Custom Page Fault Handling with eBPF

Tal Zussman*, Teng Jiang*, Asaf Cidon
Columbia University

Overview

- Why custom page fault handling?
- Existing solution
- eBPF solution
- Applications

Why Custom Page Fault Handling?

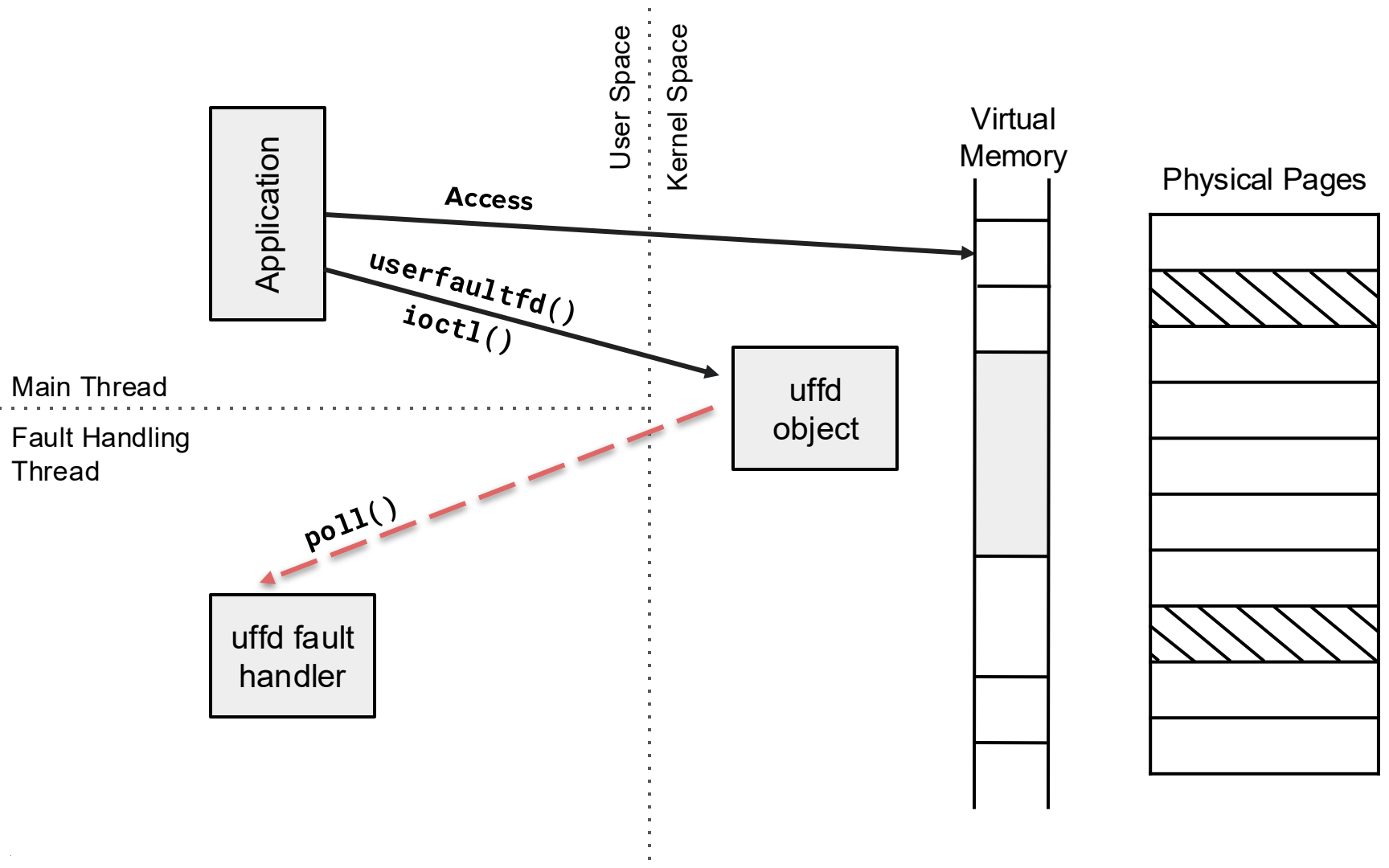
- Page access notifications
- Set faulting page contents on page-in
- **Greater application control of memory management**

