Lab 4: Preemptive Multitasking

- **Handed out:** Sunday, May 16, 2021
- **Due: 11:59 pm, Friday, June 4, 2021**
- **New 75% due: 11:59 pm, Monday June 7, 2021**
- **Invitation Link:** https://classroom.github.com/a/EVDsUsMd

Introduction

In this lab you will implement preemptive multitasking among multiple simultaneously active user-mode environments.

- In part A, you will add multiprocessor support to JOS, implement round-robin scheduling, and add basic environment management system calls (calls that create and destroy environments, and allocate/map memory).
- In part B, you will implement a Unix-like `fork()`, which allows a user-mode environment to create copies of itself.
- Finally, in part C you will add support for inter-process communication (IPC), allowing different user-mode environments to communicate and synchronize with each other explicitly. You will also add support for hardware clock interrupts and preemption.

Getting Started

1. Accept the Lab 4 assignment using the invitation link and clone the repository to your own namespace.
2. As stated in Lab 3 documentation, merge your progress from lab3 to lab4.
   2.1. Add your lab3 progress to "lab3" branch, check, and push:
   ```
   git checkout lab3
   cp -rf ../os2-lab3-[yourname]/* ./
   make grade
   make realclean
   git add -A
   git commit -am "add lab3"
   git push origin lab3
   ```
   2.2. Merge:
   ```
   git checkout main
   git checkout -b lab4
   git merge lab3
   ```

   2.3. Solving merge conflicts:

   Merge rules: compare the source code from "main" branch (lab4 materials) to "lab3" branch (lab3 materials), if the code is written by you from lab1-3, accept lab3 branch, i.e., (from "=======" to ">>>>>>> lab3"), otherwise, if the code is modified in lab4 template, then accept "main" branch, i.e., (from "<<<<<<< HEAD" to "=======").

For example: here is the conf/lab.mk with merge conflicts:

```
1 <<<<<<< HEAD
2 LAB=4
3 PACKAGEDATE=Mon Oct 8 21:31:51 PDT 2018
4 =======
5 LAB=3
6 PACKAGEDATE=Tue Sep 25 12:21:10 EDT 2018
7 >>>>>>> lab3
```

Accept the "main" branch, since we didn't modify this file in lab1-3. Then delete line1 and 4-7:

```
1 LAB=4
2 PACKAGEDATE=Mon Oct 8 21:31:51 PDT 2018
```

List of files that has merge conflicts:

```
os2 ~/cs444/s21/os2-lab4-Rogersyp 120% git merge lab3
Auto-merging student.info
CONFLICT (add/add): Merge conflict in student.info
Auto-merging lib/syscall.c
CONFLICT (add/add): Merge conflict in lib/syscall.c
Auto-merging lib/printfmt.c
CONFLICT (add/add): Merge conflict in lib/printfmt.c
Auto-merging lib/libmain.c
CONFLICT (add/add): Merge conflict in lib/libmain.c
Auto-merging lib/console.c
CONFLICT (add/add): Merge conflict in lib/console.c
Auto-merging lib/Makefrag
CONFLICT (add/add): Merge conflict in lib/Makefrag
Auto-merging kern/trapentry.S
CONFLICT (add/add): Merge conflict in kern/trapentry.S
Auto-merging kern/trap.c
CONFLICT (add/add): Merge conflict in kern/trap.c
Auto-merging kern/syscall.c
CONFLICT (add/add): Merge conflict in kern/syscall.c
Auto-merging kern/pmap.h
CONFLICT (add/add): Merge conflict in kern/pmap.h
Auto-merging kern/pmap.c
CONFLICT (add/add): Merge conflict in kern/pmap.c
Auto-merging kern/monitor.c
CONFLICT (add/add): Merge conflict in kern/monitor.c
Auto-merging kern/kernel.ld
CONFLICT (add/add): Merge conflict in kern/kernel.ld
Auto-merging kern/kdebug.c
CONFLICT (add/add): Merge conflict in kern/kdebug.c
Auto-merging kern/init.c
CONFLICT (add/add): Merge conflict in kern/init.c
Auto-merging kern/env.h
CONFLICT (add/add): Merge conflict in kern/env.h
Auto-merging kern/env.c
CONFLICT (add/add): Merge conflict in kern/env.c
Auto-merging kern/console.c
CONFLICT (add/add): Merge conflict in kern/console.c
Auto-merging kern/Makefrag
CONFLICT (add/add): Merge conflict in kern/Makefrag
Auto-merging inc/trap.h
CONFLICT (add/add): Merge conflict in inc/trap.h
Auto-merging inc/syscall.h
CONFLICT (add/add): Merge conflict in inc/syscall.h
Auto-merging inc/memlayout.h
CONFLICT (add/add): Merge conflict in inc/memlayout.h
Auto-merging inc/lib.h
CONFLICT (add/add): Merge conflict in inc/lib.h
Auto-merging inc/error.h
CONFLICT (add/add): Merge conflict in inc/error.h
Auto-merging inc/env.h
CONFLICT (add/add): Merge conflict in inc/env.h
Auto-merging conf/lab.mk
CONFLICT (add/add): Merge conflict in conf/lab.mk
Auto-merging boot/main.c
CONFLICT (add/add): Merge conflict in boot/main.c
Auto-merging GNUmakefile
CONFLICT (add/add): Merge conflict in GNUmakefile
Automatic merge failed; fix conflicts and then commit the result.
```

Note: Do not replace any source code files!

