Project #4: KSM
(Kernel Samepage Merging)

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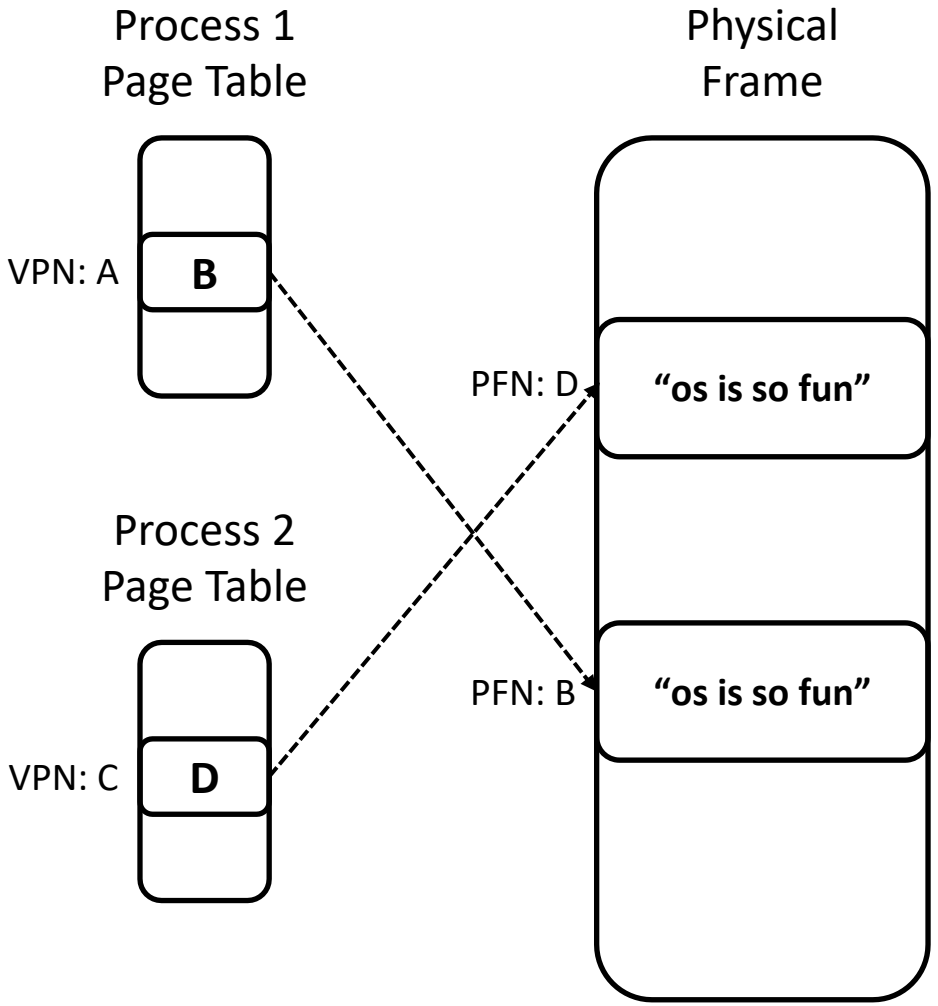
KSM (Kernel Samepage Merging)

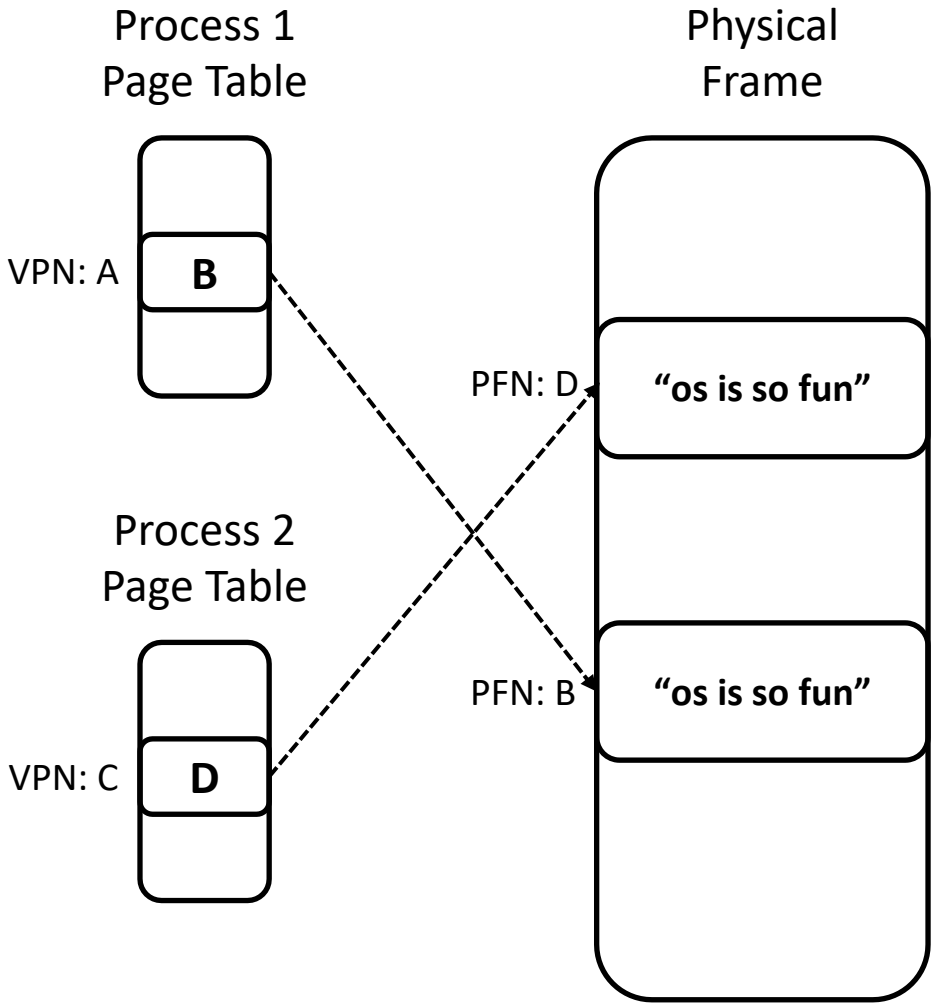
- KSM (Kernel Same page Merging) is a memory de-duplication feature that enables the kernel to consolidate identical memory pages into a single shared page across multiple processes.
- Merged pages are write-protected, therefore attempts to modify the merged page would cause a page fault.
- A modification to a merged page results in a copy-on-write action, thus preserving the integrity of the original shared page.

KSM (Kernel Samepage Merging)



- Process 1
  - VPN(A) → PFN (B)
- Process 2
  - VPN(C) → PFN (D)
- PFN (B) and PFN (D) has same contents

KSM (Kernel Samepage Merging)

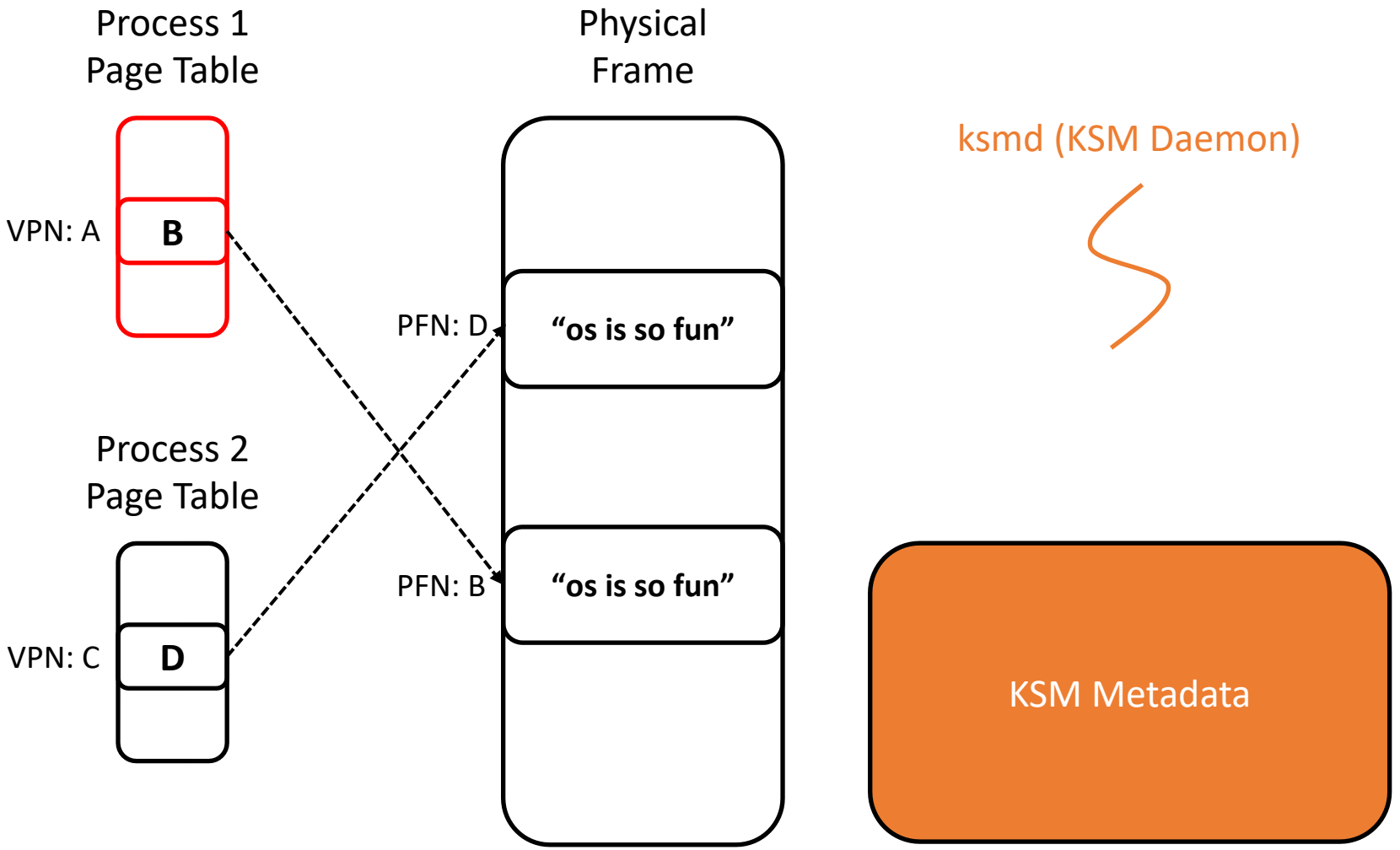


ksmd (KSM Daemon)

KSM Metadata
- **Detecting duplicate frames**
- **Manage when to free Physical frames**
- **…**

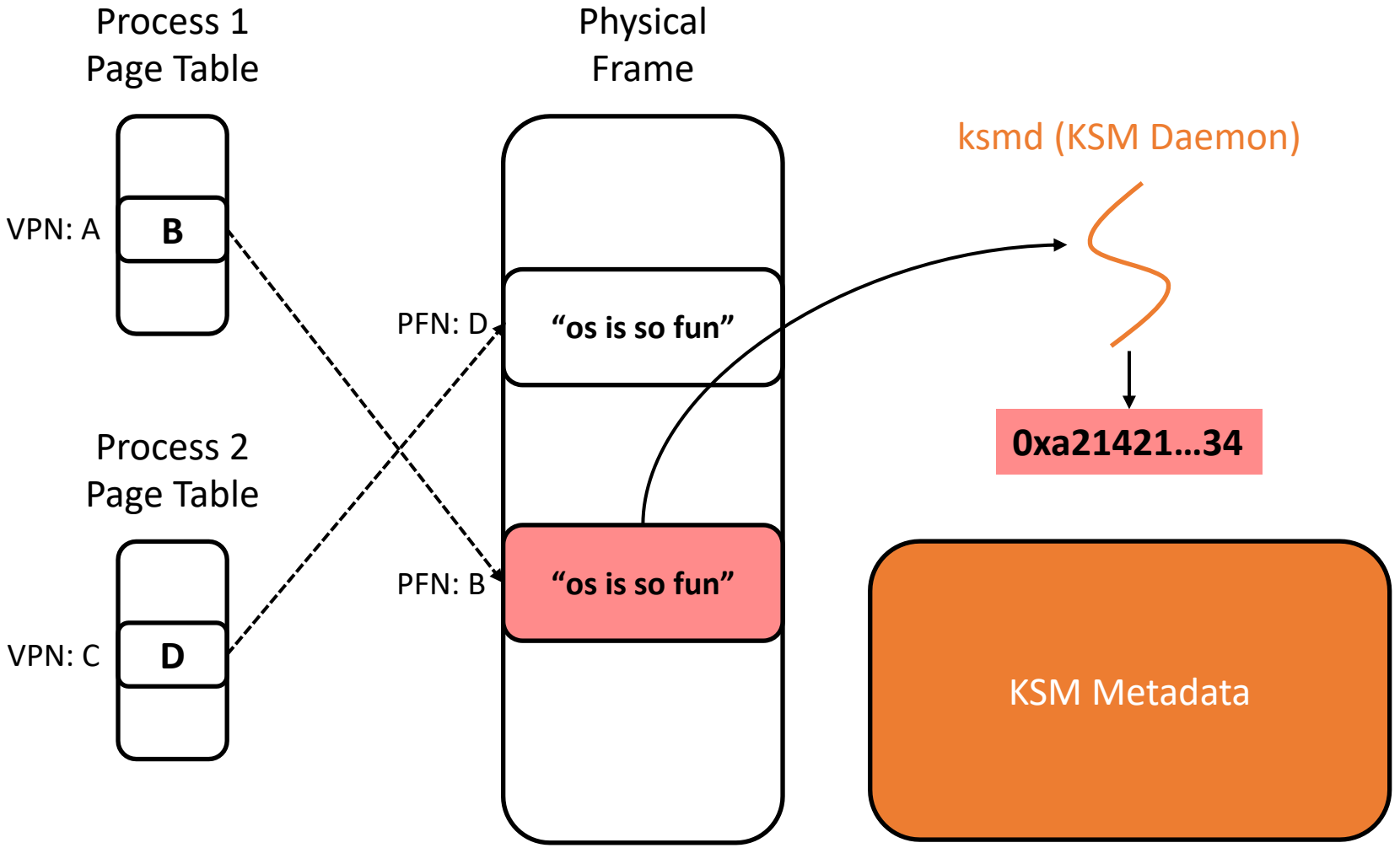
KSM Metadata

KSM (Kernel Samepage Merging)



