system calls/excpetions/context switches

Changelog

Changes made in this version not seen in first lecture:

- contexts (B running) — adjust remark about where values are saved to note that A's user regs are saved on A's kernel stack rather than being ambiguous

last time

dual-mode operation:

- kernel-mode: can do anything
- user-mode: normal programs run here, no direct access to devices

exceptions/interrupts

- hardware runs OS for important events
- only way to switch to kernel mode — do special things

address spaces:

- each program gets its own memory

system calls:

- controlled entry into kernel mode

quiz demo

syscalls in xv6

fork, exec, exit, wait, kill, getpid — process control

open, read, write, close, fstat, dup — file operations

mknod, unlink, link, chdir — directory operations

...

write syscall in xv6: user mode

syscall.h

```
...
#define SYS_write   16
...
```

main.c

```
...
write(1,
      "Hello,␣World!\n",
      14);
...
```

usys.S

(after macro replacement)

```
#include "syscall.h"
// ...
.globl write
write:
    /* 16 = SYS_write */
    movl $16, %eax
    /* 0x40 = T_SYSCALL */
    int $0x40
    ret
```

write syscall in xv6: user mode

syscall.h

```
...
#define SYS_write   16
...
```

main.c

```
...
write(1,
      "Hello, World!\n",
      14);
...
```

usys.S

(after macro replacement)

```
#include "syscall.h"
// ...
.globl write
write:
    /* 16 = SYS_write */
    movl $16, %eax
    /* 0x40 = T_SYSCALL */
    int $0x40
    ret
```

interrupt — trigger an exception similar to a keypress
parameter (`0x40` in this case) — type of exception

write syscall in xv6: user mode

syscall.h

```
...
#define SYS_write   16
...
```

main.c

```
...
write(1,
      "Hello, World!\n",
      14);
...
```

usys.S

(after macro replacement)

```
#include "syscall.h"
// ...
.globl write
write:
    /* 16 = SYS_write */
    movl $16, %eax
    /* 0x40 = T_SYSCALL */
    int $0x40
    ret
```

xv6 syscall calling convention:
eax = syscall number
otherwise: same as 32-bit x86 calling convention (arguments on stack)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`lidt` —
function (in x86.h) wrapping lidt instruction

sets the *interrupt descriptor table*
table of *handler functions* for each interrupt type

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

(from mmu.h):

```
// Set up a normal interrupt/trap gate descriptor.
// - istrap: 1 for a trap gate, 0 for an interrupt gate.
//   interrupt gate clears FL_IF, trap gate leaves FL_IF alone
// - sel: Code segment selector for interrupt/trap handler
// - off: Offset in code segment for interrupt/trap handler
// - dpl: Descriptor Privilege Level -
//        the privilege level required for software to invoke
//        this interrupt/trap gate explicitly using an int instruction.
#define SETGATE(gate, istrap, sel, off, d)                \
```

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

set the T_SYSCALL (= 0x40) interrupt to be callable from user mode via **int** instruction

(otherwise: triggers fault like privileged instruction)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

set it to use the kernel "code segment"
meaning: run in kernel mode
(yes, code segments specifies more than that — nothing we care about)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

1: do not disable interrupts during syscalls
for other types of exceptions (e.g. I/O), disable interrupts
(to make OS code that handles I/O, timers, etc. much simpler)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`vectors[T_SYSCALL]` — OS function for processor to run
set to pointer to assembly function `vector64`

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`vectors[T_SYSCALL]` — OS function for processor to run
set to pointer to assembly function `vector64`

vectors.S

```
vector64:
  pushl $0
  pushl $64
  jmp alltraps
...
```

trapasm.S

```
alltraps:
  ...
  call trap
  ...
  iret
```

trap.c

```
void
trap(struct trapframe *tf)
{
...
```

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

struct trapframe — set by assembly
interrupt type, application registers, ...
example: `tf->eax` = old value of eax

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

`myproc()` — pseudo-global variable represents currently running process

much more on this later in semester

write syscall in xv6: the trap function

trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }
  ...
}
```

syscall() — actual implementations uses `myproc()->tf` to determine what operation to do for program

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]  sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]   sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

array of functions — one for syscall

'`[number] value`': syscalls[number] = value

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]  sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

(if system call number in range)
call sys_...function from table
store result in user's eax register

write syscall in xv6: the syscall function

syscall.c

```
static int (*syscalls[])(void) = {
...
[SYS_write]  sys_write,
...
};

...

void
syscall(void)
{
...
  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
...
```

result assigned to eax
(assembly code this returns to copies `tf->eax` into `%eax`)

write syscall in xv6: sys_write

sysfile.c

```
int
sys_write(void)
{
  struct file *f;
  int n;
  char *p;

  if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
    return -1;
  return filewrite(f, p, n);
}
```

write syscall in xv6: sys_write

sysfile.c

```
int
sys_write(void)
{
  struct file *f;
  int n;
  char *p;

  if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
    return -1;
  return filewrite(f, p, n);
}
```

utility functions that read arguments from user's stack
returns -1 on error (e.g. stack pointer invalid)
(more on this later)
(note: 32-bit x86 calling convention puts all args on stack)

write syscall in xv6: sys_write

sysfile.c

```
int
sys_write(void)
{
  struct file *f;
  int n;
  char *p;

  if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
    return -1;
  return filewrite(f, p, n);
}
```

actual internal function that implements writing to a file (the terminal counts as a file)

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
...
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`trap` returns to `alltraps`
alltraps restores registers from `tf`, then returns to user-mode

vectors.S

