Netmap as a backend for VMs

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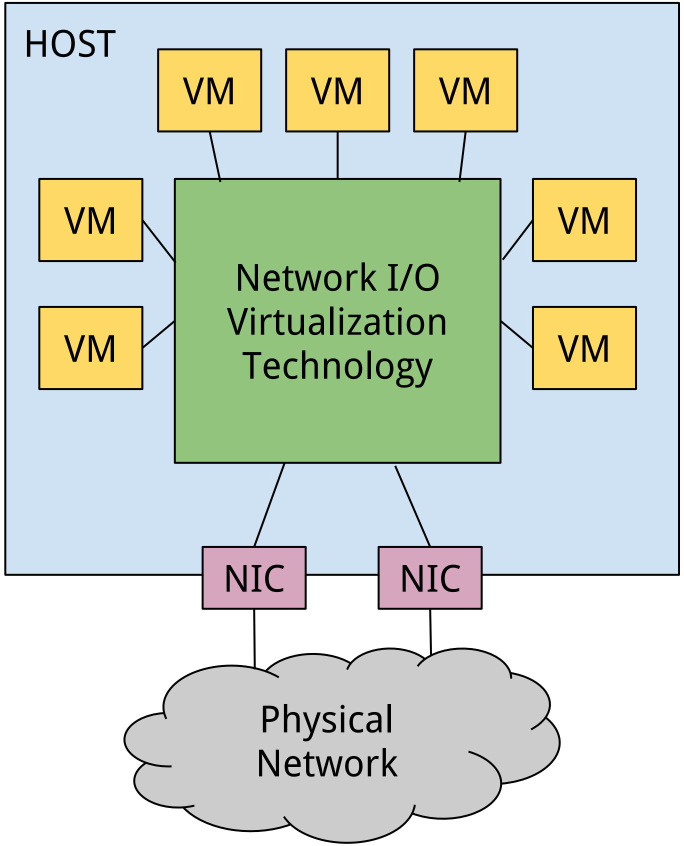
Introduction

- Network I/O virtualization is about attaching the Virtual Machines to the network of the hypervisor/host.
- Let different VMs on the same host communicate among them and with the external physical network.
- Hot use-cases → Network Function Virtualization

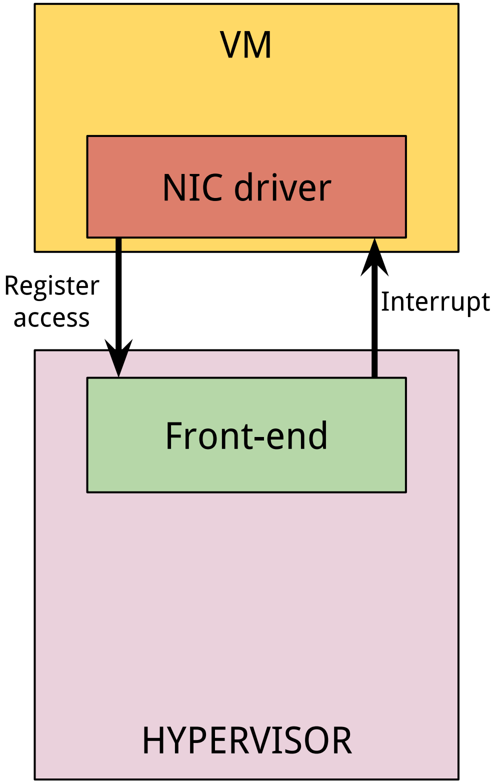


Outline

1. Traditional Virtual Machine networking
2. Netmap as an hypervisor network back-end
3. VM networking based on Netmap passthrough

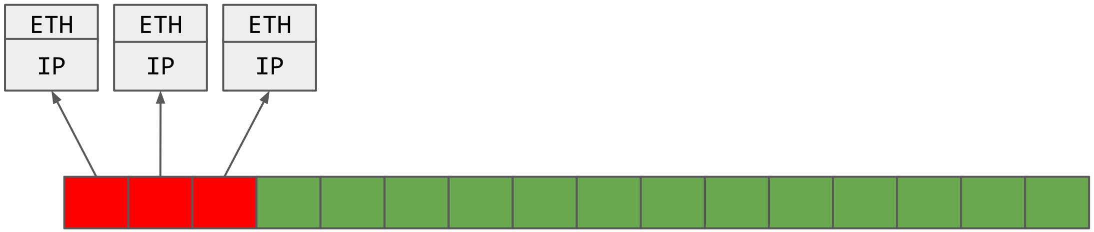
VM networking - Front-end

- VM has one or more *emulated* NICs
  - A regular driver is used to access an emulated NIC
- A guest NIC comes with its own device model
  - An emulated commercial NIC (e.g. e1000, r8169)
  - A paravirtualized NIC (e.g. virtio-net, Xen netfront, ptnet)
    - Paravirtualized NICs offer better performance, as drivers are *aware* of running in a virtualized environment
- Device model implemented by a front-end module in the hypervisor
  - Emulates device I/O register access
  - Injects PCI interrupts
  - Emulates receive and transmit functionalities, accessing the device *rings*

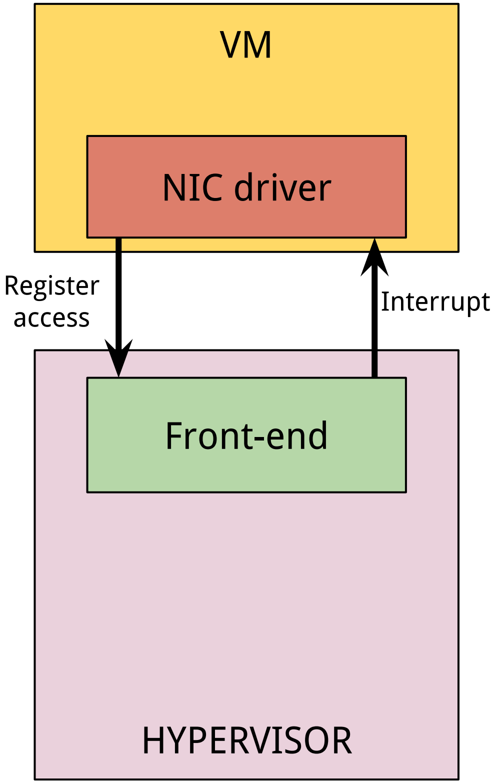


VM networking - Front-end rings

- A ring is a circular array of descriptors
- A descriptor contains information about a buffer to be used for TX or RX
  - At least the (guest) physical address and length of the buffer