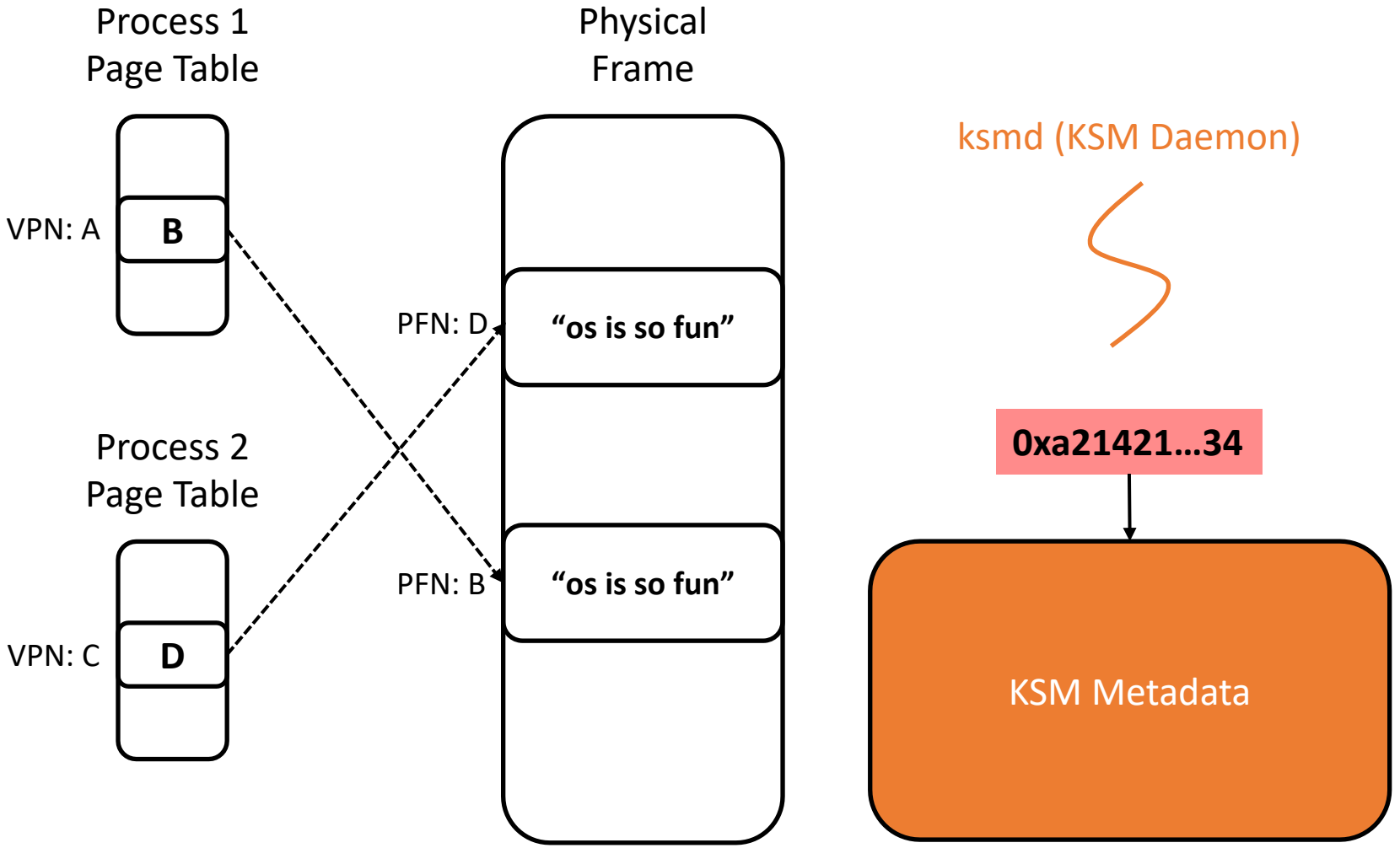
(1) ksmd Scans Process 1

KSM (Kernel Samepage Merging)



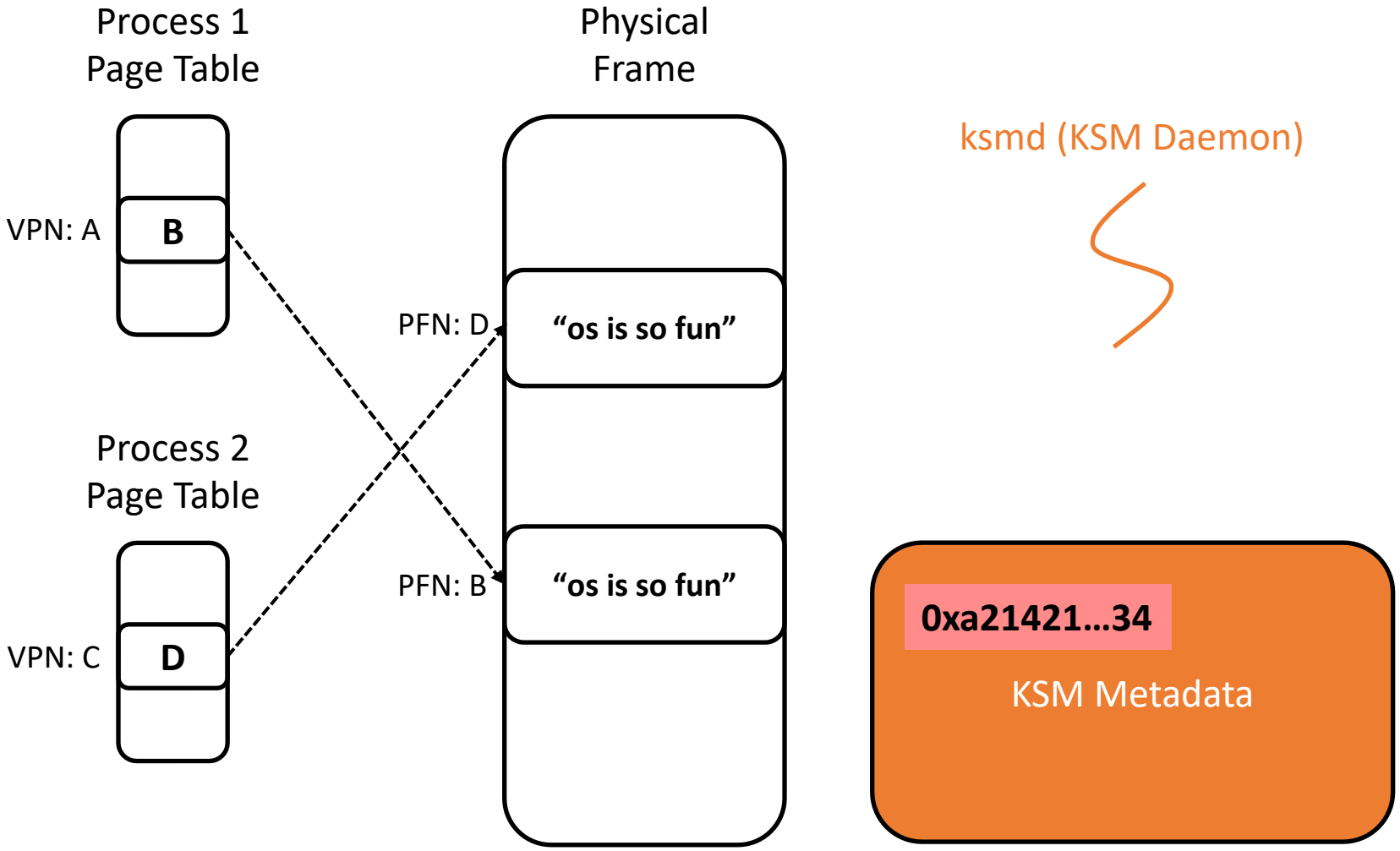
(1) ksmd Scans Process 1
(2) Hash PFN B

KSM (Kernel Samepage Merging)



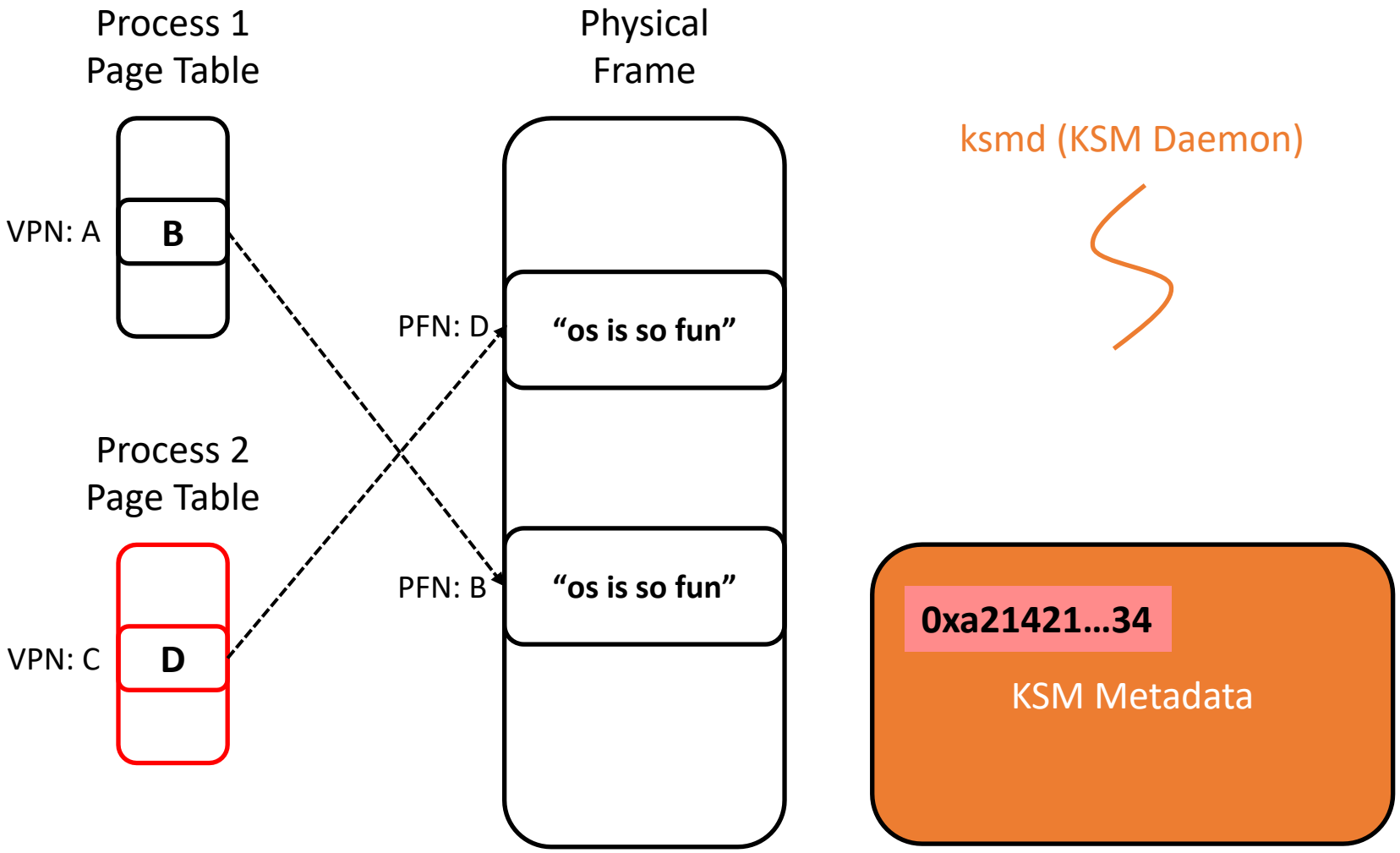
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta

KSM (Kernel Samepage Merging)



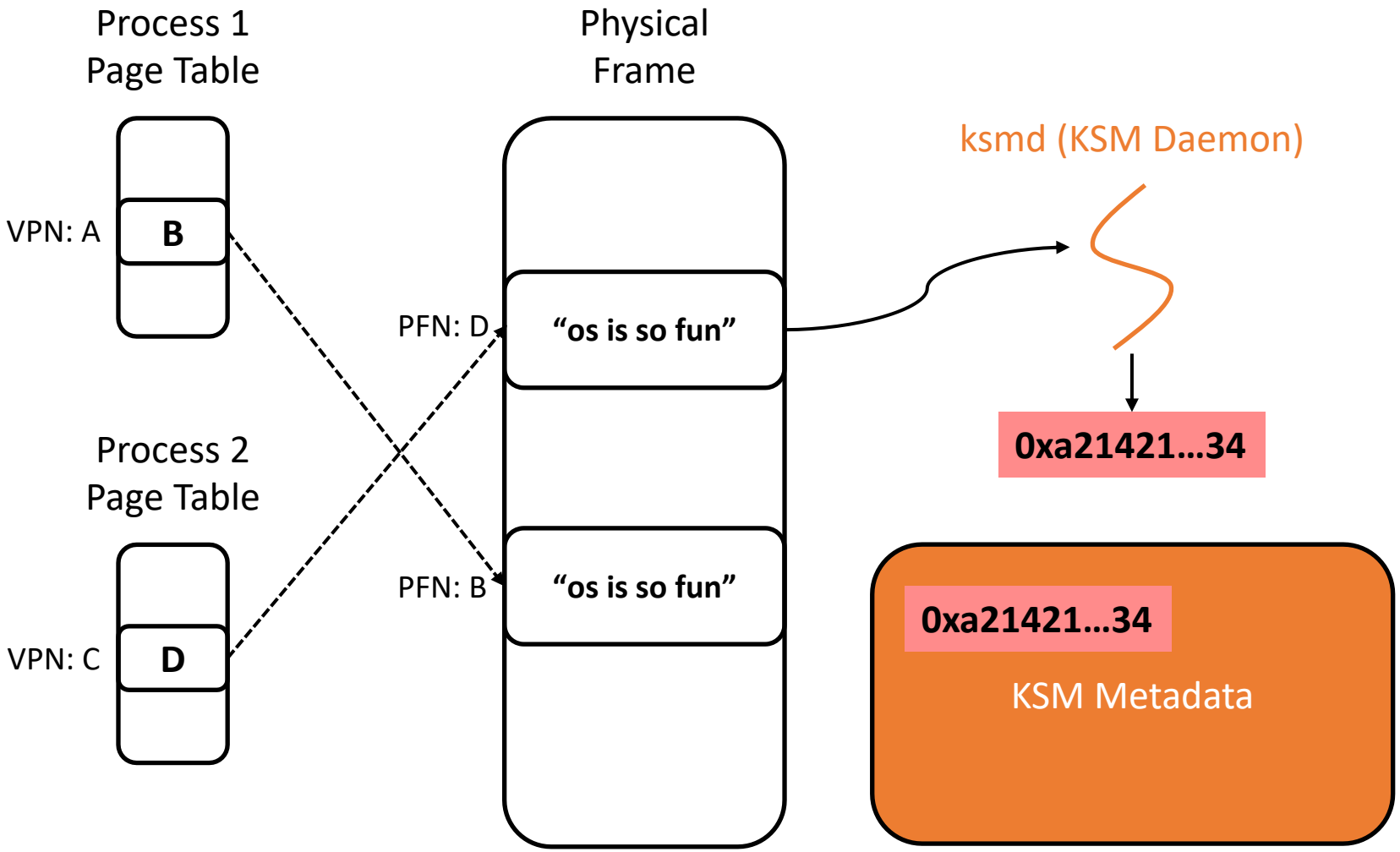
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta

KSM (Kernel Samepage Merging)



