Memory Externalization With *userfaultfd*

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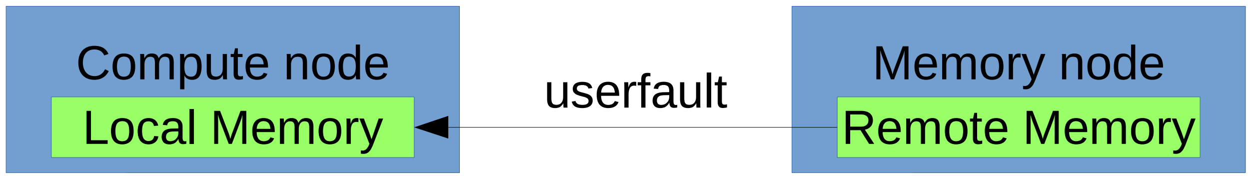
Memory Externalization

- Memory externalization is about running a program with part (or all) of its memory residing on a remote node
- Memory is transferred from the memory node to the compute node on access

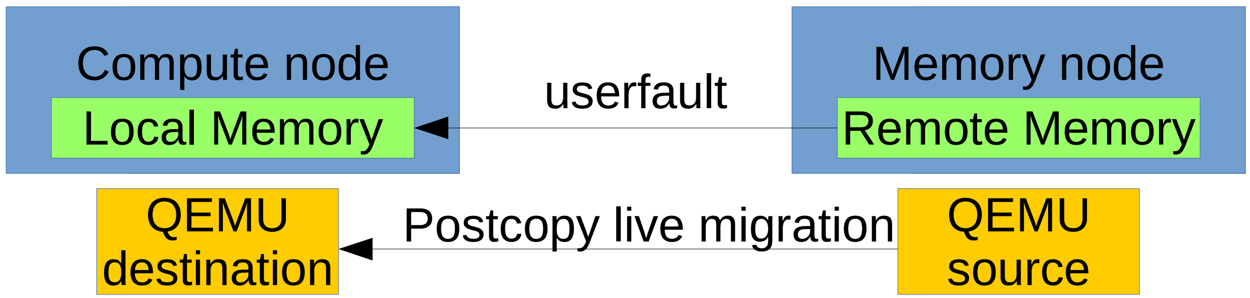


- Memory can be transferred from the compute node to the memory node if it's not frequently used during memory pressure

- The Kernel needs new VM (as in Virtual Memory) features to allow this kind of memory externalization

Postcopy Memory Externalization

- Postcopy live migration is also some some form of one-way memory externalization



- The compute node is running the qemu live migration destination
- The memory node is running the qemu live migration source
- If we solve the memory externalization problem in a generic way that can work for all linux applications, it will also allow qemu to implement postcopy live migration
  - Without requiring any KVM/virt specific patch

