Userland Page Faults and Beyond
Why How and What's Next

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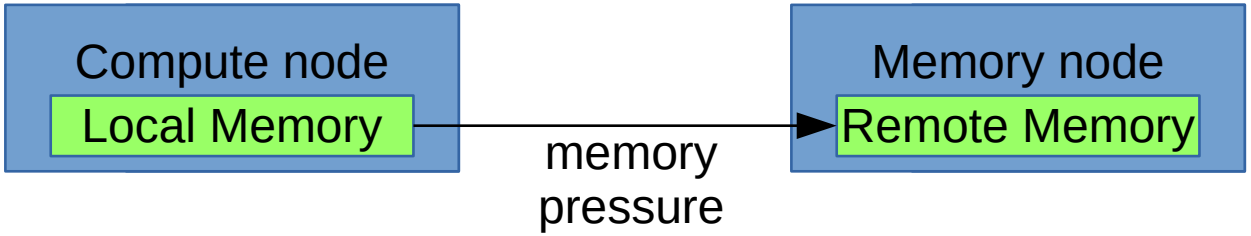
Topics

- Normally page faults are a kernel internal thing..
  - Why offload page faults to userland?
    - Initial use case that required it
- Upstream/production status
- How the userfaultfd API works
- Other use cases
- Development status
- Demo

Why: Memory Externalization

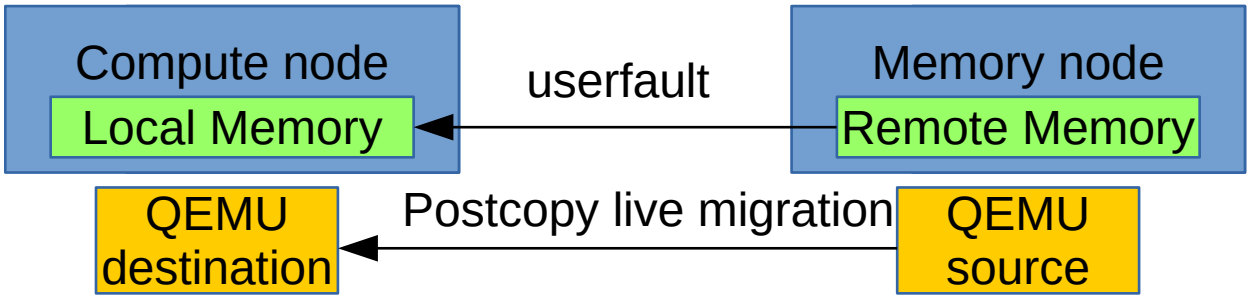
- Memory externalization is about running a program with part (or all) of its memory residing on a remote node
- Memory is transferred from the memory node to the compute node on access

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



Postcopy live migration

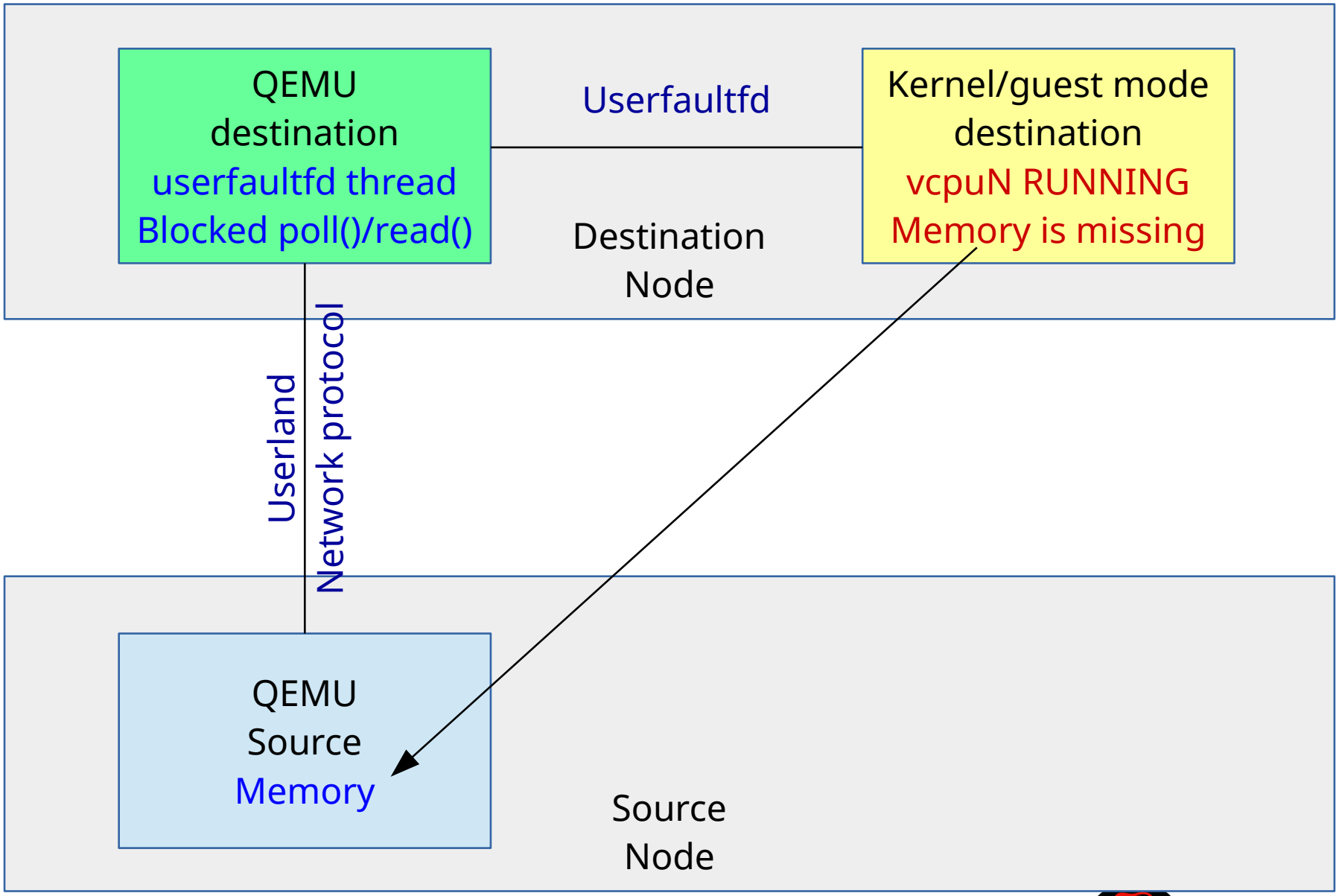
- **Postcopy live migration** is a form of memory externalization



