HoH: CSL373/CSL633 Labs

What's the best way for learning OS? Create one!

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Also available in pdf, slides. beamer. latex.

Introduction

Introduction

Hello! I'm Alice. I am your TA for this course.

In this series, you will join forces with me, and together, we will build a *kernel from the scratch*. We both will be working on this kernel.

I'll do some coding in a branch, and ask you to implement some functionality. You can get my code by merging the branch with yours, and implement the functionality I asked. Once you implement it and commit the changes in your repository, I'll again work on the kernel on some other branch..

Status so far - our kernel boots into C code

So far, I have managed to write: See osdev barebones

1. x86/boot.S : containing seven lines of 32-bit x86 assembly instructions to:

   - set the stack pointer,

     ```
     movl  $tmpstack_bottom, %esp
     ```

   - clear flags,

     ```
     pushl $0
     popf
     ```

   - call the C function

     ```
     call  core_boot
     ```

   - enter infinite loop

     ```
       cli
     loop:
       hlt
       jmp   loop
     ```

2. x86/main.cc : a C function which does nothing

   ```
   extern "C" void core_boot(){
   }
   ```

make

- Syntax:

```
bash$ make <target> B=<release/debug>
where target =
  iso      : create boot cd
  exe      : build kernel (default)
  qemu     : run qemu
  qemu-gdb : qemu with gdb
```

- Usage: make iso / make qemu / make qemu-gdb B=debug

- Try 'make qemu-direct' and 'make qemu-gdb-direct B=debug' if you face any issues.

On Boot

- CPU sets cs:ip to 0xffff:0x0000 and starts executing code from this location(BIOS ROM is memory mapped at this location. When CPU tries to load the instruction from this location, cache and memory will be bypassed, and instructions will be directly loaded from ROM).
- *CPU starts executing BIOS code directly from ROM.*
- BIOS code initializes cache, RAM and other peripherals
- BIOS code installs its handlers by modifying Interrupt descriptor table(IDT) to provide services for bootloader
- BIOS loads the boot loader(grub2) code from the boot disk at 0x0000:0x7c00 and jump to it. Now, *CPU starts executing boot loader code(grub2).*
- (specific to grub2): grub2 uses bios provided interrupt handlers to load it's configuration file /boot/grub/grub2.cfg and gets the path of kernel to be loaded, and the kernel is multiboot standard compatible - and grub2 switches the CPU to 32 bit mode.
- Bootloader(grub2) loads initial part of kernel containing ELF header from the disk (using BIOS provided interrupt handlers) into RAM
- grub2 scans kernel's initial part for 'multiboot header' to know the interface expected from the kernel - for ex: multiboot version.
- Bootloader reads the ELF header and loads each section of kernel from disk into corresponding address in RAM(as mentioned in ELF header)
- Bootloader jumps to the starting address mentioned in kernel's ELF header(usually _start)
- *CPU starts executing kernel code*(_start).

Analyzing tracefile

I've enabled qemu's instruction tracing. So after executing 'make qemu', a trace file created named qemu.log in the current working directory.

When looking at the tracefile(qemu.log), please skip the initial bios instructions

```
----------------
IN:
0xfffffff0:  ljmp   $0xf000,$0xe05b
```

and also skip the bootloader code,

```
----------------
IN:
0x00007c00:  call   0x7c03
```

Our kernel's instruction trace

Towards the end you can see our kernel's instruction trace. For example:

```
----------------
IN:
0x00100050:  mov    $0x104080,%esp
0x00100055:  push   $0x0
0x00100057:  popf
0x00100058:  call   0x1040a0
----------------
IN: core_boot
0x001040a0:  repz ret
0x0010005d:  cli
0x0010005e:  hlt
```

Boot our kernel from your laptop

Optional: Multiboot specification specifies the interface between boot loader(eg: grub) and the kernel. You can also boot our kernel from your laptop, by using any multiboot combatible boot loader.

For example: On grub2, I press 'c' to enter command prompt, and type:

```
(grub2) multiboot (hd0,msdos5)/home/alice/hohlabs/_tmp/hoh.exe
(grub2) boot
```

Setup

So here's what you should do:

Tools

Please ensure you have latest version of:

- qemu (package: qemu qemu-system)
- g++ (package: g++-multilib >=4.7)
- git (package: git-all)
- grub2 (package: grub2 grub-pc-bin)
- boost library (package: libboost-all-dev)
- xorriso (to create iso image. Otherwise you'll get a warning that)
- coreutils(for makefile)

In debian/ubuntu, do:

```
bash$ sudo apt-get install qemu qemu-system g++-multilib git-all grub2 grub-pc-bin libboost-al
```

You can see tools to know more about these tools.

Clone the repository

Since we both will work on this kernel, we need to have a version control system. We'll use git as our version control system. Please clone the repository to your local directory

```
user@host:~$ git clone ssh://<user>@palasi.cse.iitd.ac.in/misc/research/teaching/sbansal/csl
user@host:~$ cd hohlabs
user@host:~/hohlabs$
```

Procedure

For each parts, do

1. Please get the changes done by Alice by merging the corresponding branch to your master branch

   ```
   user@host:~/hohlabs$ git pull
   user@host:~/hohlabs$ git merge origin/<branch_name>
   ```

For example, to get first part, do:

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/vgatext
```

2. *Modify the files under the directory "labs" only* to add the missing functionality. For example, for the first part, you should modify the function writechar in labs/vgatext.h

   ```
   user@host:~/hohlabs$ git pull
   user@host:~/hohlabs$ vim labs/vgatext.h
   ```

   Test your code by:

   ```
   user@host:~/hohlabs$ make qemu
   ```

   (Optional) To debug:

   - From first terminal:

     ```
     user@host:~/hohlabs$ make qemu B=debug
     ```

   - From another terminal:

     ```
     user@host:~/hohlabs$ gdb
     ```

   In gdb, you can set break point for example '_start'

   ```
   (gdb) break _start
   (gdb) ni
   (gdb) continue
   ```

3. Commit your changes in your local repository

   ```
   user@host:~/hohlabs$ git add -p labs/
   user@host:~/hohlabs$ git commit -m "your log message"

   #Advanced: git add labs/ ; git commit -m "commit message" ; git stash ; ....
   ```

4. Do submit your code so far. (resubmissions are allowed)

Submission

- To submit the assignment, from palasi:
  - make sure your changes are available in palasi. Skip this step, if you're working in GCL.
  - submit your changes in palasi using:

```
user@palasi:~/hohlabs$ os-submit-lab <labid>
```

- Can be submitted from palasi only.
- Resubmissions are allowed.
- For late penalty calculations, we only consider your submission using os-submit-lab (It is possible to change git commit history and filesystem modification time)
- Make sure you check your submission is correct by using: os-get-submission

Chapter 1

Primitives

Overview

In this first part, we'll look into basic primitives required for writing an OS.

- Evaluation:
  - Code component:
    * *NOTHING : 0* Not working
    * *PARTIAL : 1* Partial/buggy - TA is able to find atleast one bug in your code
    * *TYPO : 1.5* Code is not clean
    * *CORRECT : 2* Working code
  - Viva component:
    * *FLAGGED : 0* Can not explain his/her own code
    * *JUST_IMPLEMENTED : 1* can explain his/her own code but can't explain Alice's code
    * *KNOWS_WHY : 2* can explain his/her own code + Alice's code
  - Marks for each part is computed by following equation:

$$Marks = (W_d * D + W_v * V)$$

  - For 1.1-1.3: $W_d = 0.25$ and $W_v = 0.25$
  - For 1.4-1.7: $W_d = 0.40$ and $W_v = 0.10$
  - For 1.8: $W_d = 1.20$ and $W_v = 0.30$
  - For 1.9: $W_d = 0.80$ and $W_v = 0.20$
  - For 1.10: $W_d = 1.20$ and $W_v = 0.30$
  - For 1.10-1.13: $W_d = 0.80$ and $W_v = 0.20$

- For 1.14: $W_d = 2.00$ and $W_v = 0.50$
- During Viva: If you're not able to explain why you wrote the code, we'll award you zero for both code component and viva component of that part.
  - Note: Following explanation won't be accepted:
    - You tried hit and trial and somehow it worked.
    - You forgot the code
- During viva: If you're not able to explain the code that you wrote yourself(what is the code doing) we will report you as a major copy case and demo won't be taken for any of the parts.

1.1 MMIO

MergeRequest

I've added few more code in origin/vgatext branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/vgatext
```

Aim

In this part, we'll program a memory mapped device while enhancing our kernel by adding the functionality to display "Hello, world!".

Information

In VGA text mode, 16 bit (2 bytes) of information is stored for each screen character and is stored in row-major order. First byte(MSB) is the ASCII code of the screen character and the next byte(LSB) encodes background(4 bit: msb) and foreground color(4 bit: lsb). Color: 0x0 corresponds to black pallete, 0x7 corresponds to white pallete, 0x1 corresponds to blue pallete.

Usage

I've added few lines of C code in x86/main.cc:

```
for(i=0;i<sizeof mesg;i++){
  vgatext::writechar(i, mesg[i], bg_color, fg_color, vgatext_base_address);
}
```

Define

You need to define the following functions in labs/vgatext.h

```
void writechar(int loc, uint8_t c, uint8_t bg, uint8_t fg, addr_t base);
```

Arguments of vgatext::writechar:

- loc: location of screen character to be written,
- c: ascii code of the character to be written(8 bit)
- bg: background color(4 bit)
- fg: foreground color(4 bit)
- base: the memory mapped address of the vga text buffer

Given

To help you with mmio, I also added util/io.h which has following functions:

```
mmio::read8(base,byte_offset)
mmio::write8(base,byte_offset,8 bit value)
mmio::read16(base,byte_offset)
mmio::write16(base,byte_offset,16 bit value)
mmio::read32(base,byte_offset)
mmio::write32(base,byte_offset,32 bit value)
```

Tip

- You might find mmio::write16/mmio::write8 useful for implementing vgatext::writechar.
- Note that both mmio::write8 and mmio::write16 takes byte offset as an argument.
- If you're using mmio::write16, please take care of endianness - x86 is little endian.
- When using bit shift operations, we recommend you to use unsigned integer types

Turn in

You're required to implement vgatext::writechar() in labs/vgatext.h

Check

The kernel shall print 'Hello, world!' in the top left corner of the screen.

