Backing Chain Management in libvirt and qemu

Eric Blake <eblake@redhat.com>
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In this presentation

- How does the qcow2 format track point-in-time snapshots
- What are the qemu building blocks for managing backing chains
- How are these building blocks used together in libvirt

Part I

Understanding qcow2

qcow2 history

- qcow format (QEMU Copy On Write) documented in 2006
- qcow2 created in 2008, adding things like:
  - Internal snapshots with reference counting
- Hacky addition in 2009 to add header extensions
  - Backing file format, to avoid format probing CVEs
- qcow2v3 created in April 2012, adding things like:
  - Feature bits (extension is easier!)
  - Efficient zero cluster management

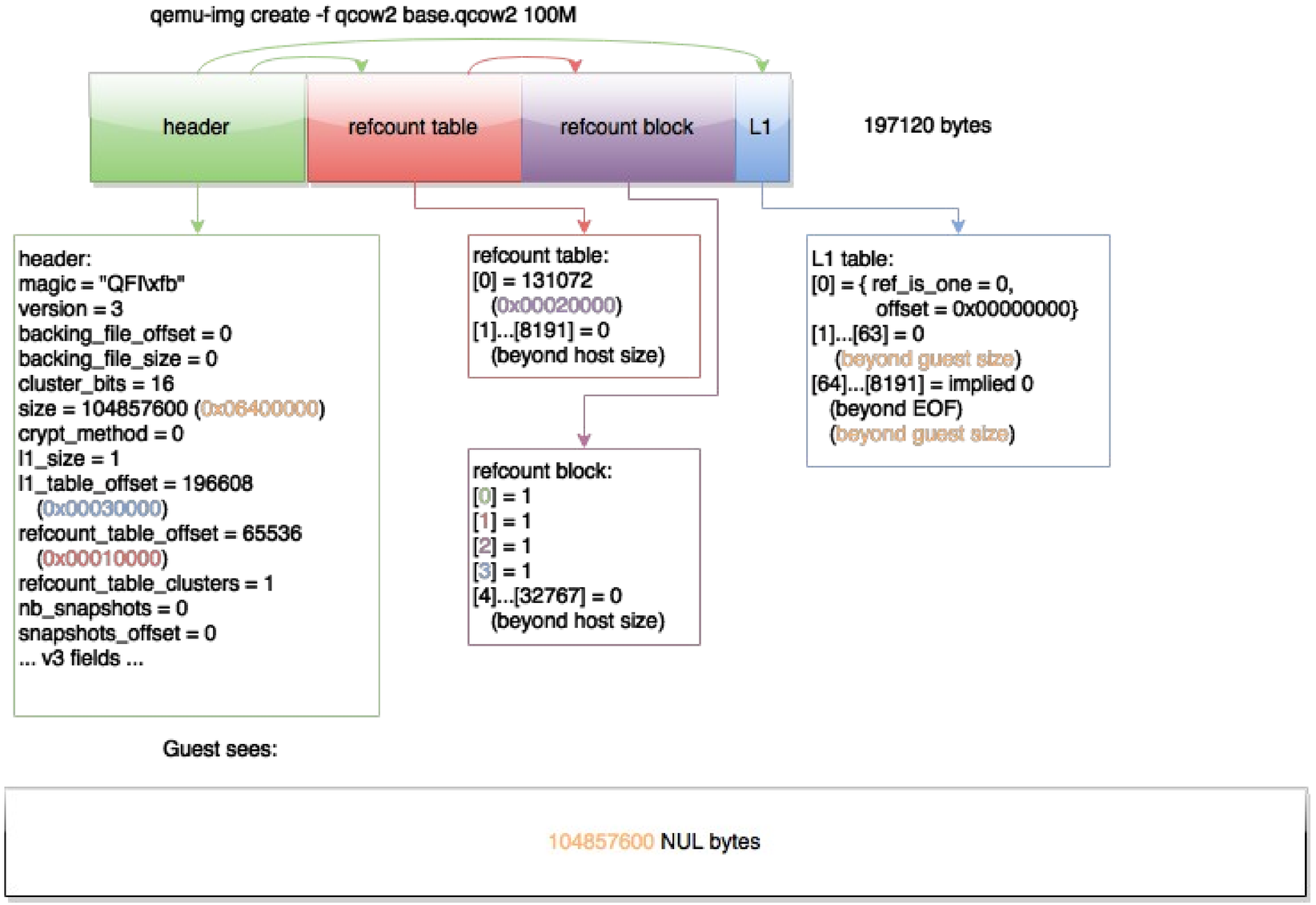
Let's look under the hood

- Create a new file
- Write some guest data
- Create an internal snapshot
- Write more guest data
- Create an external snapshot
- Write even more guest data

Create a new file

qemu-img create -f qcow2 base.qcow2 100M

Create a new file



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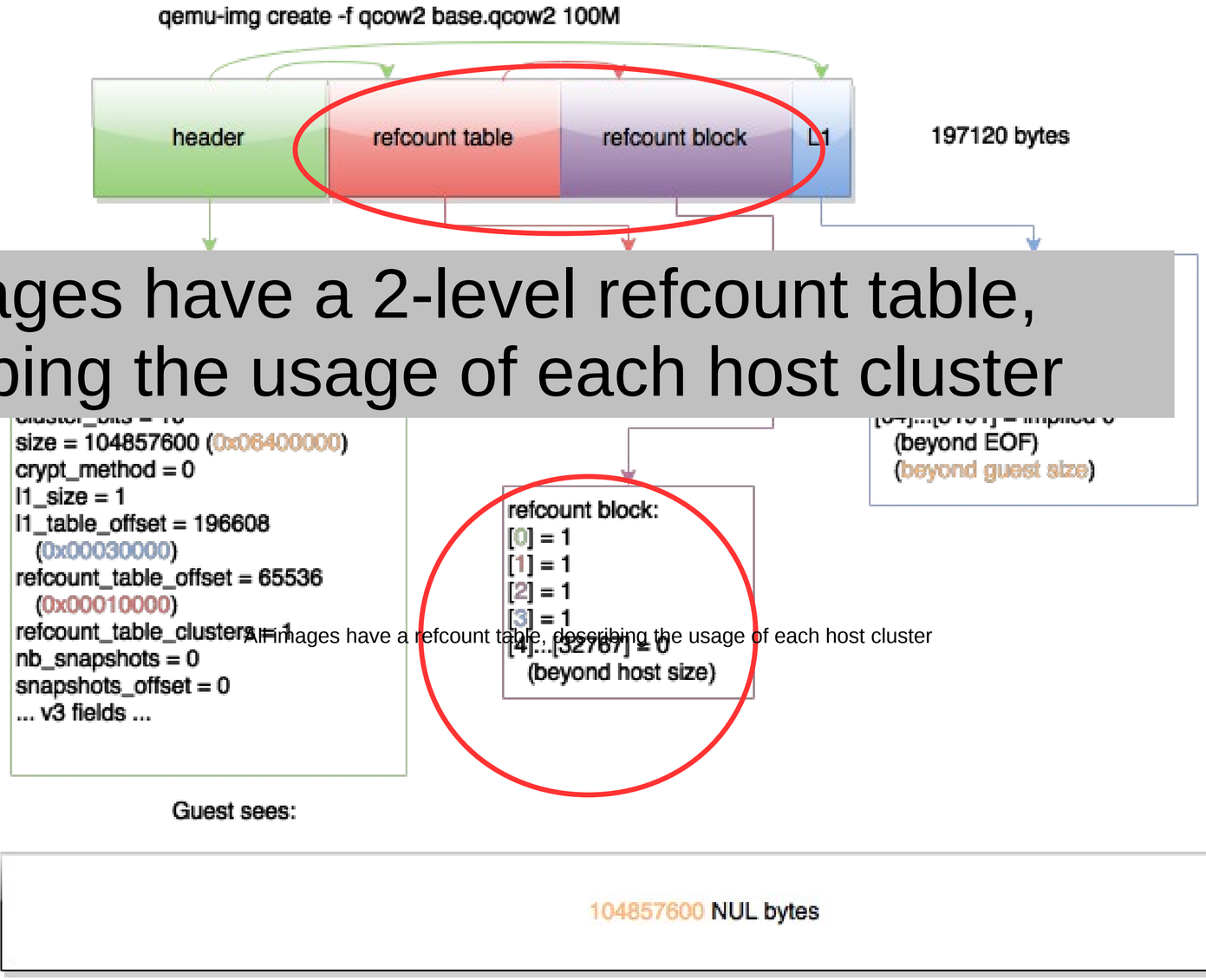

All images have a 2-level refcount table, describing the usage of each host cluster

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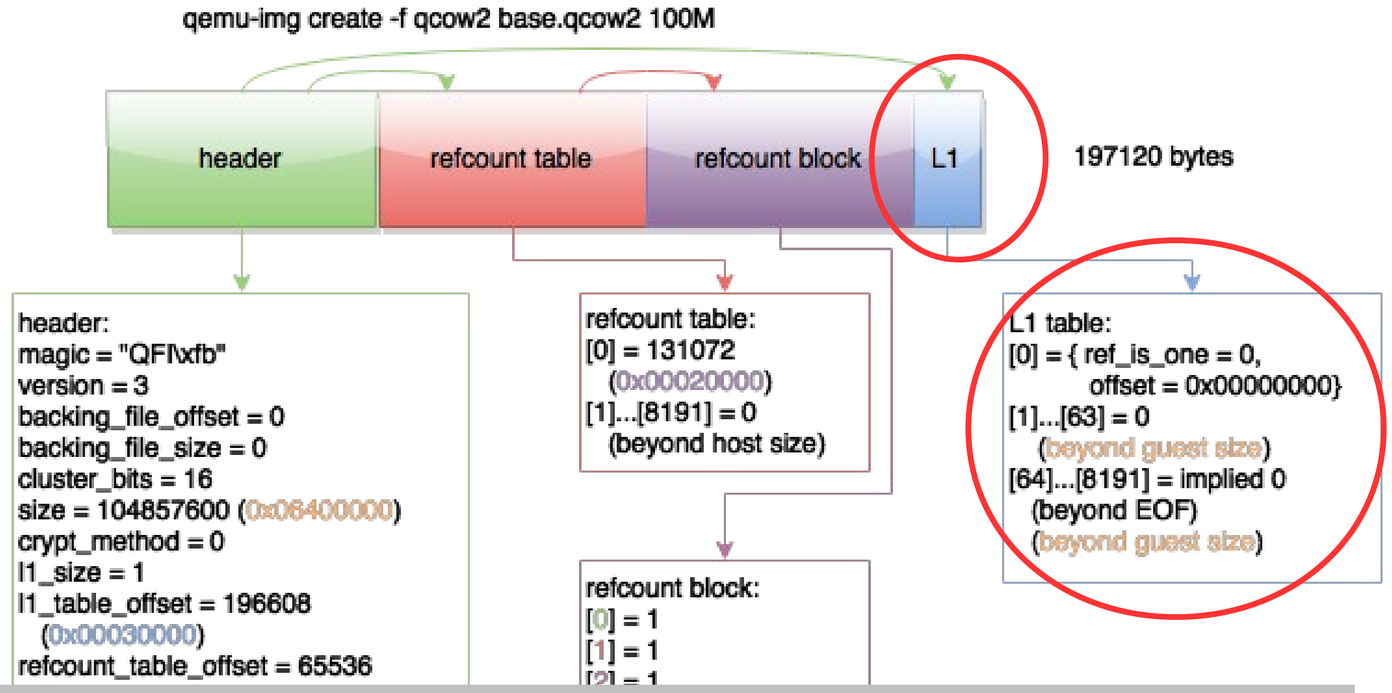
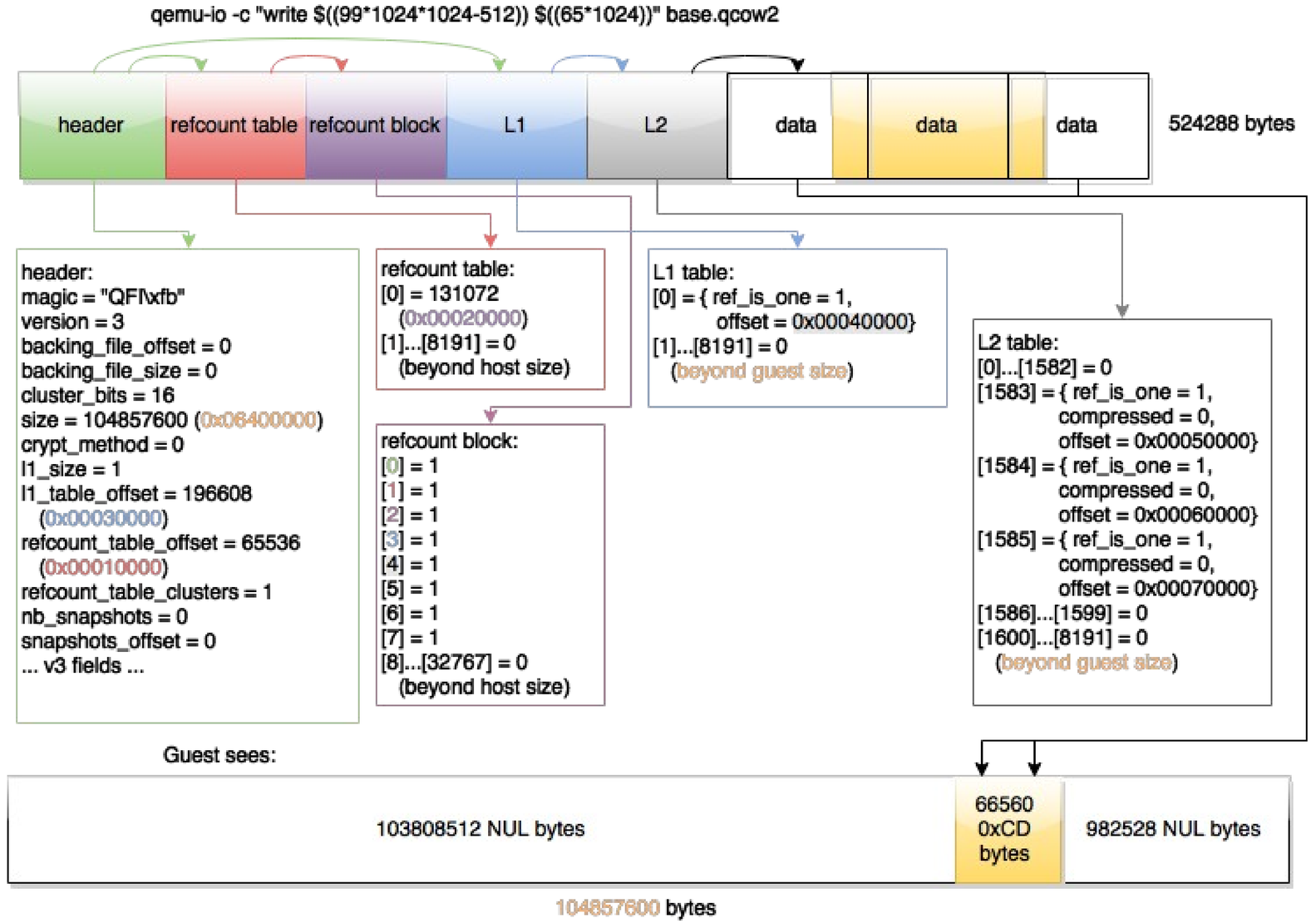


All images have an L1/L2 table,
describing the mapping of each guest cluster
(but with no data mapped, L2 is omitted)

Write some guest data

qemu-io -c “write $((99*1024*1024-512)) $((65*1024))” base.qcow2

Write some guest data



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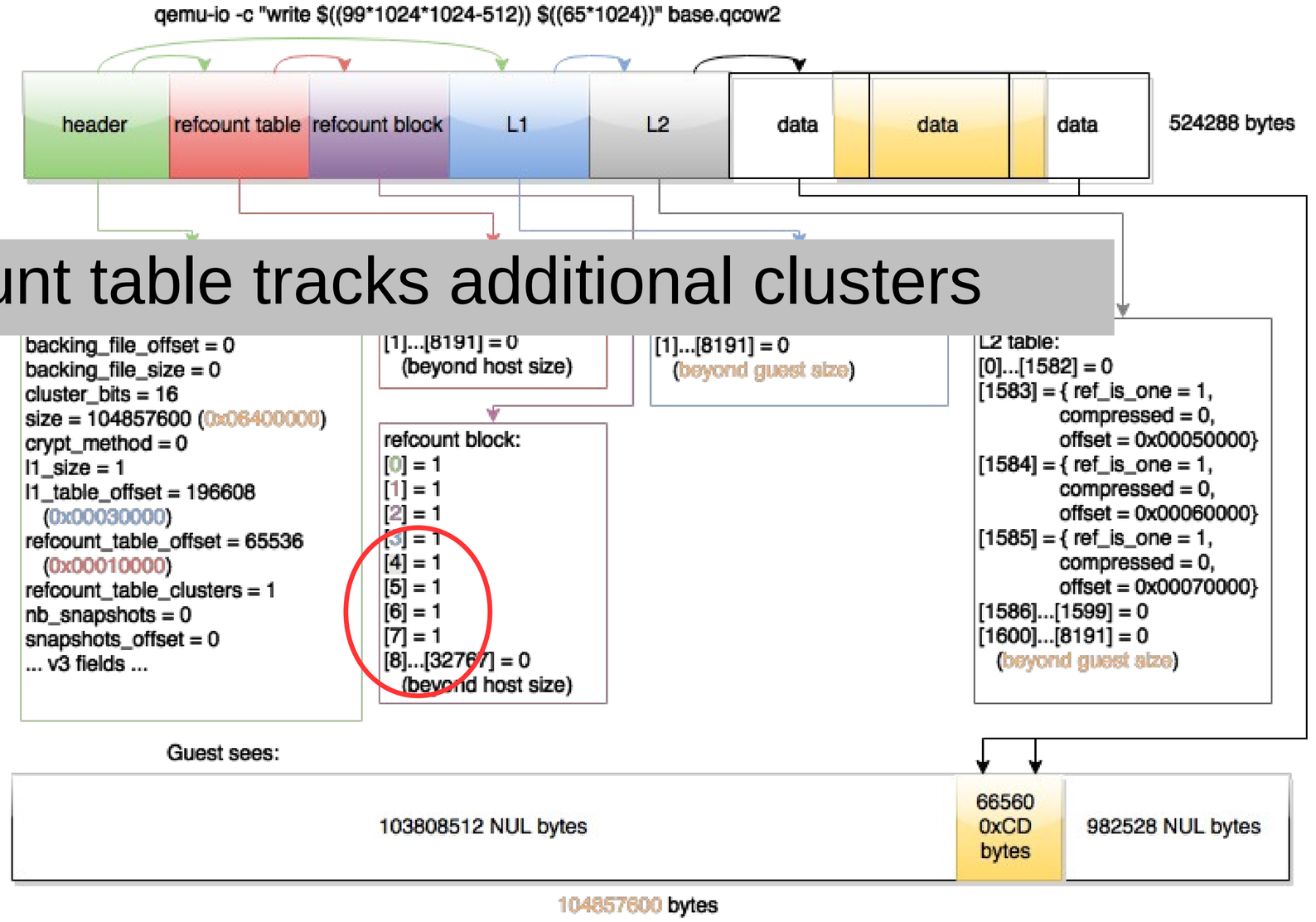

