Traps

RISC-V assembly (easy)

1. **Which registers contain arguments to functions? For example, which register holds 13 in main's call to printf?**
According to the RISC-V calling convention, arguments to functions are typically passed in registers `a0-a7`. In the `main` function's call to `printf`, the argument `13` is passed in register `a2`. You can refer to the official RISC-V manual or the diagram I provided for more information on the convention for using registers.

Register	ABI Name	Description	Saver
x0	zero	Hard-wired zero	—
x1	ra	Return address	Caller
x2	sp	Stack pointer	Callee
x3	gp	Global pointer	—
x4	tp	Thread pointer	—
x5–7	t0–2	Temporaries	Caller
x8	s0/fp	Saved register/frame pointer	Callee
x9	s1	Saved register	Callee
x10–11	a0–1	Function arguments/return values	Caller
x12–17	a2–7	Function arguments	Caller
x18–27	s2–11	Saved registers	Callee
x28–31	t3–6	Temporaries	Caller
f0–7	ft0–7	FP temporaries	Caller
f8–9	fs0–1	FP saved registers	Callee
f10–11	fa0–1	FP arguments/return values	Caller
f12–17	fa2–7	FP arguments	Caller
f18–27	fs2–11	FP saved registers	Callee
f28–31	ft8–11	FP temporaries	Caller

2. **Where is the call to function f in the assembly code for main? Where is the call to g? (Hint: the compiler may inline functions.)**

```
# in the main function
printf("%d %d\n", f(8)+1, 13);
24: 4635                li      a2,13
26: 45b1                li      a1,12
28: 00000517            auipc   a0,0x0
2c: 7b050513            addi    a0,a0,1968 # 7d8 <malloc+0xe8>
30: 00000097            auipc   ra,0x0
34: 608080e7            jalr    1544(ra) # 638 <printf>
```

In the `main` function, the call to function `f` is found as the instruction `28: 00000517 auipc a0,0x0`, which loads the address of `f` into register `a0` and prepares to jump to it. However, the call to `f` has been optimized by the compiler and inlined into a single instruction, `26: 45b1 li a1,12`, which loads the immediate value `12` into register `a1`. This value represents the result of calling `f(8)+1`, as indicated by the `printf` statement.
The call to function `g` is similarly inlined and optimized by the compiler. In the original definition of function `f`, the call to `g` appears as the instruction `14: 250d addiw a0,a0,3`, which adds the immediate value `3` to the value in register `a0`. However, this call has benn inlined and simplified to a load-immediate instruction `li a1,12`, as inferred from the difinition of function `f`.
Below are the declarations of function `g` and `f`, and the original call for function `g` is in the definition of function `f`.

```
0000000000000000 <g>:

int g(int x) {
0: 1141                 addi  sp,sp,-16
2: e422                 sd    s0,8(sp)
4: 0800                 addi  s0,sp,16
return x+3;
}
6: 250d                 addiw a0,a0,3
8: 6422                 ld    s0,8(sp)
a: 0141                 addi  sp,sp,16
c: 8082                 ret

000000000000000e <f>:

int f(int x) {
e: 1141                 addi  sp,sp,-16
10: e422                sd    s0,8(sp)
12: 0800                addi  s0,sp,16
return g(x);
}
14: 250d                addiw a0,a0,3
16: 6422                ld    s0,8(sp)
18: 0141                addi  sp,sp,16
1a: 8082                ret
```

3. **At what address is the function printf located?**

```
0000000000000638 <printf>:

void
printf(const char *fmt, ...)
{
 638: 711d                  addi  sp,sp,-96
 63a: ec06                  sd    ra,24(sp)
 63c: e822                  sd    s0,16(sp)
 63e: 1000                  addi  s0,sp,32
 ...
 662: dce080e7              jalr  -562(ra) # 42c <vprintf>
}
 666: 60e2                  ld    ra,24(sp)
 668: 6442                  ld    s0,16(sp)
 66a: 6125                  addi  sp,sp,96
 66c: 8082                  ret
```

The function `printf` is located at address `0x0000000000000638` in the assembly code of `call.asm`. It's important to note that the absolute address of a function may change depending on the structure and content of the program. For example, before working on the traps lab, the address of `printf` was `0x0000000000000628` on my machine rather than the current address shown in the code.

