Project #2: System Calls

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System Calls

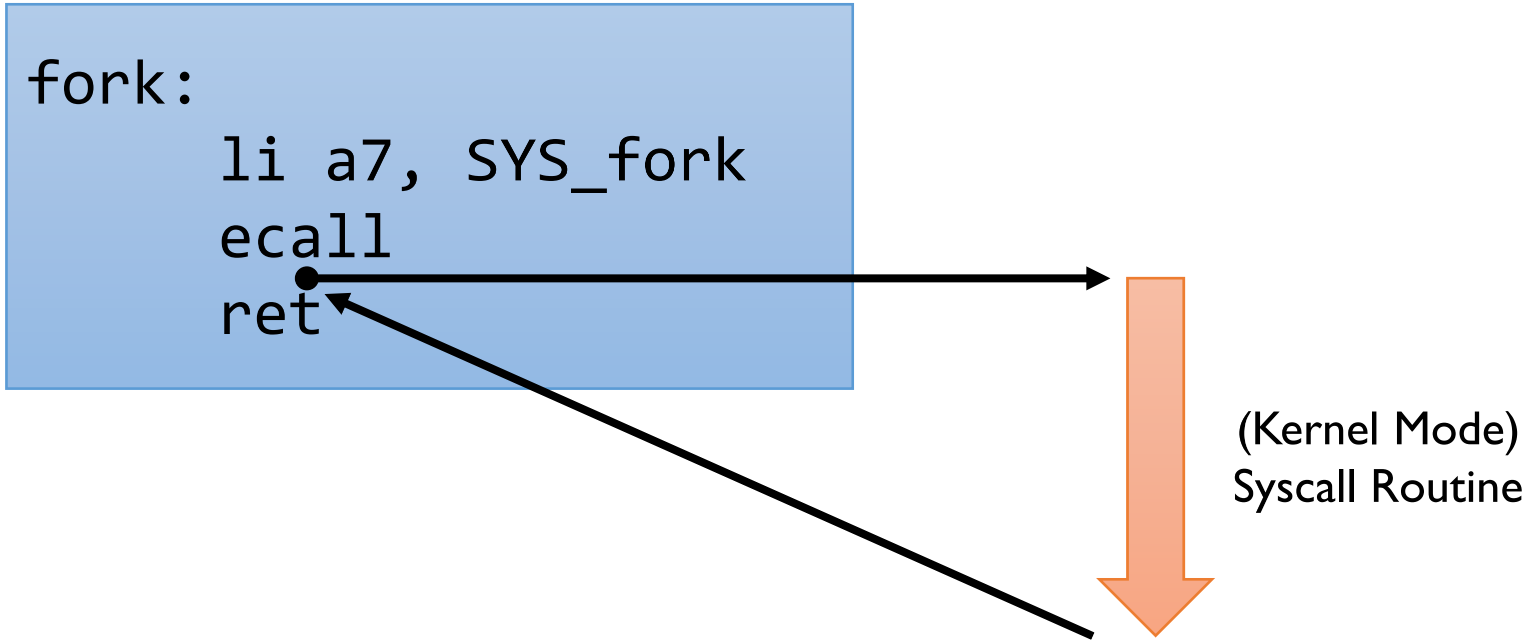
- User applications can access the operating system kernel in a restricted way
- The interfaces that allow user applications to request services from the operating system kernel
- The operating system kernel does the requested task on behalf of user applications

Three RISC-V Privilege Modes

- Machine Mode (M-mode)
  - CPU starts in machine mode
- Supervisor Mode (S-mode)
  - Allowed to execute privileged instructions
    - Enable/Disable interrupts
    - Modify the page table base register
    - …
  - The operating system kernel runs in supervisor mode
- User Mode (U-mode)
  - User processes run in user mode

ecall

- User applications execute the `ecall` instruction to invoke system calls
- E.g., `fork()`

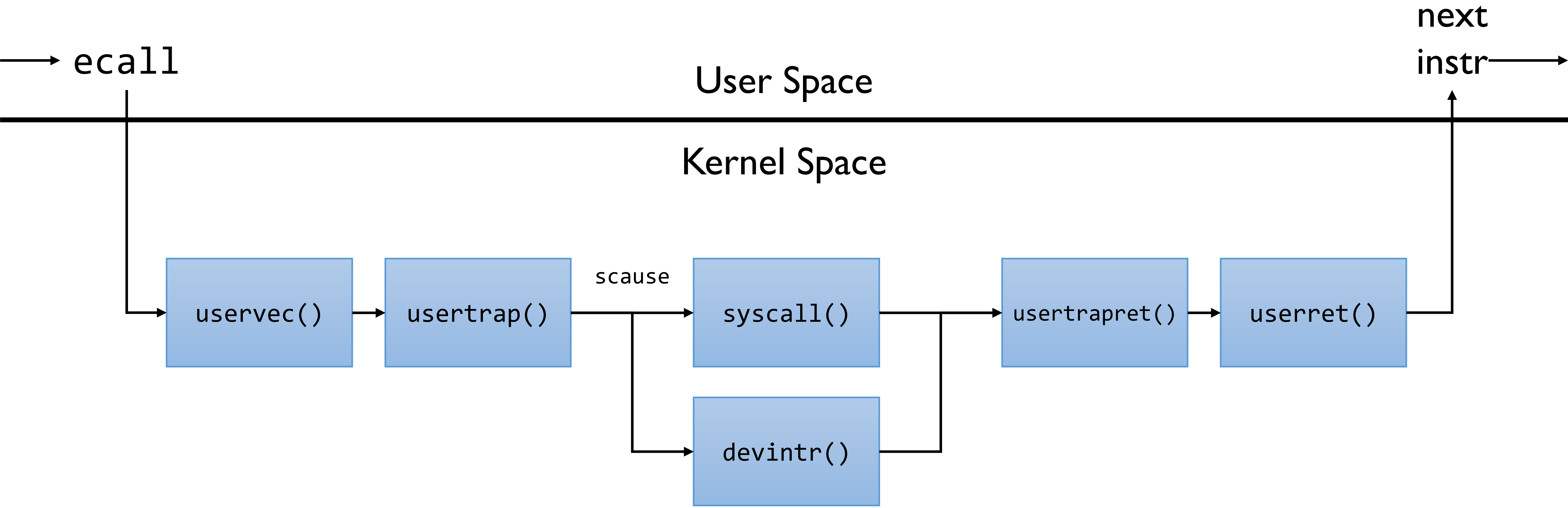


```
fork:
        li a7, SYS_fork
        ecall
        ret
```

(Kernel Mode)
Syscall Routine

Traps from User Space

- U-mode → S-mode



Some Registers

- `satp`
  - Pointer to page table
- `scause (mcause)`
  - Event which caused a trap
- `sepc (mepc)`
  - Program counter when a trap occurs
- `sscratch (mscratch)`
  - A dedicated register for use by supervisor (machine) mode
- `stvec (mtvec)`
  - Pointer to trap vector

What Happens on `ecall`

- The RISC-V hart performs all these steps as a single operation
  - Copy the `pc` into `sepc`
  - Set `scause` to reflect the trap's cause
  - Set the `stval` if necessary (e.g., fault address)
  - Set the mode to supervisor
  - Copy `stvec` (which is `uservec()` in xv6) to the `pc`
  - Start executing at the new `pc`
  - Note: the hart doesn't save any registers other than the `pc`

uservec()

- Start in supervisor mode
- Save registers values to trapframe
- Initialize kernel stack pointer
- Install the kernel page table
- Jump to usertrap()

`usertrap()`

- Install the kernel trap vector
- Save user program counter
- Handle an interrupt, exception, or system call depending on the value of `scause` register
- Call `usertrapret()` when it is done

`usertrapret()`

- Install the user trap vector
- Restore user program counter
- Jump to `userret()`

userret()

- Switch to the user page table
- Restore registers from trapframe
- Return to user mode

What Happens on `sret`

- The RISC-V hart performs all these steps as a single operation
  - Copy the `sepc` into `pc`
  - Start executing at the new `pc`

Physical Memory Protection

- Physical Memory Protection (PMP)
  - A hardware feature that provides fine-grained control over access to memory regions
  - It allows the system to define a set of rules governing which memory regions can be accessed by different privilege levels (such as U-mode or S-mode)
  - RISC-V supports up to 64 PMP entries, with each PMP entry defined by an 8-bit configuration register (e.g., `pmp0cfg`) and a corresponding 64-bit address register (e.g., `pmpaddr0`)
  - Each bit in the PMP configuration register specifies whether the corresponding memory region has permission for read(R), write(W), or instruction execution(X)
  - PMP address and configuration registers are only accessible in M-mode