2.4 Add, commit, and push to "lab4" branch

```
git add -A
git commit -am "merged lab3 into lab4"
git push origin lab4
```

Lab 4 contains a number of new source files, some of which you should browse before you start:

`kern/cpu.h`	Kernel-private definitions for multiprocessor support
`kern/mpconfig.c`	Code to read the multiprocessor configuration
`kern/lapic.c`	Kernel code driving the local APIC unit in each processor
`kern/mpentry.S`	Assembly-language entry code for non-boot CPUs
`kern/spinlock.h`	Kernel-private definitions for spin locks, including the big kernel lock
`kern/spinlock.c`	Kernel code implementing spin locks
`kern/sched.c`	Code skeleton of the scheduler that you are about to implement

Lab Requirements

This lab is divided into three parts, A, B, and C.

As before, you will need to do all of the regular exercises described in the lab and provide a writeup that briefly answers to the questions posed in the lab. Place the write-up in a file called `answers-lab4.txt` in the top level of your repository directory before handing in your work.

Part A: Multiprocessor Support and Cooperative Multitasking

In the first part of this lab, you will first extend JOS to run on a multiprocessor system, and then implement some new JOS kernel system calls to allow user-level environments to create additional new environments. You will also implement

cooperative round-robin scheduling, allowing the kernel to switch from one environment to another when the current environment voluntarily relinquishes the CPU (or exits). Later in part C you will implement *preemptive* scheduling, which allows the kernel to re-take control of the CPU from an environment after a certain time has passed even if the environment does not cooperate.

Multiprocessor Support

We are going to make JOS support "symmetric multiprocessing" (SMP), a multi-processor model in which all CPUs have equivalent access to system resources such as memory and I/O buses. While all CPUs are functionally identical in SMP, during the boot process they can be classified into two types: the bootstrap processor (BSP) is responsible for initializing the system and for booting the operating system; and the application processors (APs) are activated by the BSP only after the operating system is up and running. Which processor is the BSP is determined by the hardware and the BIOS. Up to this point, all your existing JOS code has been running on the BSP.

In an SMP system, each CPU has an accompanying local APIC (LAPIC) unit. The LAPIC units are responsible for delivering interrupts throughout the system. The LAPIC also provides its connected CPU with a unique identifier. In this lab, we make use of the following basic functionality of the LAPIC unit (in `kern/lapic.c`):

- Reading the LAPIC identifier (APIC ID) to tell which CPU our code is currently running on (see `cpunum()`).
- Sending the `STARTUP` interprocessor interrupt (IPI) from the BSP to the APs to bring up other CPUs (see `lapic_startap()`).
- In part C, we program LAPIC's built-in timer to trigger clock interrupts to support preemptive multitasking (see `apic_init()`).

A processor accesses its LAPIC using memory-mapped I/O (MMIO). In MMIO, a portion of *physical* memory is hardwired to the registers of some I/O devices, so the same load/store instructions typically used to access memory can be used to access device registers. You've already seen one IO hole at physical address `0xA0000` (we use this to write to the VGA display buffer). The LAPIC lives in a hole starting at physical address `0xFE000000` (32MB short of 4GB), so it's too high for us to access using our usual direct map at `KERNBASE`. The JOS virtual memory map leaves a 4MB gap at `MMIOBASE` so we have a place to map devices like this. Since later labs introduce more MMIO regions, you'll write a simple function to allocate space from this region and map device memory to it.

Note

Exercise 1. Implement `mmio_map_region()` in `kern/pmap.c`. To see how this is used, look at the beginning of `lapic_init()` in `kern/lapic.c`. You'll have to do the next exercise, too, before the tests for `mmio_map_region()` will run.

Application Processor Bootstrap

Before booting up APs, the BSP should first collect information about the multiprocessor system, such as the total number of CPUs, their APIC IDs and the MMIO address of the LAPIC unit. The `mp_init()` function in `kern/mpconfig.c` retrieves this information by reading the MP configuration table that resides in the BIOS's region of memory.

The `boot_aps()` function (in `kern/init.c`) drives the AP bootstrap process. APs start in real mode, much like how the bootloader started in `boot/boot.S`, so `boot_aps()` copies the AP entry code (`kern/mpentry.S`) to a memory location that is addressable in the real mode. Unlike with the bootloader, we have some control over where the AP will start executing code; we copy the entry code to `0x7000` (`MPENTRY_PADDR`), but any unused, page-aligned physical address below 640KB would work.

After that, `boot_aps()` activates APs one after another, by sending `STARTUP` IPIs to the LAPIC unit of the corresponding AP, along with an initial `CS:IP` address at which the AP should start running its entry code (`MPENTRY_PADDR` in our case). The entry code in `kern/mpentry.S` is quite similar to that of `boot/boot.S`. After some brief setup, it puts the AP into protected mode with paging enabled, and then calls the C setup routine `mp_main()` (also in `kern/init.c`). `boot_aps()` waits for the AP to signal a `CPU_STARTED` flag in `cpu_status` field of its `struct CpuInfo` before going on to wake up the next one.

Note

Exercise 2. Read `boot_aps()` and `mp_main()` in `kern/init.c`, and the assembly code in `kern/mpentry.S`. Make sure you understand the control flow transfer during the bootstrap of APs. Then modify your implementation of `page_init()` in `kern/pmap.c` to avoid adding the page at `MPENTRY_PADDR` to the free list, so that we can safely copy and run AP bootstrap code at that physical address. Your code should pass the updated `check_page_free_list()` test (but might fail the updated `check_kern_pgdir()` test, which we will fix soon).

Note

Question 1. Compare `kern/mpentry.S` side by side with `boot/boot.S`. Bearing in mind that `kern/mpentry.S` is compiled and linked to run above `KERNBASE` just like everything else in the kernel, what is the purpose of macro `MPBOOTPHYS`? Why is it necessary in `kern/mpentry.S` but not in `boot/boot.S`? In other words, what could go wrong if it were omitted in `kern/mpentry.S`? Hint: recall the differences between the link address and the load address that we have discussed in Lab 1.