4. **What value is in the register ra just after the jalr to printf in main?**
   After the `jalr` instruction at address `0x34`, the value in register `ra` will be the address of the instruction immediately following the `jalr` instruction. In this case, the address of the instruction following the `jalr` instruction should be `0x38`, so the value in register `ra` will be `0x38`.
5. **Run the following code.**

```
unsigned int i = 0x00646c72;
printf("H%x Wo%s", 57616, &i);
```

What is the output? Here's an ASCII table that maps bytes to characters.
The output depends on that fact that the RISC-V is little-endian. If the RISC-V were instead big-endian what would you set i to in order to yield the same output? Would you need to change 57616 to a different value?
The output of the code should be `He110 World` because the integer value `57616` is stored in little-endian format as the

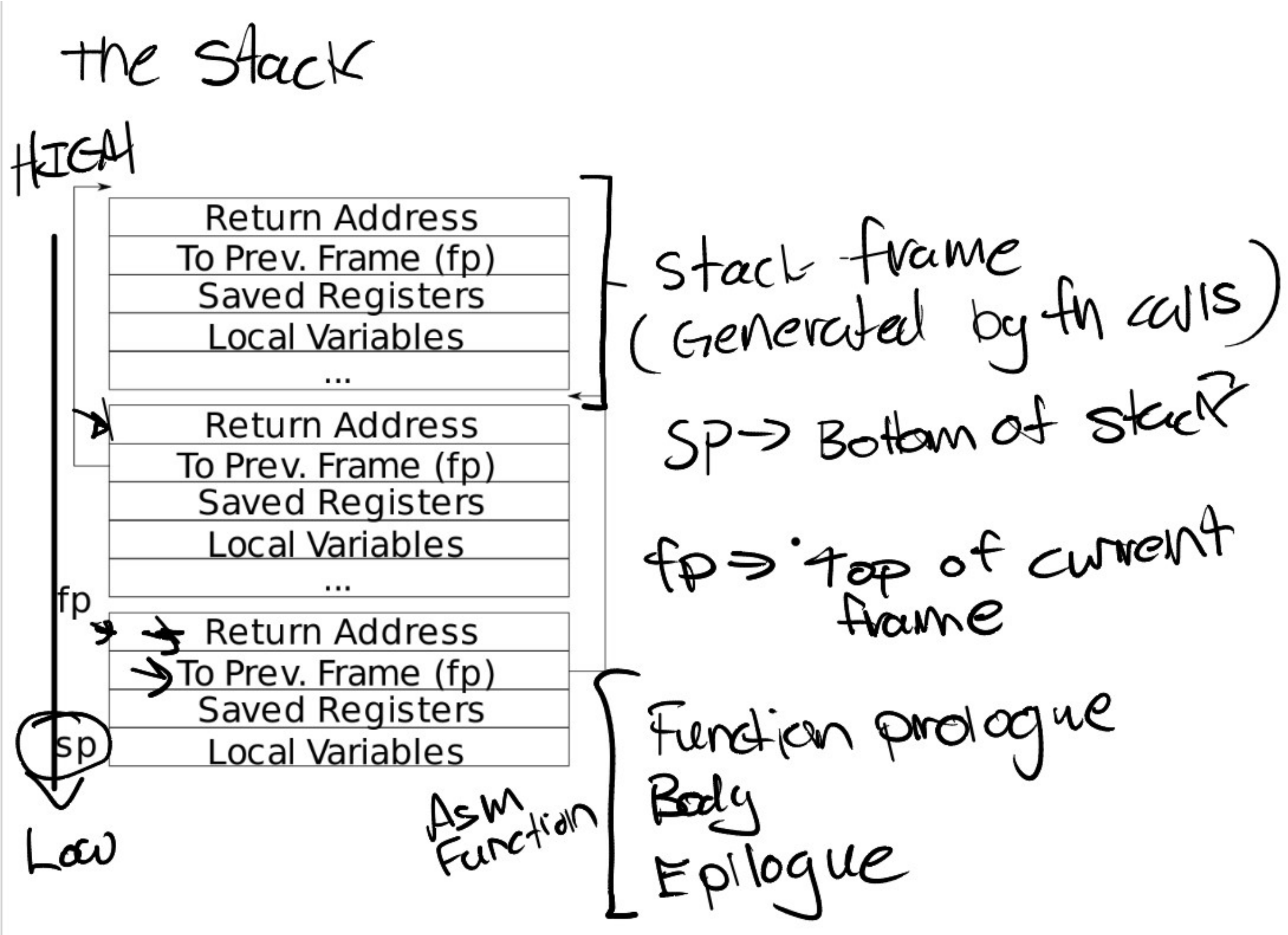
bytes `72`, `6c`, and `64`, which correspond to the ASCII characters `'r'`, `'l'`, and `'d'`, respectively. In little-endian architecture, the lowest-order byte (the rightmost digit in the hexadecimal representation) is stored at the lowest memory address.
If the RISC-V were instead big-endian, the integer value `57616` would be stored as the bytes `64`, `6c`, and `72`, which would correspond to the ASCII characters `'d'`, `'l'`, and `'r'`, respectively. In this case, to yield the same output as in little-endian architecture, you would need to set i to the value `0x00726c64`. This value would be stored as the bytes `72`, `6c`, and `64`, which would correspond to the ASCII characters `'r'`, `'l'`, and `'d'`. There is no need to change the value of `57616`, as it would be printed as the same hexadecimal value as it is, regardless of the endianness of the architecture.

