CS 3214
Computer Systems

Virtual Memory

Godmar Back

Brief Review from CompOrg

- Virtual address:
  - addresses used by user programs, linkers, etc. printf("%p\n", ptr);
  - Range: 0…2^addresswidth
- Physical address:
  - address used internally to address memory; not visible to user
  - Range: 0…X where X is memory in computer
- Page: contiguous range of addresses, typical sizes are 4K
  - Virtual page – contiguous range of virtual address
  - Physical page (frame) – contiguous range of physical addresses
- MMU: Memory management unit that maps virtual to physical pages based on information found in *page tables*
- TLB: Translation Lookaside Buffer:
  - Caches such mappings

Virtual Memory

- Is not a “kind” of memory
- Is a technique that combines one or more of the following concepts:
  - Address translation (always)
  - Paging from/to disk (usually)
  - Protection (usually)
- Can make storage that isn’t physical DRAM appear as though it were

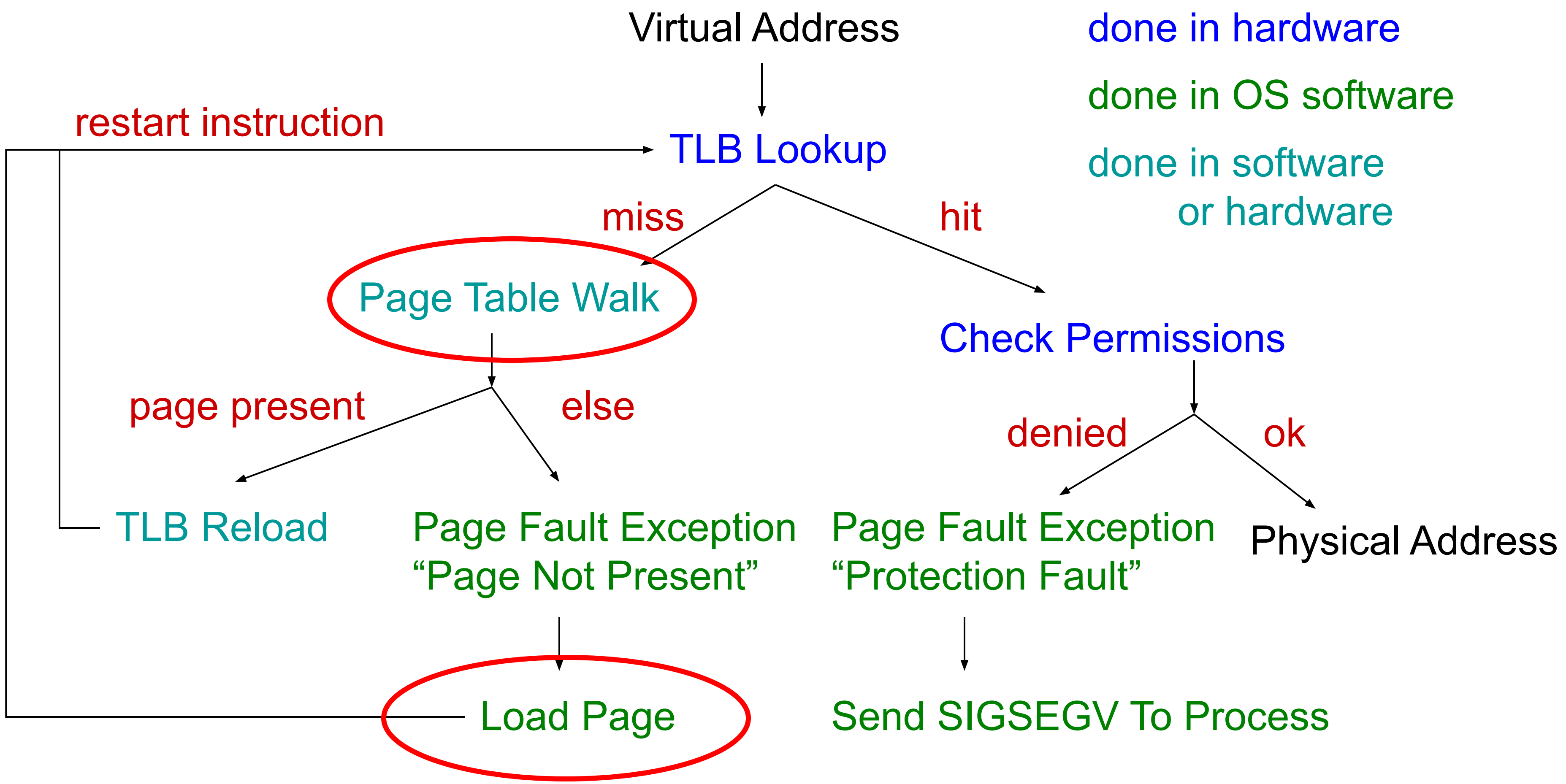
Key goals for Virtual Memory

- Virtualization
  1. Maintain illusion that each process has entire memory to itself
     - Per-process address spaces
  2. Allow processes access to more memory than is really in the machine (or: sum of all memory used by all processes > physical memory)
     - Makes DRAM a cache for disk
- Protection
  1. make sure there’s no way for any process to access another process’s data unintentionally
  2. protect system-internal data/kernel data

Address Translation

- Provides a way for OS to interpose on memory accesses
- OS maintains *for each process* a mapping
  { virtual addresses } → { physical addresses }
  in a per-process page table
  - Which virtual addresses are valid (depends on process memory layout)
  - Where they map to (depends on availability of physical memory)
  - What kind of accesses are allowed (read/write/execute)
- OS manages page tables
  - Based on input/commands from user processes
  - Based on resource management decisions