Note

- Expected: 1-2 line of C++ code. If you find yourself adding more than 10 lines of code in this part, please raise an alarm. After 10 logical lines of code, each logical line of code you add, 10% of mark will be substracted.
- Optional: Boot our kernel from a PC/laptop instead of qemu.

Note

- Endianness is a property of CPU - it's about what should be the memory contents "when a CPU executes Write instruction to memory" or what is the value of register if we execute read instruction from memory.

  When we say: MSB: char(8 bits) and LSB: bgfg (8 bits) - it's independent of endianness.

  It means: first byte should be char. and next byte is bgfg.

  It specifies what should be the memory contents after you execute the CPU instruction. And depending on the target CPU's (in which your OS is written for) endianness, you need to figure out what value you should write.

Demo Tip

Be prepared to answer following viva questions:

- How to program with memory mapped devices?
- What happens between 'programming from cpu' to 'device recieving the command/data' (Refer: Computer Architecture course)
- How to boot your kernel into C/C++ code?

1.2 PMIO

MergeRequest

Now it's my turn. I've added few more code in origin/serial branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/serial
```

Aim

In this part, we'll program an I/O mapped device while enhancing our kernel by adding debugging routines which will print debug messages to serial port.

Information

Serial port aka pc16550d uart(universal asynchronous receiver transmitter). In pc16550d uart,

Registers:

- the "transmitter holding" register of size 8 bits(1 byte) is I/O mapped at zeroth offset, and
- the "line status" register of size 8 bits(1 byte) is I/O mapped at fifth offset.

The line status register has several fields (in lsb order):

```
name="dr",          size="1 bit", description="Data ready"
name="oe",          size="1 bit", description="Overrun error"
name="pe",          size="1 bit", description="Parity error"
name="fe",          size="1 bit", description="Framing error"
name="bi",          size="1 bit", description="Break interrupt"
name="thre",        size="1 bit", description="Transmitter holding register"
name="temt",        size="1 bit", description="Transmitter empty"
name="erfifo",      size="1 bit", description="Error in RCVR FIFO"
```

Before one writes a character(data) to transmitter holding register, one need to ensure that "thre" bit ([5:5] from lsb: fifth bit indexed from zero) in the line status register is set.

Usage

I've added hoh_debug macro in util/debug.h, which will convert the arguments into string and call serial::print for each character in the string. Usage:

In x86/main.cc: I've added the following line.

```
hoh_debug("Hello, serial!");
```

hoh_debug macro will expand to a call to serial::print()

I also added serial::print function in util/debug.cc:

```
void serial::print(char c){
   wait until serial::is_transmitter_ready(serial_portbase) is true
   call serial::writechar(c,serial_portbase)
}
```

So, once you implement the required two functions, you'll be able to see "Hello, serial!" in your terminal.

Define

You need to define the following functions in labs/serial.h

```
bool is_transmitter_ready(io_t baseport);
void writechar(uint8_t c, io_t baseport);
```

Given

To help you with I/O(in and out asm), I had added following functions in util/io.h:

```
io::write8(baseport, offset, 8 bit value)
io::write16(baseport, offset, 16 bit value)
io::read8(baseport,offset)
io::read16(baseport,offset)
```

Tip

- You may find: io::read8(baseport,offset) and io::write8(baseport, offset, value) defined in util/io.h useful.
- When using bit shift operations, we recommend you to use unsigned integer types

Turn in

You're required to implement serial::is_transmitter_ready() and serial::writechar() in labs/serial.h

Check

The kernel shall print 'Hello, serial!' in your terminal.

Note

- Expected: 2-4 line of C++ code. If you find yourself adding more than 20 lines of code in this part, please raise an alarm. After 20 logical lines of code, each logical line of code you add, 5% of mark will be substracted.

Demo Tip

Be prepared to answer following viva questions:

- How to program with io mapped devices?
- What happens between 'programming from cpu' to 'device recieving the command/data' (Refer: Computer Architecture course)

1.3 Abstract mmio/pmio

MergeRequest

I've added few more code in origin/keyboard branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/keyboard
```

Aim

In this part, we'll look at one way of abstracting out details of mmio::read8 vs io::read8 while enhance our kernel by adding a simple keyboard driver.

Information

In Keyboard(8042, name=lpc_kbd), there are two main registers

- status register: size="8 bits" The status register has several fields

```
name="perr",     size="1 bit", description="Parity error"
name="timeout",  size="1 bit", description="General timeout"
name="aobf",     size="1 bit", description="Auxiliary device output buffer full"
name="is",       size="1 bit", description="Inhibit switch"
name="cd",       size="1 bit", description="Command/data"
name="sf",       size="1 bit", description="System flag"
name="ibf",      size="1 bit", description="Input buffer full"
name="obf",      size="1 bit", description="Output buffer full"
```

- input register: size="8 bits"

Before reading "input" register value, we need to make sure that the input buffer(of size 1) has data. Data availability in input buffer is indicated by the "Output Buffer full" bit in "status" register(Keyboard's output buffer to CPU). So, we need to make sure that "Output Buffer full" bit is set in the "status" register.

To read value of register, use:

```
regiser_value = <devicename>_<registername>_rd(address of device info structure);
```

To extract value of a field from register value, use:

```
field_value = <devicename>_<registername>_<fieldname>_extract(register_value);
```

For example, generated/lpc_kbd.h contains following functions:

Usage

```
core_loop_step():
    if(!has_key(dev)){
      return;
    }
    input=get_key(dev);
    hoh_debug("Got key: "<<input);

core_loop():
    repeat core_loop_step
```

Define

You need to define the following functions in labs/keyboard.h

```
bool has_key(lpc_kbd_t& dev);
uint8_t get_key(lpc_kbd_t& dev);
```

Given

Following functions are defined in generated/lpc_kbd.h(generated from spec/lpc_kbd.spec using modified mackerel):

```
lpc_kbd_status_rd()           : return the value of "status" register  of "lpc_kbd"
lpc_kbd_status_obf_extract()  : extract "obf" field from "status" register   of "l
lpc_kbd_input_rd()            : return the value of "input" register of "lpc_kbd" o
```

Tip

Trivial.

Turn in

You’re required to implement the required functions in labs/keyboard.h

Check

Kernel shall print scancode of each key pressed in your terminal(hoh_debug).

Note

- Expected: 2-4 line of C++ code. If you find yourself adding more than 10 lines of code in this part, please raise an alarm. After 10 logical lines of code, each logical line of code you add, 10% of mark will be substracted.

Demo Tip

Be prepared to answer following viva questions:

- Is keyboard memory mapped(mmio::read8) or io mapped(io::read8)?
- What’s the offset of status register and input register from basemem/baseport?
- Which bits corresponds to obf field in status regiser? How to extract those bitfields from value of status register?
- Endianness?
- Is knowing answer to above questions necessary while using the given functions?

Credits

Device interface functions in generated/lpc_kbd.h are generated by a modified version of mackerel.

1.4 kShell

MergeRequest

I’ve added few more code in origin/shell branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/shell
```

Aim

In this part, we'll look at one design approach while implementing a toy shell supporting builtin functions only.

- You need to implement the shell by implementing the given interfaces(in labs/shell.h and labs/shell.cc).
- You are *not* allowed to modify the interface and it's usage in x86/main.cc.
- You are *not* allowed to use any global variables or static variables in your functions.
- To make sure we have a personalized UI for each student, exact user interface is open - So be creative!
  - While rendering, you may:
    * use menu based interface: with or without buttons, use: up/down arrows, or: (each builtin command could be a menu item).
    * command based interface:
    * a combination of above or invent a new one.
  - While handling keyboard event, you may:
    * use up/down/left/right arrows, enter and esc keys to navigate, or:
    * directly assign shortcuts to each menu, or
    * a combination of above or invent a new one.
- Exact builtin commands/functionality that you need to support is open - Be creative! You may support multiple builtin commands, like:
  - computation tasks: factorial, fibnocci etc
  - string commands like simple echo.
- You're required to provide atleast two functionalities:
  - A status bar showing number of key presses so far. Whenever user pressed a key, number should be updated on the screen.
  - one long computation task which will take atleast few seconds to compute.

Information

Reuses previous parts of this series to create a shell.

Usage

```
core_loop_step():
    if user has pressed key, get the key and do:
        shell_update(ro: key, rw: shell_state);

    // execute shell for one time slot to do some computation, if required.
    shell_step(rw: shell_state);

    // shellstate -> renderstate: compute render state from shell state
    shell_render(ro: shell_state, wo: render_state);

    if not render_eq(last renderstate and new renderstate):
        render(ro: render_state, wo: vga text buffer);
```

Define

You need to define the following structures in labs/shell.h

```
// state for shell
struct shellstate_t{
};
// state required to render( for ex: intermediate results shouldnt be in render)
struct renderstate_t{
};
```

You also need to define the following functions in labs/shell.cc

```
void shell_init(shellstate_t& state);

// input: handle keyboard event
void shell_update(uint8_t scankey, shellstate_t& stateinout);

// computation: do one step of computation, if required
void shell_step(shellstate_t& stateinout);

// copy necessary information required to render the UI to renderstate
void shell_render(const shellstate_t& shell, renderstate_t& render);

