POSIX API 3 / Scheduling 1

Changelog

Changes made in this version not seen in first lecture:

31 Jan 2019: update process states to have transitions in both diretions between ready/running

last time

shells

file descriptors

open, read, write, close

kernel and other buffering

dup2 and start pipes

homework notes

late submission of HW1
  - had trouble submitting late due to submission system? email me
  - joined the class very late? email me

shell homework: two errors in tests; one in instructions
  - one flakey test for background processes (timing dependent)
  - one erroneous test
  - instructions referred to Makefile target that wasn't included
  - corrected version of instructions, tests

pipes

special kind of file: pipes

bytes go in one end, come out the other — once

created with `pipe()` library call

intended use: communicate between processes

- like implementing shell pipelines

pipe()

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error();
/* normal case: */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
```

then from one process...

```
write(write_fd, ...);
```

and from another

```
read(read_fd, ...);
```

pipe() and blocking

BROKEN example:

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error();
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
write(write_fd, some_buffer, some_big_size);
read(read_fd, some_buffer, some_big_size);
```

This is likely to not terminate. What's the problem?

pipe example (1)

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe example (1)

'standard' pattern with fork()

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe example (1)

read() will not indicate end-of-file if write fd is open (any copy of it)

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe example (1)

have habit of closing
to avoid ‘leaking’ file descriptors
you can run out

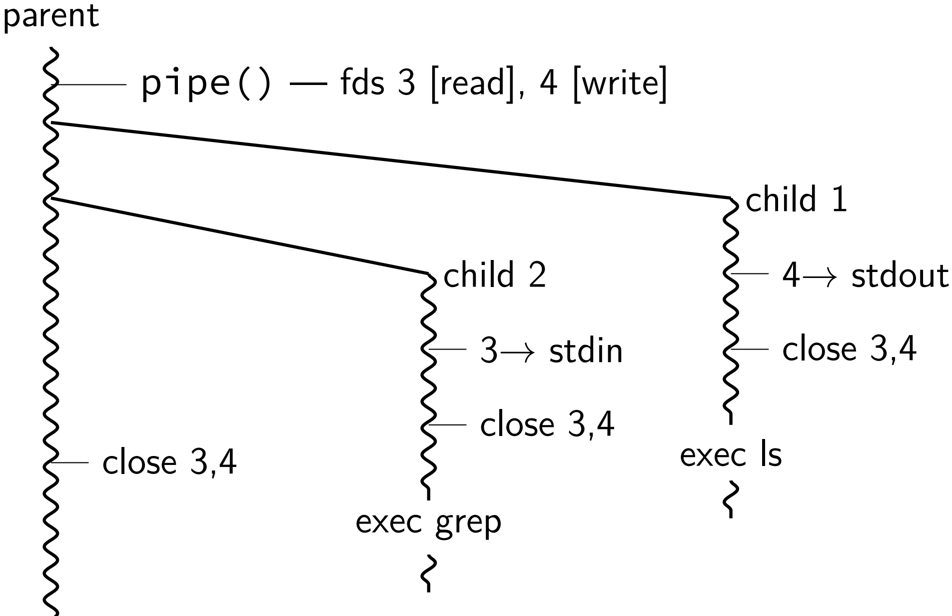
```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe and pipelines

```
ls -1 | grep foo
```

```
pipe(pipe_fd);
ls_pid = fork();
if (ls_pid == 0) {
    dup2(pipe_fd[1], STDOUT_FILENO);
    close(pipe_fd[0]); close(pipe_fd[1]);
    char *argv[] = {"ls", "-1", NULL};
    execv("/bin/ls", argv);
}
grep_pid = fork();
if (grep_pid == 0) {
    dup2(pipe_fd[0], STDIN_FILENO);
    close(pipe_fd[0]); close(pipe_fd[1]);
    char *argv[] = {"grep", "foo", NULL};
    execv("/bin/grep", argv);
}
close(pipe_fd[0]); close(pipe_fd[1]);
/* wait for processes, etc. */
```

example execution



exercise

```
pid_t p = fork();
int pipe_fds[2];
pipe(pipe_fds);
if (p == 0) { /* child */
  close(pipe_fds[0]);
  char c = 'A';
  write(pipe_fds[1], &c, 1);
  exit();
} else { /* parent */
  close(pipe_fds[1]);
  char c;
  int count = read(pipe_fds[0], &c, 1);
  printf("read␣%d␣bytes\n", count);
}
```

The child is trying to send the character A to the parent.

But the above code outputs `read 0 bytes` instead of `read 1 bytes`.

What happened?

exercise solution

pipe() is after fork — two pipes, one in child, one in parent

exercise

```
int pipe_fds[2]; pipe(pipe_fds);
pid_t p = fork();
if (p == 0) {
  close(pipe_fds[0]);
  for (int i = 0; i < 10; ++i) {
    char c = '0' + i;
    write(pipe_fds[1], &c, 1);
  }
  exit();
}
close(pipe_fds[1]);
char buffer[10];
ssize_t count = read(pipe_fds[0], buffer, 10);
for (int i = 0; i < count; ++i) {
  printf("%c", buffer[i]);
}
```

Which are possible outputs (if pipe, read, write, fork don't fail)?

A. `0123456789` B. `0` C. (nothing)

D. A and B E. A and C F. A, B, and C

exercise

```
int pipe_fds[2]; pipe(pipe_fds);
pid_t p = fork();
if (p == 0) {
  close(pipe_fds[0]);
  for (int i = 0; i < 10; ++i) {
    char c = '0' + i;
    write(pipe_fds[1], &c, 1);
  }
  exit();
}
close(pipe_fds[1]);
char buffer[10];
ssize_t count = read(pipe_fds[0], buffer, 10);
for (int i = 0; i < count; ++i) {
  printf("%c", buffer[i]);
}
```

Which are possible outputs (if pipe, read, write, fork don't fail)?

A. `0123456789` B. `0` C. (nothing)

D. A and B E. A and C F. A, B, and C

partial reads

read returning 0 always means end-of-file

- by default, read always waits *if no input available yet*
- but can set read to return *error* instead of waiting

read can return less than requested if not available

- e.g. child hasn't gotten far enough

Unix API summary

spawn and wait for program: `fork` (copy), then
- in child: setup, then `execv`, etc. (replace copy)
- in parent: `waitpid`

files: open, read and/or write, close
- one interface for regular files, pipes, network, devices, ...

file descriptors are indices into per-process array
- index 0, 1, 2 = stdin, stdout, stderr
- `dup2` — assign one index to another
- `close` — deallocate index

redirection/pipelines
- open() or pipe() to create new file descriptors
- dup2 in child to assign file descriptor to index 0, 1

xv6: process table

```
struct {
  struct spinlock lock;
  struct proc proc[NPROC]
} ptable;
```

fixed size array of all processes

lock to keep more than one thing from accessing it at once

- rule: don't change a process's state (RUNNING, etc.) without 'acquiring' lock

xv6: allocating a struct proc