Trap Delegation

- By default, all traps at any privilege level are handled in M-mode

- Setting a bit in `medeleg` or `mideleg` will delegate the corresponding trap, when occurring in S-mode or U-mode, to the S-mode trap handler

- xv6 delegates all interrupts and exceptions to S-mode
  - When the kernel executes the `ecall` instruction in S-mode, control is transferred to the S-mode trap handler (instead of M-mode trap handler)
  - You must make another (nested) system call from S-mode to M-mode to access PMP registers

Project #2

1. Implement the `nenter()` system call (30 points)

```
int nenter();
```

- It returns the total count of `[ENTER]` key presses from the console input device since the system booted
- The system call number is already assigned to 22

Project #2

2. Implement the `getpmpaddr()` system call (50 points)

```
void *getpmpaddr(int n);
```

- It returns the 64-bit physical address stored in the PMP address register
- The first (and the only) parameter denotes the index of the PMP address register
  - E.g., 0 for `pmpaddr0`, 1 for `pmpaddr1`, etc
- The system call number is already assigned to 23

Project #2

3. Implement the `getpmpcfg()` system call (20 points)

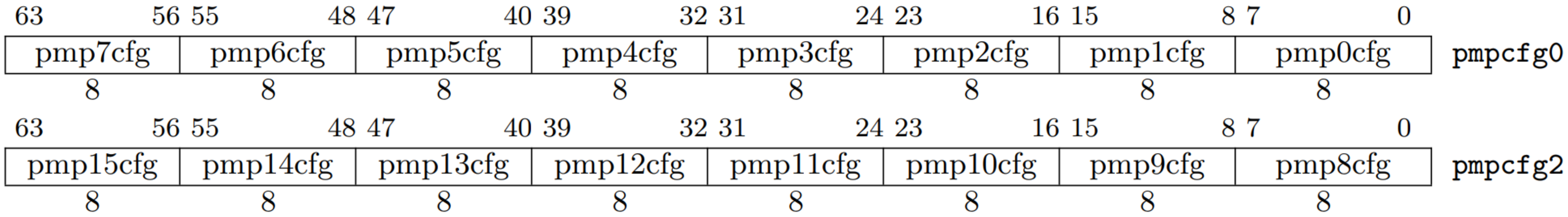
```
int getpmpcfg(int n);
```

- It returns an integer, where the lower 8 bits represent the content of the specified PMP configuration register
- The first (and the only) parameter denotes the index of the PMP configuration register
  - E.g., 0 for `pmp0cfg`, 1 for `pmp1cfg`, etc
- The system call number is already assigned to 24

Project #2

3. Implement the `getpmpcfg()` system call (20 points) (cont'd)

- Since individual 8-bit PMP configuration registers cannot be read directly, you must read the entire 64-bit `pmpcfg0` register



63 56	55 48	47 40	39 32	31 24	23 16	15 8	7 0	
pmp7cfg	pmp6cfg	pmp5cfg	pmp4cfg	pmp3cfg	pmp2cfg	pmp1cfg	pmp0cfg	**pmpcfg0**
8	8	8	8	8	8	8	8	

63 56	55 48	47 40	39 32	31 24	23 16	15 8	7 0	
pmp15cfg	pmp14cfg	pmp13cfg	pmp12cfg	pmp11cfg	pmp10cfg	pmp9cfg	pmp8cfg	**pmpcfg2**
8	8	8	8	8	8	8	8	

Project #2

- Tips
  - Read Chap. 4.1 of the xv6 book to understand RISC-V's privileged modes and trap handling mechanism
  - Read Chap. 4.2 ~ 4.5 of the xv6 book to see how traps are handled in xv6
  - Read Chap. 5 of the xv6 book to learn about hardware interrupts
  - More detailed information on physical memory protection (PMP) can be found in Chap. 3.7 of the RISC-V Privileged Architecture manual

Project #2

- You may want to consult:
  - `kernel/console.c`
    - Console-related functions
  - `kernel/kernelvec.S`
    - M-mode and S-mode trap vectors
  - `kernel/riscv.h`
    - Architecture-dependent codes
  - `kernel/start.c`
    - xv6 kernel boot up code
  - `kernel/syscall.c`
    - General system call handling
  - `kernel/sysproc.c`
    - Several system call implementations
  - `kernel/trap.c`
    - Trap handling
  - And other files if necessary

Project #2

- Restrictions
  - You should use the QEMU version 8.2.0 or higher
  - Do not change the predefined system call numbers
  - You only need to change the files in the `kernel` directory
  - Do not change the `kernel/pmp.c` file

Project #2

- Skeleton Code
  - You should work on the pa2 branch of the `xv6-riscv-snu` repository as follows:

```
$ git clone https://github.com/snu-csl/xv6-riscv-snu
$ git checkout pa2
```

  - The pa2 branch has a user-level utility program named `nenter` and `pmptest` which can be built from the `user/nenter.c` and the `user/pmptest.c`, respectively

Project #2

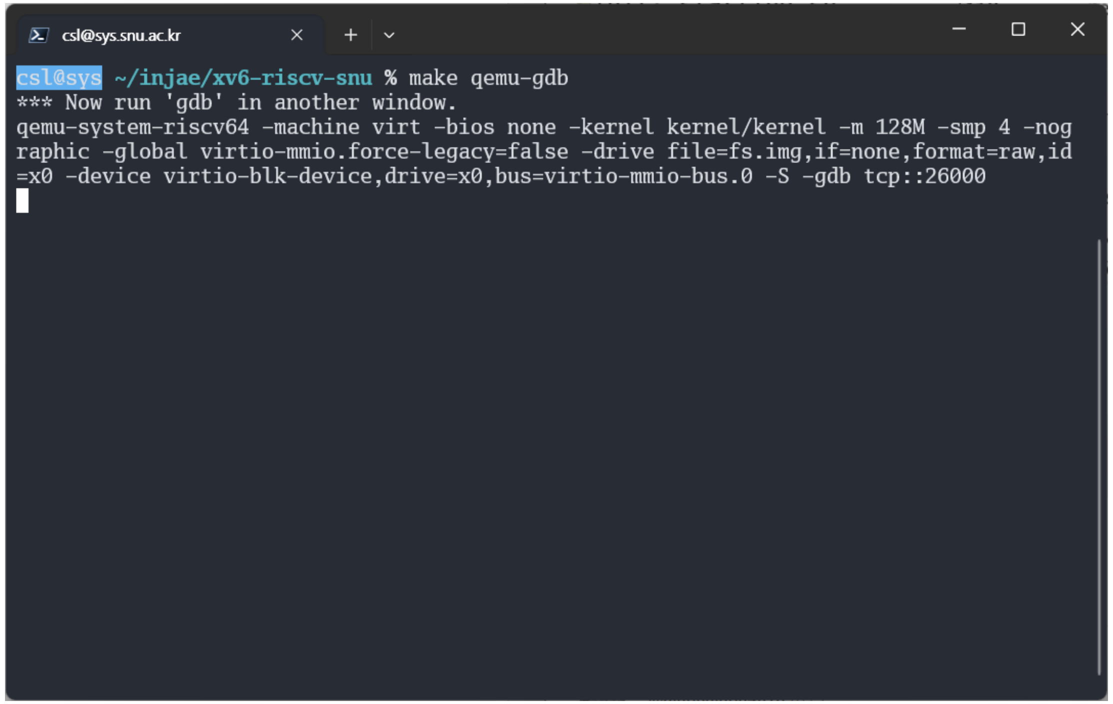
- Due
  - 11:59 PM, October 6 (Sunday)

- Submission
  - Run `make submit` to generate a tarball named `xv6-pa2-{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 30
  - Only the version marked FINAL will be considered for the project score
  - In this project, you do not need to submit a report

