Condition Variables

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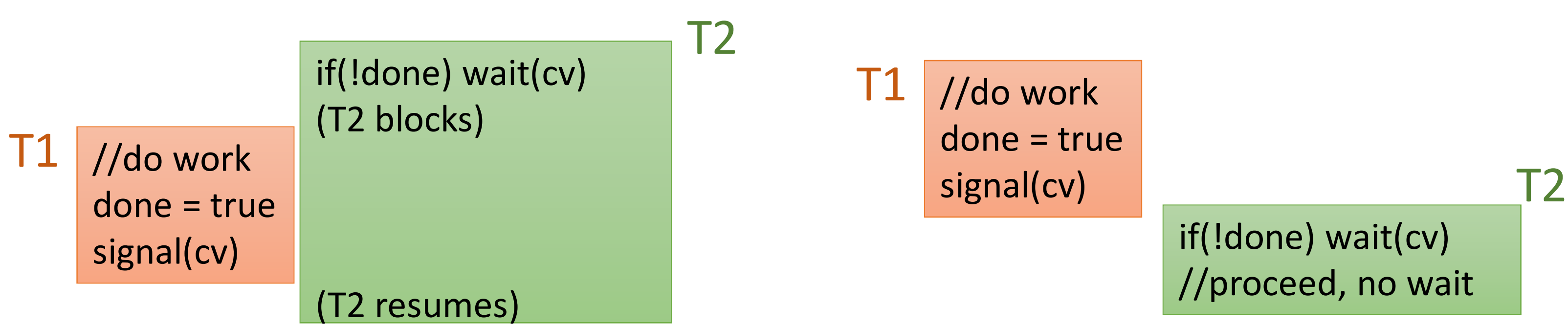
Wait and signal mechanisms for threads

- Locks allow one type of synchronization between threads – mutual exclusion when accessing critical sections
- Another common requirement in multi-threaded applications – waiting for events and signaling when event occurs
  - E.g., Thread T2 wants to run only after T1 has finished some task (T1→T2)
- Naive solution: T2 keeps checking periodically if T1 is done
  - Wastes CPU cycles, inefficient
  - Need a new synchronization primitive to wait for an event

Condition variables

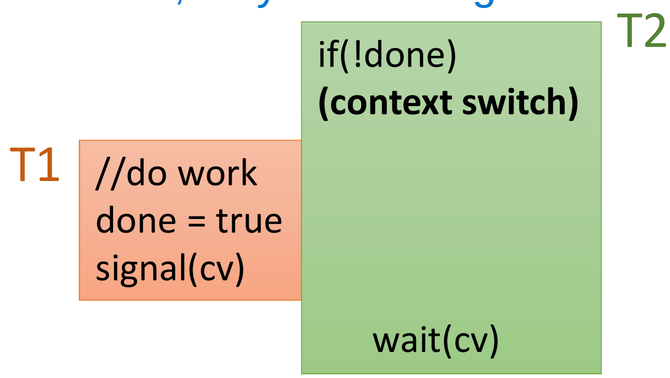
- Pthread library provides special variables called condition variables (CV)
  - A thread calls wait function on a CV, it is blocked and gets added to a list of threads waiting on that CV
  - Another thread calls signal on a CV, one of the waiting threads gets ready to run again, will be scheduled in the future (no immediate context switch)
- Example: we want T2 to run only after T1 does its work (T1→T2)
  - T1 does its work and calls signal
  - T2 checks if work is done, and calls wait if work is not done



Atomicity in wait and signal (1)

- Checking condition and waiting must be atomic, deadlock otherwise
  - Thread T2 checks condition is false, context switch just before blocking
  - Meanwhile T1 makes condition true, calls signal. But signal doesn't wake up anyone (none sleeping yet)
  - T2 resumes, goes to sleep forever (no one will signal again)
- This is called missed wakeup problem: how to fix?

There isn't a signal buffer, so you do things of wait and wakeup with lock's held.