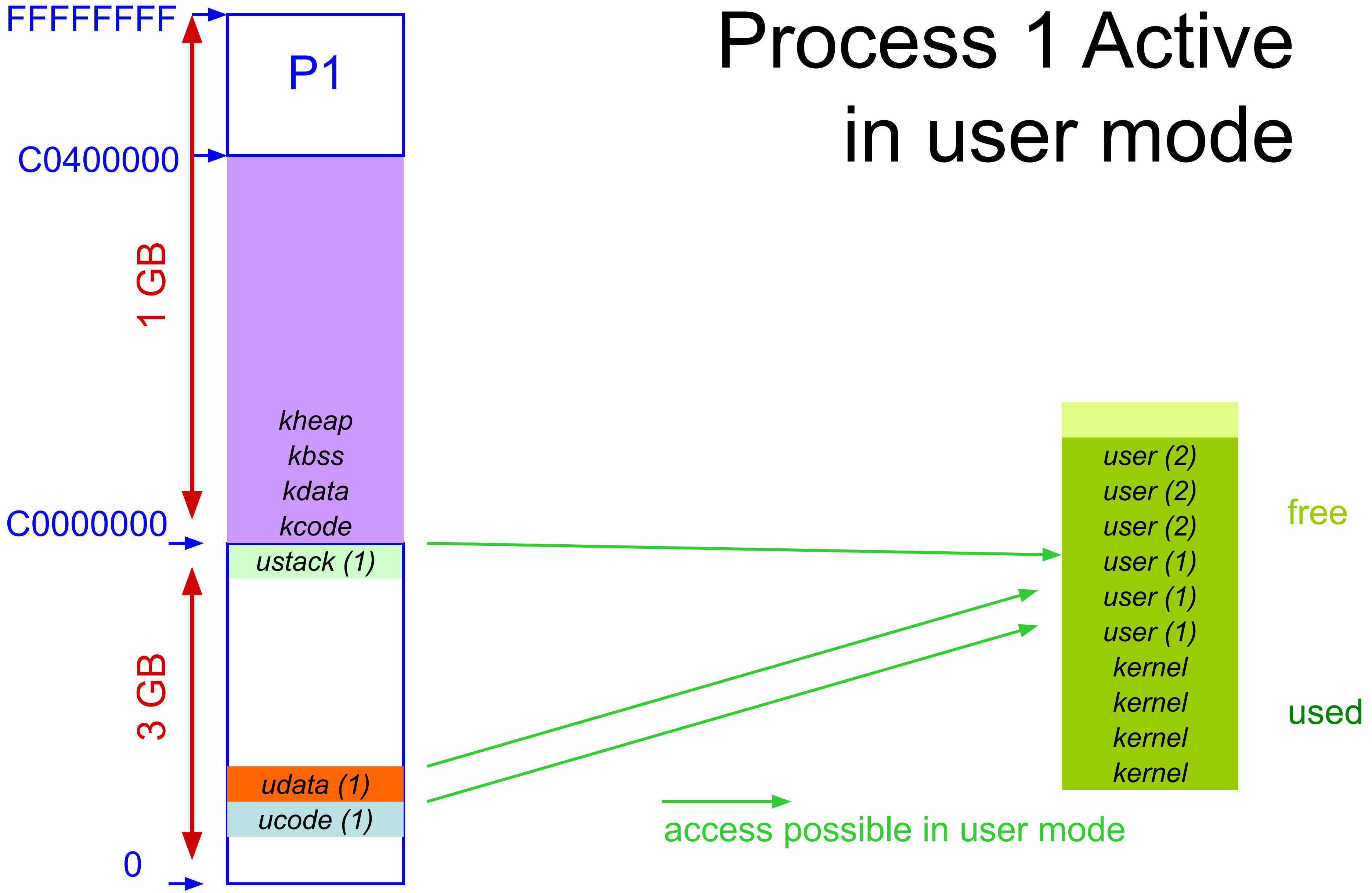
Address Translation & TLB



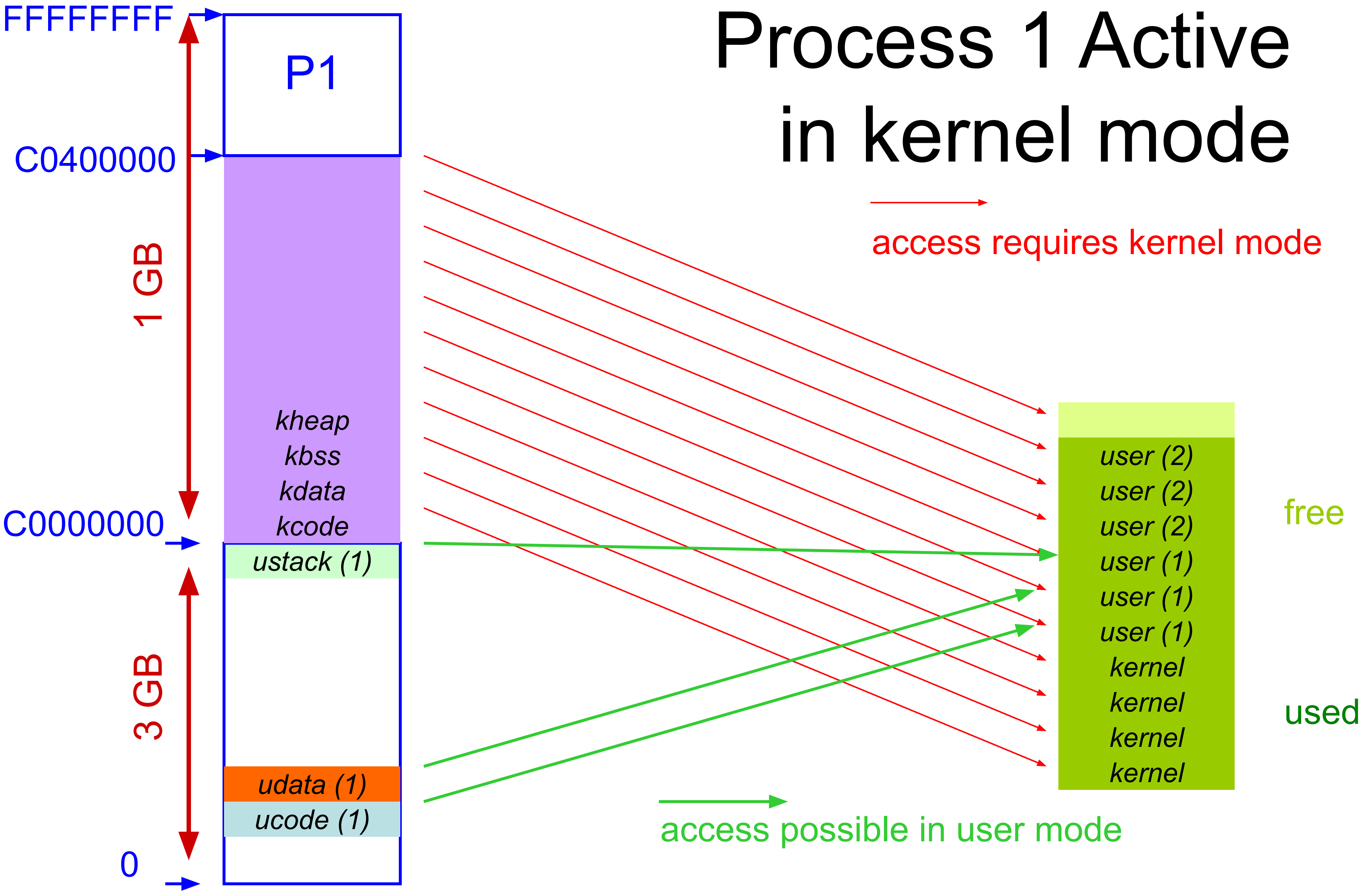
Switching Address Spaces

- Following slides show how virtual-to-physical mappings change on mode switch/context switch/mode switch sequence
  - Show a bit of kernel-level implementation detail
- In multi-threaded case, context switch *may or may not* involve a change in current address space
- Costs of switching address spaces adds to context switch cost
  - Mainly opportunity cost: need to flush TLB & then take the misses to repopulate it