```
vector64:
  pushl $0
  pushl $64
  jmp alltraps
...
```

trapasm.S

```
alltraps:
  ...
  call trap
  ...
  iret
```

trap.c

```
void
trap(struct trapframe *tf)
{
...
```

write syscall in xv6: summary

`write` function — syscall wrapper uses `int $0x40`

interrupt table entry setup points to assembly function `vector64`
(and switches to kernel stack)

…which calls `trap()` with trap number set to 64 (`T_SYSCALL`)
(after saving all registers into `struct trapframe`)

…which checks trap number, then calls `syscall()`

…which checks syscall number (from eax)

…and uses it to call `sys_write`

…which reads arguments from the stack and does the write

…then registers restored, return to user space

write syscall in xv6: summary

`write` function — syscall wrapper uses `int $0x40`

interrupt table entry setup points to assembly function `vector64`
(and switches to kernel stack)

…which calls `trap()` with trap number set to 64 (`T_SYSCALL`)
(after saving all registers into `struct trapframe`)

…which checks trap number, then calls `syscall()`

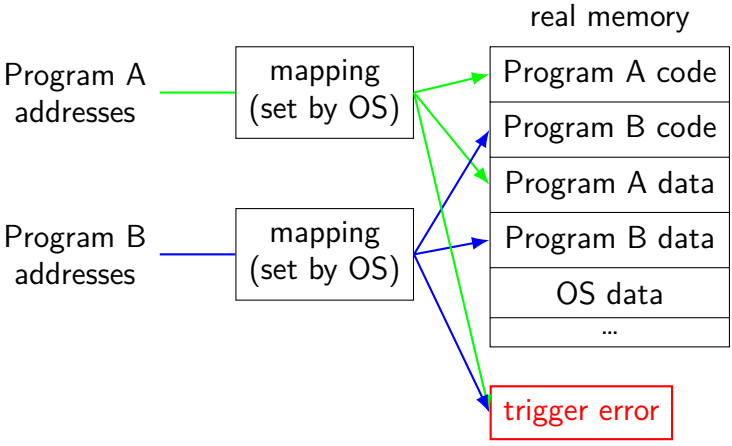
…which checks syscall number (from eax)

…and uses it to call `sys_write`

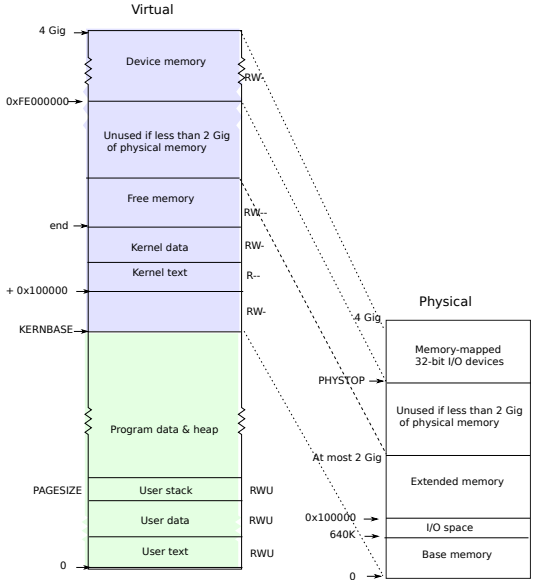
…which reads arguments from the stack and does the write

…then registers restored, return to user space

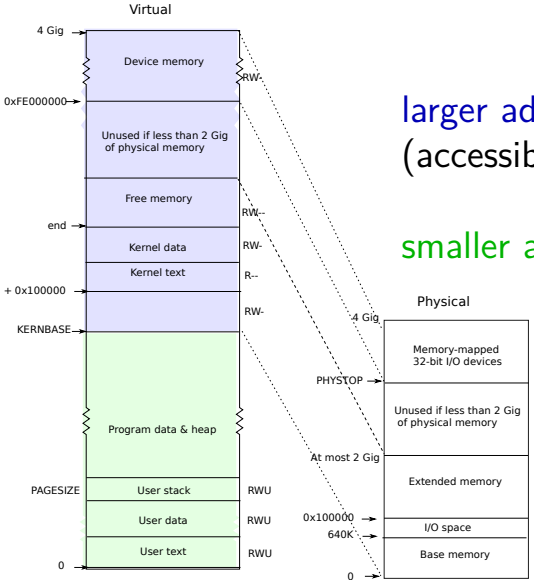
recall: address translation



xv6 memory layout



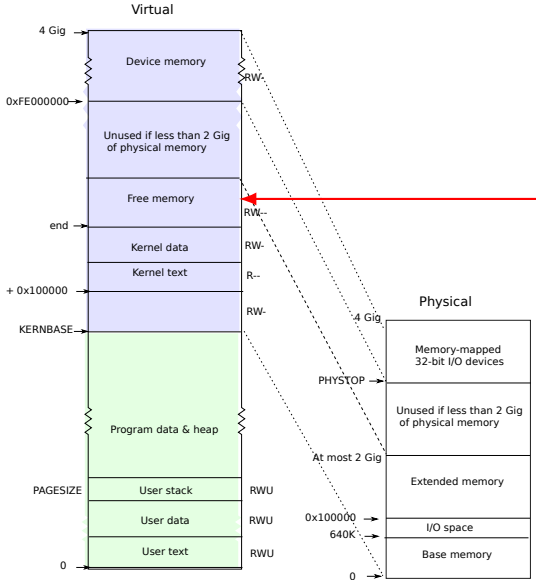
xv6 memory layout



larger addresses are for kernel (accessible in kernel mode *only*)

smaller addresses are for applications

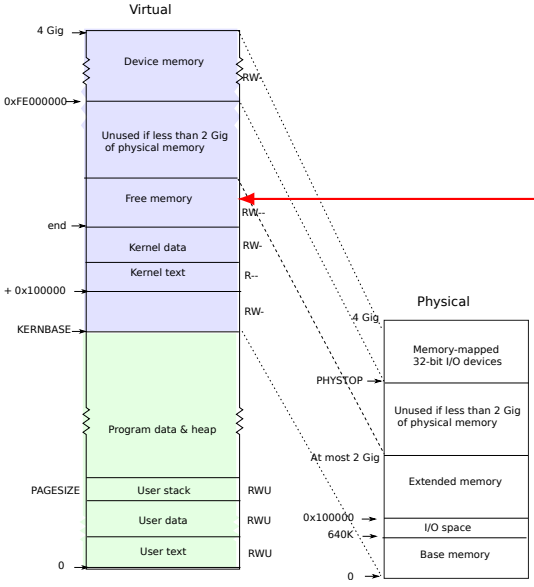
xv6 memory layout



kernel stack allocated here

processor switches stacks
when execption/interrupt/...happens
location of stack stored
in special "task state selector"

xv6 memory layout



kernel stack allocated here

one kernel stack per process

change which one exceptions use

as part of switching which processes is active on a processor

aside: nested exceptions

x86 switches to kernel stack on exception...

assuming it's switching to kernel mode

system call or timer interrupt in user mode

- start at top of kernel stack

timer interrupt during system call

- continue using current kernel stack

write syscall in xv6: summary

`write` function — syscall wrapper uses `int $0x40`

interrupt table entry setup points to assembly function `vector64`
(and switches to kernel stack)

…which calls `trap()` with trap number set to 64 (`T_SYSCALL`)
(after saving all registers into `struct trapframe`)

…which checks trap number, then calls `syscall()`

…which checks syscall number (from eax)

…and uses it to call `sys_write`

…which reads arguments from the stack and does the write

…then registers restored, return to user space

non-system call exceptions

xv6: there are traps other than system calls

timer interrupt — every hardware "tick"

action: schedule new process

faults — e.g. access invalid memory

I/O — handle I/O

aside: interrupt descriptor table

x86's interrupt descriptor table has an entry for each kind of exception

- segmentation fault
- timer expired ("your program ran too long")
- divide-by-zero
- system calls
- ...

shown earlier: being set for syscalls — SETGATE macro

xv6 sets all the table entries

...and they always call the `trap()` function

- xv6 design choice: could have separate functions for each

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
for (int i = 0; i < 256; i++)
  SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`lidt` —
function (in x86.h) wrapping lidt instruction

sets the *interrupt descriptor table*
table of *handler functions* for each interrupt type

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
for (int i = 0; i < 256; i++)
  SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`lidt` —
function (in x86.h) wrapping lidt instruction

sets the *interrupt descriptor table*
table of *handler functions* for each interrupt type

write syscall in xv6: interrupt table setup

trap.c (run on boot)