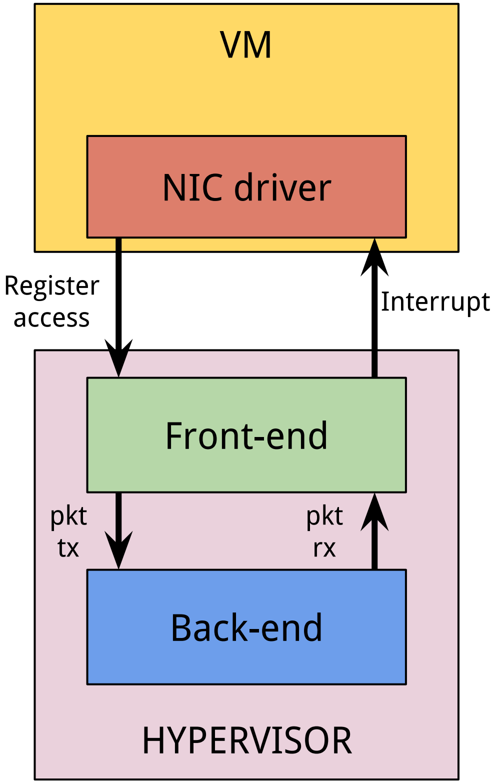


- Different front-ends, different ring/descriptor formats
  - Virtio-net: VirtQueues, Avail and Used rings, …
  - Xen netfront: I/O rings
  - Commercial NICs: hardware specs Intel, Realtek, … use formats specified in their documentation



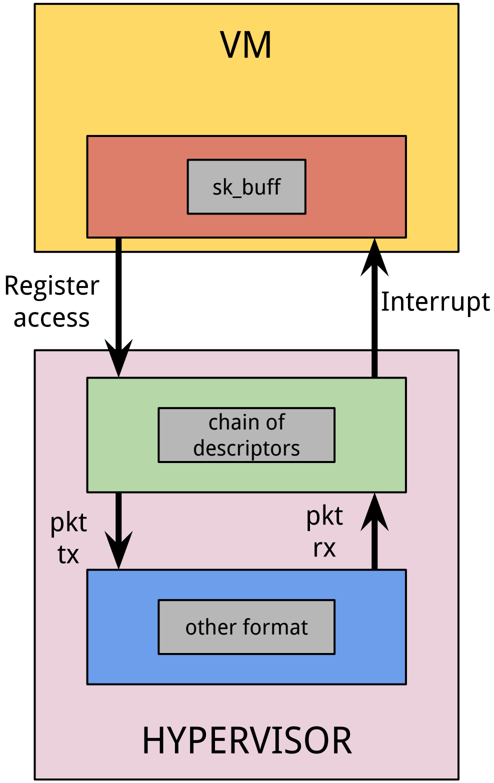
VM networking - Back-end

- A back-end module allows VM network traffic to leave the hypervisor towards the host network
- Front-end and back-end interact to transmit and receive packets to/from the host network
- Different back-ends usually available:
    - TAP: inject/receive packets from host TCP/IP stack
    - Socket: packets forwarded through a TCP or UDP socket
    - NAT: backend implements NAT (in user-space) to give a VM easy internet access
    - Netmap/DPDK: Packets injected/received from an high performance userspace networking framework
- Different back-ends, different packet representations



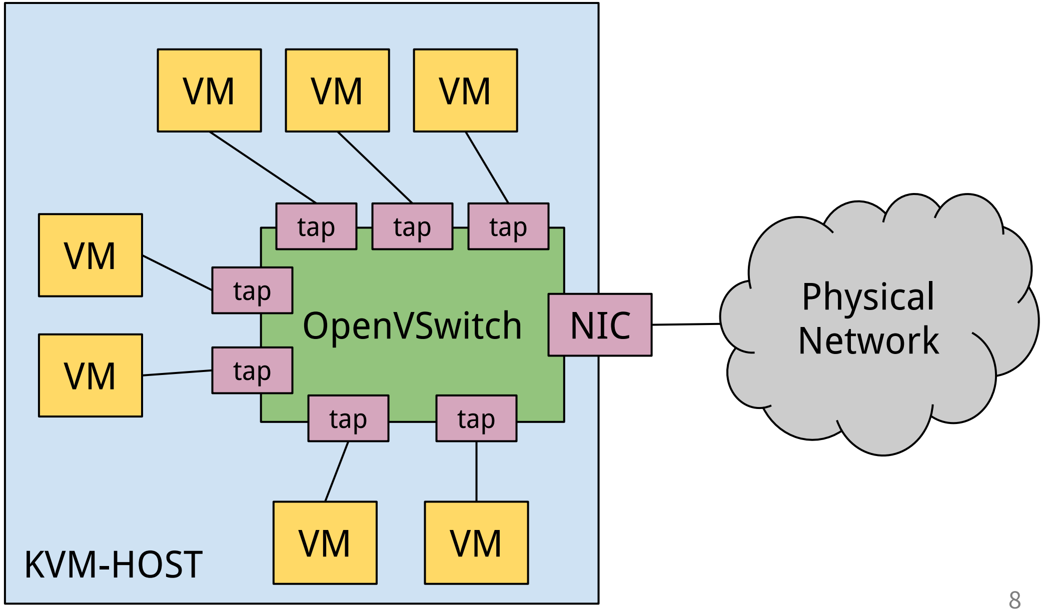
VM networking - Journey of a packet

- The journey of a TX/RX packet is convoluted
- Guest OS/driver uses sk_buff/mbuf
- Front-end uses a chain of descriptors in a ring/queue
- Backend may use multiple formats, e.g.:
  - TAP and sockets uses sk_buffs/mbufs
  - Netmap uses its API (netmap rings and slots)
- Packet representation conversions is needed at each step
  - Conversions require processing
  - Copies may be needed
  - Front-end and/or back-end usually run in a separate I/O thread
    - Need driver/front-end synchronization and/or front-end/back-end synchronization



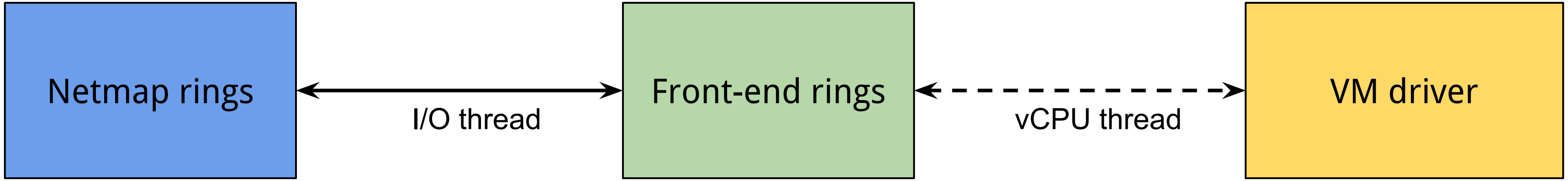
A traditional deployment

- QEMU-KVM hypervisor
- virtio-net front-end
  - With vhost acceleration
- TAP back-end attached to either
  - OpenVswitch switch instance, or
  - Standard in-kernel L2 bridge
- Many bottlenecks:
  - read/write to TAP interfaces
    - not batched
  - virtual switch processing
    - not batched
  - driver/front-end conversions and synchronization



