CS3210 Lab 1

Processes, Threads, and Synchronization Basics

Theodore's slides; heavily inspired by Sriram's, Richard's, Cristina's and Zhi Heng's slides.

About myself

Theodore Leebrant

(Theodore/Theo is good!)

- Computer Science + Mathematics
  - was a PL nerd, mostly with Rust
- Plays too much Final Fantasy XIV
- Out-of-tutorial communication:
  - Email: theo@comp.nus.edu.sg for consults, questions
  - Telegram: details later
  - Will reply messages within 24 hours – *except 2 days before deadlines*

Quick admin stuff

Telegram group:

- Things that are OK
  - Banter
  - Interesting finds
  - Lab cluster issues / requests
- Things that are **not OK**
  - Code debugging help
    (unless you spot something funny in our code)

Slides will be uploaded after every session

Anonymous feedback: bit.ly/feedback-theodore

Why are we here?

Make things go fast

(latency)

Make ***things*** finish ***quickly***

(throughput)

Make things go fast **efficiently**

(energy efficiency)

CS3210 from 30,000 feet in the sky

Part 1: OpenMP	Part 2: CUDA	Part 3: MPI
Making **single-node CPU** programs faster	Making **single-node GPU-able** programs faster	Making **multi-node** programs faster
Complex tasks that are relatively **less parallelizable** (10s of tasks)	**Simpler tasks** that are relatively **more parallelizable** (millions of tasks even)	**Large, mixed workloads** (slow communication between nodes is worth it due to size / parallelizabilty of work)

The complexity: how to **harness** this power effectively?

Our goals for the semester

(not just “finish the tutorials & labs” and “pass your *exams*”)

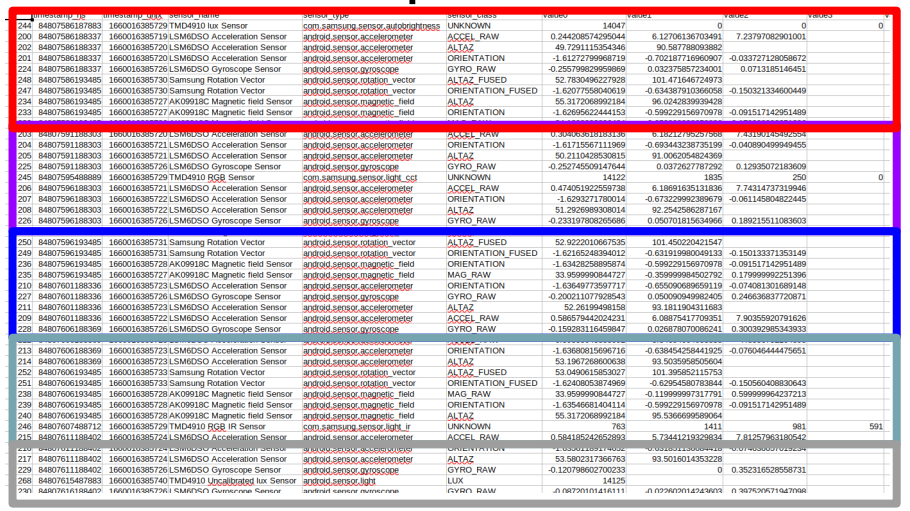
1. Learn how to **decompose problems into tasks** in your sleep

sometimes a curse: cannot unsee this :)

Task parallelism

```
/*
  scheduler table - all regular tasks apart from the fast_loop()
  should be listed here, along with how often they should be called
  (in 10ms units) and the maximum time they are expected to take (in
  microseconds)
 */
static const AP_Scheduler::Task scheduler_tasks[] PROGMEM = {
    { update_GPS,           2,     900 },
    { update_nav_mode,      1,     400 },
    { medium_loop,          2,     700 },
    { update_altitude,     10,    1000 },
    { fifty_hz_loop,        2,     950 },
```

Data parallelism



Our goals for the semester

(not just “finish the tutorials & labs” and “pass your *exams*”)

