# Condition Variables

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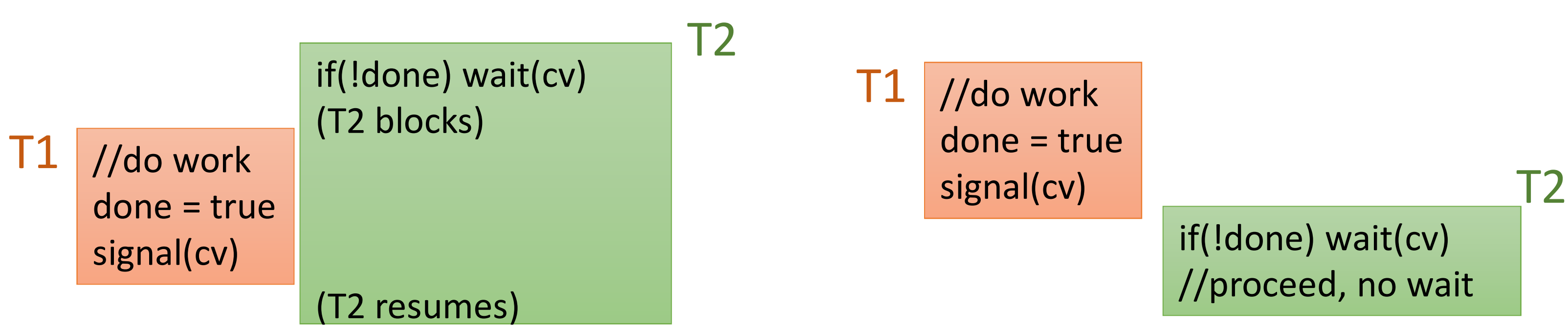
# Wait and signal mechanisms for threads

- 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

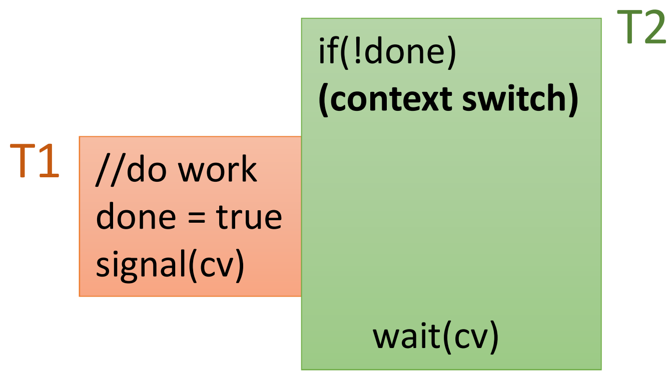
# Condition variables

- 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



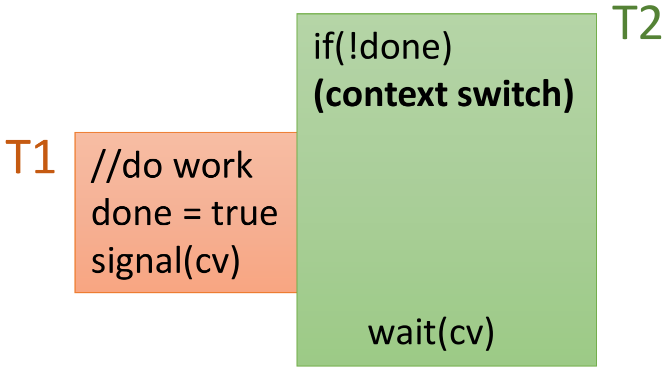
# Atomicity in wait and signal (1)