Per-CPU State and Initialization

When writing a multiprocessor OS, it is important to distinguish between per-CPU state that is private to each processor, and global state that the whole system shares. `kern/cpu.h` defines most of the per-CPU state, including `struct CpuInfo`, which stores per-CPU variables. `cpunum()` always returns the ID of the CPU that calls it, which can be used as an index into arrays like `cpus`. Alternatively, the macro `thiscpu` is shorthand for the current CPU's `struct CpuInfo`.

Here is the per-CPU state you should be aware of:

- **Per-CPU kernel stack**. Because multiple CPUs can trap into the kernel simultaneously, we need a separate kernel stack for each processor to prevent them from interfering with each other's execution. The array `percpu_kstacks[NCPU][KSTKSIZE]` reserves space for NCPU's worth of kernel stacks.
  In Lab 2, you mapped the physical memory that `bootstack` refers to as the BSP's kernel stack just below `KSTACKTOP`. Similarly, in this lab, you will map each CPU's kernel stack into this region with guard pages acting as a buffer between them. CPU 0's stack will still grow down from `KSTACKTOP`; CPU 1's stack will start `KSTKGAP` bytes below the bottom of CPU 0's stack, and so on. `inc/memlayout.h` shows the mapping layout.
- **Per-CPU TSS and TSS descriptor**. A per-CPU task state segment (TSS) is also needed in order to specify where each CPU's kernel stack lives. The TSS for CPU *i* is stored in `cpus[i].cpu_ts`, and the corresponding TSS descriptor is defined in the GDT entry `gdt[(GD_TSS0 >> 3) + i]`. The global `ts` variable defined in `kern/trap.c` will no longer be useful.
- **Per-CPU current environment pointer**. Since each CPU can run different user process simultaneously, we redefined the symbol `curenv` to refer to `cpus[cpunum()].cpu_env` (or `thiscpu->cpu_env`), which points to the environment *currently* executing on the *current* CPU (the CPU on which the code is running).
- **Per-CPU system registers**. All registers, including system registers, are private to a CPU. Therefore, instructions that initialize these registers, such as `lcr3()`, `ltr()`, `lgdt()`, `lidt()`, etc., must be executed once on each CPU. Functions `env_init_percpu()` and `trap_init_percpu()` are defined for this purpose.

Note

Exercise 3. Modify `mem_init_mp()` (in `kern/pmap.c`) to map per-CPU stacks starting at `KSTACKTOP`, as shown in `inc/memlayout.h`. The size of each stack is `KSTKSIZE` bytes plus `KSTKGAP` bytes of unmapped guard pages. Your code should pass the new check in `check_kern_pgdir()`.

Note

Exercise 4. The code in `trap_init_percpu()` (`kern/trap.c`) initializes the TSS and TSS descriptor for the BSP. It worked in Lab 3, but is incorrect when running on other CPUs. Change the code so that it can work on all CPUs. (Note: your new code should not use the global `ts` variable any more.)

When you finish the above exercises, run JOS in QEMU with 4 CPUs using `make qemu CPUS=4` (or `make qemu-nox CPUS=4`), you should see output like this:

```
...
Physical memory: 66556K available, base = 640K, extended = 65532K
check_page_alloc() succeeded!
```

```
check_page() succeeded!
check_kern_pgdir() succeeded!
check_page_installed_pgdir() succeeded!
SMP: CPU 0 found 4 CPU(s)
enabled interrupts: 1 2
SMP: CPU 1 starting
SMP: CPU 2 starting
SMP: CPU 3 starting
```

Locking

Our current code spins after initializing the AP in `mp_main()`. Before letting the AP get any further, we need to first address race conditions when multiple CPUs run kernel code simultaneously. The simplest way to achieve this is to use a *big kernel lock*. The big kernel lock is a single global lock that is held whenever an environment enters kernel mode, and is released when the environment returns to user mode. In this model, environments in user mode can run concurrently on any available CPUs, but no more than one environment can run in kernel mode; any other environments that try to enter kernel mode are forced to wait.

`kern/spinlock.h` declares the big kernel lock, namely `kernel_lock`. It also provides `lock_kernel()` and `unlock_kernel()`, shortcuts to acquire and release the lock. You should apply the big kernel lock at four locations:

- In `i386_init()`, acquire the lock before the BSP wakes up the other CPUs.
- In `mp_main()`, acquire the lock after initializing the AP, and then call `sched_yield()` to start running environments on this AP.
- In `trap()`, acquire the lock when trapped from user mode. To determine whether a trap happened in user mode or in kernel mode, check the low bits of the `tf_cs`.
- In `env_run()`, release the lock *right before* switching to user mode. Do not do that too early or too late, otherwise you will experience races or deadlocks.

Note

Exercise 5. Apply the big kernel lock as described above, by calling `lock_kernel()` and `unlock_kernel()` at the proper locations.

How to test if your locking is correct? You can't at this moment! But you will be able to after you implement the scheduler in the next exercise.

Note

Question 2. It seems that using the big kernel lock guarantees that only one CPU can run the kernel code at a time. Why do we still need separate kernel stacks for each CPU? Describe a scenario in which using a shared kernel stack will go wrong, even with the protection of the big kernel lock.

Optional Challenge (no extra-credit)! The big kernel lock is simple and easy to use. Nevertheless, it eliminates all concurrency in kernel mode. Most modern operating systems use different locks to protect different parts of their shared state, an approach called *fine-grained locking*. Fine-grained locking can increase performance significantly, but is more difficult to implement and error-prone. If you are brave enough, drop the big kernel lock and embrace concurrency in JOS!