```
acquire(&ptable.lock);

for(p = ptable.proc; p < &ptable.proc[NPROC]; p++)
  if(p->state == UNUSED)
    goto found;

release(&ptable.lock);
```

just search for PCB with “UNUSED” state

not found? fork fails

if found — allocate memory, etc.

xv6: creating the first process

struct proc with initial kernel stack
setup to return from swtch, then from exception

```
// Set up first user process.
void
userinit(void)
{
  struct proc *p;
  extern char _binary_initcode_start[], _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  ...
  inituvm(p->pgdir, _binary_initcode_start,
            (int)_binary_initcode_size);
  ...
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  ...
  p->state = RUNNABLE;
```

xv6: creating the first process

load into user memory
hard-coded “initial program”
calls execv() of `/init`

```
// Set up first user process.
void
userinit(void)
{
  struct proc *p;
  extern char _binary_initcode_start[], _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  ...
  inituvm(p->pgdir, _binary_initcode_start,
             (int)_binary_initcode_size);
  ...
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  ...
  p->state = RUNNABLE;
```

xv6: creating the first process

modify user registers
to start at address 0

```
// Set up first user process.
void
userinit(void)
{
  struct proc *p;
  extern char _binary_initcode_start[], _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  ...
  inituvm(p->pgdir, _binary_initcode_start,
            (int)_binary_initcode_size);
  ...
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  ...
  p->state = RUNNABLE;
```

xv6: creating the first process

set initial stack pointer

```
// Set up first user process.
void
userinit(void)
{
  struct proc *p;
  extern char _binary_initcode_start[], _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  ...
  inituvm(p->pgdir, _binary_initcode_start,
            (int)_binary_initcode_size);
  ...
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  ...
  p->state = RUNNABLE;
```

xv6: creating the first process

set process as runnable

```
// Set up first user process.
void
userinit(void)
{
  struct proc *p;
  extern char _binary_initcode_start[], _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  ...
  inituvm(p->pgdir, _binary_initcode_start,
            (int)_binary_initcode_size);
  ...
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  ...
  p->state = RUNNABLE;
```

threads versus processes

for now — each process has one thread

Anderson-Dahlin talks about thread scheduling

thread = part that gets run on CPU

- saved register values (including own stack pointer)
- save program counter

rest of process

- address space
- open files
- current working directory
- …

xv6 processes versus threads

xv6: one thread per process

so part of the process control block
is really a *thread control block*

```
// Per-process state
struct proc {
  uint sz;                     // Size of process memory (bytes)
  pde_t* pgdir;                // Page table
  char *kstack;                // Bottom of kernel stack for this process
  enum procstate state;        // Process state
  int pid;                     // Process ID
  struct proc *parent;         // Parent process
  struct trapframe *tf;        // Trap frame for current syscall
  struct context *context;     // swtch() here to run process
  void *chan;                  // If non-zero, sleeping on chan
  int killed;                  // If non-zero, have been killed
  struct file *ofile[NOFILE];  // Open files
  struct inode *cwd;           // Current directory
  char name[16];               // Process name (debugging)
};
```

xv6 processes versus threads

xv6: one thread per process

so part of the process control block
is really a *thread control block*

