# TCSS 422: OPERATING SYSTEMS

## Lock-based data structures, Midterm review

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

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## OBJECTIVES – 5/4

- Questions from 4/29
- C Tutorial - Pointers, Strings, Exec in C
- Assignment 1 – May 11
- Quiz 2 – CPU Scheduling Algorithms
- Chapter 29: Lock Based Data Structures
  - Sloppy Counter
  - Concurrent Structures: Linked List, Queue, Hash Table
- 2nd hour: Midterm Review
  - Practice Questions

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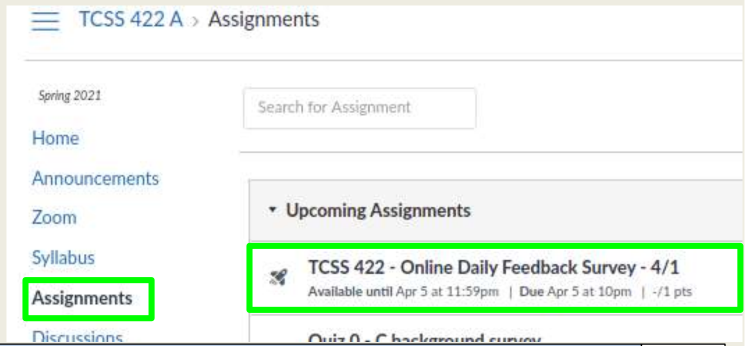
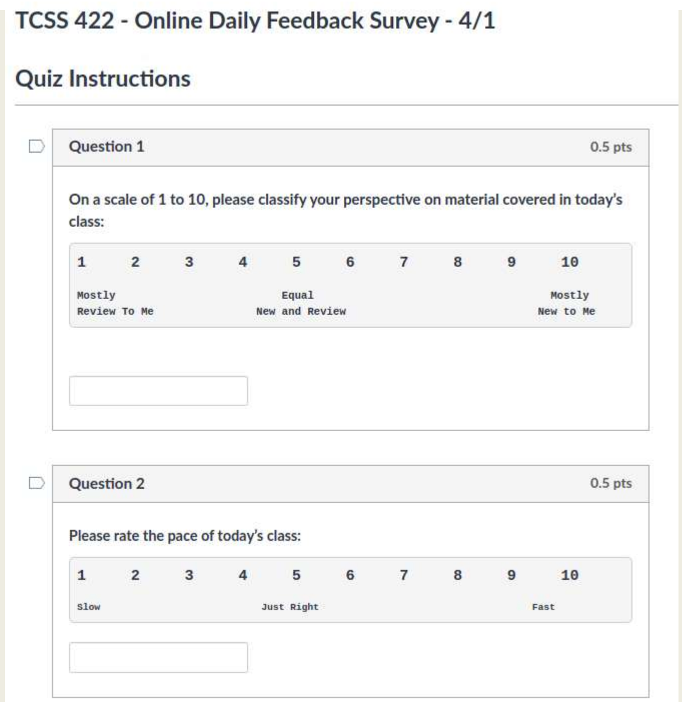
# ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 11:59p
- Thursday surveys: due ~ Mon @ 11:59p





# MATERIAL / PACE

- Please classify your perspective on material covered in today's class (57 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.89 (↑ - previous 6.56)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.85 (↑ - previous 5.73)**



# FEEDBACK

- ***What's difference between thread_wait and lock?***
  - What's difference between `pthread_cond_wait()` and `pthread_mutex_lock()`?
  - Pthread_mutex_lock() tries to obtain a lock protecting a critical section of code
    - The lock is either available (YES), or unavailable (NO)
    - If the lock is unavailable, then the API call will BLOCK indefinitely *i.e. forever*
    - When the lock is available, it is random which thread obtains it next
  - Pthread_cond_wait() adds signaling mechanism to manage locks
    - Other threads can wake up waiting threads
    - Order is based on a FIFO wait queue
    - Thread waiting longest obtains the lock first
    - State variable is used with condition variable to test if it is OKAY to proceed - ***If not we go back to sleep***

