143A: Principles of Operating Systems

Lecture 13: Synchronization

Anton Burtsev
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Starting other CPUs

Started from main()

```
main(void)
{
...
  startothers(); // start other processors
  kinit2(P2V(4*1024*1024), P2V(PHYSTOP));
  userinit(); // first user process
  mpmain();
}
```

Starting other CPUs

- Copy start code in a good location
  - 0x7000 (remember same as the one used by boot loader)
- Pass start parameters on the stack
  - Allocate a new stack for each CPU
  - Send a magic inter-processor interrupt (IPI) with the entry point (mpenter())

Start other CPUs

```
startothers(void)
{
  code = P2V(0x7000);
  memmove(code, _binary_entryother_start,
          (uint)_binary_entryother_size);

  for(c = cpus; c < cpus+ncpu; c++){
    if(c == cpus+cpunum()) // We've started already.
      continue;
...
    stack = kalloc();
    *(void**)(code-4) = stack + KSTACKSIZE;
    *(void**)(code-8) = mpenter;
    *(int**)(code-12) = (void *) V2P(entrypgdir);

    lapicstartap(c->apicid, V2P(code));
```

- Copy start code to 0x7000
- Start code is linked into the kernel
  - `_binary_entryother_start`
  - `_binary_entryother_size`

Start other CPUs

```
startothers(void)
{
  code = P2V(0x7000);
  memmove(code, _binary_entryother_start,
          (uint)_binary_entryother_size);

  for(c = cpus; c < cpus+ncpu; c++){
    if(c == cpus+cpunum()) // We've started already.
      continue;
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    *(void**)(code-4) = stack + KSTACKSIZE;
    *(void**)(code-8) = mpenter;
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    lapicstartap(c->apicid, V2P(code));
```

- Allocate a new kernel stack for each CPU
- What will be running on this stack?

Start other CPUs

```
startothers(void)
{
  code = P2V(0x7000);
  memmove(code, _binary_entryother_start,
          (uint)_binary_entryother_size);

  for(c = cpus; c < cpus+ncpu; c++){
    if(c == cpus+cpunum()) // We've started already.
      continue;
...
    stack = kalloc();
    *(void**)(code-4) = stack + KSTACKSIZE;
    *(void**)(code-8) = mpenter;
    *(int**)(code-12) = (void *) V2P(entrypgdir);

    lapicstartap(c->apicid, V2P(code));
```

- Allocate a new kernel stack for each CPU
- What will be running on this stack?
  - Scheduler

Start other CPUs

```
startothers(void)
{
  code = P2V(0x7000);
  memmove(code, _binary_entryother_start,
              (uint)_binary_entryother_size);

  for(c = cpus; c < cpus+ncpu; c++){
    if(c == cpus+cpunum()) // We've started already.
      continue;
...
    stack = kalloc();
    *(void**)(code-4) = stack + KSTACKSIZE;
    *(void**)(code-8) = mpenter;
    *(int**)(code-12) = (void *) V2P(entrypgdir);

    lapicstartap(c->apicid, V2P(code));
```

- What is done here?

Start other CPUs

```
startothers(void)
{
  code = P2V(0x7000);
  memmove(code, _binary_entryother_start,
          (uint)_binary_entryother_size);

  for(c = cpus; c < cpus+ncpu; c++){
    if(c == cpus+cpunum()) // We've started already.
      continue;
...
    stack = kalloc();
    *(void**)(code-4) = stack + KSTACKSIZE;
    *(void**)(code-8) = mpenter;
    *(int**)(code-12) = (void *) V2P(entrypgdir);

    lapicstartap(c->apicid, V2P(code));
```

- What is done here?
  - Kernel stack
  - Address of mpenter()
  - Physical address of entrypgdir

Start other CPUs

```
startothers(void)
{
  code = P2V(0x7000);
  memmove(code, _binary_entryother_start,
               (uint)_binary_entryother_size);

  for(c = cpus; c < cpus+ncpu; c++){
    if(c == cpus+cpunum()) // We've started already.
      continue;
...
    stack = kalloc();
    *(void**)(code-4) = stack + KSTACKSIZE;
    *(void**)(code-8) = mpenter;
    *(int**)(code-12) = (void *) V2P(entrypgdir);

    lapicstartap(c->apicid, V2P(code));
```

- Send “magic” interrupt
- Wake up other CPUs

entryother.S

```
.code16
.globl start
start:
  cli

  xorw %ax,%ax
  movw %ax,%ds
  movw %ax,%es
  movw %ax,%ss

```

- Disable interrupts
- Init segments with 0

entryother.S

- Load GDT
- Switch to 32bit mode
  - Long jump to start32
- Load segments

```
  lgdt gdtdesc
  movl %cr0, %eax
  orl $CR0_PE, %eax
  movl %eax, %cr0
  ljmpl $(SEG_KCODE<<3), $(start32)

.code32
start32:
  movw $(SEG_KDATA<<3), %ax
  movw %ax, %ds
  movw %ax, %es
  movw %ax, %ss
  movw $0, %ax
  movw %ax, %fs
  movw %ax, %gs
```

```
  # Turn on page size extension for 4Mbyte pages
  movl %cr4, %eax
  orl $(CR4_PSE), %eax
  movl %eax, %cr4
  # Use enterpgdir as our initial page table
  movl (start-12), %eax
  movl %eax, %cr3
# Turn on paging.
  movl %cr0, %eax
  orl $(CR0_PE|CR0_PG|CR0_WP), %eax
  movl %eax, %cr0

  # Switch to the stack allocated by startothers()
  movl (start-4), %esp
  # Call mpenter()
  call *(start-8)
```

entryother.S

```
  # Turn on page size extension for 4Mbyte pages
  movl %cr4, %eax
  orl $(CR4_PSE), %eax
  movl %eax, %cr4
  # Use enterpgdir as our initial page table
  movl (start-12), %eax
  movl %eax, %cr3
# Turn on paging.
  movl %cr0, %eax
  orl $(CR0_PE|CR0_PG|CR0_WP), %eax
  movl %eax, %cr0

  # Switch to the stack allocated by startothers()
  movl (start-4), %esp
  # Call mpenter()
  call *(start-8)
```

entryother.S

entryother.S

```
# Turn on page size extension for 4Mbyte pages
movl %cr4, %eax
orl $(CR4_PSE), %eax
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# Use enterpgdir as our initial page table
movl (start-12), %eax
movl %eax, %cr3
# Turn on paging.
movl %cr0, %eax
orl $(CR0_PE|CR0_PG|CR0_WP), %eax
movl %eax, %cr0

# Switch to the stack allocated by startothers()
movl (start-4), %esp
# Call mpenter()
call *(start-8)
```

```
# Turn on page size extension for 4Mbyte pages
movl %cr4, %eax
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movl %eax, %cr4
# Use enterpgdir as our initial page table
movl (start-12), %eax
movl %eax, %cr3
# Turn on paging.
movl %cr0, %eax
orl $(CR0_PE|CR0_PG|CR0_WP), %eax
movl %eax, %cr0

# Switch to the stack allocated by startothers()
movl (start-4), %esp
# Call mpenter()
call *(start-8)
```

entryother.S

```
static void
mpenter(void)
{
    switchkvm();
    seginit();
    lapicinit();
    mpmain();
}
```

```
static void
mpenter(void)
{
    switchkvm();
    seginit();
    lapicinit();
    mpmain();
}
```

Init segments

Init segments

```
seginit(void)
{
  struct cpu *c;

  // Map "logical" addresses to virtual addresses using identity map.
  // Cannot share a CODE descriptor for both kernel and user
  // because it would have to have DPL_USR, but the CPU forbids
  // an interrupt from CPL=0 to DPL=3.
  c = &cpus[cpuid()];
  c->gdt[SEG_KCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, 0);
  c->gdt[SEG_KDATA] = SEG(STA_W, 0, 0xffffffff, 0);
  c->gdt[SEG_UCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, DPL_USER);
  c->gdt[SEG_UDATA] = SEG(STA_W, 0, 0xffffffff, DPL_USER);
  lgdt(c->gdt, sizeof(c->gdt));
}
```

Per-CPU variables

- Variables private to each CPU

Per-CPU variables

- Variables private to each CPU
  - Current running process
  - Kernel stack for interrupts
    - Hence, TSS that stores that stack

```
struct cpu cpus[NCPU];
```

```
// Per-CPU state
struct cpu {
  uchar apicid;                // Local APIC ID
  struct context *scheduler;   // swtch() here to enter scheduler
  struct taskstate ts;         // Used by x86 to find stack for
interrupt
  struct segdesc gdt[NSEGS];   // x86 global descriptor table
  volatile uint started;       // Has the CPU started?
  int ncli;                    // Depth of pushcli nesting.
  int intena;                  // Were interrupts enabled before
pushcli?
  struct proc *proc;           // The process running on this cpu or
null
};

extern struct cpu cpus[NCPU];
```

cpuid()

```
// Must be called with interrupts disabled
int cpuid() {
  return mycpu()-cpus;
}
struct cpu* mycpu(void)
{
  int apicid, i;

  if(readeflags()&FL_IF)
    panic("mycpu called with interrupts enabled\n");

  apicid = lapicid();
  // APIC IDs are not guaranteed to be contiguous. Maybe we should have
  // a reverse map, or reserve a register to store &cpus[i].
  for (i = 0; i < ncpu; ++i) {
    if (cpus[i].apicid == apicid)
      return &cpus[i];
  }
  panic("unknown apicid\n");
}
```

mpmain()

```
// Common CPU setup code.
static void
mpmain(void)
{
  cprintf("cpu%d: starting %d\n", cpuid(), cpuid());
  idtinit();       // load idt register
  xchg(&(mycpu()->started), 1); // tell startothers() we're up
  scheduler();     // start running processes
}
```