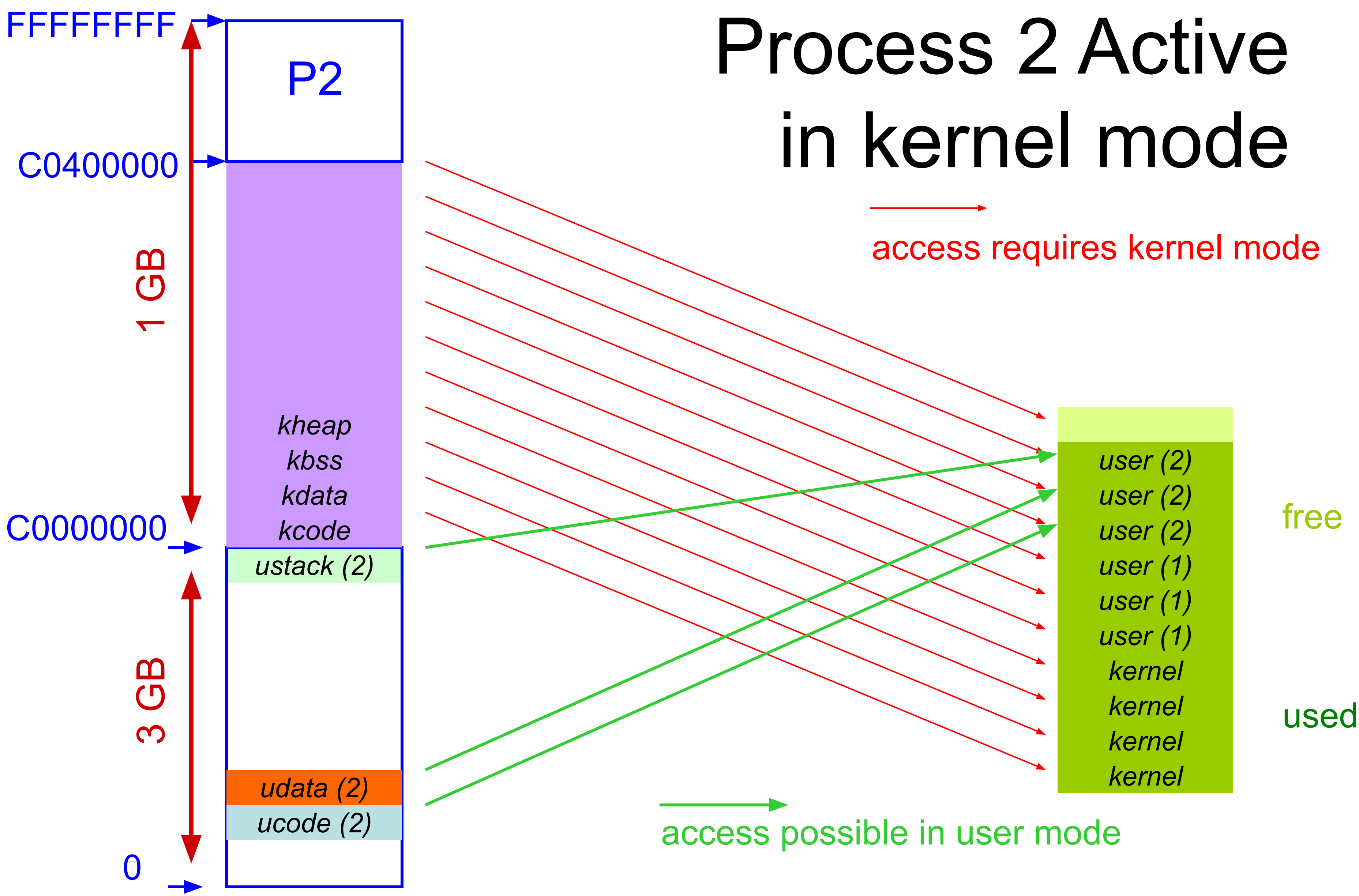
Process 1 Active in user mode



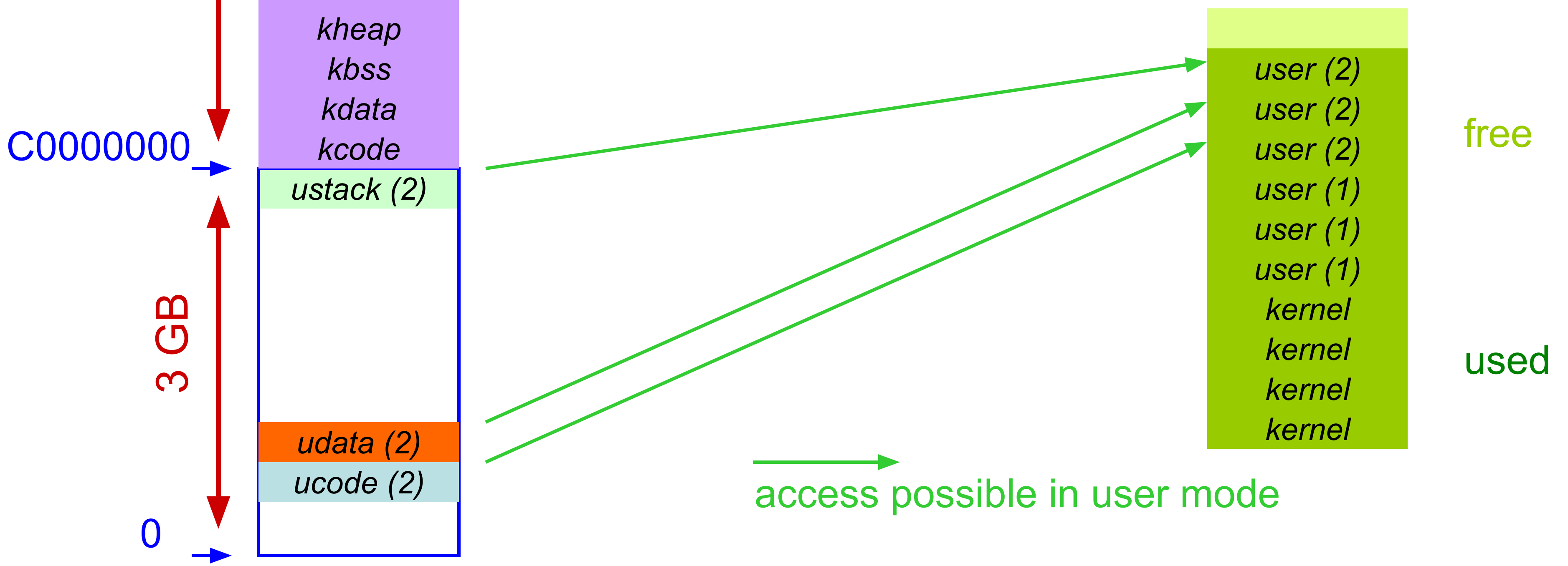
Process 1 Active in kernel mode



Process 2 Active in kernel mode



Process 2 Active in user mode



Meltdown Mitigation

- Post Meltdown, kernel and user mode no longer use the same page table.
- Therefore, the (red) kernel mappings are no longer immediately accessible once the processor switches into kernel mode.
- Requires additional page table switch once the kernel is entered (expensive), otherwise, it's the same setup.