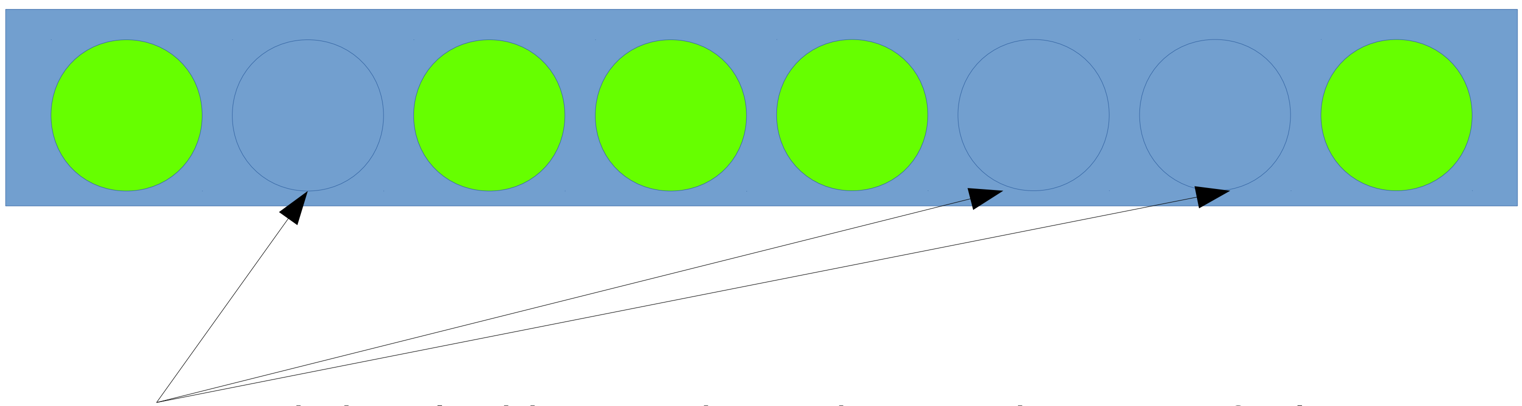
Initial Postcopy Live Migration

- The initial KVM postcopy live migration prototype from Isaku Yamahata was very inspiring
- Great prototype to demonstrate it, but in production environments its kernel backend would have disabled:
  - Overcommit and swap
  - THP
  - KSM
  - NUMA balancing
  - NUMA hard bindings (mbind/set_mempolicy etc..)
- A special device driver would have required special privileges similar to mlock()
- It could have been hardly adopted by non-virt users
  - i.e. volatile pages on tmpfs

First problem: userfault

- qemu destination running in the compute node must be notified the first time a page fault happens if a page is still missing

Destination guest virtual memory (kernel side is a vma)



Unmapped virtual addresses (pages) must trigger userfault on access

- To get the notification through SIGBUS (info->si_addr) we introduced:
  - madvise(MADV_USERFAULT)
  - madvise(MADV_NOUSERFAULT)

SIGBUS userfault not enough

- SIGBUS is ok to trap userland accesses (like *volatile pages*)
- SIGBUS generates *failures* when kernel code tries to access the unmapped virtual addresses:
  - get_user_pages would return -EFAULT
    - KVM page fault
    - O_DIRECT I/O
  - syscalls using copy_from_user/copy_to_user
    - write()
    - read()
    - ...
- In qemu we might handle a special error from the /dev/kvm ioctl, but we don't want to handle errors for **all** syscalls

Userfault ideal behavior

- What should happen when an userfault trigger is:
  - The page fault of the thread that touched the unmapped page is blocked
  - One thread of the application is notified by the kernel about an userfault having triggered at a certain address
  - The thread transfers the missing page from the (remote) memory node to the (local) compute node
  - The thread maps the missing page at the userfault address atomically
  - The thread tells the kernel to wakeup any blocked page fault for a certain virtual address range that was just mapped
  - The waken up page fault retries the fault and finds the virtual page mapped

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Problem in blocking the page fault

- We want the userfault feature not to require special privilege
- Page faults runs while holding the mmap_sem for reading
- We cannot indefinitely block a page fault while holding a core kernel lock
- The page fault flag *“FAULT_FLAG_ALLOW_RETRY”* if set allows us to drop the mmap_sem (it was written to drop the mmap_sem before I/O)
- Problem: many get_user_pages users don't set *FAULT_FLAG_ALLOW_RETRY* when simulating the page fault
- get_user_pages_locked/unlocked fixes get_user_pages users to always use *FAULT_FLAG_ALLOW_RETRY*

ufd = userfaultfd() - syscall

- The userfaultfd syscall provides userland a protocol to control the userfaults in a way that is transparent to all syscalls and get_user_pages kernel users
- An userland thread responsible to manage the userfaults can listen to the userfaultfd to know the virtual addresses where any userfault triggered
- After resolving the userfaults the thread just need to notify the kernel about it, to wakeup any page fault that was blocked
- There can be an unlimited number of userfaultfd per process
  - Shared libs can use userfaultfd independently of each other and the main program
  - Each userfaultfd must register its own userfault range
    - MADV_USERFAULT must be set as well

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How to resolve an userfault

- We must fill the unmapped virtual address
- The unmapped virtual address must be filled ***atomically***
- We cannot remove MADV_USERFAULT if other threads could access the unmapped address while we map the virtual address
- A new syscall can fill unmapped virtual pages atomically
  - remap_anon_pages(userfault_addr, tmp_addr, PAGE_SIZE)
- remap_anon_pages allows also to atomically “remove” a mapped page from the userfault virtual range, to turn it into a unmapped hole
  - It works both ways

