QEMU

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Introduction to QEMU

What is QEMU?

- QEMU (Quick EMUlator - http://qemu.org) is an open source **machine emulator and hosted VMM**
- Feature full virtualization of the CPU through Dynamic Binary Translation
- Can use Linux KVM module (requires Intel VT-x or AMD-V) for hardware assisted virtualization of the CPU
- Emulate many hardware platforms and devices, “real” and virtual (paravirtualization)
- Emulate user-level processes → allow applications compiled for one architecture to run on another

A bit of history

- QEMU started in 2003 by geek jedi master Fabrice Bellard
  - author of FFMPEG, JSLinux and many other projects: https://bellard.org
- Origin of QEMU: portable Just In Time translation engine for cross architecture emulation
- QEMU quickly grew to system emulation
- QEMU started with PC hardware but now support many more: ARM, RISC-V, MIPS, PowerPC, Alpha, Sparc, SH4, etc.

Where is QEMU being used?

- Cloud computing:
  - everything OpenStack
  - along KVM and Xen guests
- Cross-compilation development environments
- Android Emulator (part of SDK) (fork)
- VirtualBox (fork)
- Almost every embedded SDK out there

What can QEMU do?

- Run i386[1], AMD64[2], ARM, Alpha, Sparc, PowerPC, s390 or MIPS OS on a i386, AMD64, Alpha, etc. computers
- Can run any i386 (or other) OS as a **user application**
  - complete with graphics, sound, and network support
  - don't need to be root!
- Descent emulation performance for real world OSes
  - orders of magnitude faster than Wind River Simics (simulator)

[1] i386 = x86 = IA-32 = Intel or AMD 32-bits architecture
[2] AMD64 = Intel or AMD 64-bits architecture

QEMU usage

- VM hardware is specified on the command line (by opposition to VirtualBox or VMWare!)
- Binary for AMD64 is `qemu-system-x86_64`
- Use man `qemu-system` for the manual
- Typical use:
    1. create an image disk with `qemu-img` (once)
    2. run `qemu-system-x86_64` to configure the VM with the previous disk and run it

Typical QEMU options

- Use hardware assisted virtualization via KVM

```
-enable-kvm
```

- Same CPU architecture as host, but 2 cores (vCPU):

```
-cpu host -smp cpus=2
```

- 4GB of RAM

```
-m 4096
```

- Paravirtualized graphics card

```
-vga virtio
```

- Emulated Intel 82574L GbE network card

```
-nic user,model=e1000e
```

- Paravirtualized disk controller using `disk.qcow` as hard disk

```
-drive file=disk.qcow,index=0,media=disk,format=qcow2,if=virtio
```

QEMU nested virtualization

- Pass the following argument to tell QEMU to expose a CPU with all supported host features, notably hardware virtualization instructions

```
-cpu host
```

- Provide an arbitrary level of nested virtualization!

Devices in QEMU

QEMU devices

- QEMU supports a very large number of devices, including CPU architectures:
  - emulated devices ("real" devices)
  - paravirtualized devices (mostly virtio devices)
- To list all supported devices:

```
qemu-system-x86_64 -device help
```

- To list supported options for a specific device:

```
qemu-system-x86_64 -device rtl8139,help
qemu-system-x86_64 -device virtio-net-pci,help
```

Device types

Emulated: IDE, SATA, SCSI disk controlers, network cards, etc.

- Good compatibility (drivers usually present in the guest OS)
- Low performance

Paravirtualized: virtio devices

- Good performance
- Require dedicated paravirtualized drivers in the guest OS

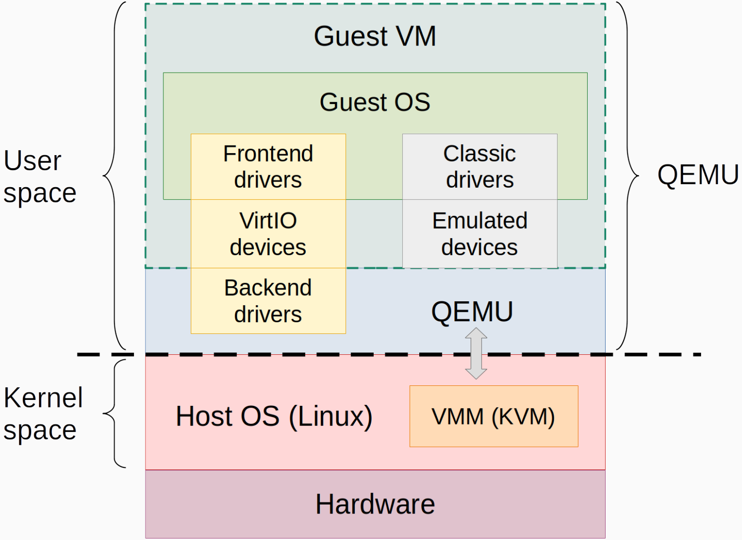
Passthrough: via VFIO

- Near native performance
- Limited number of PCI devices supported
- *Tricky* live migration
- Requires VT-d hardware extension