// output: how to render
bool render_eq(const renderstate_t& a, const renderstate_t& b);
void render(const renderstate_t& state, int w, int h, addr_t display_base);
```

Given

NA.

There're several helper functions given in the labs/shell.cc. When you execute, you'll be seeing a simple menu based interface. You may or may not use those functions. Please feel free to create your own interface.

Tip

- See the comments inside labs/shell.cc
- shell_step:
  - you may have to have a statemachine to know whether computation is in progress or not etc. (store the state in shellstate_t. pass the state to renderstate - if you want to enable/disable the menu item)
- Prefer iterative over recursive - stack size is limited to 4KB
- Use integer arithmetic instead of floats.
- Simplify render function by
  - classify all the elemnts into color and data
    - for ex: state could be color
  - displaying all the elements marked as in renderstate_t everytime in the screen.

Turn in

You're required to define the structures in labs/shell.h and implement the required functions in shell.cc

Check

A simple shell with several builtin commands including a "long computation task" and a status bar showing the "number of key presses" so far.

Note

Have you noticed that:

- Select long computation task

- Press a key
- Status bar will get updated only after the long computation task is finished?

ie. System latency to keyboard events is high - we'll improve this in next part.

Demo tip

Be prepared to answer following viva questions:

- What are the advantages and disadvantages of this design? How to improve? What are other alternative approaches?
- What happens between you pressing a key in keyboard and it appearing on screen(if it appears).

1.5 Stackless Coroutine

MergeRequest

I've added few more code in origin/coroutine branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/coroutine
```

Aim

In this part, we'll learn about "asymmetric-stackless coroutines" while enhancing our kernel to make it responsive to key presses while long computation task is running.

- You shall implement the long computation task as a stackless coroutine using the given APIs and add a new menu item/builtin command for the same.
- On key press, the status bar shall be updated with 'the number of keys pressed so far' while this long computation task is running(not after it finishes).
- If we select older menu item, shell still take seconds to respond to update status bar. If we select new menu item, shell will be updating status bar, while the computation is running.. Result of both the menu items should be same.
- Atmost one pending long computation task at any point in time.
- Only convert one long computation task to coroutine form(If your shell supports multiple long computation task).

Information

Coroutines are a generalization of coroutines which allows explicit suspend and resume operations(yield and call). Coroutines can be used for nonpremptive multitasking(fibers), event loop, and light weight pipes(producer consumer problem).

Definition of coroutine from Coroutines: A Programming Methodology, a Language Design and an Implementation(1980):

```
For the purposes of this thesis, the following will be regarded as
the fundamental characteristics of a coroutine:
(1) the values of data local to a coroutine persist between
    successive occasions on which controls enters it (that is, between
    successive calls), and
(2) the execution of a coroutine is suspended as control leaves it,
    only to carry on where it left off when control re-enters the
    coroutine at some later stage.
```

Classification of coroutines from Revisiting coroutines(2009):

- Symmetric vs Asymmetric : whether coroutine can yield to other coroutines or it's parent only.
- First class vs Constrained : First class object or not.
- Stackfulness vs Non-stackfulness: Can we call coroutine within another coroutine?

There is a proposal to support coroutines in C++. (Several languages like: C#, Perl, Python, Haskell, Erlang, Scheme, Factor supports coroutines.)

See Simon Thatham's coroutine implementation or boost coroutine's Introduction & Motivation or Protothreads for more details.

Slides: Coroutines and Fibers

Since we don't have language support yet, Let's first build a coroutine library first.

- We'll store values of "data local to a coroutine between successive calls" in a structure, say f_t.
- We'll store value of program counter from where the execution has to carry on in another structure - coroutine_t.
- coroutine_init() will initalize the program counter inside coroutine_t structure to zero.
- h_begin() will check the value of program counter, and if non-zero, will jump to that value.

- h_yield() stores the PC of next instruction to be executed in coroutine_t structure, and returns.
- h_end() resets the value of PC to zero.

You'll help me in implementing the long computation as a coroutine.

Define

You need to define the following structures in labs/coroutine.h

```
// state for your coroutine implementation:
struct f_t{
};
```

You also need to define the following functions in labs/coroutine.cc

```
shell_step_coroutine(shellstate_t&, coroutine_t&, f_t&);
```

You also need to enhance your shell implementation in labs/shell.h

```
update shellstate_t and renderstate_t structure: i
  for handling coroutine state, and
  new menu item for long computation task in coroutine form
```

You also need to enhance your shell implementation in labs/shell.cc

```
new menu item for long computation task
```

Usage

```
core_loop_step():
    if user has pressed key, get the key and do:
        shell_update(ro: key, rw: shell_state);

    // execute shell for one time slot to do some computation, if required.
    shell_step(rw: shell_state);

    // execute shell for one time slot to do some computation based on coroutine, if required.
    shell_step_coroutine(rw: shell_state, f_coro, f_locals);

    // shellstate -> renderstate: compute render state from shell state
    shell_render(ro: shell_state, wo: render_state);

    if not render_eq(last renderstate and new renderstate):
        render(ro: render_state, wo: vga text buffer);
```

Given

Following functions are defined in util/coroutine.h:

```
coroutine_t        : internal data structure to save the state of coroutine (where
coroutine_reset()  : initialize/reset coroutine_t

h_begin()          : begin coroutine ( jump to saved state )
h_yield()          : yield           ( save the state, and return)
h_end()            : end             ( infinitely call yield )
```

Example usage of coroutines

```
//
// state of function f to be preserved across multiple calls.
//
struct f_t{
 int i;
 int j;
};

//
// first time you call f(), it'll
//   execute h_yield with value 1. (i=1 and j=1 at this point)
//
// next time you resume/call it, it'll continue execution from this point,
// and  calls h_yield with value 2 (i=1 and j=2 at this point)
//
// In short, each time you resume/call f(), it'll return
//
//   1*1, 1*2, 1*3
//   2*1, 2*2, 2*3
//   3*1, 3*2, 3*3
//
//
void f(coroutine_t* pf_coro,f_t* pf_locals,int* pret,bool* pdone){
  coroutine_t& f_coro = *pf_coro; // boilerplate: to ease the transition from exis
  int& ret            = *pret;
  bool& done          = *pdone;

  int& i              = pf_locals->i;
  int& j              = pf_locals->j;

  h_begin(f_coro);
```

```
  for(i=1;i<=3;i++){
    for(j=1;j<=3;j++){
      ret=i*j; done=false; h_yield(f_coro); // yield (i*j, false)
    }
  }

  ret=0; done=true; h_end(f_coro); // yield (0,true)
}


// How to use use f()?
coroutine_t f_coro;
coroutine_reset(f_coro);
f_t f_locals;

f(f_coro,f_locals,shell.f_ret,shell.f_done); //post cond: f_ret=1*1  f_done=false
f(f_coro,f_locals,shell.f_ret,shell.f_done); //post cond: f_ret=1*2  f_done=false
f(f_coro,f_locals,shell.f_ret,shell.f_done); //post cond: f_ret=1*3  f_done=false
f(f_coro,f_locals,shell.f_ret,shell.f_done); //post cond: f_ret=2*1  f_done=false
f(f_coro,f_locals,shell.f_ret,shell.f_done); //post cond: f_ret=2*2  f_done=false
...
f(f_coro,f_locals,shell.f_ret,shell.f_done); //post cond: f_ret=0    f_done=true
```

Tip

- void f(T* px) === void f(T& x)
- Stackless => No recursion!

Turn in

- You shall implement the long computation task as a stackless coroutine using the given APIs.
- Add a new menu item/builtin command for calling it.

Check

- On key press, the status bar shall be updated with 'the number of keys pressed so far' while the long computation task is running(not after it finishes).
- Result of both the menu items should be same.

Note

- You're required to initialize the coroutine from shell_step_coroutine(). You may have a statemachine (DEAD,START,READY), and on state transition from DEAD->START, you may want to initialize the coroutine.

Note

- Have you noticed that we need to save value of local variables in a structure and that stack is not preserved? In the next part, we'll implement a stack for each coroutines, and let local variables stored on stack instead of new structure.

1.6 Fiber

MergeRequest

I've added few more code in origin/fiber branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/fiber
```

Aim

In this part, we'll learn about "fibers" while enhancing our kernel to make it responsive to key presses while long computation task is running.

- You shall implement the long computation task as a fiber using the given APIs and add a new menu item/builtin command for the same.
- On key press, the status bar shall be updated with 'the number of keys pressed so far' while this long computation task is running(not after it finishes).
- Result of all three menu items should be same.
- Atmost one pending long computation task at any point in time.
- Only convert one long computation task to fiber form(If your shell supports multiple long computation task).

Information

Usage

```
core_loop_step():
    if user has pressed key, get the key and do:
        shell_update(ro: key, rw: shell_state);

    // execute shell for one time slot to do some computation, if required.
    shell_step(rw: shell_state);

    // execute shell for one time slot to do some computation, if required.
    shell_step_coroutine(rw: shell_state, rw: f_coro, rw: f_locals);

    // execute shell for one time slot to do some computation based on fiber, if requirec
    shell_step_fiber(rw: shell_state, rw: main_stack, rw: f_stack, rw: f_array, ro: f_arr

    // shellstate -> renderstate: compute render state from shell state
    shell_render(ro: shell_state, wo: render_state);

    if not render_eq(last renderstate and new renderstate):
        render(ro: render_state, wo: vga text buffer);
```

Define

You need to define the following functions in labs/fiber.cc

```
shell_step_fiber(shellstate_t&, addr_t& main_stack, addr_t& f_stack, addr_t f_array, uint32_t
```

You also need to enhance your shell implementation in labs/shell.h

```
update shellstate_t and renderstate_t structure:
  for handling fiber state, and
  new menu item for long computation task as fibers
```

You also need to enhance your shell implementation in labs/shell.cc