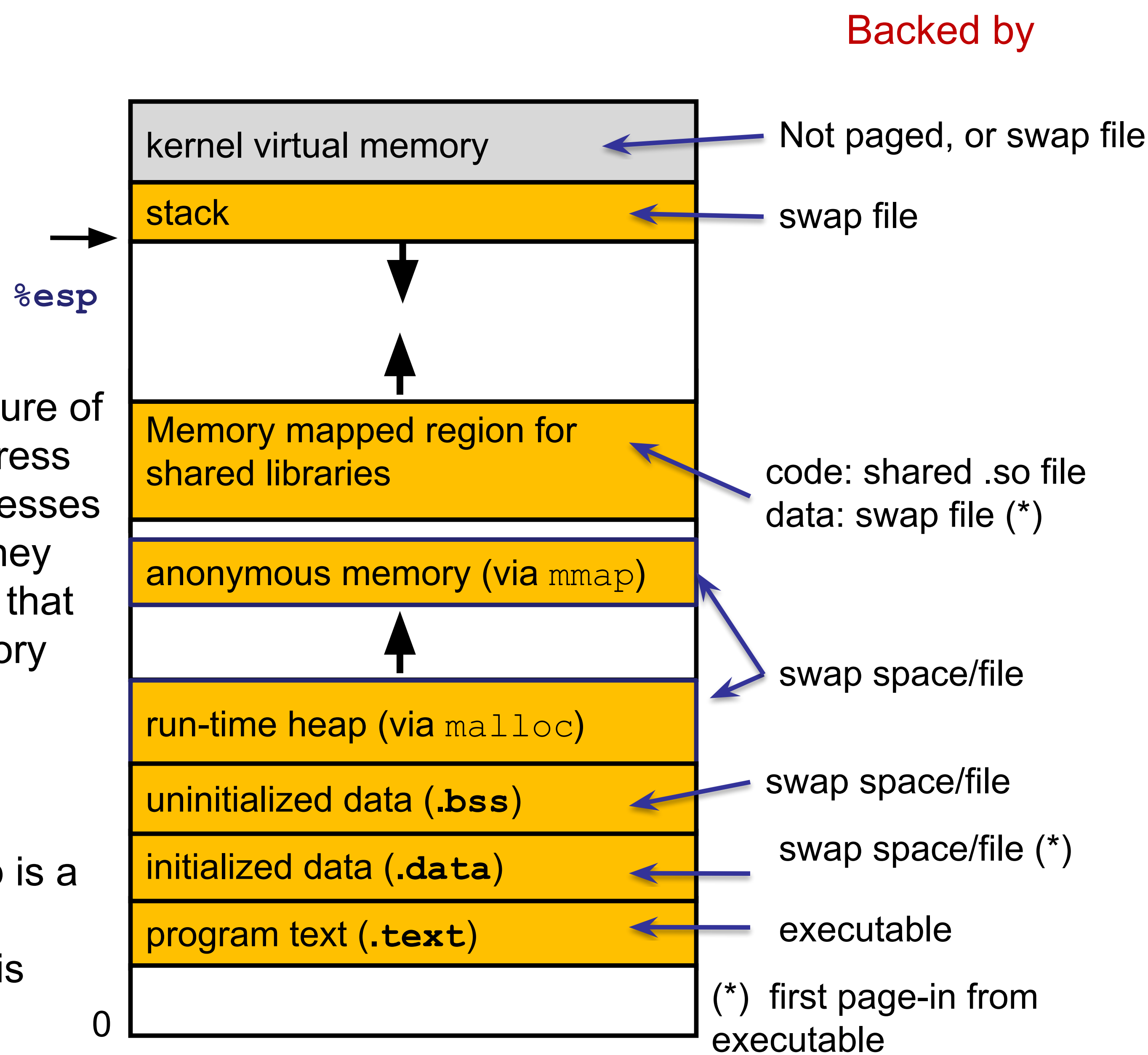
Paging to/from disk

- Idea: hold only those data in physical memory that are actually accessed by a process
- Maintain map for each process
  { virtual addresses } → { physical addresses } ∪ { disk addresses }
- OS manages mapping, decides which virtual addresses map to physical (if allocated) and which to disk
- Disk addresses include:
  - Executable .text, initialized data
  - Swap space (typically lazily allocated)
  - Memory-mapped (mmap'd) files (see example)
- **Demand paging**: bring data in from disk lazily, on first access
  - Unbeknownst to application

Process Memory Image

OS maintains structure of each process's address space – which addresses are valid, what do they refer to, even those that aren't in main memory currently

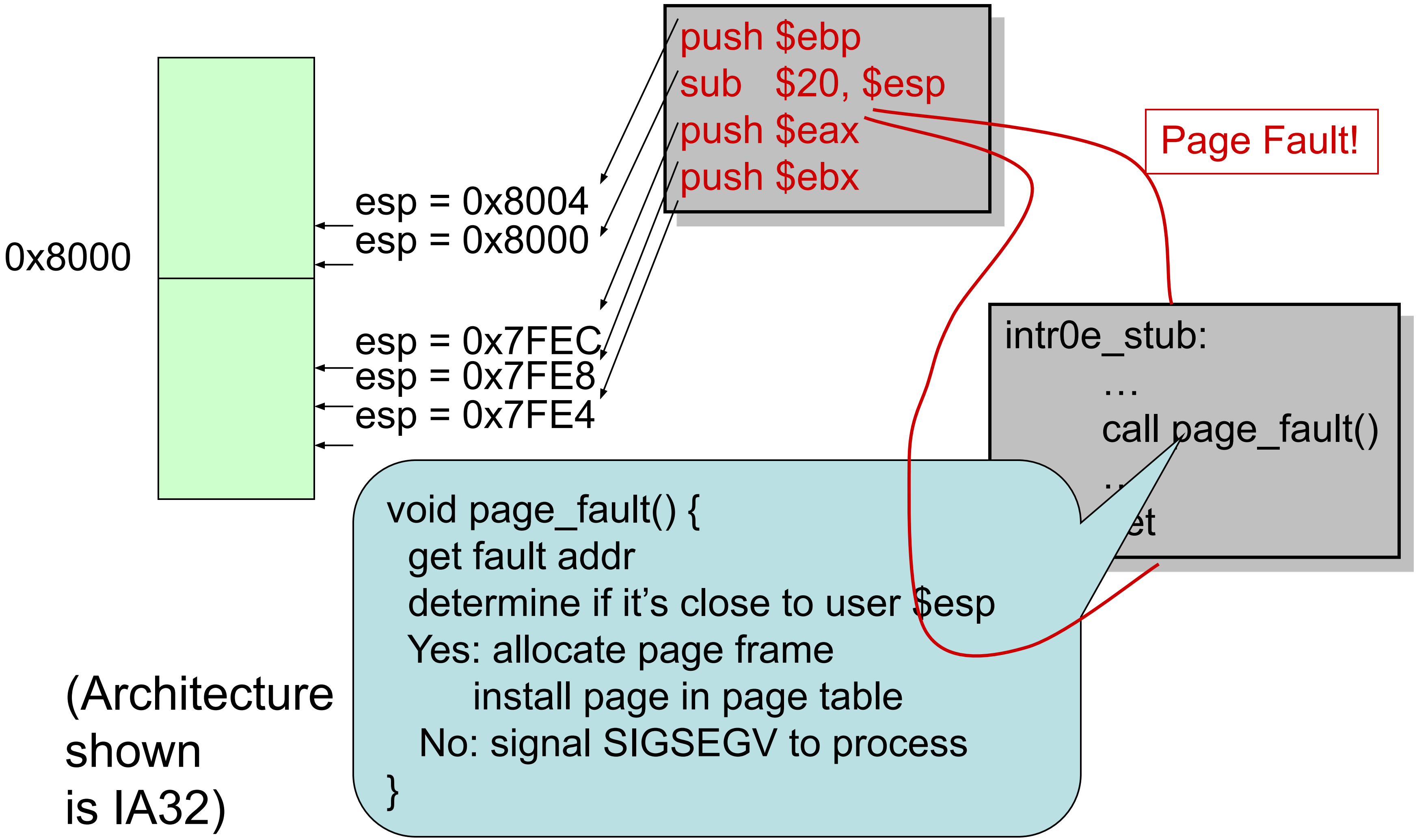
Try:
cat /proc/self/maps
(/proc/self/pagemap is a binary file with info about which pages is present)



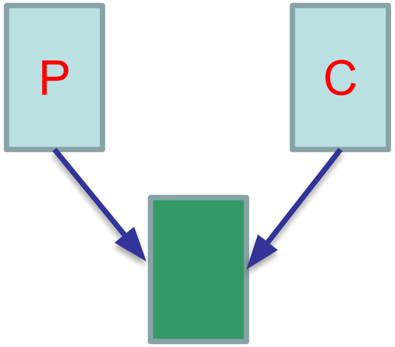
Servicing Page Faults

- When process accesses address that is not currently mapped, the hardware will signal a fault
  - If address is in kernel space, or refers to unmapped region
    - Send SIGSEGV to process
  - Else determine which region address is in
    - If heap, allocate new page (“minor fault”), or swap page from disk
    - If code segment, read code from executable
    - If first access to global variable, read data from disk; else swap from disk
    - If access to mmapped file, read data from file
  - Establish new v-p mapping in page table, and retry
- Note: there are no page faults for pages that are present in memory
  - There may be TLB misses, however – on x86, these are handled in hardware – can introduce hidden performance cost