```
// Per-process state
struct proc {
  uint sz;                     // Size of process memory (bytes)
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  struct proc *parent;         // Parent process
  struct trapframe *tf;        // Trap frame for current syscall
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  struct file *ofile[NOFILE];  // Open files
  struct inode *cwd;           // Current directory
  char name[16];               // Process name (debugging)
};
```
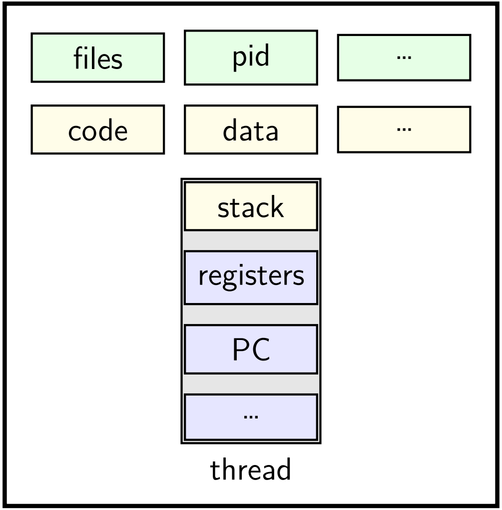
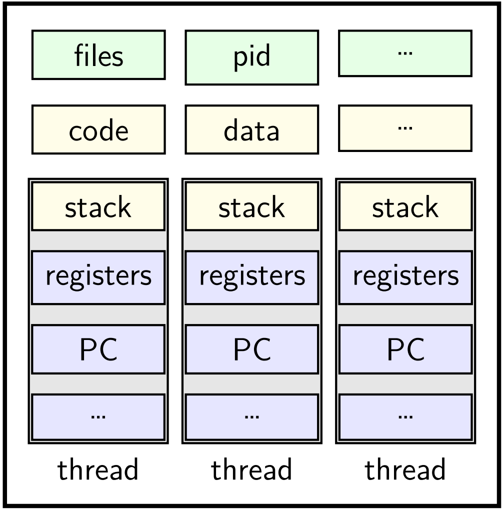

single and multithread processes

single-threaded process



files
pid
…
code
data
…
stack
registers
PC
…
thread

multi-threaded process



files
pid
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…
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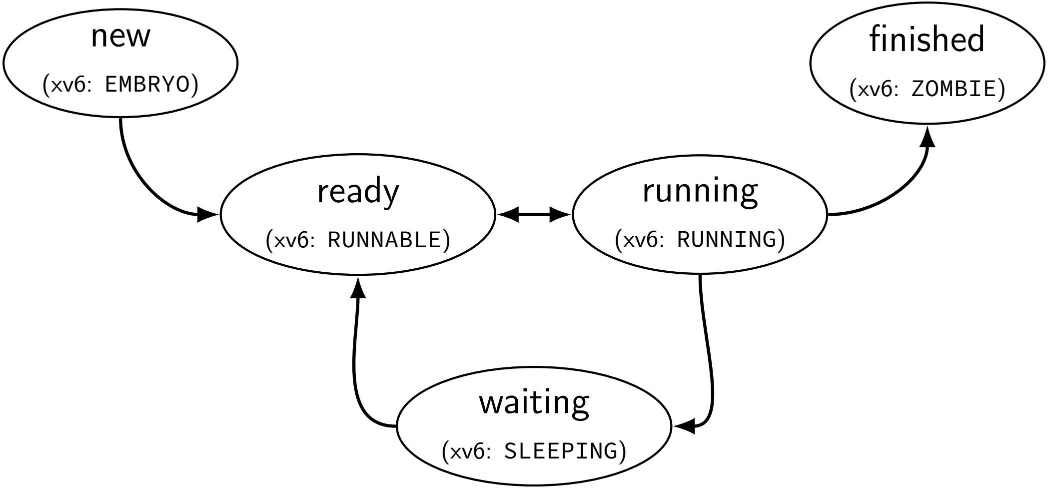
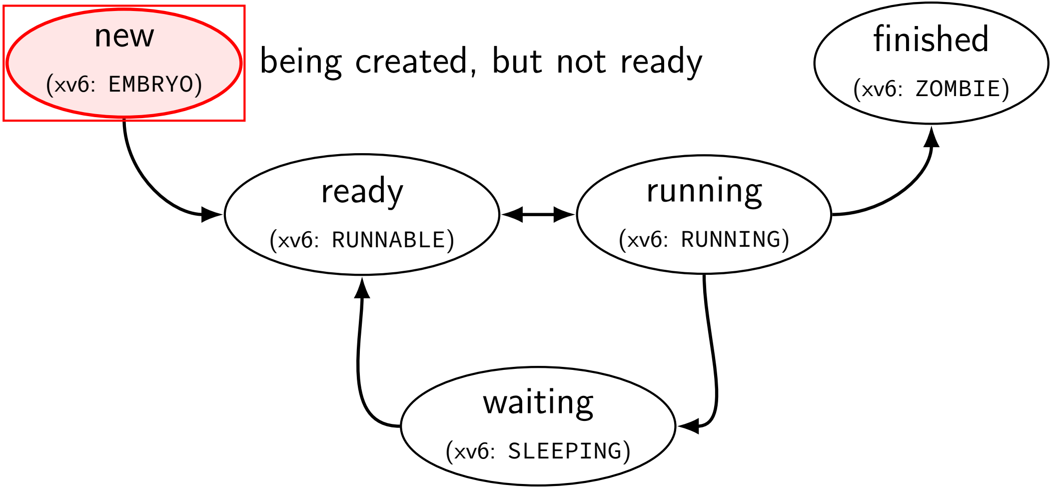
registers
PC
…
thread

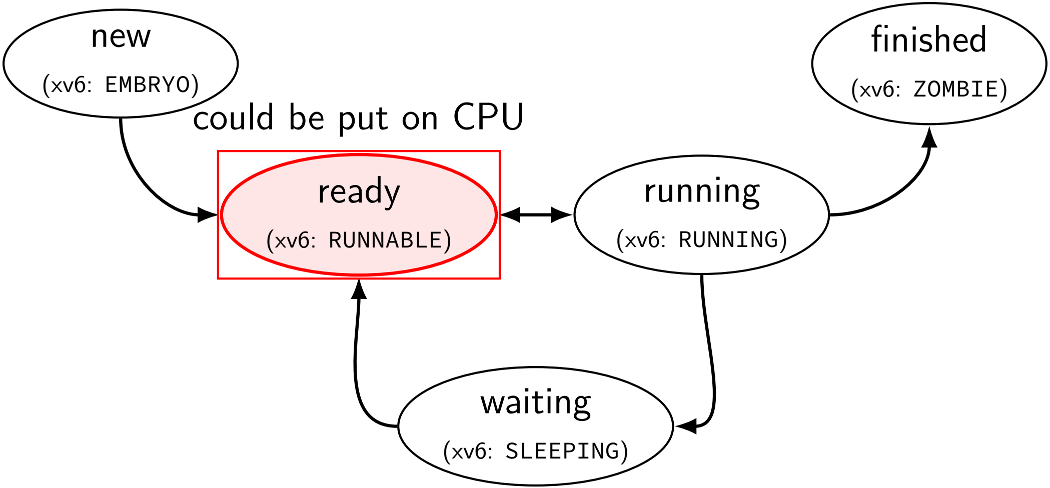
thread states



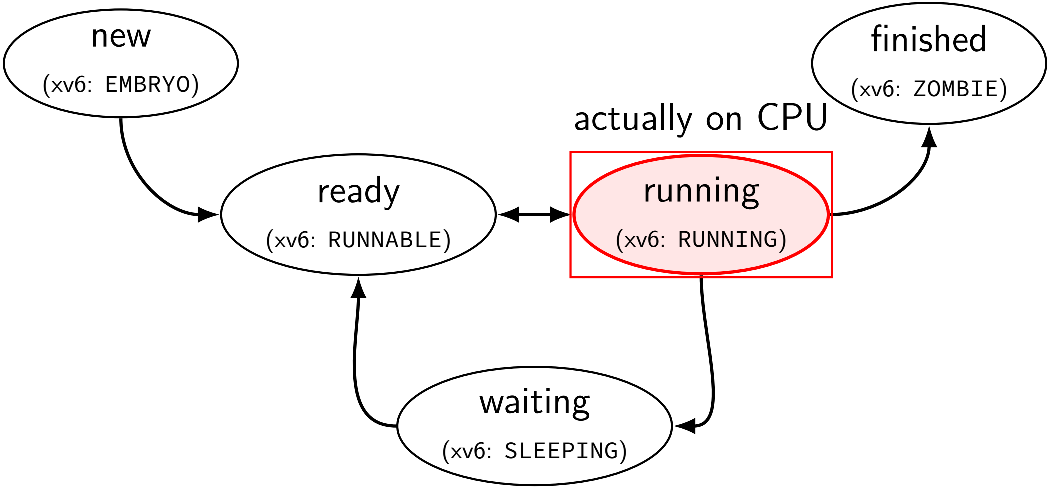
thread states



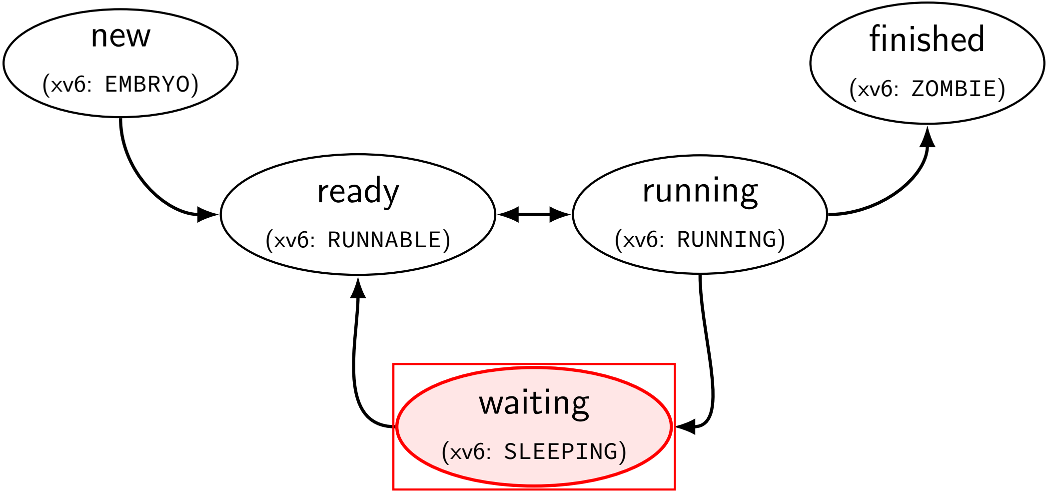
thread states



thread states



thread states



new

(xv6: `EMBRYO`)

finished

(xv6: `ZOMBIE`)

ready

(xv6: `RUNNABLE`)

running

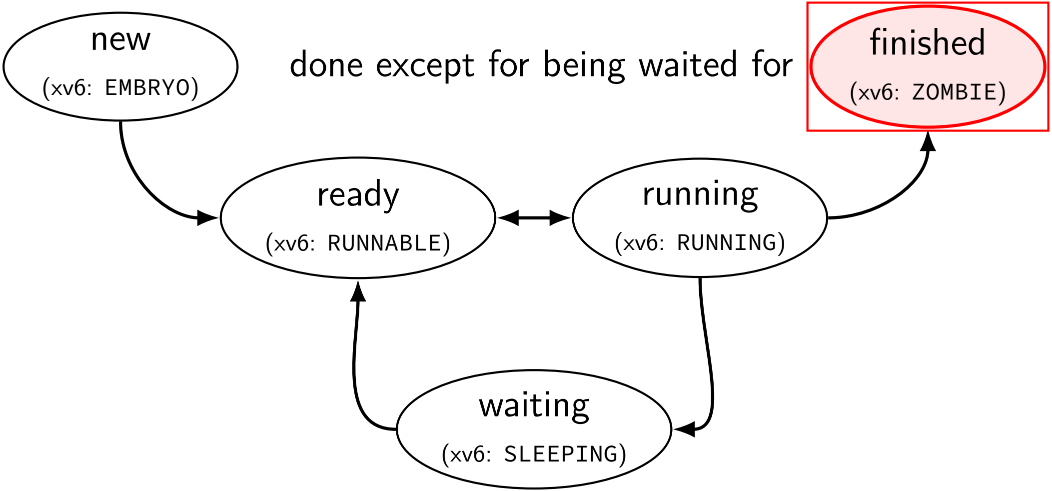
(xv6: `RUNNING`)

waiting

(xv6: `SLEEPING`)

need external event to happen

thread states



new

(xv6: `EMBRYO`)

done except for being waited for

finished

(xv6: `ZOMBIE`)

ready

(xv6: `RUNNABLE`)

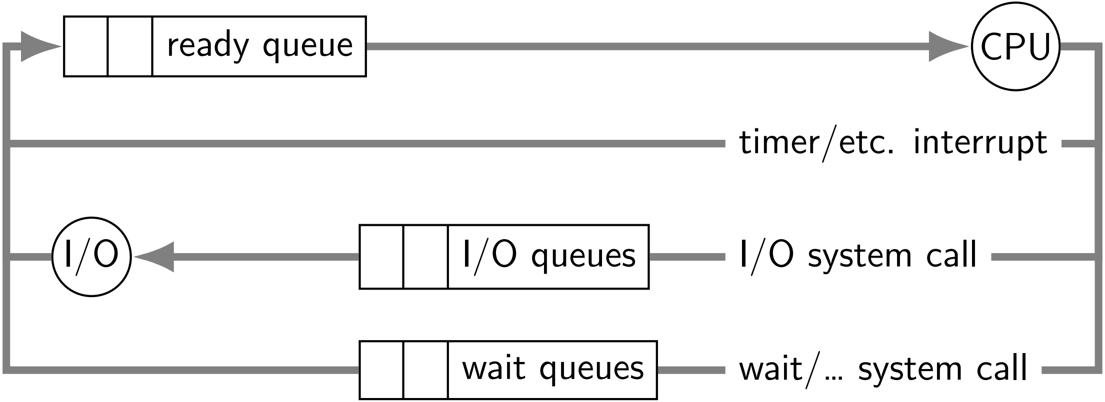
running

(xv6: `RUNNING`)

waiting

(xv6: `SLEEPING`)