6. **In the following code, what is going to be printed after 'y='? (note: the answer is not a specific value.) Why does this happen?**

```c
printf("x=%d y=%d", 3);
```

In the given code, afer the string "y=" is printed, there might not be a value displayed or a arbitrary value, because there is only one argument provided to the `printf` function, which corresponds to the format specifier `%d` for the first integer value.
The second format specifier `%d` has no corresponding argument, so the behavior of the `printf` function is undefined. This means that the output of this code could vary depending on how the compiler handles the situation. It is possible that the value of the unassigned register `a2` could be used as the second argument, resulting in an arbitrary value being printed. Alternatively, the compiler may simply ignore the second format specifier and not print anything after "y=".

Backtrace (moderate)



To print the saved return address, according to the stack frame of xv6 os shown above, we can walk up the stack by iteratively updating the value of the frame pointer (`fp`).

One way to do this is to use inline assembly to fetch the values of `sp` and `fp`:

```
asm volatile("mv %0, sp" : "=r" (sp));
asm volatile("mv %0, fp" : "=r" (fp));
```

However, the xv6 operating system provides encapsulations for inline assembly, so we can instead use the functions `r_fp()` and `r_sp()` to indirectly retrieve the values of these registers.

To ensure that we only access valid memory during the backtrace, we need to limit the range of the `fp` value to within the page of the stack pointer (`sp`) points to. This can be done by setting the range of `fp` to `PGROUNDDOWN(sp) < fp && fp < PGROUNDUP(sp)`.

To retrieve the value of the return address (`ra`) at the current stack frame, we can use the following code: `ra = *(uint64*)(fp - 8);`. To move to the next stack frame, we can update the value of `fp` like this: `fp = *(uint64*)(fp - 16)`.

