Programming for Multi-Core CPUs: Locking and Transactional Memory

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Slides 1-18 are from Professor Umakishore Ramachandran @ GaTech

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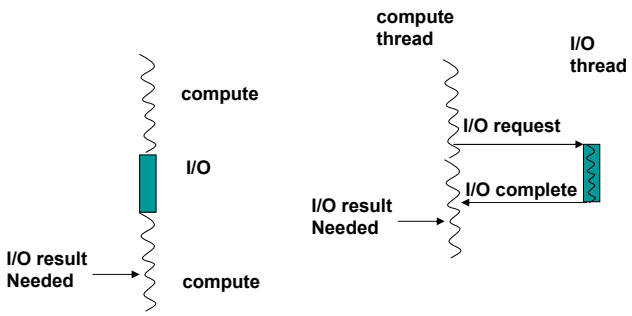
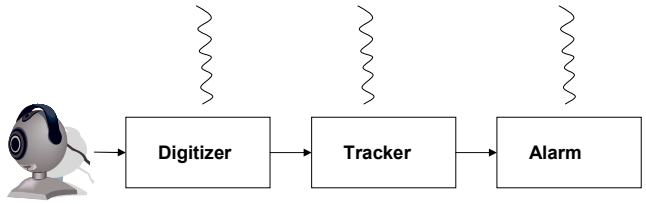
Example use of threads - 1



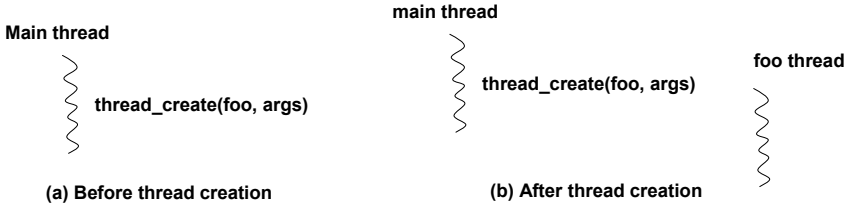
(a) Sequential process (b) Multithreaded process

Example use of threads - 2



Programming Support for Threads

- creation
  - pthread_create(top-level procedure, args)
- termination
  - return from top-level procedure
  - explicit kill
- rendezvous
  - creator can wait for children
    - pthread_join(child_tid)
- synchronization
  - mutex
  - condition variables

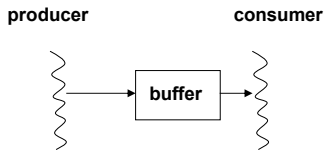


Sample program – thread create/join

```
int foo(int n)
{
  .....
  return 0;
}
int main()
{
      int f;
      thread_type child_tid;

      .....

      child_tid = thread_create (foo, &f);

      .....

      thread_join(child_tid);
}
```


Programming with Threads

- synchronization
  - for coordination of the threads
- communication
  - for inter-thread sharing of data
  - threads can be in different processors
  - how to achieve sharing in SMP?
    - software: accomplished by keeping all threads in the same address space by the OS
    - hardware: accomplished by hardware shared memory and coherent caches