```
...
lidt(idt, sizeof(idt));
for (int i = 0; i < 256; i++)
  SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
...
```

`lidt` —
function (in x86.h) wrapping lidt instruction

sets the *interrupt descriptor table*
table of *handler functions* for each interrupt type

non-system call exceptions

xv6: there are traps other than system calls

timer interrupt — every hardware "tick"

action: schedule new process

faults — e.g. access invalid memory

I/O — handle I/O

xv6: timer interrupt

```
void
trap(struct trapframe *tf)
{
  switch(tf->trapno){
  case T_IRQ0 + IRQ_TIMER:
    if(cpuid() == 0){
      acquire(&tickslock);
      ticks++;
      wakeup(&ticks);
      release(&tickslock);
    }
    lapiceoi();
    break;
  ...
  // Force process to give up CPU on clock tick.
  ...
  if(myproc() && myproc()->state == RUNNING &&
     tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();
  ...
}
```

xv6: timer interrupt

yield — maybe context switch

```
void
trap(struct trapf
{
  switch(tf->trapno){
  case T_IRQ0 + IRQ_TIMER:
    if(cpuid() == 0){
      acquire(&tickslock);
      ticks++;
      wakeup(&ticks);
      release(&tickslock);
    }
    lapiceoi();
    break;
  ...
  // Force process to give up CPU on clock tick.
  ...
  if(myproc() && myproc()->state == RUNNING &&
     tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();
  ...
```

xv6: timer interrupt

```
void
trap(struct trapf
{
  switch(tf->trap
  case T_IRQ0 + I
    if(cpuid() == 0){
      acquire(&tickslock);
      ticks++;
      wakeup(&ticks);
      release(&tickslock);
    }
    lapiceoi();
    break;
  ...
  // Force process to give up CPU on clock tick.
  ...
  if(myproc() && myproc()->state == RUNNING &&
     tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();
  ...
```

wakeup — handle processes waiting a certain amount of time (`sleep` system call)

xv6: timer interrupt

```
void
trap(struct trapf
{
  switch(tf->trapno){
  case T_IRQ0 + IRQ_TIMER:
    if(cpuid() == 0){
      acquire(&tickslock);
      ticks++;
      wakeup(&ticks);
      release(&tickslock);
    }
    lapiceoi();
    break;
  ...
  // Force process to give up CPU on clock tick.
  ...
  if(myproc() && myproc()->state == RUNNING &&
     tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();
  ...
```

lapiceoi — tell hardware we have handled this interrupt (needed for all interrupts from 'external' devices)

xv6: timer interrupt

acquire/release — related to synchronization (later)

```
void
trap(struct trapf
{
  switch(tf->trapno){
  case T_IRQ0 + IRQ_TIMER:
    if(cpuid() == 0){
      acquire(&tickslock);
      ticks++;
      wakeup(&ticks);
      release(&tickslock);
    }
    lapiceoi();
    break;
  ...
  // Force process to give up CPU on clock tick.
  ...
  if(myproc() && myproc()->state == RUNNING &&
     tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();
  ...
```

xv6: timer interrupt

```
void
trap(struct trapf
{
  switch(tf->trap
  case T_IRQ0 + I
    if(cpuid() == 0){
      acquire(&tickslock);
      ticks++;
      wakeup(&ticks);
      release(&tickslock);
    }
    lapiceoi();
    break;
  ...
  // Force process to give up CPU on clock tick.
  ...
  if(myproc() && myproc()->state == RUNNING &&
     tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();
  ...
```

myproc() retrieves running process
check state == RUNNING in case
process was just about to stop running

non-system call exceptions

xv6: there are traps other than system calls

timer interrupt — every hardware "tick"

action: schedule new process

faults — e.g. access invalid memory

I/O — handle I/O

xv6: faults