2. Become **systems detectives**: think *holistically* about performance

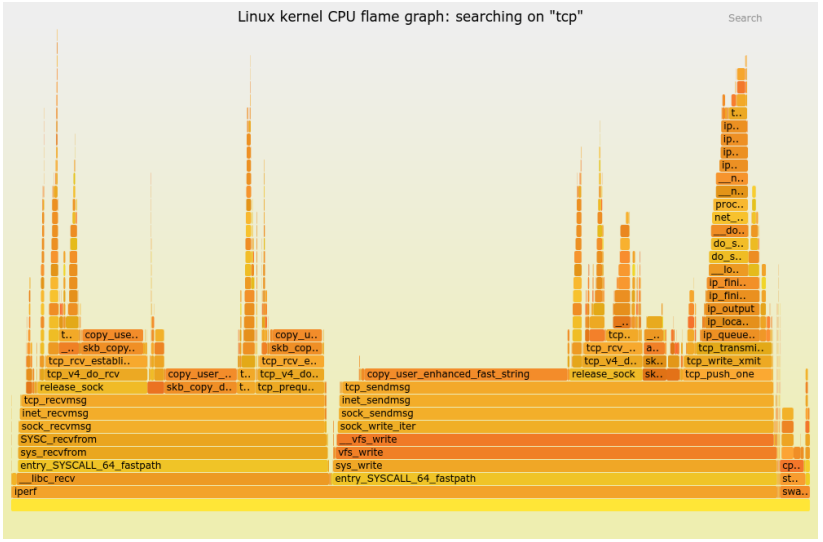
Is it the algorithm? Disk? Cache? Network?
Not enough work? Too much work? Synchronization overhead?

Theory alone is useless here.

```
Performance counter stats for 'dd if=/dev/zero of=test.iso bs=10M count=1':

         21.812281 task-clock                #    0.912 CPUs utilized
                15 context-switches          #    0.001 M/sec
                 2 CPU-migrations            #    0.000 M/sec
             2,805 page-faults               #    0.129 M/sec
        62,025,623 cycles                    #    2.844 GHz                      [51.76%]
         6,299,287 stalled-cycles-frontend   #   10.16% frontend cycles idle     [45.35%]
        24,456,020 stalled-cycles-backend    #   39.43% backend  cycles idle     [45.92%]
        12,655,619 instructions              #    0.20  insns per cycle
                                             #    1.93  stalled cycles per insn [89.86%]
         3,552,630 branches                  #  162.873 M/sec                    [76.11%]
            51,348 branch-misses             #    1.45% of all branches          [60.39%]

       0.023914596 seconds time elapsed
```



Our goals for the semester

(not just “finish the tutorials & labs” and “pass your *exams*”)

