Building Concurrency Primitives

Science

Computer Science

CS 450 : Operating Systems

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Previously …

1. Decided concurrency was a useful (sometimes necessary) thing to have
2. Assumed the presence of concurrent programming "primitives" (e.g., locks)
3. Showed how to use these primitives in concurrent programming scenarios

… but how are these primitives actually constructed?

- as usual: responsibility is shared between kernel and hardware

Agenda

- The mutex lock
- xv6 concurrency mechanisms
  - code review: implementation & usage

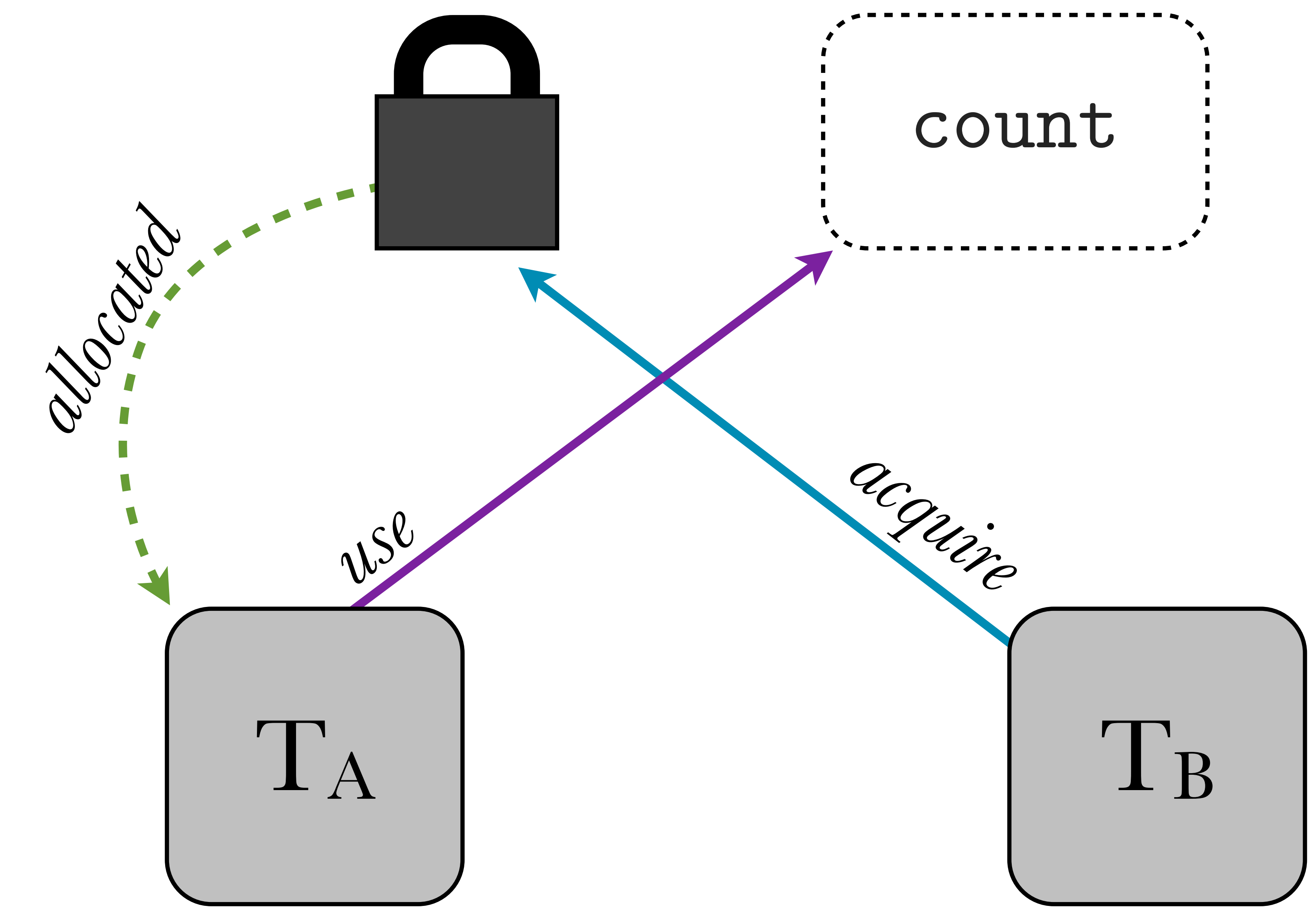
§ The mutex lock

Thread A

```
a1  count = count + 1
```

Thread B

```
b1  count = count + 1
```



basic requirement: prevent other threads from entering their critical section while one thread holds the lock

i.e., execute critical section *in mutex*

lock-polling — "spinlock":

```c
struct spinlock { int locked; };
```

```c
void acquire(struct spinlock *l) {
    while (1) {
        if (!l->locked) {
            l->locked = 1;
            break;
        }
    }
}

void release(struct spinlock *l) {
    l->locked = 0;
}
```

```c
if (!l->locked) {   // test
    l->locked = 1;  // set
    break;
}
```

problem: thread can be preempted between test & set

- again, must guarantee execution of test & set in mutex … (using a lock?!)

recognize that *preemption* is caused by a hardware *interrupt* …

… so, disable interrupts!

recall: x86 interrupt flag (IF) in FLAGS register

- cleared/set by `cli`/`sti` instructions
- restored by `iret` instruction
- note: above are all *privileged* operations — i.e., must be performed by kernel

can try to avoid spinlocks altogether:

user

```
begin_mutex();

/* critical section */

end_mutex();
```

kernel

```
asm ("cli");        asm ("sti");
```

horrible idea!