```
void
trap(struct tra
{
  ...
  switch(tf->trapno) {
  ...
  default:
    ...
    cprintf("pid %d %s: trap %d err %d on cpu %d "
        "eip 0x%x addr 0x%x--kill proc\n",
        myproc()->pid, myproc()->name, tf->trapno,
        tf->err, cpuid(), tf->eip, rcr2());
    myproc()->killed = 1;
  }
}
```

unknown exception
print message and kill running program
assume it screwed up

xv6: faults

```
void
trap(struct trapframe *tf)
{
  ...
  switch(tf->trapno) {
  ...
  default:
    ...
    cprintf("pid %d %s: trap %d err %d on cpu %d "
        "eip 0x%x addr 0x%x--kill proc\n",
        myproc()->pid, myproc()->name, tf->trapno,
        tf->err, cpuid(), tf->eip, rcr2());
    myproc()->killed = 1;
  }
}
```

prints out trap number
can lookup in `traps.h`

non-system call exceptions

xv6: there are traps other than system calls

timer interrupt — every hardware "tick"

action: schedule new process

faults — e.g. access invalid memory

I/O — handle I/O

xv6: I/O

```
void
trap(struct trapframe *tf)
{
  ...
  switch(tf->trapno) {
  ...
  case T_IRQ0 + IRQ_IDE:
    ideintr();
    lapiceoi();
    break;
  ...
  case T_IRQ0 + IRQ_KBD:
    kbdintr();
    lapiceoi();
    break;
  case T_IRQ0 + IRQ_COM1:
    uartintr();
    lapiceoi();
    break;
```

ide = disk interface
kbd = keyboard
uart = serial port (external terminal)

xv6: keyboard I/O

```
void
kbdintr(void)
{
  consoleintr(kbdgetc);
}
...
void consoleintr(...)
{
  ...
       wakeup(&input.r);
  ...
}
```

xv6: keyboard I/O

```
void
kbdintr(void)
{
  consoleintr(kbdgetc);
}
...
void consoleintr(...)
{
  ...
      wakeup(&input.r);
  ...
}
```

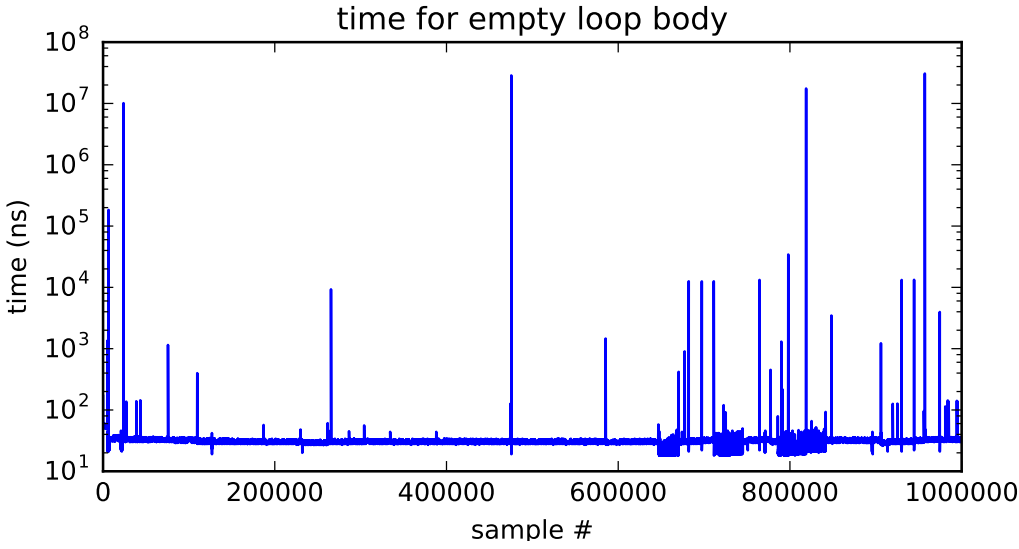
finds process waiting on console
make it run soon
(xv6 choice: usually not immediately)

timing nothing

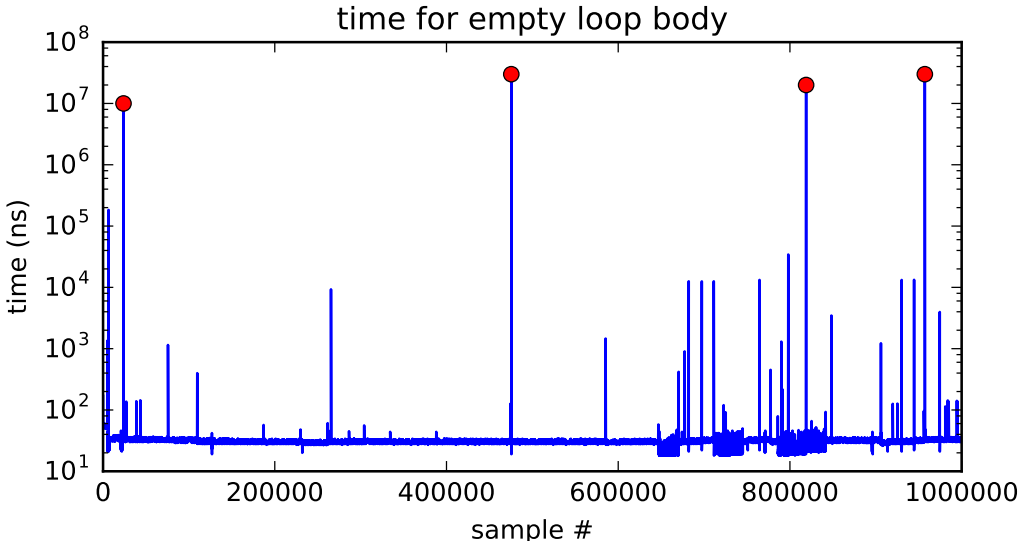
```
long times[NUM_TIMINGS];
int main(void) {
    for (int i = 0; i < N; ++i) {
        long start, end;
        start = get_time();
        /* do nothing */
        end = get_time();
        times[i] = end - start;
    }
    output_timings(times);
}
```

same instructions — same difference each time?

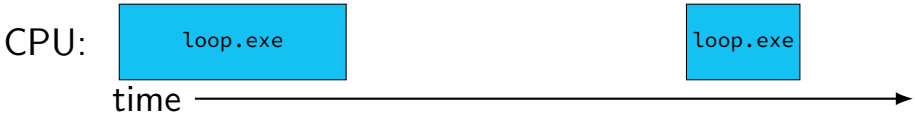
doing nothing on a busy system



doing nothing on a busy system



time multiplexing



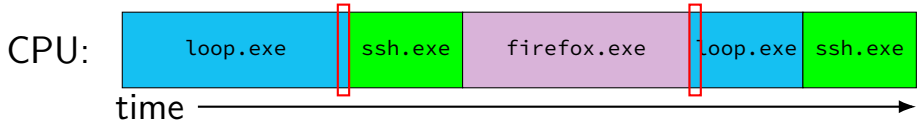
time multiplexing