alternative view: queues



ready queue

CPU

timer/etc. interrupt

I/O

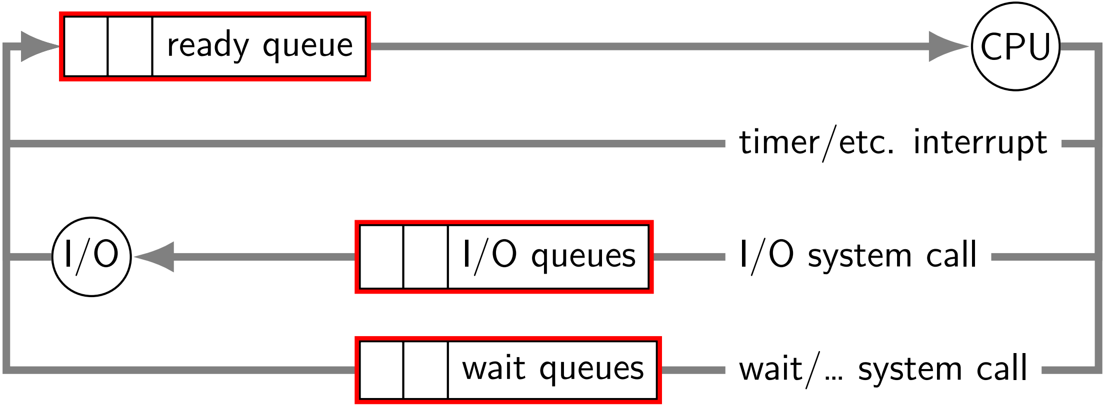
I/O queues

I/O system call

wait queues

wait/... system call

alternative view: queues



ready queue

CPU

timer/etc. interrupt

I/O

I/O queues

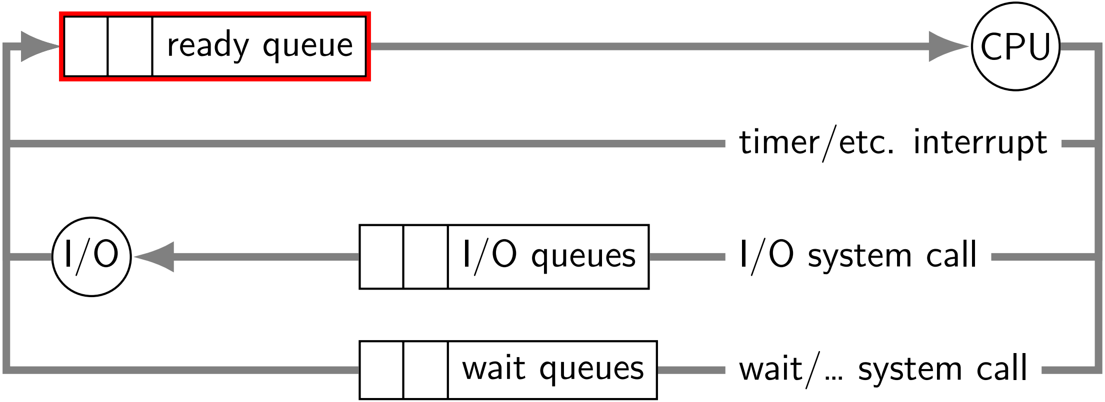
I/O system call

wait queues

wait/... system call

queues of threads

alternative view: queues



ready queue or run queue
list of running processes
question: what to take off queue first when CPU is free?

on queues in xv6

xv6 doesn't represent queues explicitly

- no queue class/struct

ready queue: process list ignoring non-RUNNABLE entries

I/O queues: process list where SLEEPING, `chan` = I/O device

real OSs: typically separate list of processes

- maybe sorted?

scheduling

scheduling = removing process/thread to remove from queue

mostly for the ready queue (pre-CPU)

- remove a process and start running it

example other scheduling problems

batch job scheduling

e.g. what to run on my supercomputer?

jobs that run for a long time (tens of seconds to days)

can't easily 'context switch' (save job to disk??)

I/O scheduling

what order to read/write things to/from network, hard disk, etc.

this lecture

main target: CPU scheduling

...on a system where programs do a lot of I/O

...and other programs use the CPU when they do

...with only a single CPU

many ideas port to other scheduling problems

- especially simpler/less specialized policies

scheduling policy

scheduling policy = what to remove from queue

the xv6 scheduler (1)