It is up to you to decide the locking granularity (the amount of data that a lock protects). As a hint, you may consider using spin locks to ensure exclusive access to these shared components in the JOS kernel: 1) The page allocator; 2) The console driver; 3) The scheduler; 4) The inter-process communication (IPC) state that you will implement in the part C.

Round-Robin Scheduling

Your next task in this lab is to change the JOS kernel so that it can alternate between multiple environments in "round-robin" fashion. Round-robin scheduling in JOS works as follows:

- The function `sched_yield()` in the new `kern/sched.c` is responsible for selecting a new environment to run. It searches sequentially through the `envs[]` array in circular fashion, starting just after the previously running environment (or at the beginning of the array if there was no previously running environment), picks the first environment it finds with a status of `ENV_RUNNABLE` (see `inc/env.h`), and calls `env_run()` to jump into that environment.
- `sched_yield()` must never run the same environment on two CPUs at the same time. It can tell that an environment is currently running on some CPU (possibly the current CPU) because that environment's status will be `ENV_RUNNING`.
- We have implemented a new system call for you, `sys_yield()`, which user environments can call to invoke the kernel's `sched_yield()` function and thereby voluntarily give up the CPU to a different environment.

Exercise 6. Implement round-robin scheduling in `sched_yield()` as described above. Don't forget to modify `syscall()` to dispatch `sys_yield()`.

Make sure to invoke `sched_yield()` in `mp_main`.

Modify `kern/init.c` to create three (or more!) environments that all run the program `user/yield.c`.

Run make qemu. You should see the environments switch back and forth between each other five times before terminating, like below.

Test also with several CPUS: make qemu-nox CPUS=2.

. . .

```
Hello, I am environment 00001000.
Hello, I am environment 00001001.
Hello, I am environment 00001002.
Back in environment 00001000, iteration 0.
Back in environment 00001001, iteration 0.
Back in environment 00001002, iteration 0.
Back in environment 00001000, iteration 1.
Back in environment 00001001, iteration 1.
Back in environment 00001002, iteration 1.
...
```

After the `yield` programs exit, there will be no runnable environment in the system, the scheduler should invoke the JOS kernel monitor. If any of this does not happen, then fix your code before proceeding.

If you use CPUS=1 at this point, all environments should successfully run. Setting CPUS larger than 1 at this time may result in a general protection or kernel page fault once there are no more runnable environments due to unhandled timer interrupts (which we will fix below!).

Note

Question 3. In your implementation of `env_run()` you should have called `lcr3()`. Before and after the call to `lcr3()`, your code makes references (at least it should) to the variable `e`, the argument to `env_run`. Upon loading the `%cr3` register, the addressing context used by the MMU is instantly changed. But a virtual address (namely `e`) has meaning relative to a given address context–the address context specifies the physical address to which the virtual address maps. Why can the pointer `e` be dereferenced both before and after the addressing switch?

4. Whenever the kernel switches from one environment to another, it must ensure the old environment's registers are saved so they can be restored properly later. Why? Where does this happen?

Note

Optional Challenge (no extra credit)! Add a less trivial scheduling policy to the kernel, such as a fixed-priority scheduler that allows each environment to be assigned a priority and ensures that higher-priority environments are always chosen in preference to lower-priority environments. If you're feeling really adventurous, try implementing a Unix-style adjustable-priority scheduler or even a lottery or stride scheduler. (Look up "lottery scheduling" and "stride scheduling" in Google.)

Write a test program or two that verifies that your scheduling algorithm is working correctly (i.e., the right environments get run in the right order). It may be easier to write these test programs once you have implemented `fork()` and IPC in parts B and C of this lab.

Optional Challenge (no extra credit)! The JOS kernel currently does not allow applications to use the x86 processor's x87 floating-point unit (FPU), MMX instructions, or Streaming SIMD Extensions (SSE). Extend the `Env` structure to provide a save area for the processor's floating point state, and extend the context switching code to save and restore this state properly when switching from one environment to another. The `FXSAVE` and `FXRSTOR` instructions may be useful, but note that these are not in the old i386 user's manual because they were introduced in more recent processors. Write a user-level test program that does something cool with floating-point.

System Calls for Environment Creation

Although your kernel is now capable of running and switching between multiple user-level environments, it is still limited to running environments that the *kernel* initially set up. You will now implement the necessary JOS system calls to allow *user* environments to create and start other new user environments.

Unix provides the `fork()` system call as its process creation primitive. Unix `fork()` copies the entire address space of calling process (the parent) to create a new process (the child). The only differences between the two observable from user space are their process IDs and parent process IDs (as returned by `getpid` and `getppid`). In the parent, `fork()` returns the child's process ID, while in the child, `fork()` returns 0. By default, each process gets its own private address space, and neither process's modifications to memory are visible to the other.

You will provide a different, more primitive set of JOS system calls for creating new user-mode environments. With these system calls you will be able to implement a Unix-like `fork()` entirely in user space, in addition to other styles of environment creation. The new system calls you will write for JOS are as follows:

- `sys_exofork`:
  This system call creates a new environment with an almost blank slate: nothing is mapped in the user portion of its address space, and it is not runnable. The new environment will have the same register state as the parent environment at the time of the `sys_exofork` call. In the parent, `sys_exofork` will return the `envid_t` of the newly created environment (or a negative error code if the environment allocation failed). In the child, however, it will return 0. (Since the child starts out marked as not runnable, `sys_exofork` will not actually return in the child until the parent has explicitly allowed this by marking the child runnable using….)

- `sys_env_set_status`:

  Sets the status of a specified environment to `ENV_RUNNABLE` or `ENV_NOT_RUNNABLE`. This system call is typically used to mark a new environment ready to run, once its address space and register state has been fully initialized.