```
new menu item for long computation task
```

Given

```
stack_reset(f_stack,f_array,f_arraysize,f_start,f_args...) : resets the stack. use std::r
stack_resetN(f_stack,f_array,f_arraysize,f_start,f_args...): resets the stack. for C/ old
stack_saverestore(from_stack,to_stack)                     : saves the context to from_st
```

Example usage of fibers

```
void f(addr_t* pmain_stack, addr_t* pf_stack, int* pret, bool* pdone){
  addr_t& main_stack = *pmain_stack; // boilerplate: to ease the transition fr
  addr_t& f_stack    = *pf_stack;
  int& ret           = *pret;
  bool& done         = *pdone;

  int i;
  int j;

  for(i=1;i<=3;i++){
    for(j=1;j<=3;j++){
      ret=i*j;done=false; stack_saverestore(f_stack,main_stack);
    }
  }
  for(;;){
    ret=0;done=true; stack_saverestore(f_stack,main_stack);
  }
}

// How to use use f()?
uint8_t f_array[F_STACKSIZE];
const size_t f_arraysize=F_STACKSIZE;

addr_t main_stack;
addr_t f_stack;

stack_reset4(f_stack, &f_array, f_arraysize, &f, &main_stack, &f_stack, &shell

stack_saverestore(main_stack,f_stack); //post cond: f_ret=1*1  f_done=false
stack_saverestore(main_stack,f_stack); //post cond: f_ret=1*2  f_done=false
stack_saverestore(main_stack,f_stack); //post cond: f_ret=1*3  f_done=false
stack_saverestore(main_stack,f_stack); //post cond: f_ret=2*1  f_done=false
stack_saverestore(main_stack,f_stack); //post cond: f_ret=2*2  f_done=false
...
stack_saverestore(main_stack,f_stack); //post cond: f_ret=0    f_done=true
```

Extra information

```
//
// Switch stacks.
```

```
//
// Algo:
//   1. Save _c's context to stack,
//   2. push ip of _c's restore handler
//   3. switch stacks
//   4. execute ip of _n's restore handler to restore _n's context from stack.
//
//
// stack layout:
//  teip[-1:-32]: continuation to restore,
//  Stack layout expected by teip:
//     ebp[ -33: -64],
//     ebx[ -65: -96],
//     eax[ -97:-128],
//     Stack layout expected by eip+4:
//        Preserved.

#define stack_saverestore(from_stack,to_stack) do {                  \
 asm volatile(                                                       \
   "  pushl %%eax      \n\t"                                         \
   "  pushl %%ecx      \n\t"                                         \
   "  pushl %%ebp      \n\t"                                         \
   "  pushl $1f        \n\t"                                         \
   "                   \n\t"                                         \
   "  movl  %%esp,(%0) \n\t"                                         \
   "  movl  (%1),%%esp \n\t"                                         \
   "                   \n\t"                                         \
   "  ret              \n\t"                                         \
   "1:                 \n\t"                                         \
   "  popl %%ebp       \n\t"                                         \
   "  popl %%ecx       \n\t"                                         \
   "  popl %%eax       \n\t"                                         \
  :                                                                  \
  :"a" (&from_stack), "c"  (&to_stack)                               \
  :_ALL_REGISTERS, "memory"                                          \
 );                                                                  \
} while(false)


//
// Initializes stack.
//
// Algo:
//   1. Push Ip of reset handler
//         (which will reset ebp and jmp to actual eip etc)
//
```

```
// stack layout:
//  teip[-1:-32]: continuation to restore(1f),
//  Stack layout expected by teip:
//      args passed in registers when calling eip (NONE),
//      eip[-33:-64],
//      args passed in stack when calling eip (NONE),
//
// initial values: teip=t_start; eip=f_start;
//

#define stack_inithelper(_teip)  do{                                        \
 asm volatile(                                                              \
   "  movl $1f,%0      \n\t"                                                \
   "  jmp  2f          \n\t"                                                \
   "1:                 \n\t"                                                \
   "  movl $0, %%ebp   \n\t"                                                \
   "  jmp *(%%esp)     \n\t"                                                \
   "2:                 \n\t"                                                \
  :"=m" (_teip)                                                             \
  :                                                                         \
 );                                                                         \
}while(false)
```

Tip

NA

Turn in

- You shall implement the long computation task as a fiber using the given APIs.
- Add a new menu item/builtin command for calling it.

Check

- On key press, the status bar shall be updated with 'the number of keys pressed so far' while the long computation task is running(not after it finishes).
- Result of all the three menu items should be same.

Note

- To achieve responsiveness, we've to add yield points explicitly. Sometimes, it may not be easy - can we trade efficiency and implment pre-emptive scheduling? Yes, But Pre-emption requires support for timers. To use timers, we need to have support for interrupts. which means we need to write interrupt handlers and program Interrupt Descriptor Tables(IDTs)

- Before we do so, let's first implement support for multiple non-premptive threads.

- Syntax: GCC Extended Asm

```
asm [volatile] ( AssemblerTemplate
                 : OutputOperands
                 [ : InputOperands
                 [ : Clobbers ] ])
```

  Label 1f means: the immediate label 1 in the forward direction.. and label 1b means the immediate label 1 in the backward direction.. And $1f means address of label 1 in the forward direction.

  In stack_inithelper macro, the _teip gets the address of label 1f.

  :"a"(value) inside input operands means : gcc will make sure %eax is not live at that point, and Move the value into "%eax" register

  :"c"(value) inside input operands means : gcc will make sure %eax is not live at that point, and Move the value into "%ecx" register

  if a register is mentioned in clobbered list - gcc will ensure that register is not live before calling asm statement. (all the integer registers which are not pushed in the macro are mentioned in _ALL_REGISTERS as clobbered. stack_saverestore is a macro - not a function so no calling convention is applied)

Demo Tip

- On stack_savestore
  - stack_initN pushes variable number of arguments (stack_init0 pushes 2, stack_init1 pushes 3)
  - and stack_saverestore pops fixed number of arguments.
  - How is it possible?
  - Why are we saving only eax, ecx and ebp? Won't the other registers get trashed by the fiber function (after executing stack_saverestore)?

1.7 Non-preemptive scheduling

MergeRequest

I've added few more code in origin/fiber_schedular branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/fiber_schedular
```

Aim

In this part, we'll learn about non-preemptive sheduling while enhancing our shell to support mulitple pending long computation task.

- You shall support atleast two additional long computation tasks
- For these additional long computation tasks:
  - You shall support multiple pending long computation tasks
  - Add menu item/builtin command for calling additonal tasks(Retain previous menu items).
  - Same command/menu item may be entered multiple times
  - Each command may be queued at max 3 times.
  - Total number of fibers in progress shall be limited to minimum of (5 or stacks_size or arrays_size). Note: only additional long computation tasks are counted

Information

NA

Usage

```
core_loop_step():
    if user has pressed key, get the key and do:
        shell_update(ro: key, rw: shell_state);

    // execute shell for one time slot to do some computation, if required.
    shell_step(rw: shell_state);

    // execute shell for one time slot to do the computation based on coroutin
    shell_step_coroutine(rw: shell_state, rw: f_coro, rw: f_locals);
```

```
        // execute shell for one time slot to do the computation based on fiber, if required.
        shell_step_fiber(rw: shell_state, rw: main_stack, rw: f_stack, rw: f_array, ro: f_arr

        // execute shell for one time slot for additional long computation tasks.
        shell_step_fiber_schedular(rw: shell_state, rw: stackptrs, ro: stackptrs_size, rw: ar

        // shellstate -> renderstate: compute render state from shell state
        shell_render(ro: shell_state, wo: render_state);

        if not render_eq(last renderstate and new renderstate):
            render(ro: render_state, wo: vga text buffer);
```

Define

You need to define the following functions in labs/fiber_schedular.cc

```
   shell_step_fiber_schedular(shellstate_t&, addr_t stacks[], uint32_t stacks_size, addr_t arrays
```

You also need to enhance your shell implementation in labs/shell.h

```
 update shellstate_t and renderstate_t structure:
   for handling schedular state, etc
```

You also need to enhance your shell implementation in labs/shell.cc

```
 atleast two long computation tasks.
 and ui changes.etc
```

Given

NA

Tip

```
     This is the goal: So far, we have the capability to run only one fiber. We need to support m

     1. G:: GArg -> GResult
     2. H.:: HArg -> HResult

     We also want to support multiple invocations of these fibers. (atmax 3).  Question also stat

     Now, we have to store 3*(GArg,GResult) and 3*(HArg,HResult) in shellstate_t..  just like we
```

```
What should be a good data structure for storing these? Two common approaches are

1. 3*(GArg,GResult) and 3*(HArg,HResult)
2. 5* Union of (GArg,GResult) and (HArg,HResult)

How to do scheduling?

Let's say, we have a circular buffer/linked list on top of array.

When someone wanted to start an instance(press enter), just check the resource lin

and in each invocation of fiber_schedular... just pick one fiber(round robin), and
ie. in next invocation - pick the next fiber and execute it.. so on.

This is just one way to implement.. You don't need to implement this way
- mentioned at the last day to help those students who're running out of
  time.
```

Turn in

- You shall support multiple pending long computation tasks
- Add few more menu item/builtin command for calling it.

Check

Note

Optional Design check

To test how good is your design:

- commenting out shell_step_fiber:
  - is it equivalent to take fiber computation taking infinite amount of time
- commenting out shell_step_coroutine():
  - is it equivalent to take coroutine computation taking infinite amount of time

etc.