Netmap as a back-end

- When the back-end is netmap, the netmap API is used to copy packets between the rings of the emulated NIC (e.g. virtio-net, e1000) and the rings of the netmap port
  - Copies are necessary, as netmap buffers are allocated by the host, while sk_buffs are allocated by the guest OS
  - Front-end and back-end code normally runs in an I/O thread separate from the guest vCPU threads
- The netmap port can be anything:
  - A VALE switch is a good choice to connect several VMs together, and possibly also to a physical NIC.
  - A netmap pipe, to create a fast point-to-point virtual link between two VMs.
  - A physical netmap port, to give the VM exclusive access to an host physical device.



Netmap support in hypervisors

- A netmap back-end is available upstream for
  - QEMU (http://qemu.org), mainly to be used on Linux with KVM
  - bhyve (http://bhyve.org), to be used on FreeBSD hosts
- However, QEMU support for netmap passthrough is not upstream yet
  - The modified QEMU can currently be found at https://github.com/vmaffione/qemu.git
  - We will use this code through the tutorial
  - Compile QEMU with netmap support
    - `$ ./configure --target-list=x86_64-softmmu --enable-kvm --enable-vhost-net --disable-werror --enable-netmap --enable-ptnetmap`

Run a QEMU VM with a netmap back-end

- Example to run a VM with a single emulated NIC

```
# qemu-system-x86_64 img.qcow2 -enable-kvm -smp 2 -m 2G -vga std
-device virtio-net-pci,netdev=data1,mac=00:AA:BB:CC:0a:0a,ioeventfd=on,mrg_rxbuf=on
-netdev netmap,ifname=vale1:10,id=data1
```

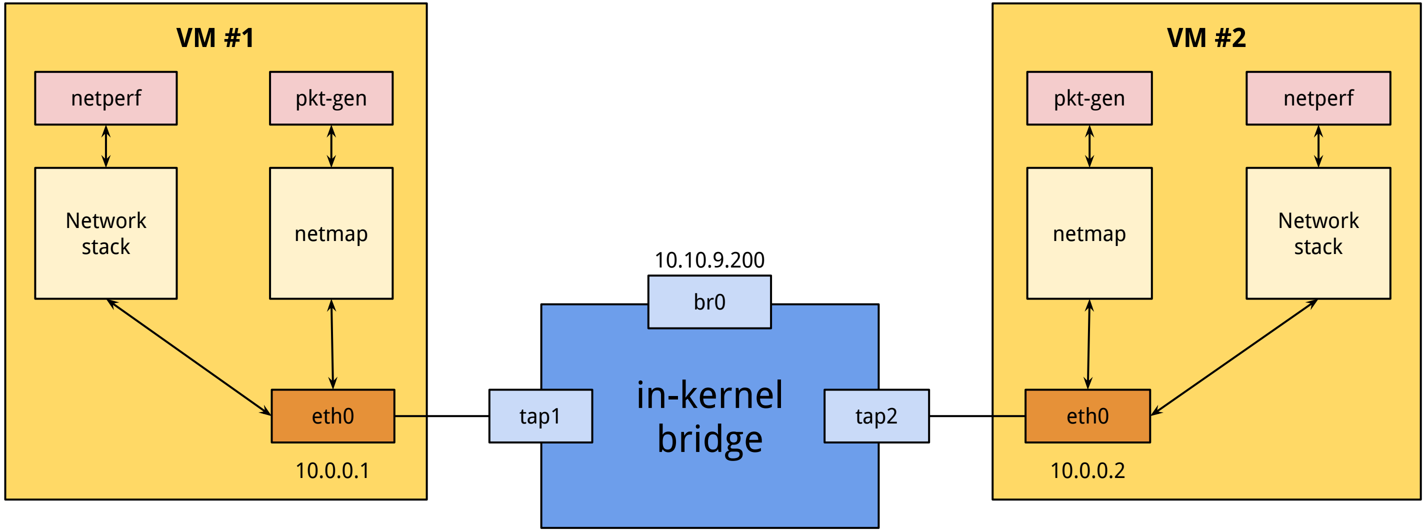
- The `-netdev` option specifies a back-end, while the `-device` option specifies a front-end. The id is used to bind a front-end to a back-end.
- The `ifname` argument specifies the netmap port. Examples:
  - “valeXX:YY” → A VALE port named “YY” on a VALE switch called “XX”
  - “netmap:eth4” → physical netmap port to access the eth4 host network device
  - “netmap:pipe0{1“ → master side of a netmap pipe called pipe0
  - “netmap:pipe0}1“ → slave side of a netmap pipe called pipe0
- Multiple occurrences of `-netdev` and `-device` allow for multiple emulated NICs

VM-to-VM performance experiments

- Two VMs running on the same host, connected through a software switch or a point-to-point link
- We run some benchmarks to measure performance
  - TCP_STREAM test for unidirectional bulk TCP transfer
  - TCP_RR test for request/response short transactions
  - Ping flood to measure average latency
  - pkt-gen tests to measure maximum packet-rate for short packets with guest OS bypass
- A VM runs the sender, while the other VM runs the receiver