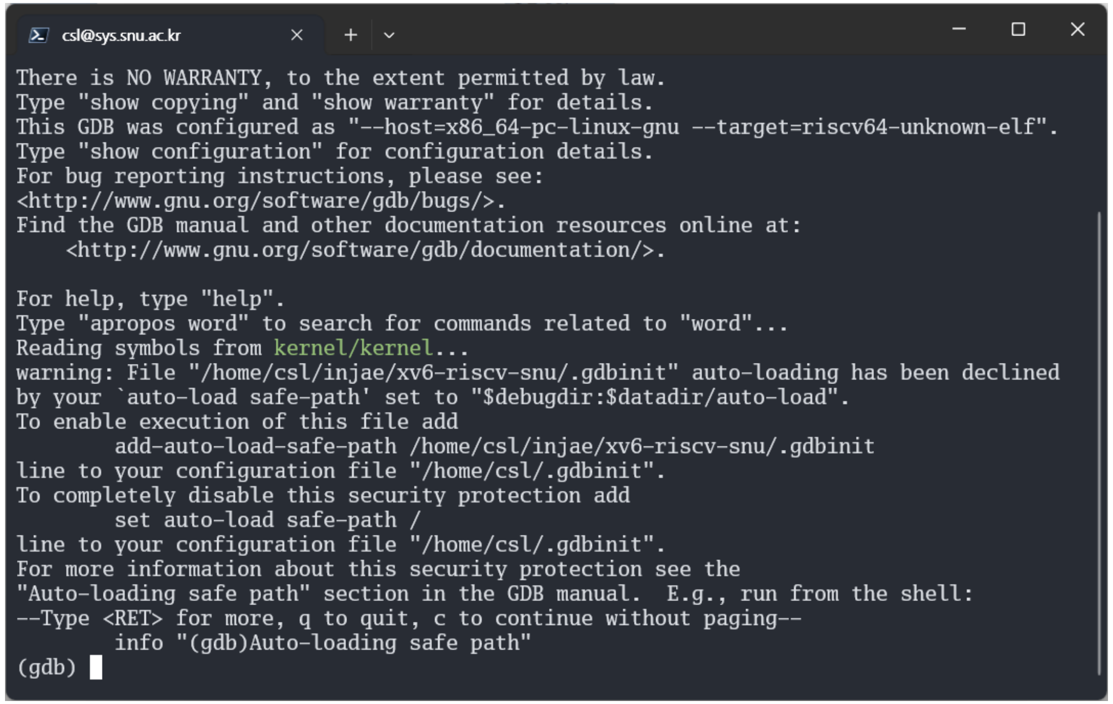
Using GDB with QEMU

GDB with QEMU (Linux)

- Run `sudo apt install gdb-multiarch`
- In the `xv6-riscv-snu` directory, run `make qemu-gdb` to run QEMU
- In another shell, run `gdb-multiarch ./kernel/kernel`



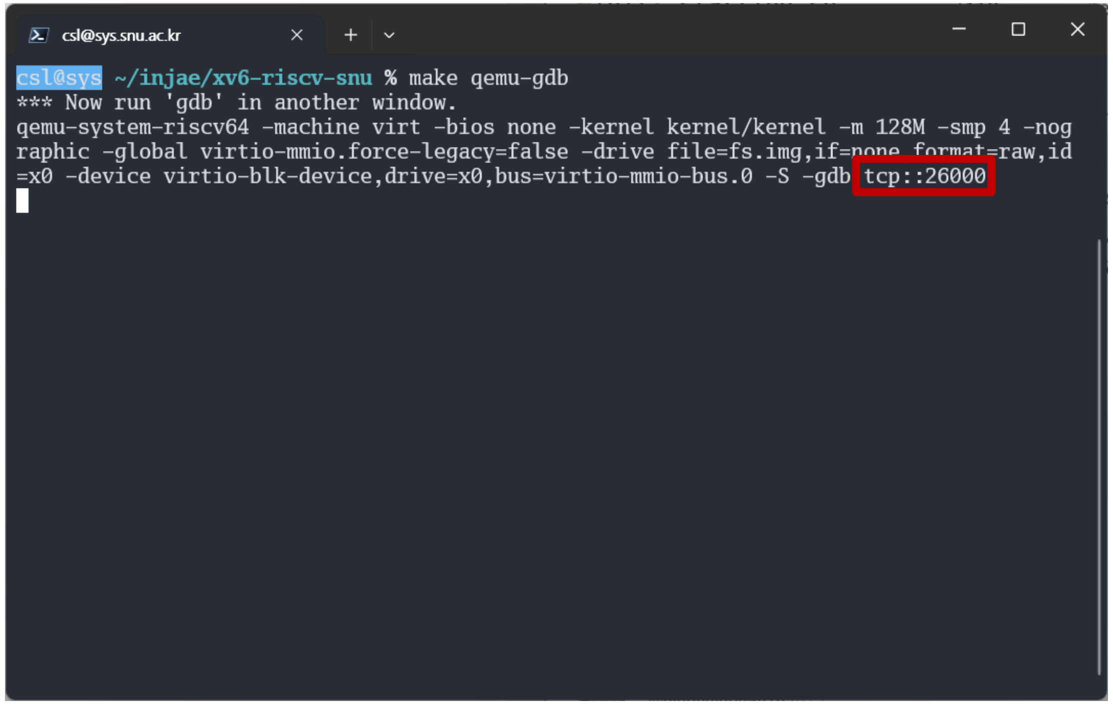
```
csl@sys ~/injae/xv6-riscv-snu % make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp 4 -nog
raphic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,format=raw,id
=x0 -device virtio-blk-device,drive=x0,bus=virtio-mmio-bus.0 -S -gdb tcp::26000
```



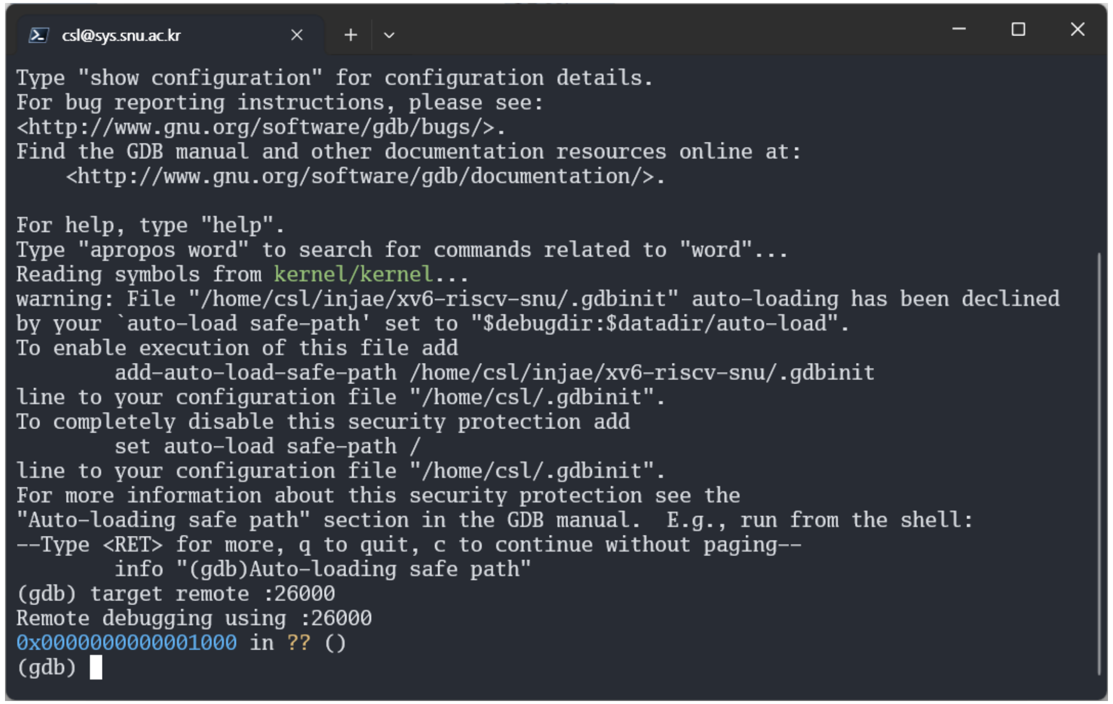
```
There is NO WARRANTY, to the extent permitted by law.
Type "show copying" and "show warranty" for details.
This GDB was configured as "--host=x86_64-pc-linux-gnu --target=riscv64-unknown-elf".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
    <http://www.gnu.org/software/gdb/documentation/>.

For help, type "help".
Type "apropos word" to search for commands related to "word"...
Reading symbols from kernel/kernel...
warning: File "/home/csl/injae/xv6-riscv-snu/.gdbinit" auto-loading has been declined
by your `auto-load safe-path' set to "$debugdir:$datadir/auto-load".
To enable execution of this file add
        add-auto-load-safe-path /home/csl/injae/xv6-riscv-snu/.gdbinit
line to your configuration file "/home/csl/.gdbinit".
To completely disable this security protection add
        set auto-load safe-path /
line to your configuration file "/home/csl/.gdbinit".
For more information about this security protection see the
"Auto-loading safe path" section in the GDB manual.  E.g., run from the shell:
--Type <RET> for more, q to quit, c to continue without paging--
        info "(gdb)Auto-loading safe path"
(gdb)
```

GDB with QEMU (Linux)