Synchronization

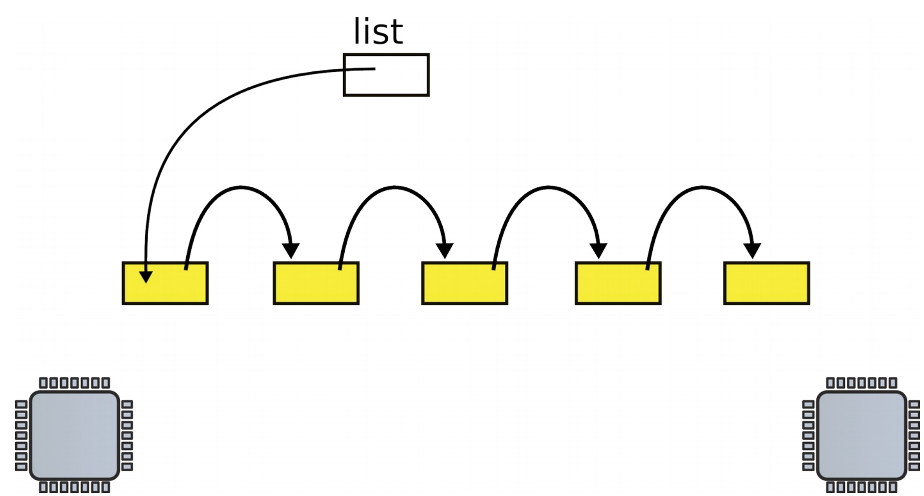
Race conditions

- Example:
  - Disk driver maintains a list of outstanding requests
  - Each process can add requests to the list

List implementation (no locks)

```
struct list {
  int data;
  struct list *next;
};
...
struct list *list = 0;
...
insert(int data)
{
  struct list *l;

  l = malloc(sizeof *l);
  l->data = data;
  l->next = list;
  list = l;
}
```

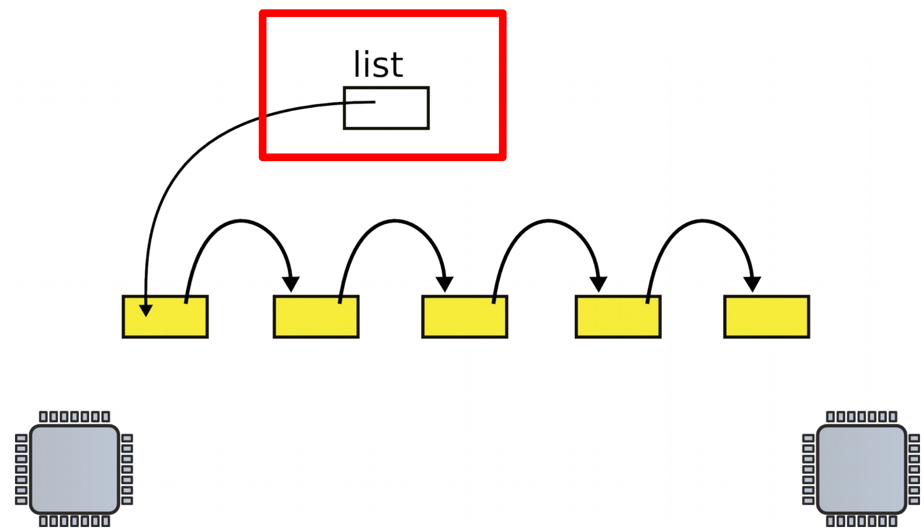
- List
  - One data element
  - Pointer to the next element



List implementation (no locks)

```
struct list {
  int data;
  struct list *next;
};
...
struct list *list = 0;
...
insert(int data)
{
  struct list *l;

  l = malloc(sizeof *l);
  l->data = data;
  l->next = list;
  list = l;
}
```

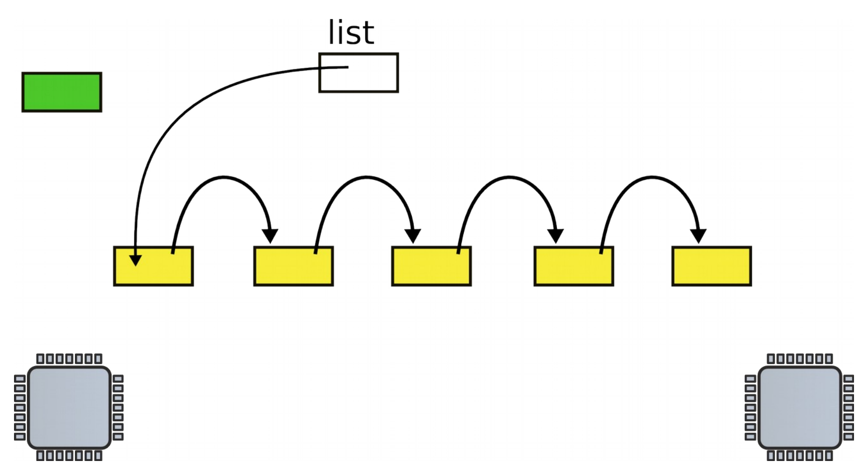
- Global head



```c
struct list {
  int data;
  struct list *next;
};
...
struct list *list = 0;
...
insert(int data)
{
  struct list *l;

  l = malloc(sizeof *l);
  l->data = data;
  l->next = list;
  list = l;
}
```

List implementation (no locks)

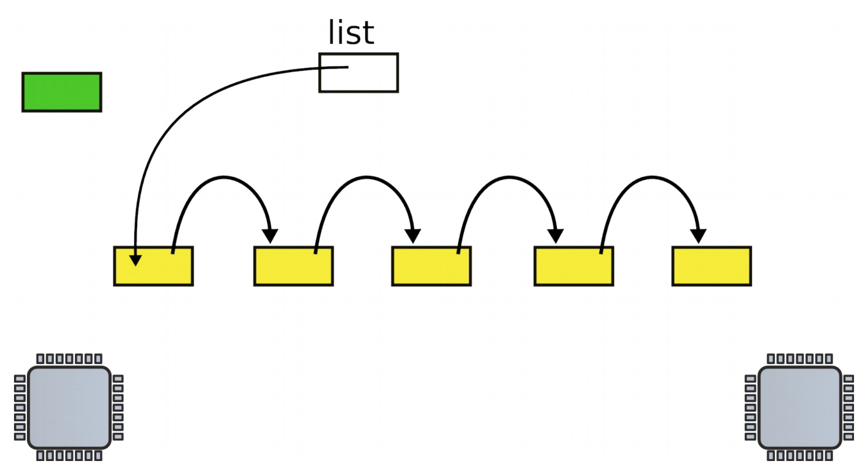
- Insertion
  - Allocate new list element



List implementation (no locks)

```
struct list {
  int data;
  struct list *next;
};
...
struct list *list = 0;
...
insert(int data)
{
  struct list *l;

  l = malloc(sizeof *l);
  l->data = data;
  l->next = list;
  list = l;
}
```

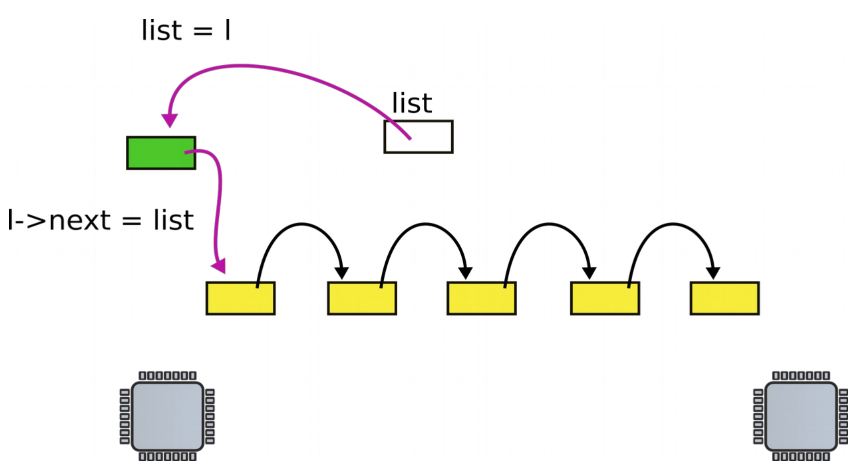
- Insertion
  - Allocate new list element
  - Save data into that element



List implementation (no locks)