3. Have fun!

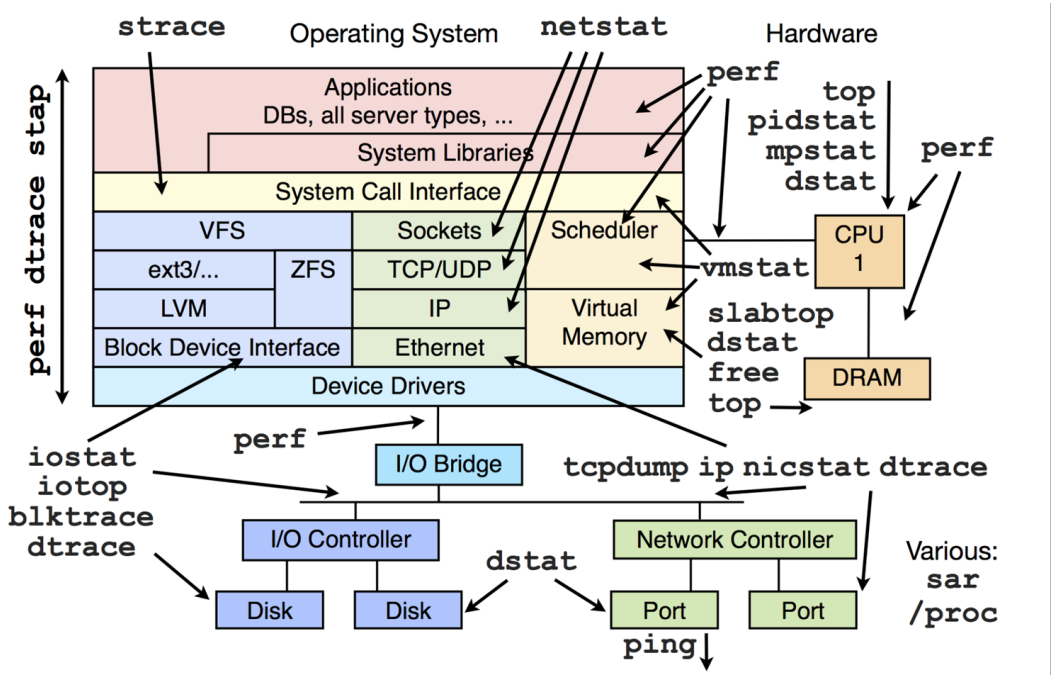
Very satisfying to make a program faster. You will hopefully understand soon :)

```
INFO: Pandarallel will run on 1 workers.
INFO: Pandarallel will use Memory file system to transfer data between t
OK, rows are already sorted by timestamp_ns, no need to sort again.
Creating subsets of dataframe to use later
Processing closest values for lux
      5.44%  2825 / 51902
```

```
INFO: Pandarallel will run on 8 workers.
INFO: Pandarallel will use Memory file system to transfer data between the main process and workers.
OK, rows are already sorted by timestamp_ns, no need to sort again.
Creating subsets of dataframe to use later
Processing closest values for lux
      0.00%  0 / 6488
      0.00%  0 / 6488
      0.00%  0 / 6488
      0.00%  0 / 6488
      0.00%  0 / 6488
      0.00%  0 / 6488
      0.00%  0 / 6487
      0.00%  0 / 6487
```

No such thing as stupid questions: ever

- "Systems" are made up of many, many parts
- Infinite learning process
- Please feel free to bring anything up
- Personal promise: all questions will be treated equally



General Lab Workflow

- For you:
  - Labs/Tutorials are for you to learn. **No stress.**
    Only a small percentage of grade. Please experiment!
  - Feel free to talk, communicate, **work together**!
    Submit separately, state who you worked with.
  - First tutorial slot challenges…
- Me:
  - I will probably not give direct answers, but I will guide :)
  - Will be hovering around, try not to be conscious of it, trying to help
  - Might interrupt with solutions and interesting behaviours / questions
  - Will start at :05 and finish in ~1h, but will stay back for questions

CS3210 Lab 01

Processes / Threads / Synchronization

Things to note for labs

- 'C-style' C++ programming language
  - C++ *only*! Even if you want to write C...
  - [Lab 1] Use only the `pthread` library.
    - (i.e. don't use `std::mutex`, `std::thread`, ...)
- **Do the lab exercises in order!**
- Submit the necessary exercises
  - Lab 1 deadline: next week, 2 Sept, **1400hrs**

Why synchronization for lab 1?

(because anyone can solve embarrassingly parallel problems.)