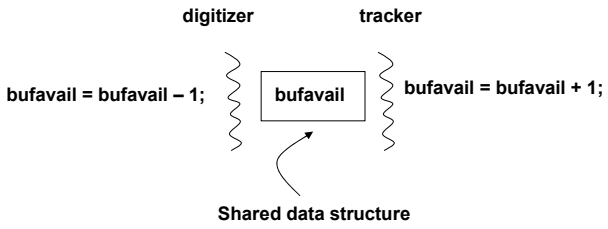


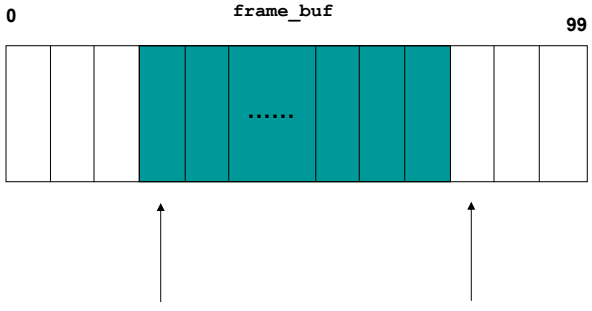
Need for Synchronization

```
digitizer()
{
 image_type dig_image;
 int tail = 0;
 loop {
  if (bufavail > 0) {
   grab(dig_image);
   frame_buf[tail mod MAX]
          = dig_image;
   tail = tail + 1;
   bufavail = bufavail - 1;
  }
 }
}
```

```
tracker()
{
 image_type track_image;
 int head = 0;
 loop {
  if (bufavail < MAX) {
   track_image =
    frame_buf[head mod MAX];
   head = head + 1;
   bufavail = bufavail + 1;
   analyze(track_image);
  }
 }
}
```

Problem?





Synchronization Primitives

- lock and unlock
  - mutual exclusion among threads
  - busy-waiting Vs. blocking
  - pthread_mutex_trylock: no blocking
  - pthread_mutex_lock: blocking
  - pthread_mutex_unlock

Fix number 1 – with locks

```
digitizer()
{
 image_type dig_image;
 int tail = 0;
 loop {
  thread_mutex_lock(buflock);
    if (bufavail > 0) {
      grab(dig_image);
      frame_buf[tail mod MAX]
         = dig_image;
      tail = tail + 1;
      bufavail = bufavail - 1;
    }
  thread_mutex_unlock(buflock);
 }
}
```

```
tracker()
(
 image_type track_image;
 int head = 0;

 loop {
  thread_mutex_lock(buflock);
    if (bufavail < MAX) {
      track_image =
         frame_buf[head mod MAX];
      head = head + 1;
      bufavail = bufavail + 1;
      analyze(track_image);
    }
  thread_mutex_unlock(buflock);
 }
}
```

Problem?

Fix number 2

```
digitizer()
{
 image_type dig_image;
 int tail = 0;

 loop {
  grab(dig_image);
  thread_mutex_lock(buflock);
   while (bufavail == 0) do
   nothing;
  thread_mutex_unlock(buflock);
  frame_buf[tail mod MAX] =
                    dig_image;
  tail = tail + 1;
  thread_mutex_lock(buflock);
   bufavail = bufavail - 1;
  thread_mutex_unlock(buflock);
 }
}
```

```
tracker()
{
 image_type track_image;
 int head = 0;

 loop {
  thread_mutex_lock(buflock);
   while (bufavail == MAX) do nothing;
  thread_mutex_unlock(buflock);
  track_image = frame_buf[head mod
                          MAX];
  head = head + 1;
  thread_mutex_lock(buflock);
   bufavail = bufavail + 1;
  thread_mutex_unlock(buflock);
  analyze(track_image);
 }
}
```

Problem?

Fix number 3

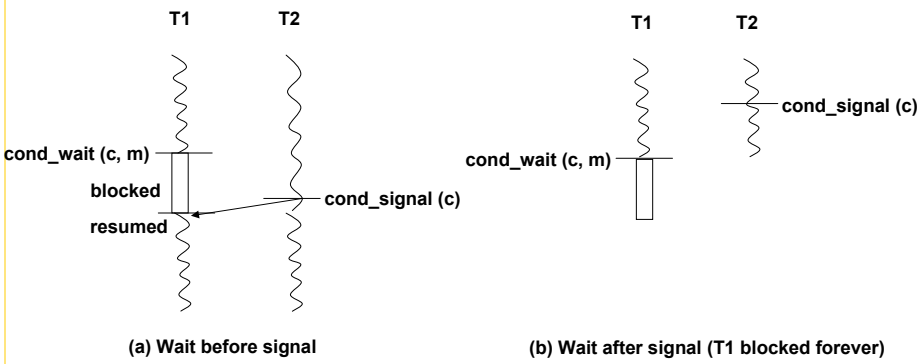
```
digitizer()
{
 image_type dig_image;
 int tail = 0;

 loop {
  grab(dig_image);
  while (bufavail == 0) do nothing;
  frame_buf[tail mod MAX] =
                    dig_image;
  tail = tail + 1;
  thread_mutex_lock(buflock);
   bufavail = bufavail - 1;
  thread_mutex_unlock(buflock);
 }
}
```

```
tracker()
{
 image_type track_image;
 int head = 0;

 loop {
  while (bufavail == MAX) do nothing;
  track_image = frame_buf[head mod
                          MAX];
  head = head + 1;
  thread_mutex_lock(buflock);
   bufavail = bufavail + 1;
  thread_mutex_unlock(buflock);
  analyze(track_image);
 }
}
```