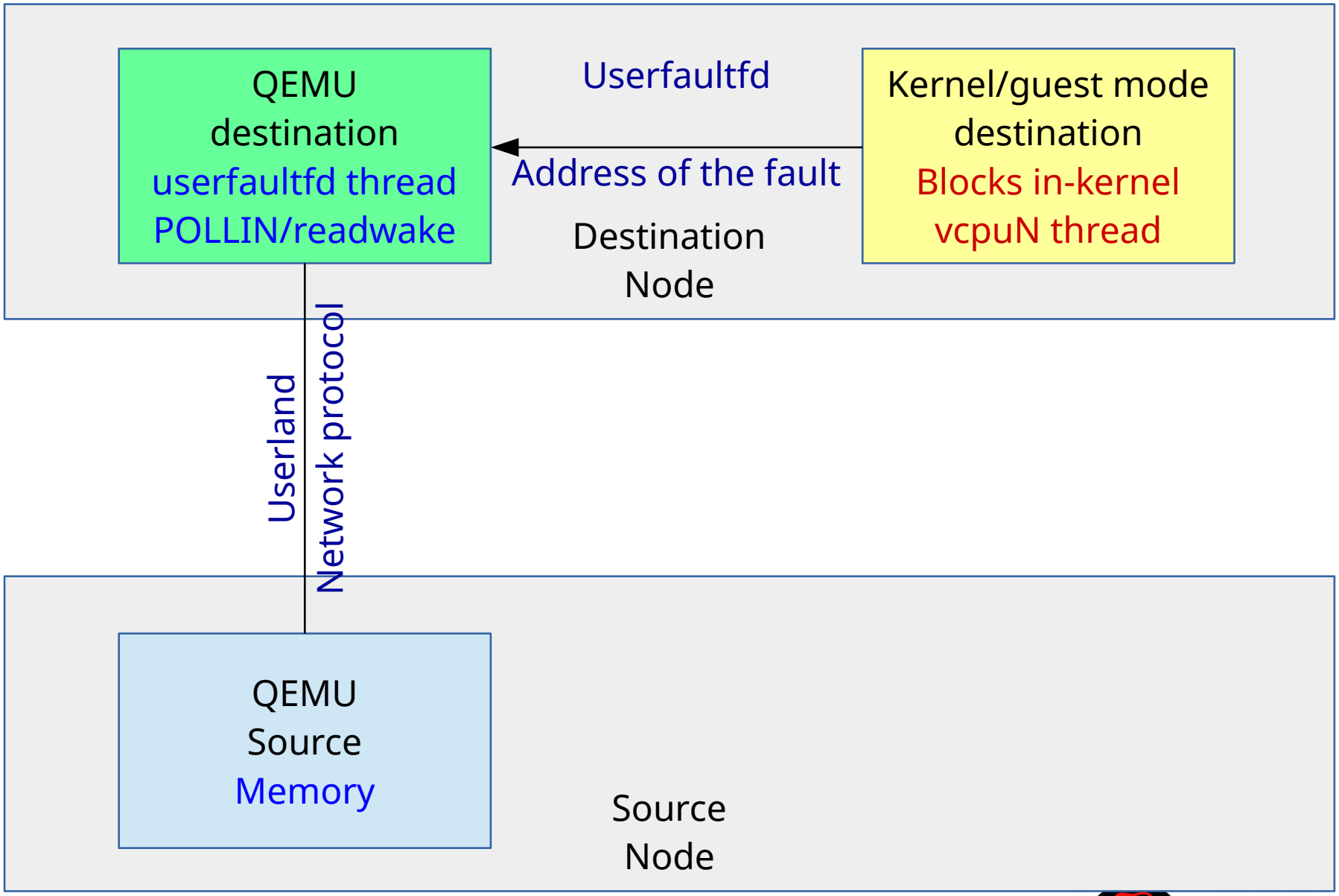
- When the QEMU compute node (destination) faults on a missing page that resides in the memory node (source) the kernel has no way to fetch the page
  - Solution: let QEMU in userland handle the pagefault