VM-to-VM performance experiments

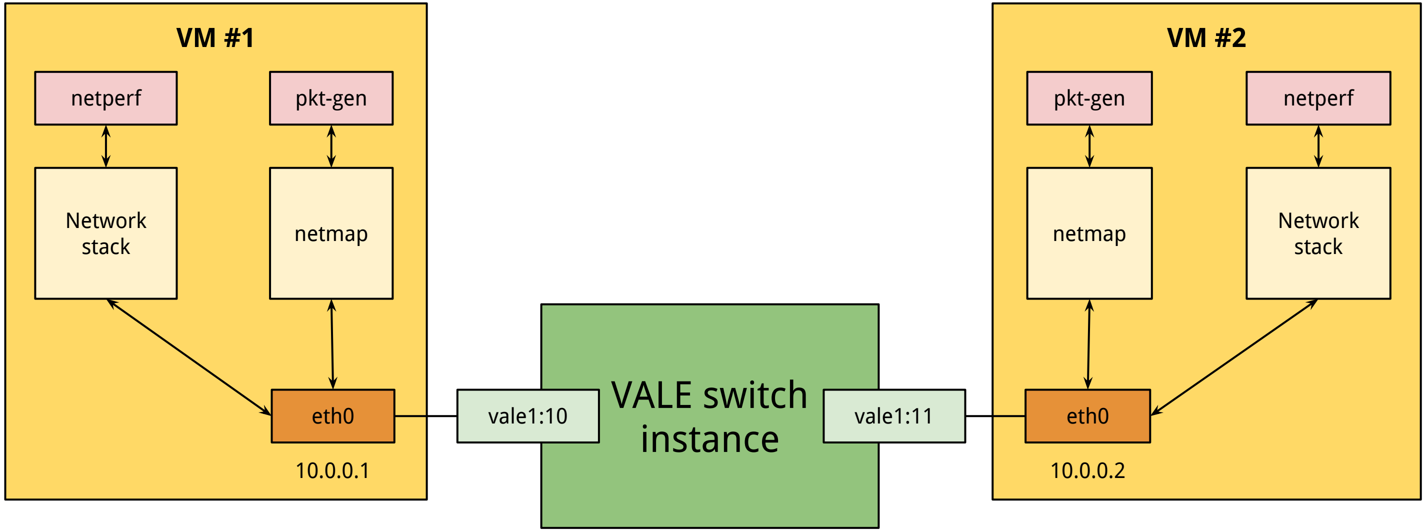
- Two VMs running on the same host, connected through an in-kernel sw bridge




```
$ qemu-system-x86_64 img.qcow2 -enable-kvm -smp 2 -m 2G -vga std -device
virtio-net-pci,netdev=data10,mac=00:AA:BB:CC:0a:0a,ioeventfd=on,mrg_rxbuf=on
-netdev tap,ifname=tap1,id=data10,vhost=off
```

VM-to-VM performance experiments

- Two VMs running on the same host, connected through a VALE software switch

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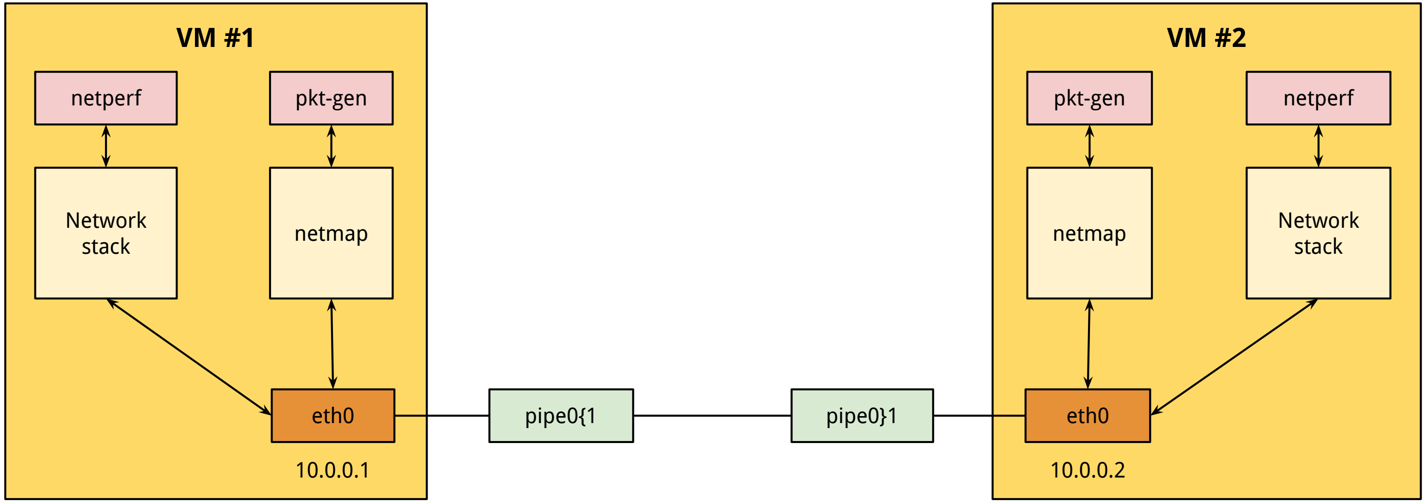
-netdev netmap,ifname=vale1:10,id=data10
```

VM-to-VM performance experiments

- Two VMs running on the same host, connected through a netmap pipe

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virtio-net-pci,netdev=data1,mac=00:AA:BB:CC:0a:01,ioeventfd=on,mrg_rxbuf=on
-netdev netmap,ifname=netmap:pipe0{1,id=data1
```

Experiment results

Front-end	Back-end	TCP_STREAM	TCP_RR	ping -f	pkt-gen
virtio-net	TAP	18.2 Gbps	18.4 Ktps	75 us	0.5 Mpps
virtio-net	netmap VALE	21 Gbps	20 Ktps	55 us	1 Mpps
virtio-net	netmap pipe	7.9 Gbps	20.5 Ktps	65 us	1 Mpps
e1000	TAP	3.5 Gbps	9.5 Ktps	80 us	1.3 Mpps
e1000	netmap VALE	2.8 Gbps	9.5 Ktps	80 us	1.4 Mpps

- Virtio-net + TAP
  - Good netperf performance because of TSO/checksum offloadings
- Virtio-net + VALE
  - Good netperf/ping numbers, because of TSO/checksum offloadings
  - Slightly better than virtio-net + TAP because of slightly reduced latency
  - However, performance gain is not evident because there is *no batching*

Experiment results

Front-end	Back-end	TCP_STREAM	TCP_RR	ping -f	pkt-gen
virtio-net	TAP	18.2 Gbps	18.4 Ktps	75 us	0.7 Mpps
virtio-net	netmap VALE	20 Gbps	20 Ktps	55 us	1 Mpps
virtio-net	netmap pipe	7.9 Gbps	20.5 Ktps	65 us	1 Mpps
e1000	TAP	3.5 Gbps	9.5 Ktps	80 us	1.3 Mpps
e1000	netmap VALE	2.8 Gbps	9.5 Ktps	80 us	1.4 Mpps

- e1000 + TAP:
  - Low performances in general, as e1000 emulation is slow and there is no batching
- e1000 + VALE/pipe
  - Similar bad performance for netperf tests
  - Good pkt-gen number → batching is actually possible because of netmap support for e1000