1.8 Preemption (threads)

MergeRequest

I've added few more code in origin/preemption branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/preemption
```

Aim

In this part, we'll learn about "preemption" while enhancing our kernel to make it responsive to key presses while long computation task is running.

- You shall enhance the fiber implementation by adding preemption.
- You need to write a part of trap handler - ring0_preempt - which should switch stack to 'main_stack'
  - We would like to reuse shell_step_fiber_schedular to do the scheduling.
- You shall program one-shot LAPIC timer to raise an interrupt after a specified time.
  - For simplicity, we'll go with dynamic timers
  - If there's no fibers running, there shouldn't be any timers firing.
- You shall also take care of the data race, if any, between the ring0_preempt and fiber's explicit yields
- Threads can be explicitly yielded using stack_saverestore(non preemptive context switch), or can be preempted by ring0_preempt from our timer's trap handler.
- Floats and SIMDs(SSE) instructions are allowed in our kernel. ring0_preempt macro shall save and restore FPU/SIMD registers (context) as well during the context switch.
- Out of two additional fibers implemented during fiber_schedular:
  - One of the fiber should be running normally with non-preemptive yields (stack_saverestore) (This is to trigger race condition between yield and ring0_preempt) and
  - another fiber shall be modified to execute without yields in between the computation (This is to check preemption is working or not)
- Those who havnt done fiber_schedular part can show preemption with fiber part

- They need to show preemption with and without yields in the fibers.

You also have to make following changes in the existing implementation:

- Fix the types of shell_step_fiber and shell_step_fiber_schedular functions in labs/fiber.{h,cc} and labs/fiber_schedular.{h,cc}
  - shell_step_fiber and shell_step_fiber_schedular are now passed extra arguments - timer device and a preempt_t structure.
  - You've to modify types of these functions to fix the compiler/linker error
- Update shell_step_fiber_schedular to use main_stack.
  - shell_step_fiber_schedular is now passed main_stack as an argument

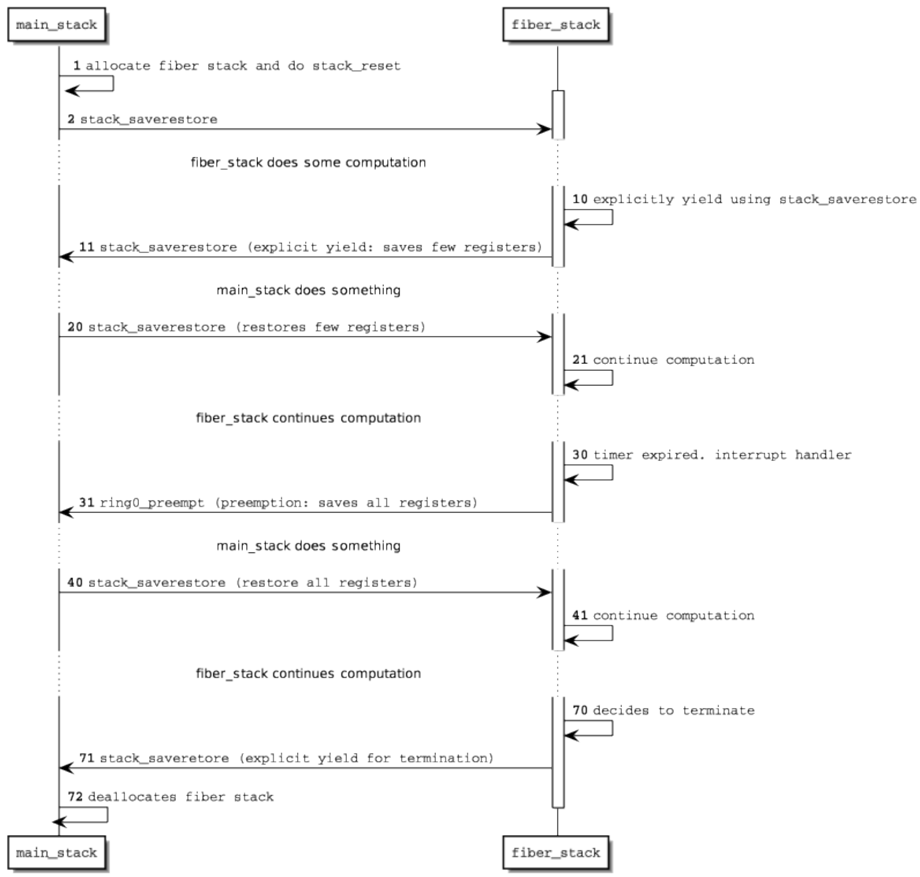
Information

- Lecture videos:
  - Trap handlers
  - Context switch
- FXSAVE and FXRSTOR assembly instructions: To save and restore FPU/SIMD registers To save/restore all these registers, Intel provided a single instruction FXSAVE/FXRSTOR.

  To know more about fxsave and fxrstor instruction, please read: Vol-1, Chapter 10, Section 5

  Note that memory address passed to fxsave and fxrstor must be 16 byte aligned. ie. must be a multiple of 16.
- Possible Control flow

  Make sure your ring0_prempt will be able to work with below scenario



- FPU: eax,ecx, edx, ebx, esp, ebp, esi, edi are all integer registers.

  Let's try to write a simple C functions which add two floats:

  ```
  float add(float a, float b){
     return a+b;
  }
  ```

  Which registers are they going to use, and which instructions? integers registers? addl instruction? No! What's the format of floats? number is represented as (sign,mantisa,exponent). To know about it, please read about IEEE754 floating point representation/basic computer architecture course. That's where legacy 8087 FPU comes into picture.

  It has 8 80-bit FPU registers: st(0),st(1), st(2)...st(7). (1 bit sign, 64 bit mantissa, 15 bit exponent) sizeof(double)=8. Floating point loads and stores will convert this 80-bit representation to 64 bit representation when it store to memory.. and viceversa. To know about FPU registers, please read: Vol-1, Chapter 8

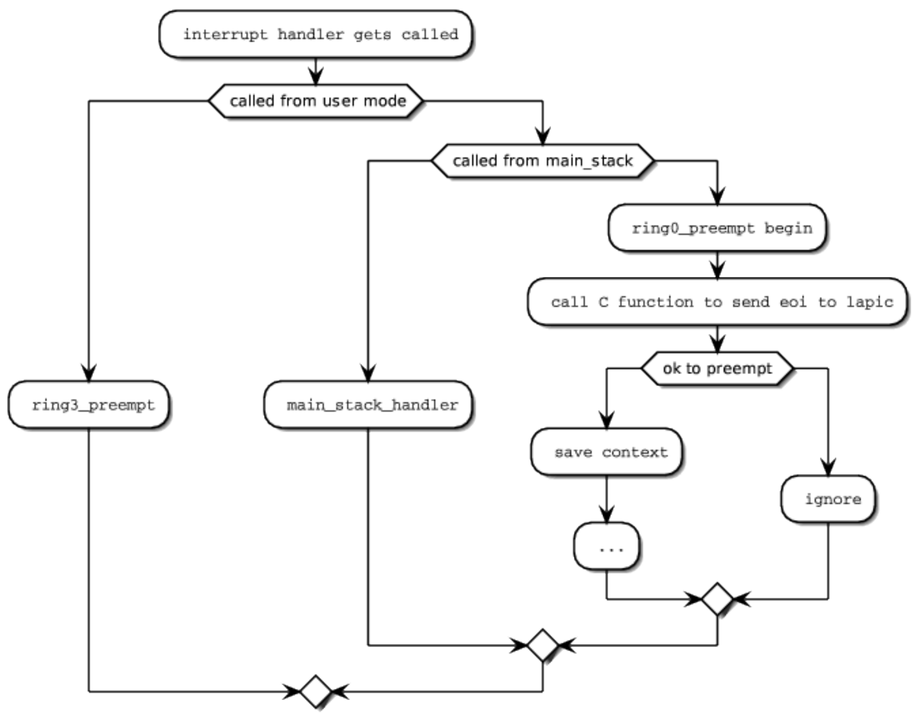
- MMX/SIMD2: With one instruction, we want to add N pairs in parallel, which means we want registers than hold N ints (or N floats).

  x86 has mm0, mm1, mm2.. mm7 (which are SIMD2, ie. N=2 - it holds two floats). To know more about MMx registers, please read: Vol-1 Chapter 9

- SSE/SIMD4: It also introduced SIMD4(128 bit registers) xmm registers. xmm0, xmm1 ... xmm7. To know more about xmm registers, please read: Vol-1 Chapter 10

- AVX/SIMD8 Intel also introduced (SIMD8) ymm registers in architectures like Sandybridge, Haswell etc. but since our gcl machines doesn't support these - we won't discuss it here.

- Overview of preemption handler's control flow:



Usage

Read the code - to understand where ring0_prempt is getting called

Define

You need to define the following structures in labs/preempt.h

```
// preempt_t : State for your timer/preemption handler
struct preempt_t{
};
```

You also need to define the following functions in labs/preempt.h

```
//
// _name: label name
// _f   : C function to be called
//
#  define  _ring0_preempt(_name,_f)            \
```

You also need to modify labs/fiber.cc and labs/fiber_schedular.cc to set the timer and reset the timer

Given

- lapic.reset_timer_count(N); to generate a timer interrupt after N timer ticks (N=0 to stop)
  - Both the shell_step_fiber and shell_step_fiber_sched are passed an dev_lapic_t object. which has a member function:

    `reset_timer_count(int count).`

    LAPIC Timer unit will decrement this count every tick, and when it reaches zero, will fire a timer interrupt.

    To know more about LAPIC Timer: please read: Vol 3A, 10.5.4.
- Our kernel does not have any global variables, and our trap handler is stateless. So we map our state to %gs. ie. %gs:0 will point to zeroth byte of core_t structure. %gs:1 will point to first byte.. so on (Read the code for more info).

Tip

- Make sure you understand the stack_saverestore(util/fiber.h) function you used in 1.6 and 1.7 parts.
- %gs: See x86/main.h and x86/except.* on usage of %gs
- Outline of ring0_preempt:

```
#define _ring0_preempt(_name,_f)
```

```
_name:
      call C function: _f

      // begin
      if thread is already inside yield,
        jmp iret_toring0

      save the CPU state to core_t.preempt.foo
      switch stack
      restore CPU state from core_t.main_stack
      // end

      jmp iret_toring0
```

Turn in

Check

- On key press, the status bar shall be updated with 'the number of keys pressed so far' while the long computation task is running(not after it finishes).
- Result of all the three menu items should be same.
- On demand timer ticks: No timer ticks if there're no fibers running.

Note

NA

1.9 SPSC Queue: Execute task on remote core

MergeRequest

I've added few more code in origin/multicore branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/multicore
```

Aim

In this part, we'll learn about multicore programming by implementing a SPSC queue and use it to send messages between two cores.