Atomicity in wait and signal (2)

- Solution: use a lock/mutex to protect atomicity of sleeping
  - T2 holds a lock, checks condition, calls wait
  - Lock released only after T2 is added to list of waiting processes (ensures atomicity of checking condition and sleeping)
  - T1 acquires **same** lock before calling signal, ensuring that signal cannot happen in between checking condition and waiting
  - Pthread CV implementation releases lock during wait, reacquires on wakeup

T2

```
if(!done)
(context switch)
```

T1

```
//do work
done = true
signal(cv)
```

T2

```
    wait(cv)
```

T2

```
lock(mutex)
if(!done)
   wait(cv, mutex)
```

T1

```
lock(mutex)
done = true
signal(cv)
unlock(mutex)
```

T2

```
unlock(mutex)
```

Use as few as possible locks, so update the local variables and with lock the shared variables to save the resources and CPU of course

Example: parent waits for child

```
int done  = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c  = PTHREAD_COND_INITIALIZER;

void thr_exit() {
    Pthread_mutex_lock(&m);
    done = 1;
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}

void thr_join() {
    Pthread_mutex_lock(&m);
    while (done == 0)
        Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

Figure 30.3: Parent Waiting For Child: Use A Condition Variable

Image credit: OSTEP

Guidelines for using condition variables

- Use the same lock for wait and signal (maybe for other variables too)
- Before calling wait, confirm that the condition is indeed false
  - T2 must check “done” variable before calling wait (what if T1 has already run?)

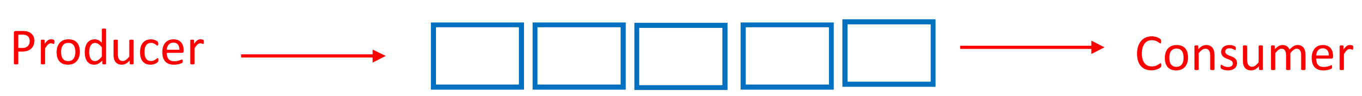
    Otherwise nobody would be there to wake you up.
- Signal broadcast wakes up all threads while signal wakes up any one
- Good habit to check condition with “while” loop and not “if”
  - To avoid corner cases of thread being woken up even when condition not true (may be an issue with some implementations)

```
if(condition)
  wait(condvar)
//small chance that condition may be false when wait returns

while(condition)
  wait(condvar)
//condition guaranteed to be true since we check in while-loop
```

Example: Producer-consumer problem

- Producer and consumer threads, sharing data via a buffer of bounded size
  - Producers produce items, add into a shared buffer
  - Consumers consume item from shared buffer
- What kind of coordination is needed between threads?
  - Producer thread produces and places items into buffer, waits if the buffer is full → Consumer signals after making space in the buffer
  - Consumer thread consumes items from buffer, waits if the buffer is empty → Producer signals after producing items



Example: Multi-threaded server

- Master thread accepts requests and puts them in a queue
- Worker threads fetch requests from this queue and process them

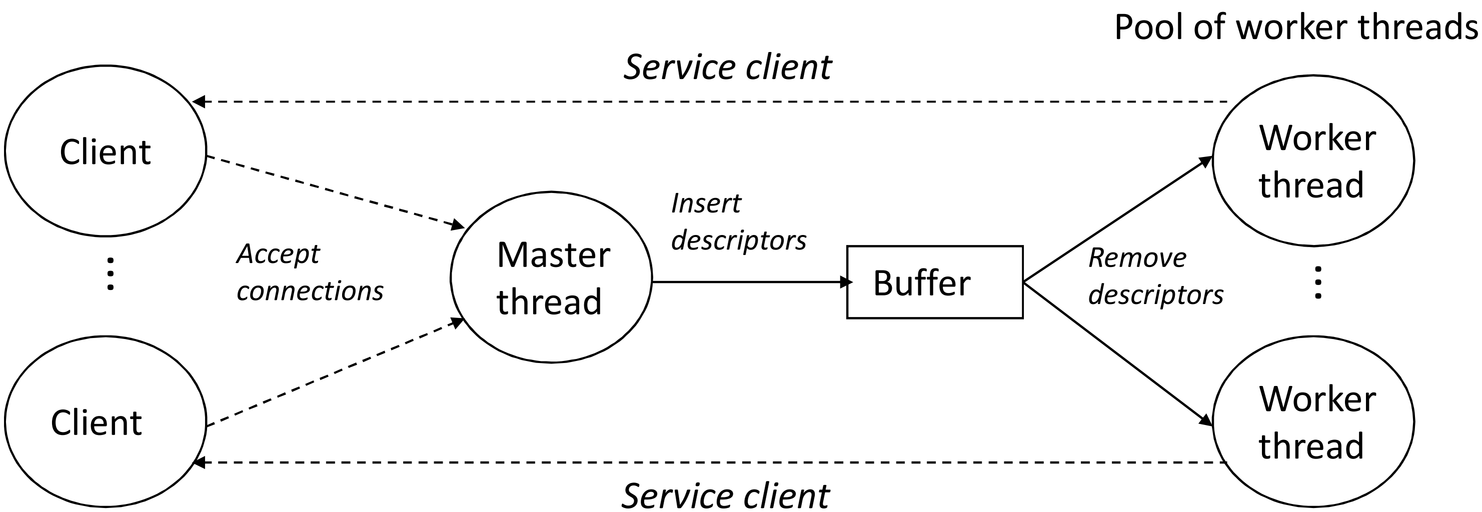


Image credit: CSAPP

Example: Producer-consumer problem

- Solution using condition variables
  - Mutex/lock used while modifying shared buffer
  - Two CVs: one for producers to wait, and one for consumers to wait