Based on these steps, the `backtrace` function can be implemented as follows:

```
void backtrace(void) {
  uint64 fp = r_fp();
  uint64 sp = r_sp();
  printf("backtrace:\n");
  while(PGROUNDDOWN(sp) < fp && fp < PGROUNDUP(sp)) {
    uint64 ra = *(uint64*)(fp - 8);
    printf("%p\n", ra);
    fp = *(uint64*)(fp - 16);
  }
}
```

Alternatively, the `while` loop can be replaced with a `for` loop like this:

```
void backtrace(void) {
  uint64 sp = r_sp();
  uint64 fp = r_fp();
  for (fp; PGROUNDDOWN(sp) < fp && fp < PGROUNDUP(sp); fp = *(uint64*)(fp - 16)) {
    uint64 ra = *(uint64*)(fp - 8);
    printf("%p\n", ra);
  }
}
```

To insert the `backtrace` function into the appropriate locations, we can follow the instructions provided here. In particular, we can add the `backtrace` function to the `sys_sleep` function to pass the test and to the `panic` function to assist with debugging later code.

The `bttest` passed, and the output of `addr2line` is as follows:

```
xv6 kernel is booting

hart 1 starting
hart 2 starting
init: starting sh
$ bttest
backtrace:
0x000000008000214a
0x0000000080002024
0x0000000080001c9e
```

```
lydia@ubuntu-22-hp-040f1b4d:~/projects/xv6-labs-2021$ addr2line -e kernel/kernel
0x000000008000214a
0x0000000080002024
/home/lydia/projects/xv6-labs-2021/kernel/sysproc.c:62
/home/lydia/projects/xv6-labs-2021/kernel/syscall.c:144
0x0000000080001c9e
/home/lydia/projects/xv6-labs-2021/kernel/trap.c:83
```

Alarm (hard)

To implement the alarm functionality, the first step is to add the system calls `sigalarm` and `sigreturn` according to the instructions on the website.

The syscall definitions for `sigalarm` and `sigreturn` are shown below. These syscalls were added to the `sysproc.c` file:

```
uint64 sys_sigalarm(void) {
  struct proc *p = myproc();
  int n;
  uint64 addr;
  if(argint(0, &n) < 0)
    return -1;
  if(argaddr(1, &addr) < 0)
    return -1;
  if(p->handling_signal == 1 || p->in_a_handler == 1)
    return -1;
  p->alarm_interval = n;
  // printf("alarm_interval: %d\n", p->alarm_interval);
  p->handler = (void *) addr; // syntax of casting a function pointer is like (void (*)()) ptr, but here, it is okay
  p->handling_signal = 1;
  if (addr == 0)
    p->handler_not_null = 0;
  else
    p->handler_not_null = 1;
  // printf("handler: %p\n", p->handler);
  return 0;
}

uint64 sys_sigreturn(void)
{
  return 0;
}
```

A key part of implementing `test0` in `alarmtest` is handling the case of a zero address function `periodic`. I tried several approaches to achieve this, including using function pointers or inline assembly, or casting the function pointer in an indirect way. However, all of these attempts failed because a process cannot visit address `0x0`, which is generally reserved and not intended for use. These attempts resulted in a kernel trap with an error message indicating that the instruction address zero could not be visited, and produced the following panic information:

```
xv6 kernel is booting

hart 1 starting
hart 2 starting
init: starting sh
$ alarmtest
test0 start
..........scause 0x000000000000000c
sepc=0x0000000000000000 stval=0x0000000000000000
panic: kerneltrap
backtrace:
0x0000000080005c68
0x0000000080001e02
0x0000000080005024
[Ctrl+A] [X]
```

The hint provided in the question suggests the correct method for determining the instruction address at which user-space code resumes execution after a trap on the RISC-V returns to user space. To do this, we can simply add an assignment statement that copies the target instruction address to the register of the current program counter (instruction pointer), like this: `p->trapframe->epc = (uint64) p->handler;`. With this modification, the code should pass the `test0` test.

```
  // in file trap.c, function usertrap()
  ...
  // give up the CPU if this is a timer interrupt.
  if(which_dev == 2) {
    p->ticks_count++;
    if (p->ticks_count >= p->alarm_interval && p->alarm_interval != 0) {
      p->ticks_count = 0;
      // problem is caused by executing the handler with address 0 (sepc=0x0000000000000000)
      if (p->handler != 0){
        ((void (*)()) p->handler)();
      } else {
        //  ((void (*)()) p->handler)();
        // call a function at address zero using asm
        // asm("jalr zero, 0(zero)");
        // asm volatile("jalr x0");
        p->trapframe->epc = (uint64) p->handler;
      }
    }
    yield();
  }
  ...
```