Virtio framework

- Specification for **paravirtualized** device (I/O) virtualization
- Abstraction layer over the hardware (devices)
- virtio provides:
    - classes of virtual devices (network, block, memory, etc.)
    - common I/O registers
    - virtual queues (shared memory)
    - device probing and configuration
- Common API for all paravirtualized devices
- Use shared memory (ring buffer) between guest OS and QEMU

Virtio vs emulated drivers



Virtio architecture

Front-end driver

- Kernel module in guest OS
- Accepts I/O requests from user process
- Transfer I/O requests to back-end driver

Back-end driver

- A device in QEMU
- Accepts I/O requests from front-end driver
- Perform I/O operations via physical device

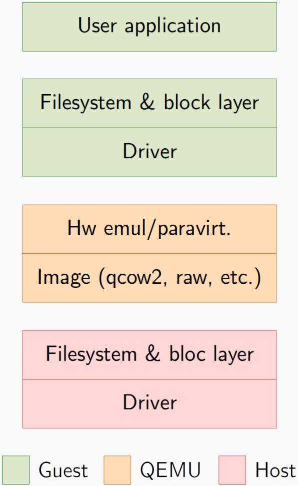
Networking

- QEMU can bridge guest network $\rightarrow$ provide direct access
- Can provide network address translation (NAT)
    - NAT address local to machine on which guest is running
    - QEMU provides address translation to guest to hide its address

Storage in QEMU

Storage stack

- Application and guest kernel work similar to bare metal
- Guest talks to QEMU via emulated hardware and/or paravirtualized devices
- QEMU performs I/O to an image file on behalf of the guest
- Host kernel treats guest I/O like any userspace application



Disk images

- QEMU supports many image formats:
  - qcow2, qed, vmdk, vhd, vdi, raw, rbd, nbd, tftp, ftp, vvfat, ftps, dmg, iscsi, parallels, bochs, quorum, etc.
- Use `qemu-img` tool to manipulate images:
  - create images
  - convert among image formats
  - resize images
  - manage disk snapshots
  - etc.

Disk images: recommendation

- Best to use either **qcow2** or **raw** formats
- **qcow2**: QEMU image format
  - most versatile and flexible
  - many features: thin provisioning, encryption, compression, snapshots, sparse files (when host filesystem permits), etc.
- **raw**: raw disk image format
  - simple and very portable (exportable to other hypervisors)
  - best portability and performance, but few features

Disk image growth

- Over time, a VM disk image can grow larger than the actual data stored within it
- Guest OS typically only marks a deleted file as zero
  - blocks are not actually deleted for performance reasons
  - qcow2 file cannot differentiate between allocated and used, and allocated but not used
- Solution to avoid disk image from growing more than necessary:
  - on the host, add these options to QEMU's `-drive` argument:

```
discard=unmap,detect-zeroes=unmap
```

  - in the guest OS, reclaim blocks from the filesystem:

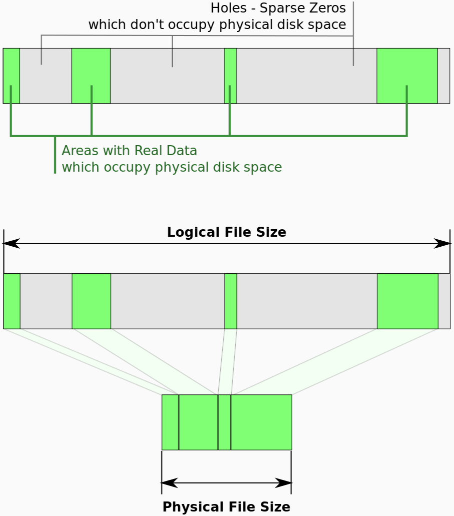
```
sudo fstrim -av
```

  - even better: automate the process with a service:

```
systemctl enable fstrim.timer && systemctl start
    fstrim.timer
```

Sparse files

- A sparse file is a file that does not store “empty” (unused) space
- Data blocks containing no data are not actually written to disk
- Most modern file systems support sparse files
  - ext4, xfs, ntfs, btrfs do
  - FAT filesystems do not



Handling sparse files

- To create a 10MB sparse file:

```
truncate -s 10M myfile
dd if=/dev/zero of=myfile bs=10M count=1 conv=sparse
```