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



```
csl@sys ~/injae/xv6-riscv-snu % make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp 4 -nog
raphic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,format=raw,id
=x0 -device virtio-blk-device,drive=x0,bus=virtio-mmio-bus.0 -S -gdb tcp::26000
```



```
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For bug reporting instructions, please see:
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For help, type "help".
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--Type <RET> for more, q to quit, c to continue without paging--
        info "(gdb)Auto-loading safe path"
(gdb) target remote :26000
Remote debugging using :26000
0x0000000000001000 in ?? ()
(gdb)
```
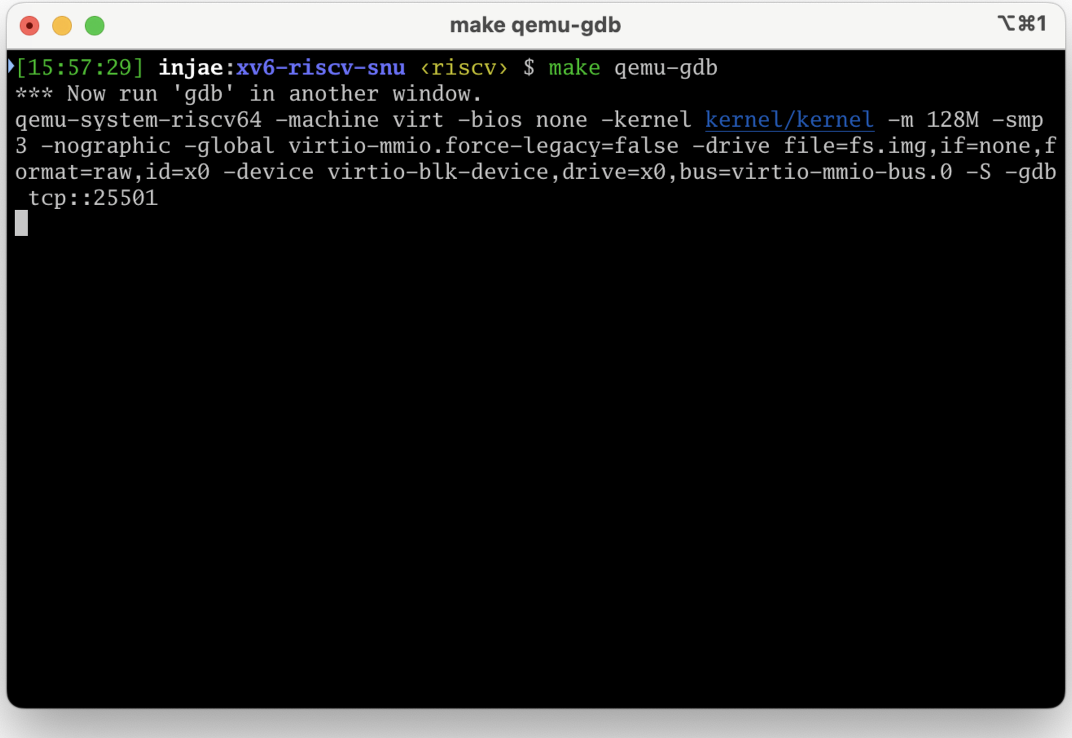
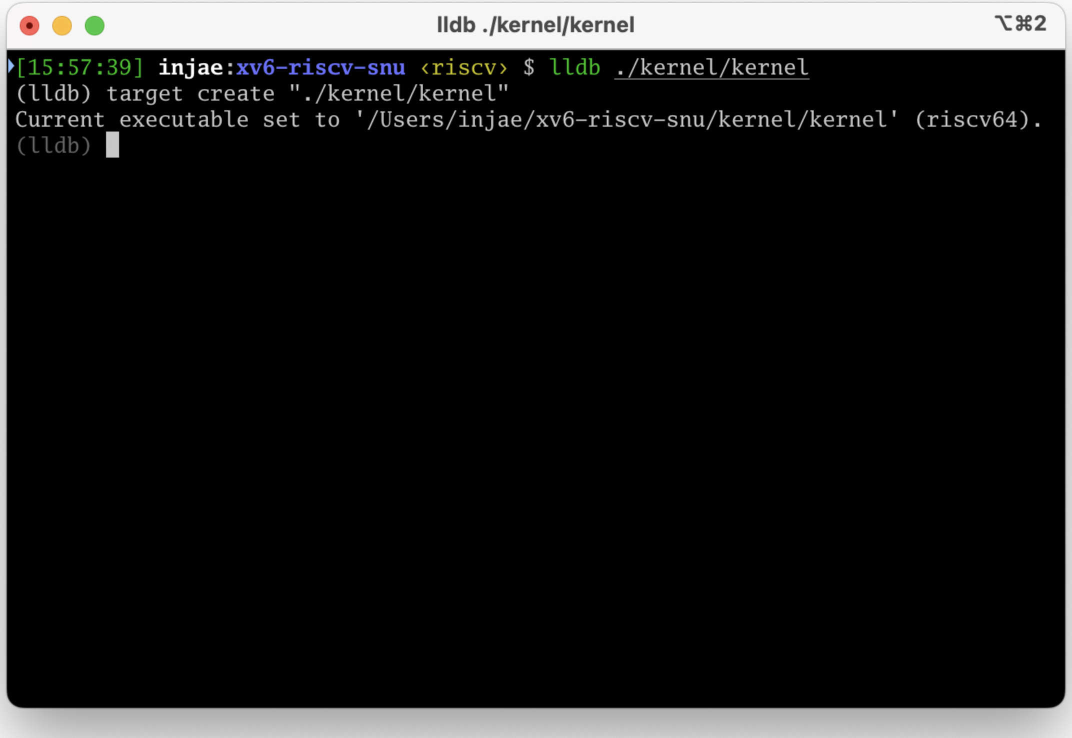

GDB with QEMU (MacOS)

- In the `xv6-riscv-snu` directory, run `make qemu-gdb` to run QEMU
- In another shell, run `lldb ./kernel/kernel`



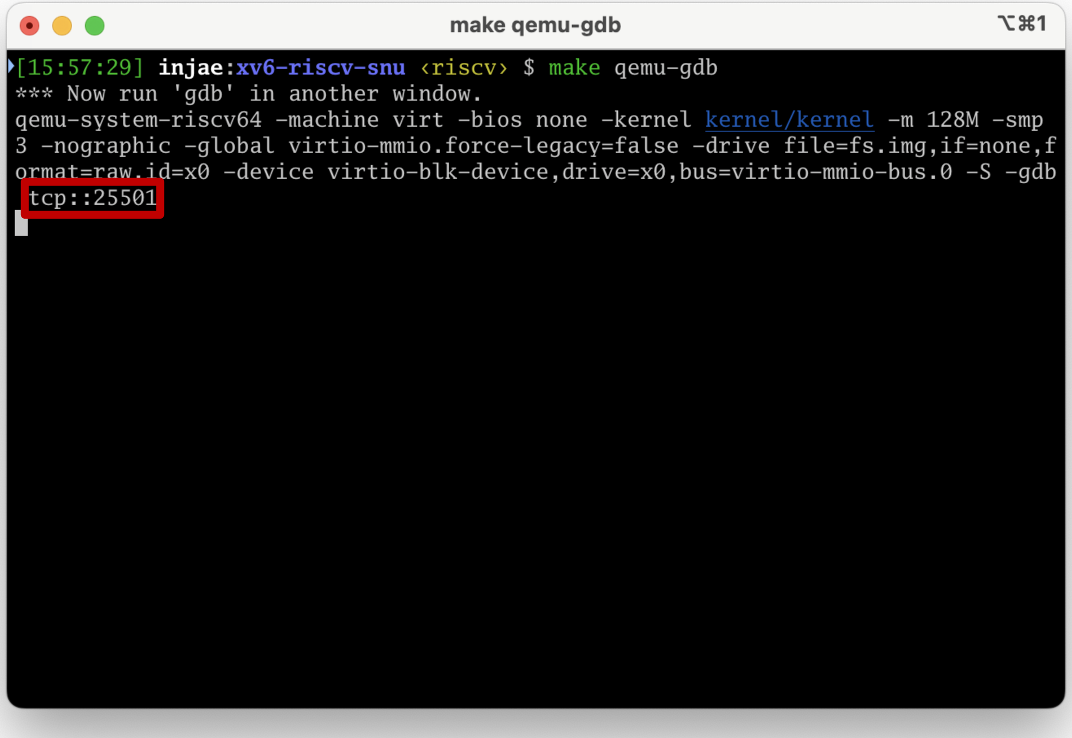
```
[15:57:29] injae:xv6-riscv-snu ‹riscv› $ make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp
3 -nographic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,f
ormat=raw,id=x0 -device virtio-blk-device,drive=x0,bus=virtio-mmio-bus.0 -S -gdb
 tcp::25501
```