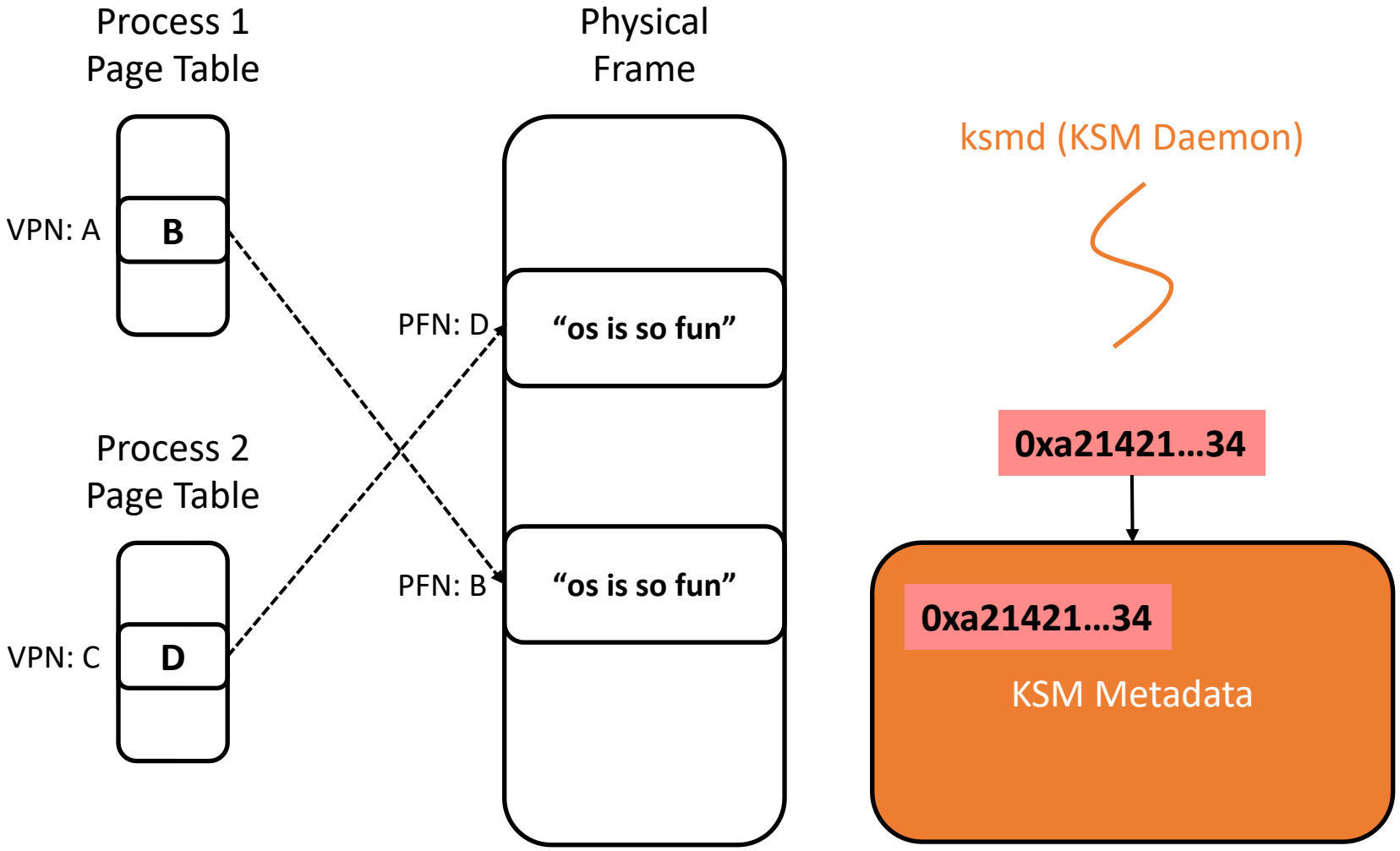
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2

KSM (Kernel Samepage Merging)



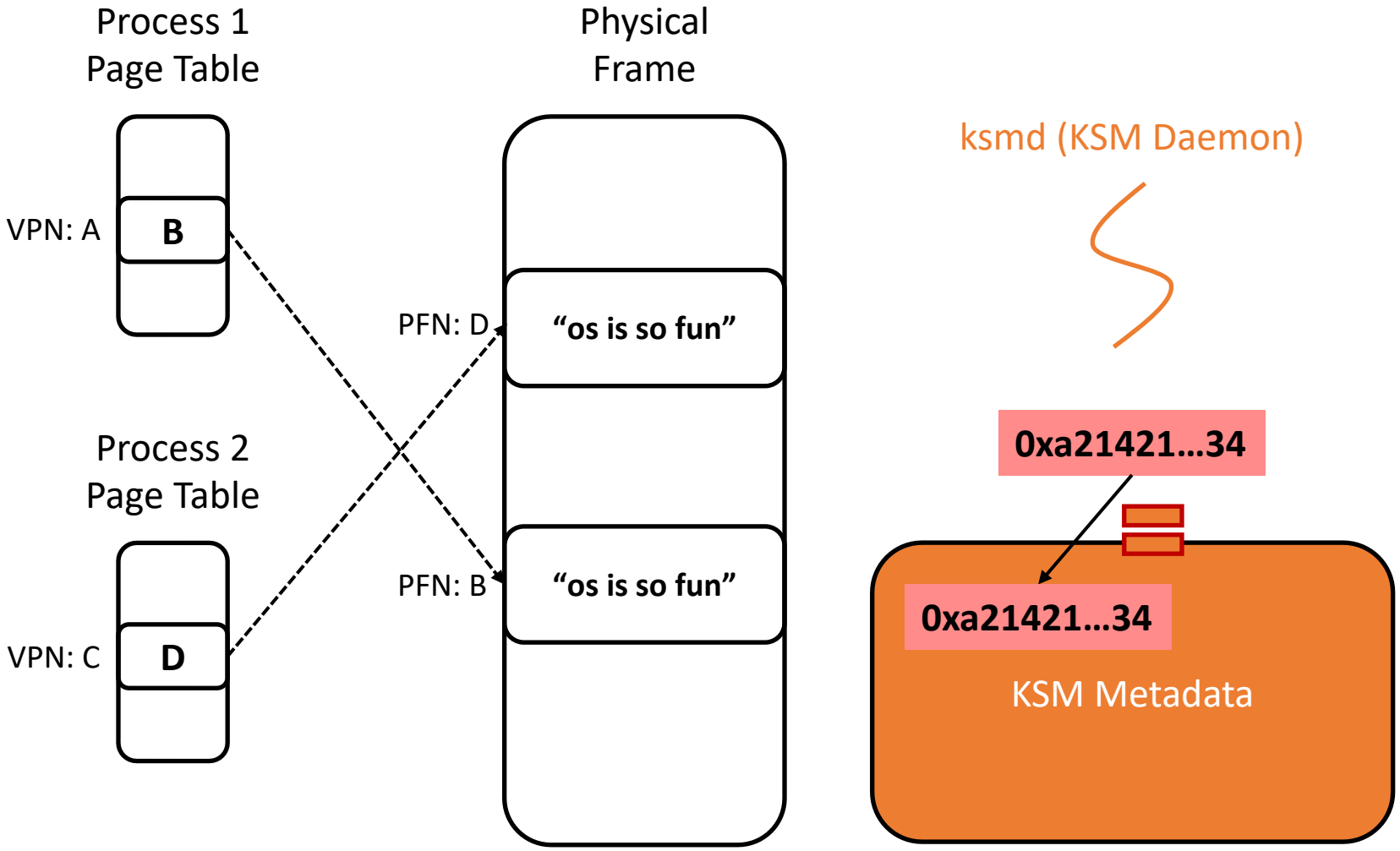
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D

KSM (Kernel Samepage Merging)



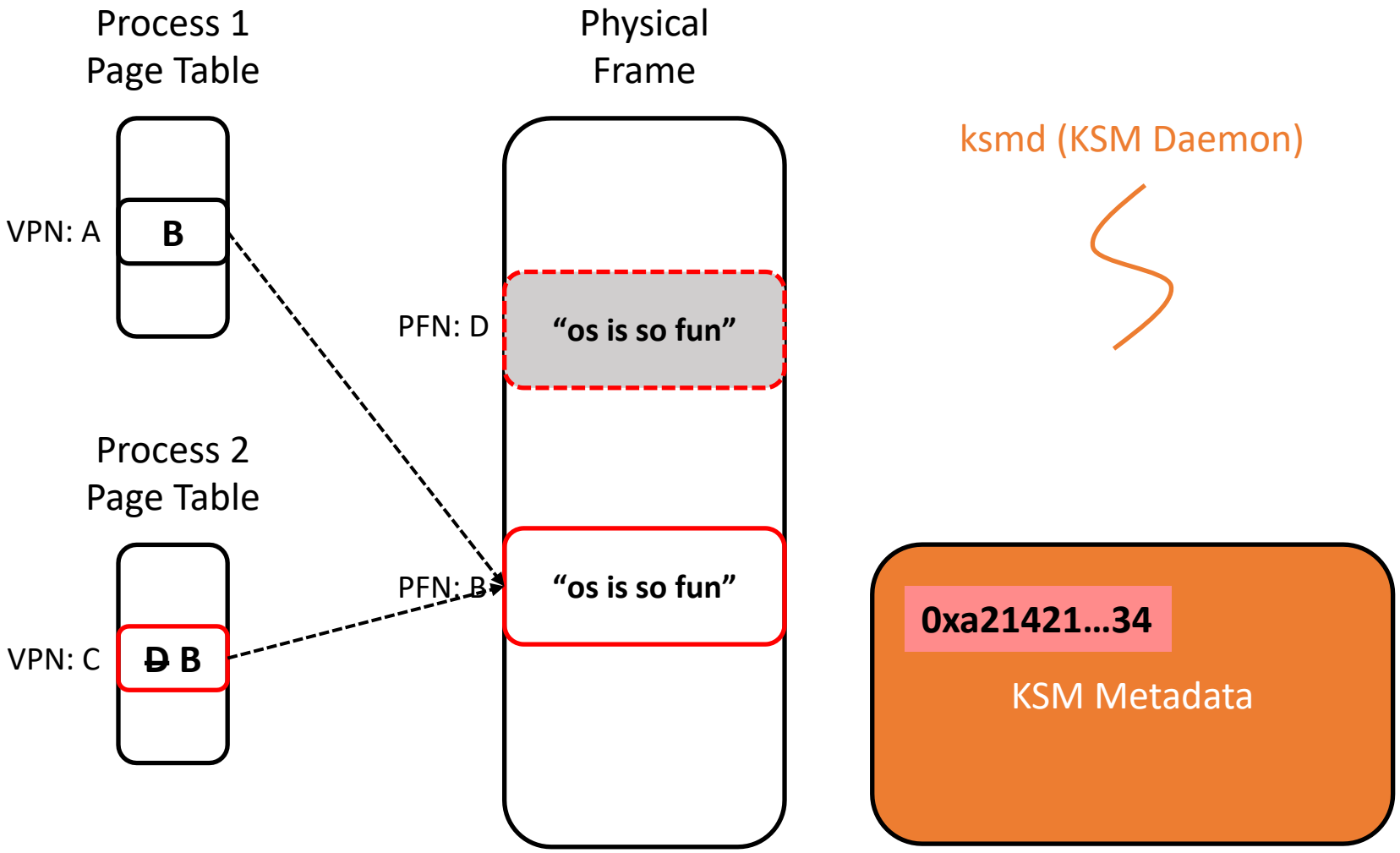
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta

KSM (Kernel Samepage Merging)



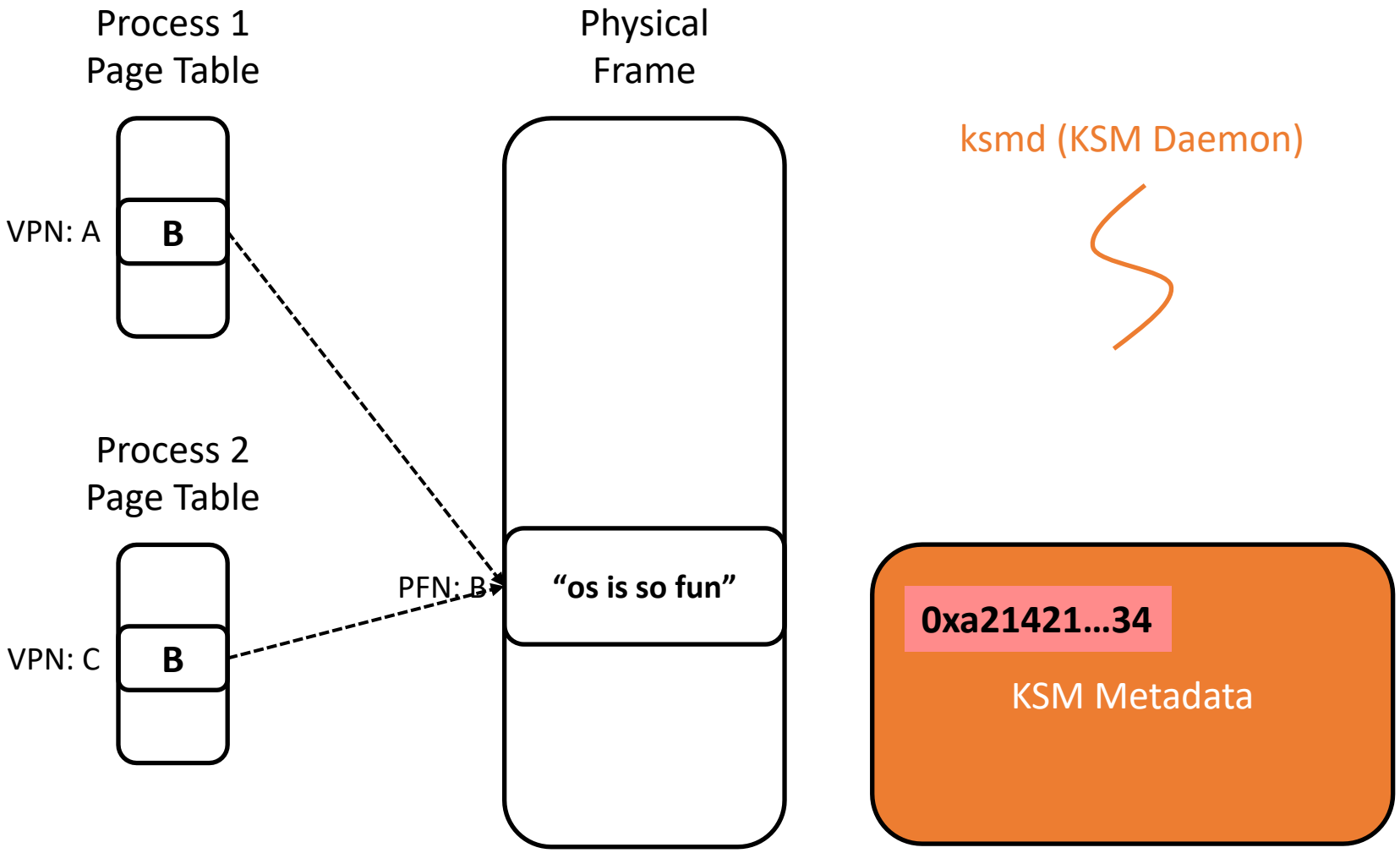
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta
(8) Found!, update KSM Meta