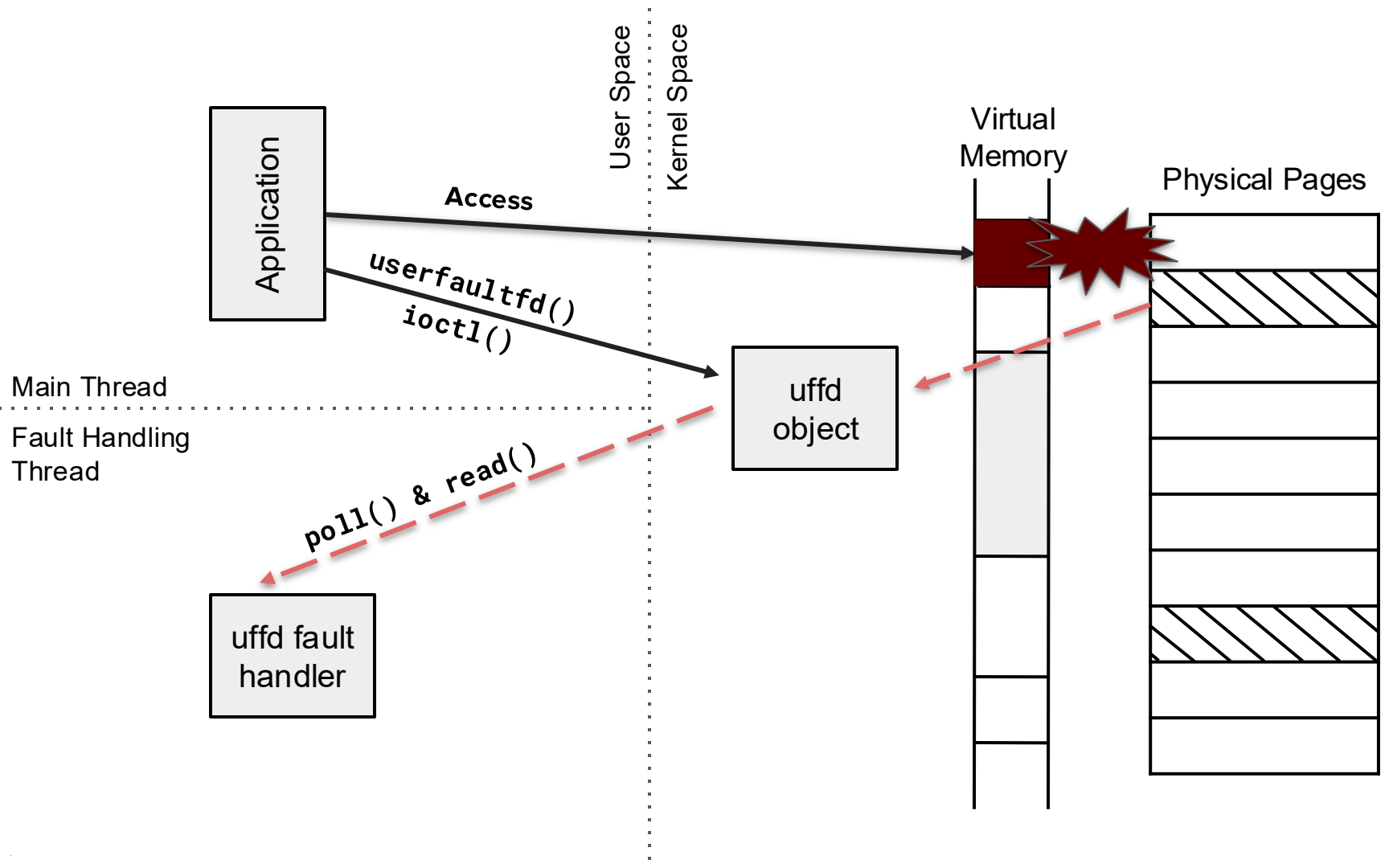
Why Custom Page Fault Handling: VM Migration