- To display a file's real allocated space:

```
ls -ls file
du file
```

- To convert a file into a sparse file:

```
fallocate -v -d file
```

- To convert a sparse file into a non-sparse file:

```
cp file nonsparse_file --sparse=never
```

Copying sparse files

- Linux transparently handles copy of sparse files
  - if unsure, use:

```
cp --sparse=always
```

- **Transfering sparse files over the network is usually not supported**
  - files lose their sparse property
  - server and client must both implement support for sparse files
  - `scp` does not support sparse files!
  - use `rsync` over `scp` instead (using ssh key pairs)

```
rsync -P --sparse source_file  destination_machine:
```

Inspecting/modifying VM disk image files

guestfish

- Shell and command-line tool for examining and modifying VM filesystems (uses `libguestfs`)
- Should not be ran as root; however, on Ubuntu `/boot/vmlinuz*` has the wrong permissions[3], thus change them with:

```
sudo chmod 0644 /boot/vmlinuz*
```

guestmount

- Mount a guest filesystem on the host using FUSE and `libguestfs`

[3] https://libguestfs.org/guestfs-faq.1.html

Snapshots in QEMU

QEMU snapshots

- QEMU supports two types of snapshots:
  - **disk snapshots**: only save content of the disk
  - **VM snapshots**: save content of disk + RAM + device state
- Snapshots are stored in qcow2 image files
- Snapshots can use two backing strategies: **internal** and/or **external**
- Disk snapshots can use either internal or external backing
- VM snapshots use internal backing

Internal vs external snapshots

Internal snapshots

- All snapshots are stored inside the same qcow2 file

External snapshots

- Each snapshot is stored in a different qcow2 file
    - chain of qcow2 files
- Last qcow2 file in a chain represents the current state and is read/written by QEMU
    - previous qcow2 files in a chain are **only read** by QEMU
- To display the chain of snapshots up to some state:

```
qemu-img info --backing-chain some_state.qcow
```

Internal disk snapshots

- Use `qemu-img` to manage both internal and external disk snapshots
- Internal disk snapshots are straightforward:

`qemu-img snapshot -c <name> <img>`	create an internal disk snapshot
`qemu-img snapshot -d <name> <img>`	delete an internal disk snapshot
`qemu-img snapshot -a <name> <img>`	apply an internal disk snapshot (revert disk to saved state)
`qemu-img snapshot -l <img>`	list all internal snapshots in the image (disk and VM)

- Deleting internal snapshots does not reduce the image file size!

External disk snapshots

- Require a base image
  - used as the backing (or base) file
  - read-only access by QEMU
- Here, create an *overlay* image (`state1.qcow`) that will store the differences from the backing file `base.qcow`

```
qemu-img create -F qcow2 -b base.qcow -f qcow2 state1.qcow
```

  Illustration of the above command where QEMU is ran to use `state1.qcow`:

```
    [base] <------------ [state1]
(backing file)       (active overlay)
```

- At any point, a new *overlay* can be added to a chain of overlays

Disk image chain & merging

- Disk images in a chain can be **merged** together
  - offline using `qemu-img`
  - online using QEMU Machine Protocol (QMP) commands[4]
- Two types of merges:
  - **commit**: merge of data from overlay files into backing files
    - committed file not removed by QEMU: must be manually removed
    - intermediate images are invalid: no more overlays can be created based on them
  - **stream**: copy of data from backing files into overlay files
    - streamed file not removed by QEMU
    - streamed file remains valid

[4] https://qemu.readthedocs.io/en/latest/interop/qemu-qmp-ref.html

Merging: commit operations

- Example of disk image chain ([A] = backing file, [D] = active overlay):

```
[A] <-- [B] <-- [C] <-- [D]
```

- Case 1, merge [B] into [A]:

```
[A] <-- [C] <-- [D]
```

- Case 2, merge [B] and [C] into [A]:

```
[A] <-- [D]
```

- Case 3, merge [B], [C] and [D] into [A]:

```
[A]
```

- Case 4, merge [C] into [B]:

```
[A] <-- [B] <-- [D]
```

- Case 5, merge [C] and [D] into [B]:

```
[A] <-- [B]
```

Merging: stream operations

- Example of disk image chain ([A] = backing file, [D] = active overlay):

```
[A] <-- [B] <-- [C] <-- [D]
```