```
...
call get_time
    // whatever get_time does
movq %rax, %rbp
```

million cycle delay

```
call get_time
    // whatever get_time does
subq %rbp, %rax
...
```

time multiplexing




```
...
call get_time
    // whatever get_time does
movq %rax, %rbp
```

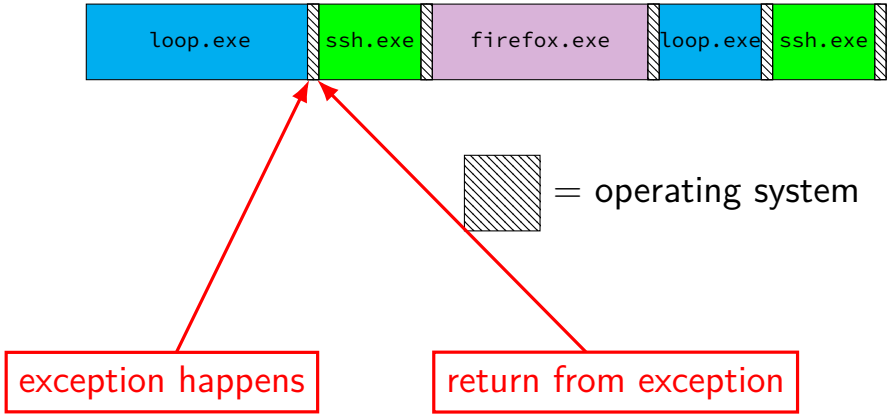
million cycle delay

```
call get_time
    // whatever get_time does
subq %rbp, %rax
...
```

time multiplexing really

 = operating system

time multiplexing really



OS and time multiplexing

starts running instead of normal program via exception

saves old program counter, registers somewhere

sets new registers, jumps to new program counter

called context switch

- saved information called context

context

all registers values

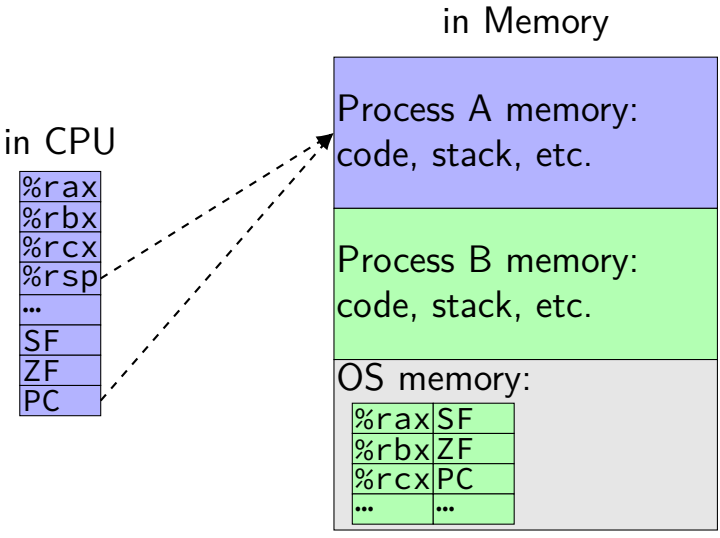
`%rax` `%rbx`, …, `%rsp`, …

condition codes

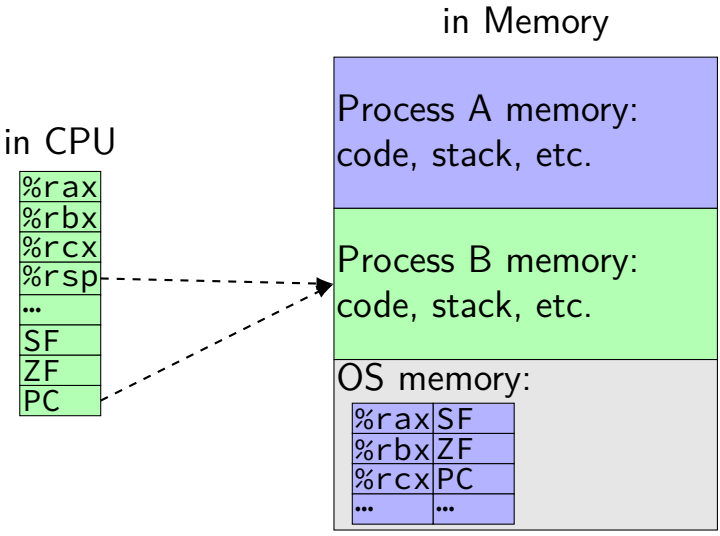
program counter

address space = page table base pointer

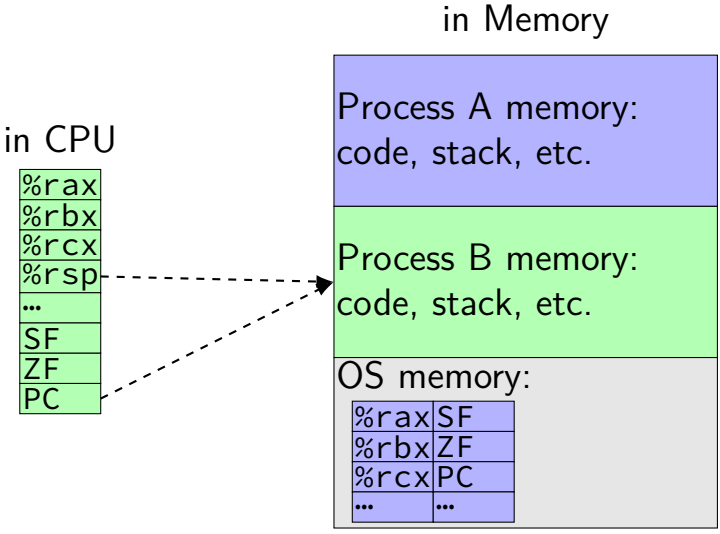
contexts (A running)



contexts (B running)



contexts (B running)



xv6: A's registers saved by exception handler into "trapframe" on A's kernel stack

context switch in xv6

xv6 context switch has two parts

switching threads

switching user address spaces + kernel stack to use for exception

context switch in xv6

xv6 context switch has two parts

switching threads

switching user address spaces + kernel stack to use for exception

context switch in xv6

xv6 context switch has two parts

switching threads

switching user address spaces + kernel stack to use for exception

thread switching