Partially funded by the Orbit *European Union* project

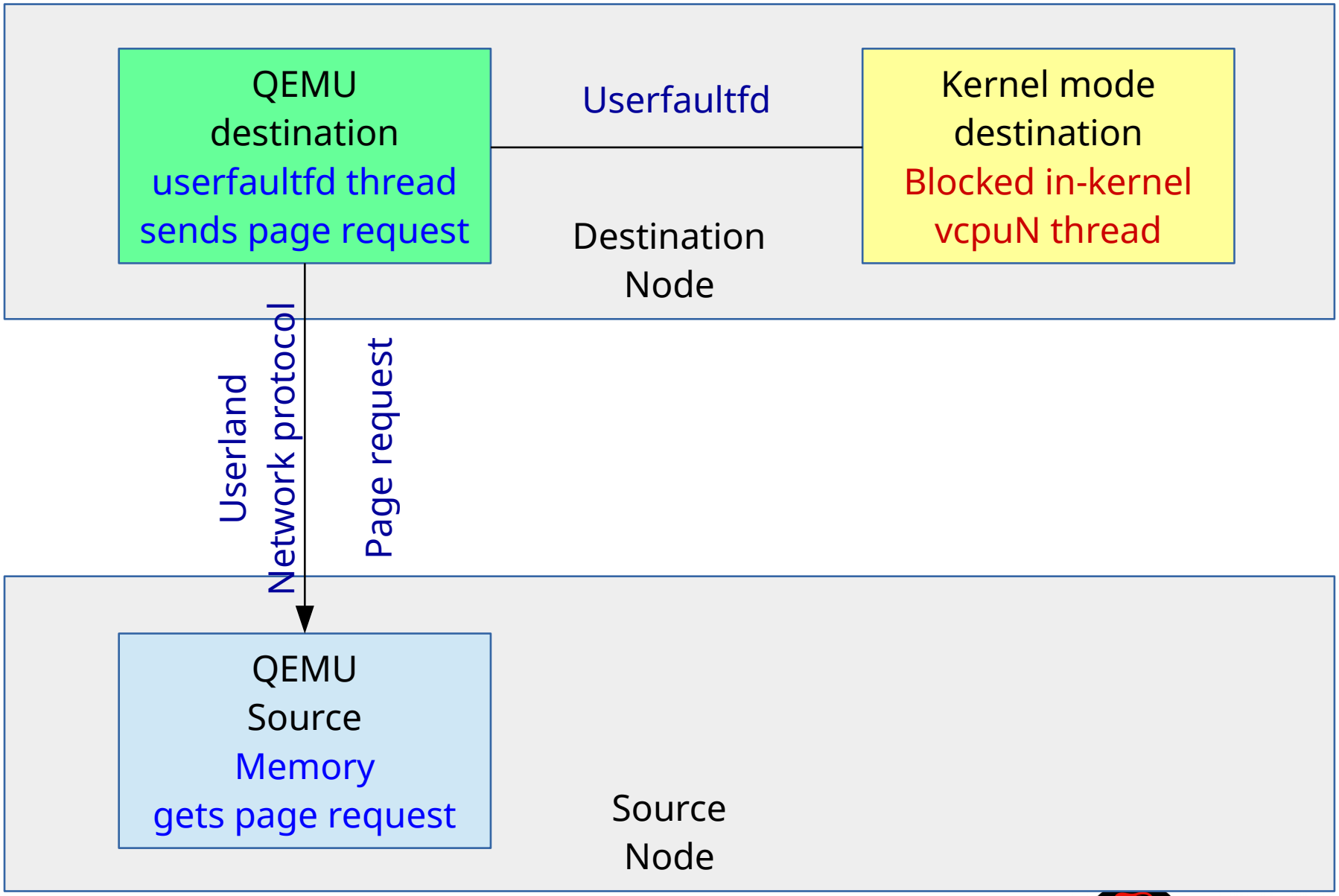
uffd postcopy live migration



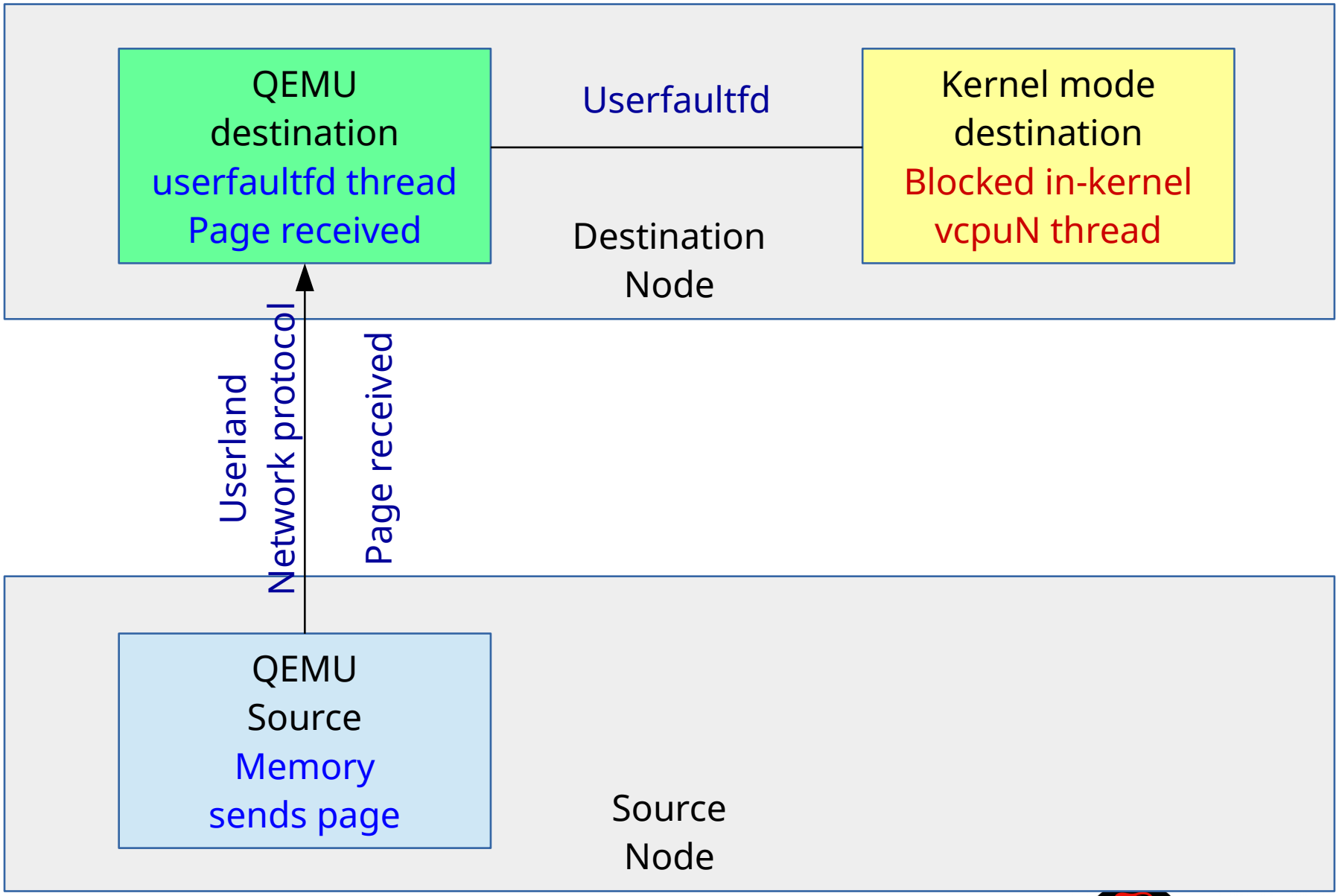
userfaultfd event notification



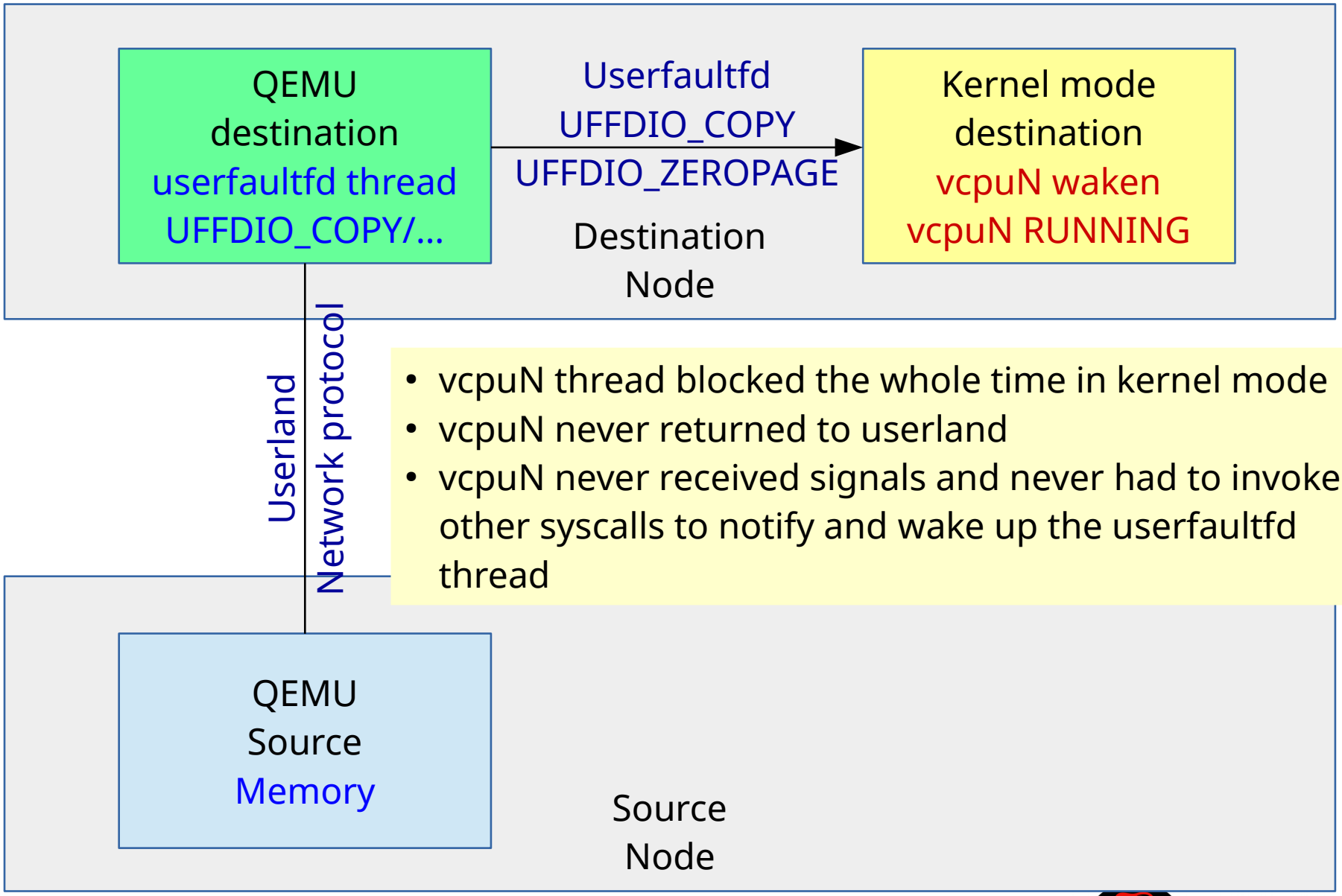
QEMU network page request



QEMU receives page