- I've modified the apps/labs.cc to execute the render() function in another core. The output of shell_render() - renderstate_t object - will be send to core #1 using the SPSQ queue. And core #1, will call the render() when it receives the renderstate_t object. Note: this means you won't see shell untill you implement SPSC queue correctly.
- You'll have to implement Leslie Lamport's portable lock-free single-producer single-consumer bounded buffer algorithm, modified to suit the given template
- Size of buffer will always be a power of 2.

Information

- Leslie Lamport's Proving the Correctness of Multiprocess Programs
- gcc atomic intrinsics
- C11/C++11 atomics

Usage

- Please read the code (apps/labs.cc) to see the usage.

Define

- Shared data structure between producer and consumer
- This data structure is shared between producer and consumer
- We'll reuse this data structure again when we implement user IPC. So you shouldn't use any instructions like cli/sti.
- This shared data structure may be accessed from different address space. ie. Producer may access this shared data structure with a different virtual address than consumer. So you shouldn't use any pointers inside this shared data structure.

```
struct channel_t{

};
```

- The producer

```
struct writeport_t{

  //
```

```
// Writer
//


// no of entries available to write
size_t write_reservesize();

// Can write 'n' entries?
bool write_canreserve(size_t n);

// Reserve 'n' entries for write
size_t write_reserve(size_t n);


//
// Deleter
//


// No of entires available to delete
size_t delete_reservesize();


// Can delete 'n' entires?
bool delete_canreserve(size_t n);


// Reserve 'n' entires for deletion
size_t delete_reserve(size_t n);



//
// Synchronized operations
//
// Note: Feel free to implement these functions the way you want.
//       You're not allowed to change the function prototype
// PS:   Don't go by the function names.
//

// Read/Write shared memory data structure
void write_sync(channel_t& ch);

// Read/Write shared memory data structure
void read_sync(channel_t& ch);
```

```
  // Update the state, if any.
  void delete_sync();

};
```

- Consumer

```
struct readport_t{

  //
  // Reader
  //

  // no of entries available to read
  size_t read_reservesize();

  // Can Read 'n' entires?
  bool read_canreserve(size_t n);

  // Reserve 'n' entires to be read
  size_t read_reserve(size_t n);

  //
  // Synchronization operation
  //
  // Note: Feel free to implement these functions the way you want.
  //       You're not allowed to change the function prototype
  // PS:   Don't go by the function names.

  // Read/write shared memory data structure
  void read_sync(channel_t& ch);

  // Read/Write shared memory data structure
  void write_sync(channel_t& ch);

};
```

Given

NA

Tip

- use `std::atomic<T>`
- Note that shell_update may be called multiple times before shell_step or other functions will be called. If you've made a hack on lab 1.4(shell): like if you assumed that shell_step() will be called exactly after shell_step() and exactly the same number of times - it's time to fix your shell.

PS: shell_update() is your keyboard handler, on every key press it will be called. it's independent of shell_step()

Turn in

Check

- Shell will start to work once you implement render() correctly.

Note

1.10 Ring3

MergeRequest

I've added few more code in origin/ring3 branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/ring3
```

Aim

In this part, we'll learn about ELF headers, page table handling and user mode switching while enhancing our kernel to load arbitary user program and execute it.

- You need to implement elf loader:
  - You shall only support Position Independent Executable.

  - The entire program memory address space specified by the program shall be read only. You can safely ignore the flags in ELF and override with 'WRITE' flags in page table.
  - The entire program memory address space shall fit into a single large page.

- The given file is already in memory. You don't need to load the file from disk. You only need to:

  - allocate new memory for the process.
  - copy the contents at right location
  - setup the process's state:

    * register values
    * page table
    * allocate memory for kernel <-> process communication.
    * setup the emergency stack layout correctly.

- kernel interrupts if occurred when CPU is in ring3, traphandlers are executed with esp=main_stack_end. So no need to save esp when you switch to ring 3.

0: core_t/systemcall(64B)	...	...	...	512*4KB: userdata_may_contain_userstack	...	...	...	PAGE_SIZE-4KB: emergency_stack(max 4KB)

- You need to load the program's page table.
- We'll implement exit system call later. We'll verify correctness by looking at qemu's instruction trace.
- Emergency Stack layout:

  - type of _start is:

```
void _start(uint32_t rank, uint32_t masterro, uint32_t masterrw, uint32_t sharedrw)
```

    * masterrw: address of page shared between kernel and user
    * value of rank, masterro, sharedrw shall be zero.

  - Emergency Stack:

    * 0: rank
    * 4: masterro
    * 8: masterrw
    * 12: sharedrw

...	0: rank	4: masterro	8: masterrw	12: sharedrw

- Page table:
  - Identity mapped - please make sure pages you tried are identity mapped, and use page table only for protection.

Information

Please see lecture videos:

- ELF headers
- Page table
- First user program

Usage

Define

- load the elf file contents from the range (from,fromsize) and initialize the process ‘proc’
- (from, fromsize) : ELF
- proc : process structure
- pool4M : a simple pool manager.

```
static inline void elf_load(addr_t from, size_t fromsize, process_t& proc, bitpool_t& p
```

- restore process’s state from proc.
  - you need to restore all the registers
  - you need to switch to process’s page table.
  - switch to user mode.
- This function shall not return. So you don’t need to save current stack pointer or local variables.

```
static inline void ring3_step(preempt_t& preempt, process_t& proc, dev_lapic_t& lapic)
```

- This function shall be called after process is preempted.

```
static inline void ring3_step_done(process_t& proc, dev_lapic_t& lapic);
```

Given

- See util/elf.h and util/ring3.h.
- user app to be executed in ring3 is already implemented for you.

Tip

Turn in

Check

- You need to verify user program execution by looking at qemu.log

Note

1.11 Ring3 Preemption

MergeRequest

I've added few more code in origin/ring3 branch. Please merge it with your master branch

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/ring3
```

Aim

In this part, we'll learn about preempting user program while enhancing our kernel to make it responsive to key presses while long computation task is running in ring3/user mode.

- We'll have single kernel stack for the all user processes.
- Note: On timer interrupt, hardware will automatically switch to main_stack. and ring3_preempt macro will eventually be called.
- You need to write a part of trap handler - ring3_preempt - which should:
  - save all register state to current running process's state.

  - intializes the kernel stack and registers to well known state and jump to core_loop (done for you).

- Floats and SIMDs(SSE) instructions are allowed in our kernel. ring3_preempt macro shall save FPU/SIMD registers (context) as well during the preemption.
- Note: kernel interrupts if occurred when CPU is in ring3, traphandlers are executed with esp=main_stack_end.
- Note: Please read the lecture videos to understand how hardware context switch works
- Note: Basic understanding of x86/except.{h,cc} is required - covered in detail during part 1.8.

Information

Please see following lecture videos: - Process context switch

- When ring3_upcall, ring3_downcall, ring3_preempt, ring0_preempt is getting called: The stack layout is:

...	0: relative_num	4: errorcode	8: user_eip	12: user_cs	16: user_flags	20: user_esp	24: user_ss

Usage

Define

In labs/ring3_preempt.h:

```
#define _ring3_preempt(_name, _f)
```

Given

NA

Tip

NA

Turn in

Check

- Responsive shell.

Note

1.12 Upcall/Signals

MergeRequest

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/ring3
```

Aim

In this part, we'll learn about upcalls by letting the user process manage the exceptions(like INT3, page faults etc).

- Whenever exception occur, You need to:
  - allocate emergency stack at the end of the page shared between kernel and user
  - setup the emergency stack layout correctly
  - Set the esp to this allocated emergency stack
  - Set the eip to proc.startip+4.
  - all other register values including eflags shall remain unchanged
- user's exception handler is located at _start+4. ie. (proc.startip+4).
- Emergency Stack layout:
  - type of (_start+4) is:

    ```
    void user_exception(uint32_t rank, uint32_t masterro, uint32_t masterrw, uint32_t shared
    ```

    * num: Exception number
    * errorcode: errorcode pushed by exception handler, if any. otherwise zero.
  - Emergency Stack:
    * 0: rank
    * 4: masterro
    * 8: masterrw
    * 12: sharedrw

* 16: num
* 20: errorcode
* 24: %old_esp
* 28: %old_eip
* 32: cr2

...	0: rank	4: masterro	8: masterrw	12: sharedrw	16: num	20: errorcode	24: old_esp	28: old_eip	32: cr2

Information

- When ring3_upcall, ring3_downcall, ring3_preempt, ring0_preempt is getting called: The stack layout is:

...	0: relative_num	4: errorcode	8: user_eip	12: user_cs	16: user_flags	20: user_esp	24: user_ss

Usage

Define

In labs/ring3_upcall.h:

```
#define _ring3_upcall(_name, _f)
```

Given

NA

Tip

NA

Turn in

Check

Generate an int3 or a page fault yourself. and see if it is getting reported correctly. ie. Match the values in qemu.log and the ones printed by user_exception handler.

Note

1.13 Downcall/System call

MergeRequest

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/ring3
```

Aim

In this part, we'll learn about downcalls/system calls by implementing following system calls: - You need to define the following function: system_call();

0. *nop*: no-operation/do-nothing

   - do-nothing
   - System call should *NOT* modify/write to the system call memory. (See Tip)

   `nop()`

1. *done*: done/exit.