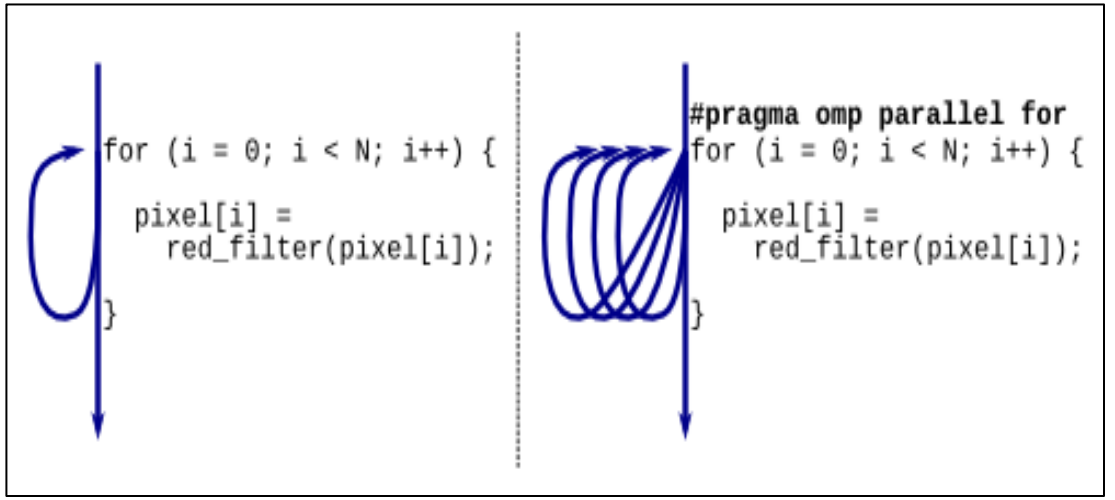
Python

multi.py

C: > Users > Administrator.SHAREPOINTSKY > multi.py > ...

```python
from multiprocessing import Pool
def num(n):
    return n*4
if __name__=='__main__':
    numbers=[3,6,9]
    pool=Pool(processes=1)
    print(pool.map(num,numbers))
```

C/C++



Why synchronization for lab 1?

(because anyone can solve embarrassingly parallel problems.)

```
INFO: Pandarallel will run on 1 workers.
INFO: Pandarallel will use Memory file system to transfer data between
OK, rows are already sorted by timestamp_ns, no need to sort again.
Creating subsets of dataframe to use later
Processing closest values for lux
5.44% 2825 / 51902
```