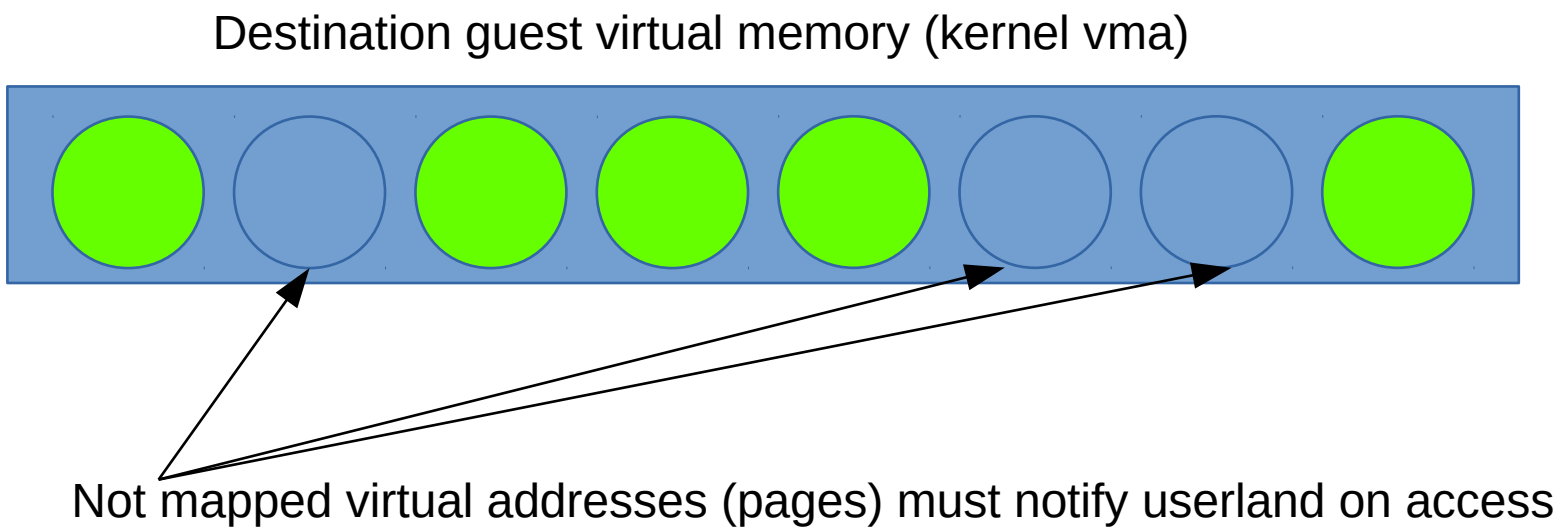
UFFDIO_ZEROPAGE/COPY



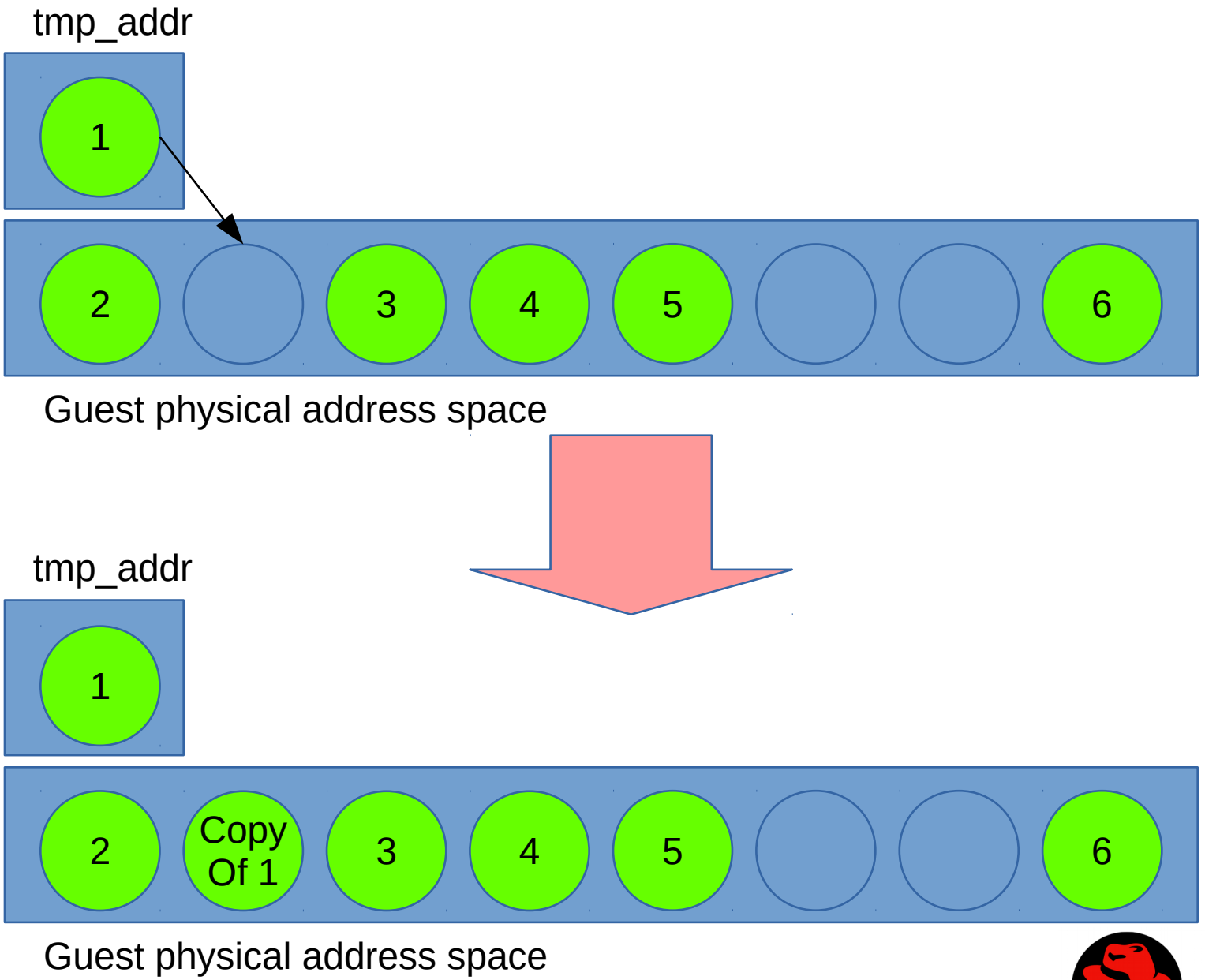
- vcpuN thread blocked the whole time in kernel mode
- vcpuN never returned to userland
- vcpuN never received signals and never had to invoke other syscalls to notify and wake up the userfaultfd thread