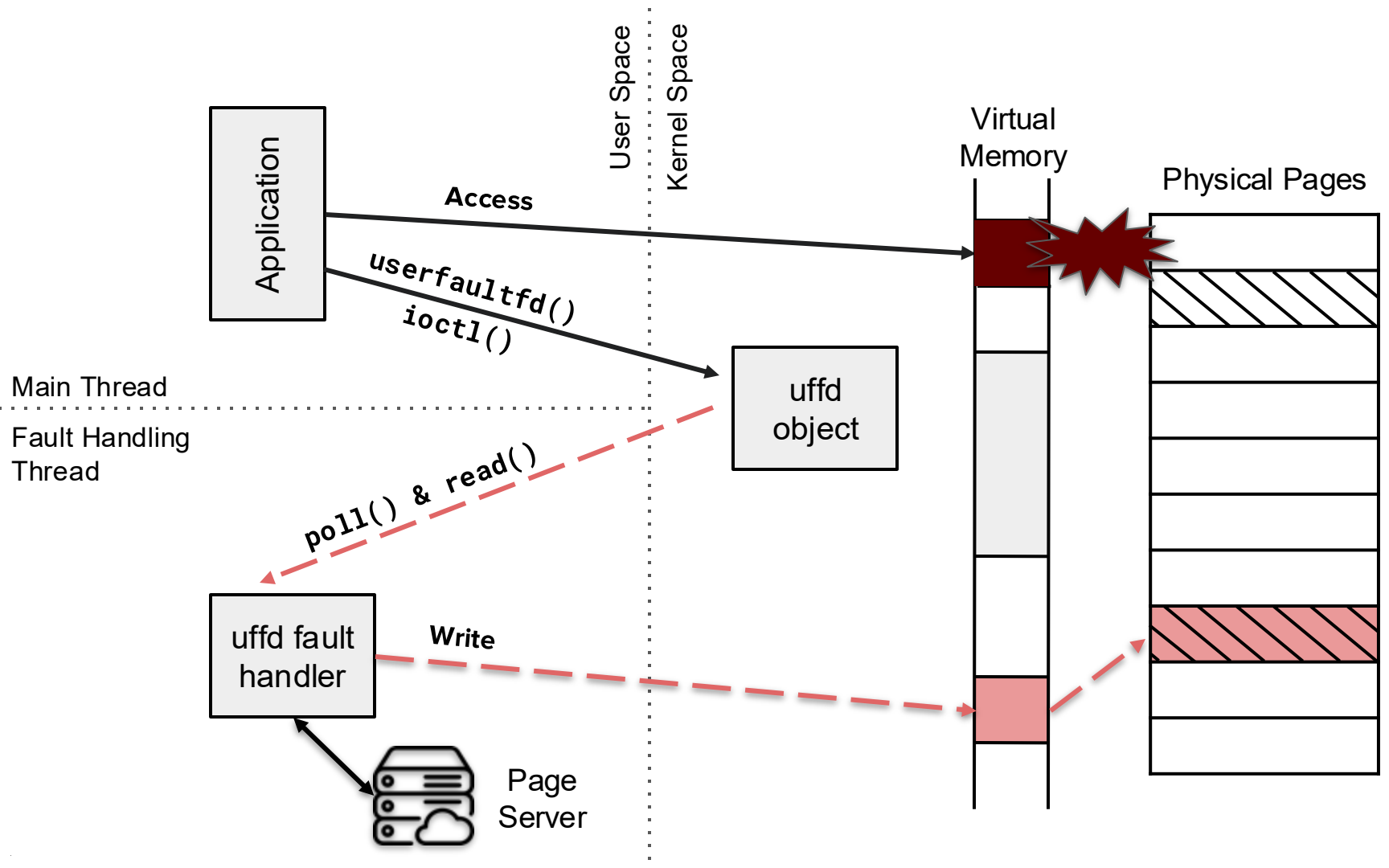
- Move VM across servers – **minimize downtime**
- Copy minimal required memory first
- Lazily copy remaining pages on access