KSM (Kernel Samepage Merging)



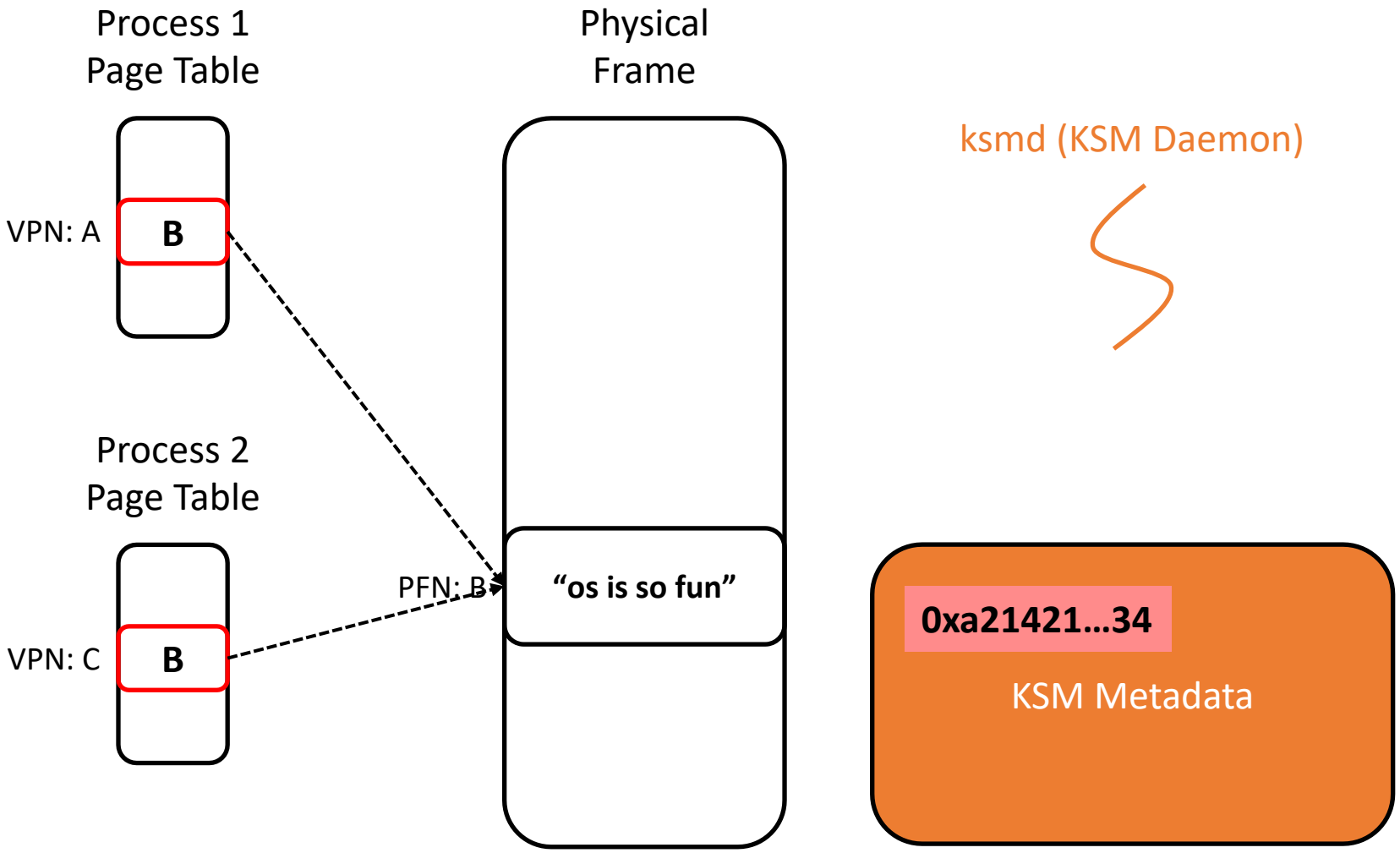
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta
(8) Found!, update KSM Meta
(9) Merge D and B

KSM (Kernel Samepage Merging)



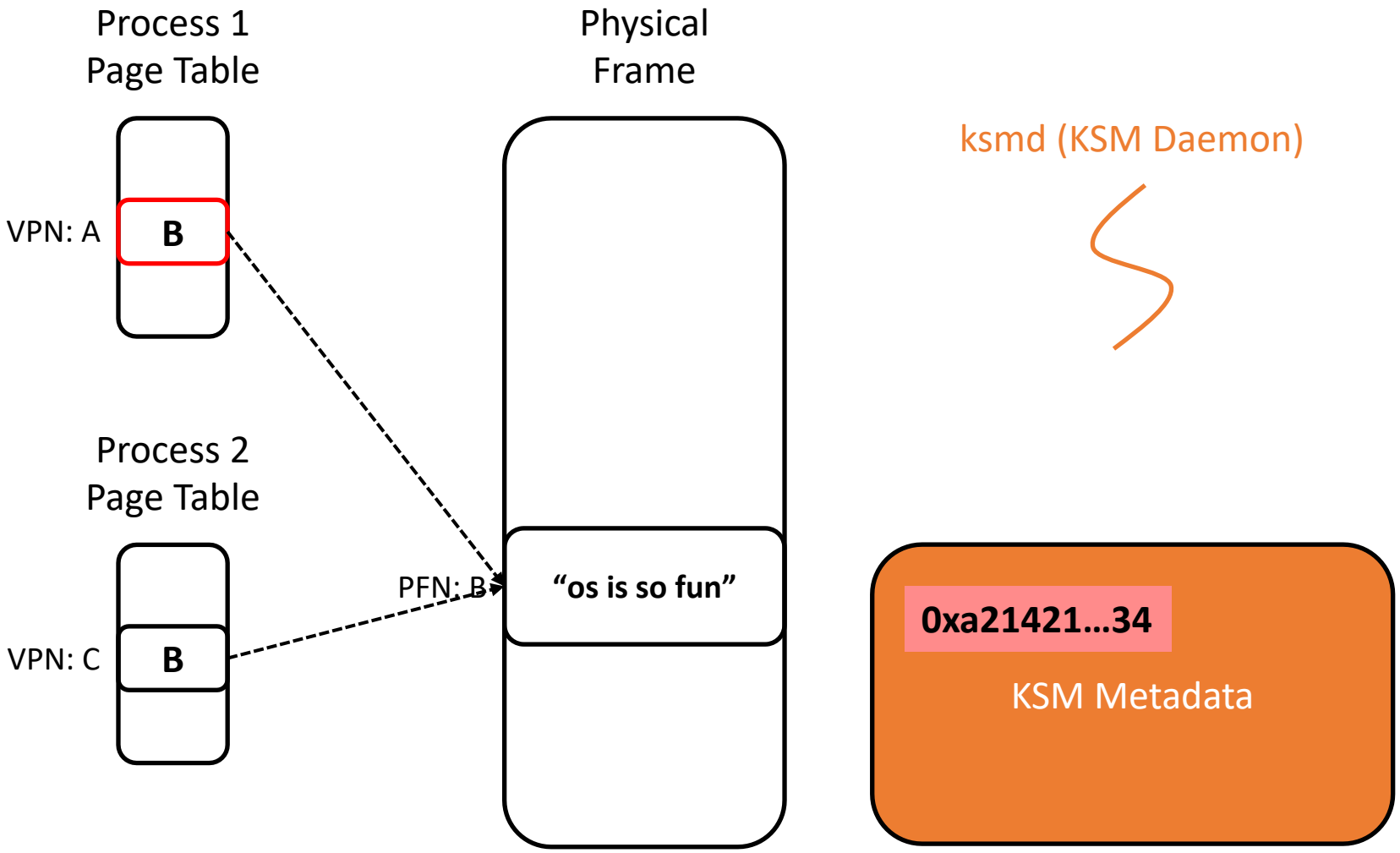
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta
(8) Found!, update KSM Meta
(9) Merge D and B
(10) Reclaim Frame D

KSM (Kernel Samepage Merging)



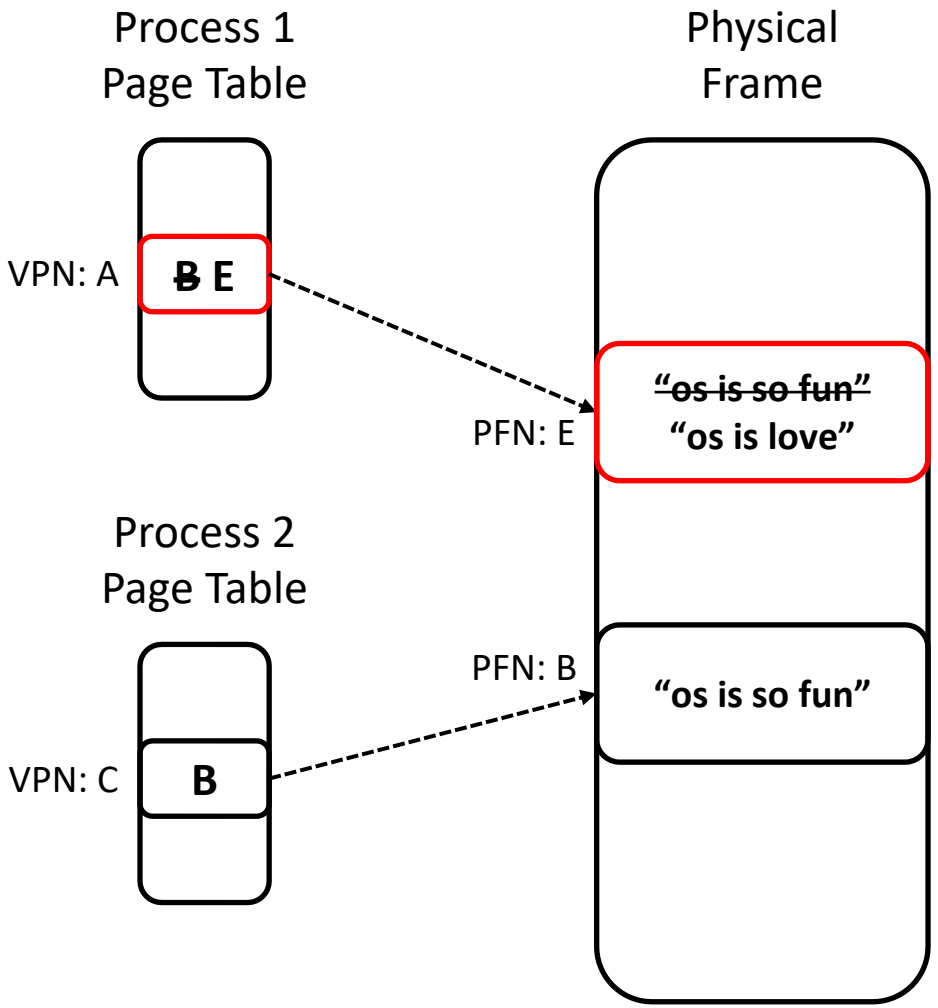
(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta
(8) Found!, update KSM Meta
(9) Merge D and B
(10) Reclaim Frame D
(11) Clear Write Bit of PTEs

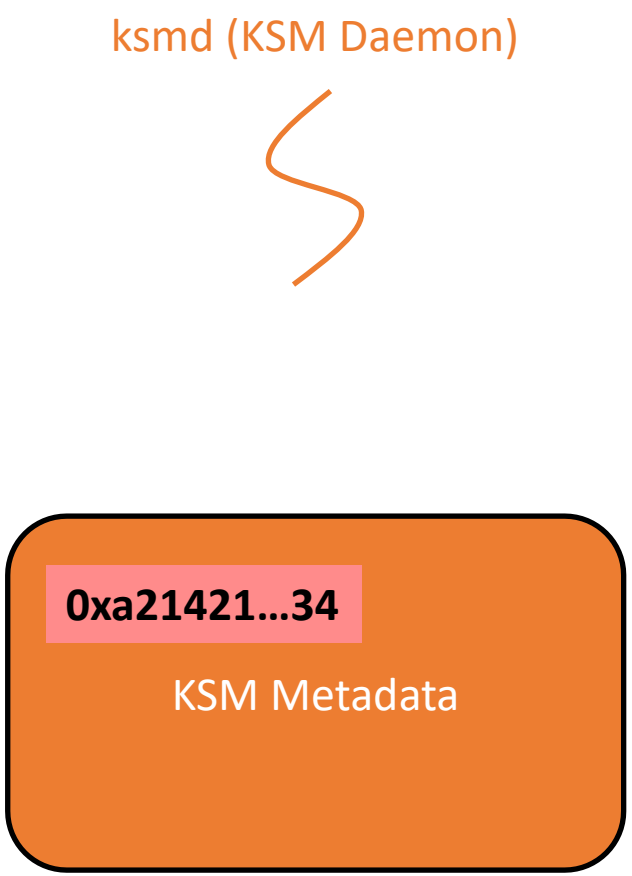
KSM (Kernel Samepage Merging)



(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta
(8) Found!, update KSM Meta
(9) Merge D and B
(10) Reclaim Frame D
(11) Clear Write Bit of PTEs
(12) Process 1 writes to VPN: A

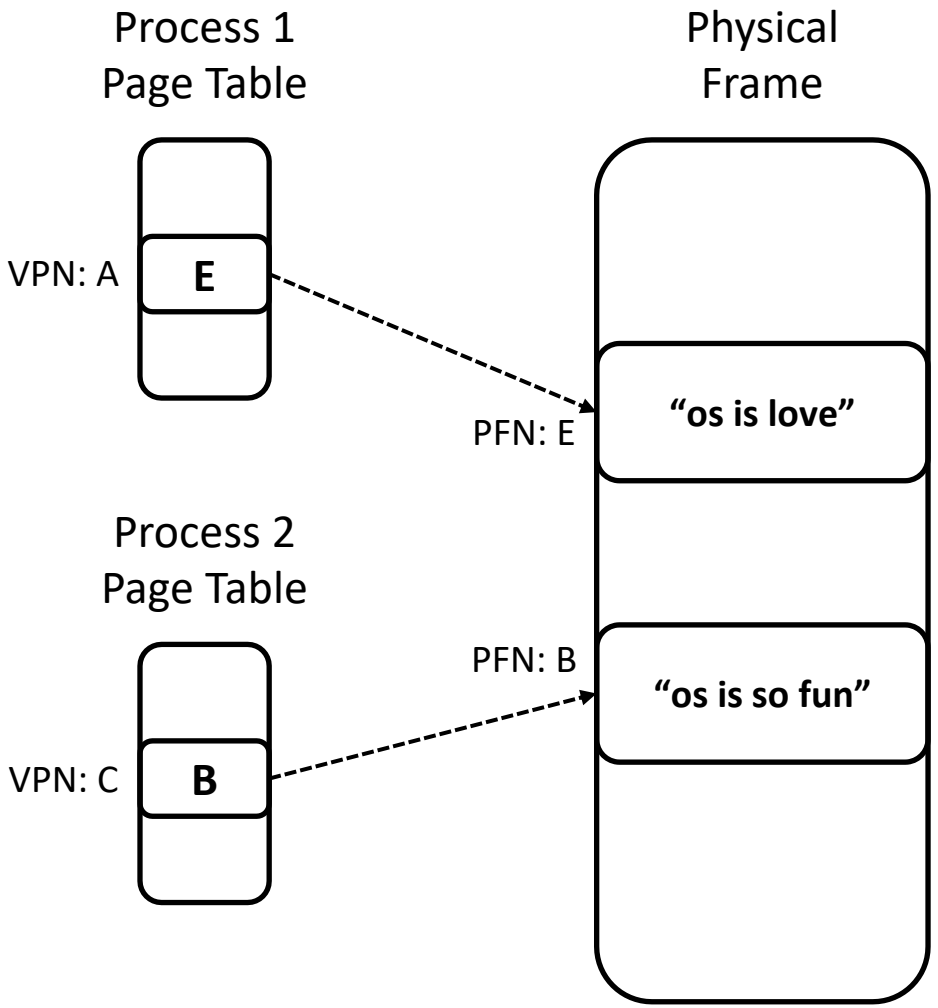
KSM (Kernel Samepage Merging)