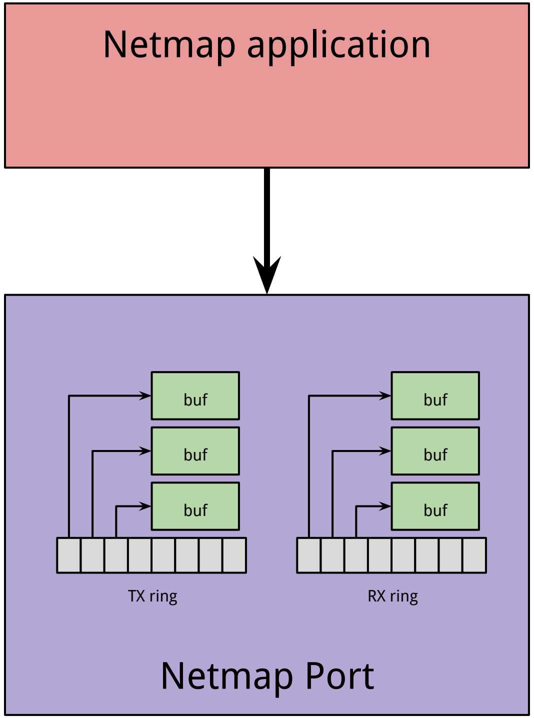
Offloadings to boost TCP performance

- virtio-net header (metadata prepended to each Ethernet frame) is the key to boost TCP performance:
    - TCP Segmentation Offloading
    - TCP/UDP checksum offloading
- Mechanism, in short:
    - VMs on the same host can exchange 32K/64K TCP packets without ever performing TCP segmentation or computing TCP checksum
    - If a TSO packet needs to leave the host system, segmentation and checksumming can be offloaded to real NIC hardware
- Header supported by the VALE switch ports and TAP interfaces

Pass-through of host netmap ports

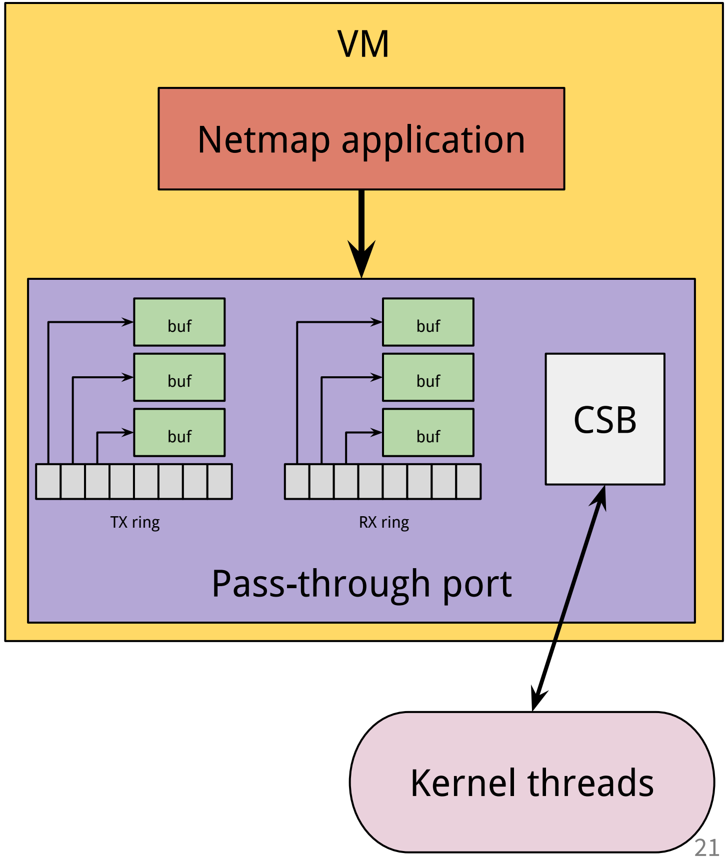
Towards an alternative approach

- A *netmap port* is accessed through the netmap API
  - Hardware-independent rings and buffers are mapped into the userspace application address space
  - TX/RX batching is a key point to remove I/O bottlenecks
- Various port types, depending on the backing I/O
  - Physical ports (NICs)
  - VALE (virtual L2 switch) ports
  - Pipes
  - Monitors
- Software running in the guest can access the front-end rings
  - So far it could not access the (back-end) netmap rings directly.



Netmap pass-through (ptnetmap)

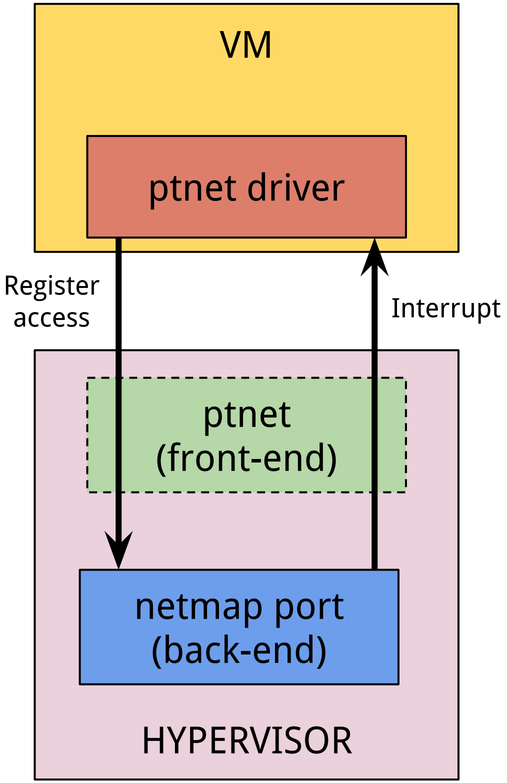
- What if we map netmap rings and buffers of an host port inside a VM?
- The VM could directly access the host port!
- A special pass-through netmap port is used to do the trick
    - I/O registers used to ask the host to TX/RX sync
    - TX/RX sync operations performed by host kernel I/O threads, or directly in the context of the I/O access
    - Shared memory (Communication Status Block) used to synchronize guest ring indices with host ring indices



*[**ANCS 2015**] - Virtual device passthrough for high speed VM networking*
*[**LANMAN 2016**] - Flexible Virtual Machine Networking Using Netmap Passthrough*