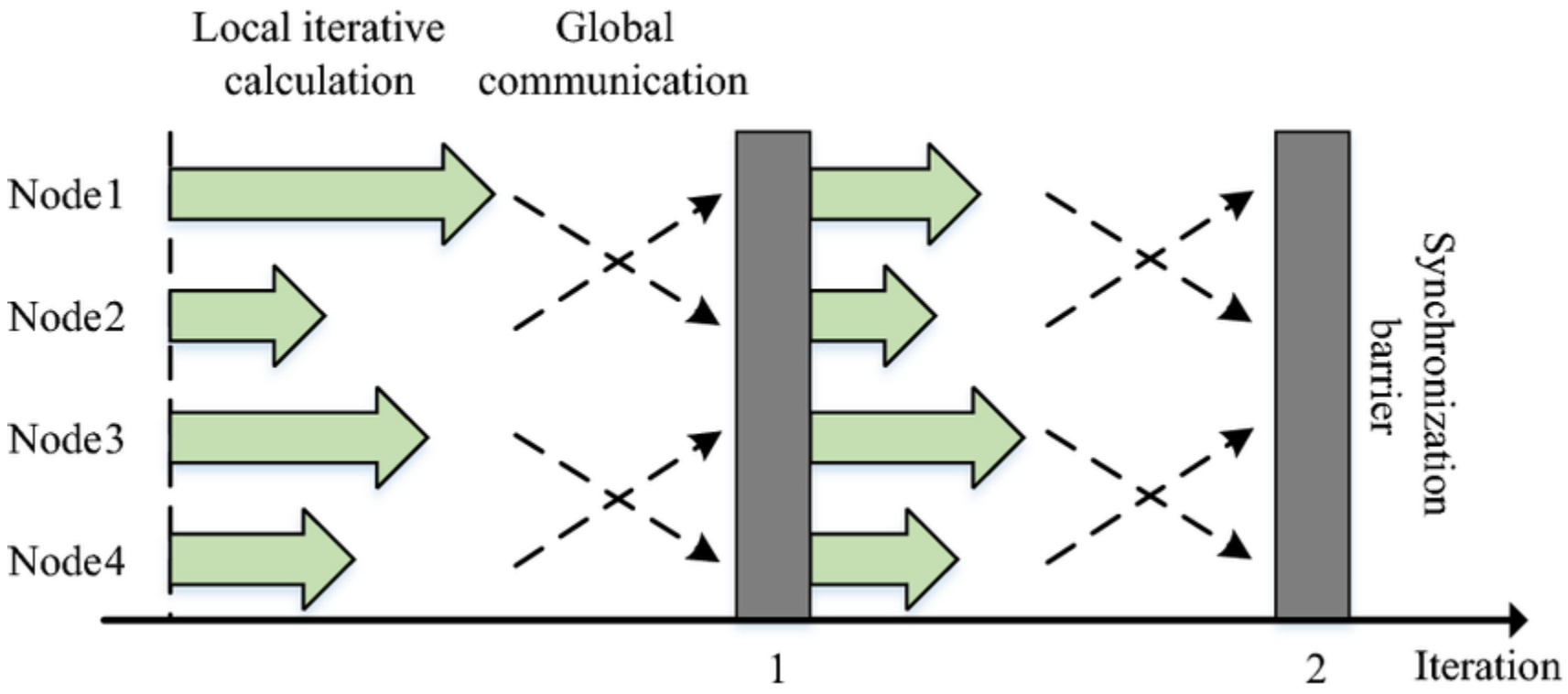
```
INFO: Pandarallel will run on 8 workers.
INFO: Pandarallel will use Memory file system to transfer data between the main process and workers.
OK, rows are already sorted by timestamp_ns, no need to sort again.
Creating subsets of dataframe to use later
Processing closest values for lux
0.00% 0 / 6488
0.00% 0 / 6488
0.00% 0 / 6488
0.00% 0 / 6488
0.00% 0 / 6488
0.00% 0 / 6488
0.00% 0 / 6487
0.00% 0 / 6487
```

```python
new_cols = df_filtered.apply(
    get_closest_impt_values_v2,
    axis=1,
    result_type="expand",
)
```

```python
new_cols = df_filtered.parallel_apply(
    get_closest_impt_values_v2,
    axis=1,
    result_type="expand",
)
```

Why synchronization for lab 1?

Anyone can solve embarrassingly parallel problems;
the difficult part is coordinating between tasks, a.k.a. synchronization!



Lab 1 Tasks

- **Connect to lab machines, download code**
- **ex1**: processes with fork/wait
- **ex2**: pthreads ordering, counter variable
- Bonus: Semaphore usage
- **ex3**: race condition
- **ex4**: pthread joining
- **ex5**: pthread mutexes
- **ex6**: condition variables (starts to get challenging)
- **ex7**: producer-consumer: pthreads **(for submission)**
- **ex8**: producer-consumer: processes and semaphores **(for submission)**
- **ex9**: explaining ex7 and ex8 **(for submission)**
- **Visiting the PDC lab downstairs**

Let's get started!

Ask for help if you can't SSH!
For advanced users: generate SSH key, copy your key to the pdc machines, set up your SSH config file…

nus-cs3210.github.io/student-guide/accessing

1. Get SoC ID
2. Check email for PDC Lab username & password
3. Get SoC VPN (not for *right now*, but for accesses outside SoC)
4. SSH to `soctf-pdc-xxx.d1.comp.nus.edu.sg`
   - `xxx` is `001-003` or `009-011`; don't crowd `001` :')
5. Download lab code into the machines and start the lab :D
   - `wget https://www.comp.nus.edu.sg/~srirams/cs3210/L1_code.zip`
   - `unzip L1_code.zip`

For VSCode users, SSH into the node with bash/powershell first to change your password before using VSCode to connect!