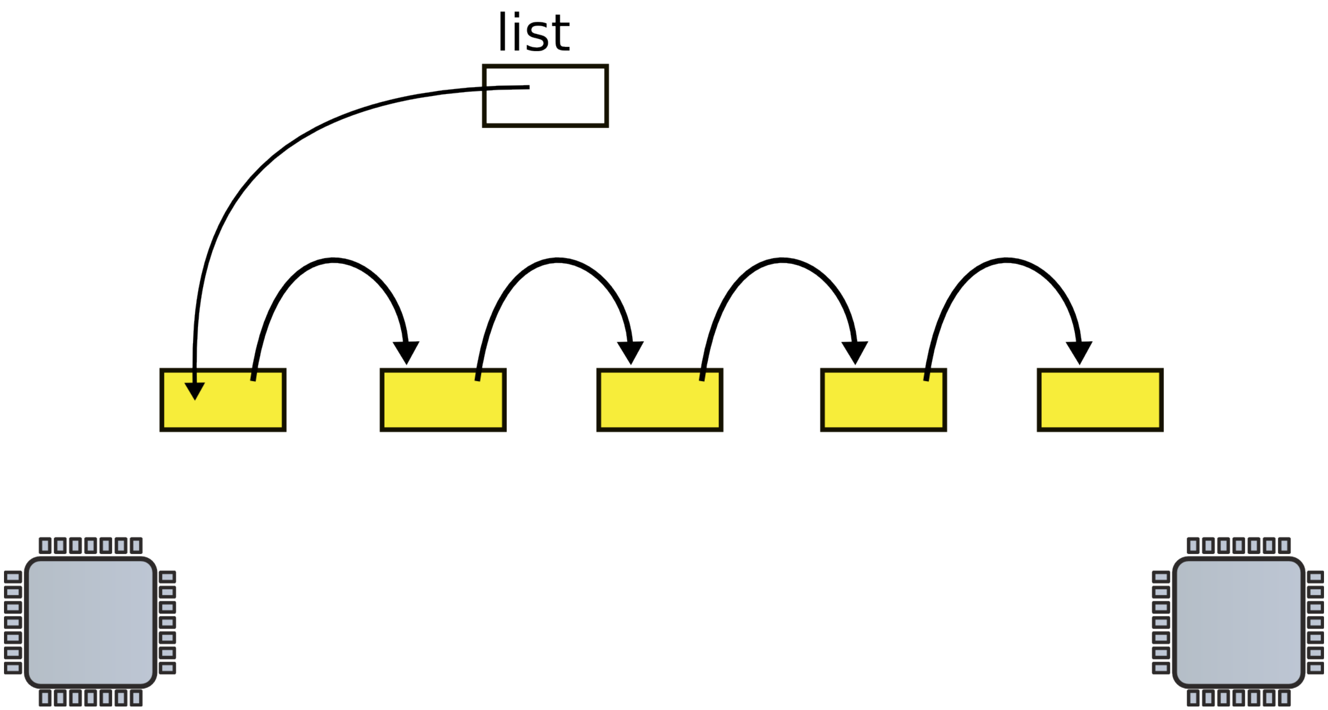
```
struct list {
  int data;
  struct list *next;
};
...
struct list *list = 0;
...
insert(int data)
{
  struct list *l;

  l = malloc(sizeof *l);
  l->data = data;
  l->next = list;
  list = l;
}
```

- Insertion
  - Allocate new list element
  - Save data into that element
  - Insert into the list



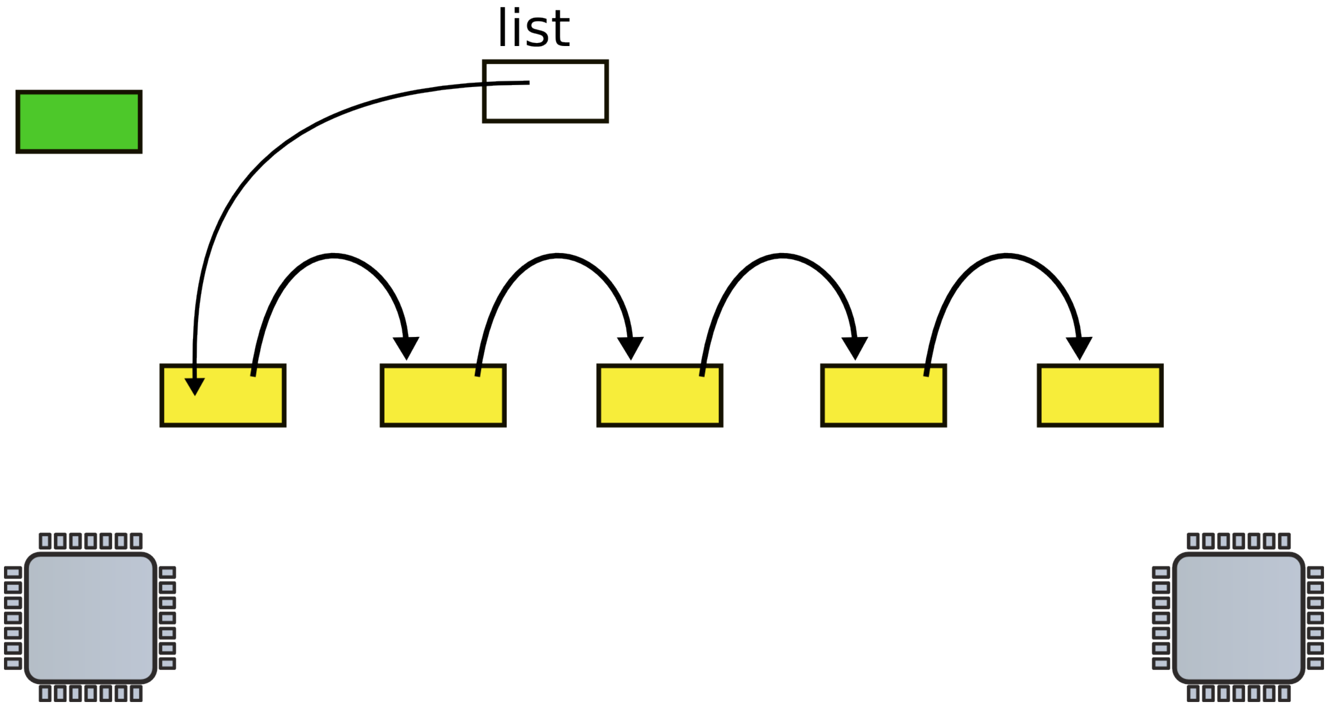
Now what happens when two CPUs access the same list

Request queue (e.g. pending disk requests)