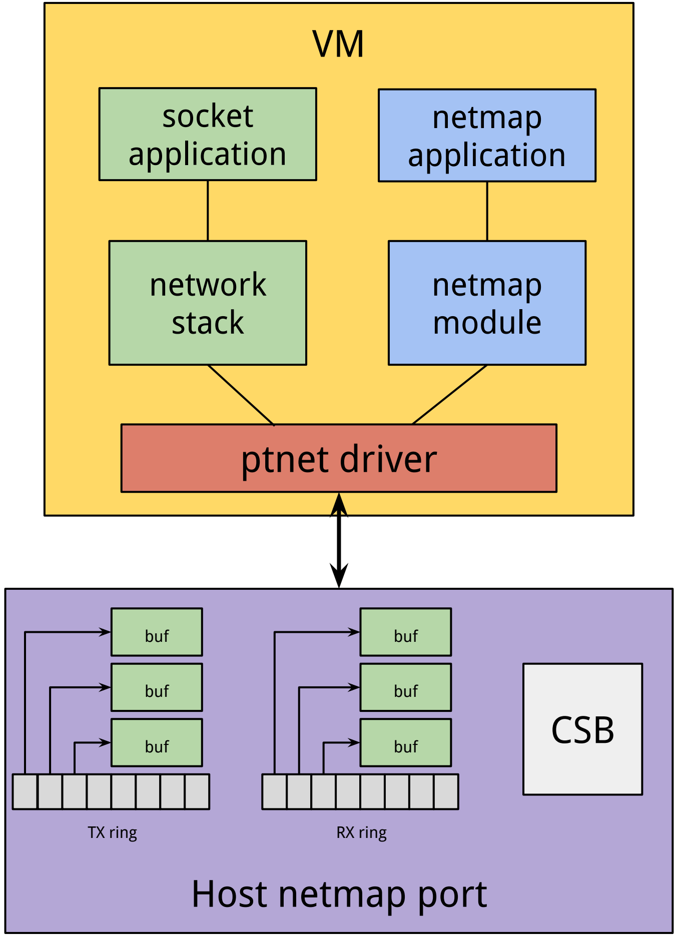
The ptnet front-end

- A device model is needed to expose the passed-through port to the guest OS
- ptnet is a paravirtualized NIC which uses the netmap API as the underlying device model
- No format conversions necessary between front-end and back-end
- Guest can access the back-end port directly, using netmap passthrough
- The front-end is used only for
  - Configuration: number of available queues
  - Control: start/stop kernel threads
  - Synchronization: kick/interrupt
- … but it’s not part of the datapath



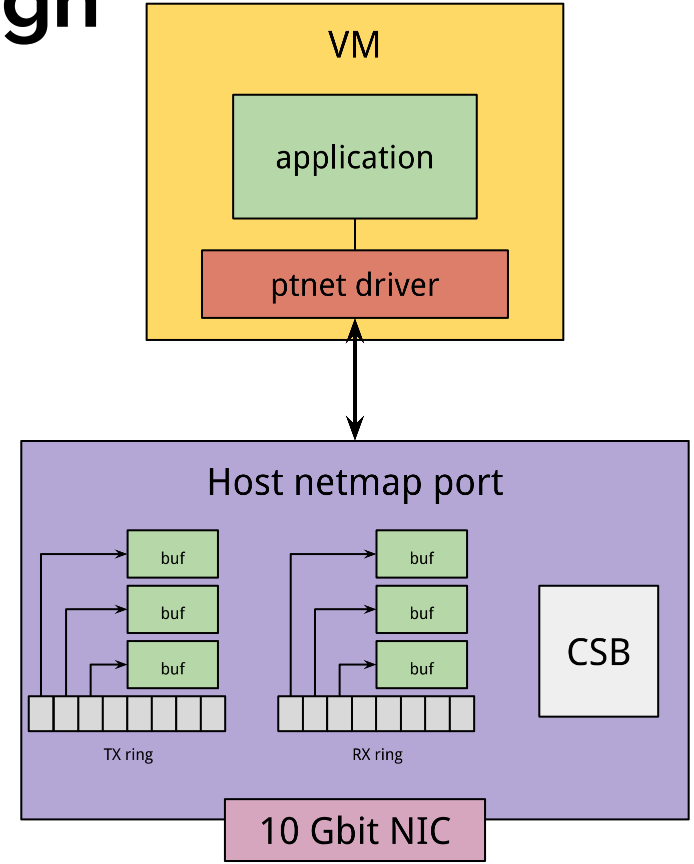
Socket API and netmap API

- Support for applications running in netmap mode
  - They directly access the back-end netmap port
- Support for traditional socket applications
  - Conversion between sk_buff/mbuf and netmap slots is performed, including a packet copy
  - The driver behaves as an application running in netmap mode
  - Support for TSO and checksum offloadings



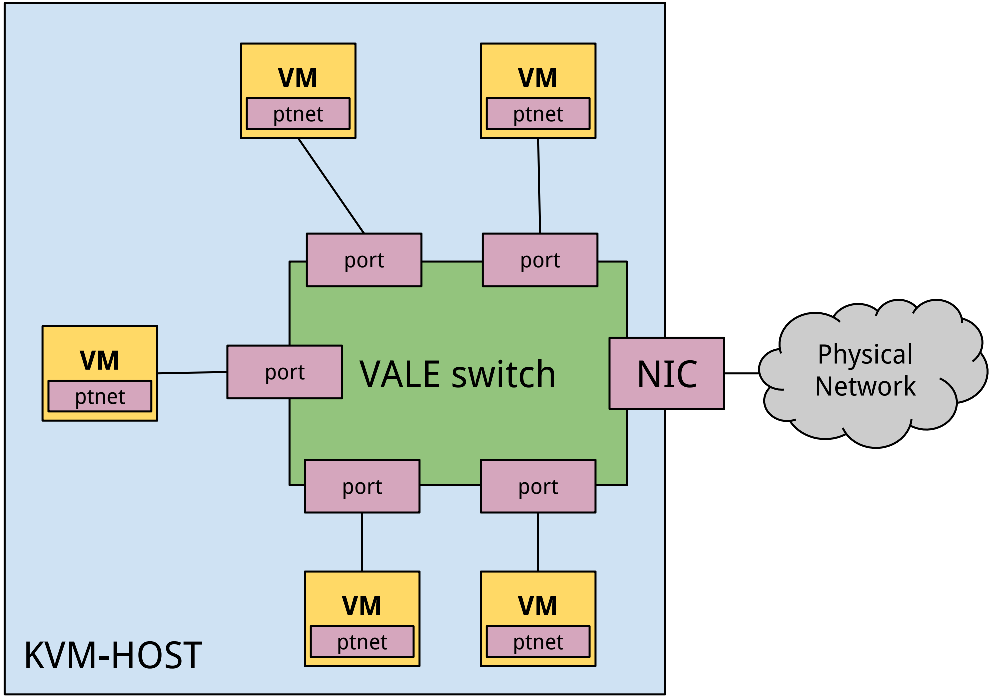
ptnetmap for NIC passthrough

- The VM sees all the queues of the physical NIC
- Netmap performance preserved in the guest
  - 14.88 Mpps TX/RX with a single core
- No PCI passthrough support needed in the hypervisor
  - Netmap code is reused