[Extra] Quality-of-life for SSH

- Consider adding the following to `~/.ssh/config`

```
Host pdc-003
    HostName soctf-pdc-003.d1.comp.nus.edu.sg
    User [insert your lab id here]
    ForwardAgent yes
```

Now you can just type `ssh pdc-003` to connect :)

- Generate your SSH key: `ssh-keygen -t ed25519`
  - Add your public key (.pub) to pdc.comp.nus.edu.sg/accounts/profile/
  - Modify your config:

```
Host pdc-003
    HostName soctf-pdc-003.d1.comp.nus.edu.sg
    User [insert your lab id here]
    ForwardAgent yes
    IdentityFile ~/.ssh/id_ed25519
```

Named vs. Unnamed Semaphores

- **Named** semaphores (created with `sem_open`) are "automatically shared between processes" - how?
  - Processes duplicate their memory spaces on `fork()`

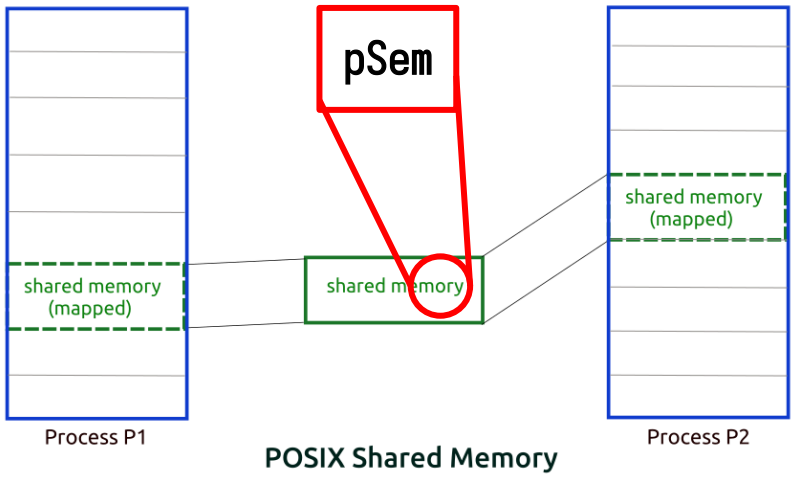
- Parent process *executes*:

```
sem_t* sem = sem_open("pSem", O_CREAT | O_EXCL, 0644, value);
```

- **So, shouldn't the semaphore be private to each process?**

Named vs. Unnamed Semaphores

- Shouldn't the semaphore be private to each process?
- OS auto-maps semaphore into shared memory for us!
  - It even saves it as a virtual file
- Try:
  - `./semaph`
  - `Ctrl+Z` after entering sem value
  - `ipcs; ls /dev/shm`
  - `fg; Ctrl+C; ipcs; ls /dev/shm;`
  - `ipcrm -M ..`



Shared Memory Usage

- You may have allocated things in shared memory within your process and terminated it prematurely before cleanup.
- To resolve:

`ipcs -cm`	Check shm usage on machine
`ipcrm -M <key>`	Delete the memory area
`ls -la /dev/shm`	Check for named semaphores
`rm /dev/shm/<sem>`	Remove named semaphores

Binary Semaphores vs. pthread Mutexes

- What is the difference?

Binary Semaphores vs. pthread Mutexes

- What is the difference?
  - Hint: who can unlock mutexes?

Condition Variables: Why?

- Semaphores can be too generic to map nicely to all problems
  - Increment / Decrement integer
- Mutex: suffers from similar issues

Condition Variables: Why?

Can you spot anything wrong with this code?

Waiting thread

```
while(true) {
    pthread_mutex_lock(&mutex);
    if (condition is satisfied) {
        // Do something when cond satisfied
        done = true;
    }
    pthread_mutex_unlock(&mutex);
    if (done) break;
}
```

Signalling thread

```
pthread_mutex_lock(&mutex);

/* change variable value to make condition
satisfied */

pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

Let's shuffle things a little bit to make it better

Waiting thread

```
pthread_mutex_lock(&mutex);
if (condition not satisfied) {
    pthread_mutex_unlock(&mutex);
    while (condition not satisfied) { //wait }
    pthread_mutex_lock(&mutex);
}
// Do something, condition satisfied

pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);

/* change variable value to make condition
satisfied */

pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

Let's shuffle things a little bit to make it better

Update:
Turns out, **there's a data race here**!
Just take this section as a conceptual idea that condition variable is an upgrade from busy wait.