Refcount table tracks additional clusters

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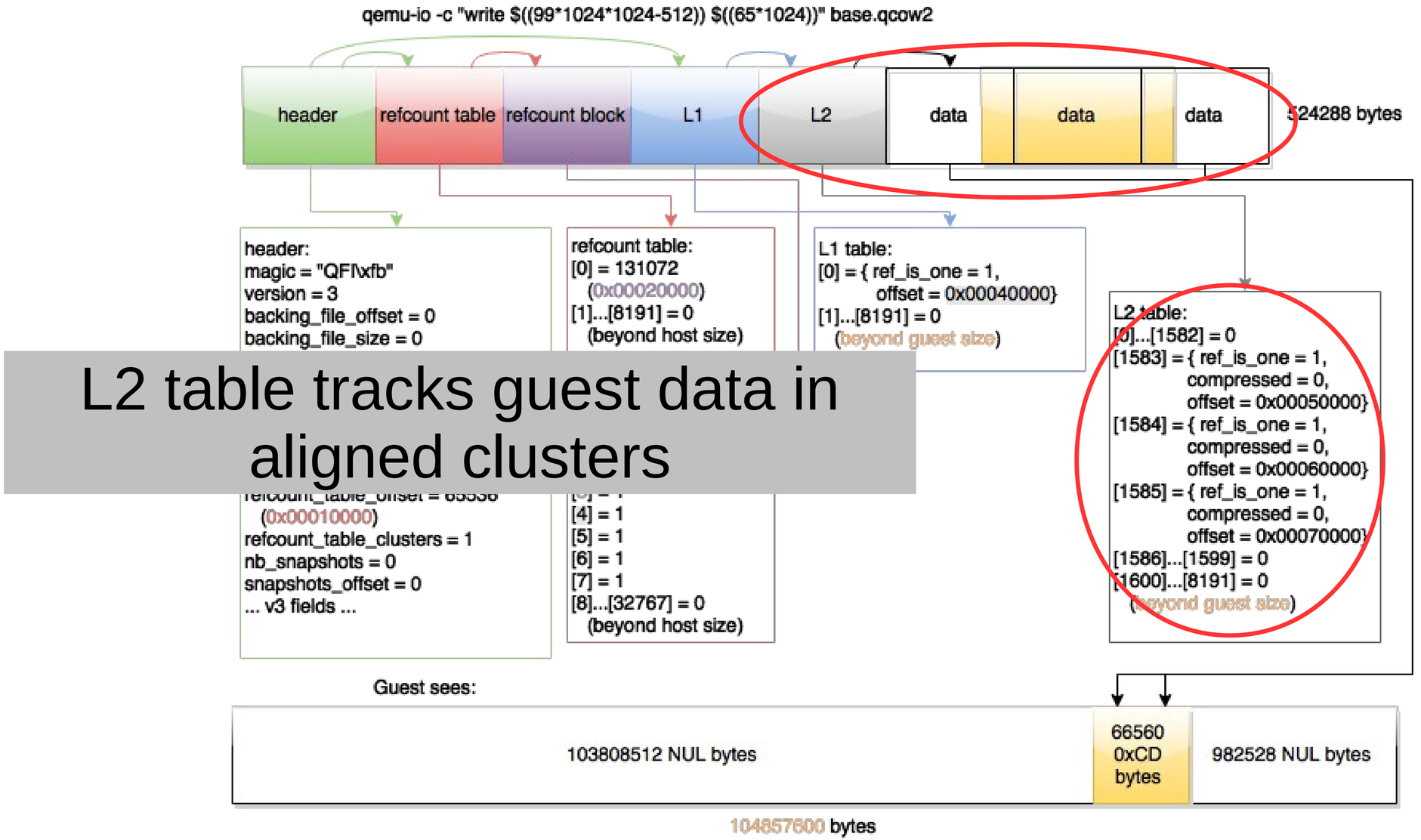
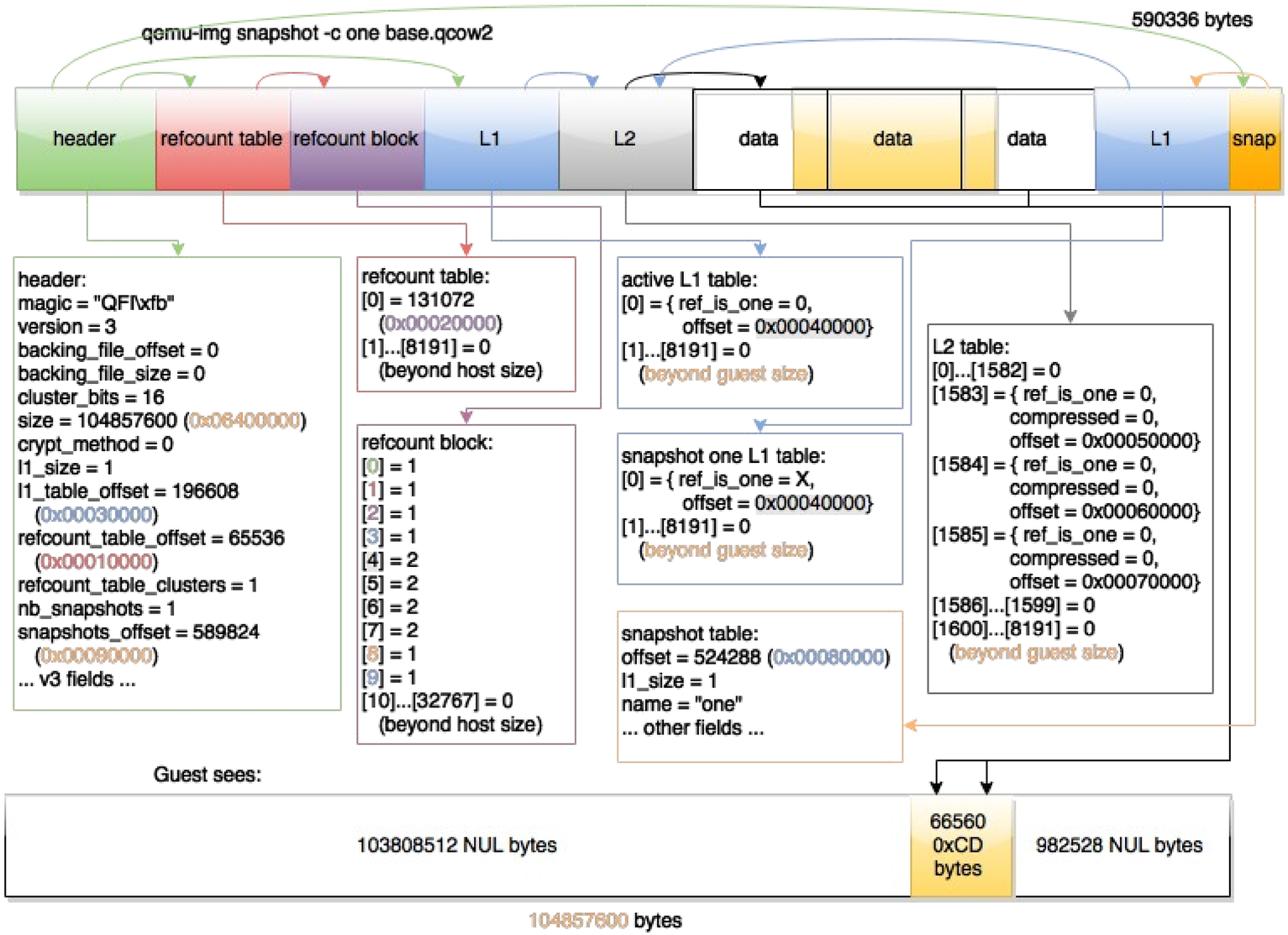


L2 table tracks guest data in aligned clusters

Create an internal snapshot

qemu-img snapshot -c one base.qcow2

Create an internal snapshot



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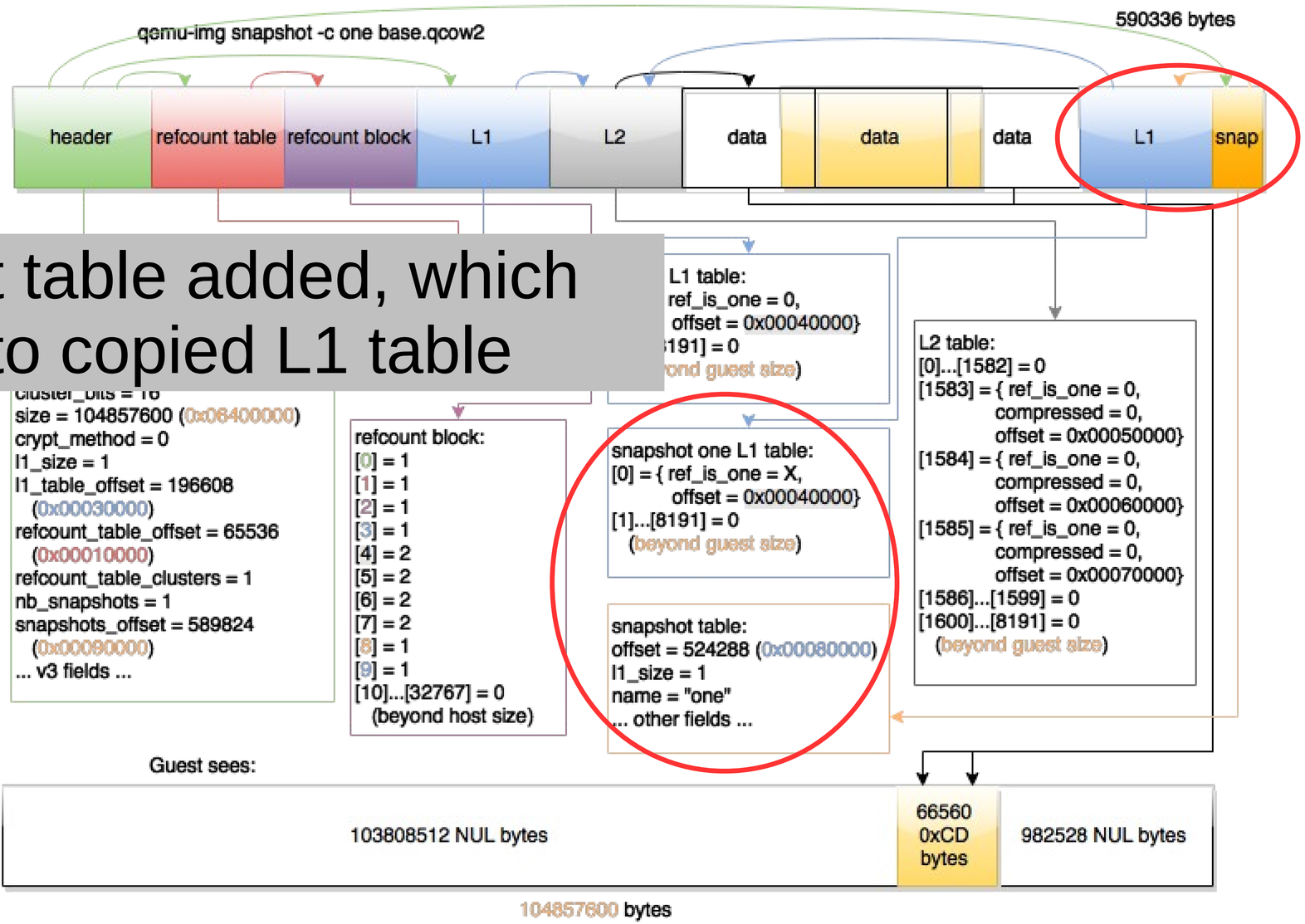
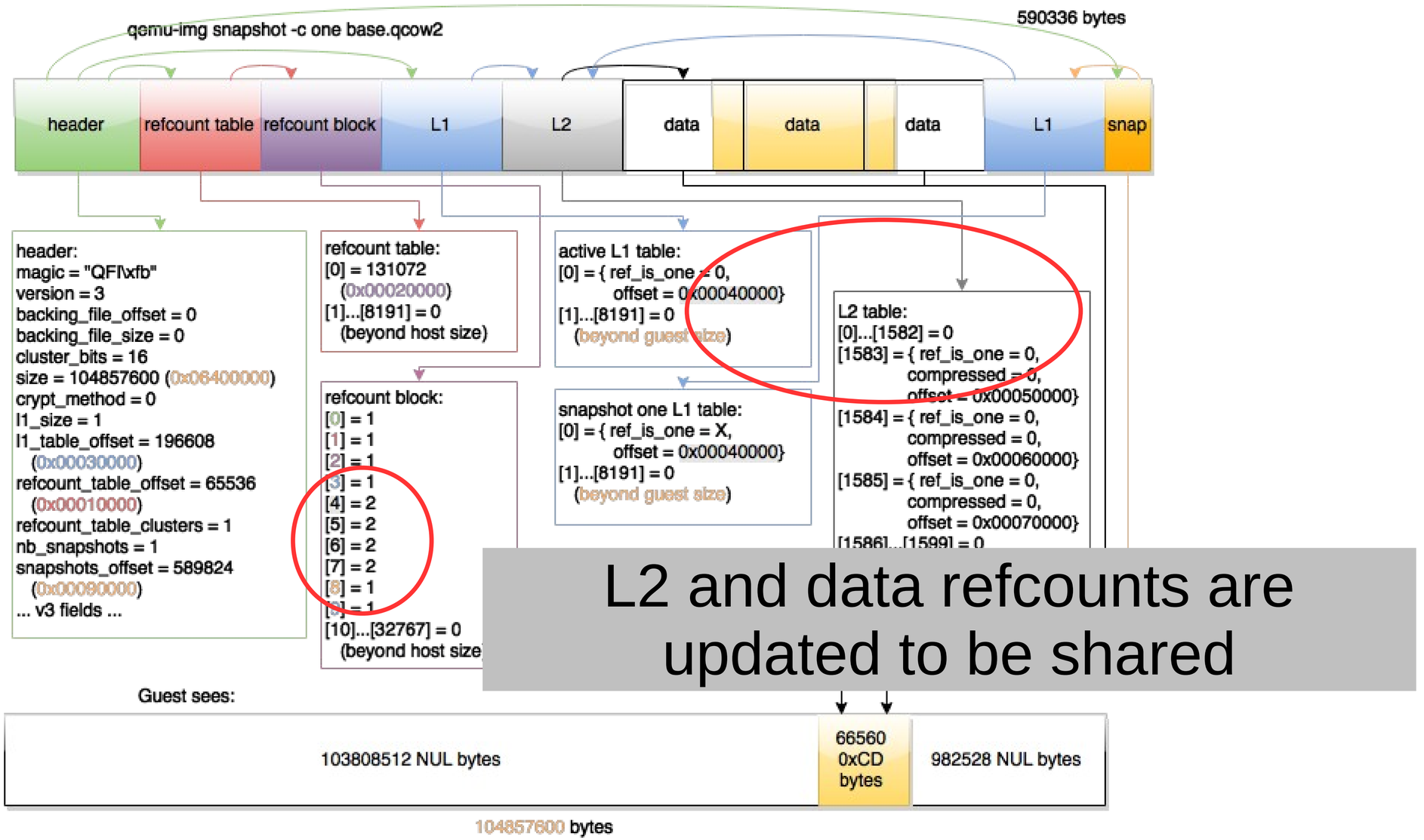