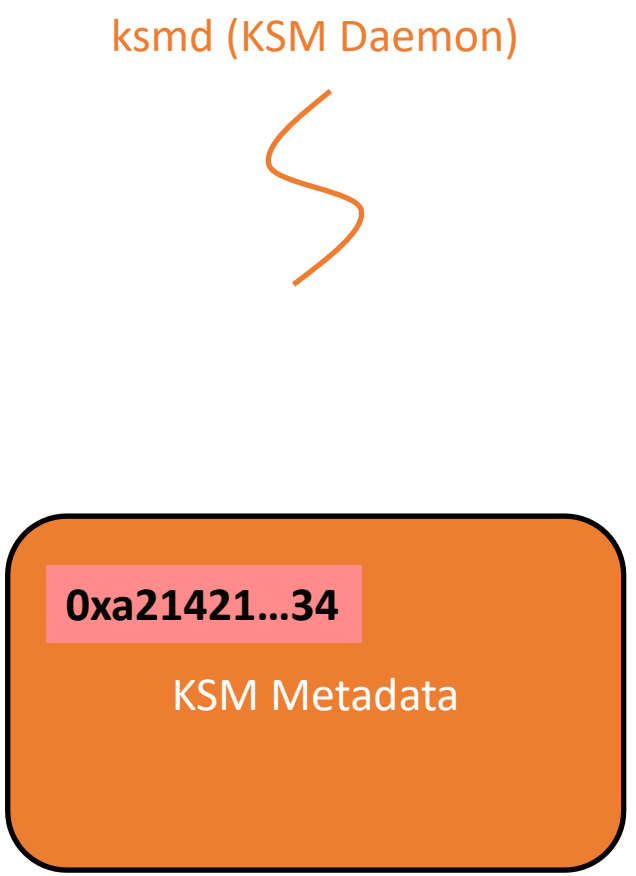




(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta
(8) Found!, update KSM Meta
(9) Merge D and B
(10) Reclaim Frame D
(11) Clear Write Bit of PTEs
(12) Process 1 writes to VPN: A
(13) Page Fault + Copy on Write

KSM (Kernel Samepage Merging)





(1) ksmd Scans Process 1
(2) Hash PFN B
(3) Lookup KSM Meta
(4) Not found, update KSM Meta
(5) ksmd Scans Process 2
(6) Hash PFN D
(7) Lookup KSM Meta
(8) Found!, update KSM Meta
(9) Merge D and B
(10) Reclaim Frame D
(11) Clear Write Bit of PTEs
(12) Process 1 writes to VPN: A
(13) Page Fault + Copy on Write
(14) Update KSM Metadata

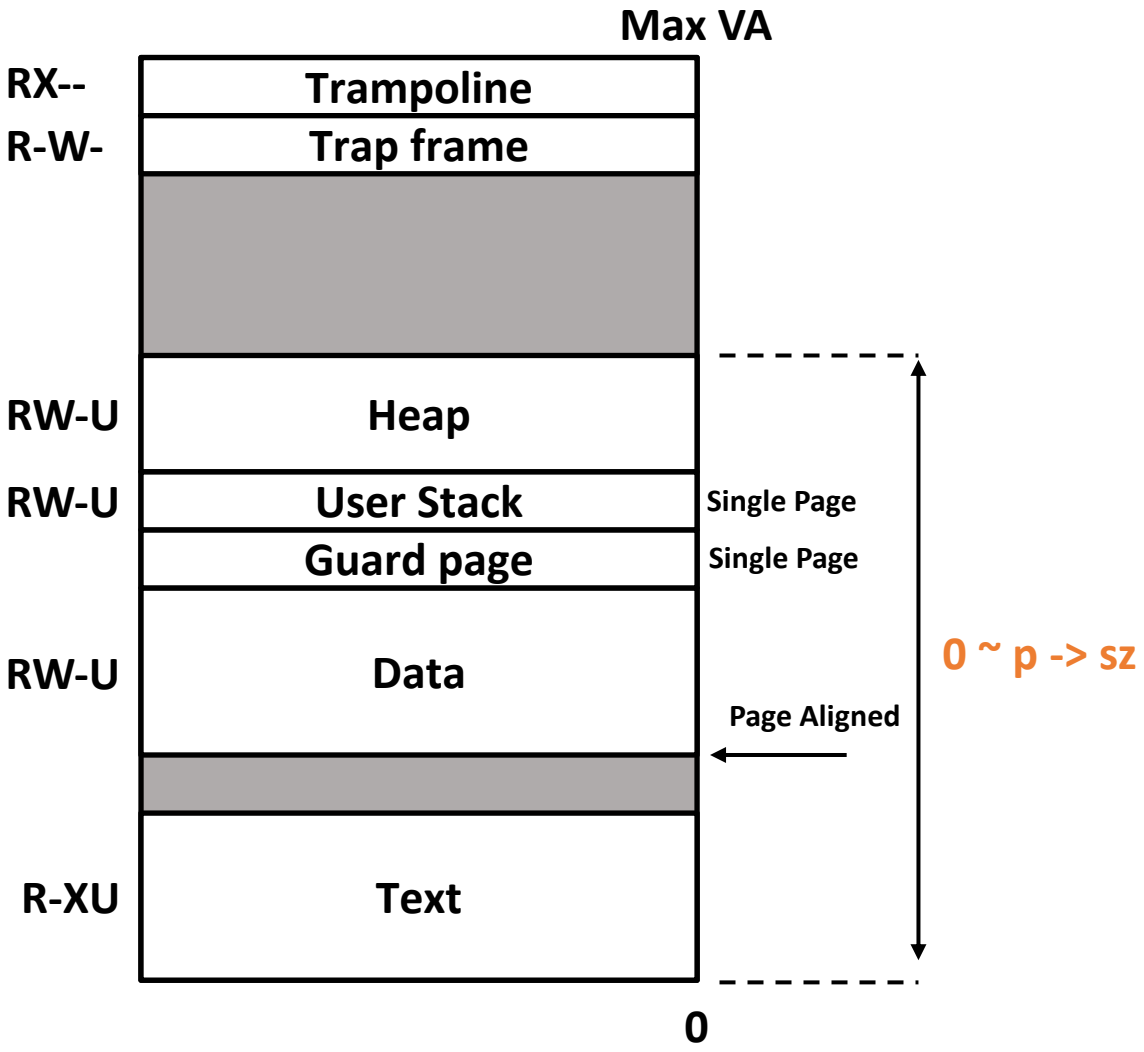
1. Implement the *ksm()* (70 points)

- Your task is to implement a new system call named ksm()
- ```
  int ksm(int *scanned, int *merged);
  ```
  - scanned: Total number of scanned frames
  - merged: Total number of merged frames
  - return value: Total number of free frames ('freemmem')
- System call number is assigned to 24 (already done in branch pa4)
- The initial free memory could differ due to implementation details.
  ```

1. Implement the *ksm()* (70 points)

- Scan the page frames used by each user process p from the virtual address 0 to p->sz. The region will contain code, data, heap, and stack (+ stack guard) pages. Exclude trampoline, trapframe, kernel stack, and page table pages from scanning as they are not targets for KSM.
- You can assume that a single physical frame can be shared by up to 16 different virtual pages, except for the zero-page. There is no limit on the number of virtual pages that can share the zero-page.
- When performing ksm(), exclude the page frames used by init process (pid 1), the sh process (pid 2), and the process invoking the ksm() system call itself from scanning. Assume that the shell process always runs with pid 2.
- Duplicated page frames are merged only through the ksm() system call; they should not be merged at the time of page allocation.
- There should be no memory leak. The freemem value should remain identical before and after executing a program.
- ksm3 user program should run with background ksmd running. To run a process background, run 'ksmd &'

User Virtual Memory




```
// Per-process state
struct proc {
  struct spinlock lock;

  // p->lock must be held when using these:
  enum procstate state;        // Process state
  void *chan;                  // If non-zero, sleeping on chan
  int killed;                  // If non-zero, have been killed
  int xstate;                  // Exit status to be returned to parent's wait
  int pid;                     // Process ID

  // wait_lock must be held when using this:
  struct proc *parent;         // Parent process

  // these are private to the process, so p->lock need not be held.
  uint64 kstack;               // Virtual address of kernel stack
  uint64 sz;                   // Size of process memory (bytes)
  pagetable_t pagetable;       // User page table
  struct trapframe *trapframe; // data page for trampoline.S
  struct context context;      // swtch() here to run process
  struct file *ofile[NOFILE];  // Open files
  struct inode *cwd;           // Current directory
  char name[16];               // Process name (debugging)
};
```

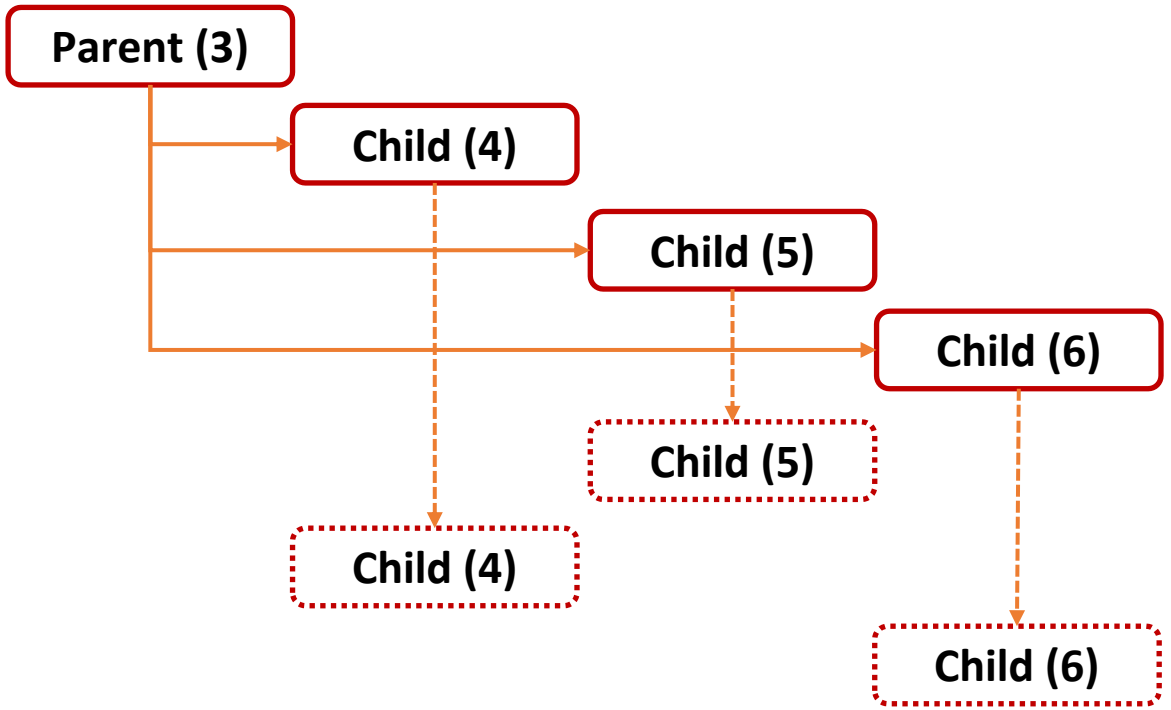
Zero Page

- You are required to preallocate a "zero-page" in the system which is filled with zeroes. Since BSS and heap pages are initialized to zero, those pages can be mapped to the zero-page.
- There is no limit on the number of virtual pages that can share the zero-page.

User program example

- ksm1

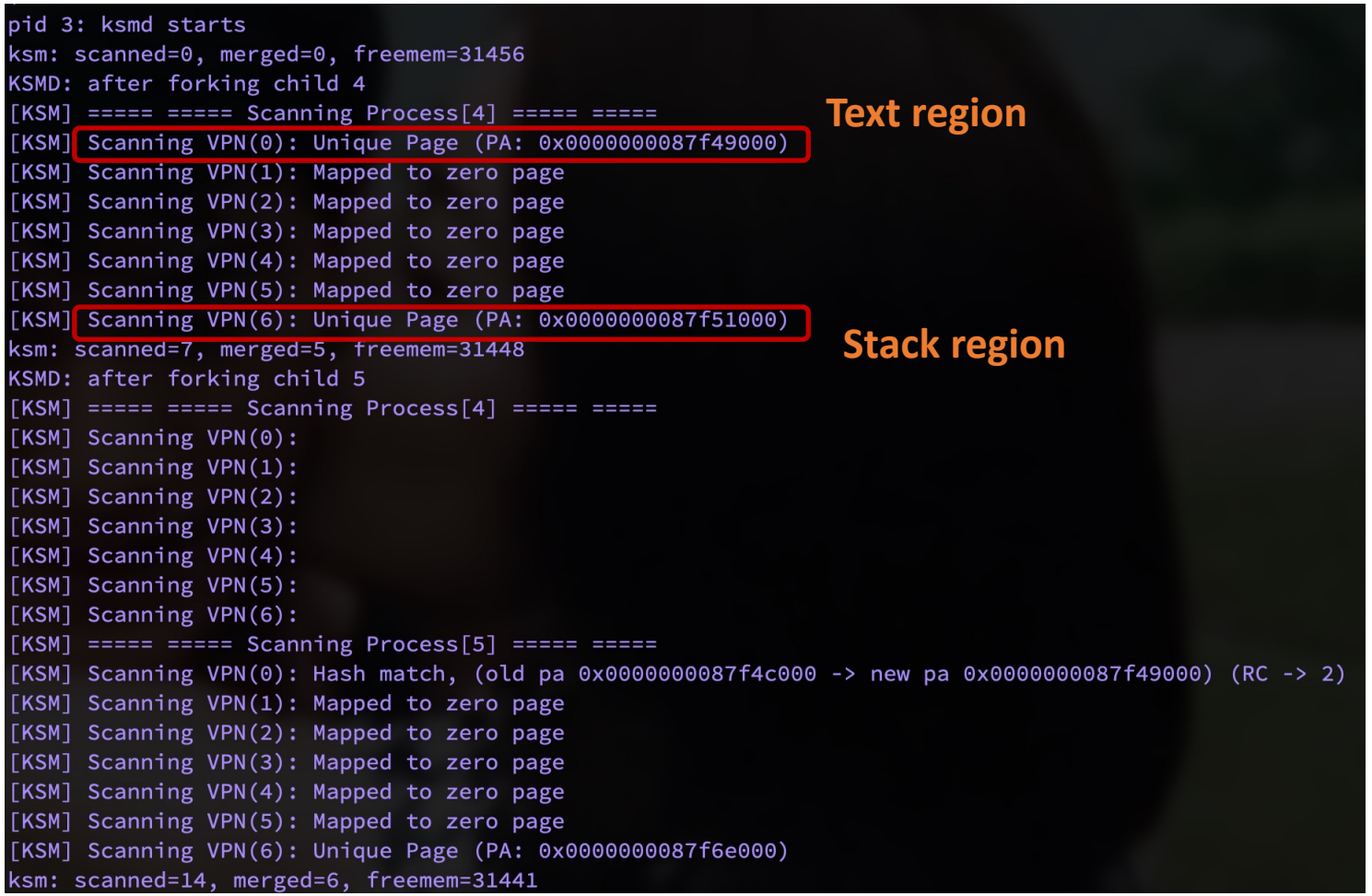
```
$ ksm1
pid 3: ksmd starts
ksm: scanned=0, merged=0, freemem=31458
KSMD: after forking child 4
ksm: scanned=7, merged=5, freemem=31450
KSMD: after forking child 5
ksm: scanned=14, merged=6, freemem=31443
KSMD: after forking child 6
ksm: scanned=21, merged=6, freemem=31436
KSMD: after terminating child 5
ksm: scanned=14, merged=0, freemem=31443
KSMD: after terminating child 4
ksm: scanned=7, merged=0, freemem=31450
KSMD: after terminating child 6
ksm: scanned=0, merged=0, freemem=31458
```



***The scanned & freemem value could differ due to implementation detail**

User program example

- ksm1 (with debug message)



User program example

- ksm1 (with debug message)