- Case 1, merge everything into [D]:

```
[D]
```

- Case 2, merge [B] and [C] into [D]:

```
[A] <-- [D]
```

- Case 3, merge [B] into [C]:

```
[A] <-- [C] <-- [D]
```

Commit operations with qemu-img

- Command `qemu-img commit` can be used to perform a merge "commit"
- The combined state up to a given overlay image can be merged back into a previous image in the chain
- Example with the previous chain:

```
[A] <-- [B] <-- [C] <-- [D]
```

  - commit changes from `[D]` into image `[A]`:

```
qemu-img commit -f qcow2 -b A.qcow D.qcow
```

VM snapshots

- VM snapshots = content of disk + RAM + device state
- Managed from the QEMU monitor:

`savevm <tag>`	creates a VM snapshot
`delvm <tag>`	deletes a VM snapshot
`loadvm <tag>`	applies a VM snapshot
`info snapshots`	lists all snapshots (disk and VM)

- QEMU argument `-loadvm <tag>` starts the VM from the specified snapshot

Tools for QEMU

QEMU monitor

- QEMU monitor = console for interacting with QEMU to:
  - control various aspects of the VM
  - inspect the running guest OS
  - change removable media and USB devices
  - take snapshots, screenshots, audio grabs
  - etc.
- Monitor access:
  - telnet server running in QEMU:
    `-monitor telnet::1234,server,nowait`
    - client side: `telnet ip_server 1234`
  - GUI: `View` → `compatmonitor0` (or similar)
  - in the shell QEMU is running in, with: `-monitor stdio`
  - [Ctrl-Alt-2] ([Ctrl-Alt-1] switches back to guest OS)

QEMU Guest Agent (QGA)

- Service installed in the guest OS
- Allow QEMU to perform many operations:
  - Get guest OS information
  - Read/write a file in the guest
  - Sync and freeze the filesystems
  - Shutdown/reset/suspend the guest
  - etc.
- Uses QEMU Guest Agent Protocol to exchange messages via a UNIX socket
- Supported commands here[5]

[5] https://qemu.readthedocs.io/en/latest/interop/qemu-ga-ref.html

QEMU guest agent example (1/2)

- VM must be started with these additional arguments:

```
-device virtio-serial
-device virtserialport,chardev=qga0,name=org.qemu.guest_agent.0
-chardev socket,path=/tmp/qga.sock,server=on,wait=off,id=qga0
```

- In the guest OS, `qemu-guest-agent` must be installed and started (usually already the case):

```
sudo apt-get install qemu-guest-agent
sudo systemctl enable qemu-guest-agent
sudo systemctl start qemu-guest-agent
```

QEMU Guest Agent example (2/2)

- Shutdown the guest:

```
{ echo '{"execute": "guest-shutdown"}'; sleep 1; } |
    socat unix-connect:/tmp/qga.sock -
```

- Close a previously opened file on the guest (handle 1000):

```
{ echo '{"execute":"guest-file-close", "arguments":{"
    handle":1000}}'; sleep 1; } | socat unix-connect:/
    tmp/qga.sock -
```

Shared directories

- QEMU uses the 9p[6] protocol to share dirs between host and guests
  - same dir can be shared by multiple guests
- **Host**: run QEMU with these additionnal arguments, where `MOUNT_TAG` is the share name:

```
-virtfs local,path=PATH_TO_SHARE,mount_tag=MOUNT_TAG,
    security_model=mapped
```

- **Guests**: mount the virtual filesystem, specifying the **9p** type:

```
sudo mount -t 9p MOUNT_TAG MOUNT_DIR
```

  - requires `9p`, `9pnet`, and `9pnet_virtio` kernel modules
    - `mount` loads them automatically
  - uses virtio

[6] https://en.wikipedia.org/wiki/9P_(protocol)

Useful QEMU commands and arguments

`man qemu-system`	Exhaustive help on QEMU
`-writeconfig <f>`	Write device configuration to
`-readconfig <f>`	Read device configuration from
`-machine <name>`	Set the machine to
`-smp cpus=<n>`	Set the number of CPUs to
`-m <mem>`	Set the ammount or RAM to
`-drive ...`	Define a new drive
`-device ...`	Add a device driver
`-netdev ...`	Configure user mode host network backend
`-nic ...`	Shortcut for configuring both the guest NIC and the host network backend
`-spice ...`	Enable a Spice server
`-monitor stdio`	Redirect the monitor to the console
`-vga ...`	Select the type of VGA card to emulate
`-redir tcp:x::y`	Redirect port y in the guest to x in the host
`-enable-kvm`	Use KVM to provide hardware full virtualization

Useful tools

Debian package that provides many VM tools: `guestfs-tools`

`virt-rescue`	run a rescue shell on a VM
`virt-builder`	build VM images quickly
`virt-copy-out`	copy files and dirs out of a VM disk image
`virt-copy-in`	copy files and dirs into a VM disk image
`virt-resize`	resize a VM disk
`virt-sparsify`	make a VM disk sparse
`virt-edit`	edit a file in a VM
`virt-ls`	list files in a VM
...	