Snapshot table added, which points to copied L1 table

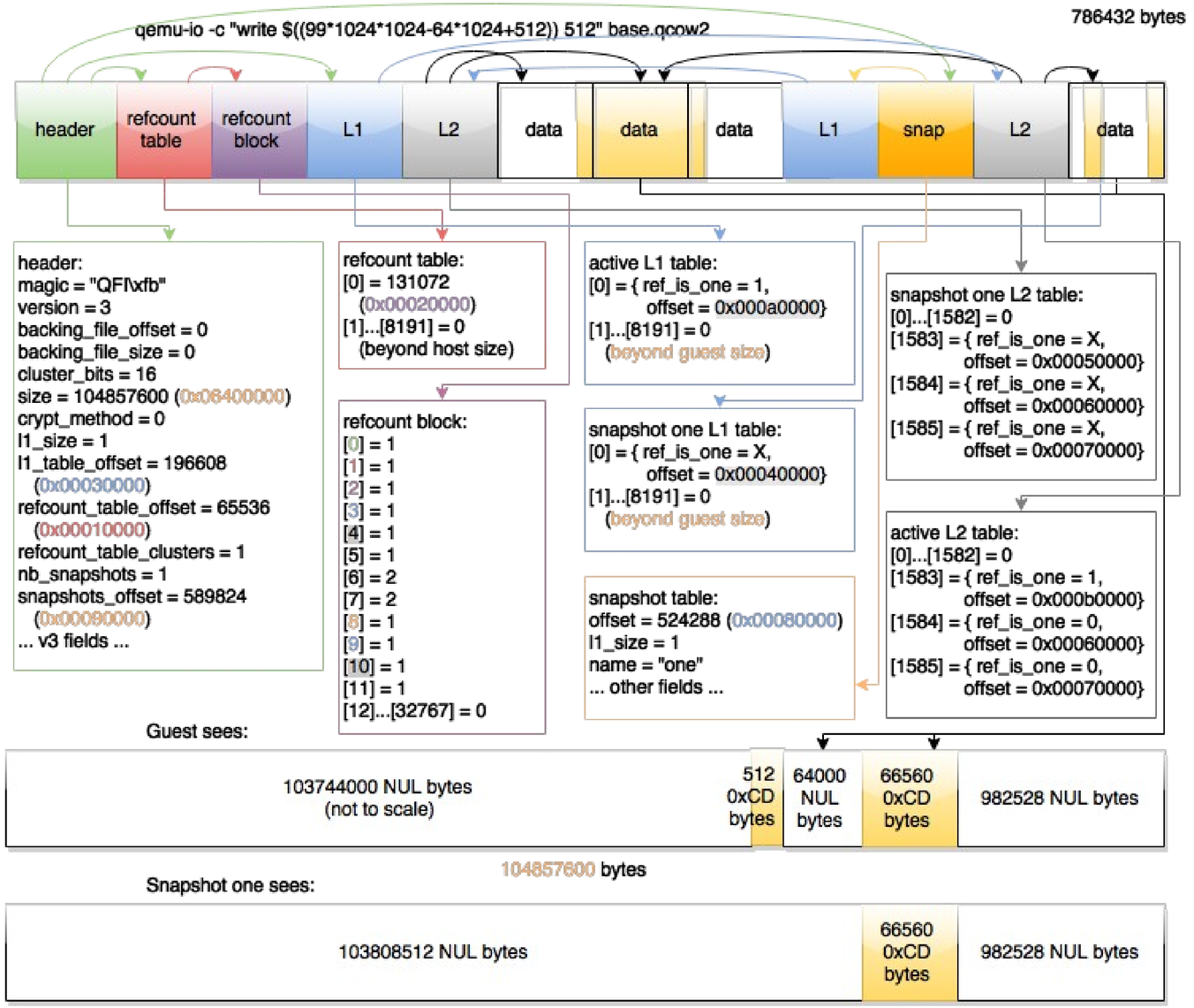
Create an internal snapshot



Write more guest data

qemu-io -c “write $((99*1024*1024-64*1024+512)) 512” base.qcow2

Write more guest data



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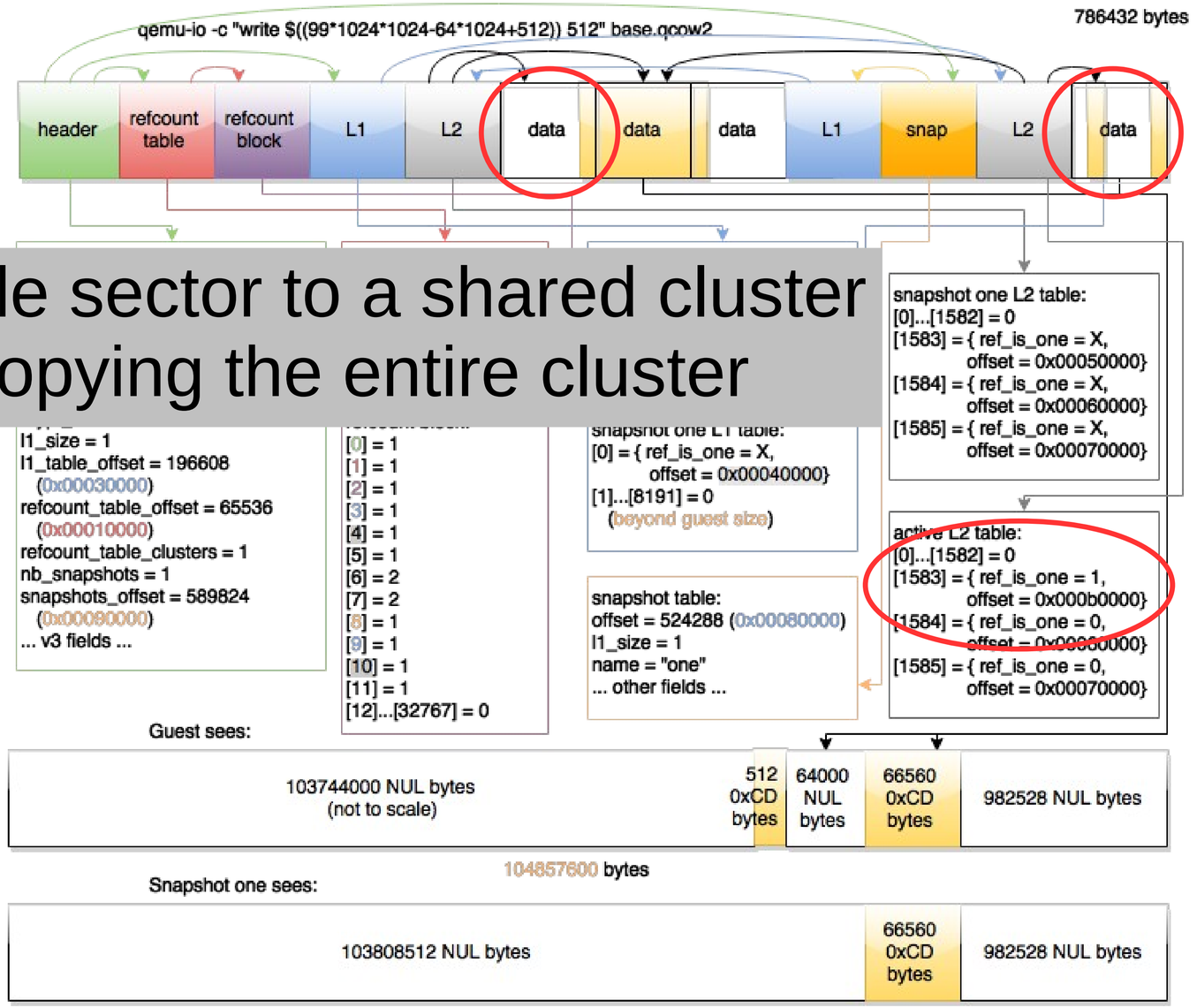
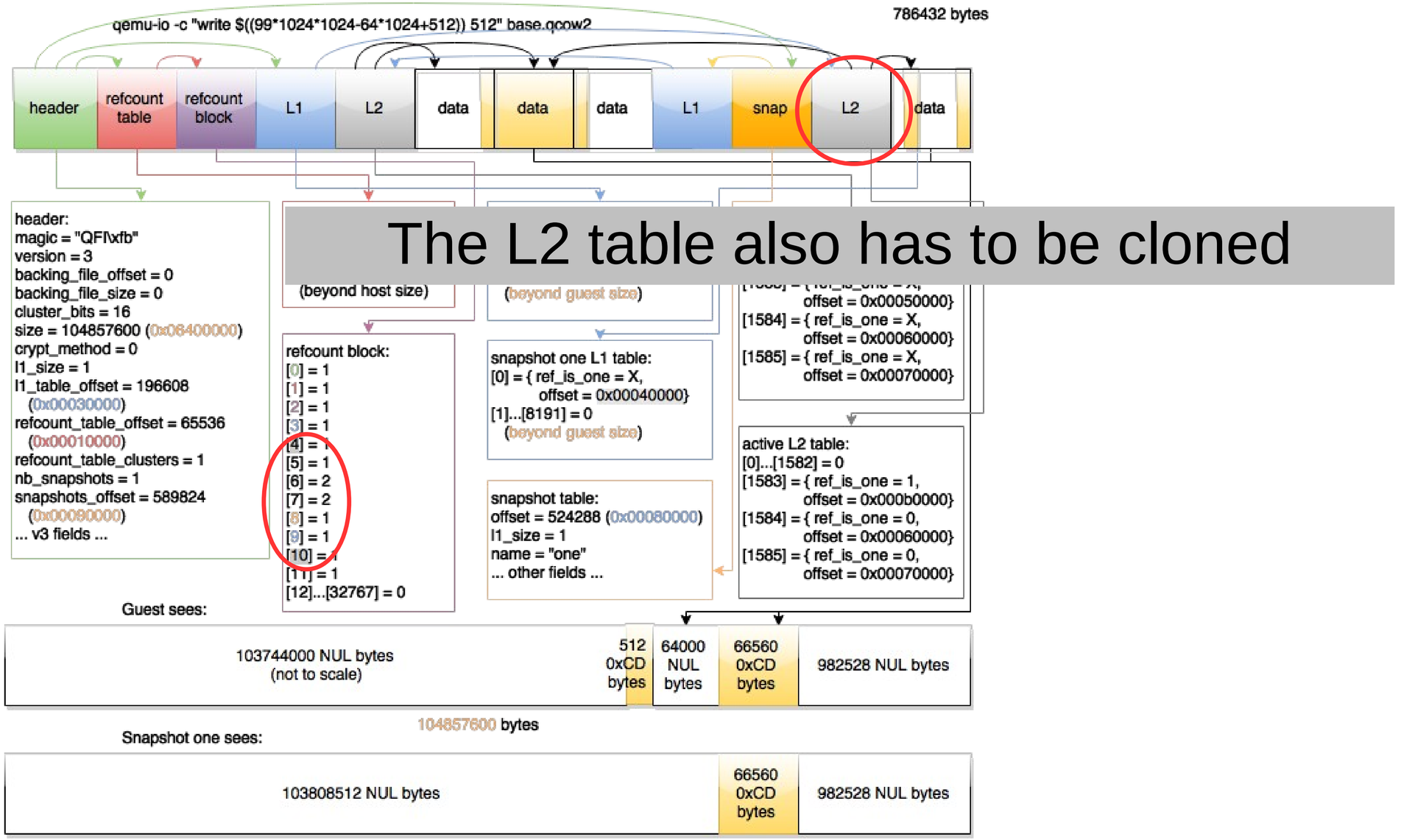


Writing a single sector to a shared cluster requires copying the entire cluster

Write more guest data



The L2 table also has to be cloned

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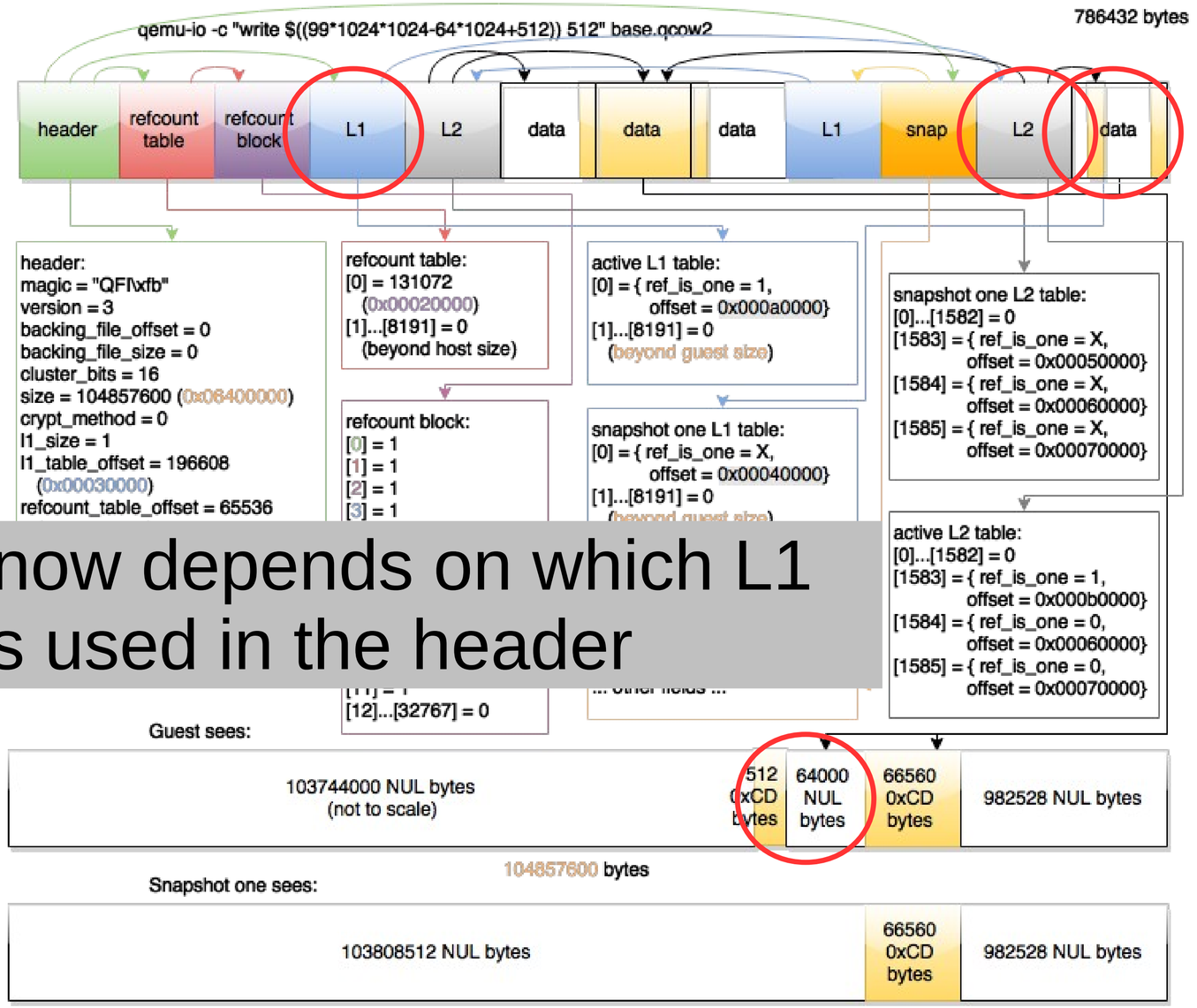

Guest view now depends on which L1 table is used in the header

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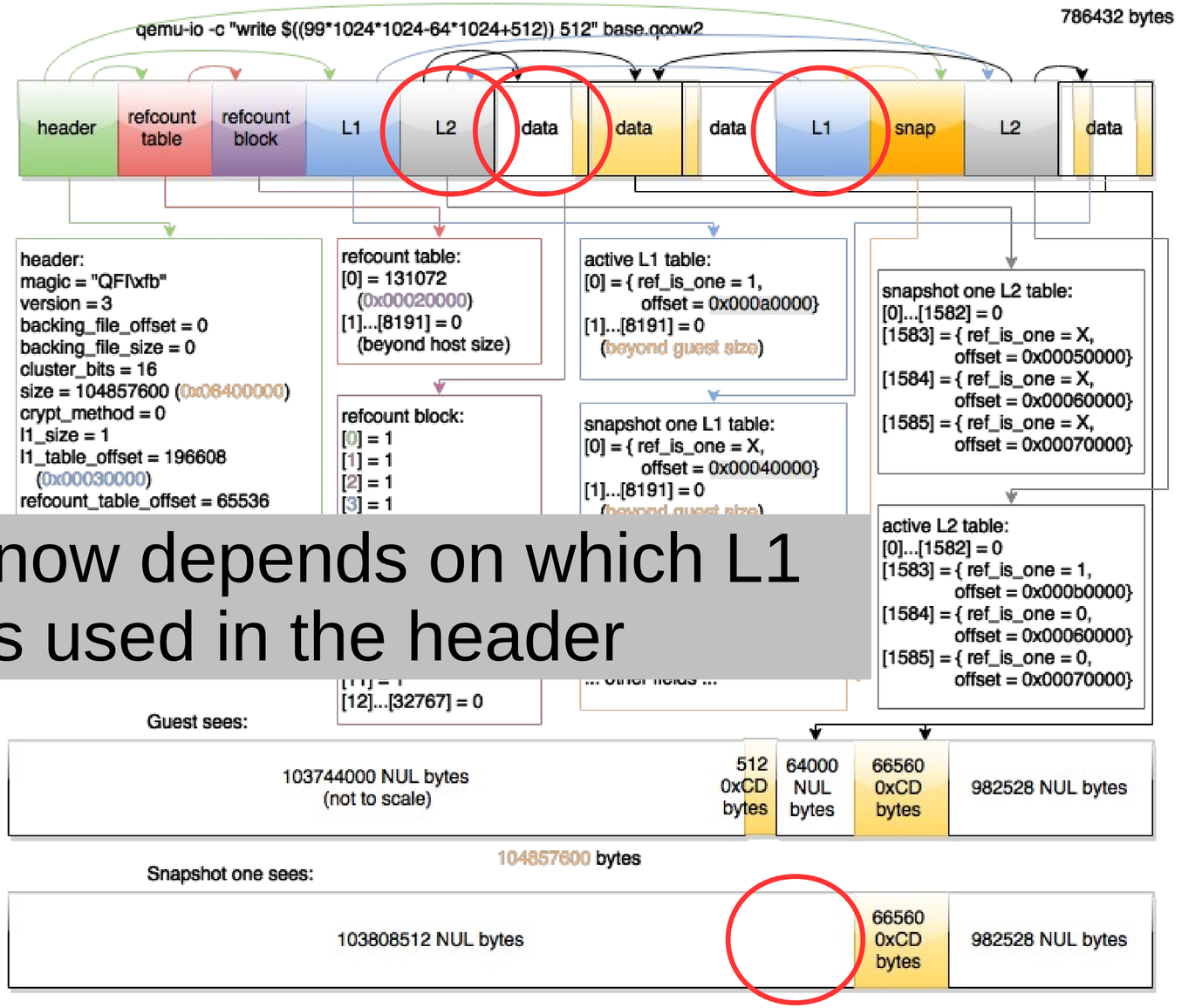
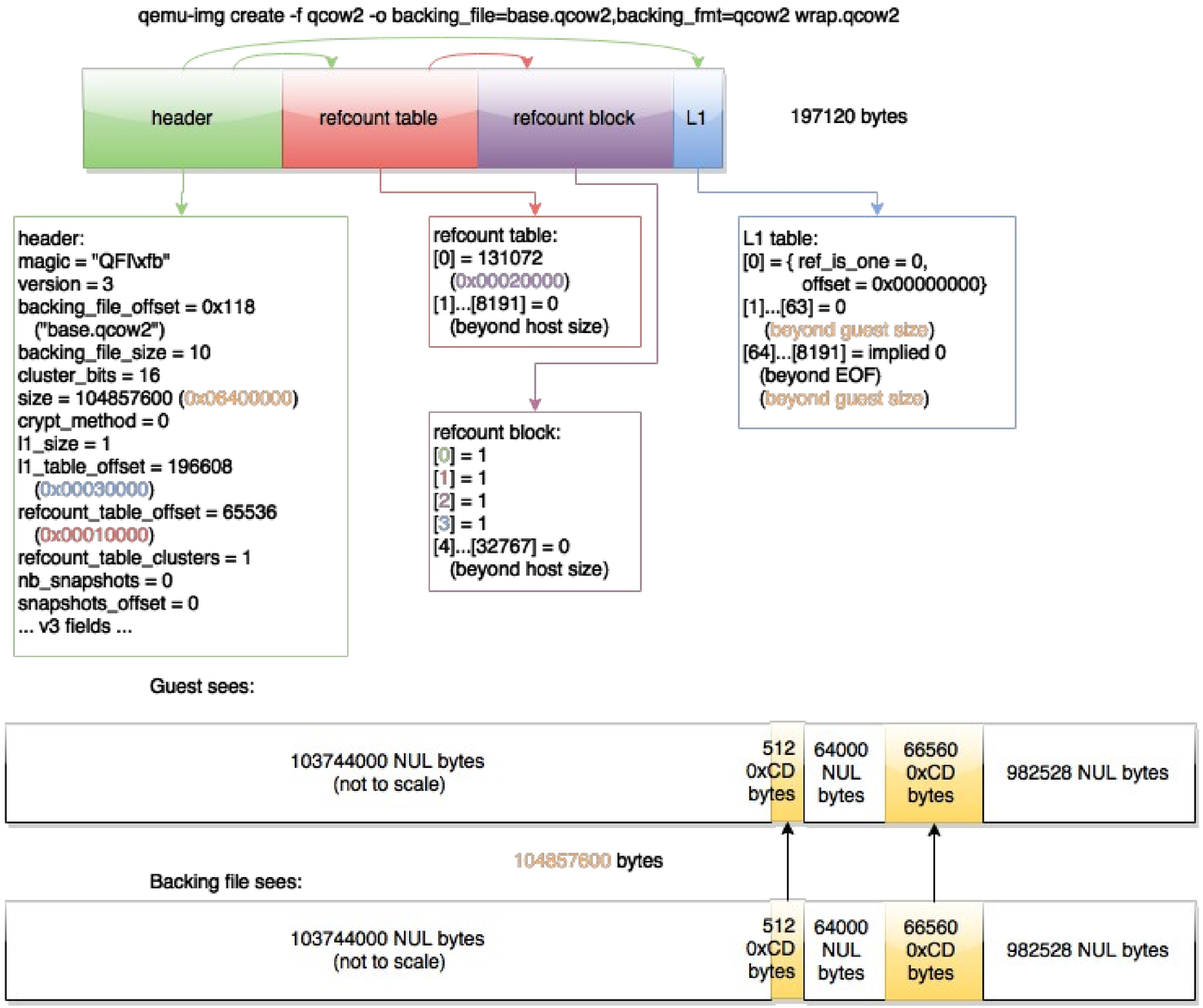