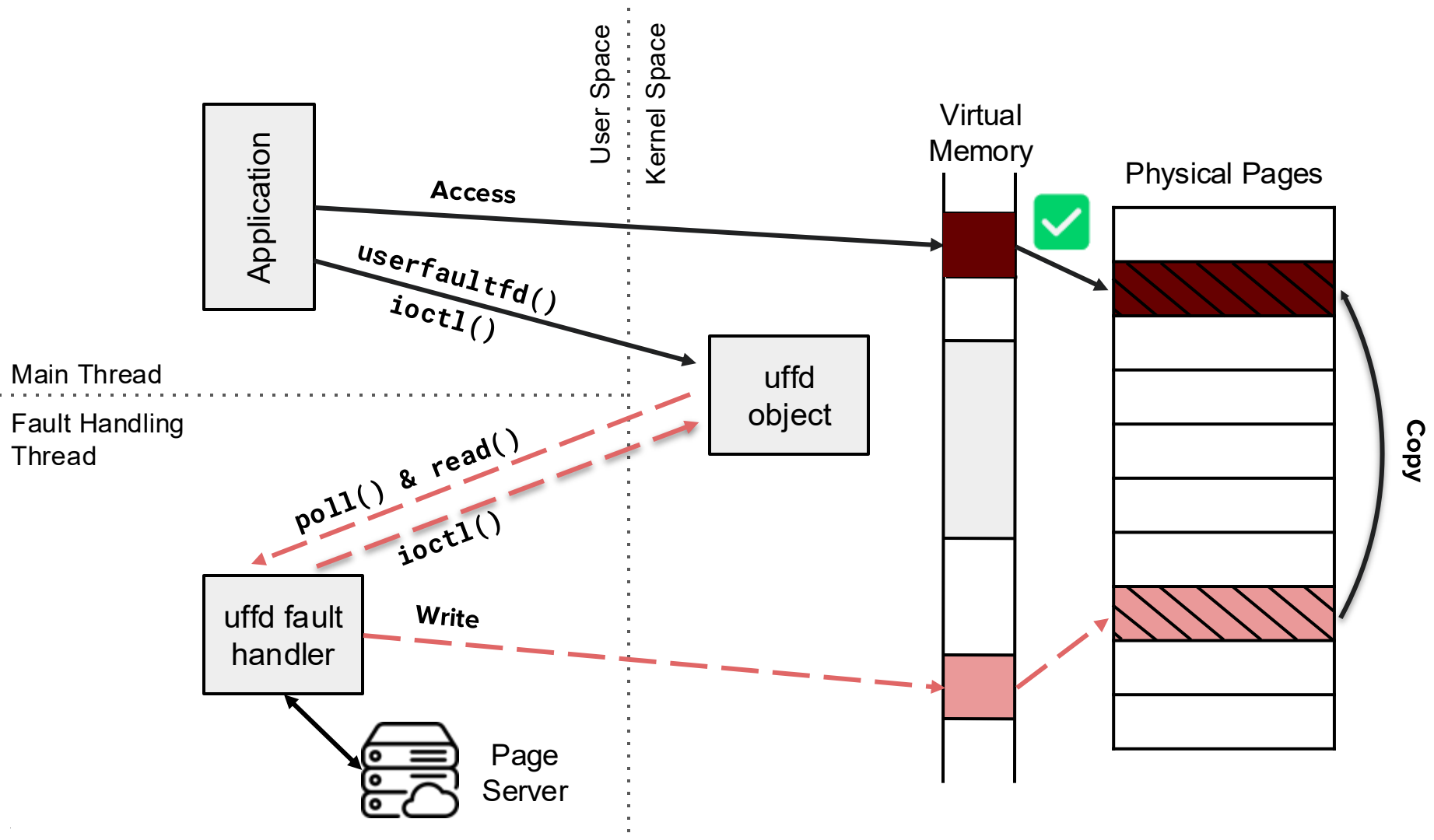
User Space Page Fault Handling

- `userfaultfd()`
- Added in Linux 4.3 (2015)
- Original motivation: post-copy VM migration
- Separate thread runs fault routine


User Space
Kernel Space
Application
Access
userfaultfd()
ioctl()
Main Thread
Fault Handling Thread
uffd object
poll()
uffd fault handler
Virtual Memory
Physical Pages