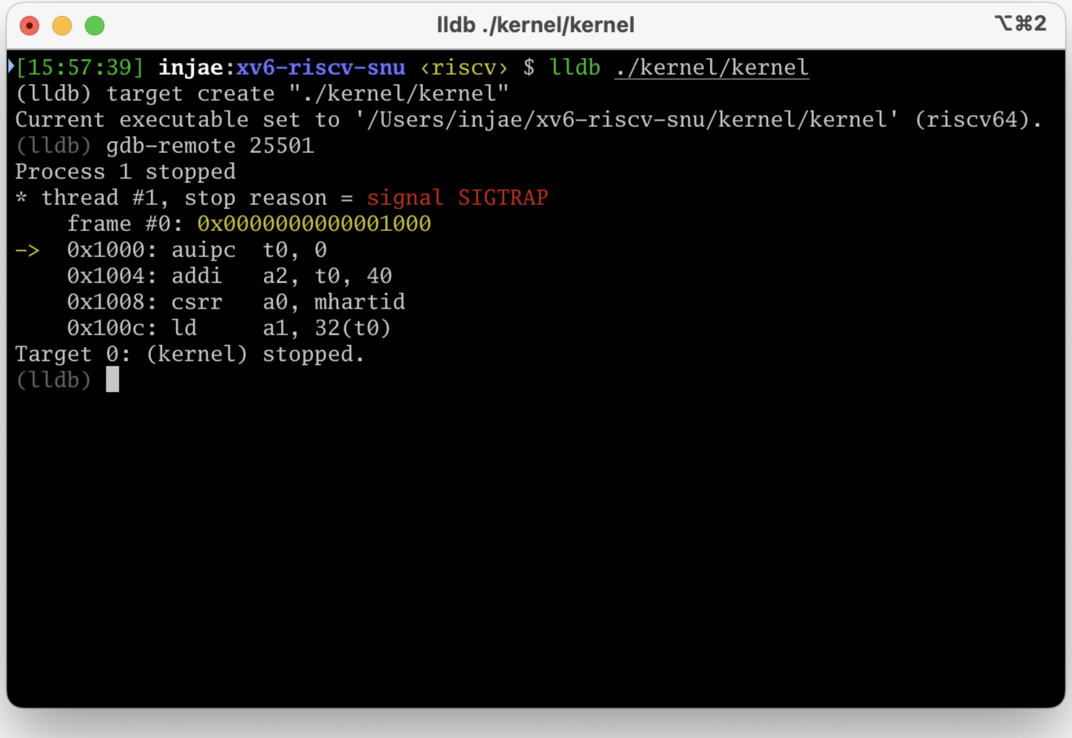
```
[15:57:39] injae:xv6-riscv-snu ‹riscv› $ lldb ./kernel/kernel
(lldb) target create "./kernel/kernel"
Current executable set to '/Users/injae/xv6-riscv-snu/kernel/kernel' (riscv64).
(lldb)
```

GDB with QEMU (MacOS)

- In LLDB, enter `gdb-remote <port>`
- You can find TCP port in the QEMU log



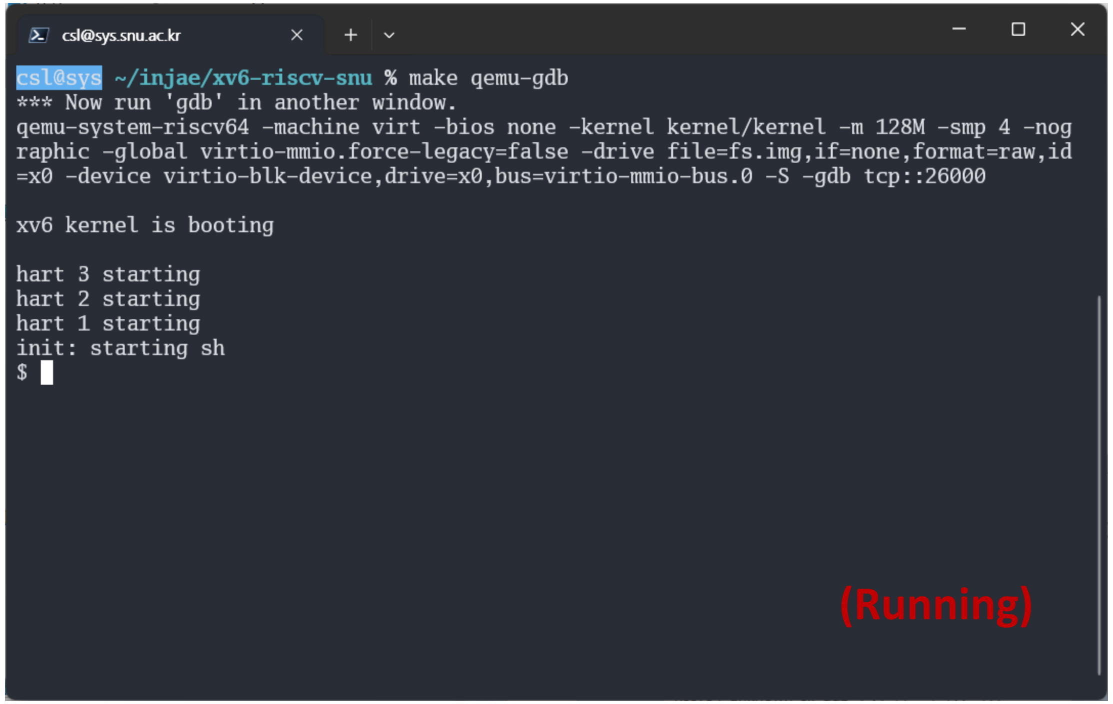
```
[15:57:29] injae:xv6-riscv-snu ‹riscv› $ make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp
3 -nographic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,f
ormat=raw,id=x0 -device virtio-blk-device,drive=x0,bus=virtio-mmio-bus.0 -S -gdb
 tcp::25501
```



```
[15:57:39] injae:xv6-riscv-snu ‹riscv› $ lldb ./kernel/kernel
(lldb) target create "./kernel/kernel"
Current executable set to '/Users/injae/xv6-riscv-snu/kernel/kernel' (riscv64).
(lldb) gdb-remote 25501
Process 1 stopped
* thread #1, stop reason = signal SIGTRAP
    frame #0: 0x0000000000001000
->  0x1000: auipc  t0, 0
    0x1004: addi   a2, t0, 40
    0x1008: csrr   a0, mhartid
    0x100c: ld     a1, 32(t0)
Target 0: (kernel) stopped.
(lldb) 
```

GDB with QEMU

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



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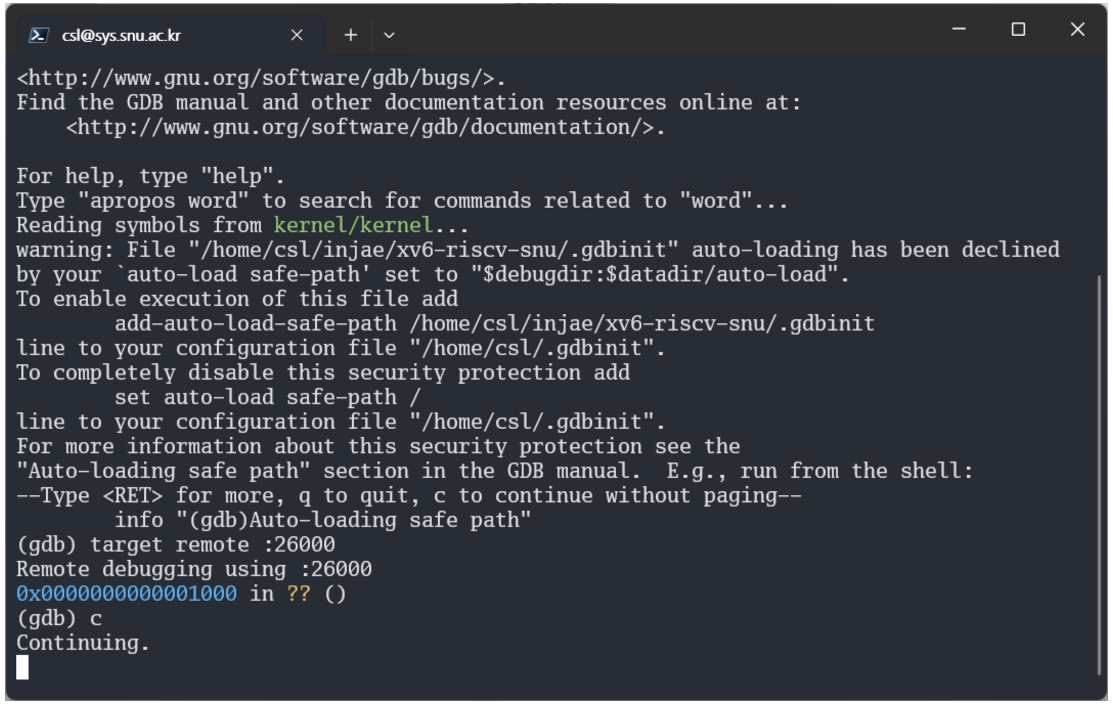
raphic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,format=raw,id
=x0 -device virtio-blk-device,drive=x0,bus=virtio-mmio-bus.0 -S -gdb tcp::26000

xv6 kernel is booting

hart 3 starting
hart 2 starting
hart 1 starting
init: starting sh
$ 
```

(Running)