```
pid 3: ksmd starts
ksm: scanned=0, merged=0, freemem=31456
KSMD: after forking child 4
[KSM] ===== ===== Scanning Process[4] ===== =====
[KSM] Scanning VPN(0): Unique Page (PA: 0x0000000087f49000)
[KSM] Scanning VPN(1): Mapped to zero page
[KSM] Scanning VPN(2): Mapped to zero page
[KSM] Scanning VPN(3): Mapped to zero page
[KSM] Scanning VPN(4): Mapped to zero page
[KSM] Scanning VPN(5): Mapped to zero page
[KSM] Scanning VPN(6): Unique Page (PA: 0x0000000087f51000)
ksm: scanned=7, merged=5, freemem=31448
KSMD: after forking child 5
[KSM] ===== ===== Scanning Process[4] ===== =====
[KSM] Scanning VPN(0):
[KSM] Scanning VPN(1):
[KSM] Scanning VPN(2):
[KSM] Scanning VPN(3):
[KSM] Scanning VPN(4):
[KSM] Scanning VPN(5):
[KSM] Scanning VPN(6):
[KSM] ===== ===== Scanning Process[5] ===== =====
[KSM] Scanning VPN(0): Hash match, (old pa 0x0000000087f4c000 -> new pa 0x0000000087f49000) (RC -> 2)
[KSM] Scanning VPN(1): Mapped to zero page
[KSM] Scanning VPN(2): Mapped to zero page
[KSM] Scanning VPN(3): Mapped to zero page
[KSM] Scanning VPN(4): Mapped to zero page
[KSM] Scanning VPN(5): Mapped to zero page
[KSM] Scanning VPN(6): Unique Page (PA: 0x0000000087f6e000)
ksm: scanned=14, merged=6, freemem=31441
```

Does nothing because it has been merged or scanned

User program example

- ksm1 (with debug message)

```
pid 3: ksmd starts
ksm: scanned=0, merged=0, freemem=31456
KSMD: after forking child 4
[KSM] ===== ===== Scanning Process[4] ===== =====
[KSM] Scanning VPN(0): Unique Page (PA: 0x0000000087f49000)
[KSM] Scanning VPN(1): Mapped to zero page
[KSM] Scanning VPN(2): Mapped to zero page
[KSM] Scanning VPN(3): Mapped to zero page
[KSM] Scanning VPN(4): Mapped to zero page
[KSM] Scanning VPN(5): Mapped to zero page
[KSM] Scanning VPN(6): Unique Page (PA: 0x0000000087f51000)
ksm: scanned=7, merged=5, freemem=31448
KSMD: after forking child 5
[KSM] ===== ===== Scanning Process[4] ===== =====
[KSM] Scanning VPN(0):
[KSM] Scanning VPN(1):
[KSM] Scanning VPN(2):
[KSM] Scanning VPN(3):
[KSM] Scanning VPN(4):
[KSM] Scanning VPN(5):
[KSM] Scanning VPN(6):
[KSM] ===== ===== Scanning Process[5] ===== =====
[KSM] Scanning VPN(0): Hash match, (old pa 0x0000000087f4c000 -> new pa 0x0000000087f49000) (RC -> 2)
[KSM] Scanning VPN(1): Mapped to zero page
[KSM] Scanning VPN(2): Mapped to zero page
[KSM] Scanning VPN(3): Mapped to zero page
[KSM] Scanning VPN(4): Mapped to zero page
[KSM] Scanning VPN(5): Mapped to zero page
[KSM] Scanning VPN(6): Unique Page (PA: 0x0000000087f6e000)
ksm: scanned=14, merged=6, freemem=31441
```

After fork, child 5 and 4 has the same text area

Stack may differ

Hints

- There are three major flows that you should modify
  - KSM flow
  - Page fault flow (copy-on-write)
  - Physical page release flow (process exit, exec, …)

- Try to print as much debug message as possible
  - PFN
  - VPN
  - Which page is merged to which
  - Which page was released
  - Which page performed a CoW

2. Design Document (30 points)

- There are limitations in simply comparing the output of the user programs to genuinely check if the KSM was properly implemented.
- You should explain what you have considered, and what you have done.
- Requirements
  - Data structures
  - Overall flowchart
  - Algorithm design
  - Implementation details
  - Testing and validation

Tips

- Read Chap. 3, Chap. 4 of the xv6 book to understand RISC-V's virtual memory subsystem and page-fault exceptions in xv6.
- For your reference, the following roughly shows the amount of changes you need to make for this project assignment.
- Each "+" symbol indicates 1~10 lines of code that should be added, deleted, or altered.

```
kernel/defs.h     | +
kernel/exec.c     | +
kernel/proc.c     | +
kernel/trap.c     | +
kernel/vm.c       | +
kernel/ksm.h      | +++++
kernel/ksm.c      | ++++++++++++++++++++++++++++++++++++++++++++
```

Restrictions

- For this project assignment, you can assume a uniprocessor RISC-V system (CPUS = 1) with a physical memory size of 128 MiB.
- Please use the qemu version 8.2.0 or later. To determine the qemu version, use the command: $ qemu-system-riscv64 --version
- We will run qemu-system-riscv64 with the -icount shift=0 option, which enables aligning the host and virtual clocks. This setting is already included in the Makefile for the pa4 branch.
- You only need to change the files in the ./kernel directory (mostly to ksm.h and ksm.c files provided in the skeleton code). Any other changes outside the ./kernel directory will be ignored during grading.

Skeleton Code

- Skeleton Code
  - You should work on the pa4 branch of the xv6-riscv-snu repository as follows:

```
$ git clone https://github.com/snu-csl/xv6-riscv-snu
$ git checkout pa4
```

  - The pa4 branch has a user-level utility program named ksmd, ksm1, ksm2, ksm3 which can be built from the user/ksmd.c, user/kms1.c, user/ksm2.c, user/ksm3.c file

Notification

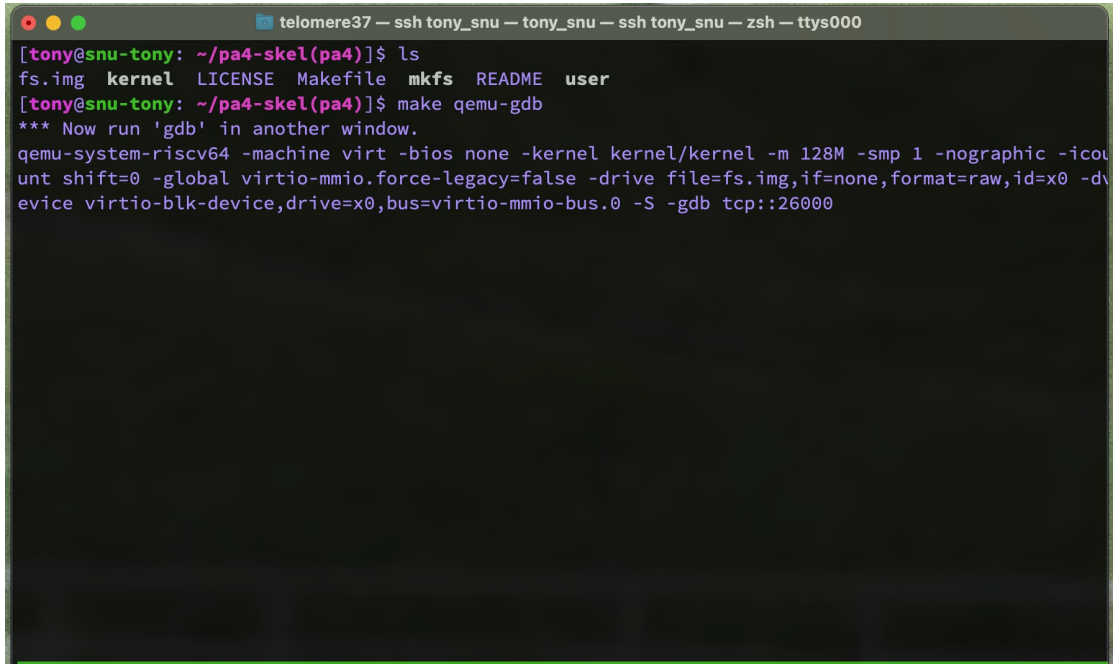
- Due
  - 11:59 PM, May 26 (Sunday)

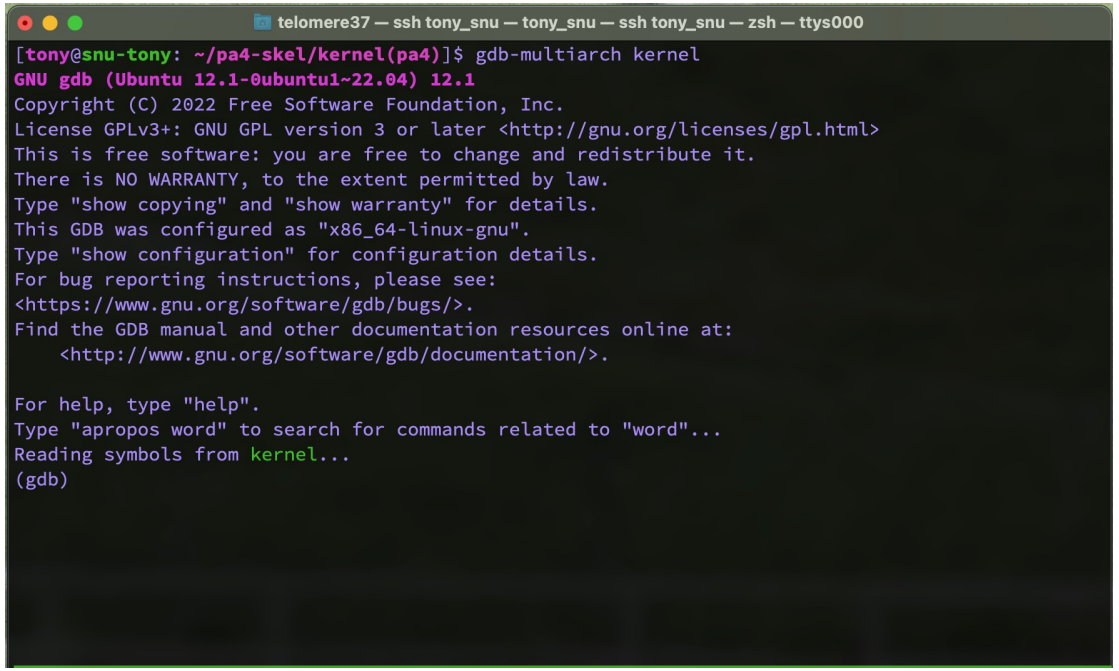
- Submission
  - Run the make submit command to generate a tarball named xv6-pa4-{STUDENTID}.tar.gz in the xv6-riscv-snu directory
  - Upload the compressed file to the submission server
  - The total number of submissions for this project will be limited to 50
  - Only the version marked FINAL will be considered for the project score

Using GDB with QEMU

GDB with QEMU

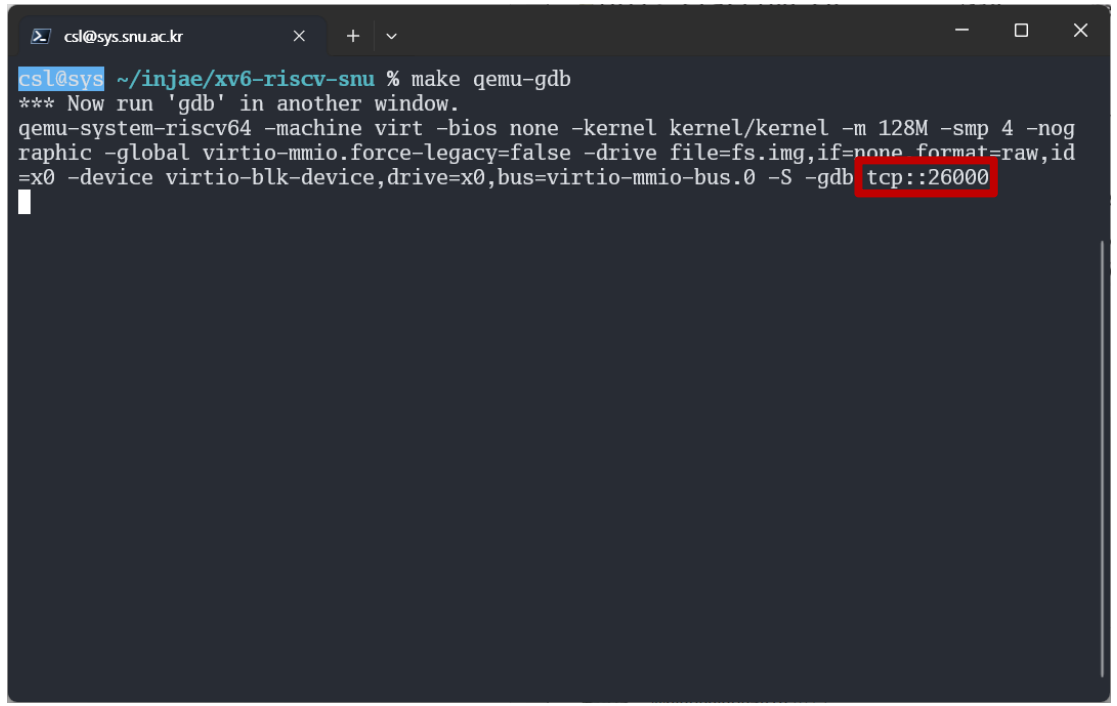
- In the xv6-riscv-snu directory,
- Run make qemu-gdb to run QEMU
- In another shell, run gdb-multiarch ./kernel/kernel
- gdb-multiarch automatically sets the target architecture to “riscv:rv64”

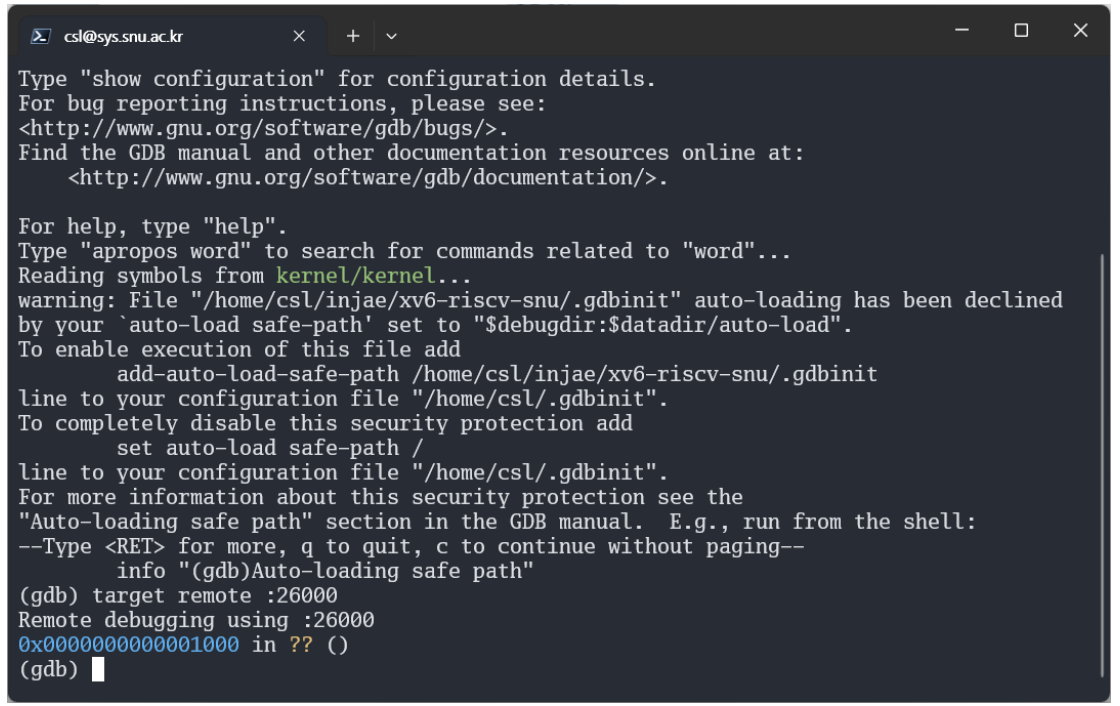




GDB with QEMU

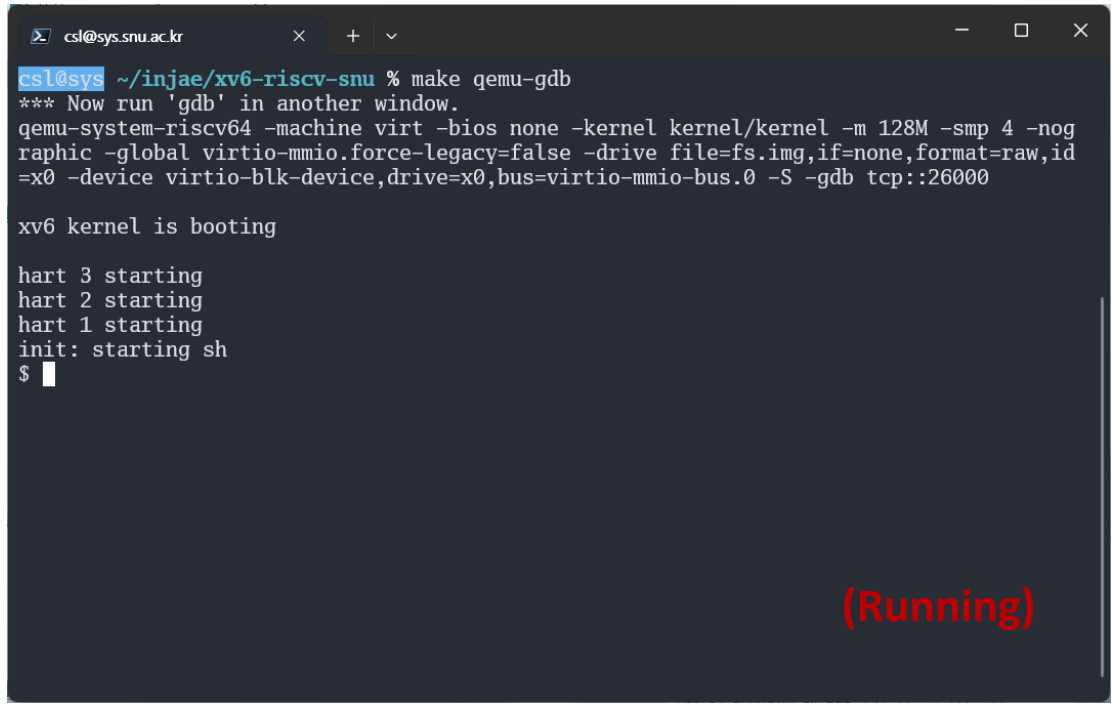
- In GDB, enter target remote :<port>