# FEEDBACK - 2

- ***What is a blocking API call?***
- Blocking API calls are system calls that interrupt execution of a thread until some resource can be obtained
- Examples from pthread API:
- pthread_mutex_lock() - block until lock is available
- pthread_cond_wait() - block until woken up-FIFO order
- pthread_join() - parent thread blocks until child thread completes
- ***What other blocking API calls have we discussed?***



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# QUIZ 2 - CPU SCHEDULING ALGORITHMS

- Quiz posted on Canvas
- Due Wednesday May 5 @ 11:59p
- Provides CPU scheduling practice problems
  - FIFO, SJF, STCF, RR, MLFQ (Ch. 7 & 8)
- Unlimited attempts allowed
- Multiple choice and fill-in the blank
- Quiz automatically scored by Canvas
  - Please report any grading problems



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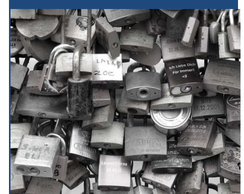
# CHAPTER 29 – LOCK BASED DATA STRUCTURES



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## LOCK-BASED CONCURRENT DATA STRUCTURES

- Adding locks to data structures make them thread safe.
- Considerations:
  - Correctness
  - Performance
  - Lock granularity

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# COUNTER STRUCTURE W/O LOCK

- Synchronization weary --- not thread safe

```
typedef struct __counter_t {
        int value;
} counter_t;

void init(counter_t *c) {
        c->value = 0;
}

void increment(counter_t *c) {
        c->value++;
}

void decrement(counter_t *c) {
        c->value--;
}

int get(counter_t *c) {
        return c->value;
}
```



# CONCURRENT COUNTER

```
typedef struct __counter_t {
        int value;
        pthread_lock_t lock;
} counter_t;

void init(counter_t *c) {
        c->value = 0;
        Pthread_mutex_init(&c->lock, NULL);
}

void increment(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        c->value++;
        Pthread_mutex_unlock(&c->lock);
}

```

- Add lock to the counter
- Require lock to change data

# CONCURRENT COUNTER - 2

- Decrease counter
- Get value

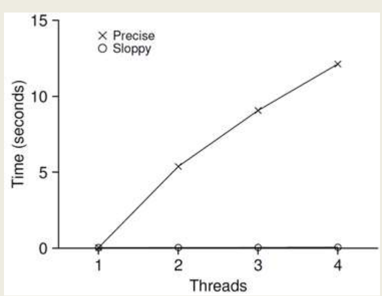
```
(Cont.)
void decrement(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        c->value--;
        Pthread_mutex_unlock(&c->lock);
}

int get(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        int rc = c->value;
        Pthread_mutex_unlock(&c->lock);
        return rc;
}
```



# CONCURRENT COUNTERS - PERFORMANCE

- iMac: four core Intel 2.7 GHz i5 CPU
- Each thread increments counter 1,000,000 times




**Synchronized counter scales poorly.**

## PERFECT SCALING

- Achieve (N) performance gain with (N) additional resources

- Throughput:
- Transactions per second (tps)

- 1 core
- N = 100 tps

- 10 cores (x10)
- N = 1000 tps (x10)



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# SLOPPY COUNTER

- Provides single logical shared counter
  - Implemented using local counters for each ~CPU core
    - 4 CPU cores = 4 local counters & 1 global counter
    - Local counters are synchronized via local locks
  - Global counter is updated periodically
    - Global counter has lock to protect global counter value
    - Sloppiness threshold (*S*): Update threshold of global counter with local values
    - Small (*S*): more updates, more overhead
    - Large (*S*): fewer updates, more performant, less synchronized
- Why this implementation? Why do we want counters local to each CPU Core?