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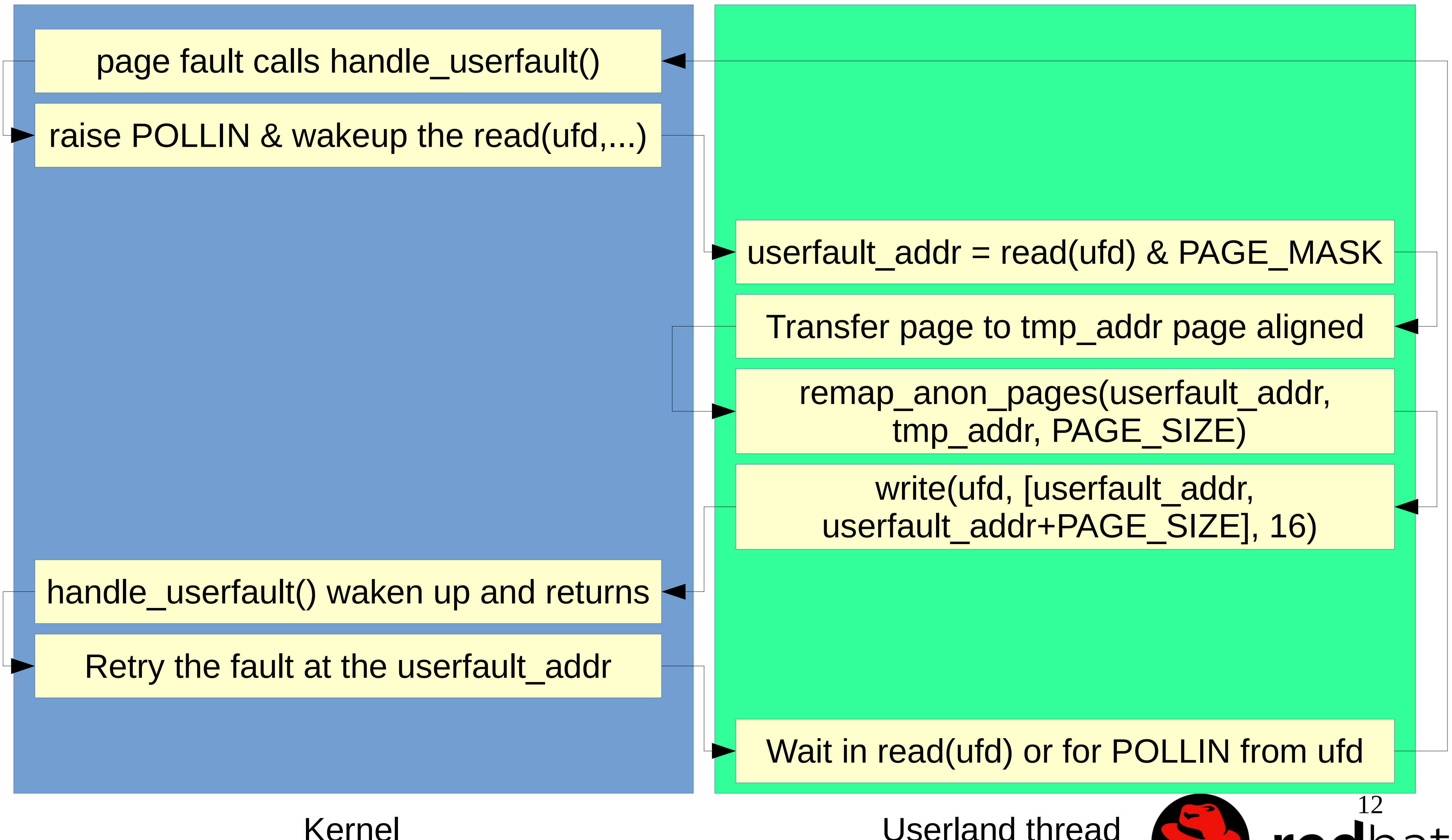
remap_anon_pages

userfaultfd + remap_anon_pages



Atomic mcopy

- A new syscall could also be exposed to userland to fill unmapped holes in anonymous or tmpfs regions atomically
  - mcopy_atomic(userfault_addr, tmp_addr, PAGE_SIZE*N)
- Pros:
  - Likely more efficient because it doesn't require TLB flushes
  - No src_addr, dst_addr page alignment constraints
  - It would work more easily for tmpfs backed userfaults, regardless of the type of memory at the source address
  - Simpler and self contained
- Cons
  - Unable to remove pages from the userfault virtual range
    - remap_anon_pages could still be used for that

mcopy_pages

tmp_addr
1
2
3
4
5
6
Guest physical address space
tmp_addr
1
2
Copy
Of 1
3
4
5
6
Guest physical address space

userfault and KVM

- Thanks to the KVM design (as usual)
  - No change to KVM kernel driver was required
  - All changes are in the core Linux Virtual Memory
  - THP/KSM/NUMA balancing/NUMA bindings are transparently supported on the userfault memory ranges
- Only the qemu balloon driver will need special handling during postcopy live migration as MADV_DONTNEED would create unmapped regions in the userfault area
  - If the guest touches ballooned pages inflated during postcopy live migration, the migration thread should not get confused about it
  - The userfault feature could also be used to enforce that the guest cannot deflate the balloon