```
struct context {
  uint edi;
  uint esi;
  uint ebx;
  uint ebp;
  uint eip;
}
```

```
void swtch(struct context **old, struct context *new);
```

thread switching

structure to save context in
yes, it looks like we're missing some registers we need...

```
struct context {
  uint edi;
  uint esi;
  uint ebx;
  uint ebp;
  uint eip;
}
```

```
void swtch(struct context **old, struct context *new);
```

thread switching

eip = saved program counter

```
struct context {
  uint edi;
  uint esi;
  uint ebx;
  uint ebp;
  uint eip;
}
```

```
void swtch(struct context **old, struct context *new);
```

thread switching

function to switch contexts
allocate space for context on top of stack
set `old` to point to it
switch to context `new`

```
struct context {
  uint edi;
  uint esi;
  uint ebx;
  uint ebp;
  uint eip;
}
```

```
void swtch(struct context **old, struct context *new);
```

thread switching in xv6: C

in thread A:

```
/* switch from A to B */

 ... // (1)
swtch(&(a->context), b->context);  /* returns to (2) */
 ... // (4)
```

---

in thread B:

```
swtch(...);  // (0) -- called earlier
 ... // (2)
...
/* later on switch back to A */
 ... // (3)
swtch(&(b->context), a->context)  /* returns to (4) */
...
```

thread switching in xv6: C

in thread A:

```
/* switch from A to B */

 ... // (1)
swtch(&(a->context), b->context);  /* returns to (2) */
 ... // (4)
```

---

in thread B:

```
swtch(...);  // (0) -- called earlier
 ... // (2)
...
/* later on switch back to A */
 ... // (3)
swtch(&(b->context), a->context)  /* returns to (4) */
...
```

thread switching in xv6: C

in thread A:

```
/* switch from A to B */

 ... // (1)
swtch(&(a->context), b->context);  /* returns to (2) */
 ... // (4)
```

---

in thread B:

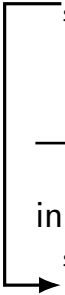
```
swtch(...);  // (0) -- called earlier
 ... // (2)
...
/* later on switch back to A */
 ... // (3)
swtch(&(b->context), a->context)  /* returns to (4) */
...
```

thread switching in xv6: C

in thread A:

```
/* switch from A to B */

... // (1)
swtch(&(a->context), b->context);  /* returns to (2) */
... // (4)
```



---

in thread B:

```
swtch(...);  // (0) -- called earlier
... // (2)
...
/* later on switch back to A */
... // (3)
swtch(&(b->context), a->context)  /* returns to (4) */
...
```

thread switching in xv6: C

in thread A:

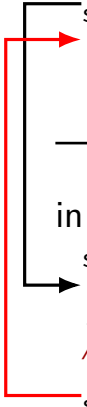
```
/* switch from A to B */

... // (1)
swtch(&(a->context), b->context);  /* returns to (2) */
... // (4)
```

---

in thread B:

```
swtch(...);  // (0) -- called earlier
... // (2)
...
/* later on switch back to A */
... // (3)
swtch(&(b->context), a->context)  /* returns to (4) */
...
```



thread switching in xv6: C

in thread A:

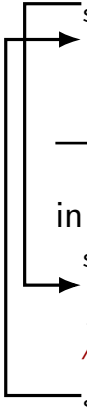
```
/* switch from A to B */

... // (1)
swtch(&(a->context), b->context);  /* returns to (2) */
... // (4)
```

---

in thread B:

```
swtch(...);  // (0) -- called earlier
... // (2)
...
/* later on switch back to A */
... // (3)
swtch(&(b->context), a->context)  /* returns to (4) */
...
```



thread switching in xv6: assembly

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

thread switching in xv6: assembly

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

two arguments:
`struct context **from_context`
= where to save current context
`struct context *to_context`
= where to find new context

context stored on thread's stack
context address = top of stack

thread switching in xv6: assembly

saved: ebp, ebx, esi, edi

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

thread switching in xv6: assembly

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

what about other parts of context?
eax, ecx, ...: saved by swtch's caller
esp: same as address of context
program counter: set by `call` of swtch

thread switching in xv6: assembly

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

save stack pointer to first argument
(stack pointer now has all info)
restore stack pointer from second argument

thread switching in xv6: assembly

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

restore program counter
(and other saved registers)
from new context

juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

from stack

caller-saved registers
`swtch` arguments
`swtch` return addr.

to stack

caller-saved registers
`swtch` arguments
`swtch` return addr.
saved ebp
saved ebx
saved esi
saved edi

juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %ed
  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

%esp →

from stack

caller-saved registers
swtch arguments
swtch return addr.

to stack

caller-saved registers
swtch arguments
swtch return addr.
saved ebp
saved ebx
saved esi
saved edi

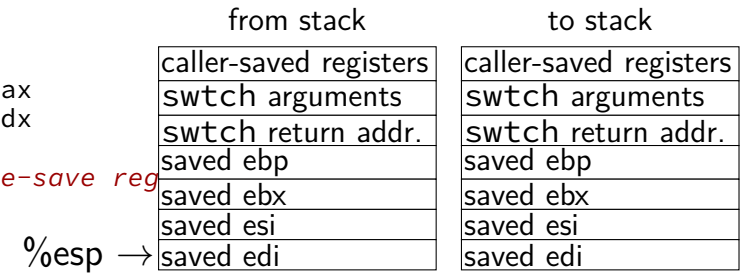
juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save reg
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```



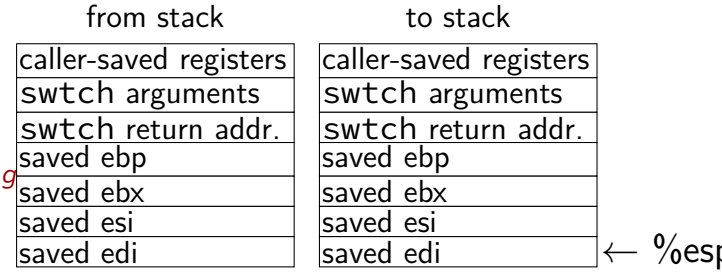
juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save reg
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```



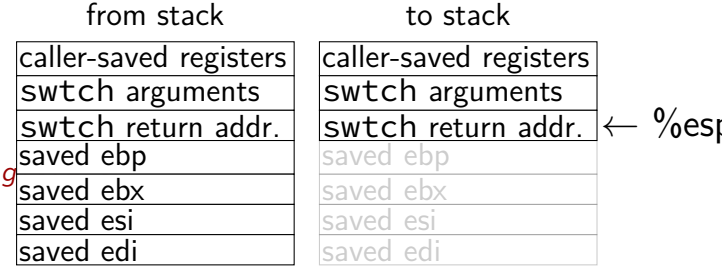
juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save reg
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```



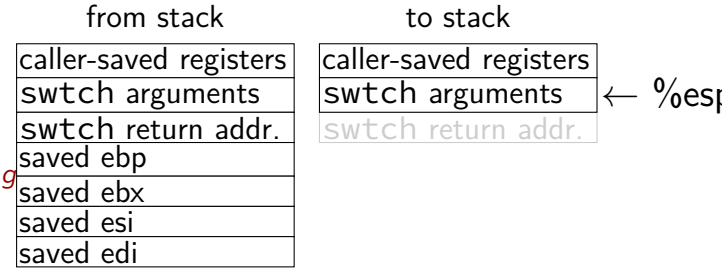
juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save reg
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```



first call to swtch?

one thread calls swtch and

...return from another thread's call to swtch

what about switching to a new thread?

creating a new thread

```
static struct proc*
allocproc(void)
{
  ...
  sp = p->kstack + KSTACKSIZE;

  // Leave room for trap frame.
  sp -= sizeof *p->tf;
  p->tf = (struct trapframe*)sp;

  // Set up new context to start executing at forkret,
  // which returns to trapret.
  sp -= 4;
  *(uint*)sp = (uint)trapret;

  sp -= sizeof *p->context;
  p->context = (struct context*)sp;
  memset(p->context, 0, sizeof *p->context);
  p->context->eip = (uint)forkret;
  ...
```

`struct proc` ≈ process
p is new `struct proc`
`p->kstack` is its new stack
(for the kernel only)

creating a new thread

new kernel stack

```
static struct proc*
allocproc(void)
{
  ...
  sp = p->kstack + KSTACKSIZE;

  // Leave room for trap frame.
  sp -= sizeof *p->tf;
  p->tf = (struct trapframe*)sp;

  // Set up new context to start executing at forkret,
  // which returns to trapret.
  sp -= 4;
  *(uint*)sp = (uint)trapret;

  sp -= sizeof *p->context;
  p->context = (struct context*)sp;
  memset(p->context, 0, sizeof *p->context);
  p->context->eip = (uint)forkret;
  ...
```

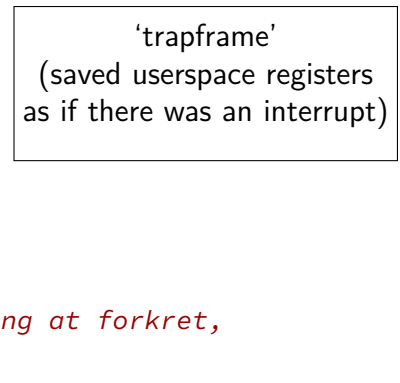
creating a new thread

```
static struct proc*
allocproc(void)
{
  ...
  sp = p->kstack + KSTACKSIZE;

  // Leave room for trap frame.
  sp -= sizeof *p->tf;
  p->tf = (struct trapframe*)sp;

