". It seems convoluted, but the idea behind it is quite simple.

Last bit missing on the host is the rule to reach the container from the host:

```
ip r add 172.19.35.2 dev veth0 scope link
```

With this we're saying that, to reach the container, the packet has to go through the veth0 interface.

Now, from the container we're able to ping the host:

```
node001:/# ping 10.141.0.1 -c1
PING 10.141.0.1 (10.141.0.1): 56 data bytes
```

```
64 bytes from 10.141.0.1: seq=0 ttl=64 time=0.077 ms

--- 10.141.0.1 ping statistics ---
1 packets transmitted, 1 packets received, 0% packet loss
round-trip min/avg/max = 0.077/0.077/0.077 ms
```

And this is the traffic passing:

```
[root@node001 ~]# tcpdump -i any host 172.19.35.2 -n
16:25:10.439980 IP 172.19.35.2 > 10.141.0.1: ICMP echo request, id 6144, seq 0,
length 64
16:25:10.440014 IP 10.141.0.1 > 172.19.35.2: ICMP echo reply, id 6144, seq 0,
length 64
```

ARP goes back and forth to determine the physical address of the local link IP:

```
[root@node001 ~]# tcpdump -i any host 172.19.35.2
16:25:15.453847 ARP, Request who-has 169.254.1.1 tell 172.19.35.2, length 28
16:25:15.453882 ARP, Reply 169.254.1.1 is-at f6:5c:53:b4:f8:03 (oui Unknown),
length 28
```

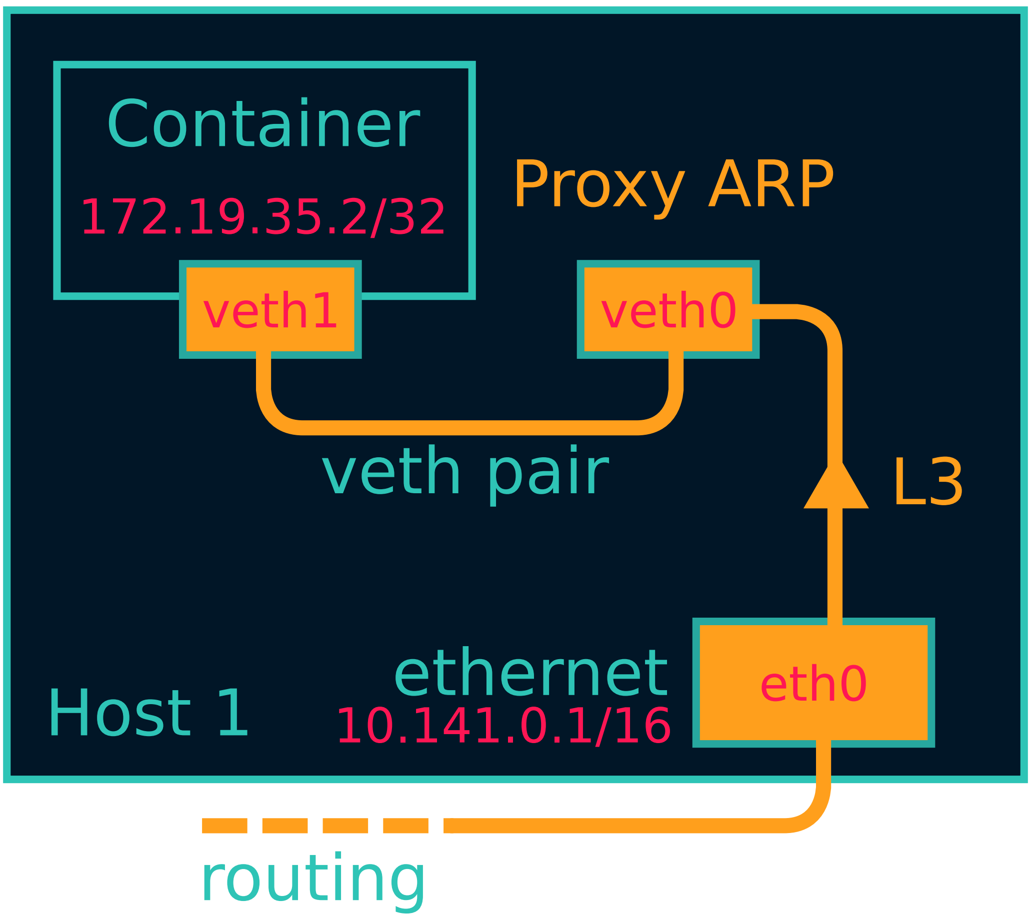
and if you look at the ARP table you'll see the cached reply:

```
node001:/# ip neigh
169.254.1.1 dev eth0 lladdr f6:5c:53:b4:f8:03 ref 1 used 2/2/2 probes 4
REACHABLE
```