User Space
Kernel Space
Application
Access
userfaultfd()
ioctl()
Main Thread
Fault Handling
Thread
uffd
object
poll() & read()
uffd fault
handler
Virtual
Memory
Physical Pages

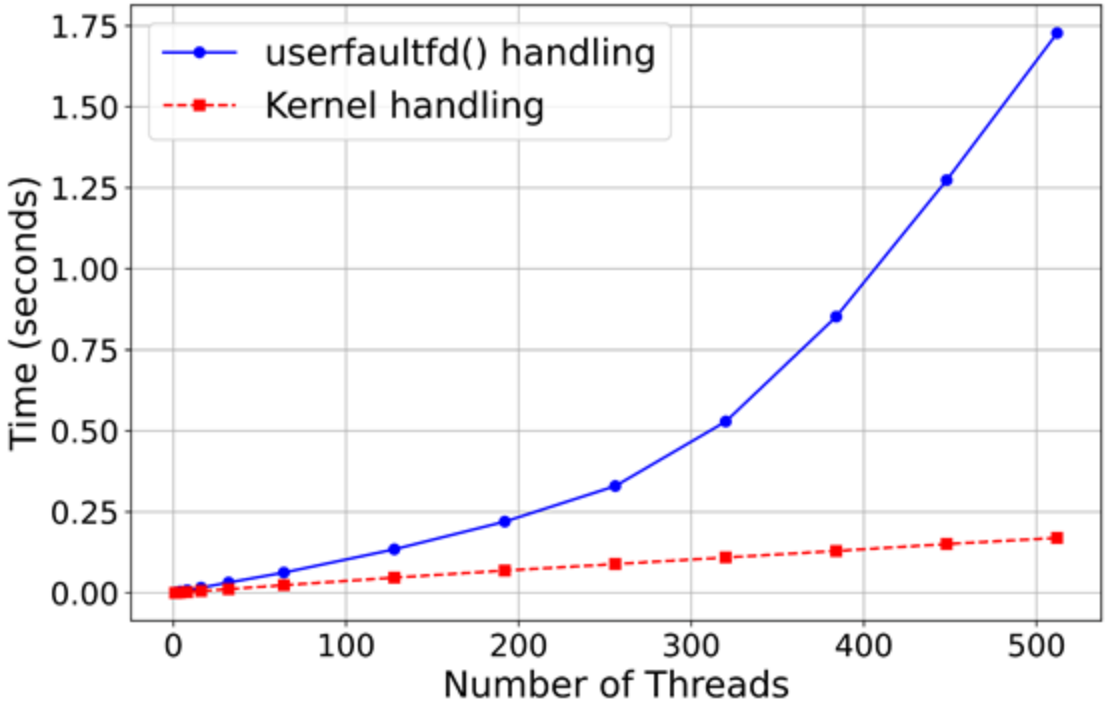

User Space
Kernel Space
Application
Access
userfaultfd()
ioctl()
Main Thread
Fault Handling Thread
uffd object
poll() & read()
uffd fault handler
Write
Page Server
Virtual Memory
Physical Pages


User Space
Kernel Space
Application
Access
userfaultfd()
ioctl()
Main Thread
Fault Handling Thread
uffd object
poll() & read()
ioctl()
uffd fault handler
Write
Page Server
Virtual Memory
Physical Pages
Copy

Performance Limitations of `userfaultfd()`

- Fault-handling thread leads to context switch
- At least three kernel-user space crossings
- Excess data copying