   - mark the process as done(proc->state=PROC_DONE). process shouldn't be scheduled after this. So make sure, in your ring3_step, you ignore the process if proc->state==PROC_DONE.

   `done/exit()`

2. *mmio_read*: read size bytes from the given address using mmio

   - call appropriate mmio::read based on the value of size.

   `mmio_read(size, addr_t) -> value`

3. *mmio_write*: write size bytes to the given address using mmio

   - call appropriate mmio::write based on the value of size.

   `mmio_write(size, addr_t, value)`

4. *pmio_read*: read size bytes from the given port address using pmio
   - call appropriate io::read based on the value of size.

     `pmio_read(size, io_t) -> value`
5. *pmio_write*: write size bytes to the given port address using pmio
   - call appropriate io::write based on the value of size.

     `pmio_write(size, io_t, value)`
6. *mmu_swapva*: swap the entry of the process's page table.
   - make sure both va1 and va2 are in VA_RANGE.
   - Note: VA_RANGE is defined as 2GB-3GB.
   - Hint: use proc.mmu.swap(..);
   - Make sure you swap the flags as well. For example: if va1 is not mapped into user page, and va2 is mapped, After swap: va1 is mapped into user page and va1 is not.

     `mmu_swapva(va1,va2)`
7. *mmu_mapmmio*: grants access to the requested page.
   - maps the corresponding page into user space with (VA=PA)
   - Note: nva should *NOT* be in VA_RANGE.
   - Note: VA_RANGE is defined as 2GB-3GB.

     `mmu_mapmmio(nva)`
8. *pmu_mappmio*: grants access to the requested io port.
   - for time being, set iopl flags to 3. ie. proc->iopl=3. and always make sure eflags = (eflags & ~(3u<<12)) | (proc->iopl<<12);

     `pmu_mappmio(io_t)`
9. *pool_alloc*: allocate a large page from pool4M and maps into user address space
   - returns 0, if a large page cannot be allocated from pool4M
   - allocates a large page from the pool4M, and
   - finds an entry in VA_RANGE which is not mapped into user space, maps the page into this unused address in VA_RANGE with user privileges. returns this new va.
   - Note: Newly allocated page is already mapped into kernel address space with VA=PA, coz of identity page table(with permissions as Kernel only). Please don't change this mapping.
   - Note: VA_RANGE is defined as 2GB-3GB.
   - Note: unused page in VA_RANGE is defined as: a page with kernel privileges.

- Note: after this page table is no longer identity mapped. So make sure you save and restore kernel's page table.
- Note: This system call returns either 0 or a va within the range VA_RANGE.

  `pool_alloc() -> va`

Note: No need to implement authorization. We haven't implemented support for capabilities in this kernel yet. We'll implement capabilities in IPC part only.

User shall pass arguments through begin of page shared between user and kernel. Memory layout:

- 0: reserved. must be zero.
- 4: Syscall num. Zero indicates No syscall request pending.
- 8: Syscall Arg1 / Syscall Ret1.
- 12: Syscall Arg2 / Syscall Ret2.
- 16: Syscall Arg3 / Syscall Ret3.

0: reserved	4: sys_num	8: arg1/ret1	12: arg2/ret2	16: arg3/ret3

Kernel may execute system call asynchronously by reading the shared page. User can alternatively force the use of system call execution, by using INT 0x48.

Note: Make sure In elf_load() you clears first 64 byte of proc.masterrw. esp. initialize proc.masterrw[0] as zero.

Information

NA

Usage

```
static inline void xsyscall(uint32_t* systemcallmmio, uint32_t fnum, uint32_t arg1, uint32_t arg2

  systemcallmmio[2]=arg1;
  systemcallmmio[3]=arg2;
```

```
  systemcallmmio[4]=arg3;
  systemcallmmio[1]=fnum; //write this field at the end.

  hoh_debug("Shell Before making system call");
  asm volatile("int $0x48":::"memory");
  hoh_debug("Shell After making system call");

  hoh_assert(systemcallmmio[1]==0,"XXX");
  ret1=systemcallmmio[2];
  ret2=systemcallmmio[3];
  ret3=systemcallmmio[4];

  hoh_debug("Syscall ret: "<<ret1<<","<<ret2<<","<<ret3);

}



  // call test_systemcall by:

  //swapva
  uint32_t ret1;
  uint32_t ret2;
  uint32_t ret3;
  xsyscall(core.syscallmmio, 0x6, xxx, yyy, 0, ret1, ret2, ret3);


  //pool_alloc
  uint32_t ret1;
  uint32_t ret2;
  uint32_t ret3;
  xsyscall(systemcallmmio, 0x9, 0,0,0, ret1,ret2,ret3);
  hoh_debug("Allocated at: "<<ret1);
```

Define

Given

NA

Tip

```
uint32_t* systemcall_mmio = cast<uint32_t*>(proc.masterrw);
uint32_t fnum =systemcall_mmio[1];  //read fnum first.

if(fnum==0){ //make sure you check fnum.
  return;
}

uint32_t farg1=systemcall_mmio[2];
uint32_t farg2=systemcall_mmio[3];
uint32_t farg3=systemcall_mmio[4];

uint32_t fret1=0;
uint32_t fret2=0;
uint32_t fret3=0;

switch(fnum){
case 0: {
        }break;
case 1: {
        }break;
case 2: {
        }break;
}


if(fnum!=0){
  // do not modify the arguments if fnum is zero.
  systemcall_mmio[2]=fret1;
  systemcall_mmio[3]=fret2;
  systemcall_mmio[4]=fret3;
  systemcall_mmio[1]=0; //modify this last.
}
```

Turn in

- Implement the given 10 system calls.
- Write test cases for these 10 system calls by modifying ring3/app1(We won't check your test cases ie. No marks for test cases).

Check

Note

1.14 App: Virtual Memory

MergeRequest

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/ring3
```

Aim

In this part, we'll learn about virtual memory by emulating an array of N_v virtual pages using N_p physical pages.

- **Note: There is a change :** $N_v = 16$ **and** $N_p = 4$ **instead of** $N_v = 16$ **and** $N_p = 8$**. Ie. you need to emulate 16 page array using 4 physical pages. not 8**
- Please read lecture videos on demand paging and page replacement policy.
- You need to emulate an array of size N_v pages, say varray. Starting address of varray shall be 2GB ie. 2u<<30.
- $N_v = 16$ and $N_p = 4$

V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_10	V_11	V_12	V_13	V_14	V_15

- by using exactly N_p physical pages.

P_0	P_1	P_2	P_3

- Note: Before allocating these N_p physical pages, none of elements in varray is mapped to user space.

V_0 : K_0
V_1 : K_1
V_2: K_2
V_3: K_3
V_4 : K_4
V_5 : K_5
V_6 : K_6
V_7: K_7
V_8: K_8
V_9 : K_9
V_10 : K_10
V_11 : K_11
V_12 : K_12
V_13 : K_13
V_14 : K_14
V_15 : K_15

- You shall use pool_alloc system call to allocate a page. You shall make exactly N pool_alloc system calls in your app. Note: pool_alloc system call will always return value within VA_RANGE. Note: When you allocate pages, there is no guarantee that pool_alloc will return them in continous order.

V_0 : P_0
V_1 : P_1
V_2: P_2
V_3: P_3
V_4 : K_4
V_5 : K_5
V_6 : K_6
V_7: K_7
V_8: K_8
V_9 : K_9
V_10 : K_10
V_11 : K_11
V_12 : K_12
V_13 : K_13
V_14 : K_14
V_15 : K_15

- You need to swap the page table entries from user mode using: mmu_swapva system call. Note: mmu_swapva will only swap if the arguments are within VA_RANGE. For example, a valid mapping could be:

V_0 : K_15
V_1 : P_1
V_2: P_2
V_3: P_3
V_4 : K_4
V_5 : K_5
V_6 : K_6
V_7: K_7
V_8: K_8
V_9 : K_9
V_10 : K_10
V_11 : K_11
V_12 : K_12
V_13 : K_13
V_14 : K_14
V_15 : P_0

- You need to test your emulation of this virtual array, varray, by:
  1. storing a 3D matrix of type *const uint32_t[8][8][8]* into this varray.
     - You need to define a function to_index which will map this 3D array into varray. ie

       ```
       //access x,y,z of this 3D array by:
       varray[to_index(x,y,z)]=f(x,y,z);
       ```

```
//or:
hoh_assert(varray[to_index(x,y,z)] == f(x,y,z)," Bug");
```

  - You can map this matrix into any order - not necessarily be row-major order.
  - You need to find a mapping 'to_index' that will minimize the number of page faults and cache misses.

2. Write a function, 'for_each', which will:
   - traverse all the elements in this 3D array in some order(strided by 32),
   - and print the sum of each element's neighbourhood defined by chebyshev distance of $d = 2^6$. See: sum_neighbours or weightedsum_neigbours in the usage.
   - Note: For each point, sum_neighbours computes sum of elements in its neighbourhood within a Chebyshev distance of $d = 2^6$. (See usage).
   - You can traverse the matrix in any order - not necessarily be row-major.
   - You need to find a traversal 'for_each' that will will minimize the number of page faults and cache misses. "'c

for(uint32_t x = 0; x<256; x+=32){ for(uint32_t y = 0; y<256; y+=32){ for(uint32_t z = 0; z<256; z+=32){ sum_neighbours(x,y,z,f_lut); } } }

"' 3. You need to implement page replacement policy. You need to find a page replacement policy that will minimize the number of page faults and cache misses.

- Note: Both sum_neighbours and weightedsum_neighbours traverse its neighbourhood defined by chebyshev distance of $d = 2^6$. Make sure you optimize all the three - to_index, for_each and page replacement policy based on this behaviour.
- You also need to print the number of page fault occurred in your app.
- You're required to implement the code under ring3/app1 directory.

Motivation for the application:

- Let's say we've a long computation function

  ```
  uint32_t f(uint8_t x, uint8_t y, uint8_t z);
  ```

- Usage: Assume we want to call sum_neighbours and weightedsum_neigbours for each $x, y, z \in [0..255]$ (See usage)

- To reduce invocation of this function each time we need it. We precompute 'f' for all the possible inputs and store it in a lookup table/array. ie.