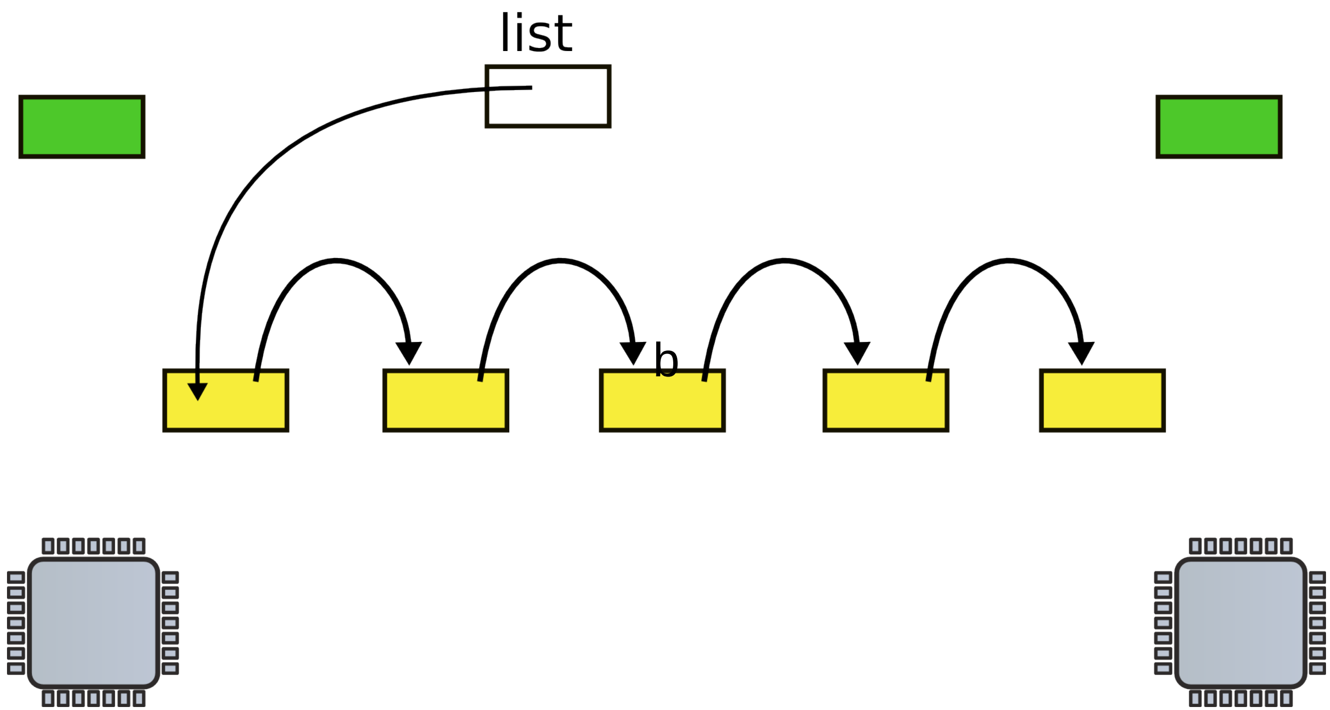


- Linked list, list is pointer to the first element

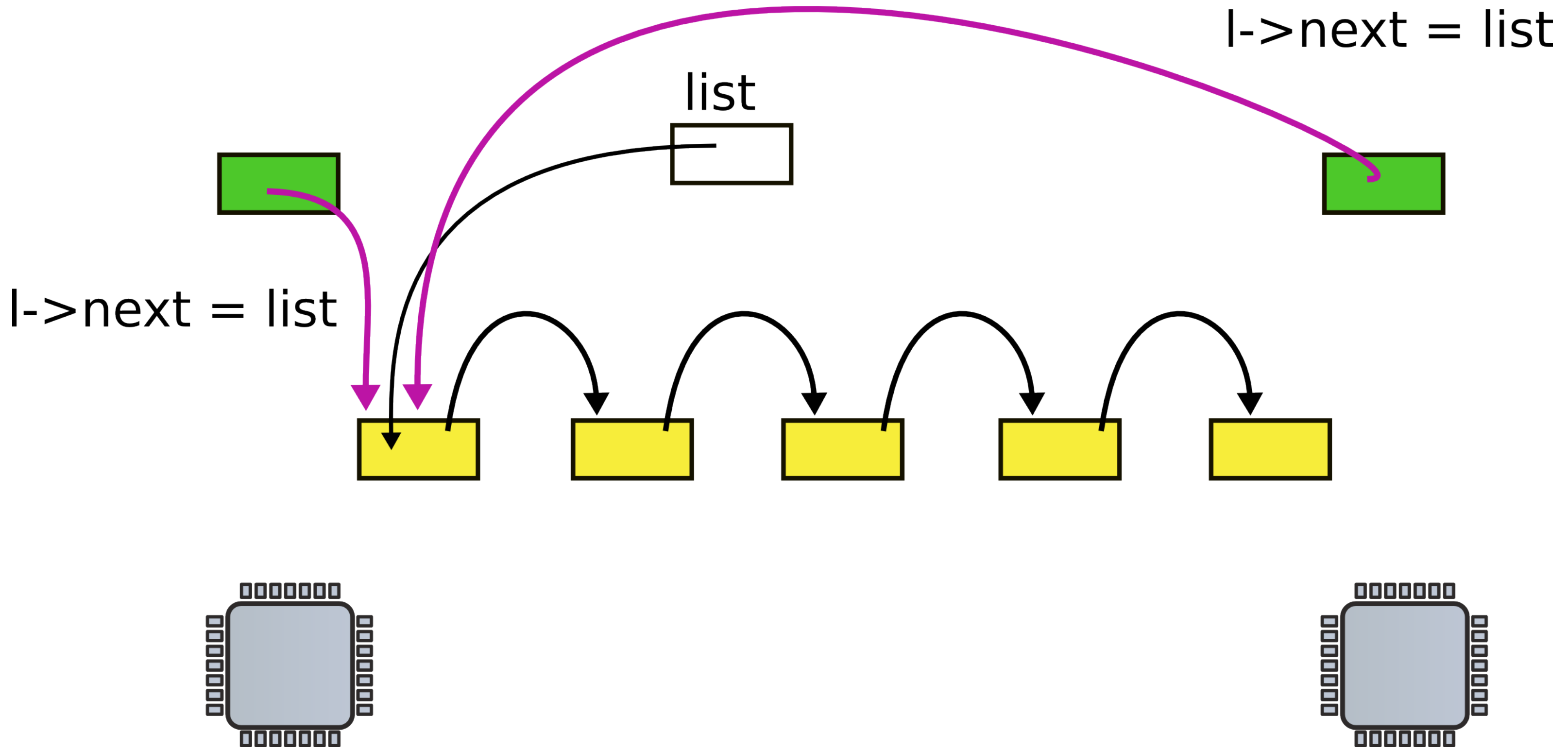
CPU1 allocates new request



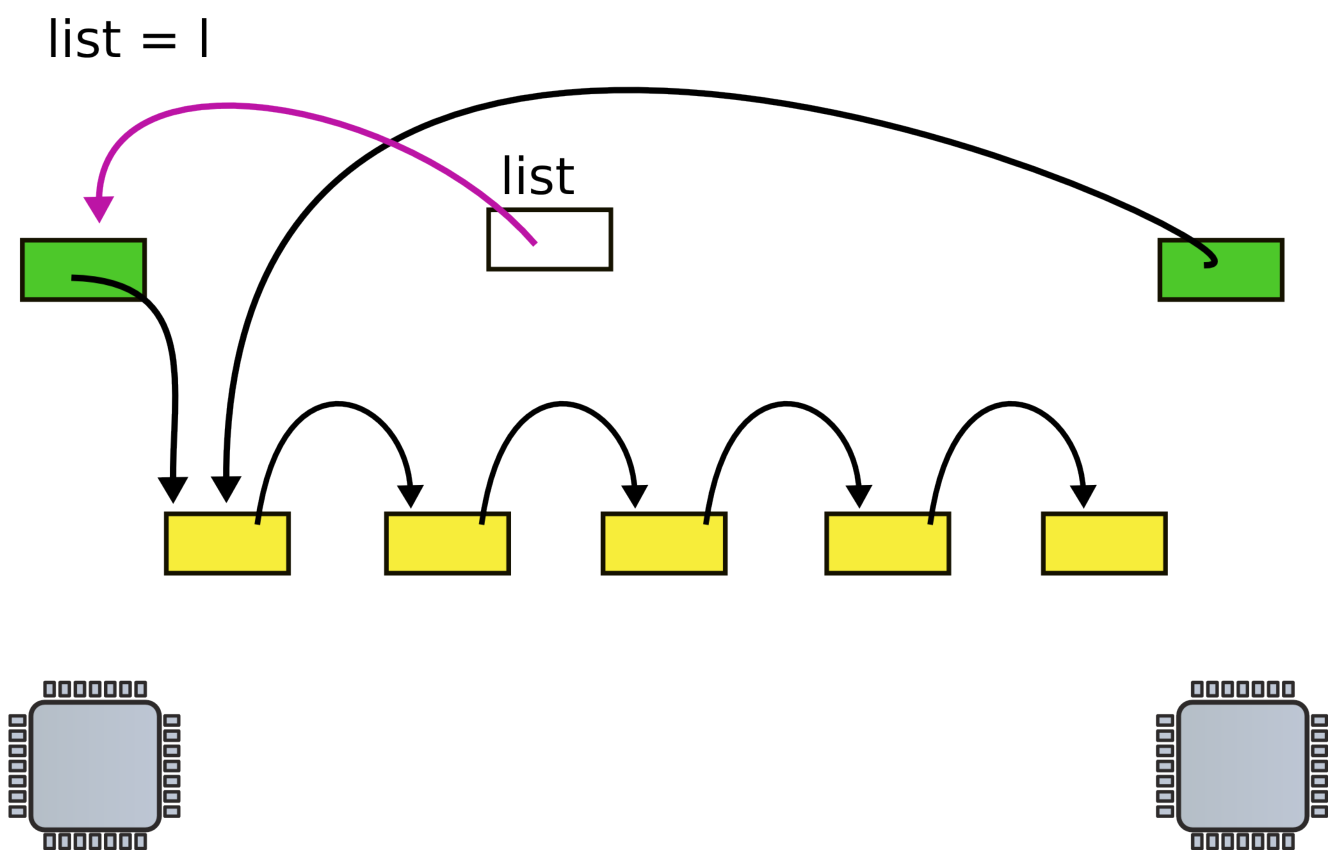
CPU2 allocates new request



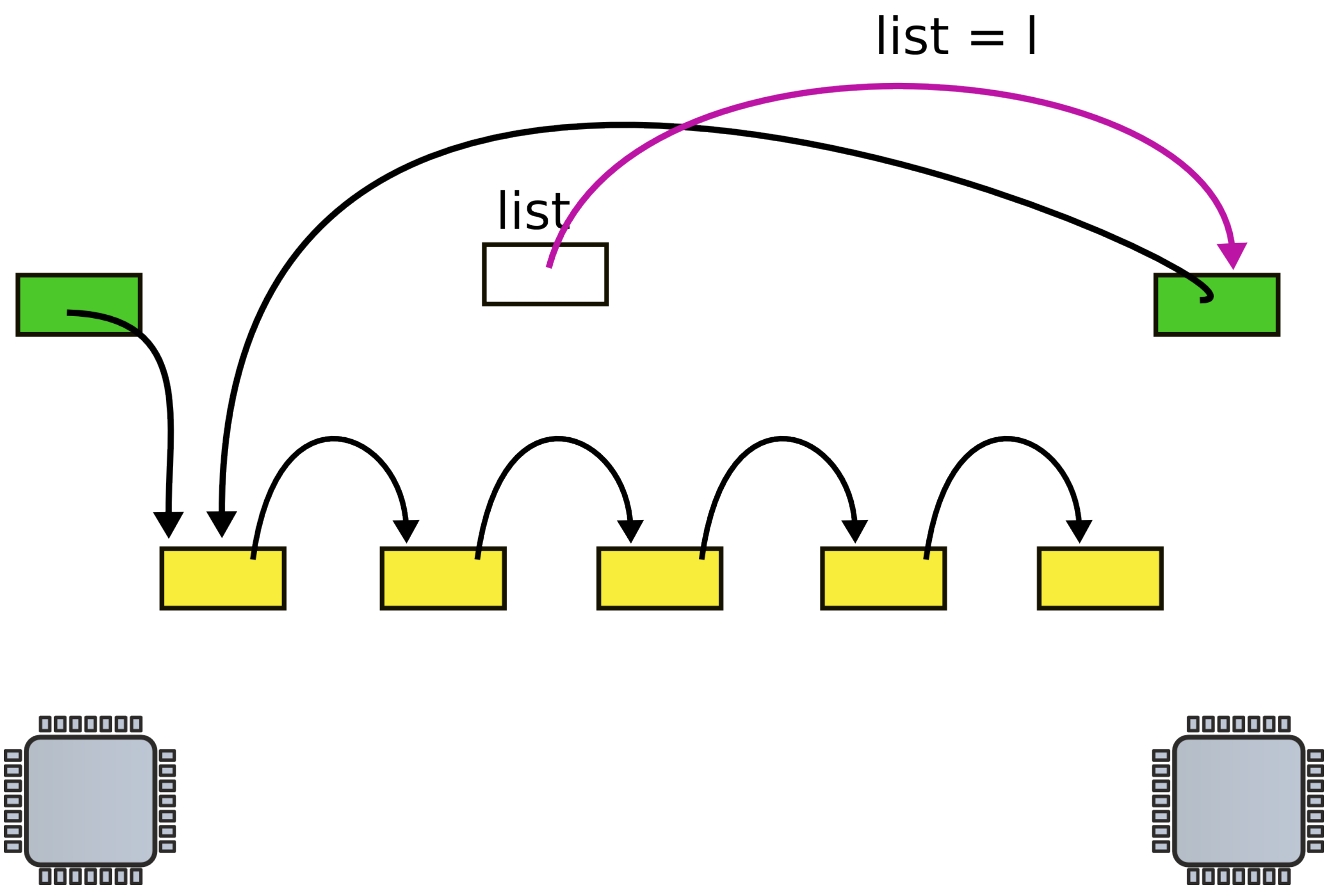
CPUs 1 and 2 update next pointer



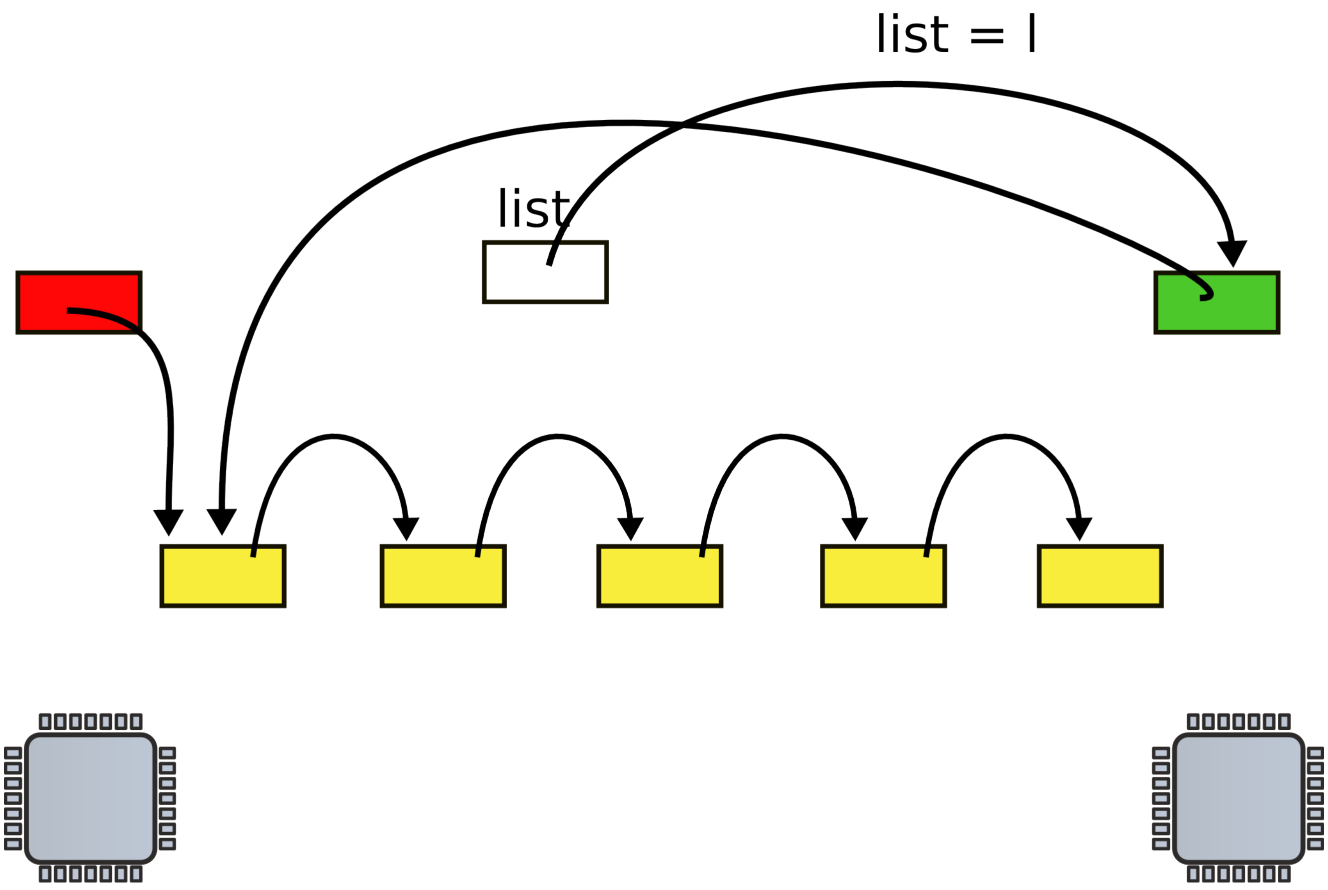
CPU1 updates head pointer



CPU2 updates head pointer



State after the race (red element is lost)



Mutual exclusion

- Only one CPU can update list at a time

List implementation with locks

```
struct list {
  int data;
  struct list *next;
};
struct list *list = 0;
struct lock listlock;
insert(int data)
{
   struct list *l;
   l = malloc(sizeof *l);
   acquire(&listlock);
   l->data = data;
   l->next = list;
   list = l;
   release(&listlock);
}
```

- Critical section

- How can we implement acquire()?

Spinlock

```
void
acquire(struct spinlock *lk)
{
  for(;;) {
    if(!lk->locked) {
      lk->locked = 1;
      break;
    }
  }
}
```

- Spin until lock is 0
- Set it to 1

Still incorrect

```
21 void
22 acquire(struct spinlock *lk)
23 {
24   for(;;) {
25     if(!lk->locked) {
26       lk->locked = 1;
27       break;
28     }
29   }
30 }
```

- Two CPUs can reach line #25 at the same time
  - See not locked, and
  - Acquire the lock