Scalability Limitations of `userfaultfd()`

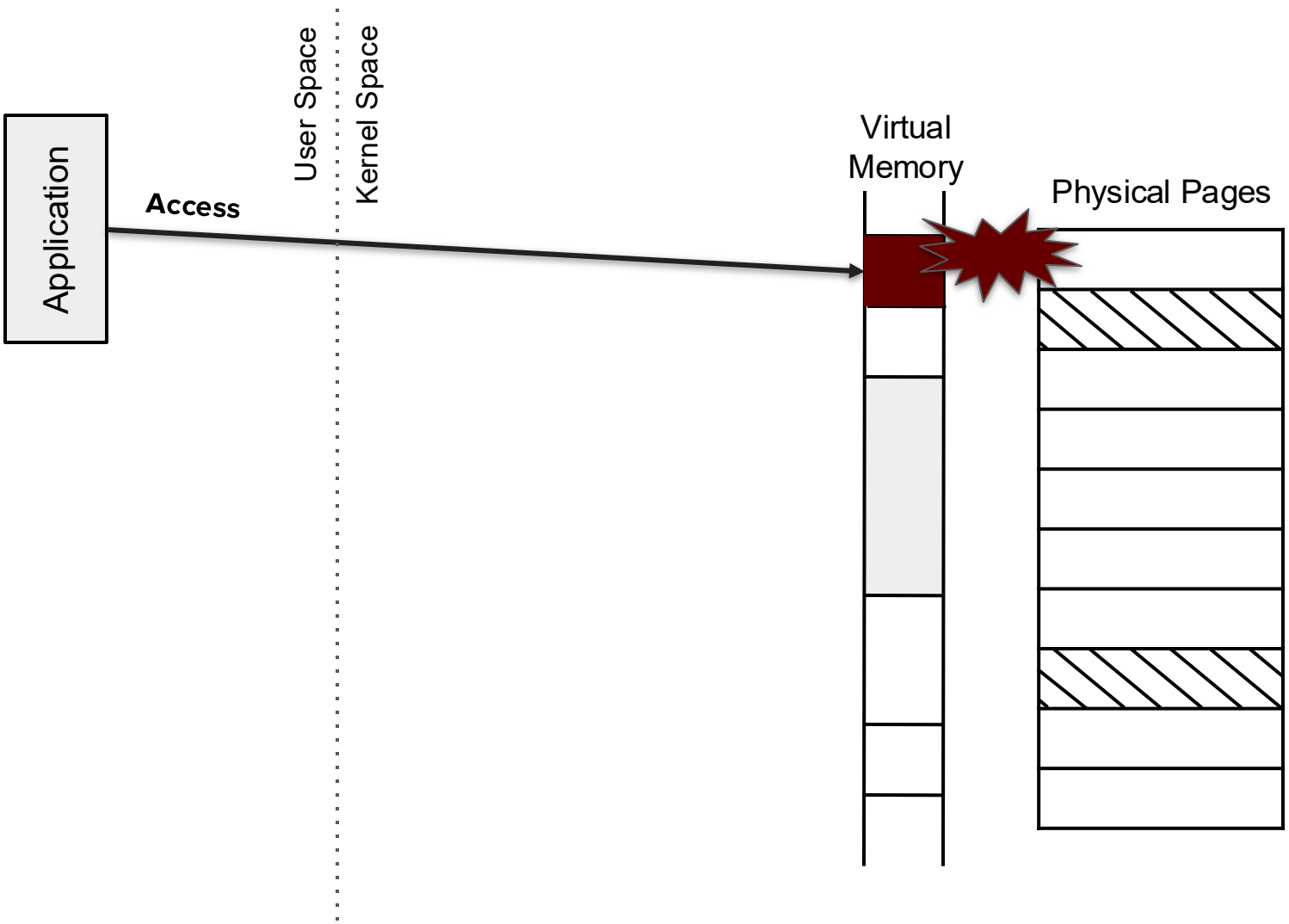


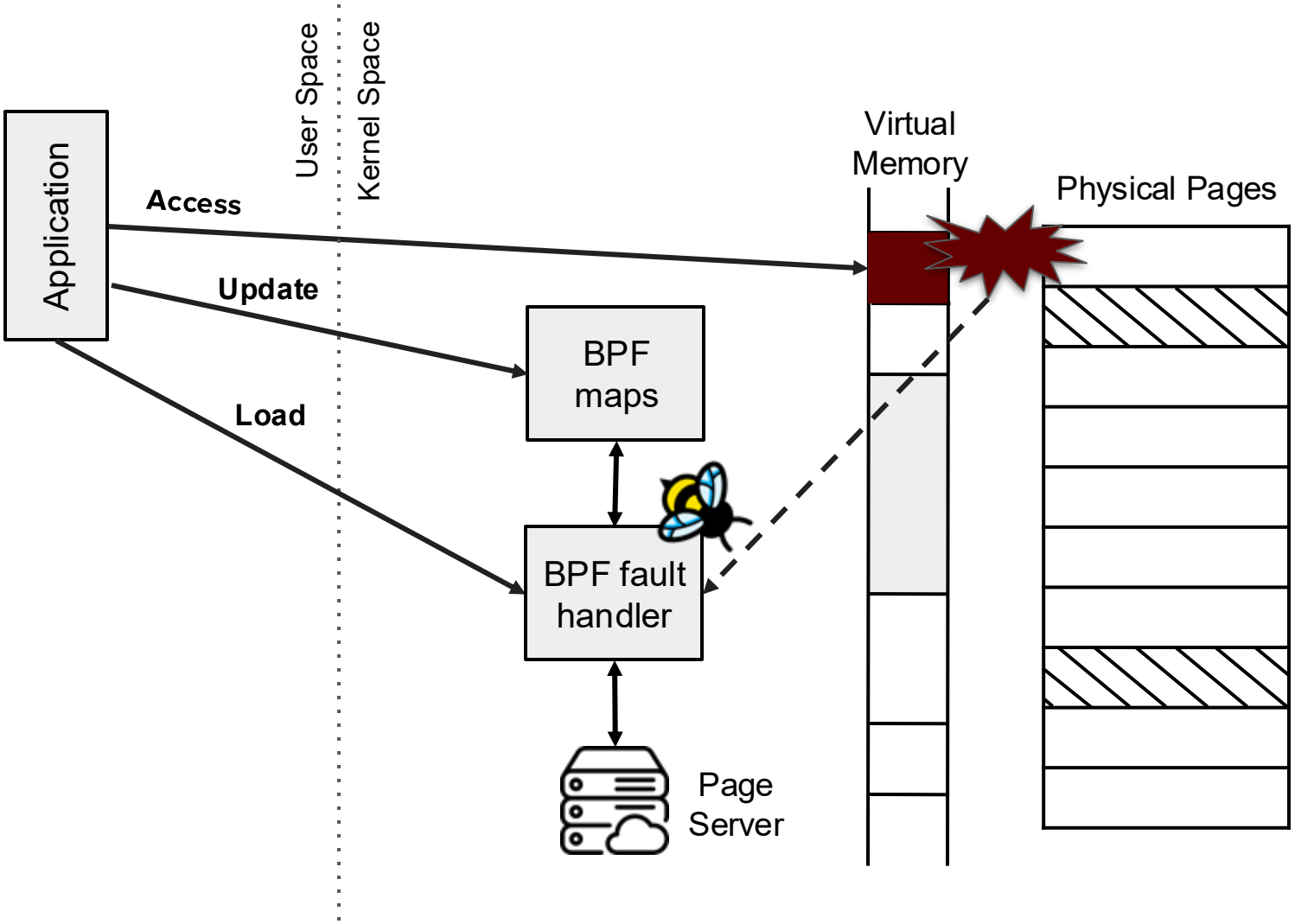
Security Limitations of `userfaultfd()`

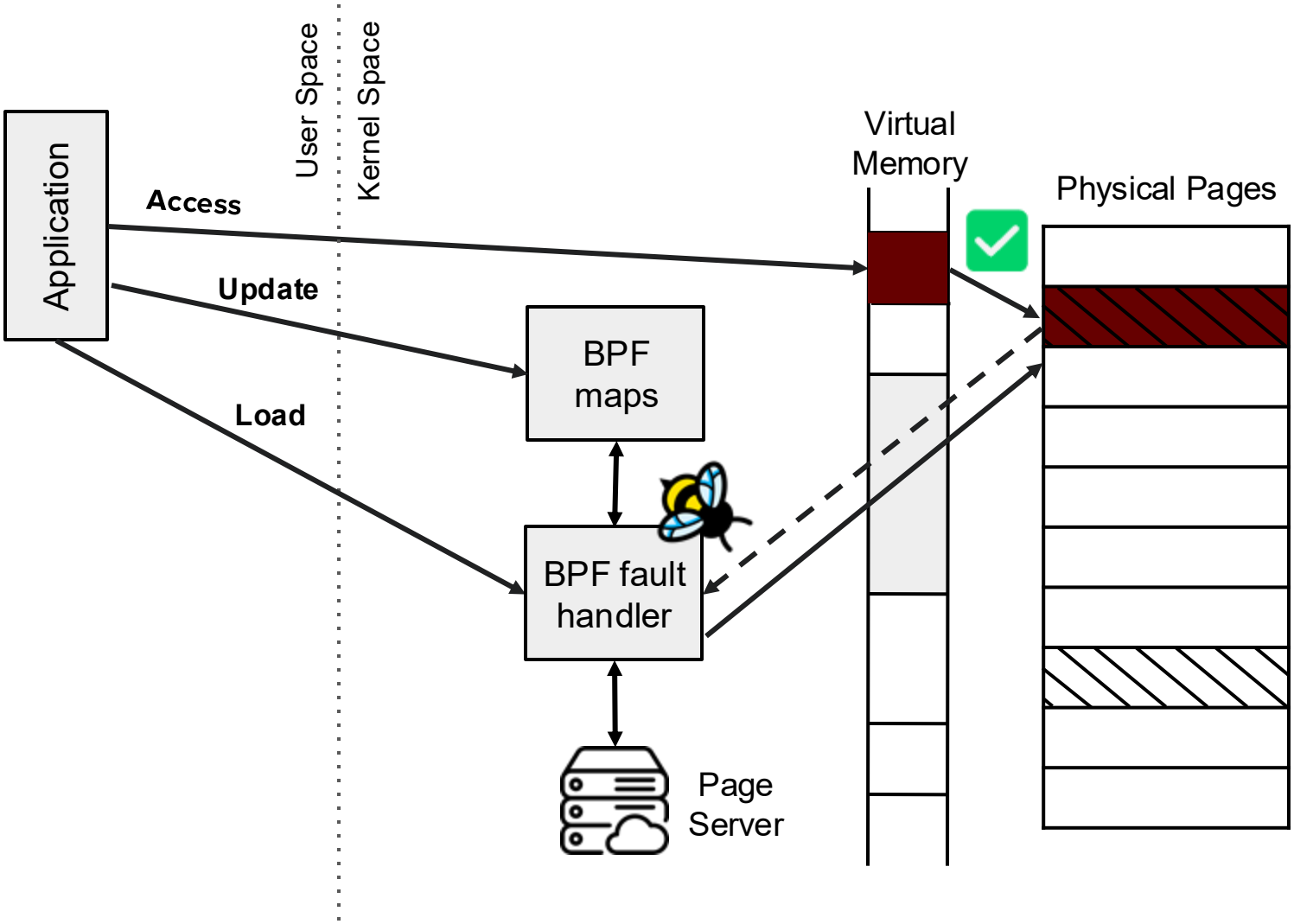
- Exploited in a number of vulnerabilities
  - Indefinitely block kernel execution at a specific point
- Disabled in some container runtimes by default

eBPF Page Fault Handling

- Push fault-handling routine into kernel
- Per-VMA eBPF programs


Application
Access
User Space
Kernel Space
Virtual
Memory
Physical Pages


User Space
Kernel Space
Application
Access
Update
Load
BPF maps
BPF fault handler
Page Server
Virtual Memory
Physical Pages


User Space
Kernel Space
Application
Access
Update
Load
BPF maps
BPF fault handler
Page Server
Virtual Memory
Physical Pages

Benefits of eBPF Fault Handling

- No fault-handling thread – each thread handles own page faults
- At least one kernel-user space crossing
- Potential for zero-copy fault handling

Applications

- Post-copy VM migration
- Faster Java garbage collection
- Accelerating start-up of serverless functions
- Performant memory debugging
- more…

Conclusion

- Applications desire custom page fault handling
- `userfaultfd()` has real limitations
- We propose eBPF-based page fault handling

Thank you!

Contact:

Tal Zussman
tz2294@columbia.edu

Teng Jiang
tj2488@columbia.edu