# SLOPPY COUNTER – MAIN POINTS

- Idea of Sloppy Counter is to ***RELAX*** the synchronization requirement for counting
  - Instead of synchronizing global count variable each time: `counter=counter+1`
  - Synchronization occurs only every so often: e.g. *every 1000 counts*
- Relaxing the synchronization requirement ***drastically*** reduces locking API overhead by trading-off split-second accuracy of the counter
- Sloppy counter: trade-off accuracy for speed
  - It's sloppy because it's not so accurate (until the end)

# SLOPPY COUNTER - 2

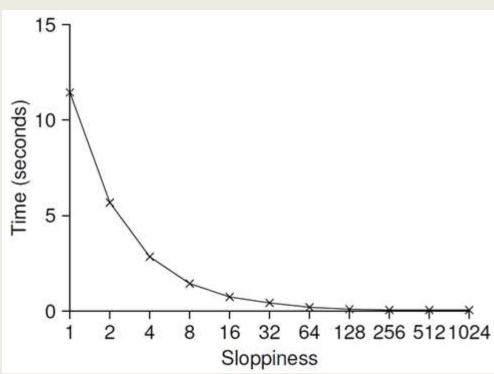
- Update threshold (*S*) = 5
- Synchronized across four CPU cores
- Threads update local CPU counters

| Time | $L_1$ | $L_2$ | $L_3$ | $L_4$ | G |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 1 | 1 | 0 |
| 2 | 1 | 0 | 2 | 1 | 0 |
| 3 | 2 | 0 | 3 | 1 | 0 |
| 4 | 3 | 0 | 3 | 2 | 0 |
| 5 | 4 | 1 | 3 | 3 | 0 |
| 6 | 5 → 0 | 1 | 3 | 4 | 5 (from $L_1$) |
| 7 | 0 | 2 | 4 | 5 → 0 | 10 (from $L_4$) |



# THRESHOLD VALUE *S*

- Consider 4 threads increment a counter 1000000 times each
- Low *S* → What is the consequence?
- High *S* → What is the consequence?



## SLOPPY COUNTER - EXAMPLE

- Example implementation
- Also with CPU affinity



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  - **Concurrent Structures: Linked List**, Queue, Hash Table
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# CONCURRENT LINKED LIST - 1

- Simplification - only basic list operations shown
- Structs and initialization:

```
// basic node structure
typedef struct __node_t {
        int key;
        struct __node_t *next;
} node_t;

// basic list structure (one used per list)
typedef struct __list_t {
        node_t *head;
        pthread_mutex_t lock;
} list_t;

void List_Init(list_t *L) {
        L->head = NULL;
        pthread_mutex_init(&L->lock, NULL);
}

(Cont.)
```



# CONCURRENT LINKED LIST - 2

- Insert – adds item to list
- Everything is critical!
  - There are two unlocks

```
(Cont.)
int List_Insert(list_t *L, int key) {
        pthread_mutex_lock(&L->lock);
        node_t *new = malloc(sizeof(node_t));
        if (new == NULL) {
                perror("malloc");
                pthread_mutex_unlock(&L->lock);
        return -1; // fail }
        new->key = key;
        new->next = L->head;
        L->head = new;
        pthread_mutex_unlock(&L->lock);
        return 0; // success
}
(Cont.)
```

# CONCURRENT LINKED LIST - 3

- Lookup – checks list for existence of item with key
- Once again everything is critical
  - Note - there are also two unlocks

```
(Cont.)

    int List_Lookup(list_t *L, int key) {
        pthread_mutex_lock(&L->lock);
        node_t *curr = L->head;
        while (curr) {
            if (curr->key == key) {
                pthread_mutex_unlock(&L->lock);
                return 0; // success
            }
            curr = curr->next;
        }
        pthread_mutex_unlock(&L->lock);
        return -1; // failure
    }
```



# CONCURRENT LINKED LIST

- First Implementation:
  - Lock everything inside Insert() and Lookup()
  - If malloc() fails lock must be released
    - Research has shown "***exception-based control flow***" to be error prone
    - 40% of Linux OS bugs occur in rarely taken code paths
    - Unlocking in an exception handler is considered a poor coding practice
    - There is nothing specifically wrong with this example however
- Second Implementation …