- Lines #25 and #26 need to be atomic
  - I.e. indivisible

Compare and swap: xchg

- Swap a word in memory with a new value
  - Return old value

Correct implementation

```
void
acquire(struct spinlock *lk)
{
...
  // The xchg is atomic.
  while(xchg(&lk->locked, 1) != 0)
    ;
...
}
```

xchgl instruction

```
static inline uint
xchg(volatile uint *addr, uint newval)
{
  uint result;

  // The + in "+m" denotes a read-modify-write operand.
  asm volatile("lock; xchgl %0, %1" :
               "+m" (*addr), "=a" (result) :
               "1" (newval) :
               "cc");
  return result;
}
```

Correct implementation

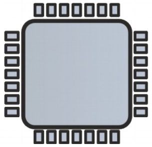
```
void
acquire(struct spinlock *lk)
{
...
  // The xchg is atomic.
  while(xchg(&lk->locked, 1) != 0)
    ;
  // Tell the C compiler and the processor to not move loads or stores
  // past this point, to ensure that the critical section's memory
  // references happen after the lock is acquired.
  __sync_synchronize();
...
}
```

Deadlocks

Deadlocks

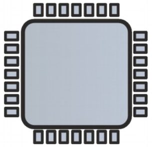
acquire(A)

```
acquire(B) {
    while(xchg(&B->locked, 1) != 0)
}
```



acquire(B)

```
acquire(A) {
    while(xchg(&A->locked, 1) != 0)
}
```



Lock ordering

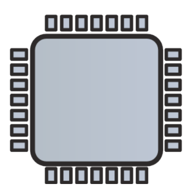
- Locks need to be acquired in the same order