- You can find TCP port in the QEMU log

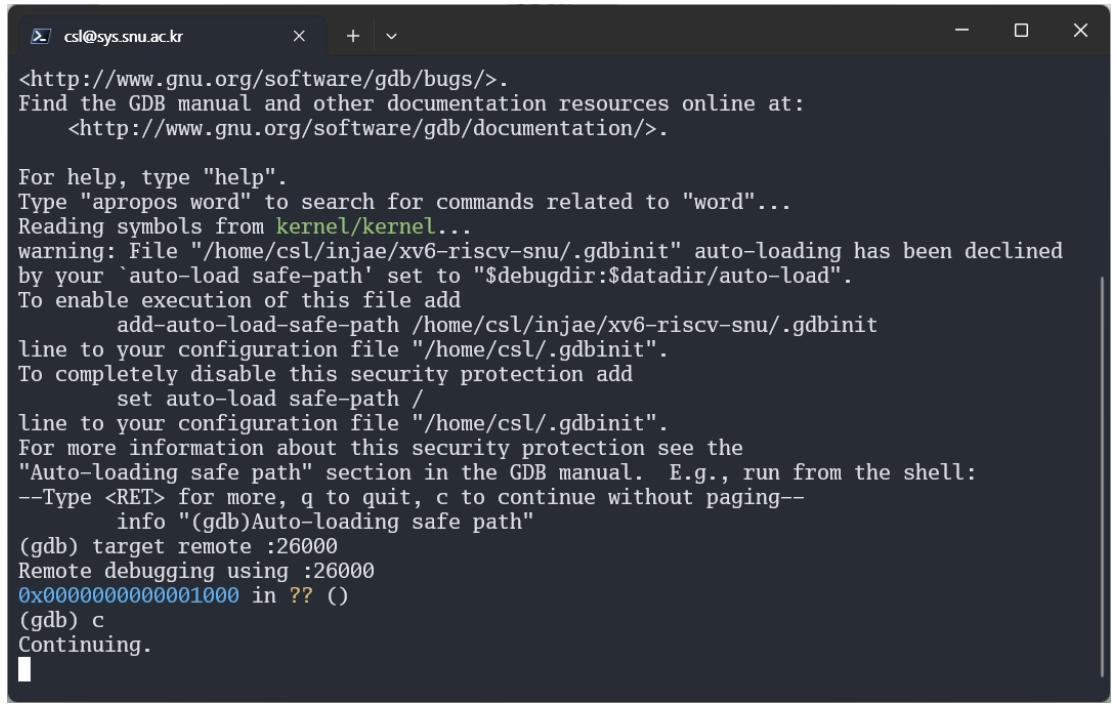




GDB with QEMU

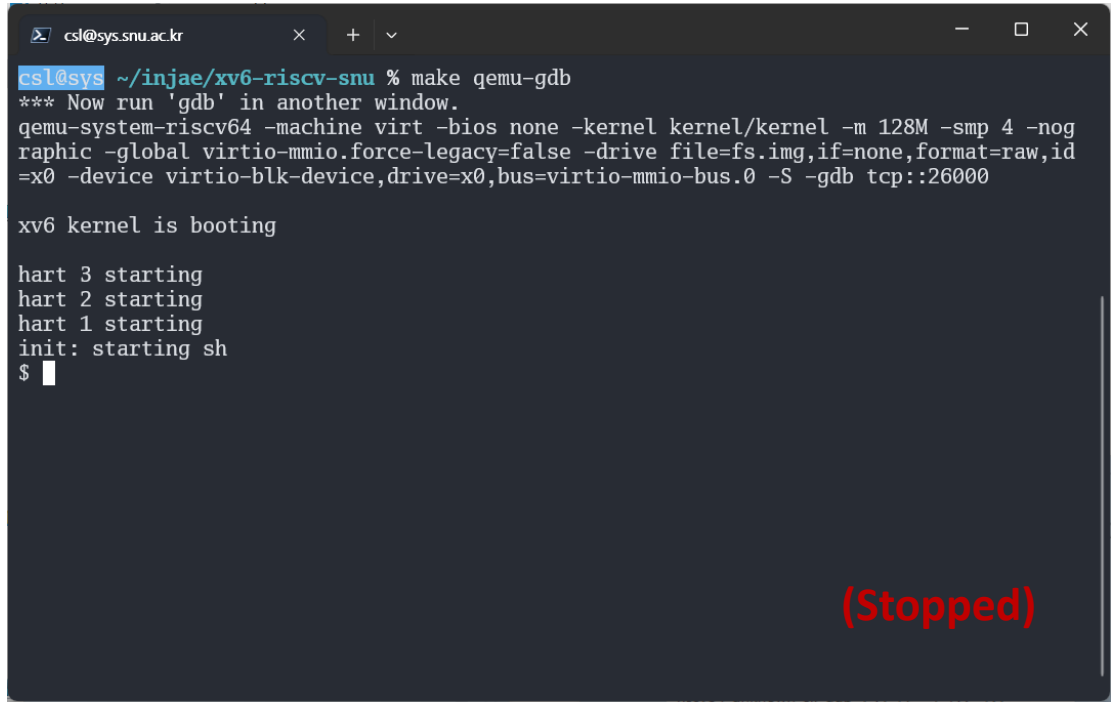
- The xv6 virtual machine has stopped at 0x1000 (the very beginning of the text section)
- To continue, enter `c` in GDB

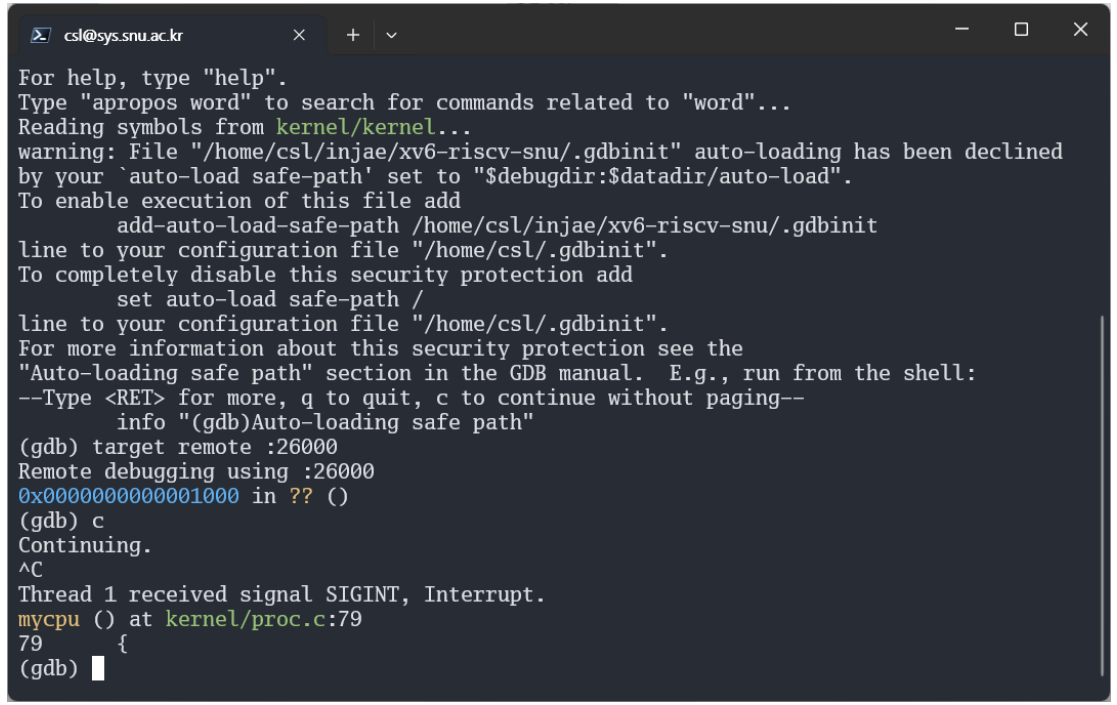




GDB with QEMU

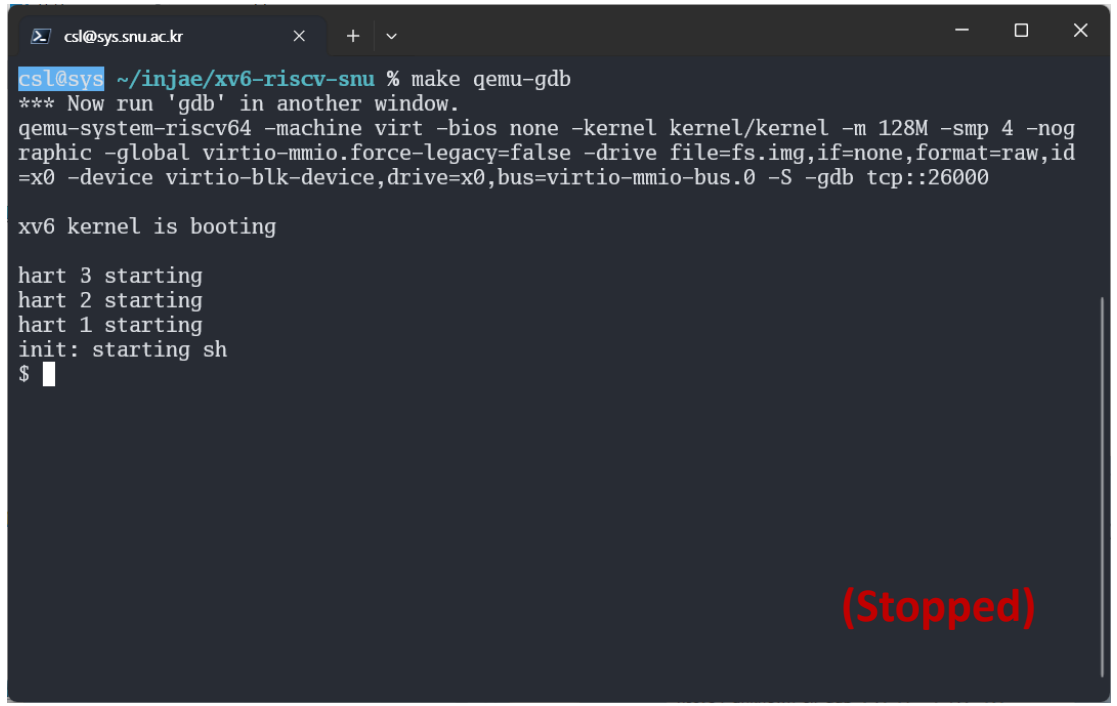
- To stop again, enter Ctrl-C in GDB
- Then the xv6 virtual machine stops immediately

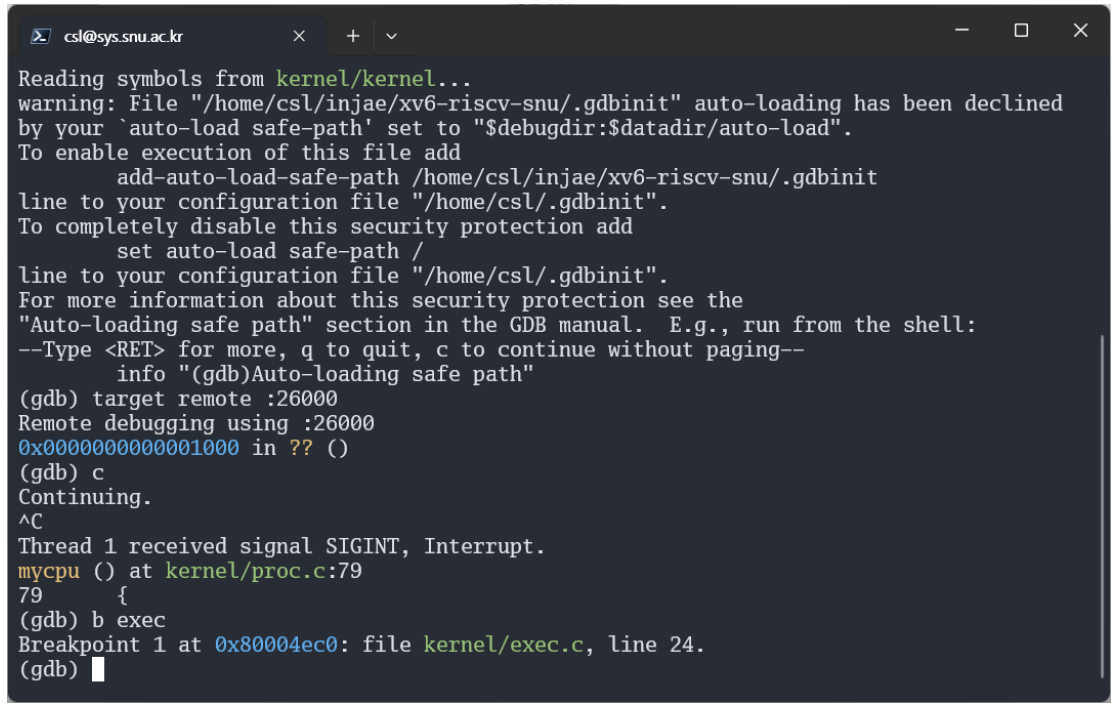




GDB with QEMU

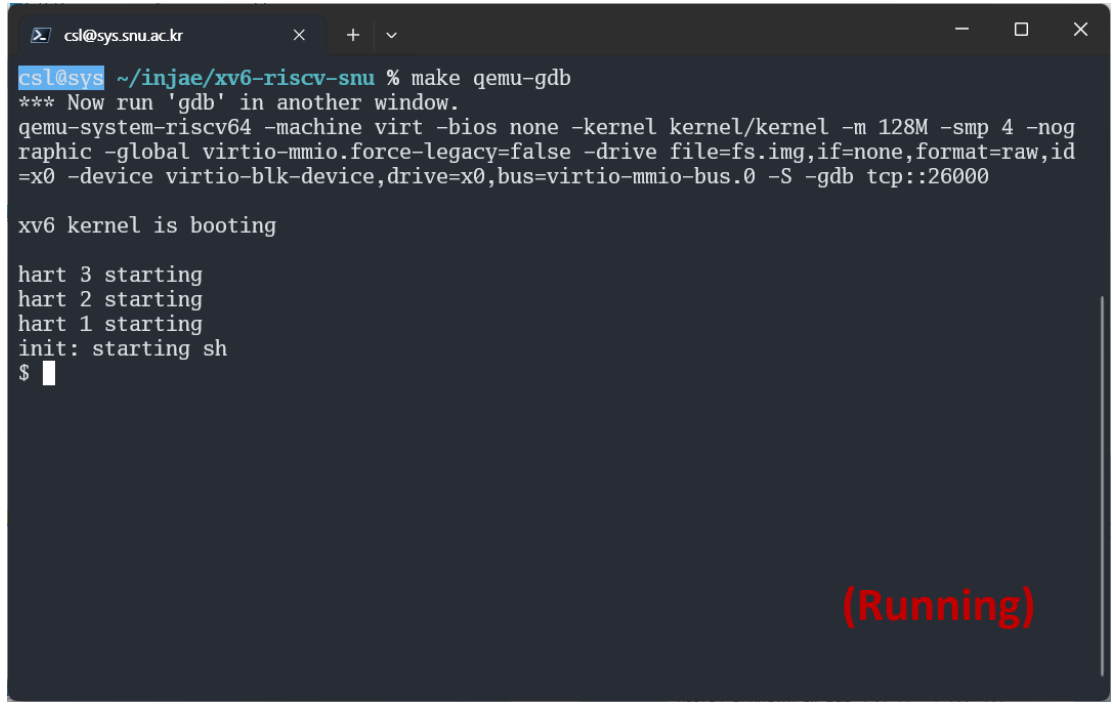
- Let's set a breakpoint at exec()
- Enter b exec in GDB

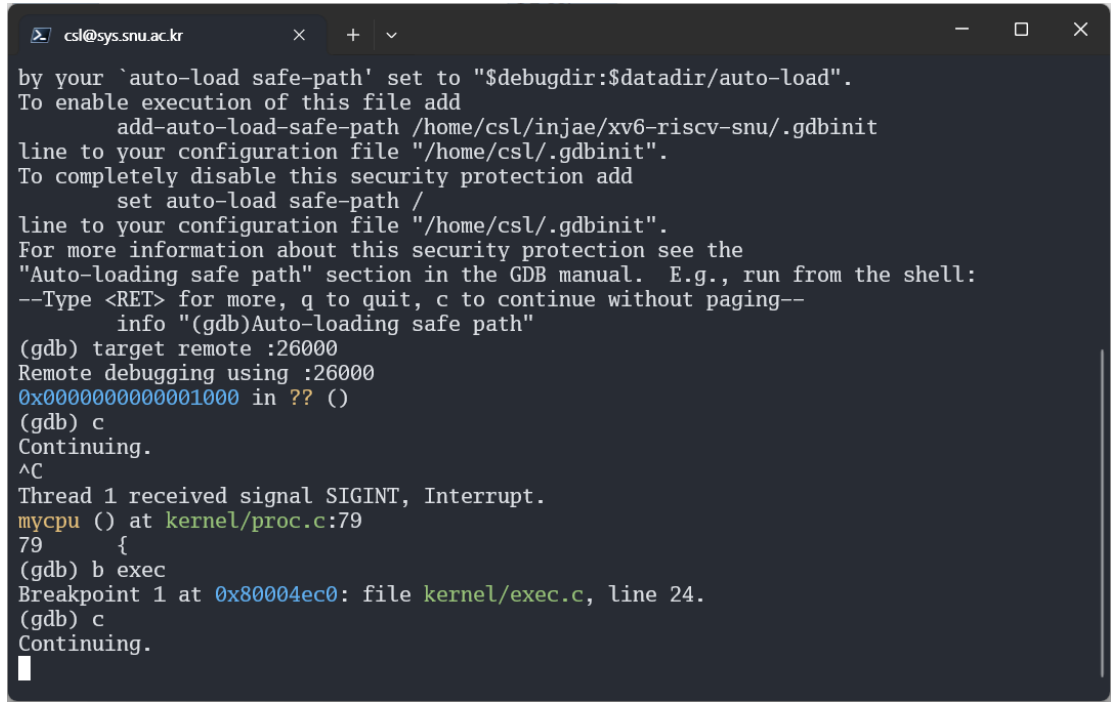




GDB with QEMU

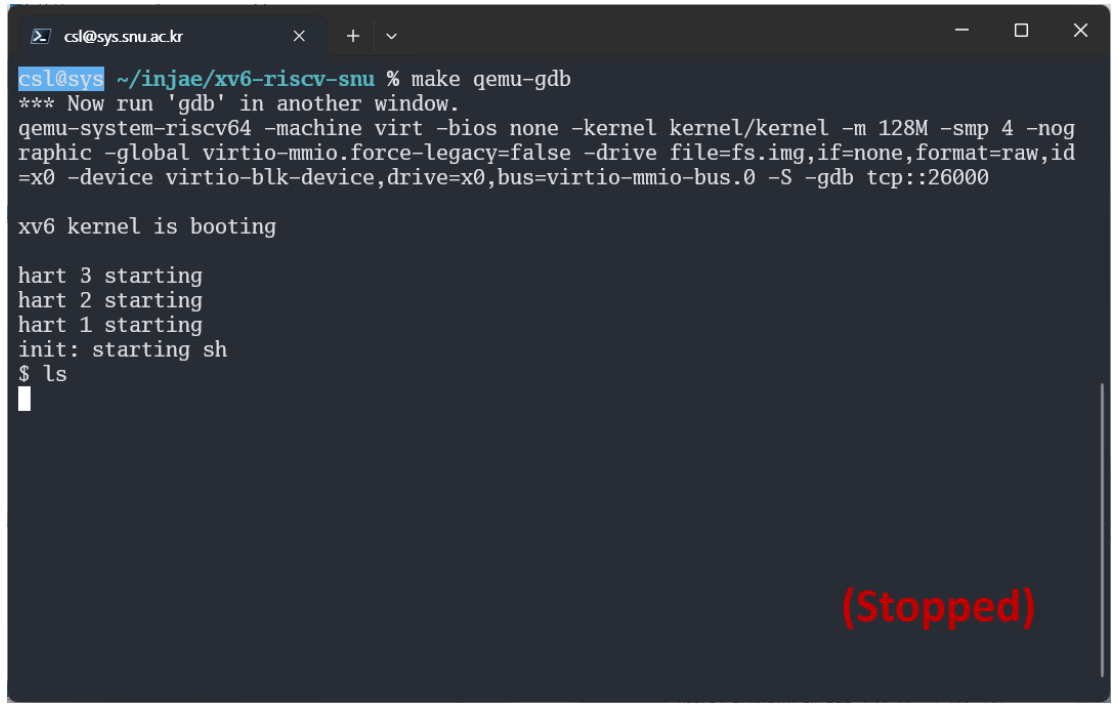
- Enter `c` in GDB to resume the xv6 machine

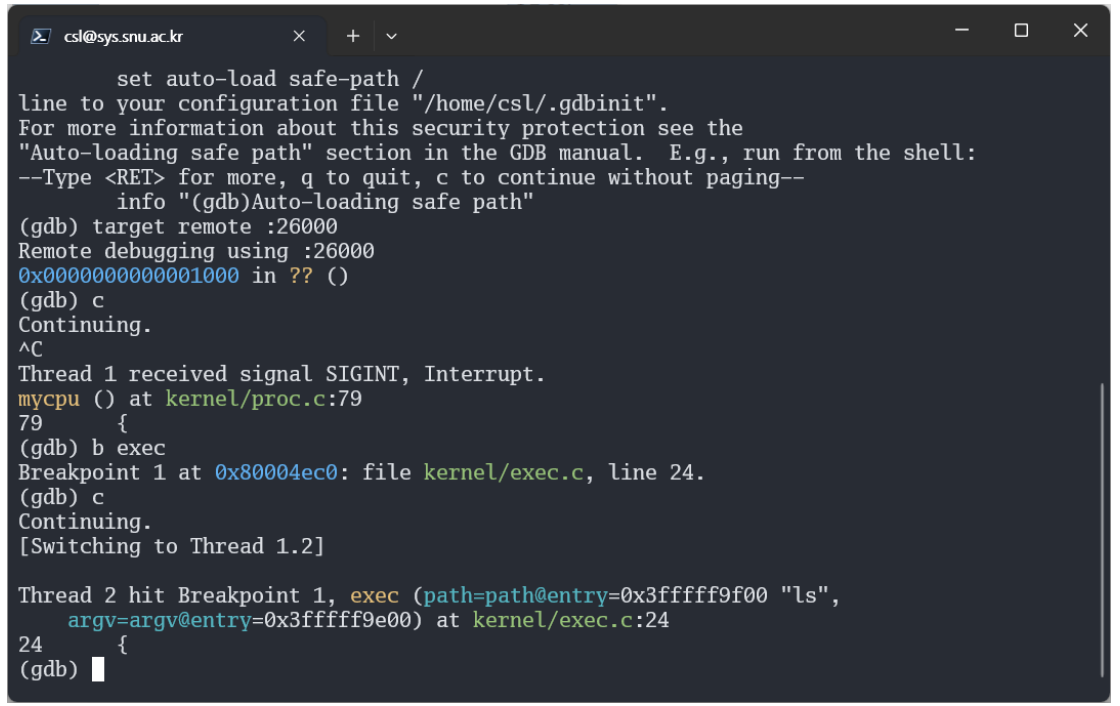




GDB with QEMU

- Run ls command in the xv6 machine
- Then the xv6 machine hits the breakpoint and stops right before starting exec() function





More about GDB

- To learn GDB in detail, search for GDB on Google
- There are many useful videos about GDB in YouTube
- [JTJ의 리눅스탐험] GDB 활용하기

Thank you!