Waiting thread

```
pthread_mutex_lock(&mutex);
if (condition not satisfied) {
    pthread_mutex_unlock(&mutex);
    while (condition not satisfied) { //wait }
    pthread_mutex_lock(&mutex);
}
// Do something, condition satisfied

pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);

/* change variable value to make condition
satisfied */

pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

What happens if there are two waiting threads?

Waiting thread 1

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

1. Both waiting threads are waiting

Waiting thread 2

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);
/* change variable value to satisfy cond */
pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

What happens if there are two waiting threads?

Waiting thread 1

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

2. Signalling thread changes the variable value

Waiting thread 2

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);
/* change variable value to satisfy cond */
pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

What happens if there are two waiting threads?

Waiting thread 1

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

3. Both waiting threads exit the busy wait; T1 gets the mutex

Waiting thread 2

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);
/* change variable value to satisfy cond */
pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

What happens if there are two waiting threads?

Waiting thread 1

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

4. T1 does something that invalidates the condition

Waiting thread 2

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);
/* change variable value to satisfy cond */
pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

What happens if there are two waiting threads?

Waiting thread 1

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

5. T1 releases mutex, T2 gets the mutex

Waiting thread 2

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);
/* change variable value to satisfy cond */
pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

What happens if there are two waiting threads?

Waiting thread 1

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

6. T2 gets to the critical section but condition might no longer be satisfied!

Waiting thread 2

```
1  pthread_mutex_lock(&mutex);
2  if (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);
/* change variable value to satisfy cond */
pthread_mutex_unlock(&mutex);
```

Condition Variables: Why?

Fixing the 'sniping' behaviour

Waiting thread 1

```
1  pthread_mutex_lock(&mutex);
2  while (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

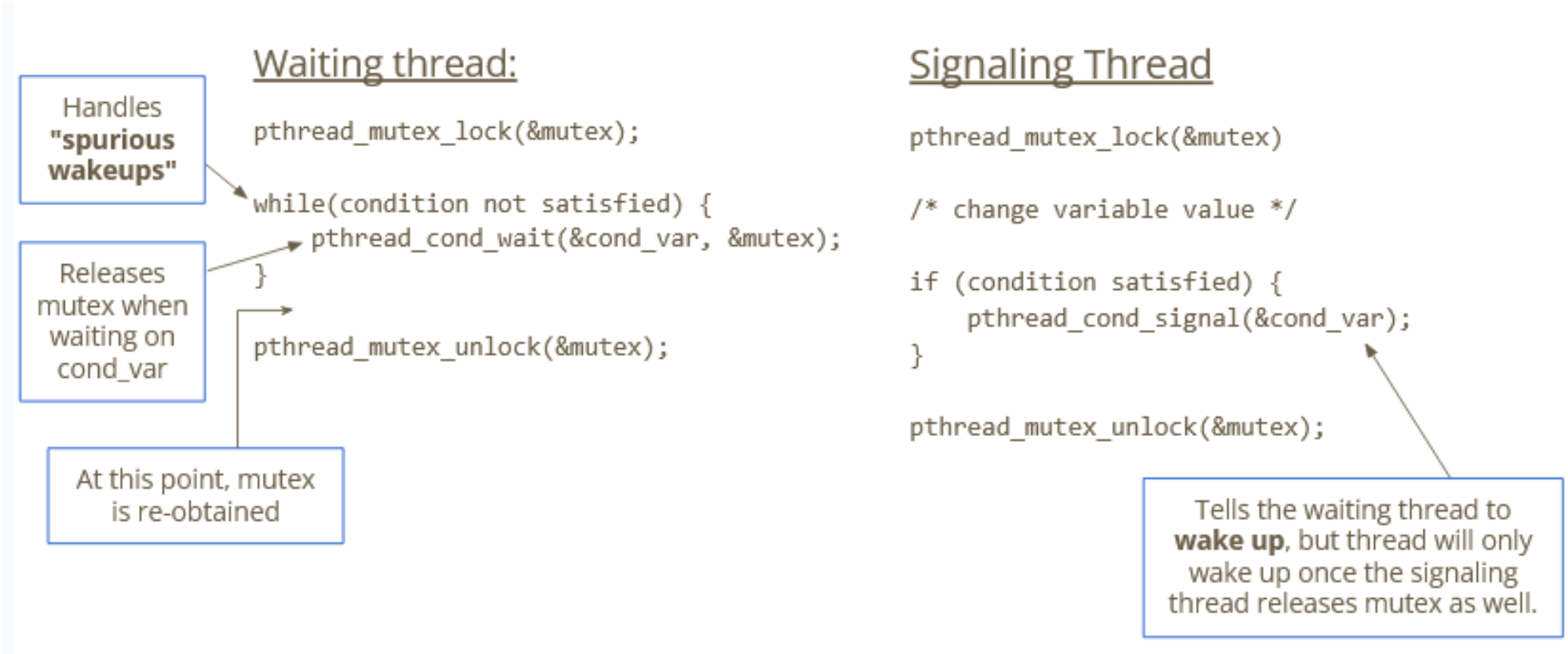
Waiting thread 2

```
1  pthread_mutex_lock(&mutex);
2  while (condition not satisfied) {
3      pthread_mutex_unlock(&mutex);
4      while (condition not satisfied) { //wait }
5      pthread_mutex_lock(&mutex);
6  }
7  // Do something, condition satisfied
8
9  pthread_mutex_unlock(&mutex);
```