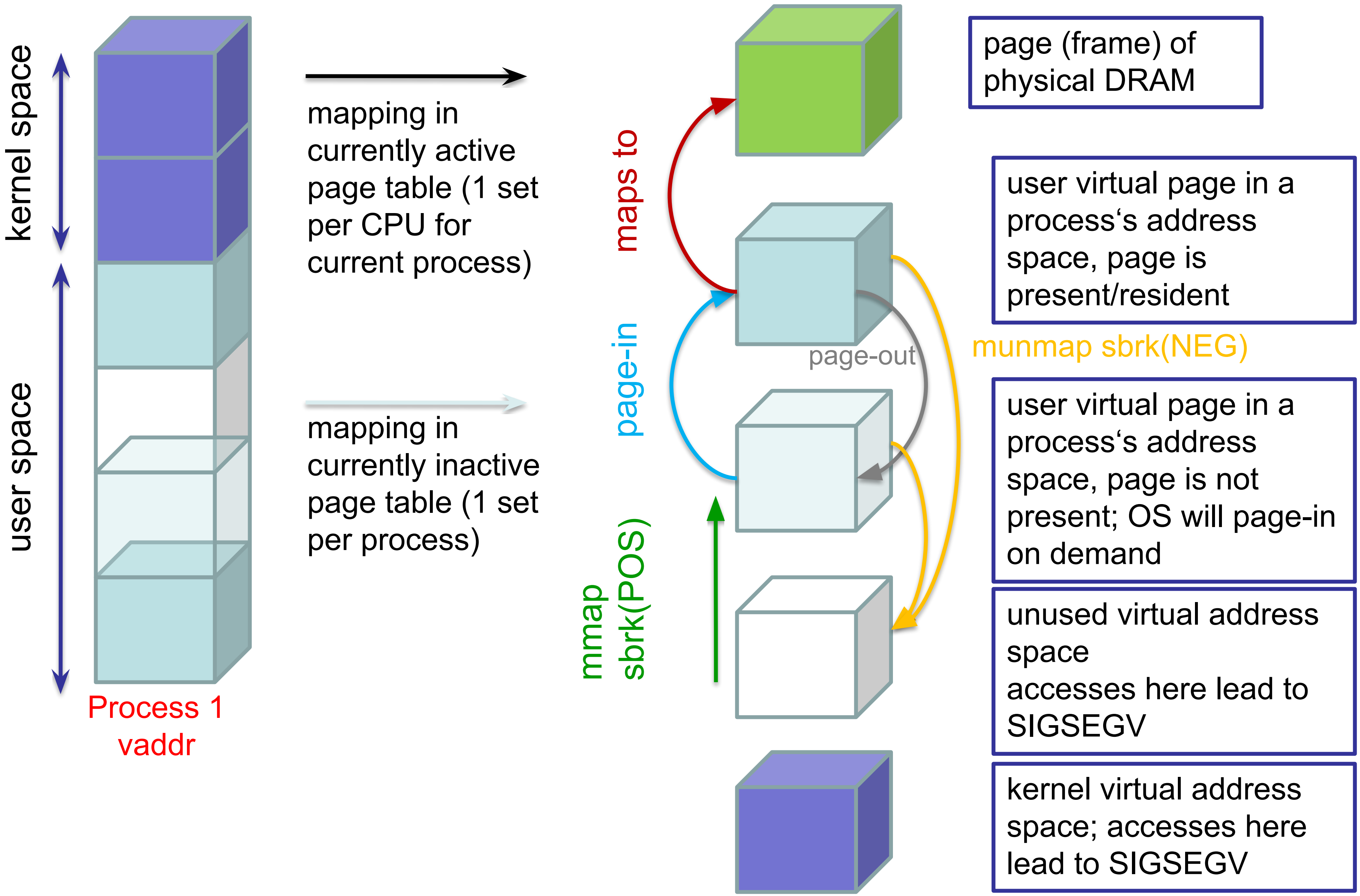
Microscopic View of Stack Growth

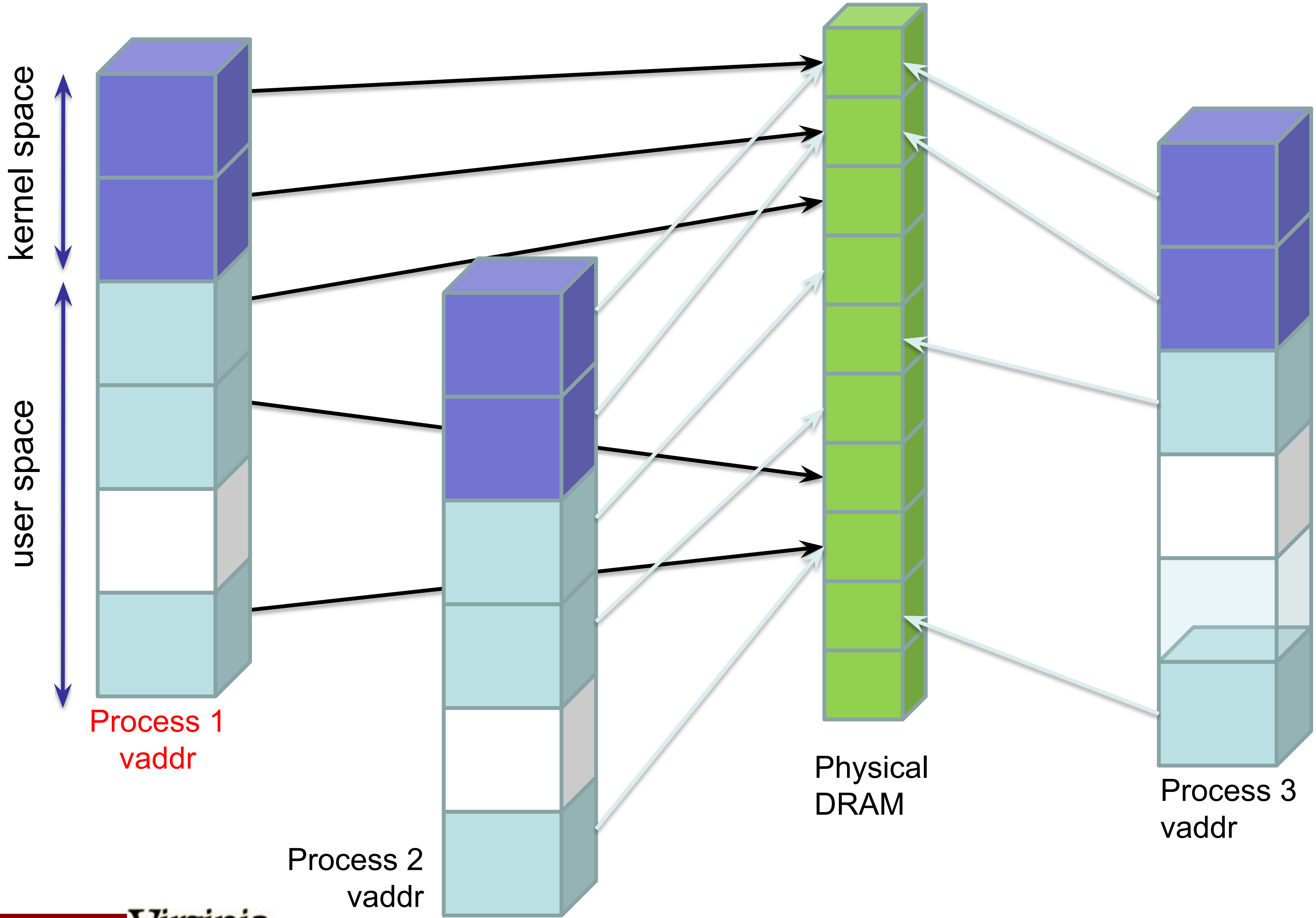


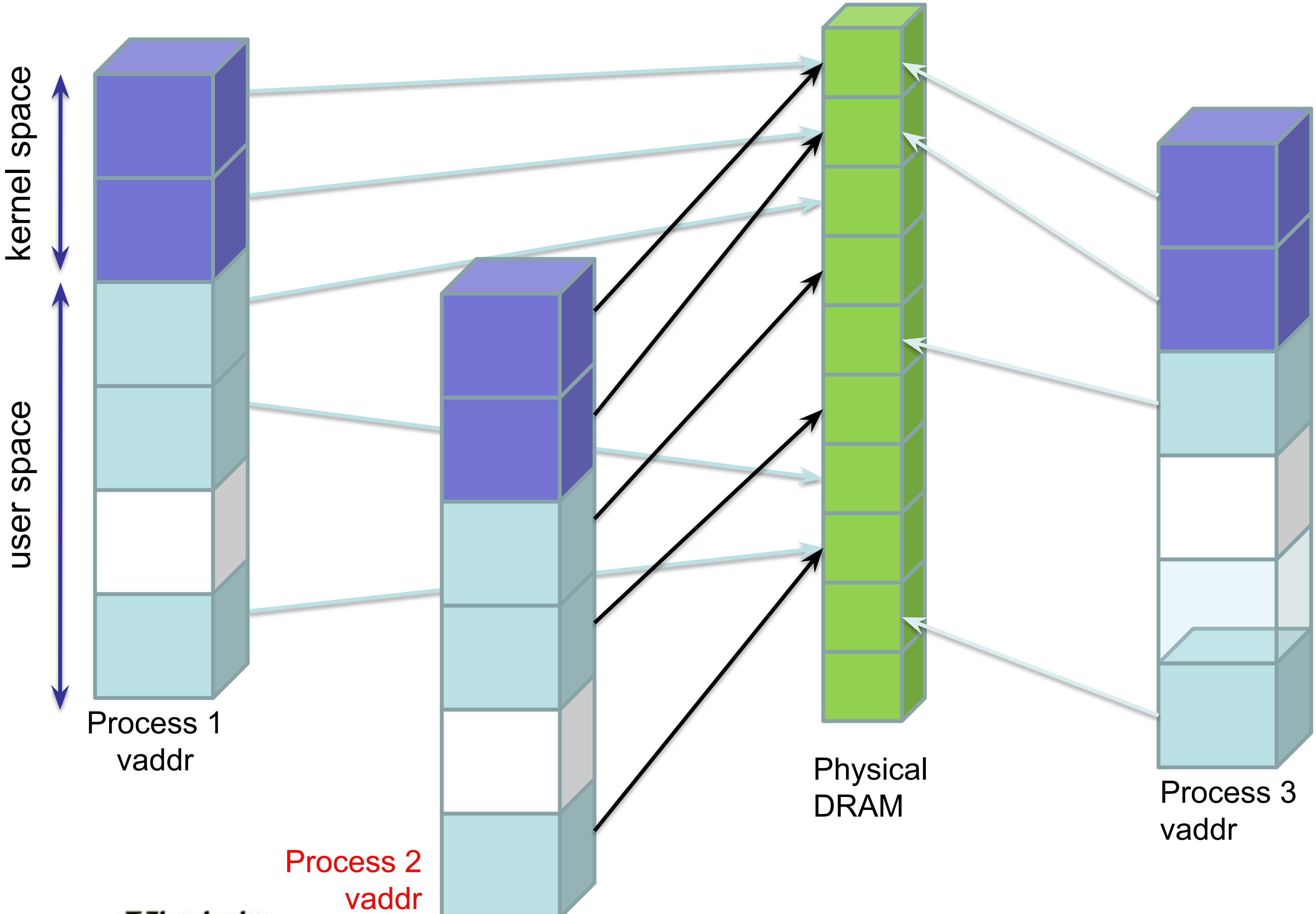
fork()/exec() revisited

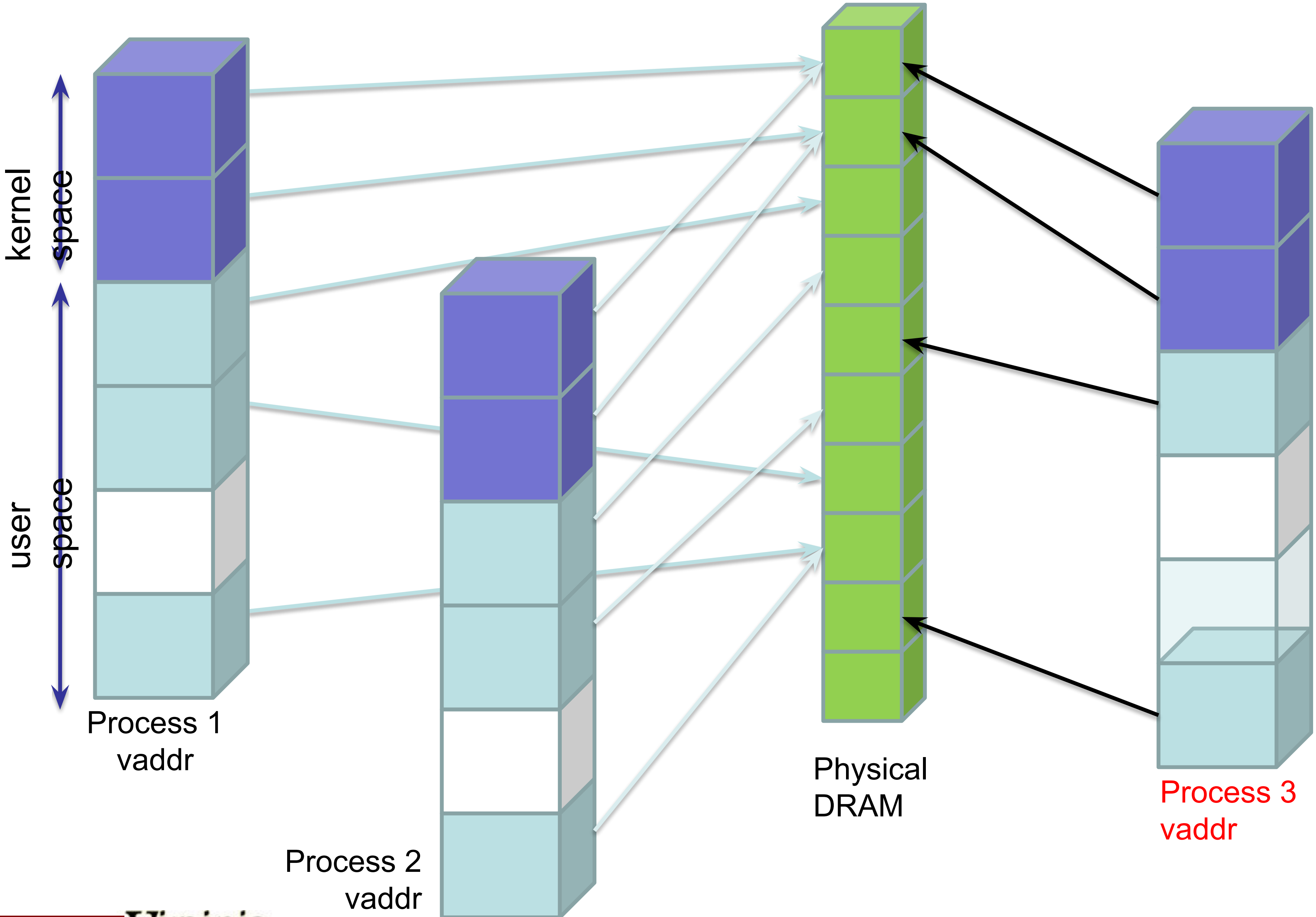


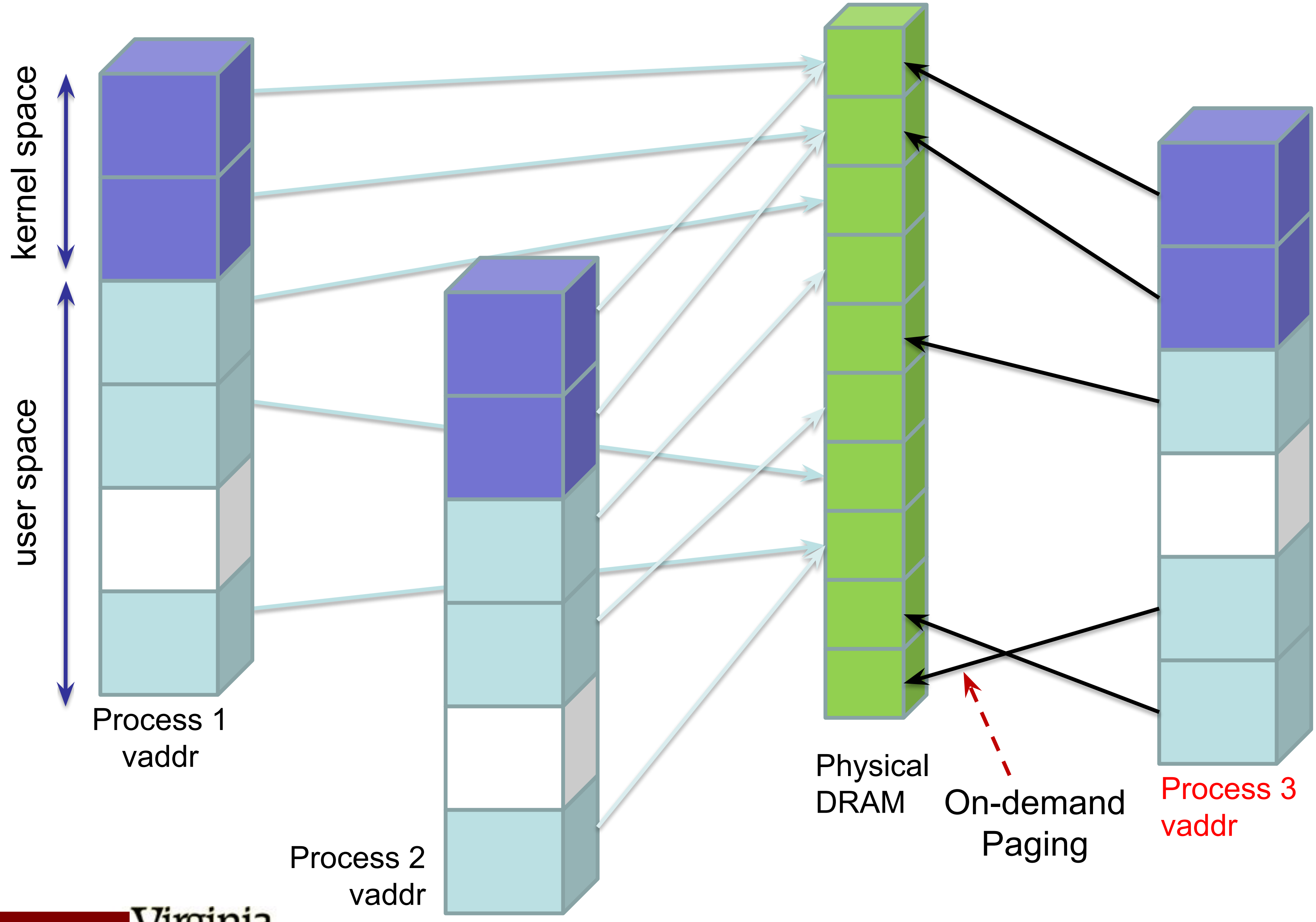
- fork():
  - Clone page table of parent
  - Set all entries read-only
  - Perform copy on write (if it happens while shared)