```
void scheduler(void)
  struct proc *p;
  struct cpu *c = mycpu();
  c->proc = 0;

  for(;;){
    // Enable interrupts on this processor.
    sti();

    // Loop over process table looking for process to run.
    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      ... /* switch to process */
    }
    release(&ptable.lock);
  }
}
```

the xv6 scheduler (1)

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    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      ... /* switch to process */
    }
    release(&ptable.lock);
  }
}
```

infinite loop
every iteration: switch to a thread
thread will switch back to us

the xv6 scheduler (1)

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  struct cpu *c = mycpu();
  c->proc = 0;

  for(;;){
    // Enable interrupts on this processor.
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    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      ... /* switch to process */
    }
    release(&ptable.lock);
  }
}
```

enable interrupts (`sti` is the x86 instruction)
…(but acquiring the process table lock disables interrupts again)

the xv6 scheduler (1)

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void scheduler(void)
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  struct cpu *c = mycpu();
  c->proc = 0;

  for(;;){
    // Enable interrupts on
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    acquire(&ptable.lock);
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      if(p->state != RUNNABLE)
        continue;
      ... /* switch to process */
    }
    release(&ptable.lock);
  }
}
```

make sure we're the only one accessing the list of processes

also make sure no one runs scheduler while we're switching to another process

(more on this idea later)

the xv6 scheduler (1)

```
void scheduler(void)
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  c->proc = 0;

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    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      ... /* switch to process */
    }
    release(&ptable.lock);
  }
}
```

iterate through all runnable processes
in the order they're stored in a table

the xv6 scheduler (1)

```
void scheduler(void)
  struct proc *p;
  struct cpu *c = mycp
  c->proc = 0;

  for(;;){
    // Enable interrupts on this processor.
    sti();

    // Loop over process table looking for process to run.
    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      ... /* switch to process */
    }
    release(&ptable.lock);
  }
}
```

switch to whatever runnable process we find
when it's done (e.g. timer interrupt)
it switches back, then next loop iteration happens

the xv6 scheduler: the actual switch

```
/* in scheduler(): */
      // Switch to chosen process.  It is the process's job
      // to release ptable.lock and then reacquire it
      // before jumping back to us.
      c->proc = p;
      switchuvm(p);
      p->state = RUNNING;

      swtch(&(c->scheduler), p->context);
      switchkvm();

      // Process is done running for now.
      // It should have changed its p->state before coming back.
      c->proc = 0;
```

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      c->proc = 0;
```

track what process is being run
so we can look it up in interrupt handler

the xv6 scheduler: the actual switch

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      c->proc = p;
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      // Process is done running for now.
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      c->proc = 0;
```

prepare: change address space, change process state

the xv6 scheduler: the actual switch

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      // Process is done running for now.
      // It should have changed its p->state before coming back.
      c->proc = 0;
```

switch to kernel thread of process

that thread responsible for going back to user mode

the xv6 scheduler: the actual switch

```
/* in schedu
      // Swi
      // to
      // bef
      c->pro
      switchuvm(p);
      p->state = RUNNING;

      swtch(&(c->scheduler), p->context);
      switchkvm();

      // Process is done running for now.
      // It should have changed its p->state before coming back.
      c->proc = 0;
```

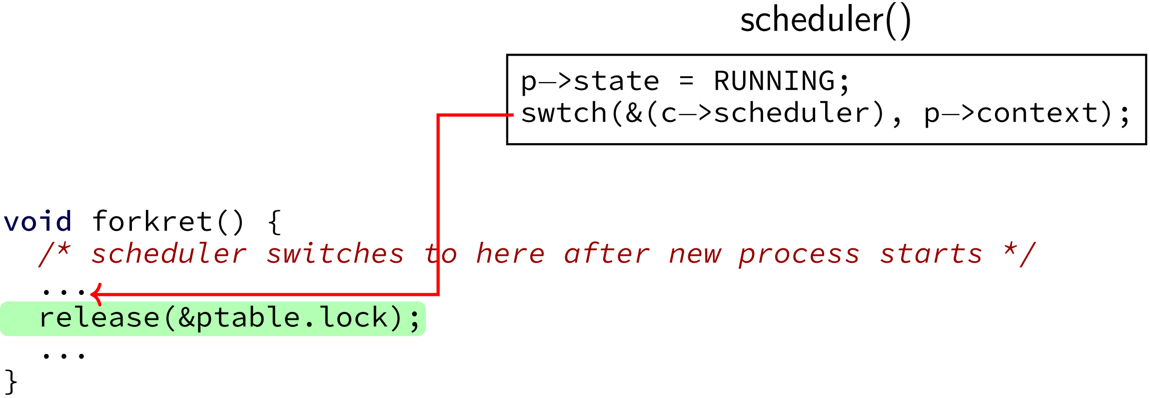
after we've run the process until it's done, we end up here

…so, change address space back away from user process

the xv6 scheduler: on process start

```
void forkret() {
  /* scheduler switches to here after new process starts */
  ...
  release(&ptable.lock);
  ...
}
```

the xv6 scheduler: on process start

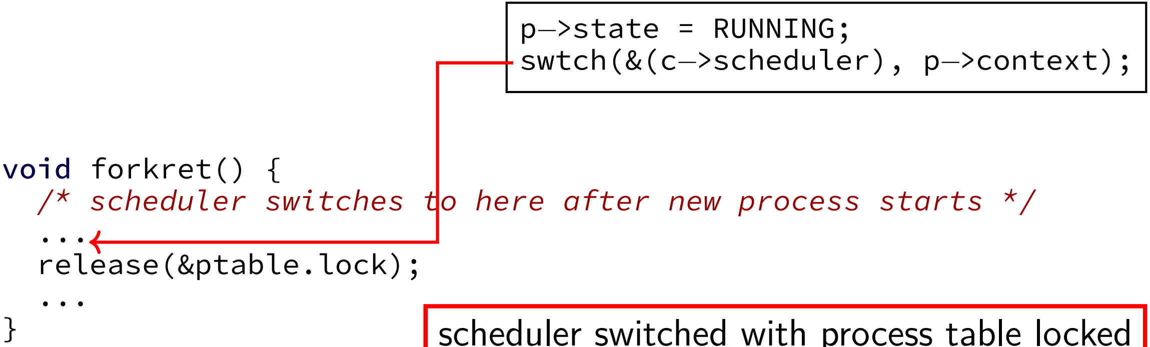


scheduler()