```
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Type "apropos word" to search for commands related to "word"...
Reading symbols from kernel/kernel...
warning: File "/home/csl/injae/xv6-riscv-snu/.gdbinit" auto-loading has been declined
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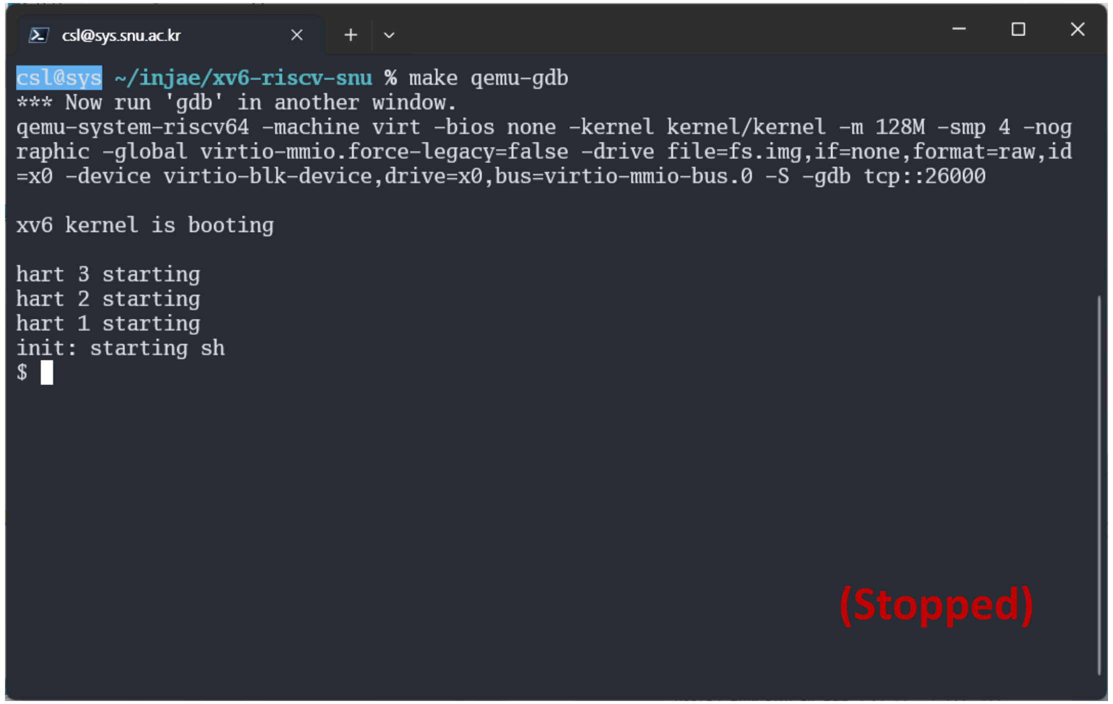
--Type <RET> for more, q to quit, c to continue without paging--
        info "(gdb)Auto-loading safe path"
(gdb) target remote :26000
Remote debugging using :26000
0x0000000000001000 in ?? ()
(gdb) c
Continuing.
```

GDB with QEMU

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



```
csl@sys ~/injae/xv6-riscv-snu % make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp 4 -nog
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xv6 kernel is booting

hart 3 starting
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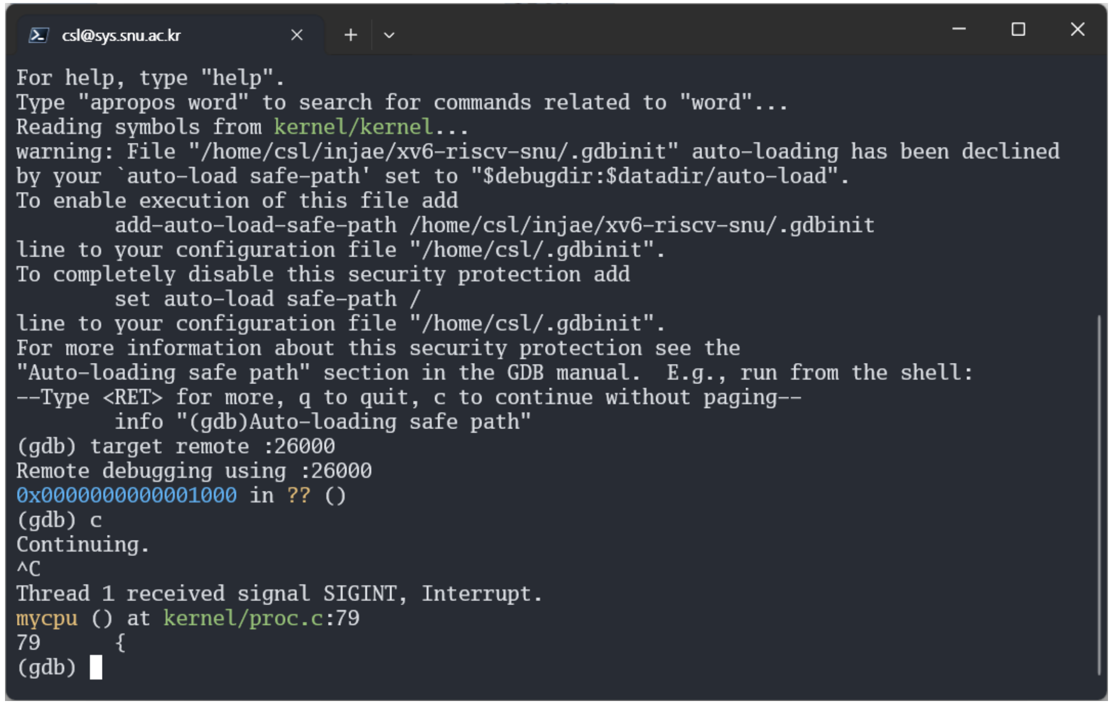
hart 1 starting
init: starting sh
$ 
```

(Stopped)



```
For help, type "help".
Type "apropos word" to search for commands related to "word"...
Reading symbols from kernel/kernel...
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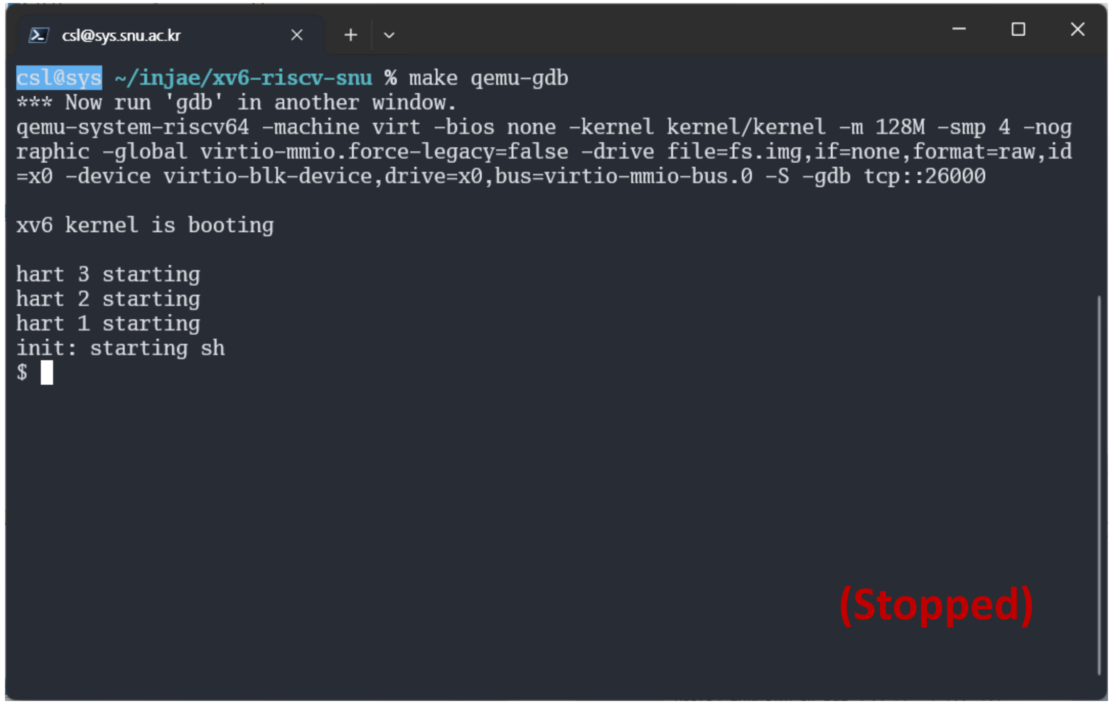
--Type <RET> for more, q to quit, c to continue without paging--
        info "(gdb)Auto-loading safe path"
(gdb) target remote :26000
Remote debugging using :26000
0x0000000000001000 in ?? ()
(gdb) c
Continuing.
^C
Thread 1 received signal SIGINT, Interrupt.
mycpu () at kernel/proc.c:79
79      {
(gdb) 
```

GDB with QEMU

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