Missing pages notification

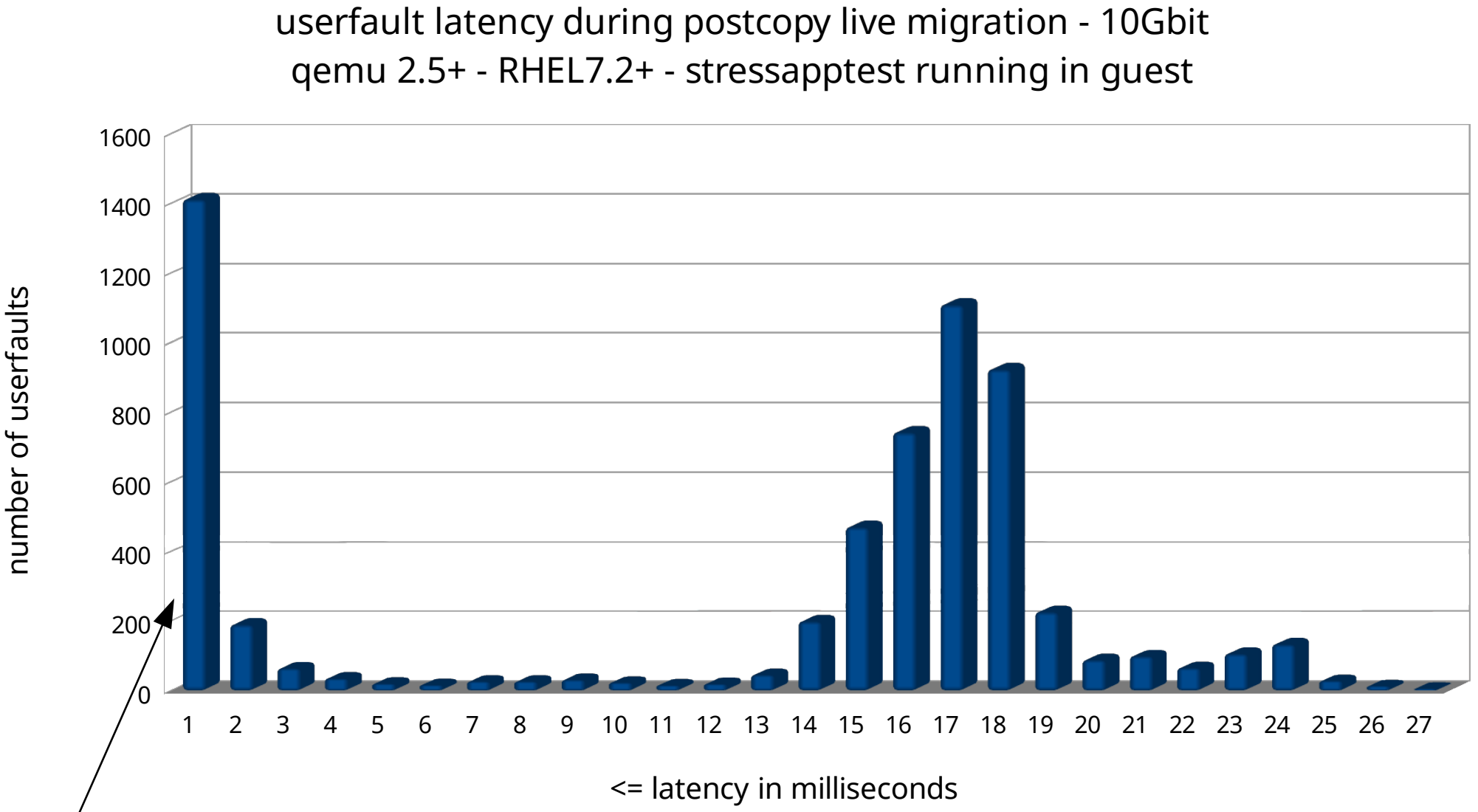
- QEMU destination running in the compute node must be notified the first time a page fault happens if a page is still missing



UFFDIO_COPY - *atomic* memcpy()



userfaultfd latency



Userfaults triggered on pages that were already in network-flight are instantaneous. Background transfer seeks at the last userfault address.

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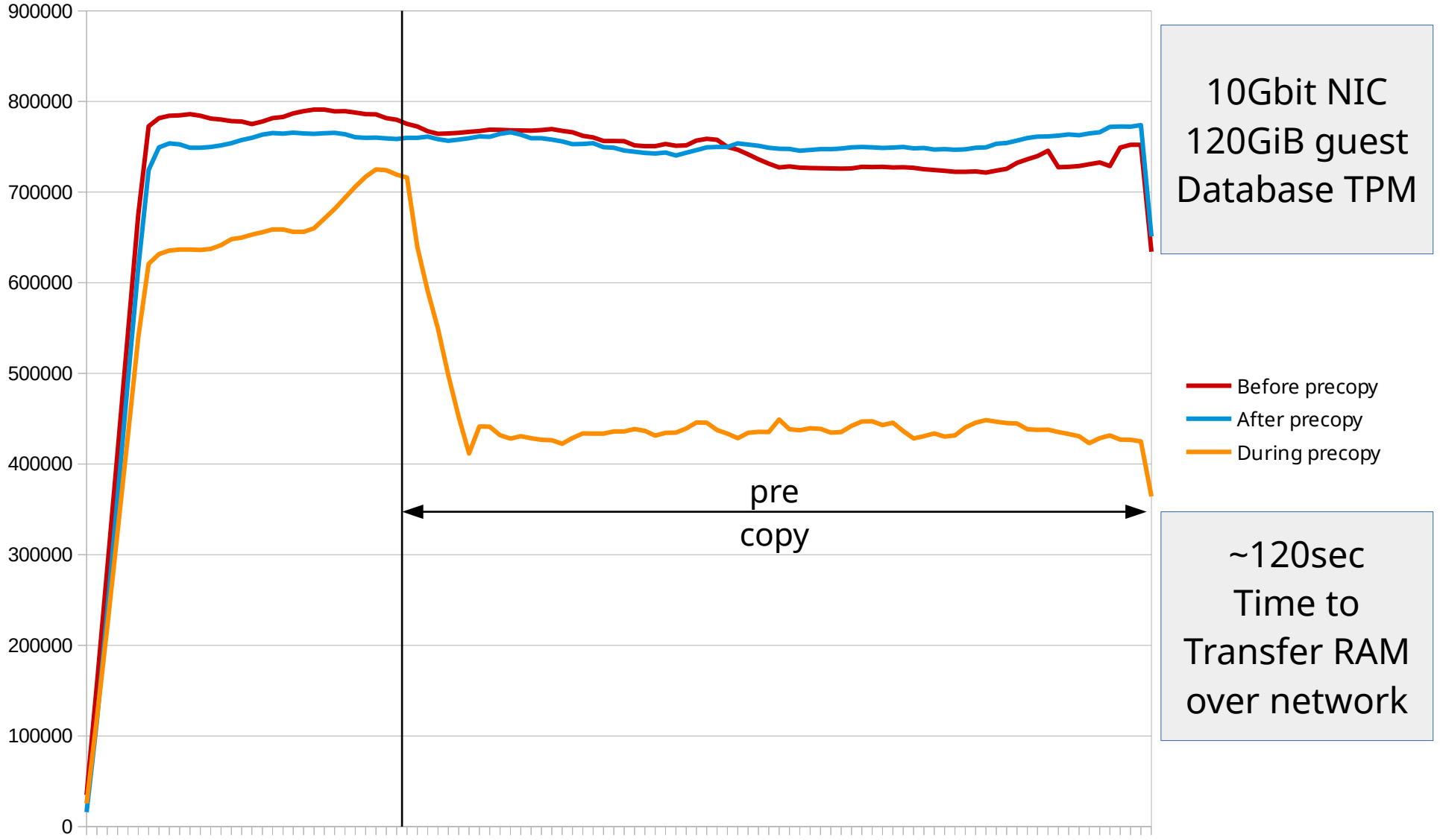
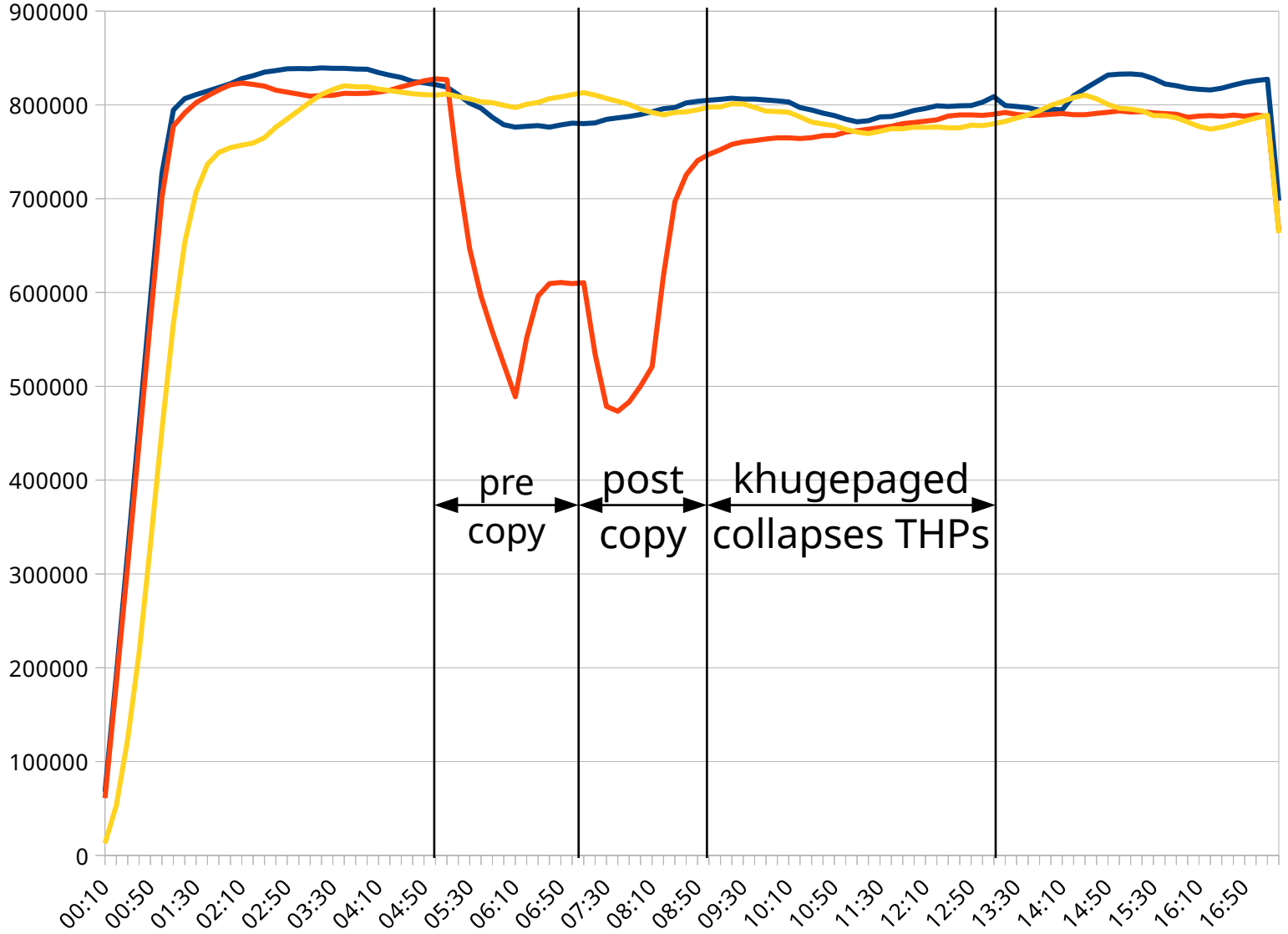
KVM precopy live migration