# CCL – SECOND IMPLEMENTATION

- Init and Insert

```
void List_Init(list_t *L) {
        L->head = NULL;
        pthread_mutex_init(&L->lock, NULL);
}

void List_Insert(list_t *L, int key) {
        // synchronization not needed
        node_t *new = malloc(sizeof(node_t));
        if (new == NULL) {
                perror("malloc");
                return;
        }
        new->key = key;

        // just lock critical section
        pthread_mutex_lock(&L->lock);
        new->next = L->head;
        L->head = new;
        pthread_mutex_unlock(&L->lock);
}
```



# CCL – SECOND IMPLEMENTATION - 2

- Lookup

```
(Cont.)
int List_Lookup(list_t *L, int key) {
        int rv = -1;
        pthread_mutex_lock(&L->lock);
        node_t *curr = L->head;
        while (curr) {
                if (curr->key == key) {
                        rv = 0;
                        break;
                }
                curr = curr->next;
        }
        pthread_mutex_unlock(&L->lock);
        return rv; // now both success and failure
}
```

# CONCURRENT LINKED LIST PERFORMANCE

- Using a single lock for entire list is not very performant
- Users must "wait" in line for a single lock to access/modify any item
- Hand-over-hand-locking (lock coupling)
  - Introduce a lock for each node of a list
  - Traversal involves handing over previous node's lock, acquiring the next node's lock…
  - Improves lock granularity
  - Degrades traversal performance
- Consider hybrid approach
  - Fewer locks, but more than 1
  - Best lock-to-node distribution?

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# MICHAEL AND SCOTT CONCURRENT QUEUES

- Improvement beyond a single master lock for a queue (FIFO)
- Two locks:
  - One for the **head** of the queue
  - One for the **tail**
- Synchronize enqueue and dequeue operations

- Add a dummy node
  - Allocated in the queue initialization routine
  - Supports separation of head and tail operations

- Items can be added and removed by separate threads at the same time



# CONCURRENT QUEUE

- Remove from queue

```
typedef struct __node_t {
        int value;
        struct __node_t *next;
} node_t;

typedef struct __queue_t {
        node_t *head;
        node_t *tail;
        pthread_mutex_t headLock;
        pthread_mutex_t tailLock;
} queue_t;

void Queue_Init(queue_t *q) {
        node_t *tmp = malloc(sizeof(node_t));
        tmp->next = NULL;
        q->head = q->tail = tmp;
        pthread_mutex_init(&q->headLock, NULL);
        pthread_mutex_init(&q->tailLock, NULL);
}

(Cont.)
```

# CONCURRENT QUEUE - 2

- Add to queue

```
(Cont.)
void Queue_Enqueue(queue_t *q, int value) {
        node_t *tmp = malloc(sizeof(node_t));
        assert(tmp != NULL);

        tmp->value = value;
        tmp->next = NULL;

        pthread_mutex_lock(&q->tailLock);
        q->tail->next = tmp;
        q->tail = tmp;
        pthread_mutex_unlock(&q->tailLock);
}
(Cont.)
```



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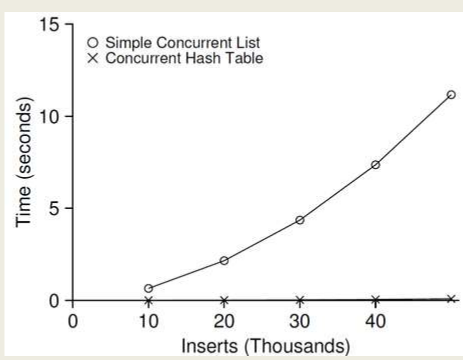
# CONCURRENT HASH TABLE

- Consider a simple hash table
  - Fixed (static) size
  - Hash maps to a bucket
    - Bucket is implemented using a concurrent linked list
    - One lock per hash (bucket)
    - Hash bucket is a linked lists