```
//Producer
lock(mutex)
if(no free space in buffer)
    wait(cv_producer, mutex)
produce item, add to buffer
signal(cv_consumer)
unlock(mutex)
```

```
//Consumer
lock(mutex)
if(no items in buffer)
    wait(cv_consumer, mutex)
consume item from buffer
signal(cv_producer)
unlock(mutex)
```

Producer/Consumer with 2 CVs

```
cond_t empty, fill;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == MAX)
            Pthread_cond_wait(&empty, &mutex);
        put(i);
        Pthread_cond_signal(&fill);
        Pthread_mutex_unlock(&mutex);
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 0)
            Pthread_cond_wait(&fill, &mutex);
        int tmp = get();
        Pthread_cond_signal(&empty);
        Pthread_mutex_unlock(&mutex);
        printf("%d\n", tmp);
```

Image credit: OSTEP

Example: Batched processing

- Example scenario: two kinds of threads in an application
  - Request threads, each containing an application request
  - Batch processor thread processes N requests at a time in a batch
- What kind of synchronization do we need?
  - Batch processing thread must wait until N requests arrive, then start batch
  - Request thread must wait until batch starts, then get processed and finish
- Example: suppose Covid-19 vaccination vial has 10 doses. Nurse waits for 10 patients to arrive, then opens the vial and vaccinates all 10

Example: Batched processing

- Solution using two CVs: one for requests to wait, one for batch processor to wait
  - Other integer and Boolean variables, mutex/lock for atomicity

This implementation has to have 'n' request threads.

```
//Request thread
lock(mutex)
count++
if(count == N)
   signal(cv_batch_processor)
while(not batch_started)
   wait(cv_request, mutex)
unlock(mutex)
```

```
//Batch processor thread
lock(mutex)
while(count < N)
   wait(cv_batch_processor, mutex)
batch_started = true
signal_broadcast(cv_request)
unlock(mutex)
```

Example: Batched processing

- What is wrong with this solution?
  - Nth request thread calls wait before invoking signal to wake up batch processor
  - Batch processor never wakes up, all threads will sleep forever
  - Before you sleep, ensure that the signaling code can run in future

```
//Request thread
lock(mutex)
count++
while(not batch_started)
   wait(cv_request, mutex)
if(count == N)
   signal(cv_batch_processor)
unlock(mutex)
```