Precopy never completes until the database benchmark completes

KVM postcopy live migration



precopy runs
From 5m
To 7m

postcopy runs
From 7m
To about ~9m
deterministic

virsh migrate .. --postcopy --timeout <sec> --timeout-postcopy

 # virsh migrate .. --postcopy --postcopy-after-precopy

All available upstream

- Userfaultfd() syscall in Linux Kernel >= v4.3
- Postcopy live migration in:
  - QEMU >= v2.5.0
    - Author: *David Gilbert @ Red Hat Inc.*
  - Postcopy in Libvirt >= 1.3.4
  - OpenStack Nova >= Newton
- … and coming soon in production starting with:
  - **RHEL 7.3**

What's Next?

- The current upstream kernel support is limited to:
  - **Missing** faults (i.e. missing pages)
  - **Anonymous** memory (i.e. malloc)
- What about:
  - other types of memory
    - **tmpfs**
    - **hugetlbfs**
    - perhaps real **filesystem pagecache** too
  - **Write Protect faults**
  - **Removing the memory** atomically… after adding it with UFFDIO_COPY
  - sending the opened userfaultfd to a different "manager" process
    - so that it can manage the memory behinds its back in a **non-cooperative** way

userfaultfd API

- The ioctl(uffd,...) API is versioned
- Can be extended in a backwards compatible way
- The current version of the API can already provide all features mentioned in the previous slide
  - Thanks to the Linux Kernel community feedback
- Not specific to postcopy:
  - new way to manage the memory to do things that weren't possible before

UFFDIO_API

```
ufd = syscall(__NR_userfaultfd, O_CLOEXEC)

struct uffdio_api api_struct;
api_struct.api = UFFD_API;
/* = 0 → userland asks for default pagefault support
   WP support if kernel returns UFFD_FEATURE_PAGEFAULT_FLAG_WP */
api_struct.features = 0;

/* non cooperative mode */
/* api_struct.features = UFFD_FEATURE_EVENT_FORK | UFFD_FEATURE_EVENT_REMAP |
                         UFFD_FEATURE_EVENT_MADVDONTNEED; */

if (ioctl(ufd, UFFDIO_API, &api_struct)) {
   /* err */
}
ioctl_mask = (__u64)1 << _UFFDIO_REGISTER |
             (__u64)1 << _UFFDIO_UNREGISTER;
if ((api_struct.ioctls & ioctl_mask) != ioctl_mask) {
   /* err */
}
```

UFFDIO_REGISTER

```
struct uffdio_register reg_struct;


reg_struct.range.start = (uintptr_t)host_addr;
reg_struct.range.len = length;
reg_struct.mode = UFFDIO_REGISTER_MODE_MISSING;


if (ioctl(mis->userfault_fd, UFFDIO_REGISTER, &reg_struct)) {
    /* err */
}
```

Wait for event

- poll() / epoll() (/ select)

```
struct pollfd pollfd[1];
pollfd[0].fd = uffd;
pollfd[0].events = POLLIN;
ret = poll(pollfd, 1, -1);
```

- Read()

```
struct uffd_msg msg;
ret = read(uffd, &msg, sizeof(msg));
```

- Check uffd_msg event

```
if (msg.event != UFFD_EVENT_PAGEFAULT) { /* err */ }
offset = (char *)(unsigned long)msg.arg.pagefault.address -
area_dst;
```

struct uffd_msg

```
struct uffd_msg {
    __u8   event;
    __u8   reserved1;
    __u16  reserved2;
    __u32  reserved3;
    union {
        struct {
            __u64  flags;
            __u64  address;
        } pagefault;
        struct {
            __u32  ufd;
        } fork;
        struct {
            __u64  from;
            __u64  to;
            __u64  len;
        } remap;
        struct {
            __u64  start;
            __u64  end;
        } madv_dn;
        struct {
            /* unused reserved fields */
            __u64  reserved1;
            __u64  reserved2;
            __u64  reserved3;
        } reserved;
    } arg;
} __packed;
```

UFFD_EVENT_* tells which part of the union is valid

sizeof(struct uffd_msg) 32bit/64bit ABI enforcement

Zeros here, can extend with UFFD_FEATURE flags

Default cooperative support tracking pagefaults
UFFD_EVENT_PAGEFAULT

Non cooperative support tracking MM syscalls
UFFD_EVENT_FORK
UFFD_EVENT_REMAP
UFFD_EVENT_MADVDONTNEED

Handle fault

- UFFDIO_COPY

```
struct uffdio_copy uffdio_copy;
uffdio_copy.dst = (unsigned long) area_dst + offset;
uffdio_copy.src = (unsigned long) area_src + offset;
uffdio_copy.len = page_size;
uffdio_copy.mode = 0;
uffdio_copy.copy = 0;
if (ioctl(uffd, UFFDIO_COPY, &uffdio_copy)) {
   /* err */
}
```

- UFFDIO_ZEROPAGE

```
struct uffdio_zeropage zero_struct;
zero_struct.range.start = (uint64_t)(uintptr_t)host;
zero_struct.range.len = getpagesize();
zero_struct.mode = 0;
if (ioctl(mis->userfault_fd, UFFDIO_ZEROPAGE, &zero_struct)) {
   /* err */
}
```

Possible use cases

- Replace mprotect/mremap+SIGSEGV
- Efficient snapshotting
- JIT/to-native compilers removal of write bits
- Non cooperative usage
- CRIU lazy restore from disk
- Add robustness to shared memory
- Add host enforcement to QEMU balloon driver backend
- Distributed shared memory
- Obsoletes soft_dirty
- Obsoletes “volatile pages” SIGBUS notification

userfaultfd vs SIGSEGV

- Note: the translation is not strictly 1:1 and many more combinations are possible...