# INSERT PERFORMANCE – CONCURRENT HASH TABLE

- Four threads – 10,000 to 50,000 inserts
  - iMac with four-core Intel 2.7 GHz CPU




**The simple concurrent hash table scales magnificently.**

# CONCURRENT HASH TABLE

```c
#define BUCKETS (101)

typedef struct __hash_t {
        list_t lists[BUCKETS];
} hash_t;

void Hash_Init(hash_t *H) {
        int i;
        for (i = 0; i < BUCKETS; i++) {
                List_Init(&H->lists[i]);
        }
}

int Hash_Insert(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Insert(&H->lists[bucket], key);
}

int Hash_Lookup(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Lookup(&H->lists[bucket], key);
}
```

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## Which is a major advantage of using concurrent data structures in your programs?

Locks are encapsulated within data structure code ensuring thread safety.

Lock granularity tradeoff already optimized inside data structurew

Multiple threads can more easily share data

All of the above

None of the above

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

# LOCK-FREE DATA STRUCTURES

- Lock-free data structures in Java
- Java.util.concurrent.atomic package
- Classes:
  - AtomicBoolean
  - AtomicInteger
  - AtomicIntegerArray
  - AtomicIntegerFieldUpdater
  - AtomicLong
  - AtomicLongArray
  - AtomicLongFieldUpdater
  - AtomicReference
- See: https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/util/concurrent/atomic/package-summary.html

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# WE WILL RETURN AT 5:00PM

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# MIDTERM REVIEW

# MIDTERM

- Thursday May 6th
- ONLINE via Canvas (for 3.5 hrs 3:40 – 7:10p)
- Test designed to take less than 2 hours
- Additional time provided in case of internet issues, etc.
- Open book, note, internet
- Individual work
- Coverage: all content up through Chapter 29, sloppy counter

- ***Preparation:***
- Practice quiz: Quiz 2: CPU scheduling (***posted***)
  - Auto grading w/ multiple attempts allowed as study aid
- Practice– second hour of lecture
  - Series of problems presented with some time to solve
  - Will then work through solutions



# FIFO EXAMPLE

- Operation of CPU schedulers can be visualized with timing graphs.

- The graph below depicts a FIFO scheduler where three jobs arrive in the sequence A, B, C, where job A runs for 10 time slices, job B for 5 time slices, and job C for 10 time slices.

```
     |
FIFO |AAAAAAAAAABBBBBCCCCCCCCCC
     |___________________________________
     0          10    15        25
```

# Q1- SHORTEST JOB FIRST (SJF) SCHEDULER

- Draw a scheduling graph for the SJF scheduler without preemption for the following jobs. Draw vertical lines for key events and be sure to label the X-axis times as in the example.

| Job | Arrival Time | Job Length |
|---|---|---|
| A | T=0 | 25 |
| B | T=5 | 10 |
| C | T=10 | 15 |

```
      |
      |
SJF   |
      |
      |___________________________________________________________
      0
```



# Q1 – SJF - 2

What is the response time (RT) and turnaround time (TT) for jobs A, B, and C?

RT Job A: ________________ TT Job A: ________________

RT Job B: ________________ TT Job B: ________________

RT Job C: ________________ TT Job C: ________________

What is the average response time for all jobs? _____________

What is the average turnaround time for all jobs? ___________

# Q2 – SHORTEST TIME TO COMPLETION FIRST (STCF) SCHEDULER

Draw a scheduling graph for the STCF scheduler with preemption for the following jobs.

Draw vertical lines for key events and be sure to label the X-axis times as in the example.

| Job | Arrival Time | Job Length |
|---|---|---|
| A | T=0 | 25 |
| B | T=5 | 10 |
| C | T=10 | 15 |

```
        |
        |
CPU     |
        |
        |____________________________________________________________
        0
```



# Q2 – STCF - 2

- What is the response time (RT) and turnaround time (TT) for jobs A, B, and C?