Problem?

- condition variables
  - pthread_cond_wait: block for a signal
  - pthread_cond_signal: signal one waiting thread
  - pthread_cond_broadcast: signal all waiting threads

Wait and signal with cond vars



(a) Wait before signal

(b) Wait after signal (T1 blocked forever)

Fix number 4 – cond var

```
digitizer()
{
 image_type dig_image;
 int tail = 0;
 loop {
  grab(dig_image);
  thread_mutex_lock(buflock);
   if (bufavail == 0)
   thread_cond_wait(buf_not_full,
      buflock);
  thread_mutex_unlock(buflock);
  frame_buf[tail mod MAX] =
    dig_image;
  tail = tail + 1;
  thread_mutex_lock(buflock);
   bufavail = bufavail - 1;
   thread_cond_signal(buf_not_empty);
  thread_mutex_unlock(buflock);
 }
}
```

```
tracker()
{
 image_type track_image;
 int head = 0;
 loop {
  thread_mutex_lock(buflock);
   if (bufavail == MAX)
    thread_cond_wait(buf_not_empty,
       buflock);
  thread_mutex_unlock(buflock);
  track_image = frame_buf[head mod
    MAX];
  head = head + 1;
  thread_mutex_lock(buflock);
   bufavail = bufavail + 1;
   thread_cond_signal(buf_not_full);
  thread_mutex_unlock(buflock);
  analyze(track_image);
 }
}
```

This solution is correct so long as there is exactly one producer and one consumer

Gotchas in programming with cond vars

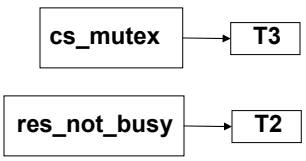
```
acquire_shared_resource()
{
 thread_mutex_lock(cs_mutex);
  if (res_state == BUSY)
   thread_cond_wait (res_not_busy,
    cs_mutex);
  res_state = BUSY;
 thread_mutex_unlock(cs_mutex);
}
release_shared_resource()
{
 thread_mutex_lock(cs_mutex);
  res_state = NOT_BUSY;
  thread_cond_signal(res_not_busy);
 thread_mutex_unlock(cs_mutex);
}
```

T3 is here

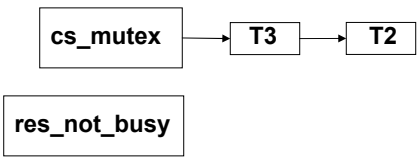
T2 is here

T1 is here

State of waiting queues



(a) Waiting queues before T1 signals



(a) Waiting queues after T1 signals

Gotchas in programming with cond vars

```
acquire_shared_resource()
{
  thread_mutex_lock(cs_mutex);
    if (res_state == BUSY)
      thread_cond_wait (res_not_busy,
      cs_mutex);
    res_state = BUSY;                    <-- T2 is here (get the lock)
  thread_mutex_unlock(cs_mutex);         <-- T3 is here (release the lock)
}
release_shared_resource()
{
  thread_mutex_lock(cs_mutex);
    res_state = NOT_BUSY;
    thread_cond_signal(res_not_busy);
  thread_mutex_unlock(cs_mutex);
}
                                         <-- T1 is here
```