- `sys_page_alloc`:

Allocates a page of physical memory and maps it at a given virtual address in a given environment's address space.

- `sys_page_map`:

    Copy a page mapping (*not* the contents of a page!) from one environment's address space to another, leaving a memory sharing arrangement in place so that the new and the old mappings both refer to the same page of physical memory.

- `sys_page_unmap`:

    Unmap a page mapped at a given virtual address in a given environment.

For all of the system calls above that accept environment IDs, the JOS kernel supports the convention that a value of 0 means "the current environment." This convention is implemented by `envid2env()` in `kern/env.c`.

We have provided a very primitive implementation of a Unix-like `fork()` in the test program `user/dumbfork.c`. This test program uses the above system calls to create and run a child environment with a copy of its own address space. The two environments then switch back and forth using `sys_yield` as in the previous exercise. The parent exits after 10 iterations, whereas the child exits after 20.

Note

Exercise 7. Implement the system calls described above in `kern/syscall.c`. You will need to use various functions in `kern/pmap.c` and `kern/env.c`, particularly `envid2env()`. For now, whenever you call `envid2env()`, pass 1 in the `checkperm` parameter. Be sure you check for any invalid system call arguments, returning `-E_INVAL` in that case. Test your JOS kernel with `user/dumbfork` and make sure it works before proceeding.

Note

Optional Challenge (no extra-credit)! Add the additional system calls necessary to *read* all of the vital state of an existing environment as well as set it up. Then implement a user mode program that forks off a child environment, runs it for a while (e.g., a few iterations of `sys_yield()`), then takes a complete snapshot or *checkpoint* of the child environment, runs the child for a while longer, and finally restores the child environment to the state it was in at the checkpoint and continues it from there. Thus, you are effectively "replaying" the execution of the child environment from an intermediate state. Make the child environment perform some interaction with the user using `sys_cgetc()` or `readline()` so that the user can view and mutate its internal state, and verify that with your checkpoint/restart you can give the child environment a case of selective amnesia, making it "forget" everything that happened beyond a certain point.

This completes Part A of the lab; check your progress using `make grade`. If you are trying to figure out why a particular test case is failing, run `./grade-lab4 -v`, which will show you the output of the kernel builds and QEMU runs for each test, until a test fails. When a test fails, the script will stop, and then you can inspect `jos.out` to see what the kernel actually printed.

Part B: Copy-on-Write Fork

As mentioned earlier, Unix provides the `fork()` system call as its primary process creation primitive. The `fork()` system call copies the address space of the calling process (the parent) to create a new process (the child).

A naive implementation of `fork()` would be done by copying all data from the parent's pages into new pages allocated for the child. This is essentially the same approach that `dumbfork()` takes. The copying of the parent's address space into the child is the most expensive part of the `fork()` operation.

However, a call to `fork()` is frequently followed almost immediately by a call to `exec()` in the child process, which replaces the child's memory with a new program. This is what the the shell typically does, for example. In this case, the time spent copying the parent's address space is largely wasted, because the child process will use very little of its memory before calling `exec()`.

For this reason, later versions of Unix took advantage of virtual memory hardware to allow the parent and child to *share* the memory mapped into their respective address spaces until one of the processes actually modifies it. This technique is known as *copy-on-write*. To do this, on `fork()` the kernel would copy the address space *mappings* from the parent to the child instead of the contents of the mapped pages, and at the same time mark the now-shared pages read-only. When one of the two processes tries to write to one of these shared pages, the process takes a page fault. At this point, the Unix kernel realizes that the page was really a "virtual" or "copy-on-write" copy, and so it makes a new, private, writable copy of the page for the faulting process. In this way, the contents of individual pages aren't actually copied until they are actually written to. This optimization makes a `fork()` followed by an `exec()` in the child much cheaper: the child will probably only need to copy one page (the current page of its stack) before it calls `exec()`.

In the next piece of this lab, you will implement a "proper" Unix-like `fork()` with copy-on-write, as a user space library routine. Implementing `fork()` and copy-on-write support in user space has the benefit that the kernel remains much simpler and thus more likely to be correct. It also lets individual user-mode programs define their own semantics for `fork()`. A program that wants a slightly different implementation (for example, the expensive always-copy version like `dumbfork()`, or one in which the parent and child actually share memory afterward) can easily provide its own.

User-level page fault handling

A user-level copy-on-write `fork()` needs to know about page faults on write-protected pages, so that's what you'll implement first. Copy-on-write is only one of many possible uses for user-level page fault handling.

It's common to set up an address space so that page faults indicate when some action needs to take place. For example, most Unix kernels initially map only a single page in a new process's stack region, and allocate and map additional stack pages later "on demand" as the process's stack consumption increases and causes page faults on stack addresses that are not yet mapped. A typical Unix kernel must keep track of what

action to take when a page fault occurs in each region of a process's space. For example, a fault in the stack region will typically allocate and map new page of physical memory. A fault in the program's BSS region will typically allocate a new page, fill it with zeroes, and map it. In systems with demand-paged executables, a fault in the text region will read the corresponding page of the binary off of disk and then map it.

This is a lot of information for the kernel to keep track of. Instead of taking the traditional Unix approach, you will decide what to do about each page fault in user space, where bugs are less damaging. This design has the added benefit of allowing programs great flexibility in defining their memory regions; you'll use user-level page fault handling later for mapping and accessing files on a disk-based file system.

Setting the Page Fault Handler

In order to handle its own page faults, a user environment will need to register a *page fault handler entrypoint* with the JOS kernel. The user environment registers its page fault entrypoint via the new `sys_env_set_pgfault_upcall` system call. We have added a new member to the `Env` structure, `env_pgfault_upcall`, to record this information.