Virtual Desktop Infrastructure (VDI)

Desktop virtualization

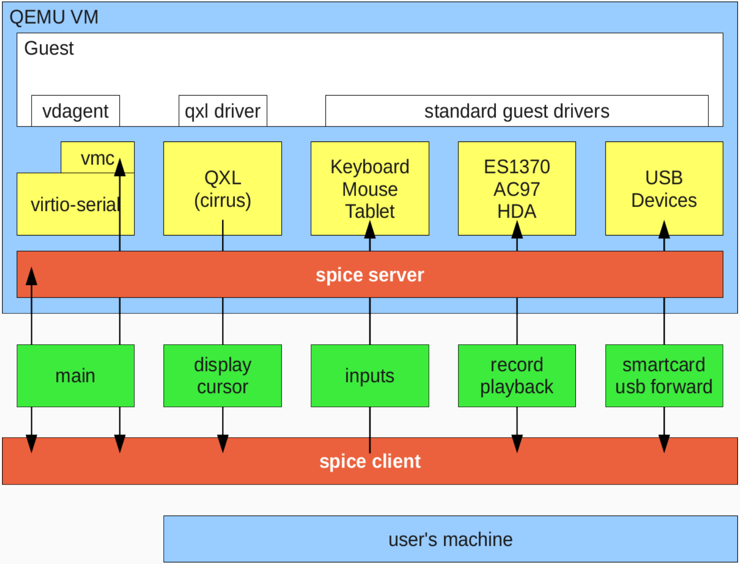
- **Server** virtualization is commonplace and offered everywhere
  - manage virtual machines: CPU, RAM, storage, network, etc.
  - administrator access: text mode (ssh), low end graphics (VNC)
- **Desktop** virtualization **needs more**:
  - better graphics (3D, multihead, etc.)
  - sound forwarding
  - video stream support
  - USB forwarding
  - desktop integration (copy/past, shared directory, dynamic display resize, etc.)

SPICE

- **S**imple **P**rotocol for **I**ndependent **C**omputing **E**nvironments[7]
- SPICE's goal is to provide desktop virtualizazion
- Provides virtual **desktop** infrastructure
  - SPICE network protocol
  - virtual hardware (virtio gpu, qxl)
  - server and client implementations
- VM remotely accessed via a dedicated port on the host (one port per VM)

[7] https://www.spice-space.org/

SPICE architecture



SPICE components

SPICE divided into 4 different components:

- **Client**: responsible to send data and translate the data from the VM so you can interact with it
  - Examples: `remote-viewer`, `spicy`, etc.
- **Server**: library used by the hypervisor to share the VM
  - Typically: `QEMU`
- **Guest**: software that must be running in the VM to make SPICE fully functional
  - Typically for Linux guest: virtio VGA driver, SPICE vdagent, etc.
- **Protocol**: the network protocol

SPICE features

- More bandwidth efficient than VNC
- Multiple channels: main, display, cursor, inputs, record, playback
  - any combination of channels can be encrypted via TLS
- Access can be password protected (or not)
- Copy/paste host $\leftrightarrow$ guest OS
- USB redirection over the network
- Shared directory over the network
- Image compression
- OpenGL acceleration

SPICE basic usage

Server side

- Require either `-vga virtio` (prefered) or `-vga qxl` paravirtualized graphics driver
- Arguments to start a SPICE server on port 8000 in the VM (without authentication):

```
-device virtio-serial-pci
-spice port=8000,disable-ticketing=on
-device virtserialport,chardev=spicechannel0,name=com.redhat.spice.0
-chardev spicevmc,id=spicechannel0,name=vdagent
```

Client side

- Require a spice client, for instance `remote-viewer` (part of `virt-viewer` Debian package):

```
remote-viewer "spice://server_ip?port=8000"
```

Resources

- QEMU documentation
  https://qemu.readthedocs.io/en/latest/index.html
- Live Block Device Operations
  https://qemu.readthedocs.io/en/latest/interop/live-block-operations.html
- QEMU shared folders with 9pfs
  https://wiki.qemu.org/Documentation/9psetup
- Using QEMU Machine Protocol (QMP)
  https://wiki.qemu.org/Documentation/QMP
- Introduction to VirtIO
  https://blogs.oracle.com/linux/post/introduction-to-virtio
- Virtio Driver Implementation
  http://www.dumais.io/index.php?article=aca38a9a2b065b24dfa1dee728062a12