The 169.254.1.1 IP is the only one reachable at level 2 from the container, as expected. The MAC address corresponds to the other end of the veth pair, as you can see from the host:

```
[root@node001 ~]# ip l show dev veth0
5: veth0@if4: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc pfifo_fast state
UP mode DEFAULT qlen 1000
    link/ether f6:5c:53:b4:f8:03 brd ff:ff:ff:ff:ff:ff link-netnsid 0
```

And this is the current situation:



Another detail is the blackhole route, to drop packets coming for unexisting containers:

```
ip r add blackhole 172.19.35.0/24
```

In this way any packet sent to the host subnet to an IP not present in the host will be dropped. Packets for exising containers still work, because their routing rules are more specific, so they take precedence:

```
[root@node001 ~]# ip r
default via 10.141.255.254 dev eth0
10.141.0.0/16 dev eth0  proto kernel  scope link  src 10.141.0.1
169.254.0.0/16 dev eth0  scope link  metric 1002
blackhole 172.19.35.0/24
172.19.35.2 dev veth0  scope link
```

In this case, if you send a packet to 172.19.35.2, it will go to veth0. If you instead try to reach 172.19.35.3, it will go to the blackhole and dropped, instead of going to the default gateway.

3.2 Reach a remote container

To reach a container running on another host, you have to replicate the setup done for this host. You have to assign to that node another /24 subnet from the container network, and use one IP from that subnet to create a container (I used the 172.19.36/24 subnet, the same as Part 2).[15]

Then you need to add the routing rules to direct the traffic to the right host. From the first host:

```
ip route add 172.19.36.0/24 via 10.141.0.2 src 10.141.0.1
```

and similarly from the second host:

```
ip route add 172.19.35.0/24 via 10.141.0.1 src 10.141.0.2
```

Done. Now the containers can reach each other. If you look at the traffic, you'll see that the source and destination IPs are preserved, and not NATted, satisfying the Kubernetes' requirements:

```
[root@node001 ~]# tcpdump -i any host 172.19.35.2
20:08:02.154031 IP 172.19.35.2 > 172.19.36.2: ICMP echo request, id 17152, seq
0, length 64
20:08:02.154045 IP 172.19.35.2 > 172.19.36.2: ICMP echo request, id 17152, seq
0, length 64
20:08:02.155088 IP 172.19.36.2 > 172.19.35.2: ICMP echo reply, id 17152, seq 0,
length 64
20:08:02.155098 IP 172.19.36.2 > 172.19.35.2: ICMP echo reply, id 17152, seq 0,
length 64
```

Success!

3.3 Reach the Internet

If you are lucky you are able to reach the external network already. This all depends on how NAT is setup in your cluster. A proper setup should allow only packets coming from the physical network to escape.

From my head node (that is also the default gateway of the other nodes), I see:

```
[root@mbrt-c-08-13-t-c7u2 ~]# iptables -L -t nat
Chain PREROUTING (policy ACCEPT)
target     prot opt source               destination

Chain INPUT (policy ACCEPT)
target     prot opt source               destination

Chain OUTPUT (policy ACCEPT)
target     prot opt source               destination

Chain POSTROUTING (policy ACCEPT)
target     prot opt source               destination
MASQUERADE  all  --  10.141.0.0/16        anywhere
```

This is precisely my case. Only packets coming from the 10.141/16 network, will be natted. To perform NAT also for packets coming from the containers network, I have to add another rule:

```
iptables -t nat -A POSTROUTING -o eth1 -j MASQUERADE -s 172.19.0.0/16
```

Looking this way in the table:

```
MASQUERADE  all  --  172.19.0.0/16        anywhere
```

Then we need a routing rule in the head node, telling it where it can find the 172.19.35/24 subnet:

```
ip route add 172.19.35.0/24 via 10.141.0.1 src 10.141.255.254
```

And now, you can finally ping the outside network from the container!