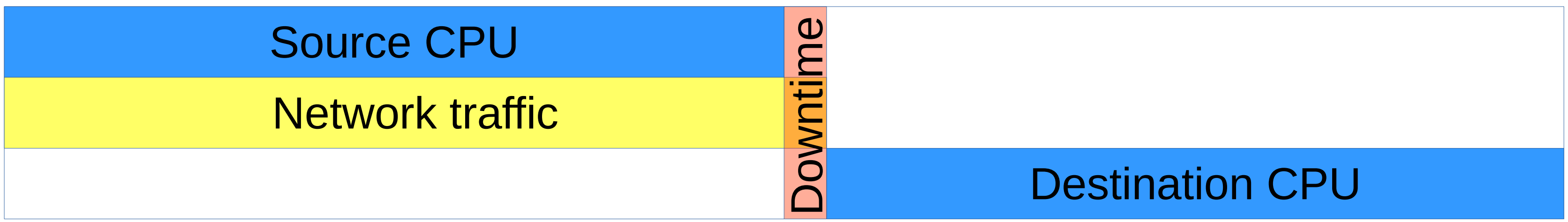
userfault and volatile pages

- Volatile pages are virtual memory ranges that the kernel can discard under memory pressure without swapping them out
- The volatile pages patchset contemplated optionally to provide the *userfault-like* SIGBUS behavior on access
- The userfault in addition to solving postcopy live migration and the memory externalization feature, can provide the SIGBUS notification to applications using volatile pages after their eviction by setting MADV_USERFAULT on the volatile page ranges
  - In addition volatile pages could also use the userfaultfd protocol to allow the kernel to access the volatile pages
  - Without userfaultfd only userland access is allowed to avoid getting unreliable errors from syscalls or get_user_pages

Userfault kernel patchset

- Last submit against 3.17-rc:
  - http://thread.gmane.org/gmane.linux.kernel.mm/123575
  - **git clone git://git.kernel.org/pub/scm/linux/kernel/git/andrea/aa.git -b userfault**
- Implements:
  - gup_locked|unlocked (kernel internal dependency)
  - gup_fast calling gup_unlocked (kernel internal dependency)
  - MADV_USERFAULT|NOUSERFAULT
    - SIGBUS info->si_addr
  - remap_anon_pages(dst,src,len)
  - ufd = userfaultfd(flags)
- Stress tested with thousands of postcopy live migrations
- Feedback is welcome to finalize the kernel API

Normal (i.e. Precopy) migration



- Keep copying state over until it's **almost** all there; long enough you can allow it to be down
- Downtime is:
  - Time to copy device state across
  - Time to copy last bit of memory across
    - Depends on guest work load – if it changes ram quickly it might never finish.

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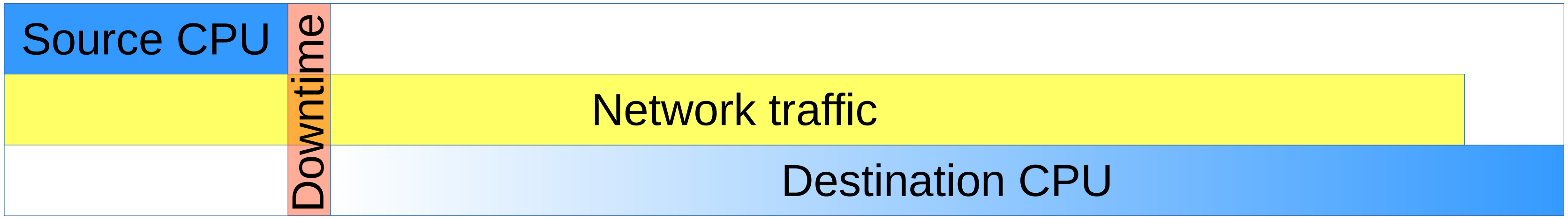
Postcopy migration