```
//Batch processor thread
lock(mutex)
while(count < N)
   wait(cv_batch_processor, mutex)
batch_started = true
signal_broadcast(cv_request)
unlock(mutex)
```

Here Request thread isn't giving the signal of wakeup to batch processor if batch processor was already sleeping, so the batch_started variable never becomes true and any requested thread will always wait on cv_request

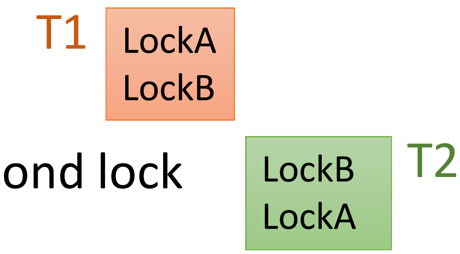
Deadlock

Synchronization patterns using CVs

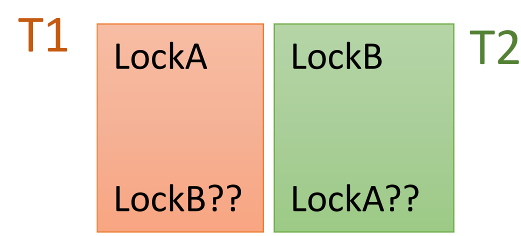
- Many examples in the practice problems
  - Scenario describing multiple threads/entities and how they should interact and coordinate with each other
  - Toy examples modelled after real world application design patterns
- How to write code with correct synchronization
  - Identify when each entity should wait and write the suitable waiting code
  - For each wait, figure out how the signaling will happen and write the code
  - Ensure that signaling path in the code is not blocked in any way, e.g., signal others first before calling wait and going to sleep
  - Update all extra variables (counts, flags) in the solution correctly
  - Run through your code in a few different scenarios and different order of execution of threads to convince yourself that it works correctly

Watch out for deadlocks

- Deadlock: threads are stuck in blocked state without making progress
- Example: thread sleeps by calling wait on CV, no other thread calls signal, so thread sleeps forever
- Example: circular wait when acquiring multiple locks
  - T1 acquires LockA and LockB, T2 acquires LockB and LockA
  - T1 acquires LockA, T2 acquires LockB, each is waiting for second lock
  - Deadlock if executions interleave in some ways



- Techniques to avoid deadlocks
  - Acquire locks in same order across all threads of process
  - When sleeping, ensure someone will wake you up!



Sleep and wakeup in xv6 (1)

- xv6 does not have userspace threads, only single threaded processes
- But multiple processes may be in kernel mode on different CPU
  - Uses locks to protect access to shared kernel data structures
- OS also needs a mechanism to let processes sleep (e.g., when process makes blocking disk read syscall) and wakeup when some events occur (e.g., disk has raised interrupt and data is ready)
- Process P1 in kernel mode calls sleep to give up CPU, gets blocked until event
- Another process P2 (in kernel mode) wakes up P1 when the event occurs

Sleep and wakeup in xv6 (2)

- A process P1 that wishes to block and give up CPU calls “sleep”
  - Example: process reads a block from disk, must block until disk read completes
  - Read syscall → sleep → sched() to give up CPU
- Another process P2 calls “wakeup” when event to unblock P1 occurs
  - P2 calls wakeup → marks P1 as runnable, no context switch immediately
  - Example: disk interrupt occurred when P2 is running, P2 runs interrupt handler, which will call wakeup
- P1 will be scheduled at a later time, will resume at sched(), return
- Spinlock protects atomicity of sleep: P1 calls sleep with some spinlock L held, P2 calls wakeup with same spinlock L held

Sleep and wakeup in xv6 (3)

- How does P2 know which process to wake up?
- When P1 sleeps, it sets a channel (void * chan) in its struct proc
  - Arguments to sleep: channel, spinlock to protect atomicity of sleep
- P2 calls wakeup on same channel
  - Arguments to wakeup: channel (lock must be held)
- Channel = any value known to both P1 and P2
  - Example: channel value for disk read can be address of disk block

Example: wait and exit

- If wait called in parent while children are running, parent calls sleep and gives up CPU (channel is parent struct proc pts, lock is ptable.lock)

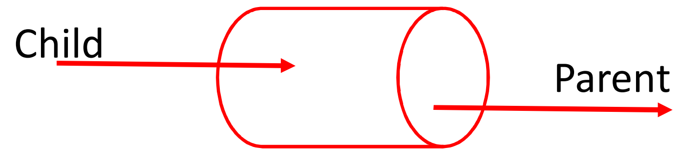
```
// Wait for children to exit.  (See wakeup1 call in proc_exit.)
sleep(curproc, &ptable.lock);
```

- In exit, child acquires ptable.lock, wakes up parent using its channel