Locks and interrupts

Network
interrupt

```
network_packet(){
    ....
    insert() {
        acquire(A)
        ...
    }

}
```

```
network_packet(){
    ....
    insert() {
        acquire(A)
        ...
    }

}
```



Locks and interrupts

- Never hold a lock with interrupts enabled

Disabling interrupts

```
void
acquire(struct spinlock *lk)
{
  pushcli(); // disable interrupts to avoid deadlock.
  if(holding(lk))
    panic("acquire");
  // The xchg is atomic.
  while(xchg(&lk->locked, 1) != 0)
    ;
...
  __sync_synchronize();
...
}
```

Simple disable/enable is not enough

- If two locks are acquired
  - Interrupts should be re-enabled only after the second lock is released
- Pushcli() uses a counter

Pushcli()/popcli()

```
pushcli(void)
{
  int eflags;

  eflags = readeflags();
  cli();
  if(cpu->ncli == 0)
    cpu->intena = eflags & FL_IF;
  cpu->ncli += 1;
}
```

Pushcli()/popcli()

```
popcli(void)
{
  if(readeflags()&FL_IF)
    panic("popcli - interruptible");
  if(--cpu->ncli < 0)
    panic("popcli");
  if(cpu->ncli == 0 && cpu->intena)
    sti();
}
```

Locks and interprocess communication

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

- Sends one pointer between two CPUs

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

Send/receive queue

```
struct q {
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    ;
  q->ptr = 0;
  return p;
}
```

- Works well, but expensive if communication is rare
  - Receiver wastes CPU cycles

Sleep and wakeup

- sleep(channel)
  - Put calling process to sleep
  - Release CPU for other work
- wakeup(channel)
  - Wakes all processes sleeping on a channel
    - If any
  - i.e., causes sleep() calls to return

Send/receive queue

```
void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q); /*wake recv*/
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    sleep(q);
  q->ptr = 0;
  return p;
}
```

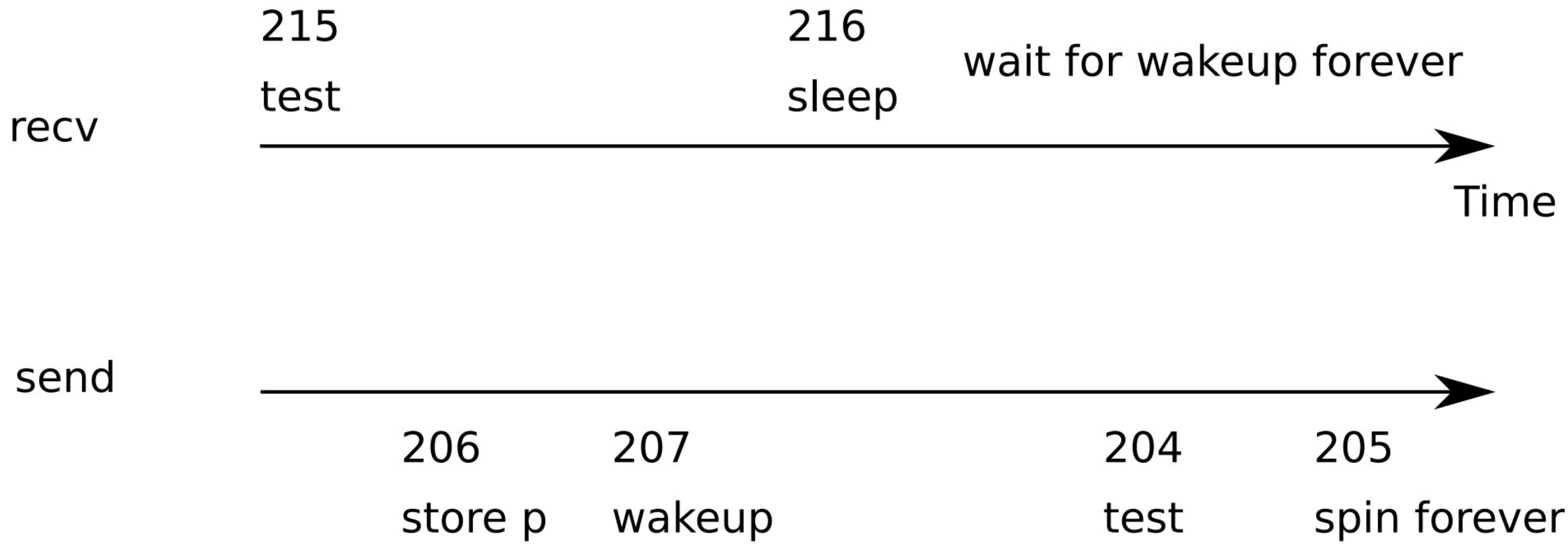
Send/receive queue

```
void*
send(struct q *q, void *p)
{
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q); /*wake recv*/
}
```

```
void*
recv(struct q *q)
{
  void *p;

  while((p = q->ptr) == 0)
    sleep(q);
  q->ptr = 0;
  return p;
}
```

- recv() gives up the CPU to other processes
  - But there is a problem...

Lost wakeup problem



Lock the queue

```
struct q {
  struct spinlock lock;
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  acquire(&q->lock);
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q);
  release(&q->lock);
}
```

```
void*
recv(struct q *q)
{
  void *p;

  acquire(&q->lock);
  while((p = q->ptr) == 0)
    sleep(q);
  q->ptr = 0;
  release(&q->lock);
  return p;
}
```

- Doesn't work either: deadlocks
  - Holds a lock while sleeping

Pass lock inside sleep()

```c
struct q {
  struct spinlock lock;
  void *ptr;
};

void*
send(struct q *q, void *p)
{
  acquire(&q->lock);
  while(q->ptr != 0)
    ;
  q->ptr = p;
  wakeup(q);
  release(&q->lock);
}
```

```c
void*
recv(struct q *q)
{
  void *p;

  acquire(&q->lock);
  while((p = q->ptr) == 0)
    sleep(q, &q->lock);
  q->ptr = 0;
  release(&q->lock);
  return p;
}
```

sleep()

```
sleep(void *chan, struct spinlock *lk)
{
...
  if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }

  // Go to sleep.
  proc->chan = chan;
  proc->state = SLEEPING;
  sched();
...
  // Reacquire original lock.
  if(lk != &ptable.lock){
    release(&ptable.lock);
    acquire(lk);
  }
}
```

- Acquire ptable.lock
  - All process operations are protected with ptable.lock

sleep()

```
sleep(void *chan, struct spinlock *lk)
{
...
  if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }

  // Go to sleep.
  proc->chan = chan;
  proc->state = SLEEPING;
  sched();
...
  // Reacquire original lock.
  if(lk != &ptable.lock){
    release(&ptable.lock);
    acquire(lk);
  }
}
```

- Acquire `ptable.lock`
  - All process operations are protected with `ptable.lock`
- Release `lk`
  - Why is it safe?

sleep()

```
sleep(void *chan, struct spinlock *lk)
{
...
  if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }

  // Go to sleep.
  proc->chan = chan;
  proc->state = SLEEPING;
  sched();
...
  // Reacquire original lock.
  if(lk != &ptable.lock){
    release(&ptable.lock);
    acquire(lk);
  }
}
```

- Acquire ptable.lock
  - All process operations are protected with `ptable.lock`
- Release `lk`
  - Why is it safe?
  - Even if new wakeup starts at this point, it cannot proceed
  - Sleep() holds `ptable.lock`

wakeup()

```
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;
}
..
wakeup(void *chan)
{
  acquire(&ptable.lock);
  wakeup1(chan);
  release(&ptable.lock);
}
```

Pipes

Pipe

```
#define PIPESIZE 512

struct pipe {
  struct spinlock lock;
  char data[PIPESIZE];
  uint nread; // number of bytes read
  uint nwrite; // number of bytes written
  int readopen; // read fd is still open
  int writeopen; // write fd is still open
};
```

Pipe

```
#define PIPESIZE 512

struct pipe {
  struct spinlock lock;
  char data[PIPESIZE];
  uint nread; // number of bytes read
  uint nwrite; // number of bytes written
  int readopen; // read fd is still open
  int writeopen; // write fd is still open
};
```