Guest view now depends on which L1 table is used in the header

Create an external snapshot

qemu-img create -f qcow2 -o backing_file=base.qcow2,backing_fmt=qcow2 wrap.qcow2

Create an external snapshot



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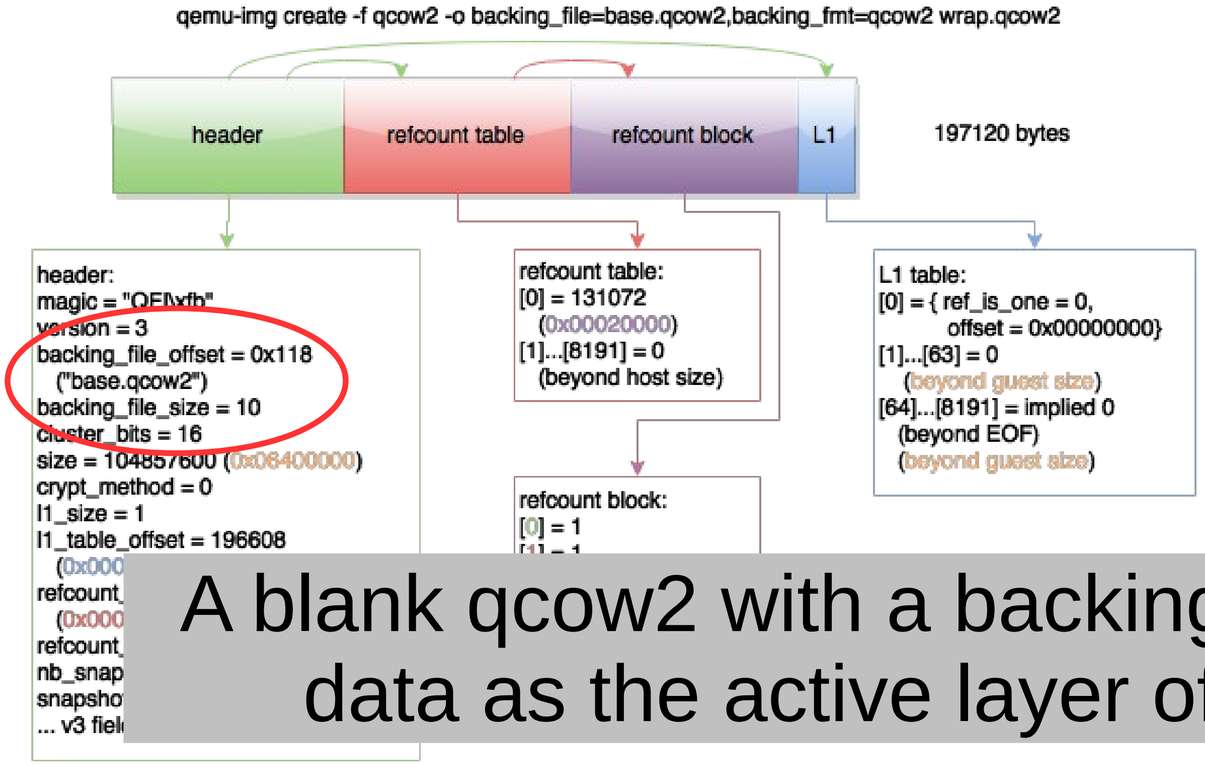
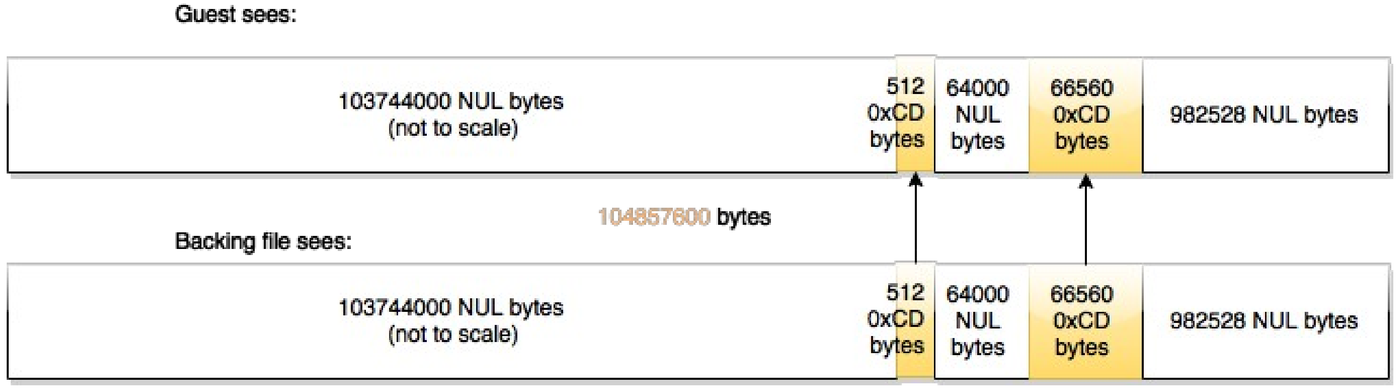


A blank qcow2 with a backing file sees the same data as the active layer of the backing file



Write even more guest data

qemu-io -c “write -P 0xff $((99*1024*1024-63*1024)) $((64*1024))” wrap.qcow2

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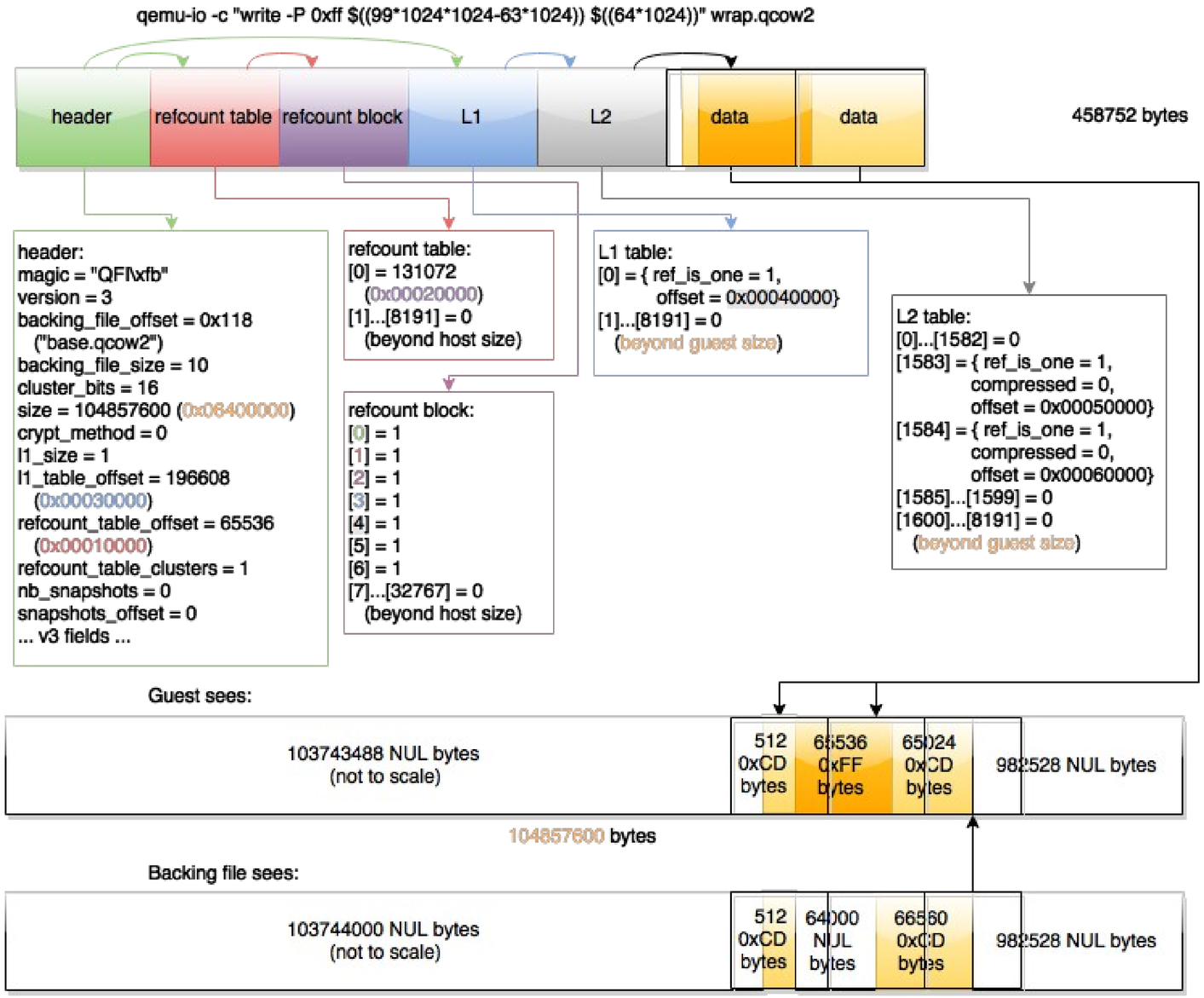

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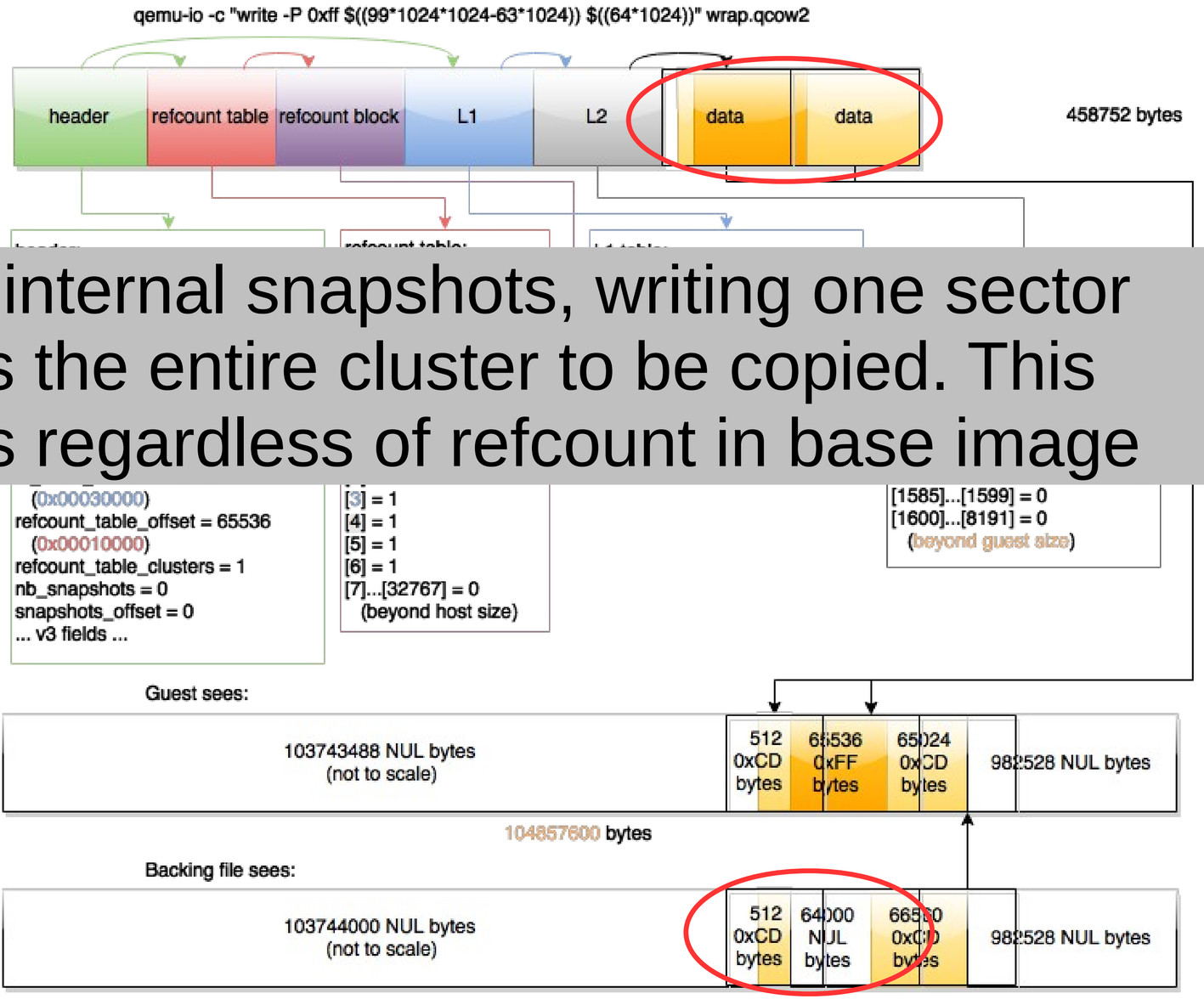
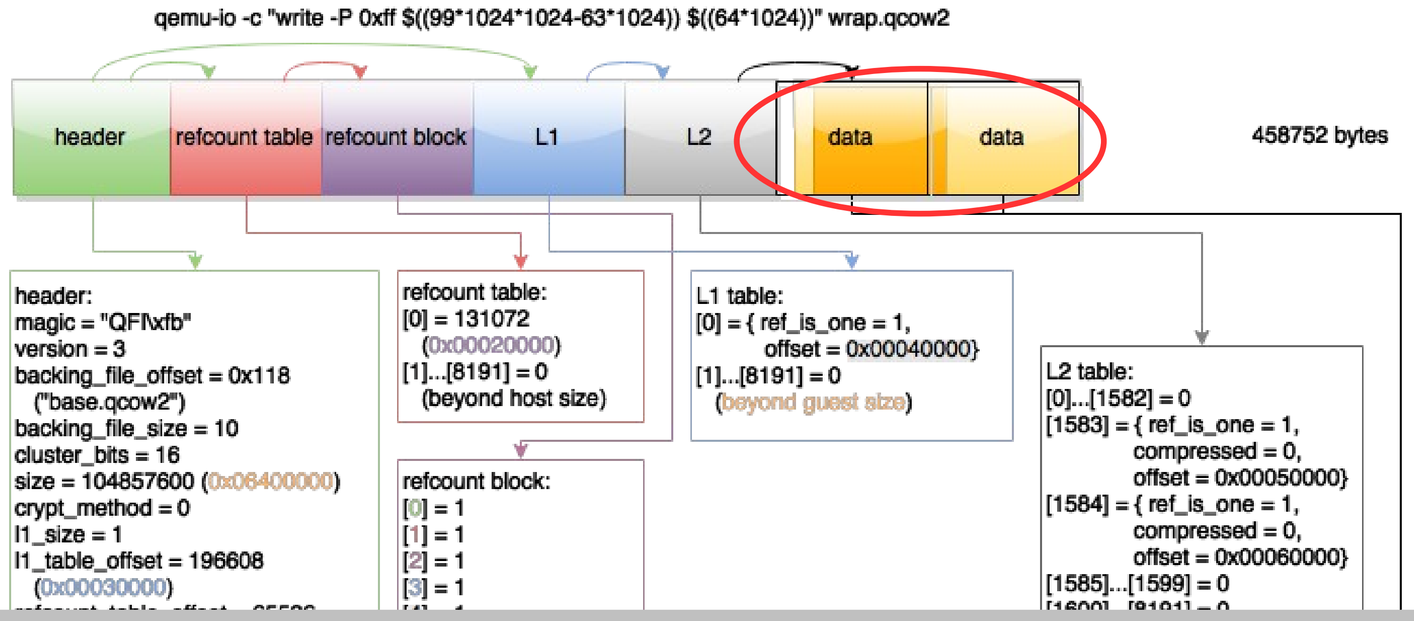
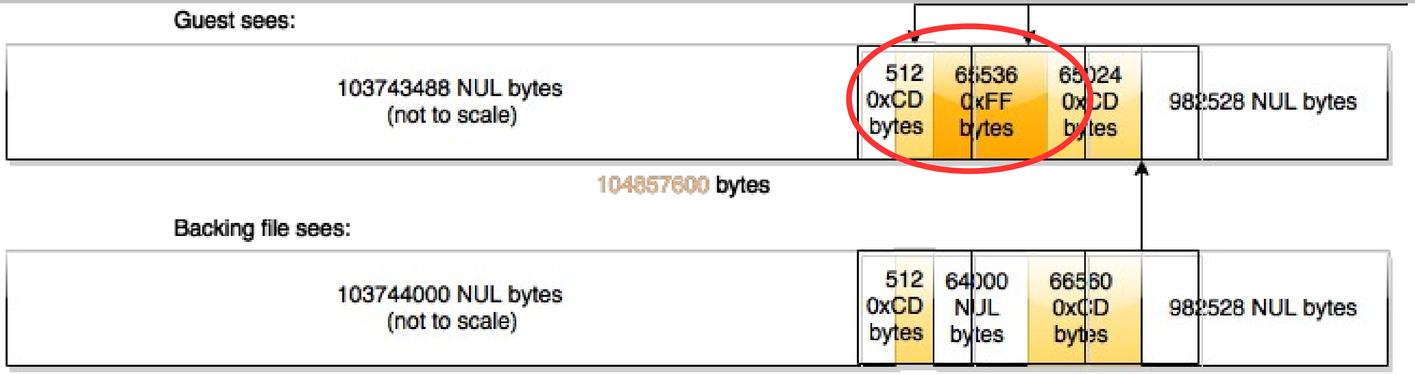


As with internal snapshots, writing one sector causes the entire cluster to be copied. This happens regardless of refcount in base image

Write even more guest data



Reading a cluster finds the first file from the top of the chain that contains the cluster



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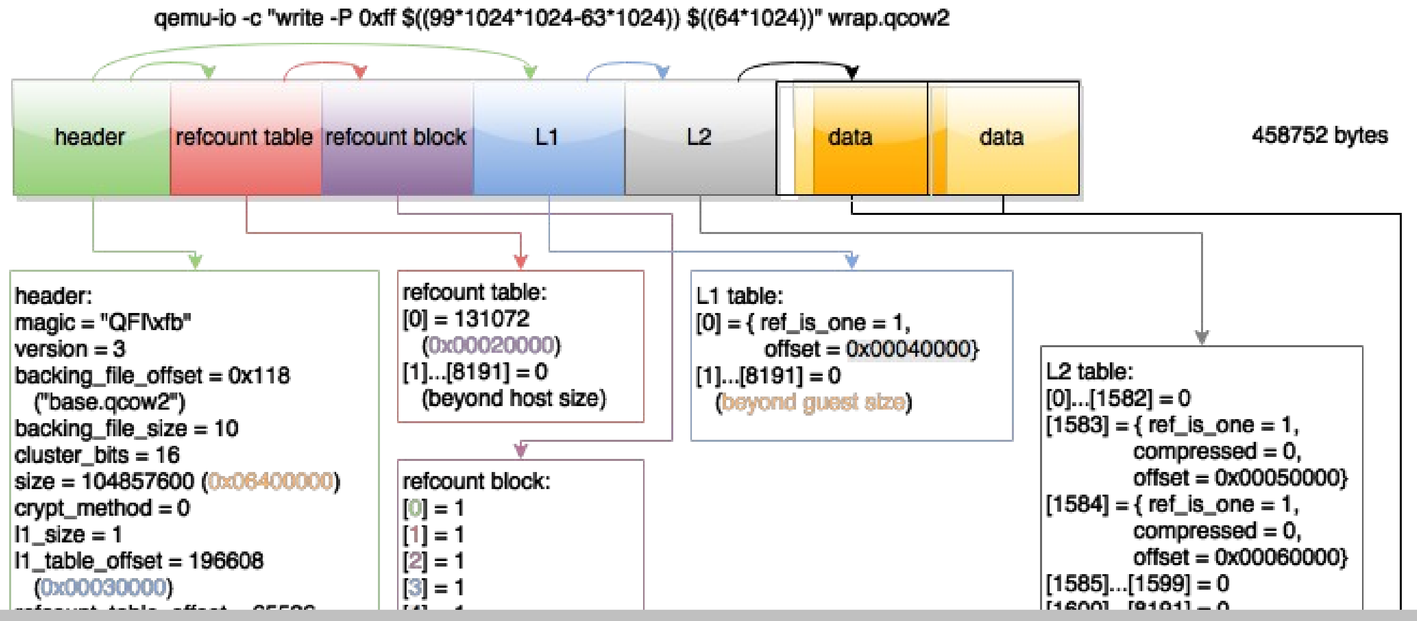