UFFDIO_REGISTER_MODE_MISSING UFFDIO_COPY UFFDIO_ZEROPAGE poll() / epoll() / blocking read()	mprotect(PROT_NONE) mprotect(PROT_READ|PROT_WRITE) SIGSEGV signal
UFFDIO_REGISTER_MODE_WP UFFDIO_WRITEPROTECT UFFDIO_WRITEPROTECT_MODE_WP poll() / epoll() / blocking read()	mprotect(PROT_READ) mprotect(PROT_READ|PROT_WRITE) SIGSEGV signal
UFFDIO_REMAP UFFDIO_* poll() / epoll() / blocking read()	mremap() SIGSEGV signal

userfaultfd vs SIGSEGV

- The poll() / epoll() / read() notification is much faster than a SIGSEGV signal
  - No signal masking complexities and inefficiencies
  - The blocked task blocks in-kernel and never returns to userland
- UFFDIO_ ioctls are faster and more SMP scalable than their syscall equivalents like mprotect/mremap
  - All locks are lightweight
  - *"vmas"* are **never** modified in fast paths
  - No risk of running out "vmas"

https://lab.nexedi.cn/kirr/wendelin.core/blob/master/bigfile/virtmem.c

Efficient Snapshotting

- Huawei working on QEMU/KVM postcopy live snapshotting
- Redis can use it too
- No need of fork()
  - Use threads instead
- COW faults can be throttled
  - COW faults after fork() cannot be throttled
- THP always enabled will run optimally
  - It is userland that decides the granularity of the fault so if it wants to COW at 4KiB granularity it can
  - THP becomes more “transparent” than it already was
- Requires WP support

https://lists.nongnu.org/archive/html/qemu-devel/2016-01/msg00664.html

http://redis.io/topics/latency

Optimize away JIT/to-native compilers write bits

- JIT/to-native compilers always set a bit to track which “Cards”/pages were modified
- WP support can allow the garbage collector to track which pages were modified to avoid collecting write bits
- Similar to dirty logging mode in QEMU/KVM
- IIRC this was one the targeted optimizations of the OSv unikernel
  - userfaultfd ***might*** achieve the equivalent result but without linking the JVM run time in the kernel
- Requires WP support

https://medium.com/@MartinCracauer/generational-garbage-collection-write-barriers-write-protection-and-userfaultfd-2-8b0e796b8f7f

http://jcdav.is/2015/11/09/More-JVM-Signal-Tricks/

Non cooperative usage

- Virtuozzo and IBM working on it
- QEMU is aware of the uffd, the guest apps are not
- The app sends a “uffd” to a “manager” and then it keeps running unaware the “manager” is managing the memory behinds its back
- Container postcopy live migration
- fork()/mremap() and other VM syscalls must send userfaultfd events
  - Not only page faults will send events to userland
- Nesting of uffds is going to be *“interesting”*

http://www.slideshare.net/kerneltlv/userfaultfd-and-postcopy-migration

CRIU lazy restore from disk

- Start the restored task immediately
  - Despite the load of its memory from disk isn’t complete
- Conceptually similar to postcopy live migration
  - The program memory is read from disk instead of being transferred through the network

https://criu.org/Userfaultfd

Add robustness to shmem

- Oracle contributed the UFFDIO_MISSING support to hugetlbfs
- IBM contributed the UFFDIO_MISSING support to tmpfs
- If the database hits a bug and accidentally writes a byte in a shmem file hole, a new page is ***silently*** allocated and the corruption goes unnoticed
- An accidental read of zeros from a shmem file hole would also go unnoticed
- userfaultfd **at zero cost** notifies the database that something unexpectedly tried to read or write to a hugetlbfs or tmpfs file hole
  - "no vma split" and UFFDIO_COPY are the main feature here
  - For this use case if an userfaultfd event ever happens, it is sign a bug is causing memory corruption

Host enforcement for memory ballooning

- The QEMU/KVM memory balloon driver is not host enforced
- After the host backend driver calls MADV_DONTNEED, the guest can still deflate the memory balloon
- userfaultfd UFFDIO_MISSING support, at **zero cost**, can allow QEMU/KVM to notice the guest is malicious and terminate it

Distributed shared memory

- Distributed Shared Memory project at Berkeley
- Other research interest
- Needs **UFFDIO_REMAP** to extract memory
  - mremap() equivalent
- Needs WP support to allow read-shared, write-exclusive model
- Can interact with HMM (Heterogeneous Memory Management) and NVIDIA's unified memory
  - GPU userfaults?

Obsoletes soft_dirty

- Soft dirty tells userland, which pages were modified during a certain runtime
- It has to scan all pagetables of all memory that could possibly have been modified to find out
  - O(N) complexity where N is the number of pages
  - It still requires an initial wrprotect fault
- WP support is likely to simply obsolete soft_dirty because it will still scale well with an unlimited amount of memory
  - Similar to Intel VMM PML hw feature (Page Modification Logging)
  - Main drawback is that userfaultfd blocks the WP fault
  - It should be possible to add an event async queue model to turn on and off at run time with an UFFDIO_ASYNC ioctl, to prevent the wrprotect fault to block

Obsoletes volatile pages SIGBUS

- *"Volatile pages"* may be reclaimed and freed by the Linux Virtual Memory at any time
  - They could contain uncompressed graphic bitmaps that can be re-created at low cost
    - Worth to keep in memory only as long as there is no Virtual Memory pressure
  - A prominent *"volatile pages"* use case is Android
- userfaultfd can tell userland if the volatile page is missing
- No need of their own missing *"volatile page"* SIGBUS framework to notify userland

Development status

- **tmpfs, hugetlbfs support works** (selftests provided for both)
- **Write Protect support works**
  - Needs accuracy with ***swapping***, blocker but in progress..
- WP|MISSING support works but it may need some extension
  - UFFDIO_COPY will always add the page read-write
  - Zeropages created by UFFDIO_ZEROCOPY remains readonly forever
- **non cooperative support works**
  - Minor issues:
    - Cannot recreate shared anon pages
    - Cannot handle uffd nesting
- **UFFDIO_REMAP is implemented** but not in aa.git and shall be revisited
  - Only distributed shared memory needs it