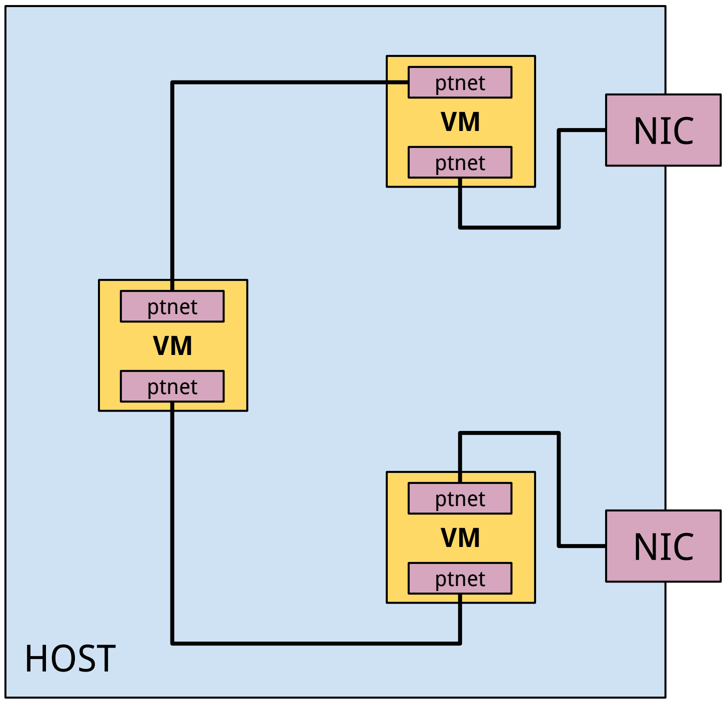
ptnetmap with VALE

- VALE as *software switch* between VMs and the NIC
- VALE ports are passed through to the VMs
- Up to 20 Mpps between different VMs
    - When using the netmap API



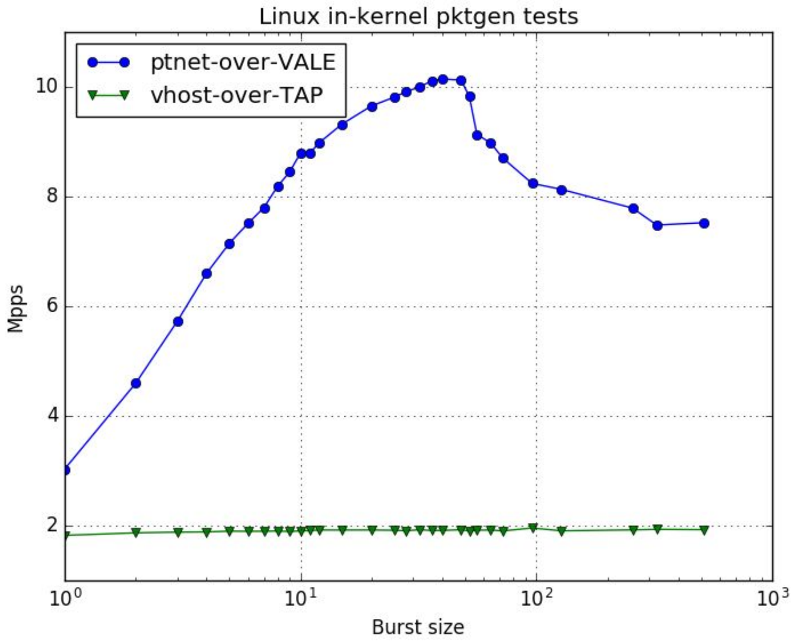
ptnetmap with netmap pipes for NVF

- Netmap pipes allow for zerocopy packet forwarding
- They make it easy to setup high speed NVF chains
- Netmap applications run in the VMs
- How does it compare to traditional VirtIO deployments?



ptnetmap vs VirtIO: in-kernel pkt-gen

- Even traditional network stack is able to benefit from ptnet batching



- Why the Mpps drop? ***[ANCS 2016]*** *A Study of Speed Mismatches Between Communicating Virtual Machines*

ptnetmap vs VirtIO: socket applications

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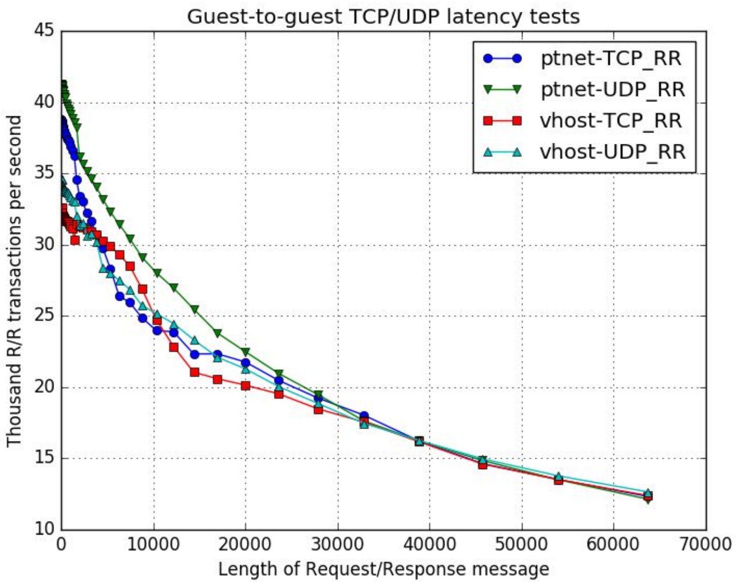
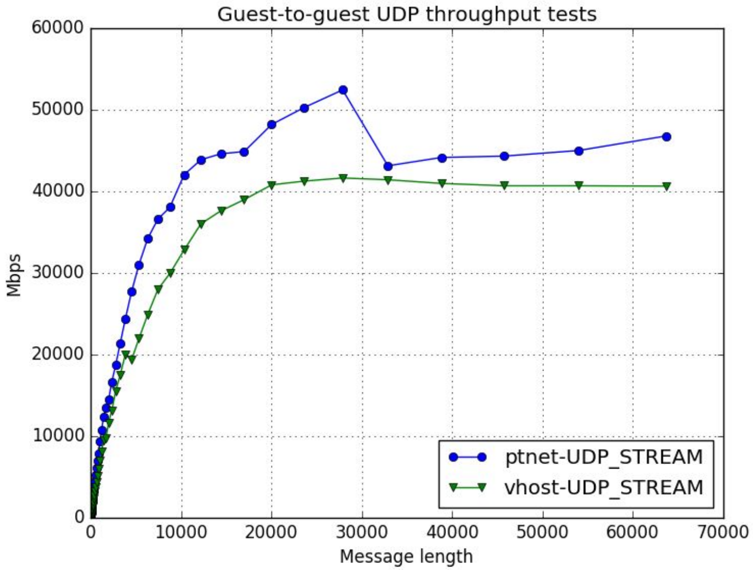