```
p->state = RUNNING;
swtch(&(c->scheduler), p->context);
```

```
void forkret() {
  /* scheduler switches to here after new process starts */
  ...
  release(&ptable.lock);
  ...
}
```

the xv6 scheduler: on process start



scheduler()

```
p->state = RUNNING;
swtch(&(c->scheduler), p->context);
```

```
void forkret() {
  /* scheduler switches to here after new process starts */
  ...
  release(&ptable.lock);
  ...
}
```

scheduler switched with process table locked
need to unlock before running user code
(so other cores, interrupts can use table or run scheduler)

the xv6 scheduler: going from/to scheduler

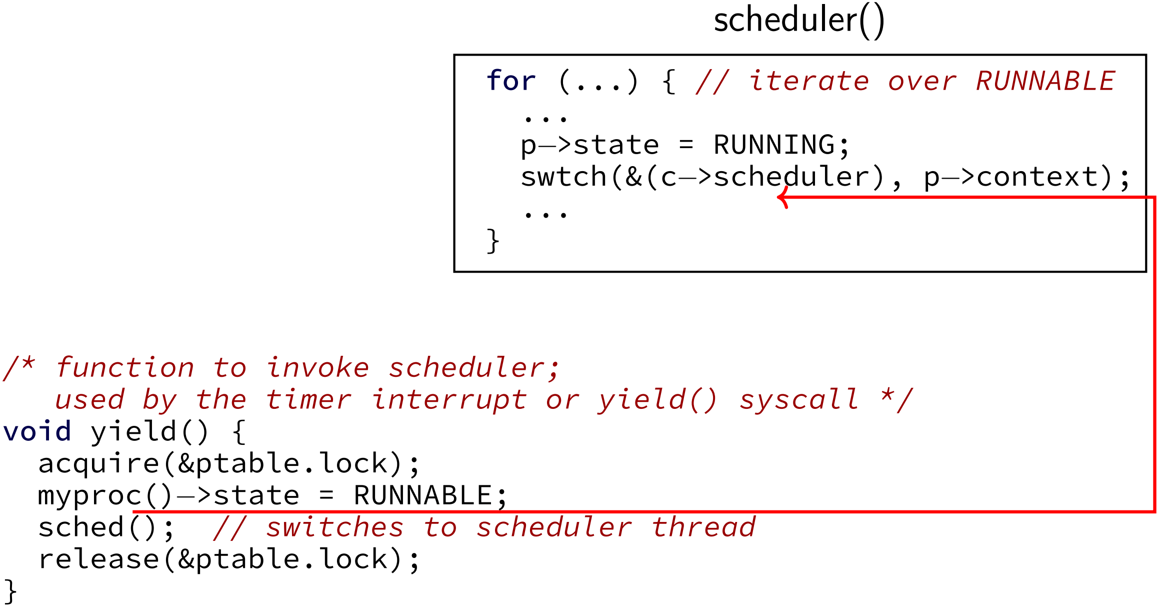
```
/* function to invoke scheduler;
   used by the timer interrupt or yield() syscall */
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();  // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: going from/to scheduler

yield: function to call scheduler
called by timer interrupt handler

```
/* function to invoke scheduler;
   used by the timer interrupt or yield() syscall */
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();  // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: going from/to scheduler



scheduler()

```
for (...) { // iterate over RUNNABLE
    ...
    p->state = RUNNING;
    swtch(&(c->scheduler), p->context);
    ...
}
```

```
/* function to invoke scheduler;
   used by the timer interrupt or yield() syscall */
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();  // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: going from/to scheduler

scheduler()

```
for (...) { // iterate over RUNNABLE
  ...
  p->state = RUNNING;
  swtch(&(c->scheduler), p->context);
  ...
}
```

make sure we're the only one accessing the process list before changing our process's state and before running scheduler loop

```
/* function to
   used by the
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();  // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: going from/to scheduler

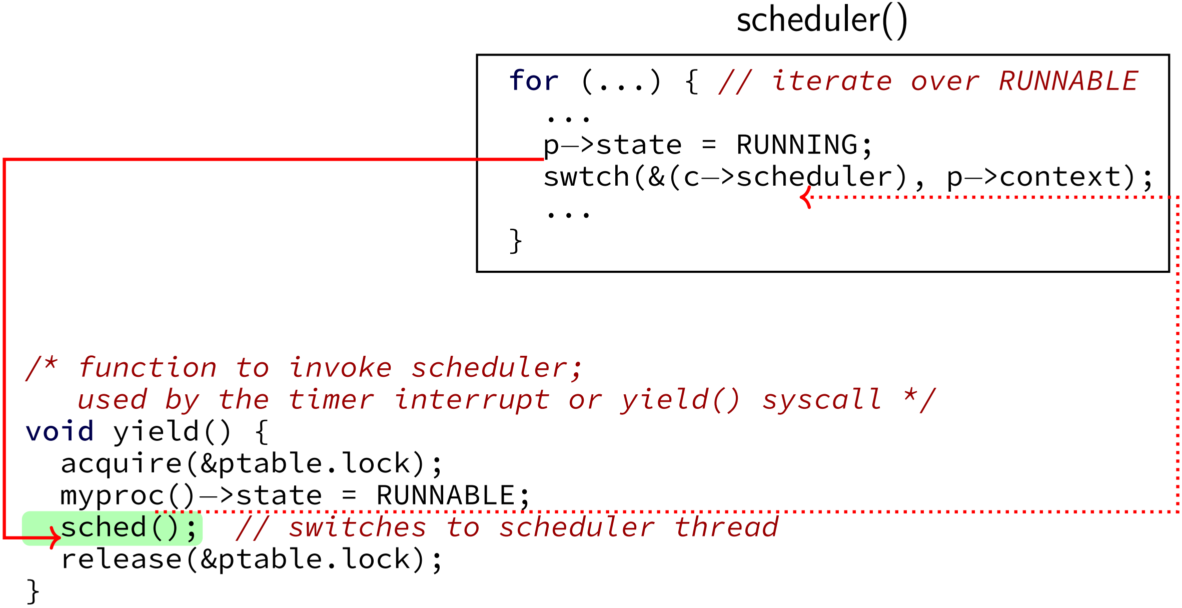
scheduler()

```
for (...) { // iterate over RUNNABLE
  ...
  p->state = RUNNING;
  swtch(&(c->scheduler), p->context);
  ...
}
```

set us as RUNNABLE (was RUNNING)
then switch to infinite loop in scheduler

```
/* function to invoke schedul
   used by the timer interrupt or yield() syscall */
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();  // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: going from/to scheduler