```
csl@sys ~/injae/xv6-riscv-snu % make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp 4 -nog
raphic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,format=raw,id
=x0 -device virtio-blk-device,drive=x0,bus=virtio-mmio-bus.0 -S -gdb tcp::26000

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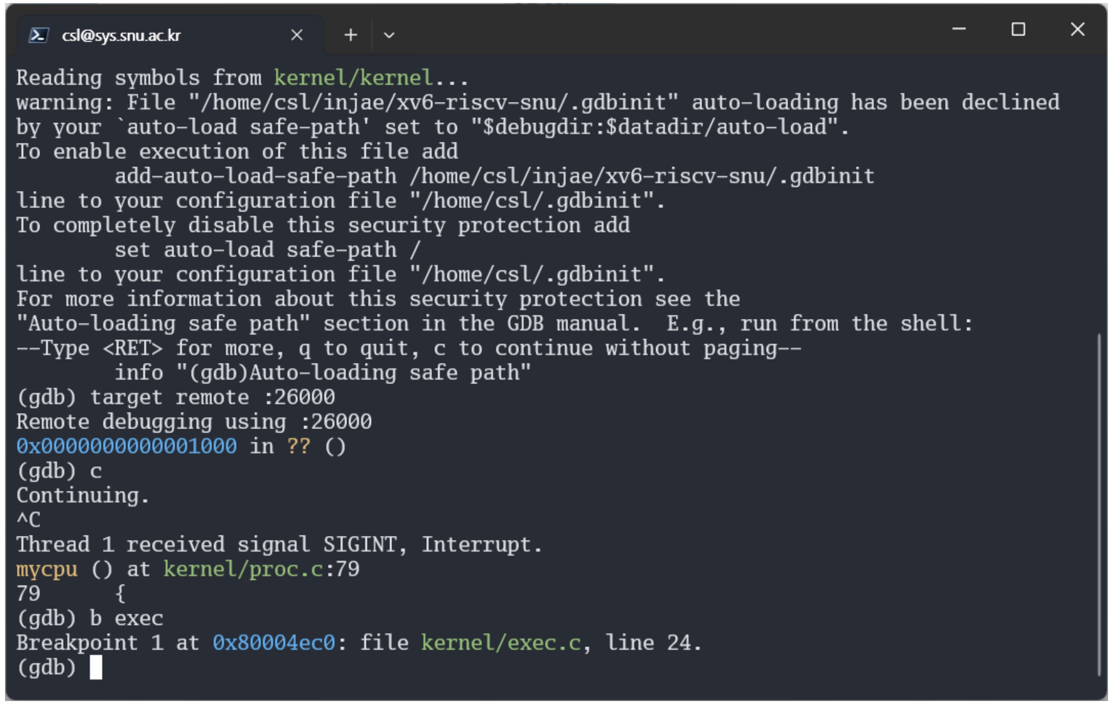
```

(Stopped)



```
Reading symbols from kernel/kernel...
warning: File "/home/csl/injae/xv6-riscv-snu/.gdbinit" auto-loading has been declined
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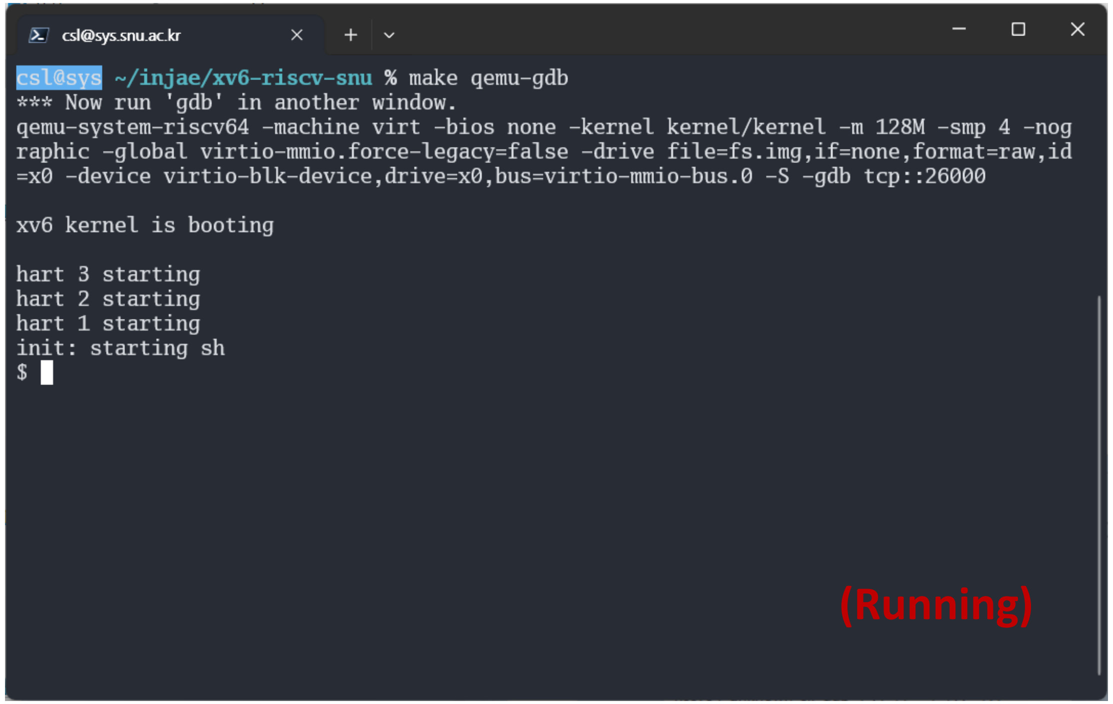
--Type <RET> for more, q to quit, c to continue without paging--
        info "(gdb)Auto-loading safe path"
(gdb) target remote :26000
Remote debugging using :26000
0x0000000000001000 in ?? ()
(gdb) c
Continuing.
^C
Thread 1 received signal SIGINT, Interrupt.
mycpu () at kernel/proc.c:79
79      {
(gdb) b exec
Breakpoint 1 at 0x80004ec0: file kernel/exec.c, line 24.
(gdb) 
```

GDB with QEMU

- Enter c in GDB to resume the xv6 machine



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csl@sys ~/injae/xv6-riscv-snu % make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp 4 -nog
raphic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,format=raw,id
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xv6 kernel is booting

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```
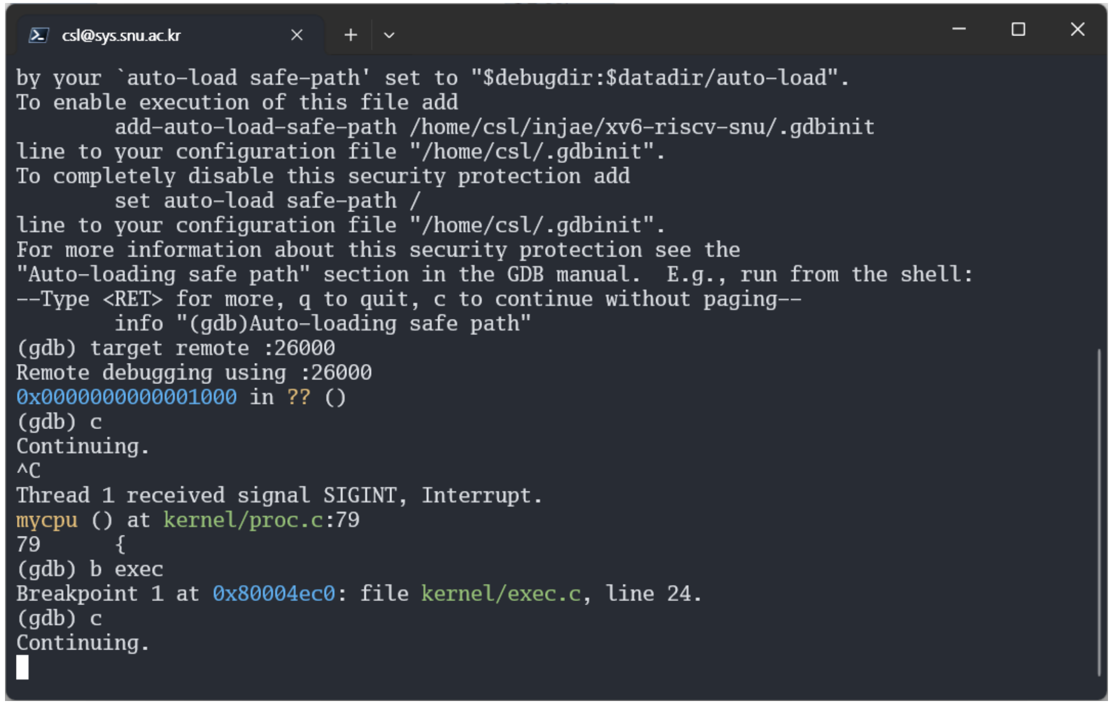
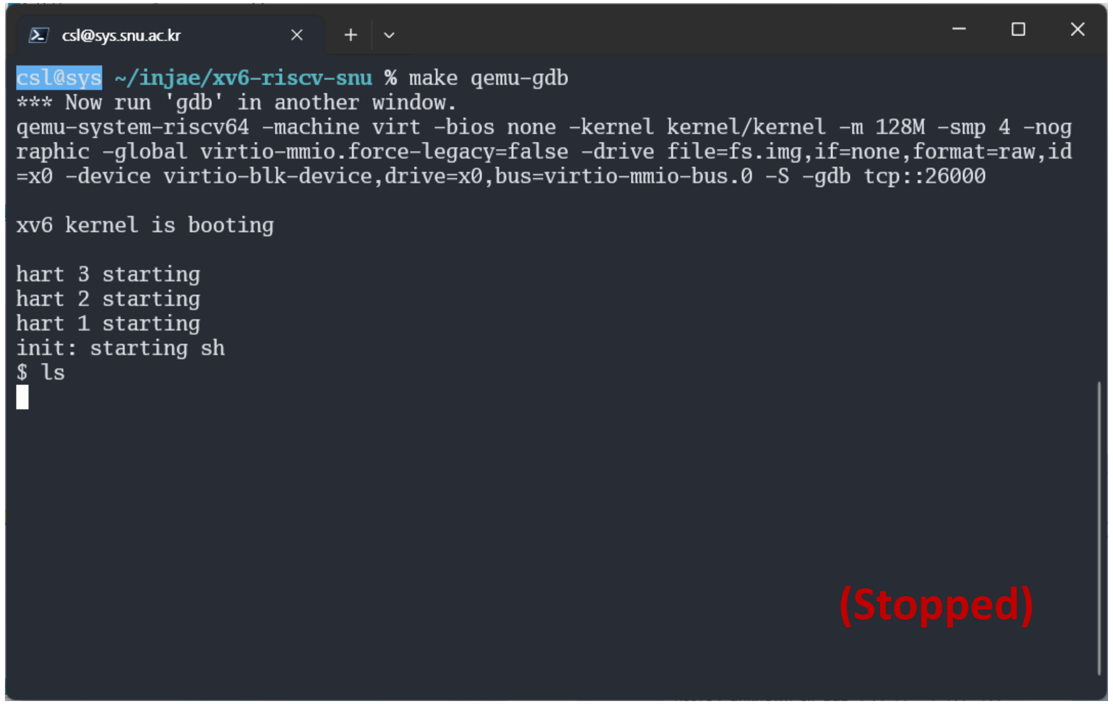

(Running)