- exec():
  - Remove all existing page table entries
    - Unshares parent's entries
  - Start over as per instructions in executable
- Optimizes common case: child does an exec() shortly after fork()

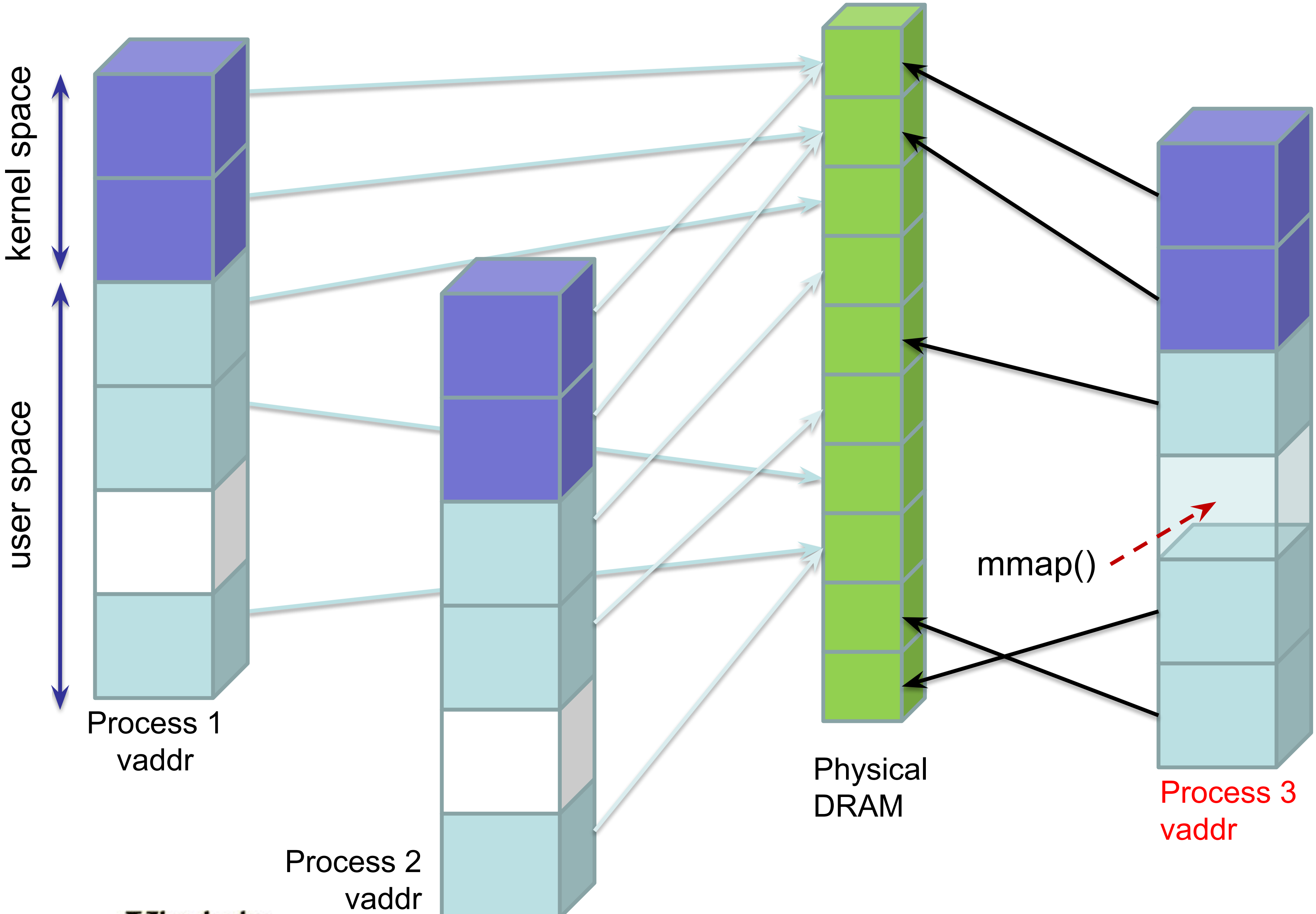

kernel space
user space
Process 1
vaddr
mapping in
currently active
page table (1 set
per CPU for
current process)
mapping in
currently inactive
page table (1 set
per process)
maps to
page-in
page-out
mmap
sbrk(POS)
munmap sbrk(NEG)
page (frame) of
physical DRAM
user virtual page in a
process's address
space, page is
present/resident
user virtual page in a
process's address
space, page is not
present; OS will page-in
on demand
unused virtual address
space
accesses here lead to
SIGSEGV
kernel virtual address
space; accesses here
lead to SIGSEGV