- Start the destination straight away – before all the RAM is over
- Downtime just the time to transfer other devices
- Each page copied once – upper bound on migration time
- Destination CPU stalls as it waits for pages of RAM
  - Performance of destination reduced until finished
- Can mix with precopy
  - e.g. precopy, switch to postcopy if it's taking too long)
  - Source sends pages anyway before waiting for postcopy requests
- Many previous attempts
  - Yabusame, Hecatonchire, Hines and Gopalan

'Destination CPU stalls as it waits for pages of RAM'

- '***userfault***' to mark all of RAM
- '***remap_anon_pages***' to place RAM as it arrives
  - Guest CPUs are running – this must be atomic
- Not just guest CPUs
  - QEMU device threads
  - Tricky when loading device state
    - Must be able to service page requests while loading device state from same stream.

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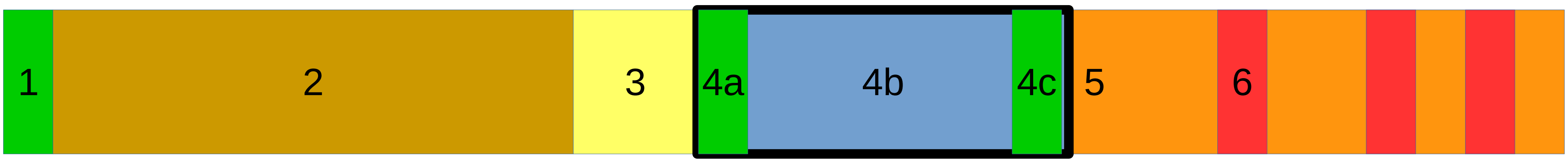
Flow

Kernel		mmap USER-FAULT		Pause guest notify fd				remap		restart guest	
QEMU	Init	Start guest			read fd, ask for page		read page		write fd		
Guest			Access								Full access
Net-work											
Remote page						Provide page					

Components

- *Return path – Dest->src path along same socket*
- *Command section* – for sending commands to destination (to change postcopy state)
  - Both Return path and Commands designed to be general
- *Sent map* – source records pages it sent – used by....
- *Discard* – for discarding pages that have been sent during precopy, but are now dirty on the source
- *Incoming map* – destination records pages received and pages requested
- *Userfault handler*

The migration stream



1 'advise' command – Postcopy might happen later

2 normal precopy migration stream of pages

3 'discard' – Sparse bitmap of pages in (2) that have become dirty

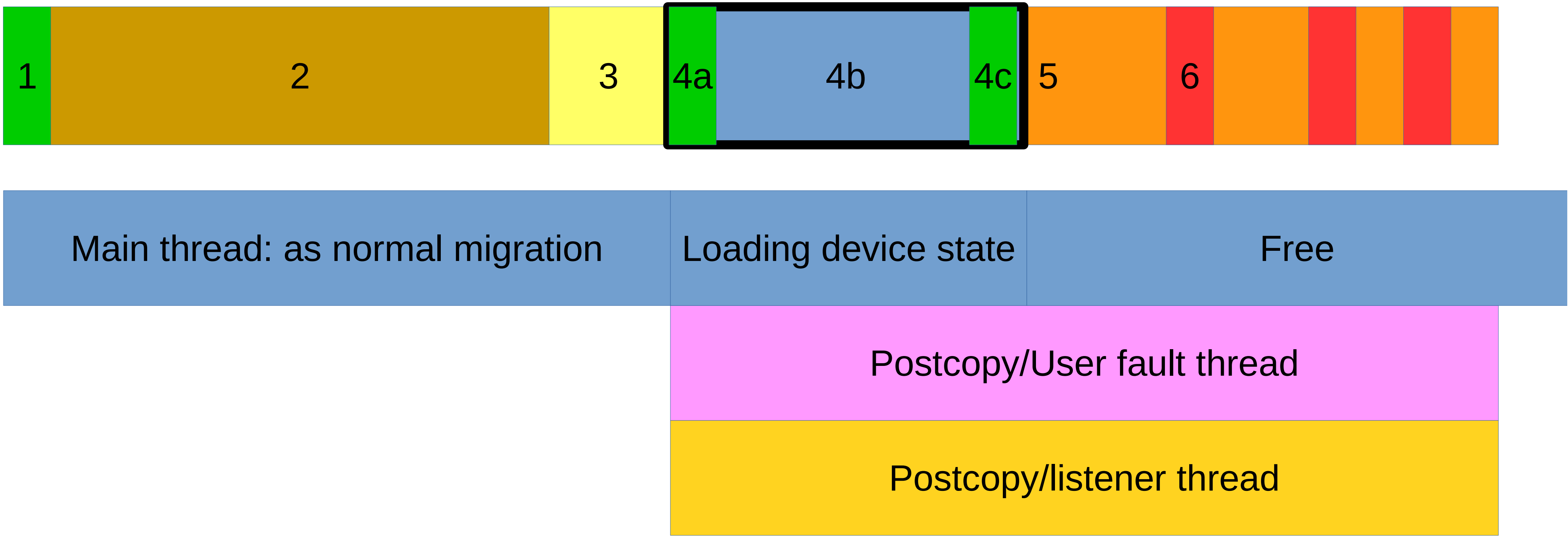
4 'package' – A chunk of data loaded off the wire in one go