Signalling thread

```
pthread_mutex_lock(&mutex);
/* change variable value to satisfy cond */
pthread_mutex_unlock(&mutex);
```

Condition Variables



Condition Variables

Update
Check telegram group for discussion on signal; as well as switching the order on performance and correctness.

Waiting thread:

```
pthread_mutex_lock(&mutex);

while(condition not satisfied) {
    pthread_cond_wait(&cond_var, &mutex);
}

pthread_mutex_unlock(&mutex);
```

Handles **"spurious wakeups"**

Releases mutex when waiting on cond_var

At this point, mutex is re-obtained

Signaling Thread

```
pthread_mutex_lock(&mutex)

/* change variable value */

if (condition satisfied) {
    pthread_cond_signal(&cond_var);
}

pthread_mutex_unlock(&mutex);
```

Tells the waiting thread to **wake up**, but thread will only wake up once the signaling thread releases mutex as well.

Condition Variables: Spurious Wakeups

- Why do we not use **if** statements for checking condition in the waiting thread?

Waiting thread:

```
pthread_mutex_lock(&mutex);

if (condition not satisfied) {
    pthread_cond_wait(&cond_var, &mutex);
}

// do something to maybe make condition invalid

pthread_mutex_unlock(&mutex);
```

Signaling thread:

```
pthread_mutex_lock(&mutex)

// do something to make condition satisfied

if (condition satisfied) {
    pthread_cond_signal(&cond_var);
}

pthread_mutex_unlock(&mutex);
```

Condition Variables: Spurious Wakeups

- Spurious wakeup: occurs when a thread wakes up from waiting and finds that the condition is still unsatisfied. (Credit: Wikipedia)
- It can happen due to (but is not limited to):
  - Implementation
    - the thread blocked suddenly wakes up even though no signal or broadcast occurs
  - Race conditions
    - what happens if two threads wake up at the same time?

Summary

- Connecting to lab machines
- Processes and threads
- Mutexes / Semaphores / Condition Variables

End of Lab 1

- Telegram group: scan on right

- Slides will be uploaded after every session
- Feedback: bit.ly/feedback-theodore
- Email: theo@comp.nus.edu.sg

- Now: PDC Lab Visit (and back again)