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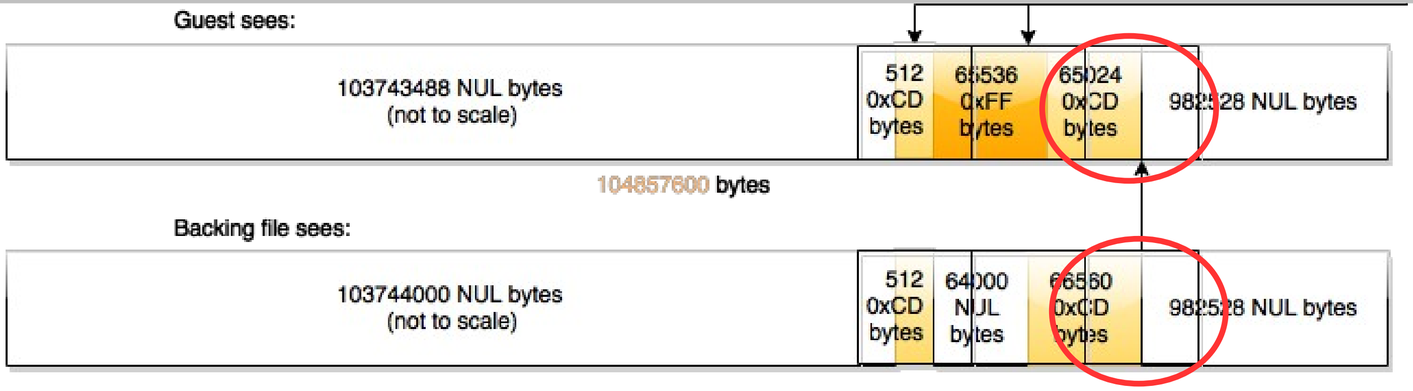


Part II

Backing Chains

Internal Snapshots

Pros

- Single file contains everything, optionally including live VM state
- Reverting is easy and supported by libvirt
- No I/O penalties to active state

Cons

- Cannot read snapshot while image is in use by guest; does not allow live backups
- QMP internal snapshot management is inefficient
- qcow2 file size can greatly exceed guest size
- No defragmentation

External Snapshots

Pros

- Live backups and storage migration are easy
- Optimized QMP performance
- Building blocks can be combined in a number of useful patterns
- Great for cluster provisioning from a common base install

Cons

- Deleting snapshots is trickier, libvirt currently delegates to manual qemu-img usage
- Multiple files to track
- I/O overhead in long chains

Backing Chain diagrams

- Notation “A ← B” for “image A backs image B”
- More recent wrappers listed on the right (also called top)
- The chain we created earlier is represented as:
  - base.qcow2 ← wrap.qcow2
- 'qemu-img map' can show where clusters live

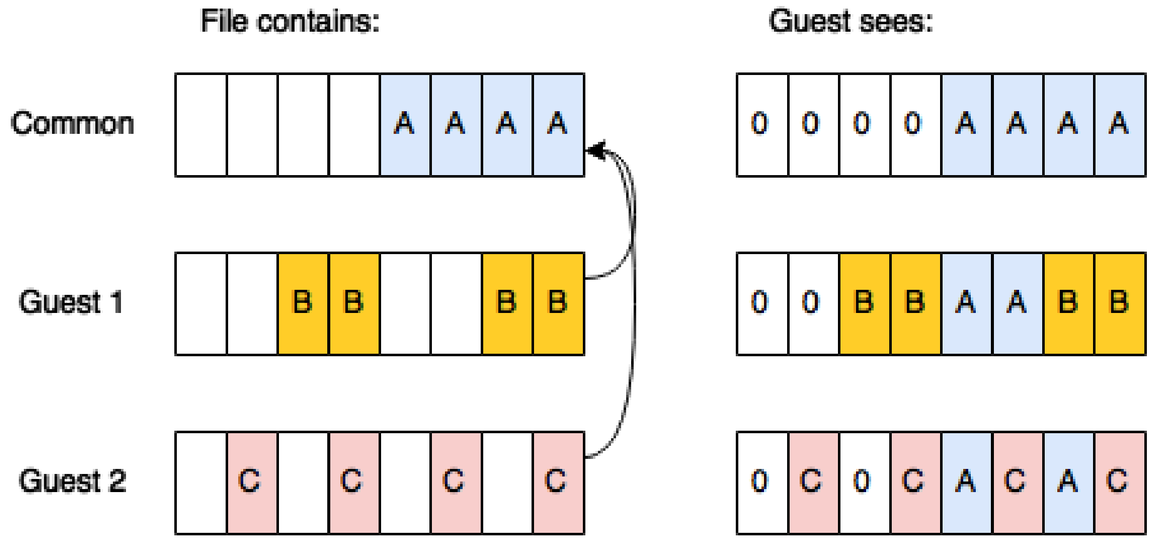
```
$ qemu-img map wrap.qcow2
Offset    Length  Mapped to File
0x62f0000 0x20000 0x50000   wrap.qcow2
0x6300000 0x10000 0x70000   base.qcow2
```

Points in time vs. file names

- Given the chain “A ← B ← C”, we have 2 points in time and an active layer
- Point 1: Guest state when B was created, contained in file A
- Point 2: Guest state when C was created, contained in A+B
- Active layer: Current guest state, contained in A+B+C
- Be careful with naming choices:
  - Naming a file after the time it is created is misleading – the guest data for that point in time is NOT contained in that file
  - Rather, think of files as a delta from the backing file

Backing files must not change

- Qcow2 block operations are NOT a substitute for overlayfs
- Observe what happens if a common backing file is modified
- Data seen by dependent images is now different from any state ever possibly observed by the guest, also different from base



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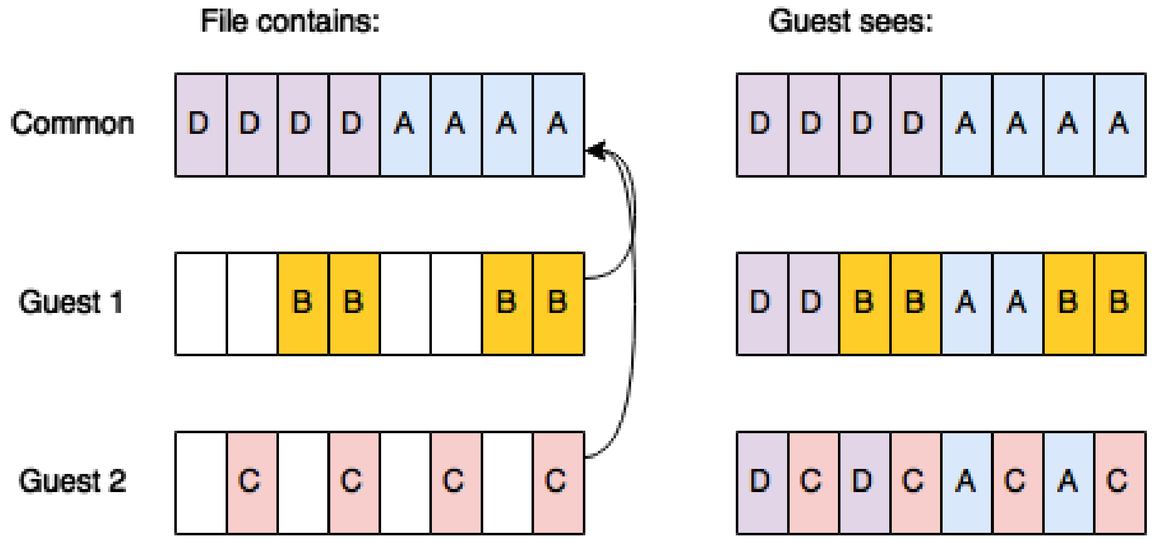
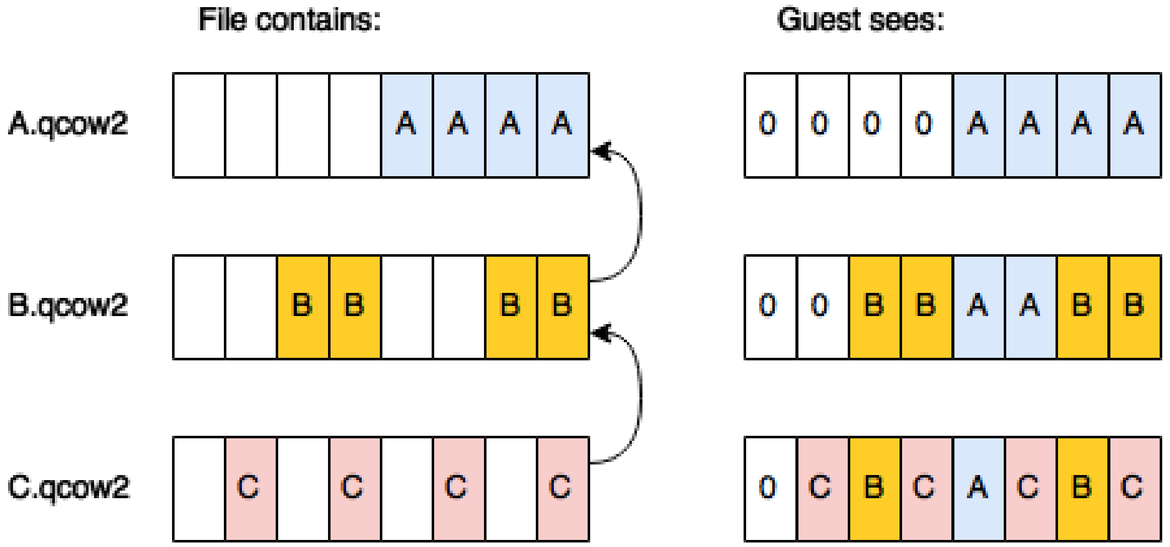


Block-stream primitive (“pull”)

- Starting with “A ← B ← C”, copy/move clusters towards the top
- Additionally, rewrite backing data to drop now-redundant files
- qemu 2.4 limited to top image (A+B into C, or B into C), but qemu 2.5 will add intermediate streaming (A into B)
- Always safe, restartable



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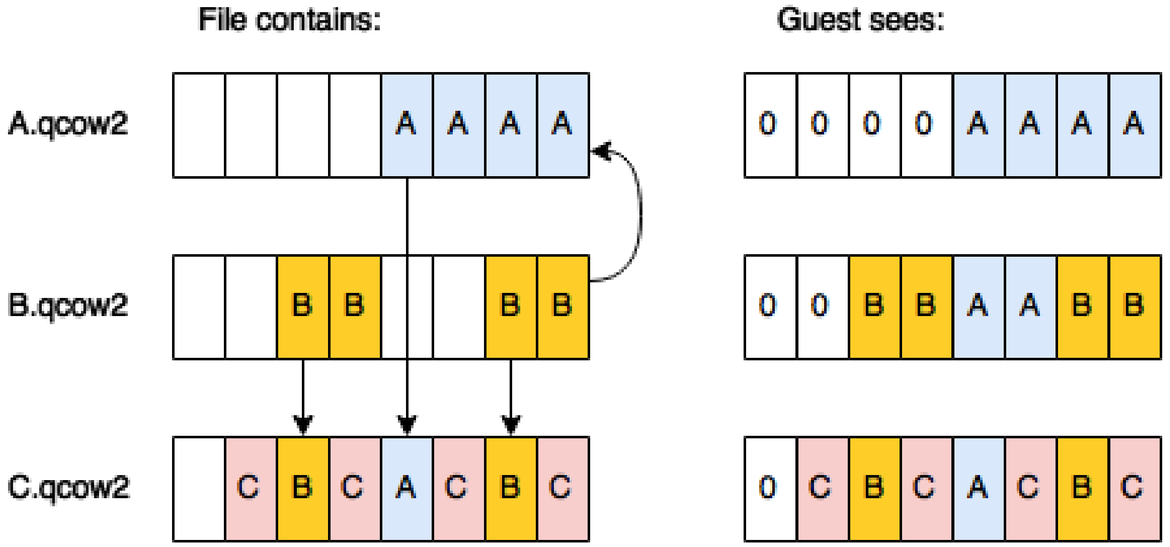

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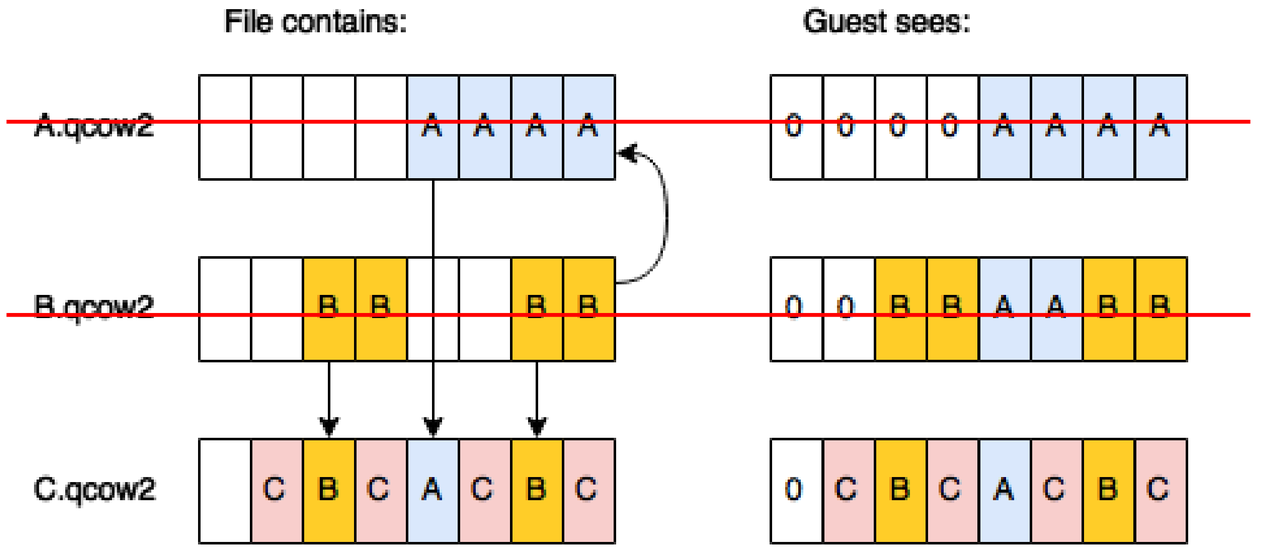

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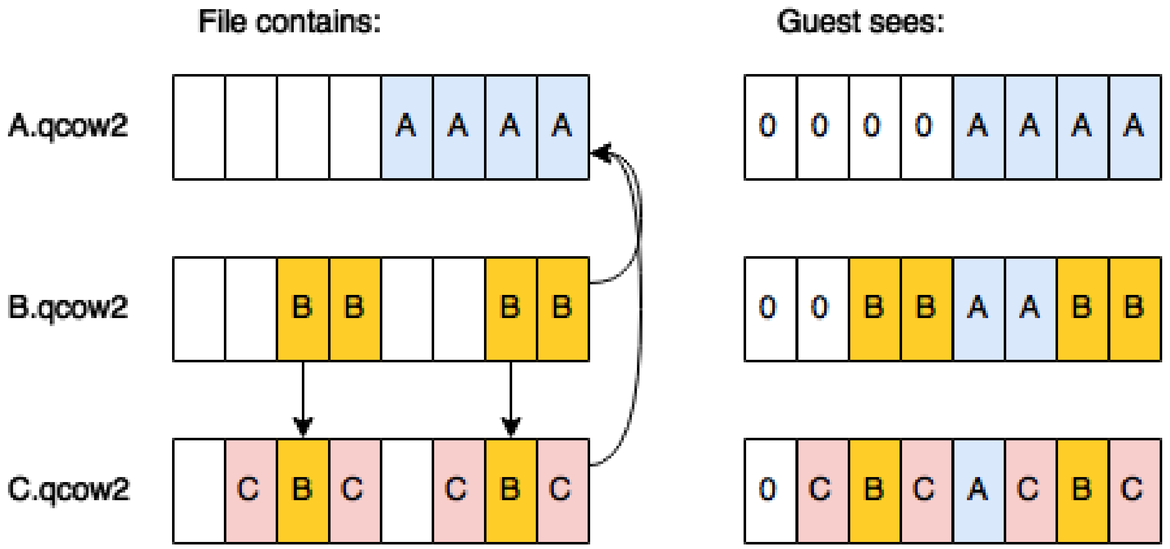

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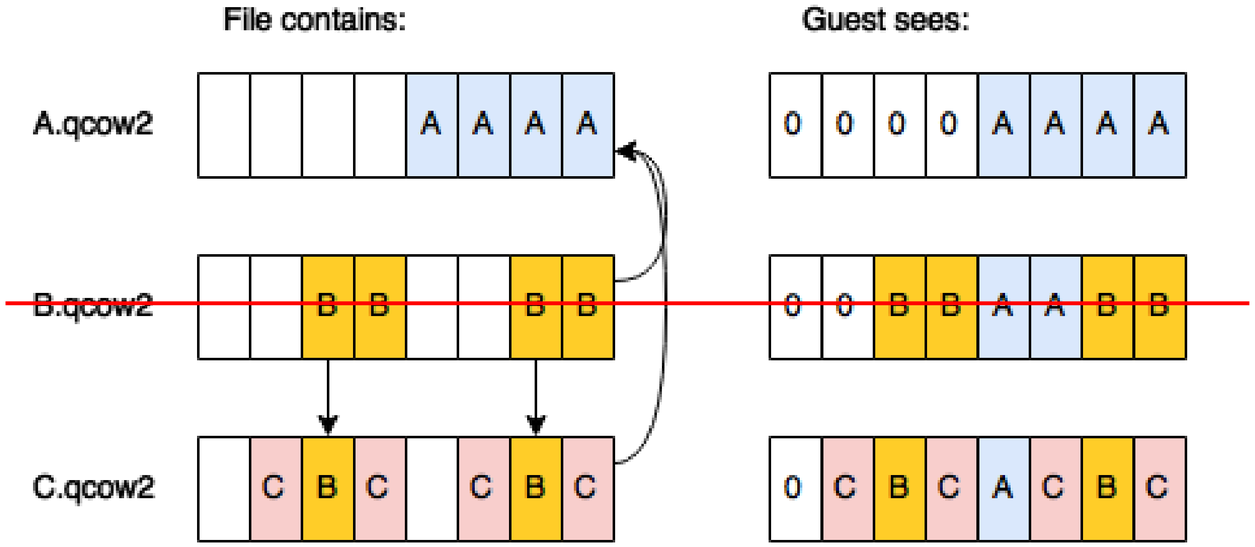