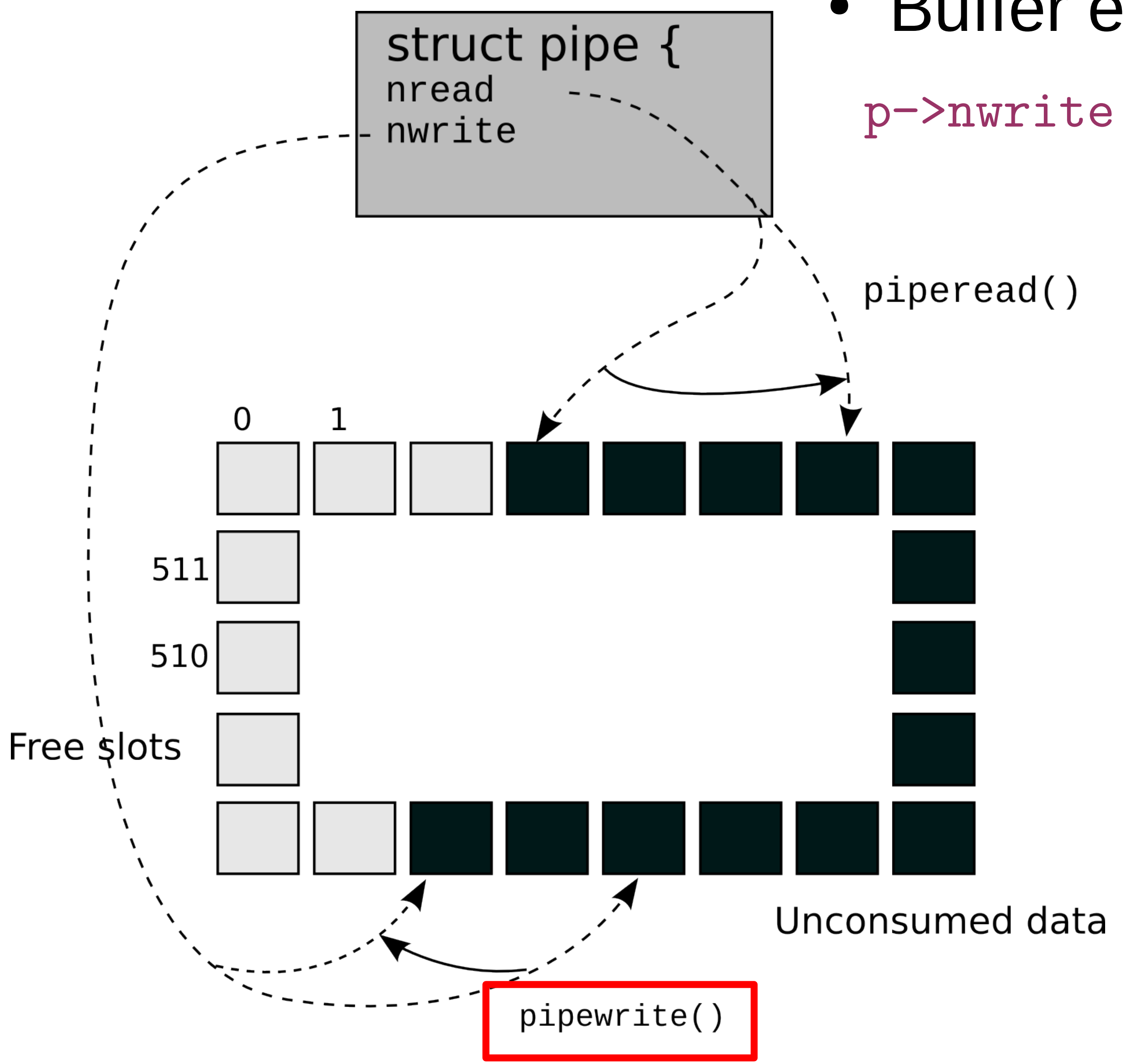
Pipe buffer

- Buffer full

`p->nwrite == p->nread + PIPESIZE`

- Buffer empty

`p->nwrite == p->nread`



Pipe buffer

- Buffer full

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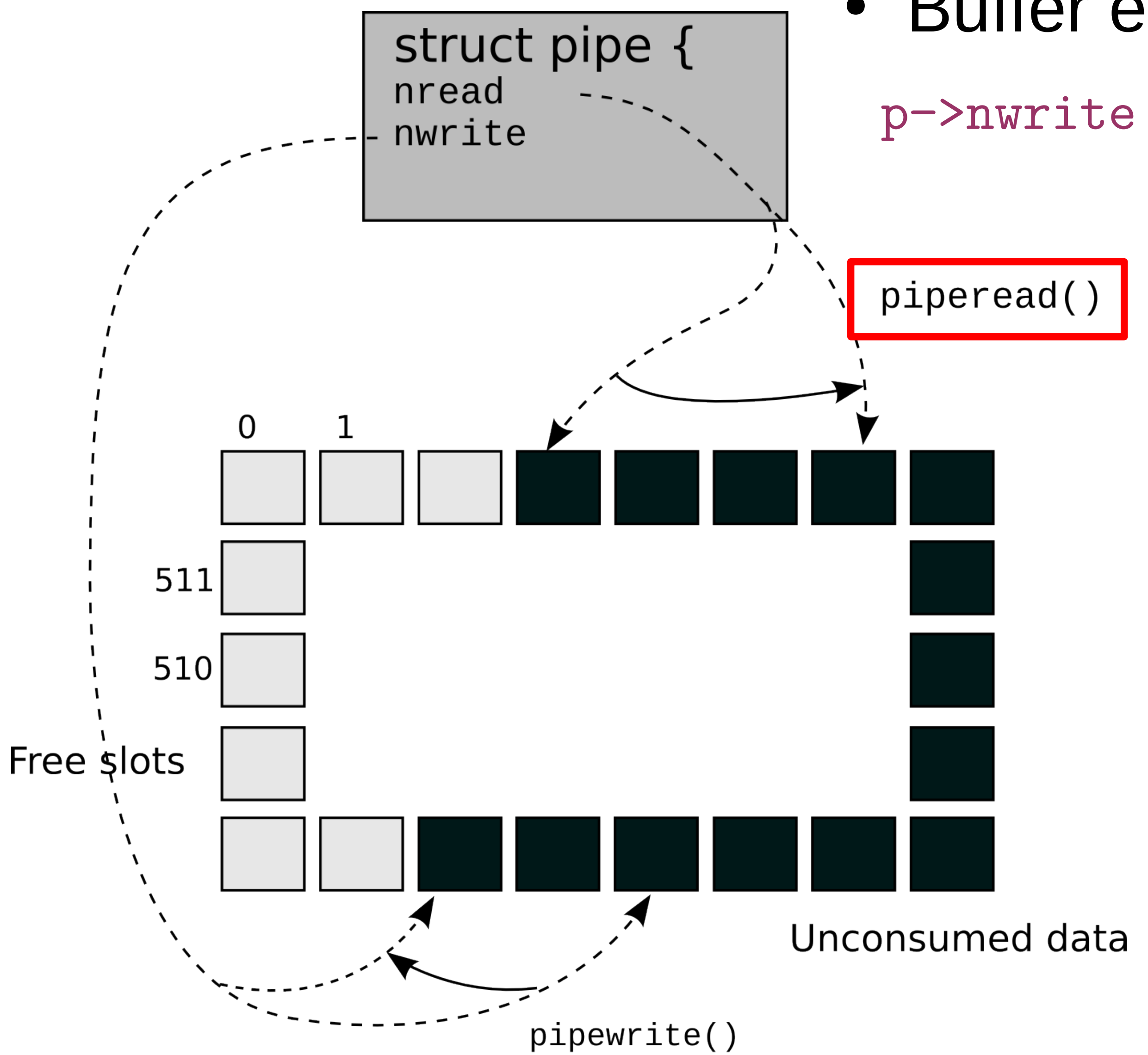