```
for(x=0;x<=255;x++){
 for(y=0;y<=255;y++){
  for(z=0;z<=255;z++){
    varray[to_index(x,y,z)] = f(x,y,z);
  }
 }
}

//then, we can replace f with f2 where
uint32_t f2(uint8_t x,uint8_t y,uint8_t z){
  return varray[to_index(x,y,z)];
}
```

- To memoize the entire function, we require $2^8 * 2^8 * 2^8 * sizeof(uint32_t) = 64MB$ ie. 16 large pages.
- But we have only 4 pages. ie. You can only allocate 4 large pages(call pool_alloc system call 4 times).
- To get f2 working, without any modifications: We will emulate the array 'varray' of 16 larges pages within VA_RANGE.

```
addr_t varray = addr_t(2<<30); //2GB
```

- We allocate 4 pages, make sure they're mapped into this array and intializes the value. If the allocated page is not mapped within [varray,varray + 16*LARGE_PAGE_SIZE) then: use mmu_swap system call to swap with an unmapped page. (Note: To do this you need to maintain already mapped pages. (use a bit for each of 16 pages to mark if they're being mapped or not)
- When f2 tries to access varray: if the page is *not* mapped, hardware will generate a page fault.
- On page-fault: We will swap this page with already initialized page. We will use per-process page replacement policy. And we'll reinitialize the page data.
- You also need to print the number of page fault occurred in the system.
- Demo tip: What should be to_index(x,y,z) so that it will minimize number of page-faults
- Demo tip: We need to call f2(x,y,z) for all possible x,y and z. What should be the order in which we should call f(x,y,z) so that it will minimize number of page-faults
- Demo tip: What should be to_index(x,y,z) so that it will minimize number of cache-line misses and tlb misses

- Demo tip: We need to call f2(x,y,z) for all possible x,y and z. What should be the order in which we should call f(x,y,z) so that it will minimize number of cache-line misses and tlb misses

Note: Please don't publish the code even after your demo is done(Code is part of my PhD work).

Information

Usage

```
//
// Call sum_neighbours for each x<-[0..255], y<-[0..255], z<-[0..255]
//
// You're allowed to change this implementation:
// Note: d is defined to be 2^6. and cannot be changed
uint32_t sum_neighbours(uint8_t x, uint8_t y, uint8_t z){
   //computes sum of all the elements in the list defined by
   //       [f(x+i,y+j,z+k) | i<-[-d, -(d-1),...,-1,0,1,...,(d-1),d],
   //                         j<-[-d, -(d-1),...,-1,0,1,...,(d-1),d],
   //                         k<-[-d, -(d-1),...,-1,0,1,...,(d-1),d]]
   //ie.  Note d=2^6
   size_t sum=0;
    for(int i=-d; i<d; i++){
      for(int j=-d; j<d; j++){
         for(int k=-d; k<d; k++){
           sum += f2(x+i, y+j, z+k);
         }
      }
    }
}

//
// Call weightedsum_neighbours for each x<-[0..255], y<-[0..255], z<-[0..255]
//
// You're allowed to change this implementation:
// Note: d is defined to be 2^6. and cannot be changed
uint32_t weightedsum_neighbours(uint8_t x, uint8_t y, uint8_t z){
   //computes sum of all the elements in the list defined by
   //       [f(x+i,y+j,z+k) | i<-[-d, -(d-1),...,-1,0,1,...,(d-1),d],
   //                         j<-[-d, -(d-1),...,-1,0,1,...,(d-1),d],
   //                         k<-[-d, -(d-1),...,-1,0,1,...,(d-1),d]]
   //ie.  Note d=2^6
   size_t sum=0;
    for(int i=-d; i<d; i++){
```

```
      for(int j=-d; j<d; j++){
         for(int k=-d; k<d; k++){
           sum += w(i,j,k,d) * f2(x+i, y+j, z+k);
         }
      }
    }
}

//
// Call another traversal for each x<-[0..255], y<-[0..255], z<-[0..255]
//
void for_aach(){
  for each element in 3D array:
     print sum_neighbours(element);
}
```

Notation: [f(x) | x<-[1..10]] as: list of all f(x) *such that* x ∈ [1..10]

Notation: Read '|' as *such that*. Read '<-' as ∈.

Define

Given

Tip

Turn in

Check

- for all x,y,z: hoh_assert(f2(x,y,z) == f(x,y,z), "XXX");
- Number of pages allocated shall be 4.

Note

App: Shell in user mode

Hello! Alice here!

Congrats on making it so far! It's been a pleasure working with you.

Hope you enjoyed it as well!

Let's try to summarize the plot:

- You wrote a shell in kernel mode.
- Then I split the shell into two and rendered the UI on another core.
- Now I've moved your shell into user mode.
- And then I'll split the user shell into two and render the UI on another process.

In short: - You've implemented kernel coroutines, kernel threads and a kernel thread scheduler. And implmented a kernel application - shell. - You also have implemented user coroutines, user threads and a user thread schedular. And implemented a user application - shell.

Shell is already done for you! Your shell which you implemented in part 1.4 is already moved to user mode as an application. So the role has been revereed - whatever you've done till parts 1.9 are now in user mode. And parts 1.10 - parts 1.13 are in kernel.

MergeRequest

```
user@host:~/hohlabs$ git pull
user@host:~/hohlabs$ git merge origin/ring3_shell
```

Aim

Get User shell working

Please don't make the source code public even after you finish this course - The code you been working on is part of my PhD. Give me few months - Once we publish our paper, we'll release the entire code under AGPL3 licence(Current LICENSE doesn't allow the code). Till then please don't make the publish.

Btw: alice at hohlabs dot in is a real id, and will be active soon.

Wanted to do BTP/MTP/PhD with Sorav Bansal? Send your resume to sbansal at cse.

End of lab one

```
Please make sure you submit the feedback form
--
Regards,
Alice H
Hoh labs
```

Chapter 2

Applications

Overview

In this lab, we'll use the components we implemented in previous lab to make a fully functional kernel.

We'll test our kernel by having two applications:

1. File system in RAM
2. Virtual Memory

- Evaluation:
  - Code component:
    * *NOTHING : 0* Not working
    * *PARTIAL : 1* Partial/buggy - TA is able to find atleast one bug in your code
    * *TYPO : 1.5* Code is not clean
    * *CORRECT : 2* Working code
  - Viva component:
    * *FLAGGED : 0* Can not explain his/her own code
    * *JUST_IMPLEMENTED : 1* can explain his/her own code but can't explain Alice's code
    * *KNOWS_WHY : 2* can explain his/her own code + Alice's code
  - Marks for each part is computed by following equation:

    $$Marks = (W_d * D + W_v * V)$$

  - For 2.1-2.4:

    $$W_d = 0.80$$

    and

    $$W_v = 0.20$$

2.1 Shell in Ring 3 : User level Schedular

MergeRequest

Aim

Information

Usage

Define

Given

Tip

Turn in

Check

Note

2.2 User IPC: send_message

MergeRequest

Aim

Information

Usage

Define

Given

Tip

Turn in

Check

Note

2.3 File system server in user mode

MergeRequest

Aim

Information

Usage

Define

End of lab two

```
Please make sure you submit the feedback form
--
Regards,
Alice H
Hoh labs
```

Chapter 3

HoH Kernel

Overview

- .
- .

3.1 kernel: Verification of User's Long computation task(Trust by verification)

MergeRequest

Aim

Information

Usage

Define

Given

Tip

Turn in

Check

Note

3.2 Uniform schedular : tasks, coroutines, threads, user pgm

MergeRequest

Aim

Information

Usage

Define

Given

Tip

Turn in

Check

Note

3.3 H: Introduction to H

MergeRequest

Aim

Information

End of lab three

```
Please make sure you submit the feedback form
--
Regards,
Alice H
Hoh labs
```

Troubleshooting

- If your development environment is EFI, please make sure you have grub-pc-bin package installed.

  ```
  bash$ sudo apt-get install grub-pc-bin
  ```

- If gdb fails to load hohlabs/.gdbinit, try adding the following line to ~/.gdbinit

  ```
  set auto-load safe-path /
  ```

- If you don't have palasi account, please submit your request at gcl

- makefile uses "ln -r" : assumes latest version of coreutils. If you're using older versions of coreutils, in make/footer.mk: change

  ```
  @$(LN) -sfr $< $O/$(NAME).exe
  ```

  to

  ```
  @cd $O ; ln -sf $(NAME).$H.exe $(NAME).exe
  ```

- grub-mkrescue issue: Please make sure you've xorriso package installed

- Following errors:

  ```
  "File '_tmp/hoh.iso' too big (1234567 bytes). Max allowed: 1000000 bytes."
  "File 'qemu.log' too big (1234567 bytes). Max allowed: 1000000 bytes."
  ```

  Before you submit, do:

  ```
  user@palasi:~/hohlabs$ make clean; rm -f _tmp/hoh.iso qemu.log
  ```