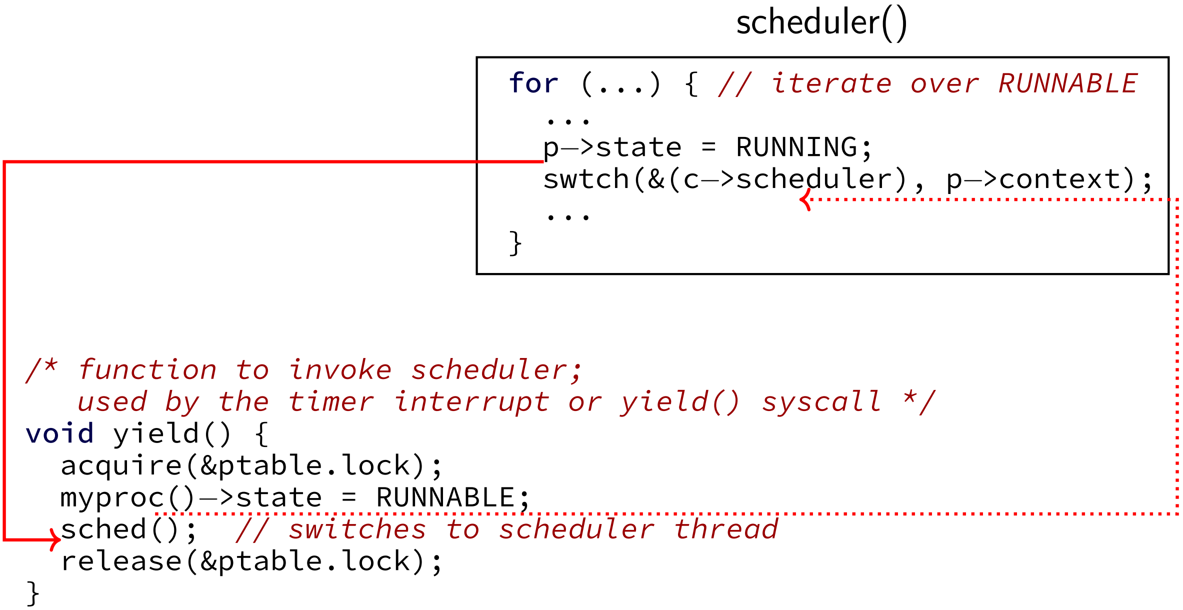


scheduler()

```
for (...) { // iterate over RUNNABLE
  ...
  p->state = RUNNING;
  swtch(&(c->scheduler), p->context);
  ...
}
```

```
/* function to invoke scheduler;
   used by the timer interrupt or yield() syscall */
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();   // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: going from/to scheduler

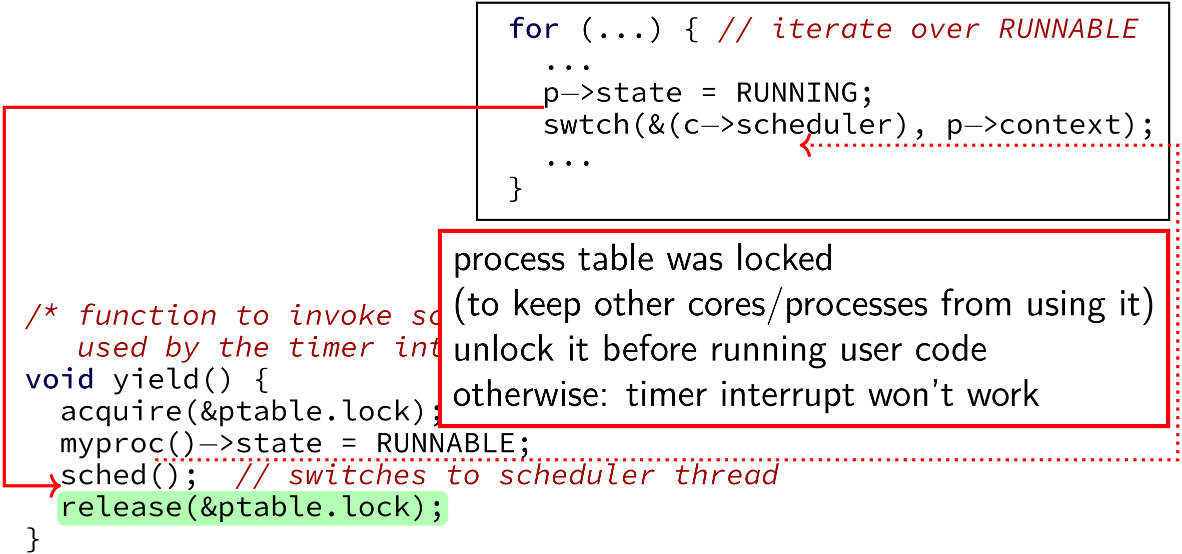


scheduler()

```
for (...) { // iterate over RUNNABLE
    ...
    p->state = RUNNING;
    swtch(&(c->scheduler), p->context);
    ...
}
```

```
/* function to invoke scheduler;
   used by the timer interrupt or yield() syscall */
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();  // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: going from/to scheduler



scheduler()

```
for (...) { // iterate over RUNNABLE
    ...
    p->state = RUNNING;
    swtch(&(c->scheduler), p->context);
    ...
}
```

process table was locked

(to keep other cores/processes from using it)

unlock it before running user code

otherwise: timer interrupt won't work

```
/* function to invoke sc
   used by the timer int
void yield() {
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();  // switches to scheduler thread
  release(&ptable.lock);
}
```

the xv6 scheduler: entering/leaving for sleep

```
void sleep(void *chan, struct spinlock *lk) {
  ...
    acquire(&ptable.lock);
  ...
  p->chan = chan;
  p->state = SLEEPING;

  sched();

  ...
    release(&ptable.lock);
  ...
```

the xv6 scheduler: entering/leaving for sleep

```
void sleep(void *chan, struct s
  ...
    acquire(&ptable.lock);
  ...
  p->chan = chan;
  p->state = SLEEPING;

  sched();

  ...
    release(&ptable.lock);
  ...
```

get exclusive access to process table
before changing our state to sleeping
and before running scheduler loop

the xv6 scheduler: entering/leaving for sleep

```
void sleep(void *chan, struct
  ...
    acquire(&ptable.lock);
  ...
  p->chan = chan;
  p->state = SLEEPING;

  sched();

  ...
    release(&ptable.lock);
  ...
```

set us as SLEEPING (was RUNNING)
use “chan” to remember why
(so others process can wake us up)

the xv6 scheduler: entering/leaving for sleep

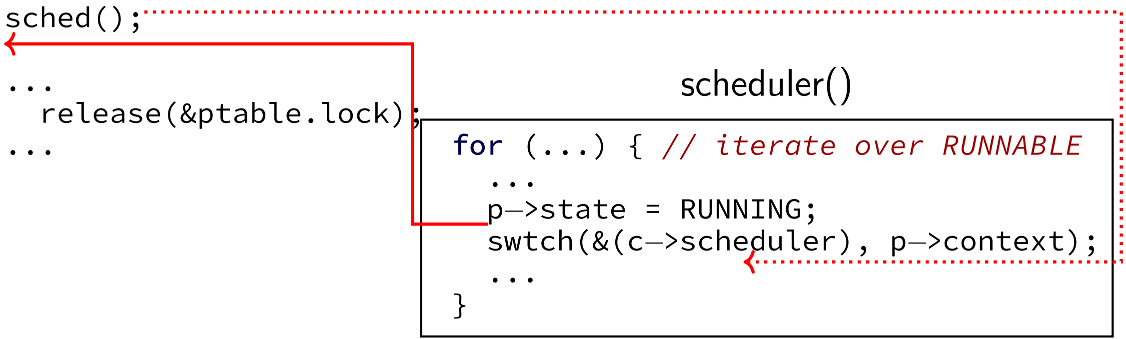
```
void sleep(void *chan, str
  ...
    acquire(&ptable.lock);
  ...
  p->chan = chan;
  p->state = SLEEPING;

  sched();

  ...
    release(&ptable.lock);
  ...
```