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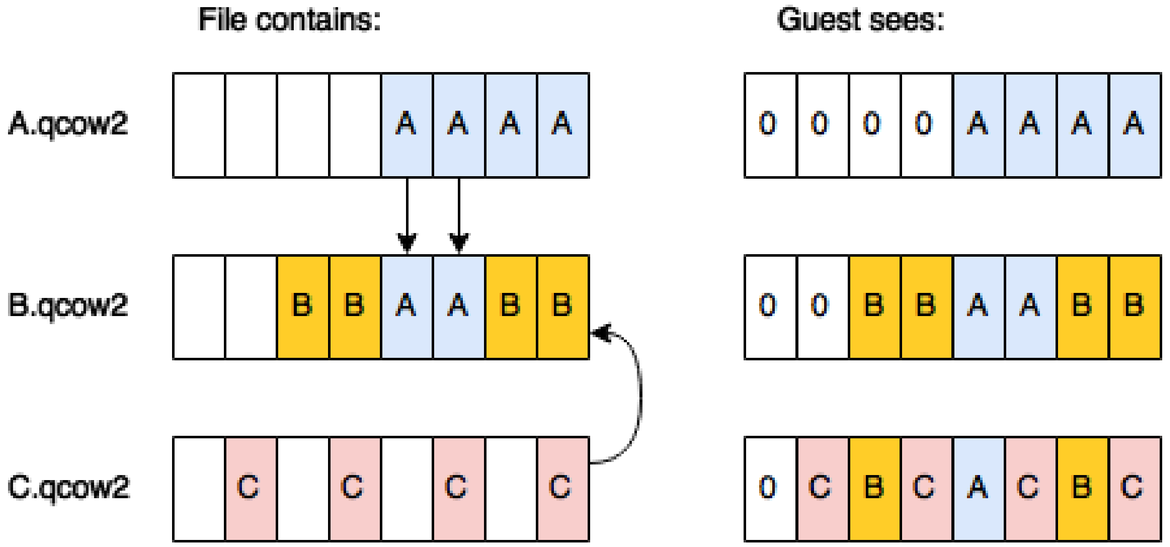

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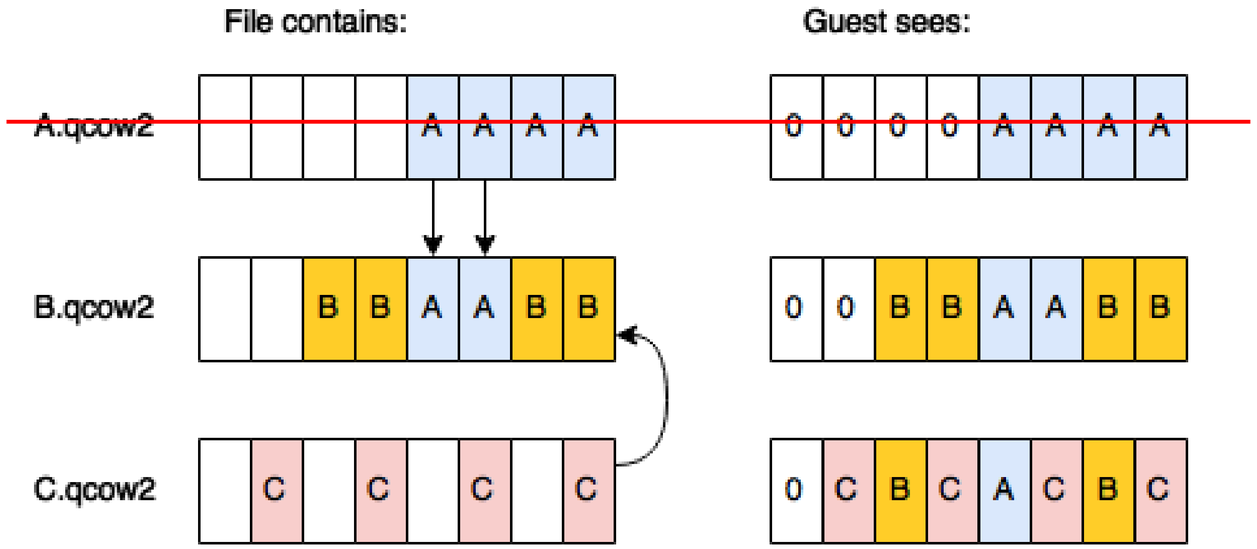

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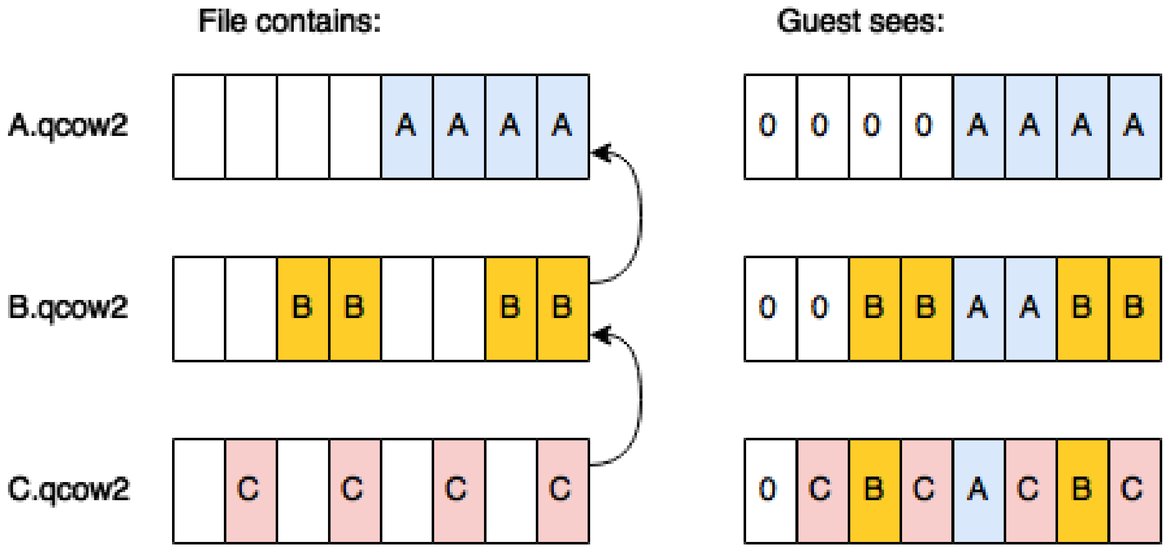

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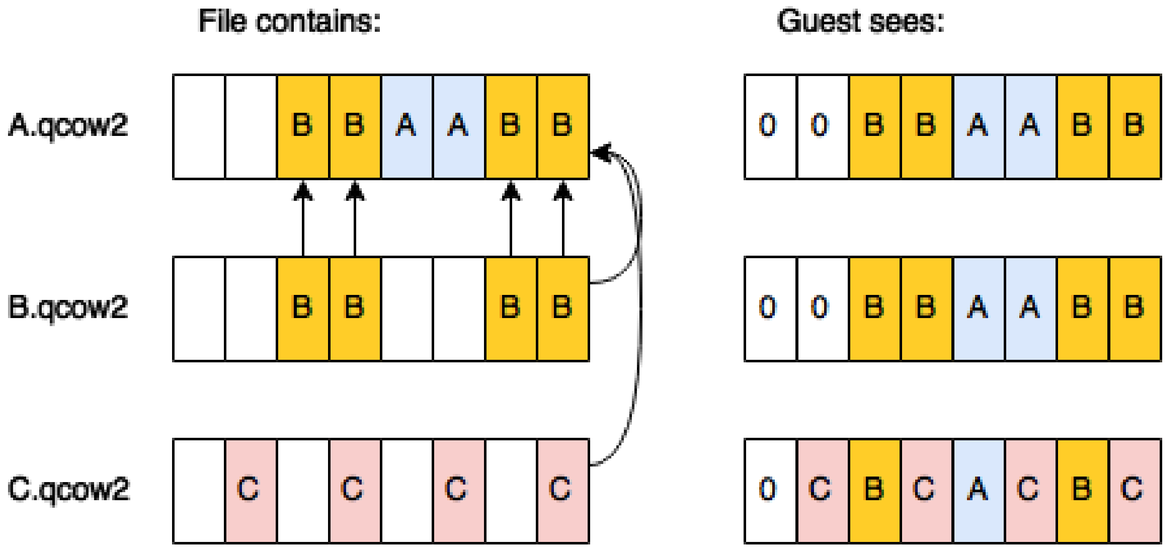

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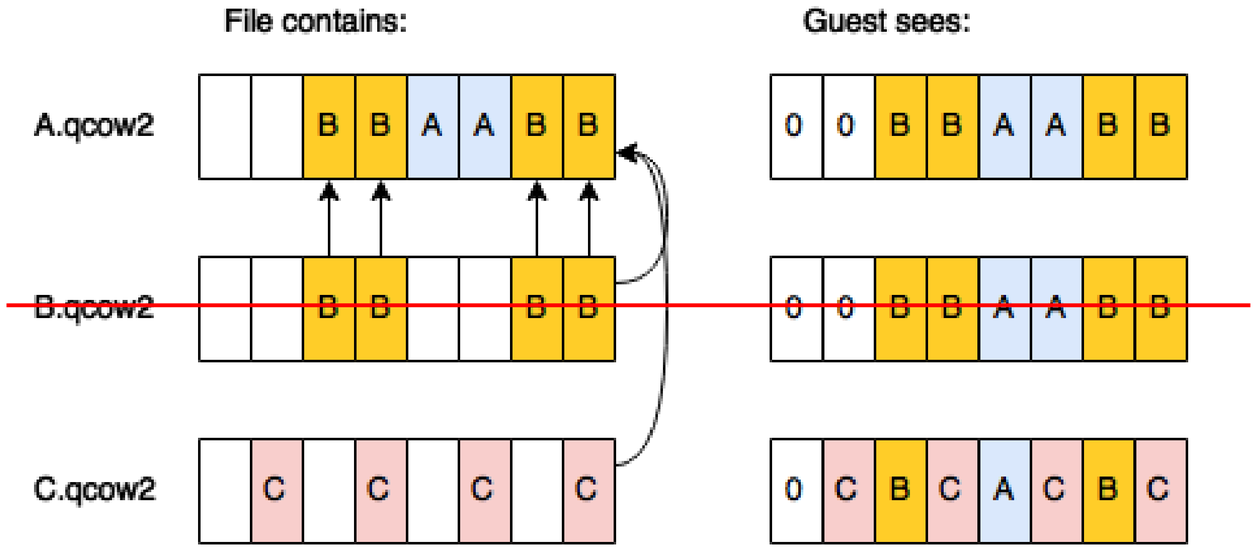

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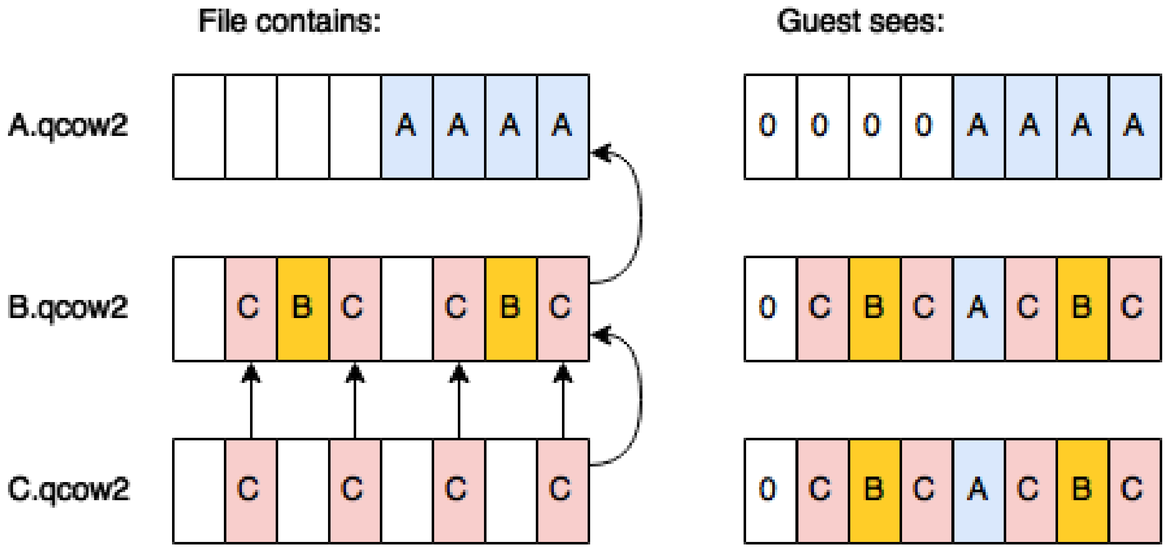

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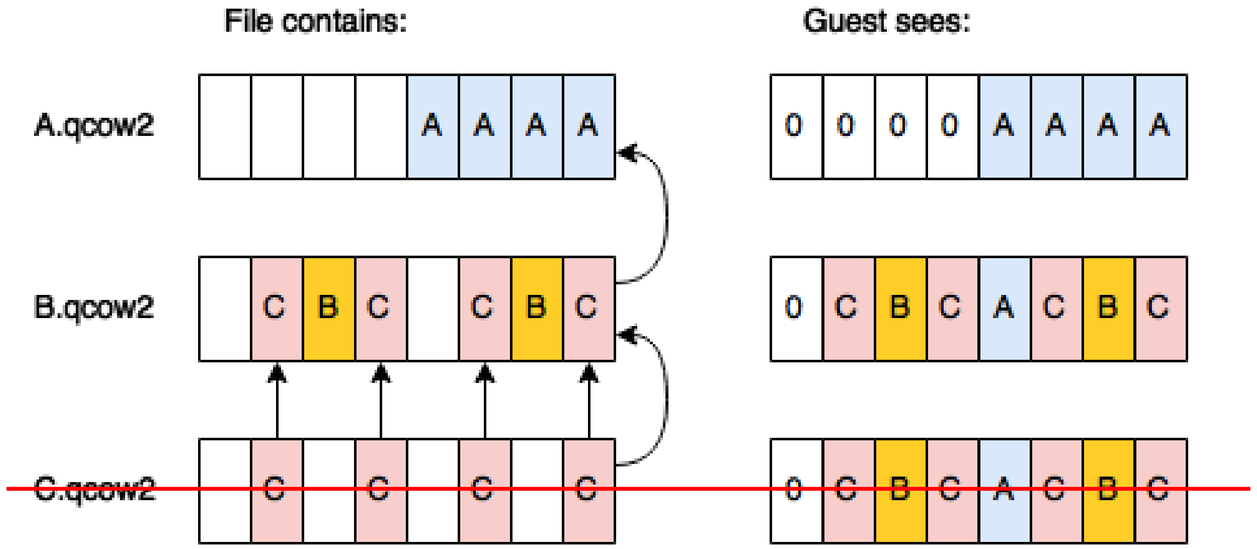

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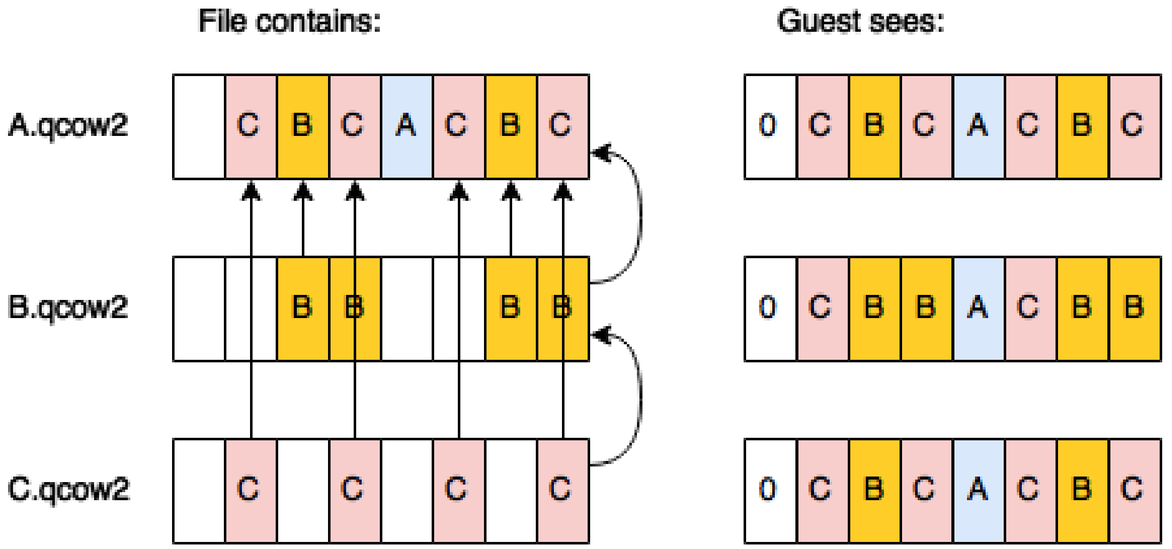

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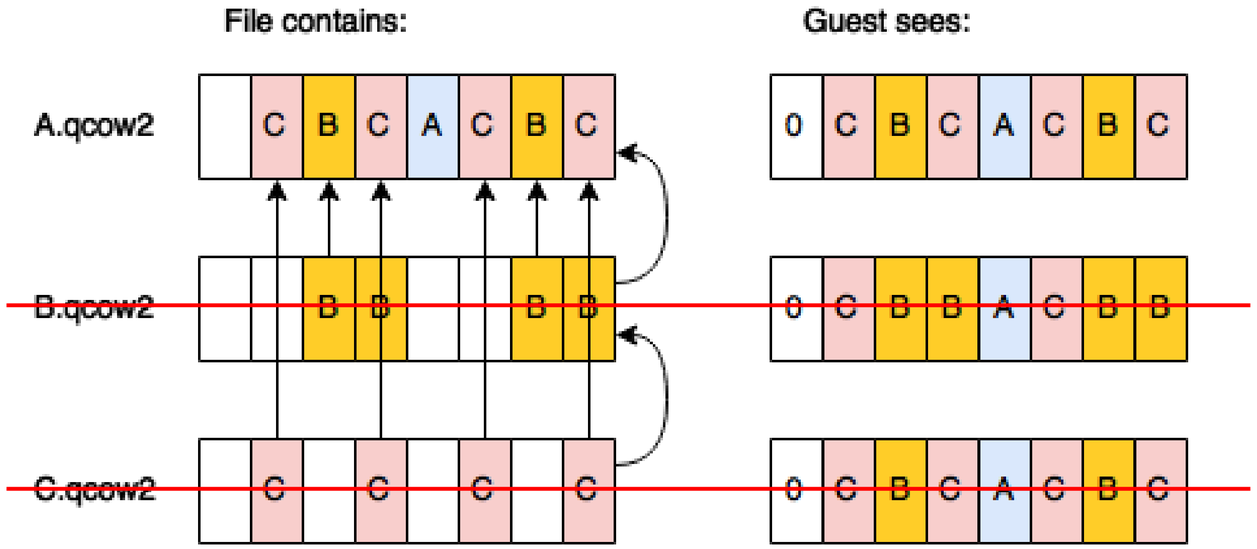