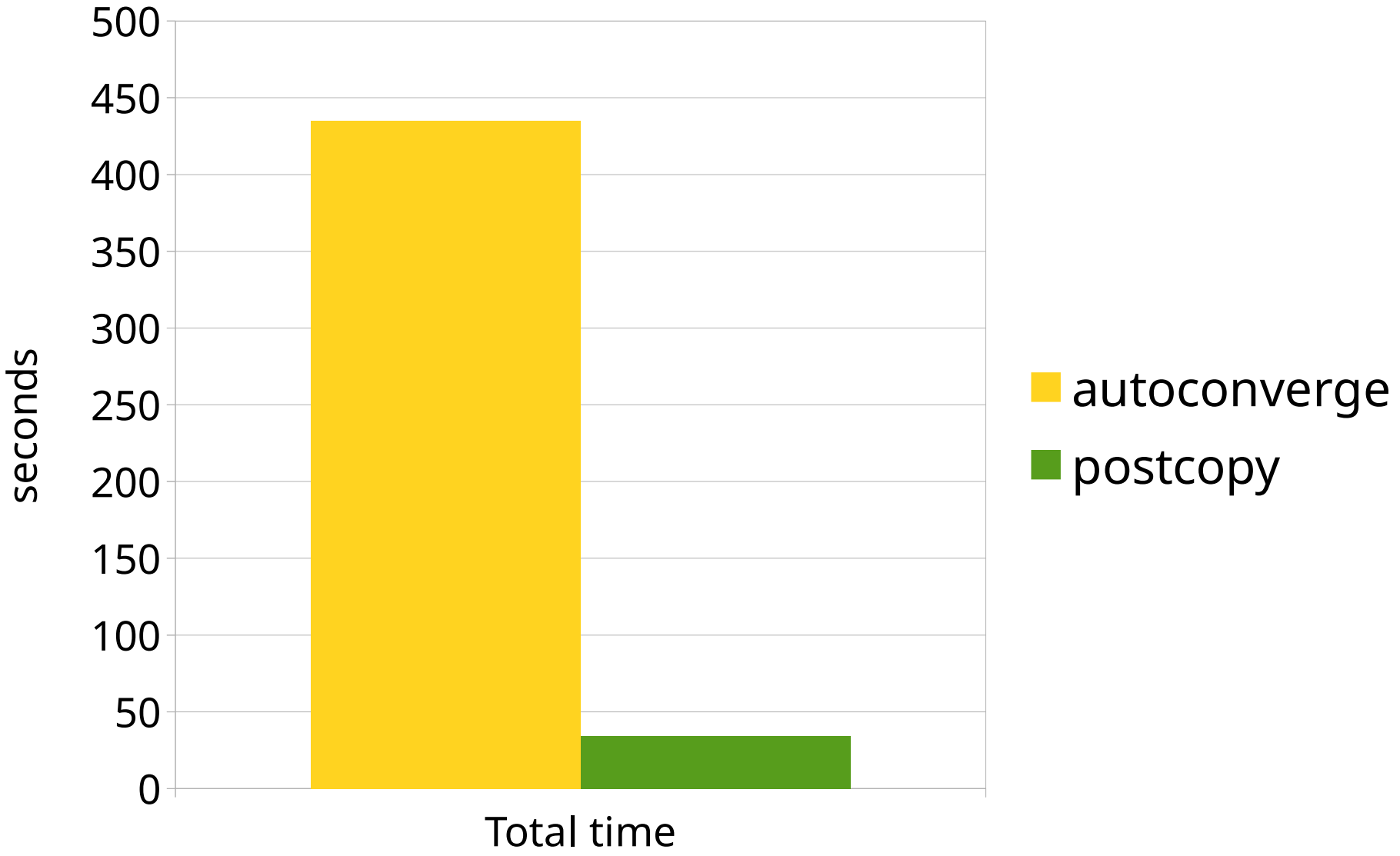
Git userfault branch

- **https://git.kernel.org/cgit/linux/kernel/git/andrea/aa.git/log/?h=userfault**

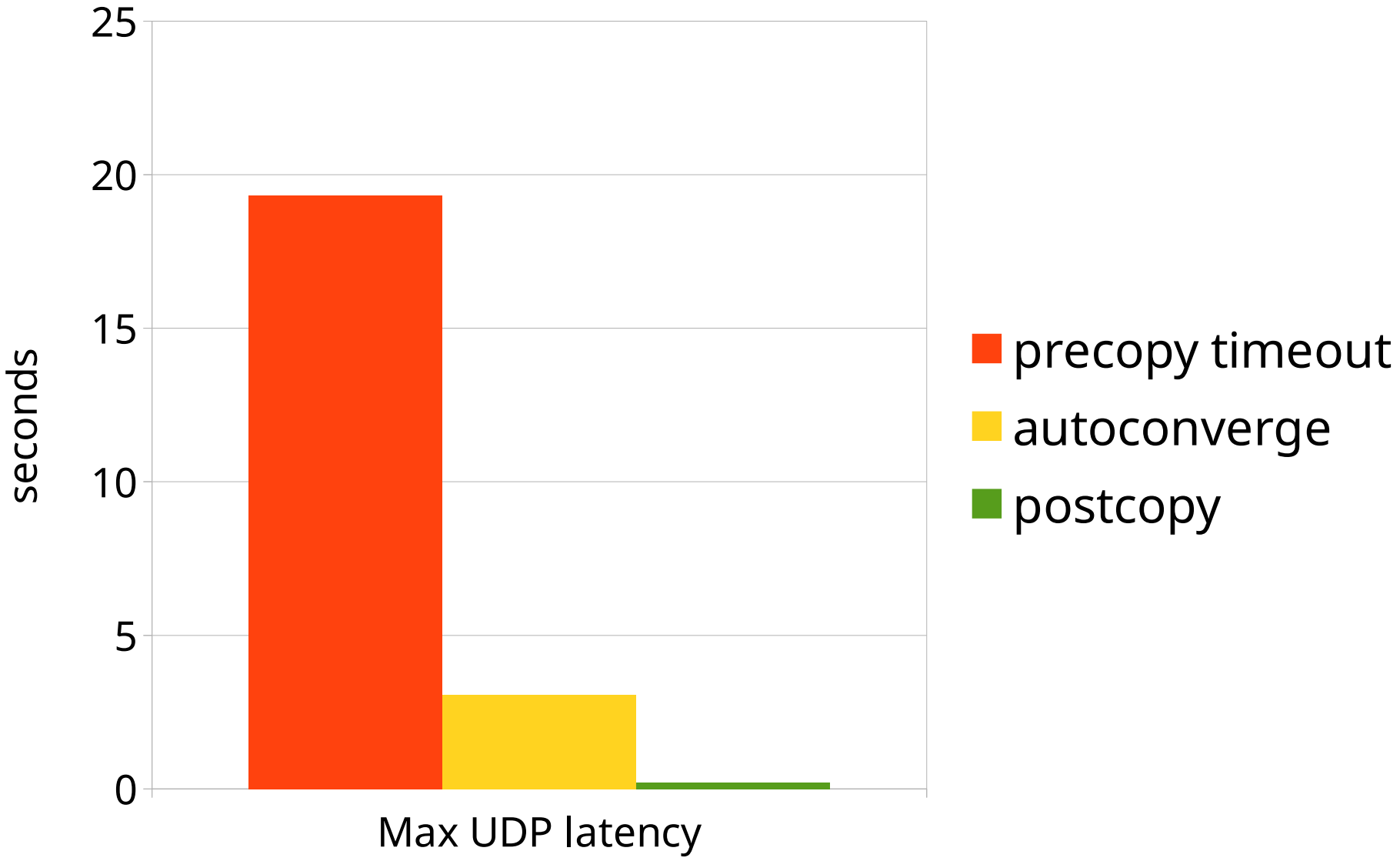
userfaultfd in action

- Time for a live migration demo!

Live migration total time



Live migration max perceived downtime latency



Q/A

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