However, the code currently fails in the `test1` and `test2` tests. We will need to fix these bugs in the following steps. The failure information for these tests can be seen in the output.

```
xv6 kernel is booting

hart 1 starting
hart 2 starting
init: starting sh
$ alarmtest
test0 start
........alarm!
test0 passed
test1 start
.alarm!
.alarm!
.alarm!
.alarm!
.alarm!
alarm!
.alarm!
.alarm!
.alarm!
.alarm!

test1 failed: foo() executed fewer times than it was called
test2 start
........scause 0x000000000000000c
sepc=0x000000000000003a stval=0x000000000000003a
panic: kerneltrap
backtrace:
0x0000000080005c68
0x0000000080001e04
0x0000000080005024
[Ctrl+A] [X]
```

To fix these issues, we should follow the instructions provided by 6.S081 to implement our code. These instructions tell us that we should save the appropriate registers to handle the traps correctly. However, the instructions also note that "(Hint: it will be many)", indicating that we may easily miss some necessary registers.

To simplify the process, we can just copy all of the registers from the `trapframe`, and restore them all when we return, like this:

```
// in file trap.c, function usertrap()
  ...
  // give up the CPU if this is a timer interrupt.
  if(which_dev == 2) {
    p->ticks_count++;
    if (p->ticks_count >= p->alarm_interval && p->alarm_interval != 0) {
      p->ticks_count = 0;
      if (p->handler != 0){
        ((void (*)()) p->handler)();
      } else {
        // save running states
        p->old_trapframe = (struct trapframe *)kalloc();
        memmove(p->old_trapframe, p->trapframe, sizeof(struct trapframe));
        p->old_alarm_interval = p->alarm_interval;
        p->old_ticks_count = p->ticks_count;
        p->old_handling_signal = p->handling_signal;
        p->old_handler_not_null = p->handler_not_null;
        p->old_handler = p->handler;
        // copy the target instruction address to pc
        p->trapframe->epc = (uint64) p->handler;
      }
    }
    yield();
  }
  ...
```

Additionally, when we return from the trap, we should free any allocated memory and restore the process to its running state.

```
// in file sysproc.c
uint64 sys_sigreturn(void)
{
  struct proc *p = myproc();
  if(p->handling_signal == 0)
    return -1;
  p->handling_signal = 0;
  p->alarm_interval = 0;
  p->handler = 0;
  if (p->handler_not_null == 0) {
    // means that the handler was null
    // so we need to restore the old trapframe
    memmove(p->trapframe, p->old_trapframe, sizeof(struct trapframe));
    kfree(p->old_trapframe);
    p->old_trapframe = 0;
    p->alarm_interval = p->old_alarm_interval;
    p->handler_not_null = p->old_handler_not_null;
    p->handler = p->old_handler;
    p->handling_signal = p->old_handling_signal;
  }
  return 0;
}
```

After making these changes and running the `alarmtest` program, we should see that `test1` has passed. However, the program will still fail when running `test2`. The terminal output for this test should look like:

```
xv6 kernel is booting

hart 2 starting
hart 1 starting
init: starting sh
$ alarmtest
test0 start
.........alarm!
test0 passed
test1 start
..alarm!
.alarm!
.alarm!
..alarm!
..alarm!
.alarm!
alarm!
.alarm!
.alarm!
..alarm!
test1 passed
test2 start
........scause 0x000000000000000c
sepc=0x000000000000003a stval=0x000000000000003a
panic: kerneltrap
backtrace:
0x0000000080005d48
0x0000000080001e48
0x0000000080005104
[Ctrl+A] [X]
```

The instructions provided by 6.S081 tell us about the cause of this failure in `test2`:

> "Prevent re-entrant calls to the handler----if a handler hasn't returned yet, the kernel shouldn't call it again. test2 tests this."