- user code *cannot be preempted*; kernel effectively neutered
- also, prohibits all concurrency (not just for related critical sections)

ought only block interrupts in kernel space, and minimize blocked time frame

```
void acquire(struct spinlock *l) {
    int done = 0;
    while (!done) {
        asm ("cli");
        if (!l->locked)
            done = l->locked = 1;
        asm ("sti");
    }
}

void release(struct spinlock *l) {
    l->locked = 0;
}
```

but!

- preventing interrupts only helps to avoid concurrency *due to preemption*
- insufficient on a multiprocessor system!
  - where we have true *parallelism*
  - each processor has its own interrupts

(fail)

```
asm ("cli");
if (!l->locked)
    done = l->locked = 1;
asm ("sti");
```

instead of general mutex, recognize that all we need is to make *test* (read) & *set* (write) operations on lock *atomic*

```
if (!l->locked)
    done = l->locked = 1;
```

enter: x86 *atomic exchange* instruction (`xchg`)

- atomically *swaps* reg/mem content
- guarantees no out-of-order execution

```
# note: pseudo-assembly!
loop:
    movl  $1, %eax          # set up "new" value in reg
    xchgl l->locked, %eax   # swap values in reg & lock
    test  %eax, %eax
    jne   loop              # spin if old value ≠ 0
```

xv6: spinlock.c

```
void acquire(struct spinlock *lk) {
  ...
  // keep looping until we atomically "swap" a 0 out of the lock
  while(xchg(&lk->locked, 1) != 0) ;
}

void release(struct spinlock *lk) {
  xchg(&lk->locked, 0);
  ...
}
```

xv6 uses spinlocks *internally*

e.g., to protect proc array in scheduler:

```
void scheduler(void) {
    ...
    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      proc = p;
      swtch(&cpu->scheduler, proc->context);
    }
    release(&ptable.lock);
}
```

maintains mutex across parallel execution of scheduler on separate CPUs in theory, scheduler execution may also be interrupted by the clock … which causes the current thread to *yield*:

```
void yield(void) {
  acquire(&ptable.lock);
  proc->state = RUNNABLE;
  sched();
  release(&ptable.lock);
}
```

what could go wrong?

```c
void yield(void) {
  acquire(&ptable.lock);
  proc->state = RUNNABLE;
  sched();
  release(&ptable.lock);
}
```

```c
void scheduler(void) {
  acquire(&ptable.lock);
  ...
  release(&ptable.lock);
}
```

Locks are designed to enforce mutex *between threads*.

If one thread tries to acquire a lock more than once, it will have to *wait for itself* to release the lock …

… which it can't/won't. Deadlock!

xv6's (ultra-conservative) policy:

- *never* hold a lock with interrupts enabled
- corollary: can only enable interrupts when *all* locks have been released (may hold more than one at any time)
  - must be careful about re-enabling interrupts prematurely when releasing a lock

```c
// maintain a "stack" of cli/sti calls
void pushcli(void) {
  int eflags;

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

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

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

void release(struct spinlock *lk)
{
  ...
  xchg(&lk->locked, 0);
  popcli();
}
```

spinlock usage:

- when to lock?
- how long to hold onto a lock?

spinlocks are *very inefficient*!

- lock polling is indistinguishable from application logic — will burn through scheduler time quanta
- not intended for long-term synchronization (e.g., “blocking”)

a “blocked” thread shouldn’t consume CPU cycles until some condition(s) necessary for it to run are true

- e.g., data from I/O request is ready; child process ready for reaping by parent (via `wait`) xv6 implements `sleep` and `wakeup` mechanism for blocking threads on semantic "channels" (`proc.c`)

- distinct scheduler state (`SLEEPING`) prevents re-activation

```c
// Put calling process to sleep on chan
void
sleep(void *chan)
{
  proc->chan = chan;
  proc->state = SLEEPING;
  sched(); // context switch away from proc
  proc->chan = 0;
}
```

```c
// Wake up all processes sleeping on chan.
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;
}
```

Q: What happens if sleep and wakeup are called simultaneously?

A: Race condition! Wakeup may be "lost".

```c
void
sleep(void *chan, struct spinlock *lk)
{
  // Acquire ptable.lock so we don't miss
  // and wakeups
 if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }

  // Go to sleep.
  proc->chan = chan;
  proc->state = SLEEPING;
  sched(); // note: scheduler releases lock

  proc->chan = 0;

  // Reacquire original lock.
  if(lk != &ptable.lock){
    release(&ptable.lock);
    acquire(lk);
  }
}
```

```c
// Wake up all processes sleeping on chan.
void
wakeup(void *chan)
{
  acquire(&ptable.lock);
  wakeup1(chan);
  release(&ptable.lock);
}


// Wake up all processes sleeping on chan.
// The ptable lock must be held.
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;
}
```

Sample usage: `wait` / `exit`

```c
// Wait for a child process to exit.
int
wait(void)
{
  struct proc *p;
  int havekids, pid;

  acquire(&ptable.lock);
  for(;;){
    for(p=ptable.proc; p<&ptable.proc[NPROC]; p++){
      if(p->parent != proc)
        continue;
     if(p->state == ZOMBIE){
        pid = p->pid;
       release(&ptable.lock);
        return pid;
      }
    }

   sleep(proc, &ptable.lock);
  }
}
```

```c
// Exit the current process.
// An exited process remains a zombie until its
// parent calls wait() to find out it exited.
void
exit(void)
{
  struct proc *p;
 acquire(&ptable.lock);

  wakeup1(proc->parent);

  // Pass orphaned children to init.
  for(p=ptable.proc; p<&ptable.proc[NPROC]; p++){
    if(p->parent == proc){
      p->parent = initproc;
      if(p->state == ZOMBIE)
        wakeup1(initproc);
    }
  }

  proc->state = ZOMBIE;
  sched();
  panic("zombie exit");
}
```