Note

Exercise 8. Implement the `sys_env_set_pgfault_upcall` system call. Be sure to enable permission checking when looking up the environment ID of the target environment, since this is a "dangerous" system call.

Normal and Exception Stacks in User Environments

During normal execution, a user environment in JOS will run on the *normal* user stack: its `ESP` register starts out pointing at `USTACKTOP`, and the stack data it pushes resides on the page between `USTACKTOP-PGSIZE` and `USTACKTOP-1` inclusive. When a page fault occurs in user mode, however, the kernel will restart the user environment running a designated user-level page fault handler on a different stack, namely the *user exception* stack. In essence, we will make the JOS kernel implement automatic "stack switching" on behalf of the user environment, in much the same way that the x86 *processor* already implements stack switching on behalf of JOS when transferring from user mode to kernel mode!

The JOS user exception stack is also one page in size, and its top is defined to be at virtual address `UXSTACKTOP`, so the valid bytes of the user exception stack are from `UXSTACKTOP-PGSIZE` through `UXSTACKTOP-1` inclusive. While running on this exception stack, the user-level page fault handler can use JOS's regular system calls to map new pages or adjust mappings so as to fix whatever problem originally caused the page fault. Then the user-level page fault handler returns, via an assembly language stub, to the faulting code on the original stack.

Each user environment that wants to support user-level page fault handling will need to allocate memory for its own exception stack, using the `sys_page_alloc()` system call introduced in part A.

Invoking the User Page Fault Handler

You will now need to change the page fault handling code in `kern/trap.c` to handle page faults from user mode as follows. We will call the state of the user environment at the time of the fault the *trap-time* state.

If there is no page fault handler registered, the JOS kernel destroys the user environment with a message as before. Otherwise, the kernel sets up a trap frame on the exception stack that looks like a `struct UTrapframe` from `inc/trap.h`:

```
                            <-- UXSTACKTOP
    trap-time esp

    trap-time eflags

    trap-time eip

    trap-time eax         start of struct PushRegs

    trap-time ecx

    trap-time edx

    trap-time ebx

    trap-time esp

    trap-time ebp

    trap-time esi

    trap-time edi         end of struct PushRegs

    tf_err (error code)

    fault_va              <-- %esp when handler is run
```

The kernel then arranges for the user environment to resume execution with the page fault handler running on the exception stack with this stack frame; you must figure out how to make this happen. The `fault_va` is the virtual address that caused the page fault.

If the user environment is *already* running on the user exception stack when an exception occurs, then the page fault handler itself has faulted. In this case, you should start the new stack frame just under the current `tf->tf_esp` rather than at `UXSTACKTOP`. You should first push an empty 32-bit word, then a `struct UTrapframe`.

To test whether `tf->tf_esp` is already on the user exception stack, check whether it is in the range between `UXSTACKTOP-PGSIZE` and `UXSTACKTOP-1`, inclusive.

Exercise 9. Implement the code in `page_fault_handler` in `kern/trap.c` required to dispatch page faults to the user-mode handler. Be sure to take appropriate precautions when writing into the exception stack. (What happens if the user environment runs out of space on the exception stack?)

User-mode Page Fault Entrypoint

Next, you need to implement the assembly routine that will take care of calling the C page fault handler and resume execution at the original faulting instruction. This assembly routine is the handler that will be registered with the kernel using `sys_env_set_pgfault_upcall()`.

Exercise 10. Implement the `_pgfault_upcall` routine in `lib/pfentry.S`. The interesting part is returning to the original point in the user code that caused the page fault. You'll return directly there, without going back through the kernel. The hard part is simultaneously switching stacks and re-loading the EIP.

Finally, you need to implement the C user library side of the user-level page fault handling mechanism.

Exercise 11. Finish `set_pgfault_handler()` in `lib/pgfault.c`.

Testing

Run `user/faultread` (make run-faultread-nox). You should see:

...

```
[00000000] new env 00001000
[00001000] user fault va 00000000 ip 0080003a
TRAP frame ...
[00001000] free env 00001000
```

Run `user/faultdie` (make run-faultdie-nox). You should see:

...

```
[00000000] new env 00001000
i faulted at va deadbeef, err 6
[00001000] exiting gracefully
[00001000] free env 00001000
```

Run `user/faultalloc` (make run-faultalloc-nox).. You should see:

...

```
[00000000] new env 00001000
fault deadbeef
this string was faulted in at deadbeef
fault cafebffe
fault cafec000
this string was faulted in at cafebffe
```

```
[00001000] exiting gracefully
```

```
[00001000] free env 00001000
```

If you see only the first "this string" line, it means you are not handling recursive page faults properly.

Run `user/faultallocbad` (make run-faultallocbad-nox). You should see:

...

```
[00000000] new env 00001000
```

```
[00001000] user_mem_check assertion failure for va deadbeef
```

```
[00001000] free env 00001000
```

Make sure you understand why `user/faultalloc` and `user/faultallocbad` behave differently.

Implementing Copy-on-Write Fork

You now have the kernel facilities to implement copy-on-write `fork()` entirely in user space.

We have provided a skeleton for your `fork()` in `lib/fork.c`. Like `dumbfork()`, `fork()` should create a new environment, then scan through the parent environment's entire address space and set up corresponding page mappings in the child. The key difference is that, while `dumbfork()` copied *pages*, `fork()` will initially only copy page *mappings*. `fork()` will copy each page only when one of the environments tries to write it.