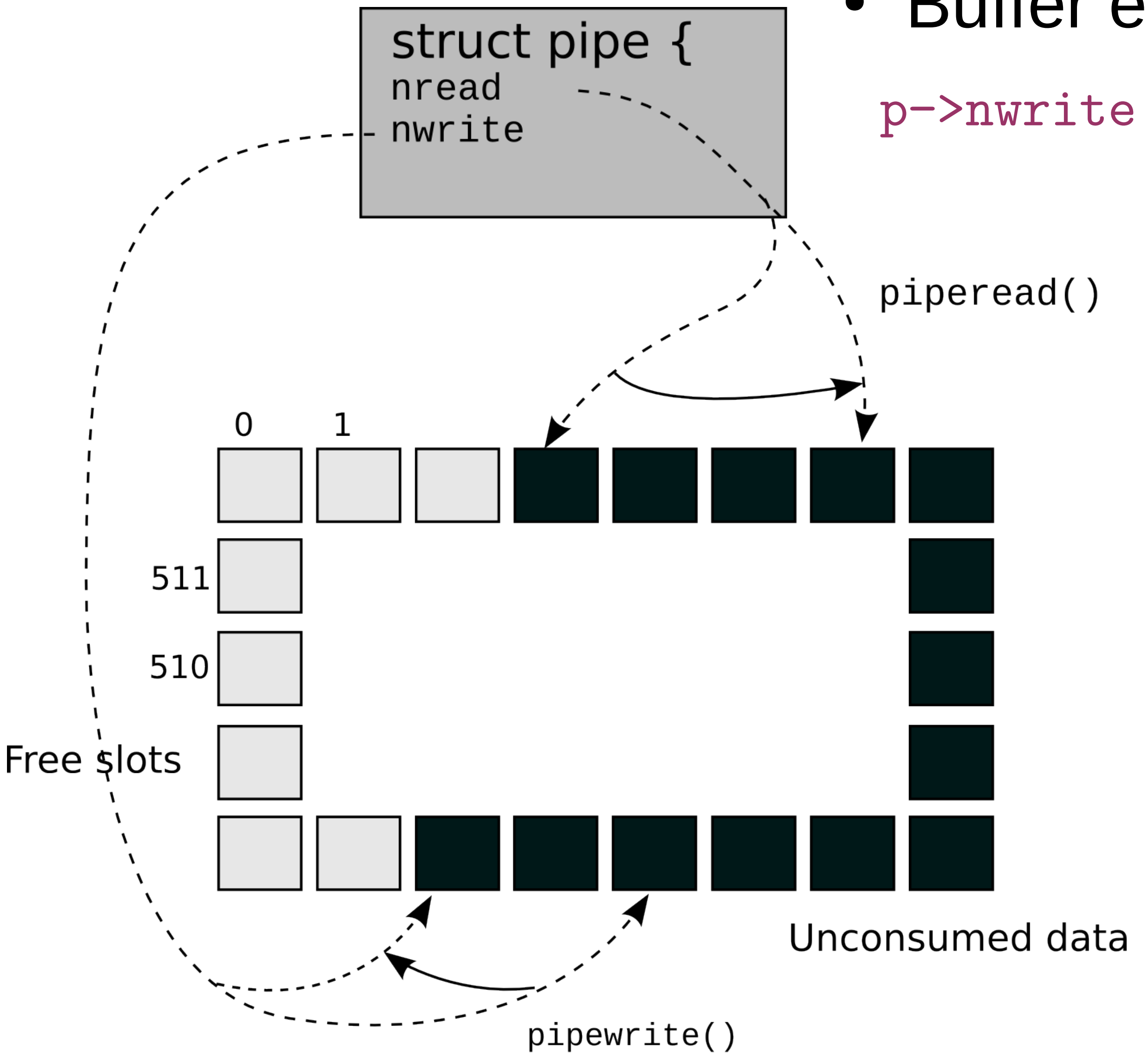
Pipe buffer

- Buffer full

$\boxed{\texttt{p->nwrite == p->nread + PIPESIZE}}$

- Buffer empty

`p->nwrite == p->nread`



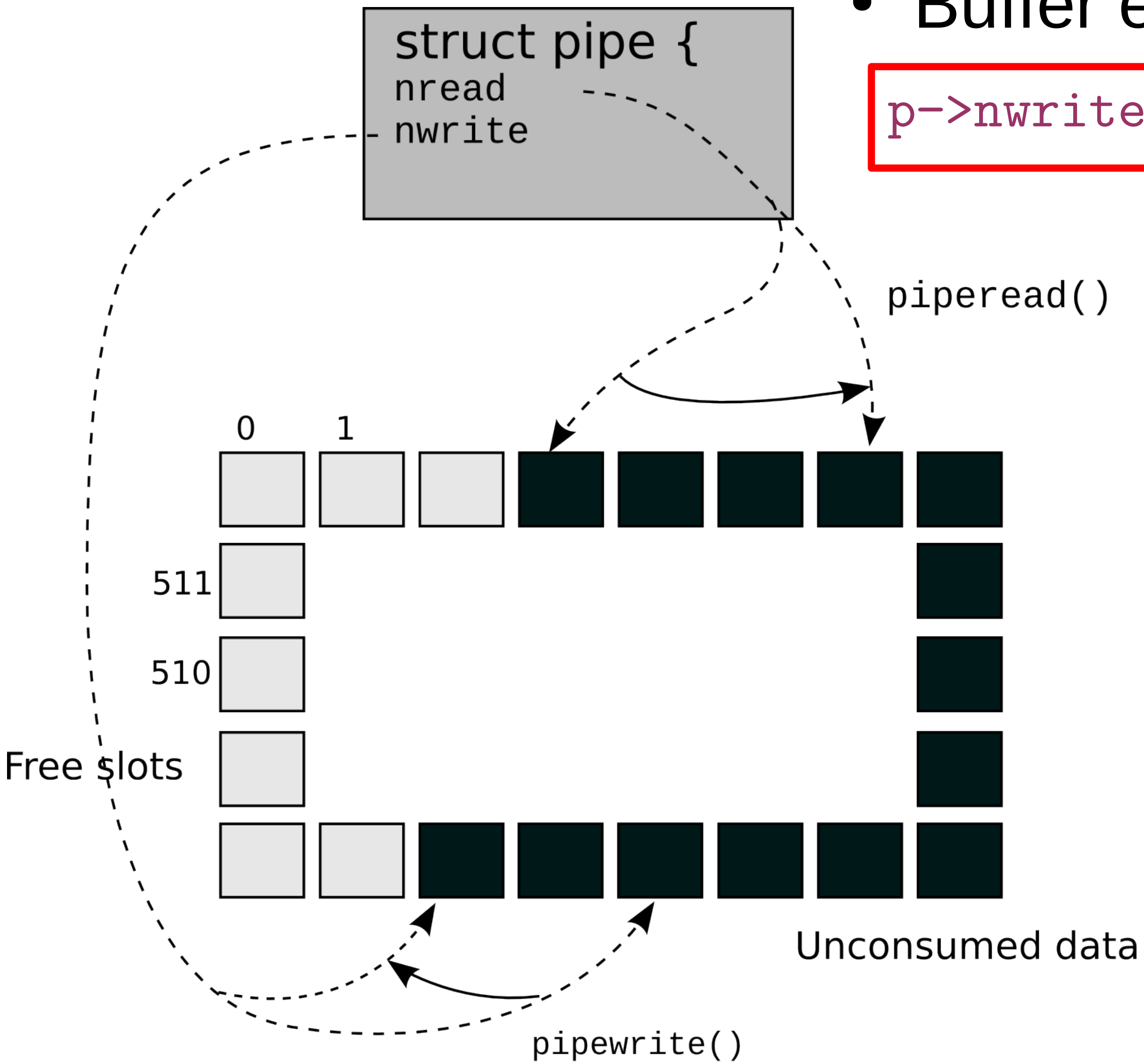
Pipe buffer

- Buffer full

`p->nwrite == p->nread + PIPESIZE`

- Buffer empty

`p->nwrite == p->nread`



piperead()

```
piperead(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  while(p->nread == p->nwrite && p->writeopen){
    if(proc->killed){
      release(&p->lock);
      return -1;
    }
    sleep(&p->nread, &p->lock);
  }
  for(i = 0; i < n; i++){
    if(p->nread == p->nwrite)
      break;
    addr[i] = p->data[p->nread++ % PIPESIZE];
  }
  wakeup(&p->nwrite);
  release(&p->lock);
  return i;
}
```

- Acquire pipe lock
  - All pipe operations are are protected with the lock

piperead()

```
piperead(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  while(p->nread == p->nwrite && p->writeopen){
    if(proc->killed){
      release(&p->lock);
      return -1;
    }
    sleep(&p->nread, &p->lock);
  }
  for(i = 0; i < n; i++){
    if(p->nread == p->nwrite)
      break;
    addr[i] = p->data[p->nread++ % PIPESIZE];
  }
  wakeup(&p->nwrite);
  release(&p->lock);
  return i;
}
```

- If the buffer is empty && the write end is still open
  - Go to sleep

piperead()

```
piperead(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  while(p->nread == p->nwrite && p->writeopen){
    if(proc->killed){
      release(&p->lock);
      return -1;
    }
    sleep(&p->nread, &p->lock);
  }
  for(i = 0; i < n; i++){
    if(p->nread == p->nwrite)
      break;
    addr[i] = p->data[p->nread++ % PIPESIZE];
  }
  wakeup(&p->nwrite);
  release(&p->lock);
  return i;
}
```

- After reading some data from the buffer
  - Wakeup the writer

pipewrite()

```c
pipewrite(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  for(i = 0; i < n; i++){
    while(p->nwrite == p->nread + PIPESIZE){
      if(p->readopen == 0 || proc->killed){
        release(&p->lock);
        return -1;
      }
      wakeup(&p->nread);
      sleep(&p->nwrite, &p->lock);
    }
    p->data[p->nwrite++ % PIPESIZE] = addr[i];
  }
  wakeup(&p->nread);
  release(&p->lock);
  return n;
}
```

- If the buffer is full
  - Wakeup reader
  - Go to sleep

pipewrite()

```
pipewrite(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  for(i = 0; i < n; i++){
    while(p->nwrite == p->nread + PIPESIZE){
      if(p->readopen == 0 || proc->killed){
        release(&p->lock);
        return -1;
      }
      wakeup(&p->nread);
      sleep(&p->nwrite, &p->lock);
    }
    p->data[p->nwrite++ % PIPESIZE] = addr[i];
  }
  wakeup(&p->nread);
  release(&p->lock);
  return n;
}
```

- If the buffer is full
  - Wakeup reader
  - Go to sleep
- However if the read end is closed
  - Return an error
  - (-1)

pipewrite()

```
pipewrite(struct pipe *p, char *addr, int n)
{
  int i;

  acquire(&p->lock);
  for(i = 0; i < n; i++){
    while(p->nwrite == p->nread + PIPESIZE){
      if(p->readopen == 0 || proc->killed){
        release(&p->lock);
        return -1;
      }
      wakeup(&p->nread);
      sleep(&p->nwrite, &p->lock);
    }
    p->data[p->nwrite++ % PIPESIZE] = addr[i];
  }
  wakeup(&p->nread);
  release(&p->lock);
  return n;
}
```

- Otherwise keep writing bytes into the pipe
- When done
  - Wakeup reader

Thank you!