RT Job A: ________________ TT Job A: ________________

RT Job B: ________________ TT Job B: ________________

RT Job C: ________________ TT Job C: ________________

- What is the average response time for all jobs? ___________
- What is the average turnaround time for all jobs? __________

# Q3 - OPERATING SYSTEM APIs

1. Provide a definition for what is a blocking API call

2. Provide a definition for a non-blocking API call

3. Provide an example of a blocking API call.
Consider APIs used to manage processes and/or threads.

4. Provide an example of a non-blocking API call.
Consider APIs used to manage processes and/or threads.



# Q4 – OPERATING SYSTEM APIs - II

1. When implementing memory synchronization for a multi-threaded program list one **advantage** of combining the use of a condition variable with a lock variable via the Linux C thread API calls: `pthread_mutex_lock()` and `pthread_cond_wait()`

2. When implementing memory synchronization for a multi-threaded program using locks, list one **disadvantage** of using blocking thread API calls such as the Linux C thread API calls for: `pthread_mutex_lock()` and `pthread_cond_wait()`

3. List (2) factors that cause Linux blocking API calls to introduce **overhead** into programs:

# Q5 – PERFECT MULTITASKING OPERATING SYSTEM

In a perfect-multi-tasking operating system, every process of the same priority will always receive exactly $1/n^{th}$ of the available CPU time. Important CPU improvements for multi-tasking include: (1) fast context switching to enable jobs to be swapped in-and-out of the CPU very quickly, and (2) the use of a timer interrupt to preempt running jobs without the user voluntarily yielding the CPU. These innovations have enabled major improvements towards achieving a coveted "Perfect Multi-Tasking System".

List and describe two challenges that remain complicating the full realization of a Perfect Multi-Tasking Operating System. In other words, what makes it very difficult for all jobs (for example, 10 jobs) of the same priority to receive **EXACTLY** the same runtime on the CPU? Your description must explain why the challenge is a problem for achieving perfect multi-tasking.

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# Q6 – ROUND-ROBIN SCHEDULER

Show a scheduling graph for a Round-Robin (RR) scheduler with job preemption where newly arriving jobs will immediately run. Assume a time slice of 3 timer units. Draw vertical lines for key events and be sure to label the X-axis times as in the example.

| Job | Arrival Time | Job Length |
|---|---|---|
| A | T=0 | 25 |
| B | T=5 | 10 |
| C | T=10 | 15 |

```
      |
      |
RR    |
      |
      |_____________________________________________________
      0
```

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# Q6 – RR SCHEDULER - 2

Using the graph, from time t=10 until all jobs complete at t=50, evaluate Jain's Fairness Index:

Jain's fairness index is expressed as:

$$\mathcal{J}(x_1, x_2, \dots, x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} {x_i}^2}$$

Where n is the number of jobs, and $x_i$ is the time share of each process Jain's fairness index=1 for best case fairness, and 1/n for worst case fairness.

For the time window from t=10 to t=50, what percentage of the CPU time is allocated to each of the jobs A, B, and C?

Job A: ________ Job B: ________ Job C: ________

With these values, calculate Jain's fairness index from t=10 to t=50.



# Q7 – SLOPPY COUNTER

Below is a tradeoff space graph similar to those we've shown in class. Based on the sloppy counter threshold (S), add numbers on the <u>**left**</u> or <u>**right**</u> side of the graph for each of the following tradeoffs:

1. High number of Global Updates
2. High Performance
3. High Overhead
4. High Accuracy
5. Low number of Global Updates
6. Low Performance
7. Low Overhead
8. Low Accuracy

**Low sloppy threshold (S)** **High sloppy threshold (S)**

|_______________________________________________________________|

## MULTI-LEVEL FEEDBACK QUEUE

- Review the bonus lecture for examples of Multi-level-feedback-queue problems (MLFQ)
- https://tinyurl.com/ky7usnjb

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## QUESTIONS

# QUESTIONS

# TCSS 422

# OFFICE HOURS

# *PLEASE SAY HELLO*

# OFFICE HOURS

# HAVE STEPPED OUT

# WILL RETURN SHORTLY