3.4 Missing pieces

Among the feature that I haven't discussed, Calico has a really nice distributed firewall, applied through iptables, but I left it out of scope from this post.

4 Bonus: Debug container networking

In this section I would like to digress a bit and talk about debugging. I hope it's clear at this point that containers aren't magical, and networking isn't magical either. This means that for debugging you can use all the regular tools Linux provides. You don't need to rely on Docker or Calico to provide anything on their end, and even if they would, how do you debug them when they are broken? In the previous section I used `ping`, `iproute` and `tcpdump`, but what happens if your Docker image does not contain these tools?

```
node001:/# ip r
/bin/ash: ip: not found
```

This happens many times, and even worse if your Docker image looks like this:

```
FROM scratch
ADD main /
CMD ["/main"]
```

You don't even have a console there. What do you do?

4.1 Enter the `nsenter` magical world

There is a very simple trick you should probably remember: `nsenter`. This command enters one or more namespaces from the host. You can enter all of them and in that case you would have another console open on the container (similar to the docker exec command):

```
nsenter --pid=/proc/$CPID/ns/pid \
        --net=/proc/$CPID/ns/net \
        --mount=/proc/$CPID/ns/mnt \
        /bin/bash
```

and look, we see the same processes as the container do:

```
[root@node001 rootfs]# mount -t proc proc /proc
[root@node001 rootfs]# ps aux
USER       PID %CPU %MEM    VSZ   RSS TTY      STAT START   TIME COMMAND
root         1  0.0  0.0   1540   548 pts/0    S+   16:19   0:00 /bin/ash -l
root        97  0.0  0.2 116144  2908 pts/1    S    20:25   0:00 /bin/bash
root       127  0.0  0.1 139492  1620 pts/1    R+   20:28   0:00 ps aux
```

What's most important for our purposes is accessing the network namespace though:

```
nsenter --net=/proc/$CPID/ns/net /bin/bash
```

this way you have the same network as the container, but no other restrictions. In particular you have access to the host filesystem:

```
[root@node001 ~]# cat /etc/os-release
NAME="CentOS Linux"
VERSION="7 (Core)"
ID="centos"
ID_LIKE="rhel fedora"
VERSION_ID="7"
PRETTY_NAME="CentOS Linux 7 (Core)"
...
```

and all your favorite tools available. But the network you see is the container one:

```
[root@node001 ~]# ip r
default via 169.254.1.1 dev eth0
169.254.1.1 dev eth0  scope link
```

This, of course works with Docker too. Once you have the PID of your container, you can `nsenter` it:

```
[root@node001 ~]# docker inspect --format '{{.State.Pid}}' my-awesome-container
24028
[root@node001 ~]# nsenter --net=/proc/24028/ns/net /bin/bash
```

So, please, don't install debugging tools in your Docker images anymore. It's not really necessary.

5 Concluding remarks

With this long post I tried to reproduce two different solutions for container networking, with nothing more than Linux commands. Docker, Calico, Flannel and the others are all nice tools, but they aren't magical. They build on top of standard Linux functionality, and trying to reproduce their behavior helped me (and I hope you too) to understand them better.

Keep in mind that this is not a complete guide. There are many more interesting topics, like network policies and security in general, then a universe of different solutions, like overlay networks, Ipvlan, macvlan, MacVTap, IPsec, and I don't know how many others. For containers in general there are many other things you want to isolate, like physical resources and capabilities, as I mentioned during the first part of this post. The overwhelming amount of technical terms shouldn't discourage you to explore and expand your knowledge. You might find, like me, that it's not as hard as it seems.

That's all folks. Happy debugging!