  // Set up new context to start executing at forkret,
  // which returns to trapret.
  sp -= 4;
  *(uint*)sp = (uint)trapret;

  sp -= sizeof *p->context;
  p->context = (struct context*)sp;
  memset(p->context, 0, sizeof *p->context);
  p->context->eip = (uint)forkret;
  ...
```



creating a new thread

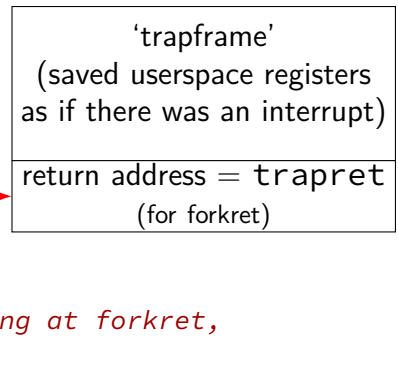
```
static struct proc*
allocproc(void)
{
  ...
  sp = p->kstack + KSTACKSIZE;
  // leave room for trap frame
  sp -= sizeof *p->tf;
  p->tf = (struct trapframe*)sp;

  // Set up new context to start executing at forkret,
  // which returns to trapret.
  sp -= 4;
  *(uint*)sp = (uint)trapret;

  sp -= sizeof *p->context;
  p->context = (struct context*)sp;
  memset(p->context, 0, sizeof *p->context);
  p->context->eip = (uint)forkret;
  ...
```

assembly code to return to user mode

same code as for syscall returns



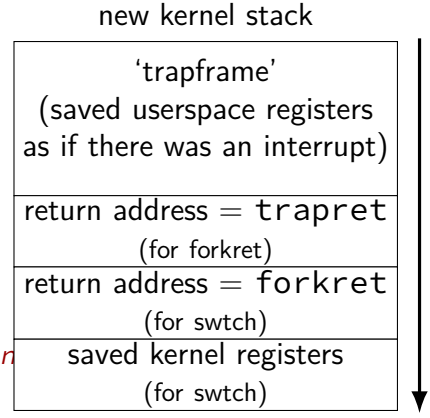
creating a new thread

```
static struct proc*
allocproc(void)
{
  ...
  sp = p->kstack + KSTACKSIZE;

  // Leave room for trap frame.
  sp -= sizeof *p->tf;
  p->tf = (struct trapframe*)sp;

  // Set up new context to start executin
  // which returns to trapret.
  sp -= 4;
  *(uint*)sp = (uint)trapret;

  sp -= sizeof *p->context;
  p->context = (struct context*)sp;
  memset(p->context, 0, sizeof *p->context);
  p->context->eip = (uint)forkret;
  ...
```



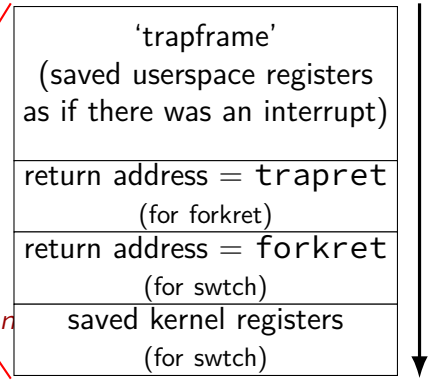
creating a new thread

```
static struct proc*
allocproc(void)
{
  ...
  sp =
  // Leave room for trap frame.
  sp -
  p->t = (struct trapframe*)sp;

  // Set up new context to start executin
  // which returns to trapret.
  sp -= 4;
  *(uint*)sp = (uint)trapret;

  sp -= sizeof *p->context;
  p->context = (struct context*)sp;
  memset(p->context, 0, sizeof *p->context);
  p->context->eip = (uint)forkret;
  ...
```

new stack says: this thread is in middle of calling `swtch` in the middle of a system call



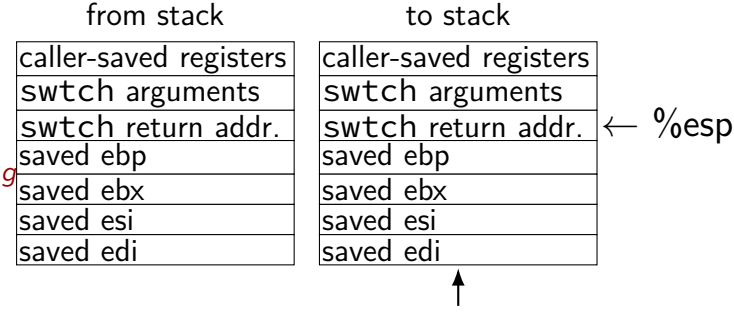
juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save reg
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```



first instruction
executed by new thread

kernel-space context switch summary

swtch function

- saves registers on current kernel stack
- switches to new kernel stack and restores its registers

initial setup — manually construct stack values

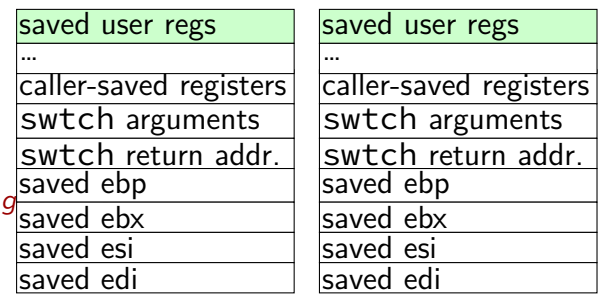
juggling stacks

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save reg
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```



the userspace part?

user registers stored in 'trapframe' struct

- created on kernel stack when interrupt/trap happens
- restored before using `iret` to switch to user mode

initial user registers created manually on stack

- (as if saved by system call)

the userspace part?

user registers stored in 'trapframe' struct

- created on kernel stack when interrupt/trap happens
- restored before using `iret` to switch to user mode

initial user registers created manually on stack

- (as if saved by system call)

other code (not shown) handles setting address space