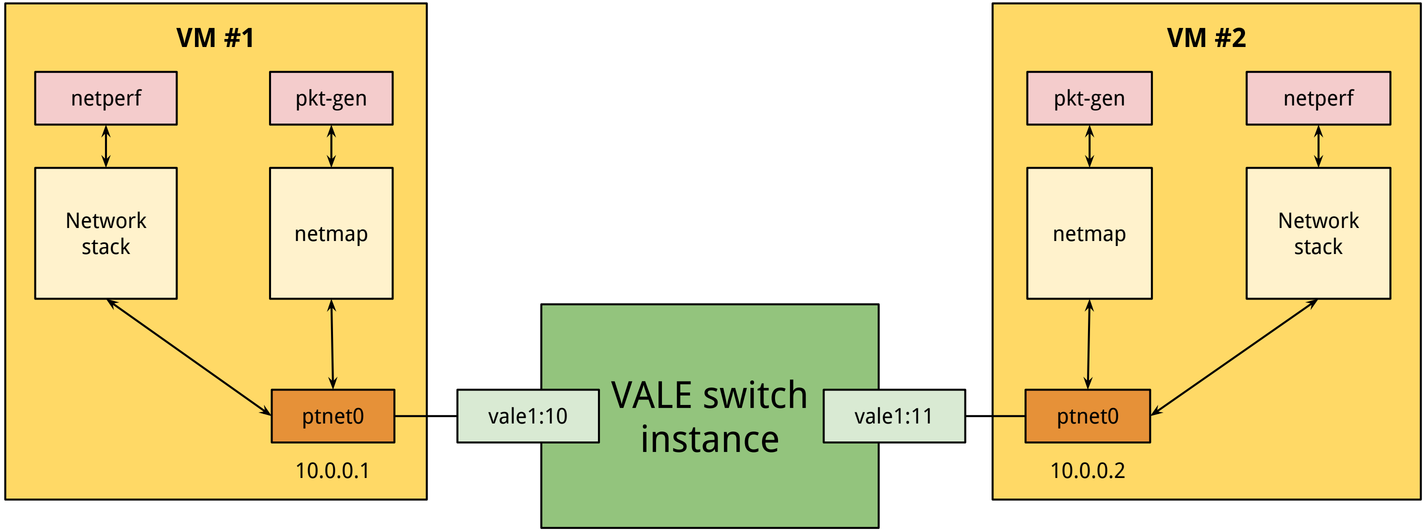


Netmap pass-through in a nutshell

- Flexible → the same tool provides multiple functions
  - NIC passthrough
  - Hypervisor software switch
  - Support for novel packet processing applications
- Easy to port
  - Code reuse is maximized, most of code is part of netmap
  - 500-1000 lines of code to add support for new hypervisors
- Good performance
  - Comparable with VirtIO + vhost-net with socket applications
  - Native netmap performance for applications using the netmap API
- ptnetmap guest drivers and host support are available for both Linux and FreeBSD
  - Not yet upstream in QEMU

VM-to-VM experiments with ptnetmap

- VALE ports are passed-through to the VMs with ptnetmap

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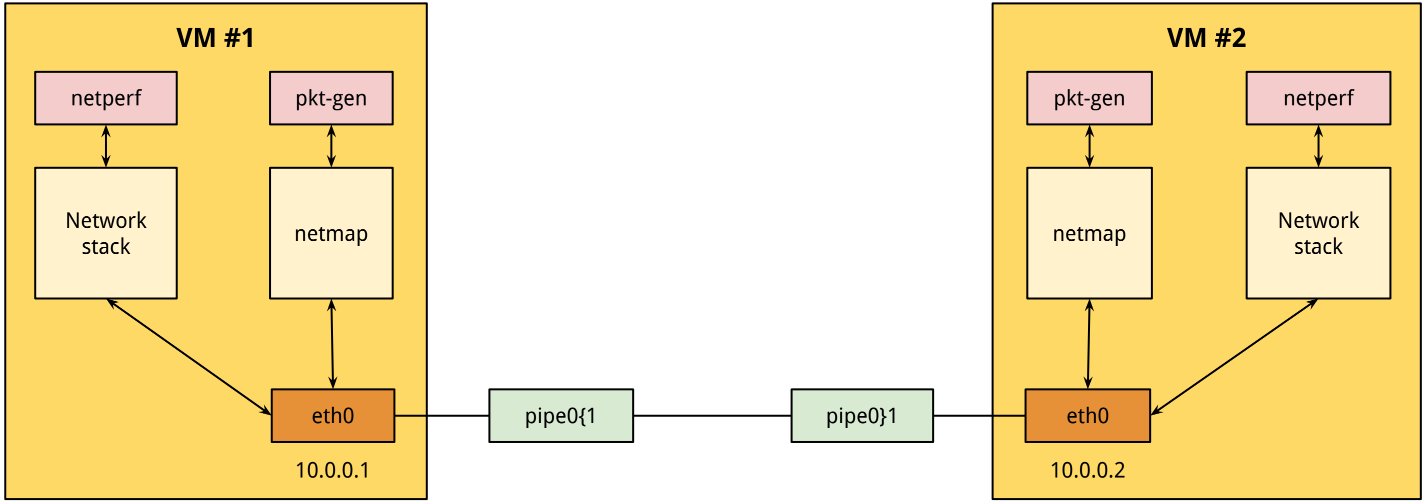
-netdev netmap,ifname=vale1:10,id=data10,passthrough=on
```

VM-to-VM experiments with ptnetmap

- The two ends ot the pipe are passed-through to the VMs with ptnetmap

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```

Experiment results

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ptnet	netmap VALE	21.7 Gbps	46.7 Ktps	28 us	19 Mpps
ptnet	netmap pipe	7.4 Gbps	47 Ktps	26 us	46 Mpps

- Virtio-net + vhost/TAP
  - Excellent netperf performance because of TSO/checksum offloadings and in-kernel vhost
- ptnet + VALE
  - Good netperf performance because of TSO/checksum offloadings and in-kernel processing, but has to pay an additional copy
  - Excellent pkt-gen numbers because of the batching provided by netmap API
- ptnet + netmap pipe
  - Excellent pkt-gen and ping numbers, but no support for offloadings

Hands on exercises