Both T2 and T3 access the shared resource (which was supposed to be accessed exclusively)

Defensive programming – retest predicate

```
acquire_shared_resource()
{
  thread_mutex_lock(cs_mutex);          ← T3 is here
    while (res_state == BUSY)
      thread_cond_wait (res_not_busy, cs_mutex);    ← T2 is here
    res_state = BUSY;
  thread_mutex_unlock(cs_mutex);
}
release_shared_resource()
{
  thread_mutex_lock(cs_mutex);
    res_state = NOT_BUSY;               ← T1 is here
    thread_cond_signal(res_not_buys);
  thread_mutex_unlock(cs_mutex);
}
```


Defensive programming – retest predicate

```
acquire_shared_resource()
{
  thread_mutex_lock(cs_mutex);
    while (res_state == BUSY)
      thread_cond_wait (res_not_busy, cs_mutex);  ← T2 is still here
                                                    (get the lock, fail the condition, wait again)
    res_state = BUSY;
  thread_mutex_unlock(cs_mutex);  ← T3 is here (release the lock)
}
release_shared_resource()
{
  thread_mutex_lock(cs_mutex);
    res_state = NOT_BUSY;
    thread_cond_signal(res_not_buys);
  thread_mutex_unlock(cs_mutex);
                                  ← T1 is here
}
```

Transactional Memory

- Borrow the 'transaction' idea from database systems
- Atomic region
  - All commit or none commit
  - Read set / write set conflict detection
  - Rollback when conflict happens
  - Software implementation using locks
  - Hardware implementation with specialize cache designs

Lock-based code

```
digitizer()
{
 image_type dig_image;
 int tail = 0;
 loop {
  thread_mutex_lock(buflock);
    if (bufavail > 0) {
      grab(dig_image);
      frame_buf[tail mod MAX]
         = dig_image;
      tail = tail + 1;
      bufavail = bufavail - 1;
    }
  thread_mutex_unlock(buflock);
 }
}
```

```
tracker()
(
 image_type track_image;
 int head = 0;

 loop {
  thread_mutex_lock(buflock);
    if (bufavail < MAX) {
      track_image =
         frame_buf[head mod MAX];
      head = head + 1;
      bufavail = bufavail + 1;
      analyze(track_image);
    }
  thread_mutex_unlock(buflock);
 }
}
```

Problem?

Transactional memory programs

```
digitizer()
{
 image_type dig_image;
 int tail = 0;
 loop {
  atomic {
     if (bufavail > 0) {
       grab(dig_image);
       frame_buf[tail mod MAX]
                    = dig_image;
       tail = tail + 1;
       bufavail = bufavail - 1;
     }
  } // end of atomic region
 }
}
```

```
tracker()
(
 image_type track_image;
 int head = 0;

 loop {
  atomic {
     if (bufavail < MAX) {
       track_image =
   frame_buf[head mod MAX];
       head = head + 1;
       bufavail = bufavail + 1;
       analyze(track_image);
     }
  } // end of atomic region
 }
}
```


Transactional memory programs

```
digitizer()
{
 image_type dig_image;
 int tail = 0;
 loop {
  if (bufavail > 0) {
       grab(dig_image);
       frame_buf[tail mod MAX]
                    = dig_image;
       tail = tail + 1;
       atomic {
       bufavail = bufavail - 1;
       } // end of atomic region
     }
}
}
```

```
tracker()
{
 image_type track_image;
 int head = 0;

 loop {

     if (bufavail < MAX) {
       track_image =
   frame_buf[head mod MAX];
       head = head + 1;
       atomic {
       bufavail = bufavail + 1;
       } // end of atomic region
       analyze(track_image);
     }
}
}
```

Challenges of TM

- I/O in atomic regions
- Nested atomic regions
- Atomic regions conflicting with code in non-atomic regions
- Etc.

- Promising research area with significant challenges