The basic control flow for `fork()` is as follows:

1. The parent installs `pgfault()` as the C-level page fault handler, using the `set_pgfault_handler()` function you implemented above.
2. The parent calls `sys_exofork()` to create a child environment.
3. For each writable or copy-on-write page in its address space below UTOP, the parent calls `duppage`, which should map the page copy-on-write into the address space of the child and then *remap* the page copy-on-write in its own address space. `duppage` sets both PTEs so that the page is not writeable, and to contain `PTE_COW` in the "avail" field to distinguish copy-on-write pages from genuine read-only pages.
   The exception stack is *not* remapped this way, however. Instead you need to allocate a fresh page in the child for the exception stack. Since the page fault handler will be doing the actual copying and the page fault handler runs on the exception stack, the exception stack cannot be made copy-on-write: who would copy it?

`fork()` also needs to handle pages that are present, but not writable or copy-on-write.

4. The parent sets the user page fault entrypoint for the child to look like its own.
5. The child is now ready to run, so the parent marks it runnable.

Each time one of the environments writes a copy-on-write page that it hasn't yet written, it will take a page fault. Here's the control flow for the user page fault handler:

1. The kernel propagates the page fault to `_pgfault_upcall`, which calls `fork()`'s `pgfault()` handler.
2. `pgfault()` checks that the fault is a write (check for `FEC_WR` in the error code) and that the PTE for the page is marked `PTE_COW`. If not, panic.
3. `pgfault()` allocates a new page mapped at a temporary location and copies the contents of the faulting page into it. Then the fault handler maps the new page at the appropriate address with read/write permissions, in place of the old read-only mapping.

The user-level `lib/fork.c` code must consult the environment's page tables for several of the operations above (e.g., that the PTE for a page is marked `PTE_COW`). The kernel maps the environment's page tables at `UVPT` exactly for this purpose. It uses a clever mapping trick to make it to make it easy to lookup PTEs for user code. `lib/entry.S` sets up `uvpt` and `uvpd` so that you can easily lookup page-table information in `lib/fork.c`.

Note

Exercise 12. Implement `fork`, `duppage` and `pgfault` in `lib/fork.c`.

Test your code with the `forktree` program. It should produce the following messages, with interspersed 'new env', 'free env', and 'exiting gracefully' messages. The messages may not appear in this order, and the environment IDs may be different.

```
1000: I am ''
1001: I am '0'
2000: I am '00'
2001: I am '000'
1002: I am '1'
3000: I am '11'
3001: I am '10'
4000: I am '100'
1003: I am '01'
5000: I am '010'
4001: I am '011'
2002: I am '110'
1004: I am '001'
1005: I am '111'
1006: I am '101'
```

This ends part B. As usual, you can grade your submission with `make grade`.

Part C: Preemptive Multitasking and Inter-Process communication (IPC)

In the final part of lab 4 you will modify the kernel to preempt uncooperative environments and to allow environments to pass messages to each other explicitly.

Clock Interrupts and Preemption

Run the `user/spin` test program. This test program forks off a child environment, which simply spins forever in a tight loop once it receives control of the CPU. Neither the parent environment nor the kernel ever regains the CPU. This is obviously not an ideal situation in terms of protecting the system from bugs or malicious code in user-mode environments, because any user-mode environment can bring the whole system to a halt simply by getting into an infinite loop and never giving back the CPU. In order to allow the kernel to *preempt* a running environment, forcefully retaking control of the CPU from it, we must extend the JOS kernel to support external hardware interrupts from the clock hardware.

Interrupt discipline

External interrupts (i.e., device interrupts) are referred to as IRQs. There are 16 possible IRQs, numbered 0 through 15. The mapping from IRQ number to IDT entry is not fixed. `pic_init` in `picirq.c` maps IRQs 0-15 to IDT entries `IRQ_OFFSET` through `IRQ_OFFSET+15`.

In `inc/trap.h`, `IRQ_OFFSET` is defined to be decimal 32. Thus the IDT entries 32-47 correspond to the IRQs 0-15. For example, the clock interrupt is IRQ 0. Thus, `IDT[IRQ_OFFSET+0]` (i.e., IDT[32]) contains the address of the clock's interrupt handler routine in the kernel. This `IRQ_OFFSET` is chosen so that the device interrupts do not overlap with the processor exceptions, which could obviously cause confusion. (In fact, in the early days of PCs running MS-DOS, the `IRQ_OFFSET` effectively *was* zero, which indeed caused massive confusion between handling hardware interrupts and handling processor exceptions!)

In JOS, we make a key simplification compared to xv6 Unix. External device interrupts are *always* disabled when in the kernel (and, like xv6, enabled when in user space). External interrupts are controlled by the `FL_IF` flag bit of the `%eflags` register (see `inc/mmu.h`). When this bit is set, external interrupts are enabled. While the bit can be modified in several ways, because of our simplification, we will handle it solely through the process of saving and restoring `%eflags` register as we enter and leave user mode.

You will have to ensure that the `FL_IF` flag is set in user environments when they run so that when an interrupt arrives, it gets passed through to the processor and handled by your interrupt code. Otherwise, interrupts are *masked*, or ignored until interrupts are re-enabled. We masked interrupts with the very first instruction of the bootloader, and so far we have never gotten around to re-enabling them.

Exercise 13. Modify `kern/trapentry.S` and `kern/trap.c` to initialize the appropriate entries in the IDT and provide handlers for IRQs 0 through 15. Then modify the code in `env_alloc()` in `kern/env.c` to ensure that user environments are always run with interrupts enabled.

The processor never pushes an error code or checks the Descriptor Privilege Level (DPL) of the IDT entry when invoking a hardware interrupt handler. You might want to re-read section 9.2 of the 80386 Reference Manual, or section 5.8 of the IA-32 Intel Architecture Software Developer's Manual, Volume 3, at this time.