To fix this issue, we need to mark whether the process is currently handling a timer interrupt. If it is, we should ignore any additional timer interrupts until the current one has returned. Since the instructions do not specify how we should handle the timer when we are in a timer interrupt, we can leave the original implementation unchanged. We can achieve this by adding a field to the `struct proc` to mark the current running state of the process. For example, we can add a `in_a_handler` tag to mark whether the process is currently handling a timer interrupt.

To modify the `sys_return` syscall to account for this, we can do the following:

```
uint64 sys_sigreturn(void)
{
  struct proc *p = myproc();
  if(p->handling_signal == 0)
    return -1;
  p->handling_signal = 0;
  p->alarm_interval = 0;
  p->handler = 0;
  // restore
  memmove(p->trapframe, p->old_trapframe, sizeof(struct trapframe));
  kfree(p->old_trapframe);
  p->old_trapframe = 0;
  p->alarm_interval = p->old_alarm_interval;
  p->handler_not_null = p->old_handler_not_null;
  p->handler = p->old_handler;
  p->handling_signal = p->old_handling_signal;
  p->in_a_handler = 0;
  return 0;
}
```

Note that in this implementation, I have updated the restore process for all handlers, not just those located at address 0x0. This simplifies the code logic. Similar modifications should also be applied to the `usertrap` function.

```
  // in file trap.c, function usertrap()
  ...
  // give up the CPU if this is a timer interrupt.
  if(which_dev == 2) {
    p->ticks_count++;
    if (p->ticks_count >= p->alarm_interval && p->alarm_interval != 0) {
      p->ticks_count = 0;
      if (!p->in_a_handler) {
        p->in_a_handler = 1;
        // save running states
        p->old_trapframe = (struct trapframe *)kalloc();
        memmove(p->old_trapframe, p->trapframe, sizeof(struct trapframe));
        p->old_alarm_interval = p->alarm_interval;
        p->old_ticks_count = p->ticks_count;
        p->old_handling_signal = p->handling_signal;
        p->old_handler_not_null = p->handler_not_null;
        p->old_handler = p->handler;
        // copy the target instruction address to pc
        p->trapframe->epc = (uint64) p->handler;
      }
    }
    yield();
  }
  ...
```

After making these changes, running the `alarmtest` program should result in all tests passing.

```
xv6 kernel is booting

hart 1 starting
hart 2 starting
init: starting sh
$ alarmtest
test0 start
.......alarm!
test0 passed
test1 start
.alarm!
.alarm!
.alarm!
...alarm!
.alarm!
.alarm!
.alarm!
.alarm!
.alarm!
.alarm!
test1 passed
test2 start
........alarm!
test2 passed
$
```

Make grade

```
make[1]: Leaving directory '/home/lydia/projects/xv6-labs-2021'
== Test answers-traps.txt == answers-traps.txt: OK
== Test backtrace test ==
$ make qemu-gdb
backtrace test: OK (4.4s)
== Test running alarmtest ==
$ make qemu-gdb
(4.3s)
== Test   alarmtest: test0 ==
  alarmtest: test0: OK
== Test   alarmtest: test1 ==
  alarmtest: test1: OK
== Test   alarmtest: test2 ==
  alarmtest: test2: OK
== Test usertests ==
$ make qemu-gdb
usertests: OK (233.8s)
== Test time ==
time: OK
Score: 85/85
lydia@ubuntu-22-hp-040f1b4d:~/projects/xv6-labs-2021$ git checkout
```

Reference

1. MIT 6.S081 2021
2. Lecture Slides
3. Question Answers