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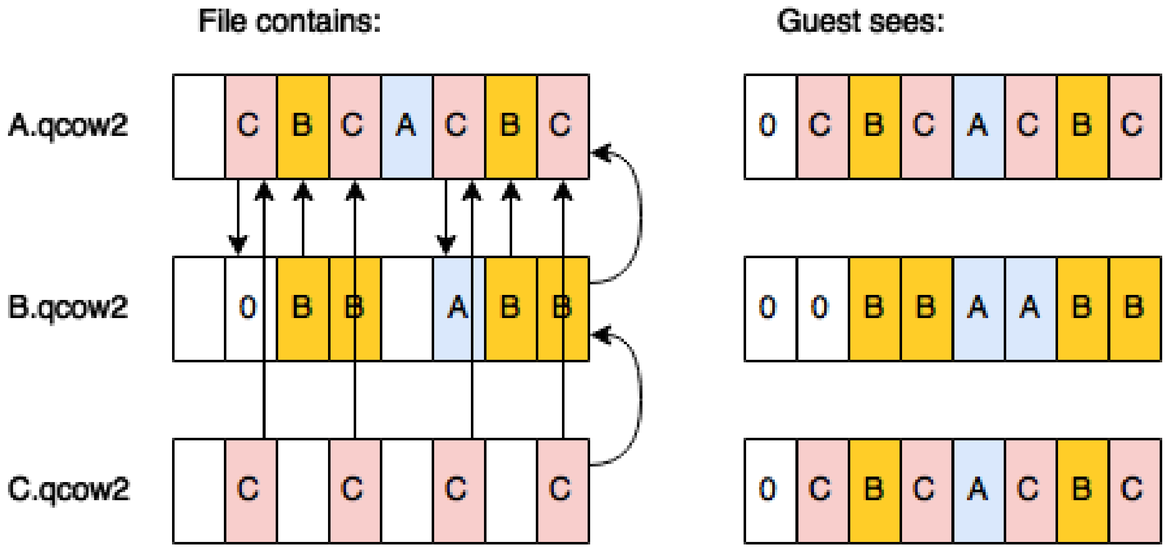

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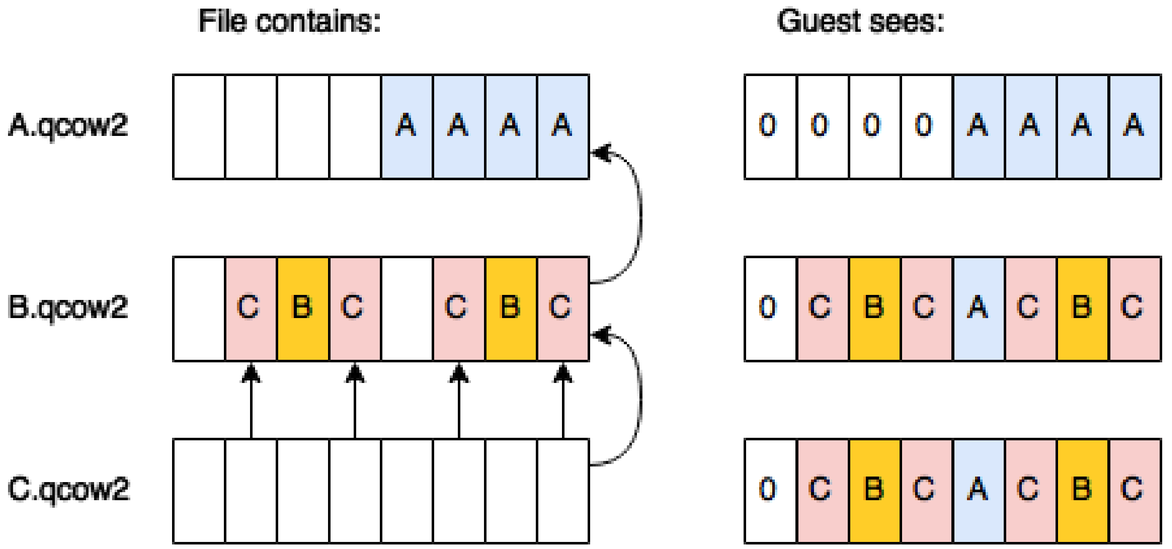

Which operation is more efficient?

- Consider removing 2nd point in time from chain “A ← B ← C ← D”
- Can be done by pulling B into C
  - Creates “A ← C' ← D”
- Can be done by committing C into B
  - Creates “A ← B' ← D”
- But one direction may have to copy more clusters than the other
- Efficiency also impacted when doing multi-step operations (deleting 2+ points in time, to shorten chain by multiple files)

Drive-mirror primitive (“copy”)

- Copy all or part of one chain to another destination
- Destination can be pre-created, as long as the data seen by the guest is identical between source and destination when starting
  - Empty qcow2 file backed by different file but same contents
- Point in time is consistent when copy is manually ended
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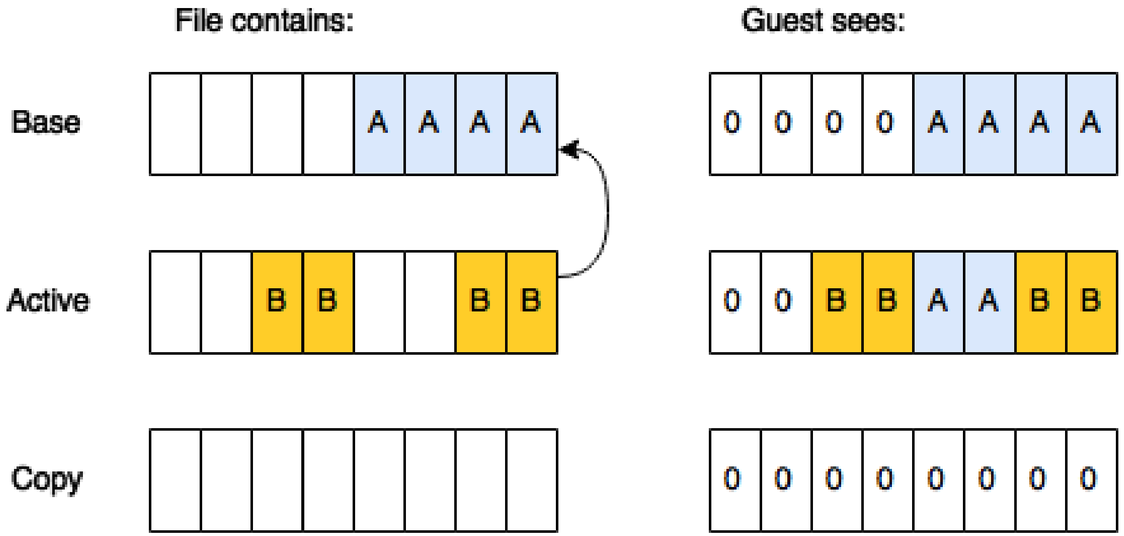

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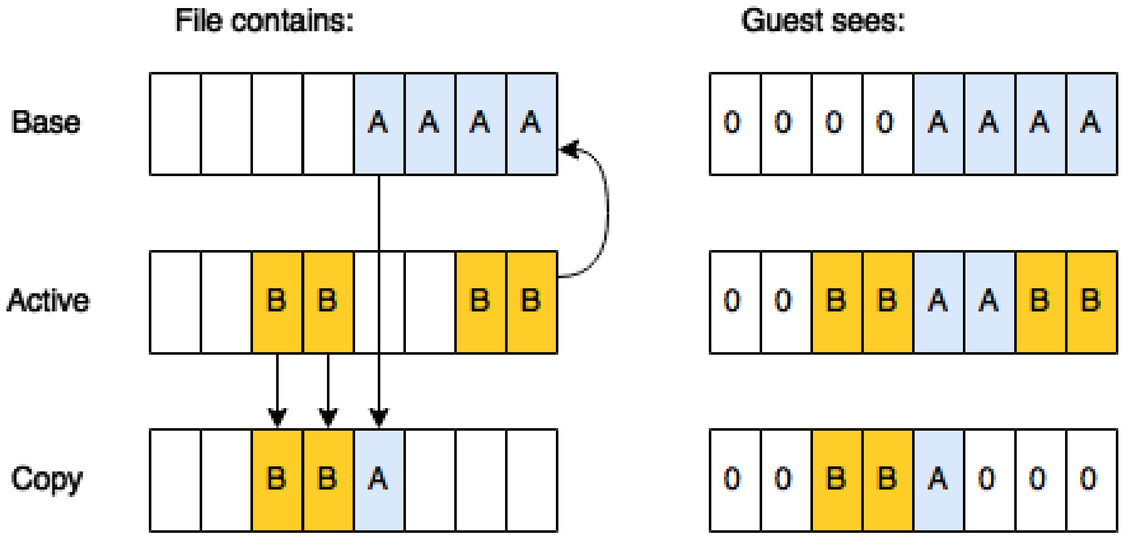

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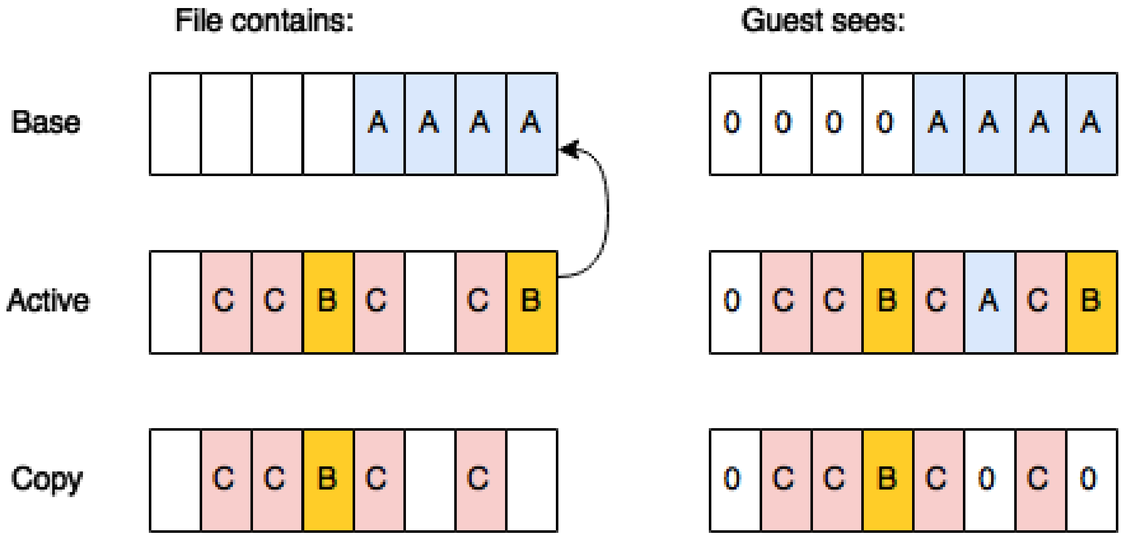

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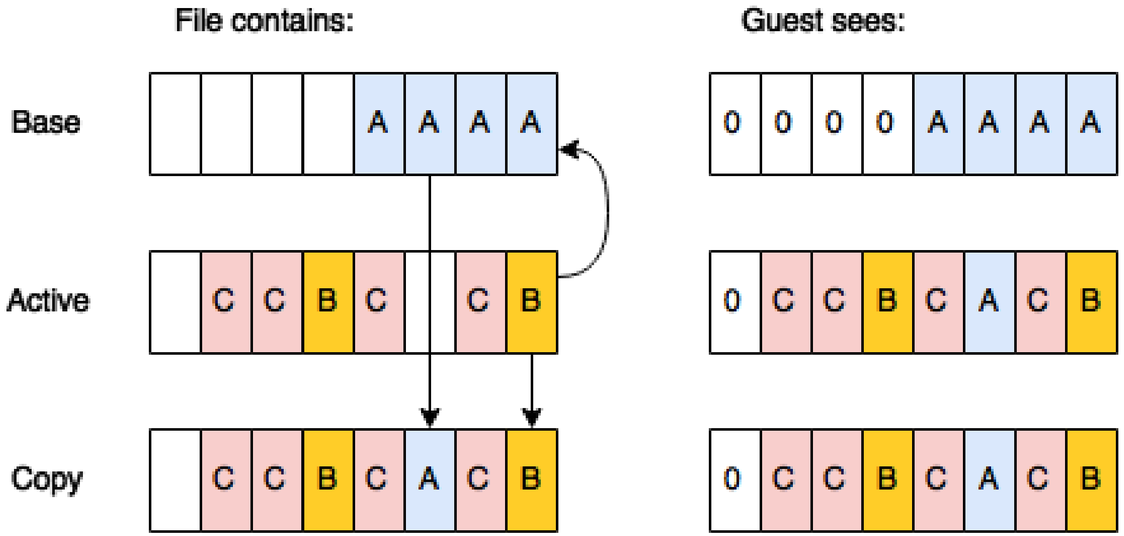

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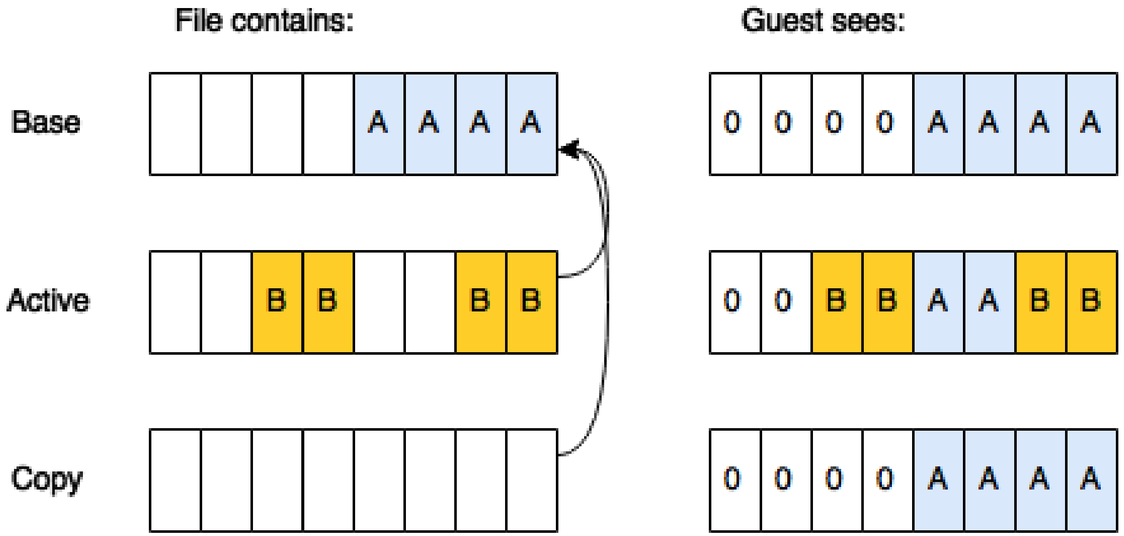

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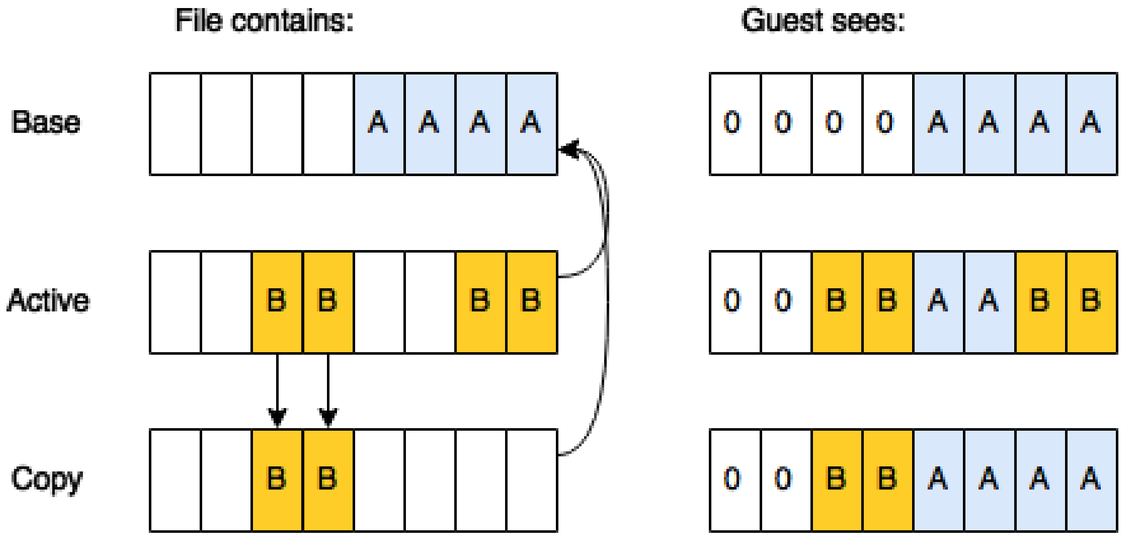

redhat.