```
// Parent might be sleeping in wait().
wakeup1(curproc->parent);
```

- Why is terminated process memory cleaned up by parent?
  - When a process calls exit, kernel stack, page table etc are in use, all this memory cannot be cleared until terminated process has been taken off the CPU

Example: pipes in xv6 (1)



- xv6 provides anonymous pipes for IPC between parent and child processes
- Example: Parent P and child C share anonymous pipe
- Child C writes into pipe, parent P reads from pipe
- One of P or C closes read end, other closes write end

```
//userspace code

int fd[2]
pipe(fd) //syscall to create pipe

int ret = fork()

if(ret == 0) {//child
   close(fd[0]) //close read end
   write(fd[1], message, ..)
}
else {//parent
   close(fd[1]) //close write end
   read(fd[0], message, ..)
}
```

Example: pipes in xv6 (2)

- Internal implementation inside kernel
  - Common shared buffer, protected by a spinlock
  - Write system call stores data in shared buffer
  - Read system call returns data from shared buffer
  - Variables nread and nwrite indicate number of bytes read/written in buffer

```
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
};
```

data is pushed in circular order, but the offset only increase, once written or read can't go back. that's gone.

Example: pipes in xv6 (3)

- Implementation of pipe read and write system calls uses sleep/wakeup
- Pipe reader sleeps if pipe is empty, pipe writer wakes it up
- Pipe writer sleeps if pipe is full, pipe reader wakes it up
- Channel for sleep/wakeup = address of pipe structure variables

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

  acquire(&p->lock);
  for(i = 0; i < n; i++){          pipe is full
    while(p->nwrite == p->nread + PIPESIZE){
      if(p->readopen == 0 || myproc()->killed){
        release(&p->lock);
        return -1;
      }                             writer's channel for sleep is
      wakeup(&p->nread);            address of nwrite variable
      sleep(&p->nwrite, &p->lock);
    } Variable value can change but address won't
    p->data[p->nwrite++ % PIPESIZE] = addr[i];
  }
  wakeup(&p->nread);wakeup anyone in reading
  release(&p->lock);channel
  return n;
}
```

When a reader finds the buffer empty, it doesn't remove any data (because there is none) and therefore doesn't free up space. And wakeup is called only when reader frees up some space in the buffer.

Example: pipes in xv6 (4)

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

  acquire(&p->lock);
```

pipe is empty

```
  while(p->nread == p->nwrite && p->writeopen){
    if(myproc()->killed){
      release(&p->lock);
      return -1;
    }
```

reader’s channel is address of nread variable

```
    sleep(&p->nread, &p->lock);
  }
```

pipe lock protects atomicity of sleep

```
  for(i = 0; i < n; i++){
    if(p->nread == p->nwrite)
```

if written content is finished, done go back.

```
      break;
    addr[i] = p->data[p->nread++ % PIPESIZE];
  }
```

offset increases only.

```
  wakeup(&p->nwrite);
```

Only if write process is waiting it'll wakeup otherwise doesn't matter

```
  release(&p->lock);
  return i;
}
```

Sleep function

- Sleep and wakeup called by processes with same lock held (to protect atomicity of sleep)
- Acquire ptable lock (if not already taken), then release other spinlock
- Reacquire original lock on return

```c
void
sleep(void *chan, struct spinlock *lk)
{
  struct proc *p = myproc();

  if(p == 0)
    panic("sleep");

  if(lk == 0)
    panic("sleep without lk");

  // Must acquire ptable.lock in order to
  // change p->state and then call sched.
  // Once we hold ptable.lock, we can be
  // guaranteed that we won't miss any wakeup
  // (wakeup runs with ptable.lock locked),
  // so it's okay to release lk.
  if(lk != &ptable.lock){
    acquire(&ptable.lock);
    release(lk);
  }
  // Go to sleep.
  p->chan = chan;
  p->state = SLEEPING;

  sched();

  // Tidy up.
  p->chan = 0;

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

Wakeup function

- Wakeup acquires ptable.lock to change process to runnable
- If lock protecting atomicity of sleep is ptable.lock itself, then directly call wakeup1
- Wakes up all processes sleeping on a channel in ptable (more like signal broadcast of condition variables)

```
// 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;
}

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