…and switch to the scheduler infinite loop

scheduler()

```
for (...) { // iterate over RUNNABLE
    ...
    p->state = RUNNING;
    swtch(&(c->scheduler), p->context);
    ...
}
```

the xv6 scheduler: entering/leaving for sleep



```
void sleep(void *chan, struct spinlock *lk) {
  ...
    acquire(&ptable.lock);
  ...
  p->chan = chan;
  p->state = SLEEPING;

  sched();

  ...
    release(&ptable.lock);
  ...
```

scheduler()

```
for (...) { // iterate over RUNNABLE
  ...
  p->state = RUNNING;
  swtch(&(c->scheduler), p->context);
  ...
}
```

the xv6 scheduler: SLEEPING to RUNNABLE

```
static void
wakeup1(void *chan)
{
  struct proc *p;

  for(p = ptable.proc; p < &ptable.proc[NPROC]; p++)
    if(p->state == SLEEPING && p->chan == chan)
      p->state = RUNNABLE;
}
```

the scheduling policy problem

what RUNNABLE program should we run?

xv6 answer: whatever's next in list

best answer?

- well, what do you care about?

some simplifying assumptions

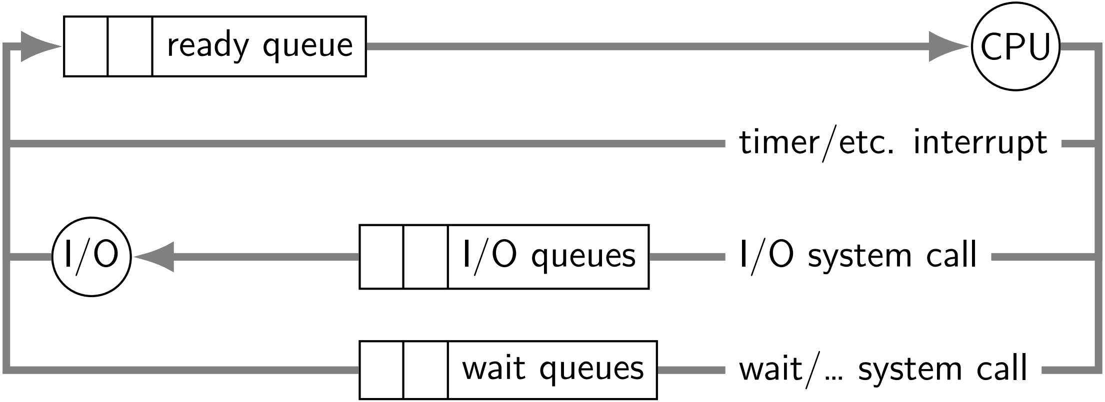
welcome to 1970:

one program per user

one thread per program

programs are independent

recall: scheduling queues



CPU and I/O bursts

...

compute
start read
(from file/keyboard/...)

wait for I/O

compute on read data
start read

wait for I/O

compute on read data
start write

wait for I/O

...

program alternates between computing and waiting for I/O

examples:
shell: wait for keypresses
drawing program: wait for mouse presses/etc.
web browser: wait for remote web server
...

CPU bursts and interactivity (one c. 1966 shared system)

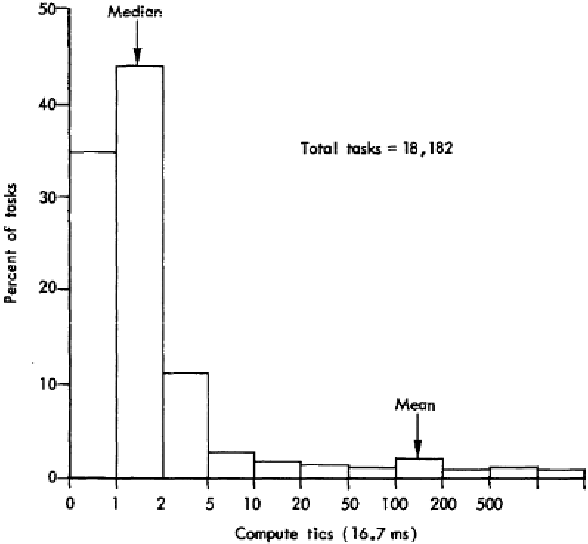
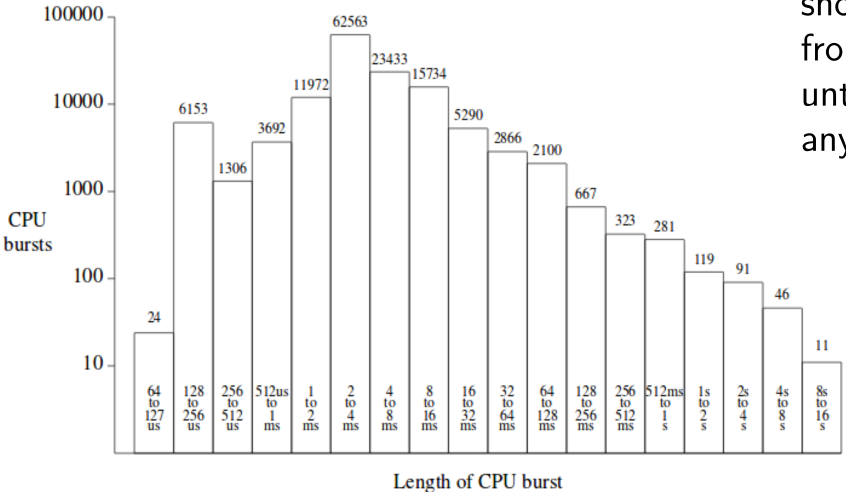


Figure 11—Compute time per task

shows compute time
from command entered
until next command prompt

from G. E. Bryan, "JOSS: 20,000 hours at a console—a statistical approach" in Proc. AFIPS 1967 FJCC

CPU bursts and interactivity (one c. 1990 desktop)



shows CPU time from RUNNING until not RUNNABLE anymore

from Curran and Stumm, "A Comparison of basic CPU Scheduling Algoirithms for Multiprocessor Unix"

CPU bursts

observation: applications alternate between I/O and CPU

- especially interactive applications
- but also, e.g., reading and writing from disk

typically short “CPU bursts” (milliseconds) followed by short “IO bursts” (milliseconds)

scheduling CPU bursts

our typical view: ready queue, bunch of CPU bursts to run

to start: just look at running what's currently in ready queue best

- same problem as 'run bunch of programs to completion'?

later: account for I/O after CPU burst

an historical note

historically applications were less likely to keep all data in memory

historically computers shared between more users

meant *more* applications alternating I/O and CPU

context many scheduling policies were developed in