When you finish this exercise, please do not forget to remove a comment in the kern/sched.c:

// LAB 4:

// Uncomment the following line after completing exercise 13

//"sti"

After doing this exercise, if you run your kernel with any test program that runs for a non-trivial length of time (e.g., `spin`), you should see the kernel print trap frames for hardware interrupts. While interrupts are now enabled in the processor, JOS isn't yet handling them, so you should see it misattribute each interrupt to the currently running user environment and destroy it. Eventually it should run out of environments to destroy and drop into the monitor.

Handling Clock Interrupts

In the `user/spin` program, after the child environment was first run, it just spun in a loop, and the kernel never got control back. We need to program the hardware to generate clock interrupts periodically, which will force control back to the kernel where we can switch control to a different user environment.

The calls to `lapic_init` and `pic_init` (from `i386_init` in `init.c`), which we have written for you, set up the clock and the interrupt controller to generate interrupts. You now need to write the code to handle these interrupts.

Exercise 14. Modify the kernel's `trap_dispatch()` function so that it calls `sched_yield()` to find and run a different environment whenever a clock interrupt takes place.

You should now be able to get the `user/spin` test to work: the parent environment should fork off the child, `sys_yield()` to it a couple times but in each case regain control of the CPU after one time slice, and finally kill the child environment and terminate gracefully.

This is a great time to do some *regression testing*. Make sure that you haven't broken any earlier part of that lab that used to work (e.g. `forktree`) by enabling interrupts. Also, try running with multiple CPUs using `make CPUS=2` *target*. You should also be able to

pass `stresssched` now. Run make grade to see for sure. You should now get a total score of 65/80 points on this lab.

Inter-Process communication (IPC)

(Technically in JOS this is "inter-environment communication" or "IEC", but everyone else calls it IPC, so we'll use the standard term.)

We've been focusing on the isolation aspects of the operating system, the ways it provides the illusion that each program has a machine all to itself. Another important service of an operating system is to allow programs to communicate with each other when they want to. It can be quite powerful to let programs interact with other programs. The Unix pipe model is the canonical example.

There are many models for interprocess communication. Even today there are still debates about which models are best. We won't get into that debate. Instead, we'll implement a simple IPC mechanism and then try it out.

IPC in JOS

You will implement a few additional JOS kernel system calls that collectively provide a simple interprocess communication mechanism. You will implement two system calls, `sys_ipc_recv` and `sys_ipc_try_send`. Then you will implement two library wrappers `ipc_recv` and `ipc_send`.

The "messages" that user environments can send to each other using JOS's IPC mechanism consist of two components: a single 32-bit value, and optionally a single page mapping. Allowing environments to pass page mappings in messages provides an efficient way to transfer more data than will fit into a single 32-bit integer, and also allows environments to set up shared memory arrangements easily.

Sending and Receiving Messages

To receive a message, an environment calls `sys_ipc_recv`. This system call de-schedules the current environment and does not run it again until a message has been received. When an environment is waiting to receive a message, *any* other environment can send it a message - not just a particular environment, and not just environments that have a parent/child arrangement with the receiving environment. In other words, the permission checking that you implemented in Part A will not apply to IPC, because the IPC system calls are carefully designed so as to be "safe": an environment cannot cause another environment to malfunction simply by sending it messages (unless the target environment is also buggy).

To try to send a value, an environment calls `sys_ipc_try_send` with both the receiver's environment id and the value to be sent. If the named environment is actually receiving (it has called `sys_ipc_recv` and not gotten a value yet), then the send delivers the message and returns 0. Otherwise the send returns `-E_IPC_NOT_RECV` to indicate that the target environment is not currently expecting to receive a value.

A library function `ipc_recv` in user space will take care of calling `sys_ipc_recv` and then looking up the information about the received values in the current environment's `struct Env`.

Similarly, a library function `ipc_send` will take care of repeatedly calling `sys_ipc_try_send` until the send succeeds.

Transferring Pages

When an environment calls `sys_ipc_recv` with a valid `dstva` parameter (below `UTOP`), the environment is stating that it is willing to receive a page mapping. If the sender sends a page, then that page should be mapped at `dstva` in the receiver's address space. If the receiver already had a page mapped at `dstva`, then that previous page is unmapped.

When an environment calls `sys_ipc_try_send` with a valid `srcva` (below `UTOP`), it means the sender wants to send the page currently mapped at `srcva` to the receiver, with permissions `perm`. After a successful IPC, the sender keeps its original mapping for the page at `srcva` in its address space, but the receiver also obtains a mapping for this same physical page at the `dstva` originally specified by the receiver, in the receiver's address space. As a result this page becomes shared between the sender and receiver.

If either the sender or the receiver does not indicate that a page should be transferred, then no page is transferred. After any IPC the kernel sets the new field `env_ipc_perm` in the receiver's `Env` structure to the permissions of the page received, or zero if no page was received.

Implementing IPC

Note

Exercise 15. Implement `sys_ipc_recv` and `sys_ipc_try_send` in `kern/syscall.c`. Read the comments on both before implementing them, since they have to work together. When you call `envid2env` in these routines, you should set the `checkperm` flag to 0, meaning that any environment is allowed to send IPC messages to any other environment, and the kernel does no special permission checking other than verifying that the target envid is valid.

Then implement the `ipc_recv` and `ipc_send` functions in `lib/ipc.c`.

Use the `user/pingpong` and `user/primes` functions to test your IPC mechanism. `user/primes` will generate for each prime number a new environment until JOS runs out of environments. You might find it interesting to read `user/primes.c` to see all the forking and IPC going on behind the scenes.

Note

Optional Challenge (no extra-credit)! Why does `ipc_send` have to loop? Change the system call interface so it doesn't have to. Make sure you can handle multiple environments trying to send to one environment at the same time.

This ends part C. Make sure you pass all of the make grade tests and don't forget to write up your answers to the questions in `answers-lab4.txt`, and tag your commit as `lab4-final`.