```
by your `auto-load safe-path' set to "$debugdir:$datadir/auto-load".
To enable execution of this file add
        add-auto-load-safe-path /home/csl/injae/xv6-riscv-snu/.gdbinit
line to your configuration file "/home/csl/.gdbinit".
To completely disable this security protection add
        set auto-load safe-path /
line to your configuration file "/home/csl/.gdbinit".
For more information about this security protection see the
"Auto-loading safe path" section in the GDB manual.  E.g., run from the shell:
--Type <RET> for more, q to quit, c to continue without paging--
        info "(gdb)Auto-loading safe path"
(gdb) target remote :26000
Remote debugging using :26000
0x0000000000001000 in ?? ()
(gdb) c
Continuing.
^C
Thread 1 received signal SIGINT, Interrupt.
mycpu () at kernel/proc.c:79
79      {
(gdb) b exec
Breakpoint 1 at 0x80004ec0: file kernel/exec.c, line 24.
(gdb) c
Continuing.
```

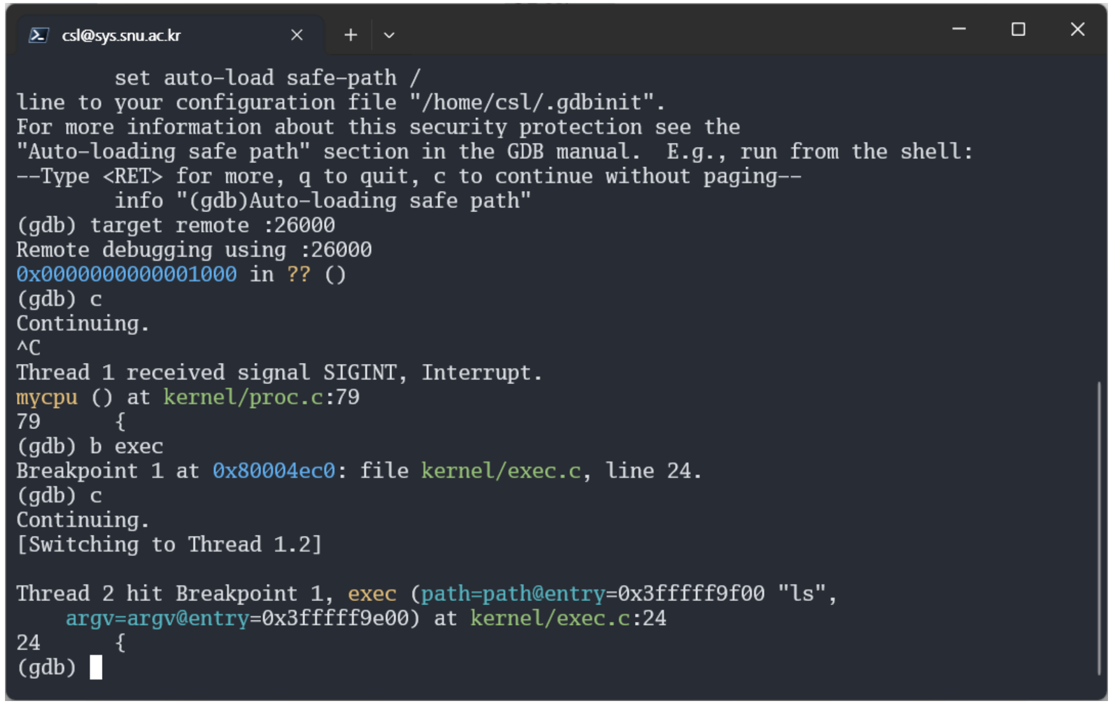
GDB with QEMU

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



```
csl@sys ~/injae/xv6-riscv-snu % make qemu-gdb
*** Now run 'gdb' in another window.
qemu-system-riscv64 -machine virt -bios none -kernel kernel/kernel -m 128M -smp 4 -nog
raphic -global virtio-mmio.force-legacy=false -drive file=fs.img,if=none,format=raw,id
=x0 -device virtio-blk-device,drive=x0,bus=virtio-mmio-bus.0 -S -gdb tcp::26000

xv6 kernel is booting

hart 3 starting
hart 2 starting
hart 1 starting
init: starting sh
$ ls
```

(Stopped)



```
        set auto-load safe-path /
line to your configuration file "/home/csl/.gdbinit".
For more information about this security protection see the
"Auto-loading safe path" section in the GDB manual.  E.g., run from the shell:
--Type <RET> for more, q to quit, c to continue without paging--
        info "(gdb)Auto-loading safe path"
(gdb) target remote :26000
Remote debugging using :26000
0x0000000000001000 in ?? ()
(gdb) c
Continuing.
^C
Thread 1 received signal SIGINT, Interrupt.
mycpu () at kernel/proc.c:79
79      {
(gdb) b exec
Breakpoint 1 at 0x80004ec0: file kernel/exec.c, line 24.
(gdb) c
Continuing.
[Switching to Thread 1.2]

Thread 2 hit Breakpoint 1, exec (path=path@entry=0x3fffff9f00 "ls",
    argv=argv@entry=0x3fffff9e00) at kernel/exec.c:24
24      {
(gdb) 
```

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!