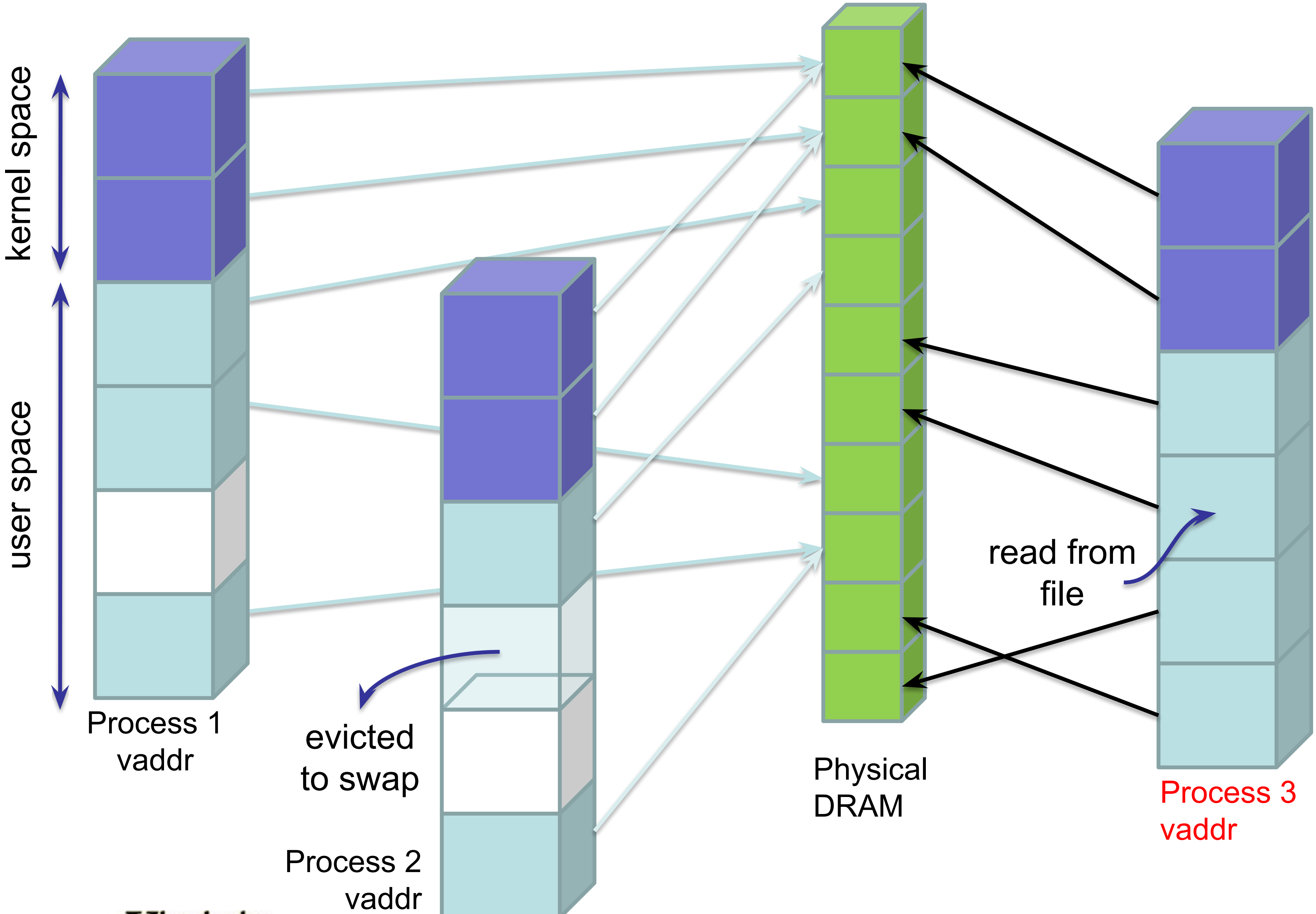

kernel space
user space
Process 1
vaddr
Process 2
vaddr
Physical
DRAM
Process 3
vaddr


kernel space
user space
Process 1
vaddr
Process 2
vaddr
Physical
DRAM
Process 3
vaddr


kernel space
user space
Process 1 vaddr
Process 2 vaddr
Physical DRAM
Process 3 vaddr


kernel space
user space
Process 1
vaddr
Process 2
vaddr
Physical
DRAM
On-demand
Paging
Process 3
vaddr


kernel space
user space
Process 1
vaddr
Process 2
vaddr
Physical
DRAM
mmap()
Process 3
vaddr


kernel space
user space
Process 1
vaddr
evicted
to swap
Process 2
vaddr
Physical
DRAM
read from
file
Process 3
vaddr

Managing Physical Memory

- OS must decide what to use physical memory for
  - Application Data
    - Mostly per process, except for shared memory areas
    - Heaps, stacks, BSS
  - File Data (Single copy per file)
    - Mmap'ed files, executables, shared libs
    - Chunks of files recently accessed via explicit I/O
- When demand is greater than supply, must rededicate physical memory by "evicting" pages to disk
  - Either done ahead of time with some hysteresis
  - Or last minute ("direct reclaim")

Page Replacement Strategies

- Prediction game: optimal strategy is to replace ("evict") the page whose data will be accessed farthest in the future
  - Of course, can't know that → use heuristics
- Most heuristics are based on "past = future" idea and approximate LRU
  - While adding guards against scenarios in which LRU is known to fail, e.g. large looping accesses or single sequential reads
  - Must approximate because per-access maintenance of LRU lists is too expensive
- Must weigh file data vs. process data
- Must weigh other pages from same process vs. all processes
  - Local vs. global replacement policies

VM Access Time & Page Fault Rate

access time = p * memory access time
+ (1-p) * (page fault service time + memory access time)

- Consider expected access time in terms of fraction p of page accesses that don't cause page faults.
- Then 1-p is page fault frequency
- Assume p = 0.99, assume memory is 100ns fast, and page fault servicing takes 10ms – how much slower is your VM system compared to physical memory?
- access time = 99ns + 0.01*(10000100) ns ≈ 100,000ns or 0.1ms
  - Compare to 100ns or 0.0001ms speed ≈ about 1000x slowdown
- Conclusion: even relatively low page fault rates lead to huge slowdown – must keep page fault rates *very low*

Thrashing

- VM works well if working set size (amount of memory accessed within an interesting time span) can be accommodated in physical memory
- If working set size grows too large, OS will continuously service page faults, and end up evicting pages accessed soon after
- Result: "thrashing"
  - Moving data to/from disk continually while not making progress on computation
  - Leads to *low* CPU utilization

Prefetching

- All modern VM systems use prefetching
  - Usual strategy: detect sequential accesses to file
    - even if done via virtual memory system & mmaped files
  - Sometimes application-guided
    - Linux readahead(2) system call
    - E.g. Windows Vista remembers which data an application touched (speeds up startup time)
- The performance of a VM system depends both on its page replacement and its prefetching strategies

VM viewed as a cache for disk

- Blocksize
  - Large (typically page), reflects high cost to initiate disk transfer
- Associativity
  - Full
- Tag storage overhead
  - Low relative to block size
- Write back cache
- Miss penalty
  - High: ~4-20ms
- Miss rate
  - Must be extremely low so that average access time ~ DRAM access time

Summary

- Virtual memory is a technique that combines
  - Address translation (Indirection)
  - Demand paging
  - Protection

to virtualize physical memory and protect applications and the kernel

- It is transparent to applications except for its possible performance impact