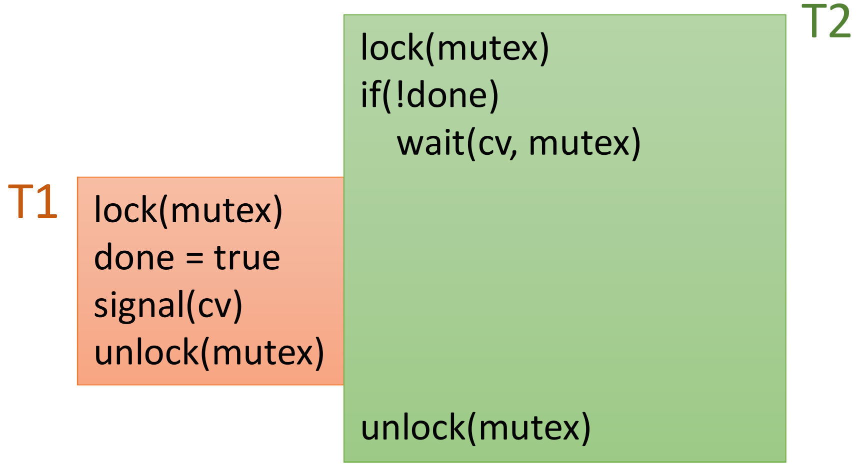
- Checking condition and waiting must be atomic, deadlock otherwise
  - Thread T2 checks condition is false, context switch just before blocking
  - Meanwhile T1 makes condition true, calls signal. But signal doesn't wake up anyone (none sleeping yet)
  - T2 resumes, goes to sleep forever (no one will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



# 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



# 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?)
- 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

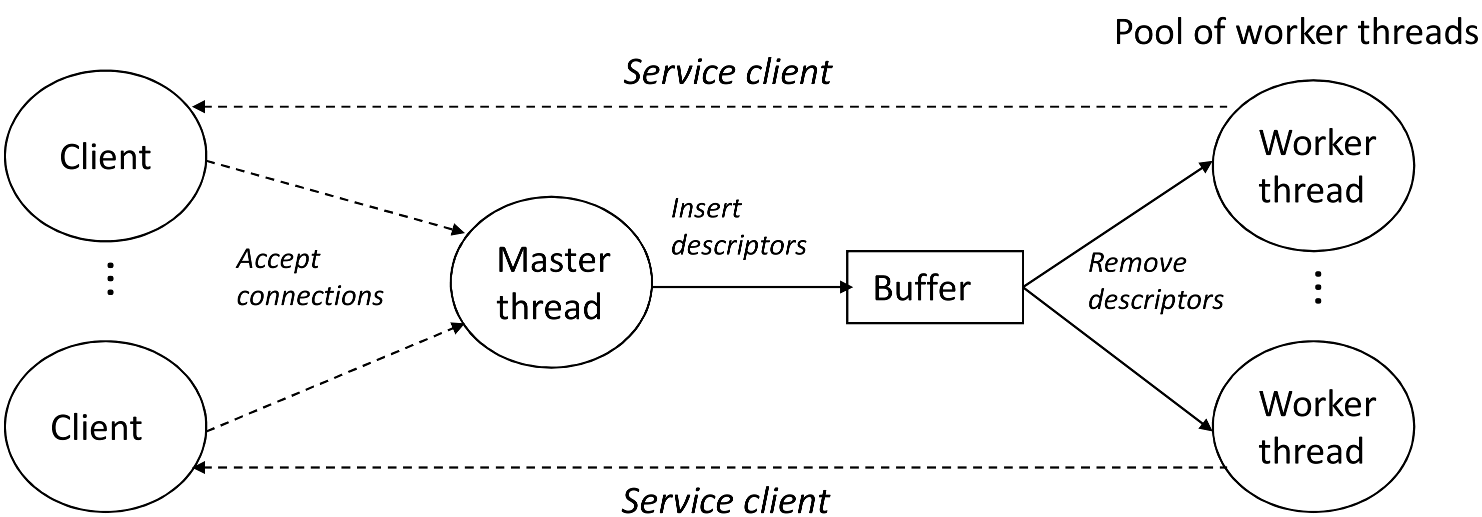



Image credit: CSAPP

# 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

```
//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)
```

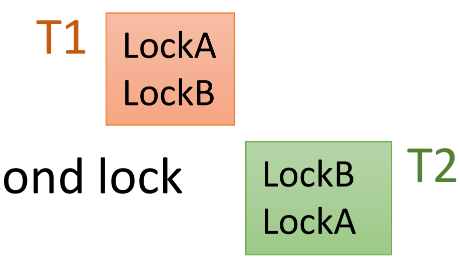
```
//Batch processor thread
lock(mutex)
while(count < N)
   wait(cv_batch_processor, mutex)
batch_started = true
signal_broadcast(cv_request)
unlock(mutex)
```

# 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!