- 4a – 'listen' command – mark RAM as userfault
- 4b – device state
- 4c – 'run' command – starts destination CPUs running

5 background page transfers

6 Postcopy page transfers - Exactly the same on the wire as (5)

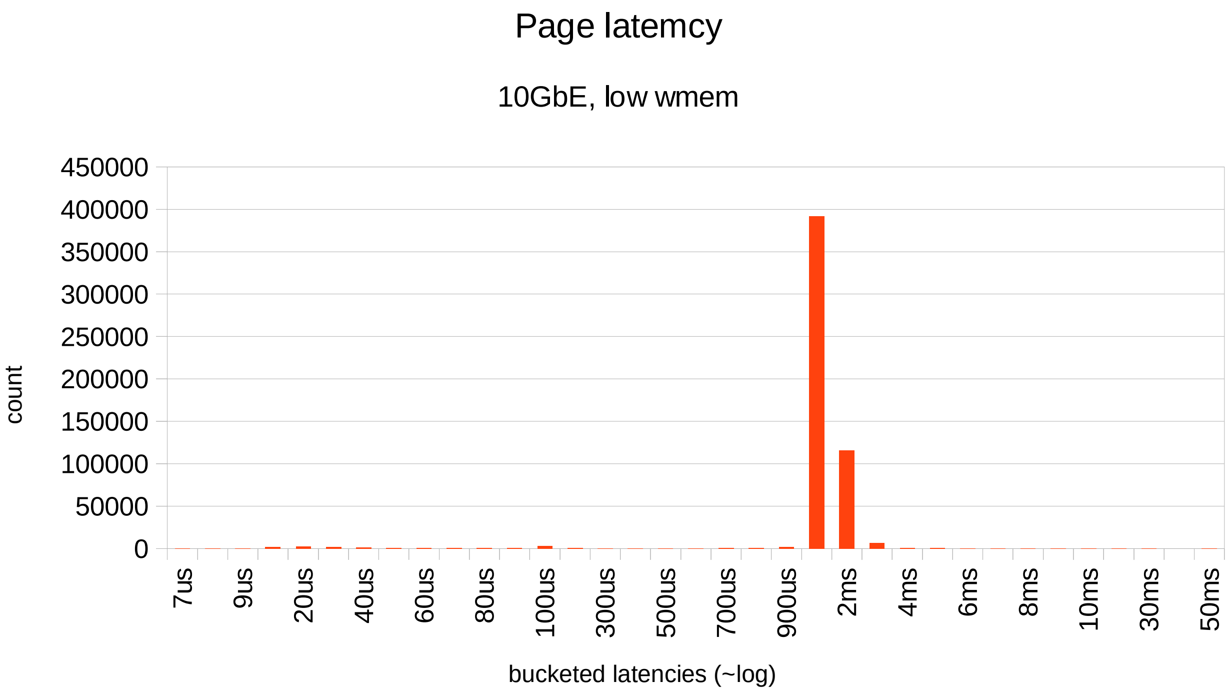
Threads



- Extra threads started before loading device state
  - Because it needs to be able to request pages during device load.
- 'User fault' thread deals with kernel requests and sending them back to source
- 'listener' thread carries on dealing with page loads

Page latencies

- With low wmem – latencies ~1ms
  – (host qemu userspace-userspace)



Page latencies...

- But with standard wmem it shoots up to ~10ms+
- Todo: Limit background page transfer rate to reduce impact on postcopy pages