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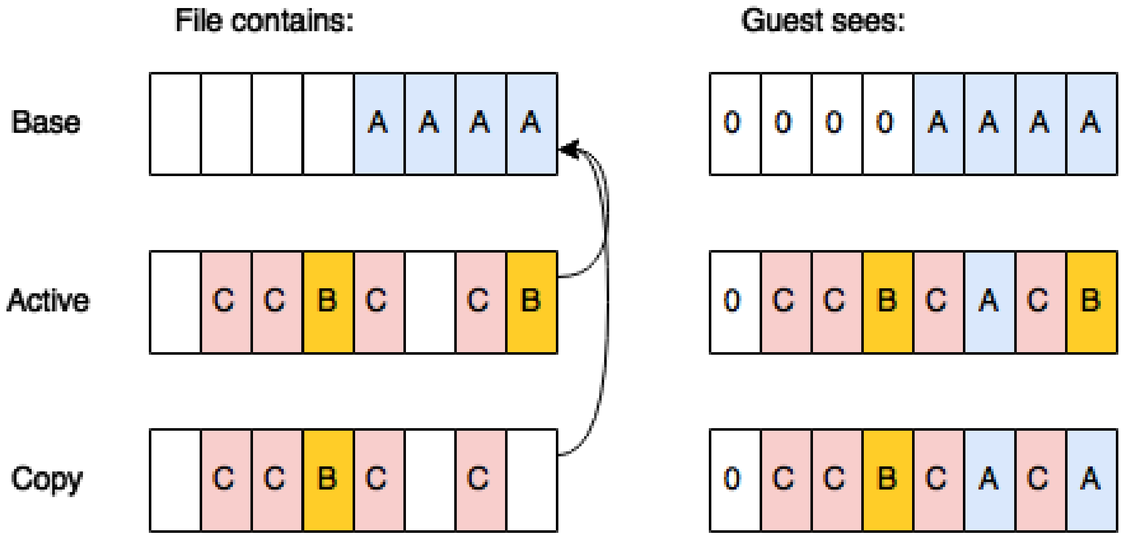

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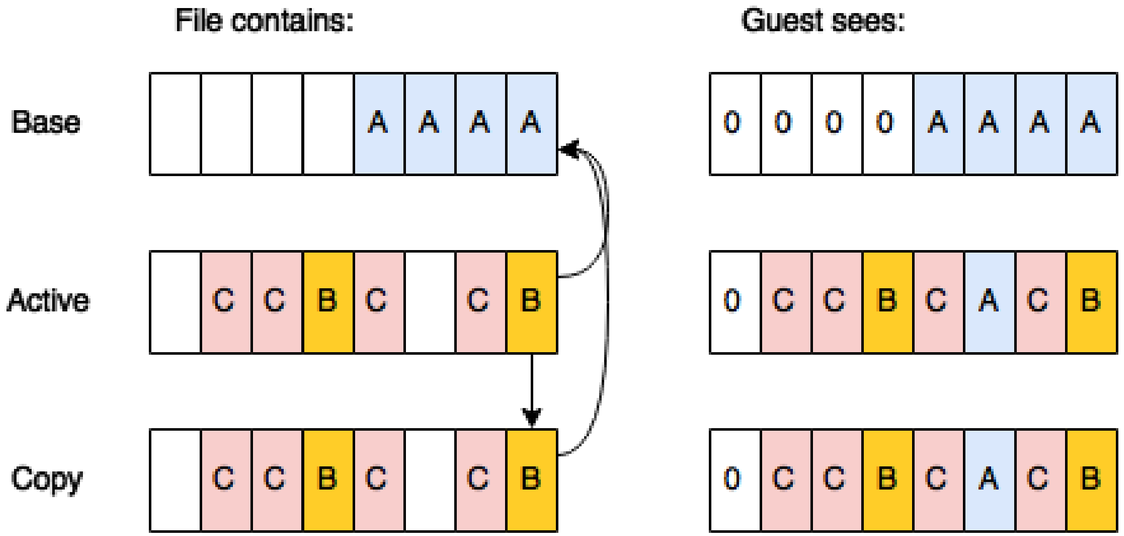
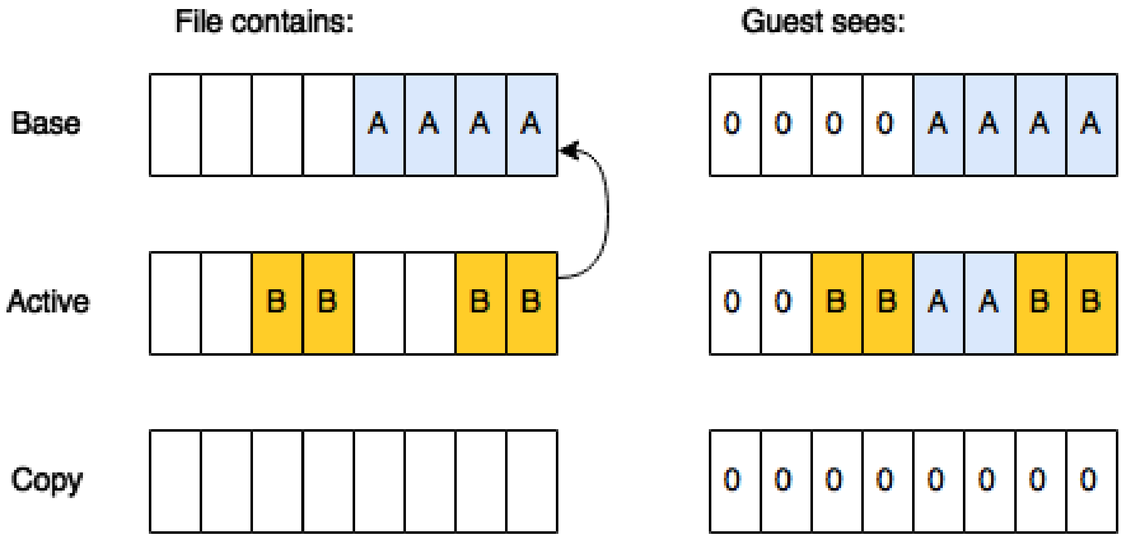


Drive-backup primitive

- Copy guest state from point in time into destination
- Any guest writes will first flush the old cluster to the destination before writing the new cluster to the source
- Meanwhile, bitmap tracks what additional clusters still need to be copied in background
- Similar to drive-mirror, but with different point in time



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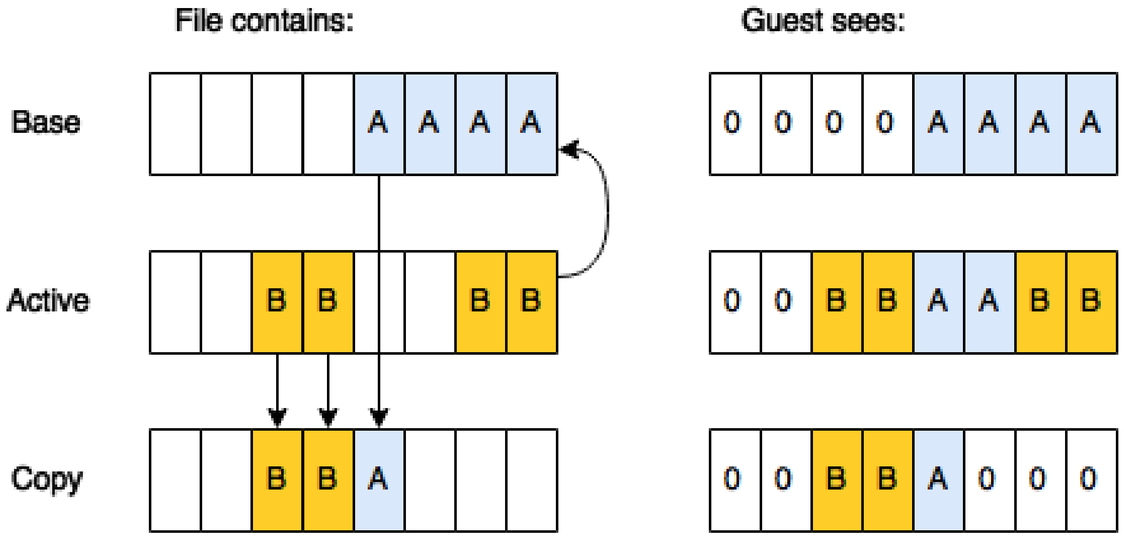

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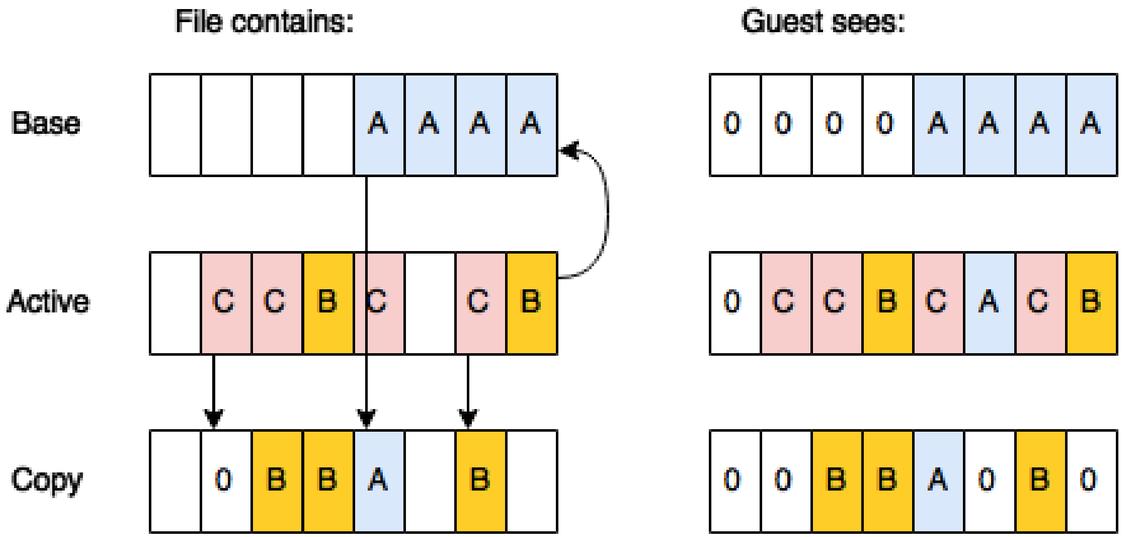

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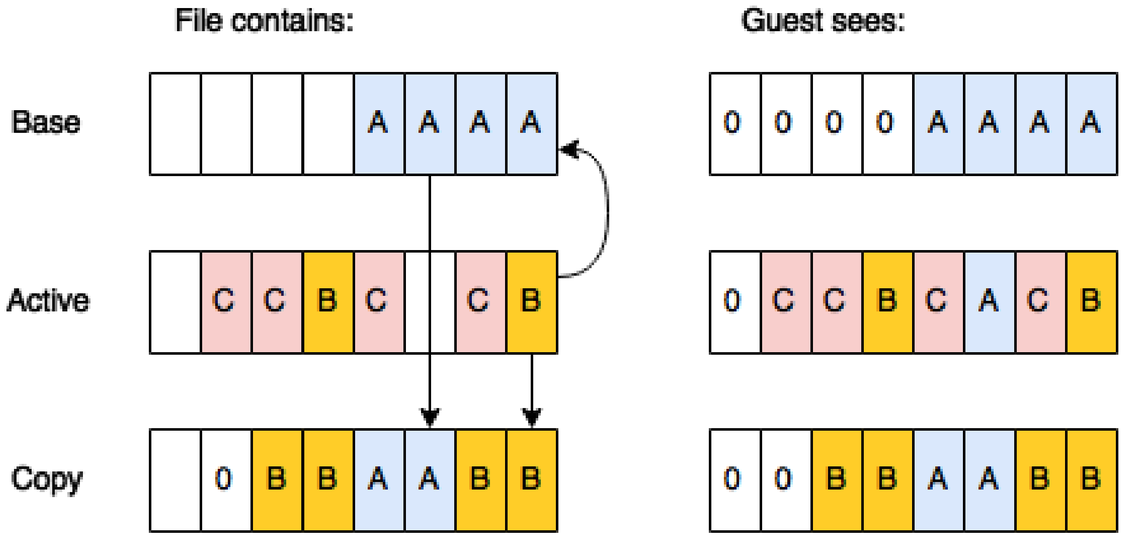

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Incremental backup

- qemu 2.5 will add ability for incremental backup via bitmaps
- User can create bitmaps at any point in guest time; each bitmap tracks guest cluster changes after that point
- While drive-mirror can only copy at backing chain boundaries, a bitmap allows extracting all clusters changed since point in time, capturing incremental state without a source backing chain
- Incremental backups can then be combined in backing chains of their own to reform full image

Part III

Libvirt control

Libvirt representation of backing chain

- virDomainGetXMLDesc() API
- `virsh dumpxml guest`
- Backing chain represented by nested children of <disk>
  - Currently only for live guests, but planned for offline guests
- Name a specific chain member by index (“vda[1]”) or filename (“/tmp/wrap.qcow2”)

```
<disk type='file' device='disk'>
 <driver name='qemu' type='qcow2'/>
 <source file='/tmp/wrap2.qcow2'/>
 <backingStore type='file' index='1'>
  <format type='qcow2'/>
  <source file='/tmp/wrap.qcow2'/>
  <backingStore type='file' index='2'>
   <format type='qcow2'/>
   <source file='/tmp/base.qcow2'/>
   <backingStore/>
  </backingStore>
 </backingStore>
 <target dev='vda' bus='virtio'/>
 ...
```

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   <backingStore/>
  </backingStore>
 </backingStore>
 <target dev='vda' bus='virtio'/>
 ...
```

Creating an external snapshot

- virDomainSnapshotCreateXML() API
- `virsh snapshot-create domain description.xml`
- `virsh snapshot-create-as domain --disk-only \`
  `--diskspec vda,file=/path/to/wrapper.qcow2`
- Maps to qemu blockdev-snapshot-sync, also manages offline chain creation through qemu-img
- Often used with additional flags:
  - --no-metadata: cause only side effect of backing chain growth
  - --quiesce: freeze guest I/O, but requires guest agent

Performing block pull

- virDomainBlockRebase() API
- `virsh blockpull domain vda --wait --verbose`
- Mapped to qemu block-stream, with current limitation of only pulling into active layer
- When qemu 2.5 adds intermediate streaming, syntax will be:
  - `virsh blockpull domain "vda[1]" --base "vda[3]"`

Performing block commit

- virDomainBlockCommit() API, plus virDomainBlockJobAbort() for active jobs
- `virsh blockcommit domain vda --top "vda[1]"`
- `virsh blockjob domain vda`
- `virsh blockcommit domain vda --shallow \`
  `--pivot --verbose --timeout 60`
- May gain additional flags if qemu block-commit adds features

Performing block copy

- virDomainBlockCopy()/virDomainBlockJobAbort() APIs
- `virsh blockcopy domain vda /path/to/dest --pivot`
- Currently requires transient domain
  - Plan to relax that with qemu 2.5 persistent bitmap support
- Currently captures point in time at end of job (drive-mirror)
  - May later add flag for start of job semantics (drive-backup)
- Plan to add --quiesce flag to job abort, like in snapshot creation, instead of having to manually use domfsfreeze/domfsthaw

Piecing it all together: efficient live backup

- Goal: create (potentially bootable) backup of live guest disk state

/my/base ← /my/image

Piecing it all together: efficient live backup

- Goal: create (potentially bootable) backup of live guest disk state

```
$ virsh snapshot-create-as domain tmp \
   --no-metadata --disk-only
```

/my/base ← /my/image ← /my/image.tmp

Piecing it all together: efficient live backup

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```
$ virsh snapshot-create-as domain tmp \
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Piecing it all together: efficient live backup

- Goal: create (potentially bootable) backup of live guest disk state

```
$ virsh snapshot-create-as domain tmp \
   --no-metadata --disk-only --quiesce
$ cp --reflink=always /my/image /backup/image
```

/my/base ← /my/image ← /my/image.tmp

/my/base ← /backup/image

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```
$ virsh snapshot-create-as domain tmp \
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$ cp --reflink=always /my/image /backup/image
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   --pivot --verbose
```

/my/base ← /my/image

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$ rm /my/image.tmp
```

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$ virsh snapshot-create-as domain tmp \
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$ cp --reflink=always /my/image /backup/image
$ virsh blockcommit domain vda --shallow \
   --pivot --verbose
$ rm /my/image.tmp
```

- No guest downtime, and with a fast storage array command, the delta contained in temporary chain wrapper is small enough for entire operation to take less than a second

Piecing it all together: revert to snapshot

- Goal: roll back to disk state in an external snapshot

/my/base ← /my/experiment

```
<disk type='file' device='disk'>
 <driver name='qemu' type='qcow2'/>
 <source file='/my/experiment'/>
...
```

Piecing it all together: revert to snapshot

- Goal: roll back to disk state in an external snapshot

```
$ virsh destroy domain
```

/my/base ← /my/experiment

```
<disk type='file' device='disk'>
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Piecing it all together: revert to snapshot

- Goal: roll back to disk state in an external snapshot

```
$ virsh destroy domain
$ virsh edit domain # update <disk> details
```

/my/base ← /my/experiment

```
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 <driver name='qemu' type='qcow2'/>
 <source file='/my/base'/>
...
```

Piecing it all together: revert to snapshot

- Goal: roll back to disk state in an external snapshot

```
$ virsh destroy domain
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$ rm /my/experiment
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/my/base

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```
$ virsh destroy domain
$ virsh edit domain # update <disk> details
$ rm /my/experiment
$ virsh start domain
```

/my/base

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...
```

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- Goal: roll back to disk state in an external snapshot

```
$ virsh destroy domain
$ virsh edit domain # update <disk> details
$ rm /my/experiment
$ virsh start domain
```

- If rest of chain must be kept consistent, use copies or create additional wrappers with qemu-img to avoid corrupting base
- If rest of chain is not needed, be sure to delete files that are invalidated after reverting

Piecing it all together: live storage migration

- Goal: rebase storage chain from network to local storage

/nfs/image

Piecing it all together: live storage migration

- Goal: rebase storage chain from network to local storage

```
$ virsh snapshot-create-as domain tmp \
   --no-metadata --disk-only
```

/nfs/image ← /nfs/image.tmp

Piecing it all together: live storage migration

- Goal: rebase storage chain from network to local storage

```
$ virsh snapshot-create-as domain tmp \
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$ cp /nfs/image /local/image
```

/nfs/image ← /nfs/image.tmp

/local/image

Piecing it all together: live storage migration

- Goal: rebase storage chain from network to local storage

```
$ virsh snapshot-create-as domain tmp \
   --no-metadata --disk-only
$ cp /nfs/image /local/image
$ qemu-img create -f qcow2 -b /local/image \
   -F qcow2 /local/wrap
```

/nfs/image ← /nfs/image.tmp

/local/image ← /local/wrap

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```
$ virsh snapshot-create-as domain tmp \
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$ cp /nfs/image /local/image
$ qemu-img create -f qcow2 -b /local/image \
   -F qcow2 /local/wrap
$ virsh undefine domain
...
```

/nfs/image ← /nfs/image.tmp

/local/image ← /local/wrap

Piecing it all together: live storage migration

- Goal: rebase storage chain from network to local storage

```
$ virsh blockcopy domain vda /local/wrap \
   --shallow --pivot --verbose --reuse-external
```

/nfs/image ← /nfs/image.tmp

/local/image ← /local/wrap

Piecing it all together: live storage migration

- Goal: rebase storage chain from network to local storage

```
$ virsh blockcopy domain vda /local/wrap \
   --shallow --pivot --verbose --reuse-external
$ virsh dumpxml domain > file.xml
$ virsh define file.xml
```

/nfs/image ← /nfs/image.tmp

/local/image ← /local/wrap

Piecing it all together: live storage migration

- Goal: rebase storage chain from network to local storage

```
$ virsh blockcopy domain vda /local/wrap \
   --shallow --pivot --verbose --reuse-external
$ virsh dumpxml domain > file.xml
$ virsh define file.xml
$ virsh blockcommit domain vda --shallow \
   --pivot --verbose
```

/nfs/image ← /nfs/image.tmp

/local/image

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$ rm file.xml /local/wrap /nfs/image.tmp
```

/nfs/image

/local/image

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$ virsh define file.xml
$ virsh blockcommit domain vda --shallow \
   --pivot --verbose
$ rm file.xml /local/wrap /nfs/image.tmp
```

- The undefine/dumpxml/define steps will drop once libvirt can use persistent bitmaps to allow copy with non-transient domains

Future work

- Libvirt support of offline chain management
- Libvirt support of revert to external snapshot
- Qemu 2.5 additions, and adding libvirt support:
  - Intermediate streaming
  - Incremental backup
  - Use persistent bitmap
- Libvirt support to expose mapping information, or at a minimum whether pull or commit would move less data
- Patches welcome!

Questions?