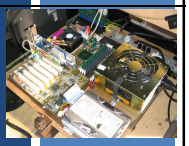
TCSS 422: OPERATING SYSTEMS



**Locks API,
Introduction to Locks,
Lock-Based Data Structures**

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FEEDBACK FROM 10/22

- **What is the purpose of a void * pointer for pthread_create() ?**
  - It is used to store a memory location to a function
  - Thread's code pointer will reference this
- How do programmers balance coarse vs. fine-grained locking with applications that have UIs?
  - Does the UI have shared memory that is operated on in parallel by multiple threads?
  - Model-View-Controller:
    Can separate Controller and Model from View

FEEDBACK - 2

- **Which is easier to implement fine-grained locking? Or coarse grained locking for parallel programming?**
- **If a thread is stuck in a lock state (*assume the thread is blocked waiting for the lock*) and the parent process (thread) does not call join, will the thread remain blocked after the parent process exits?**
  - Who holds the lock? Does the parent? Some other thread?
  - If a thread existing causes the termination of the program, the program is likely dead.

FEEDBACK - 3

- Can you go over how to make MAKE files?
- Can the 2 pages of notes for the exam be typed/printer.

OBJECTIVES

- Quiz 2 Review
- Program 1 – MASH Shell (Friday 10/26)
- Midterm – (Wed 10/31)
- **Multi-threaded Programming**
- Chapter 28 – Introduction to Locks
- Chapter 29 – Lock-based Data Structures
- Chapter 30 -

CHAPTER 28 – LOCKS

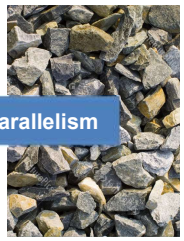
LOCKS - 4

- Program can have many mutex (lock) variables to "serialize" many critical sections
- Locks are also used to protect data structures
  - Prevent multiple threads from changing the same data simultaneously
  - Programmer can make sections of code "granular"
    - Fine grained – means just one grain of sand at a time through an hour glass
  - Similar to relational database transactions
    - DB transactions prevent multiple users from modifying a table, row, field

FINE GRAINED?

- Is this code a good example of "*fine grained parallelism*"?

```
pthread_mutex_lock(&lock);
a = b++;
b = a * c;
*d = a + b +c;
FILE * fp = fopen ("file.txt", "r");
fscanf(fp, "%s %s %s %d", str1, str2, str3, &e);
ListNode *node = mylist->head;
Int i=0
while (r
  node->
  node->subheading = str2;
  node->desc = str3;
  node->end = *e;
  node = node->next;
  i++
}
e = e – i;
pthread_mutex_unlock(&lock);
```



Example of coarse-grained parallelism

FINE GRAINED PARALLELISM

```
pthread_mutex_lock(&lock_a);
pthread_mutex_lock(&lock_b);
a = b++;
pthread_mutex_unlock(&lock_b);
pthread_mutex_unlock(&lock_a);

pthread_mutex_lock(&lock_b);
b = a * c;
pthread_mutex_unlock(&lock_b);

pthread_mutex_lock(&lock_d);
*d = a + b +c;
pthread_mutex_unlock(&lock_d);

FILE * fp = fopen ("file.txt", "r");
pthread_mutex_lock(&lock_e);
fscanf(fp, "%s %s %s %d", str1, str2, str3, &e);
pthread_mutex_unlock(&lock_e);

ListNode *node = mylist->head;
int i=0 . . .
```

EVALUATING LOCK IMPLEMENTATIONS

- Correctness
  - Does the lock work?
  - Are critical sections mutually exclusive? (atomic-*as a unit*?)
- Fairness
  - Are threads competing for a lock have a fair chance of acquiring it?
- Overhead

BUILDING LOCKS

- Locks require hardware support
  - To minimize overhead, ensure fairness and correctness
  - Special "atomic-*as a unit*" instructions to support lock implementation
  - Atomic-*as a unit* exchange instruction
    - `XCHG`
  - Compare and exchange instruction
    - `CMPXCHG`
    - `CMPXCHG8B`
    - `CMPXCHG16B`

HISTORICAL IMPLEMENTATION

- To implement mutual exclusion
  - Disable interrupts upon entering critical sections

```
1  void lock() {
2      DisableInterrupts();
3  }
4  void unlock() {
5      EnableInterrupts();
6  }
```

- Any thread could disable system-wide interrupt
  - What if lock is never released?
- On a multiprocessor processor each CPU has its own interrupts
  - Do we disable interrupts for all cores simultaneously?
- While interrupts are disabled, they could be lost
  - If not queued…

SPIN LOCK IMPLEMENTATION

- Operate without atomic-*as a unit* assembly instructions
- "Do-it-yourself" Locks
- Is this lock implementation: Correct? Fair? Performant?

```
1   typedef struct __lock_t { int flag; } lock_t;
2
3   void init(lock_t *mutex) {
4       // 0 → lock is available, 1 → held
5       mutex->flag = 0;
6   }
7
8   void lock(lock_t *mutex) {
9       while (mutex->flag == 1)  // TEST the flag
10          ;  // spin-wait (do nothing)
11      mutex->flag = 1;  // now SET it !
12  }
13
14  void unlock(lock_t *mutex) {
15      mutex->flag = 0;
16  }
```


DIY: CORRECT?

- Correctness requires luck… (e.g. *DIY lock is incorrect*)

Thread1	Thread2
call lock()	
while (flag == 1)	
interrupt: switch to Thread 2	
	call lock()
	while (flag == 1)
	flag = 1;
	interrupt: switch to Thread 1
flag = 1; // set flag to 1 (too!)	

- Here both threads have "acquired" the lock simultaneously

DIY: PERFORMANT?

```
void lock(lock_t *mutex)
{
  while (mutex->flag == 1);   // while lock is unavailable, wait…
  mutex->flag = 1;
}
```

- What is wrong with while(<cond>); ?
- Spin-waiting wastes time actively waiting for another thread
- while (1); will "peg" a CPU core at 100%
  - Continuously loops, and evaluates mutex->flag value…
  - Generates heat…

TEST-AND-SET INSTRUCTION

- C implementation: not atomic
  - Adds a simple check to basic spin lock
  - One a single core CPU system with preemptive scheduler:
  - Try this…

```
1   int TestAndSet(int *ptr, int new) {
2       int old = *ptr;  // fetch old value at ptr
3       *ptr = new;      // store 'new' into ptr
4       return old;      // return the old value
5   }
```

- lock() method checks that TestAndSet doesn't return 1
- Comparison is in the caller
- Single core systems are becoming scarce
- Try on a one-core VM

DIY: TEST-AND-SET - 2

- Requires a preemptive scheduler on single CPU core system
- Lock is never released without a context switch
- 1-core VM: occasionally will deadlock, doesn't miscount

```
1   typedef struct __lock_t {
2       int flag;
3   } lock_t;
4
5   void init(lock_t *lock) {
6       // 0 indicates that lock is available,
7       // 1 that it is held
8       lock->flag = 0;
9   }
10
11  void lock(lock_t *lock) {
12      while (TestAndSet(&lock->flag, 1) == 1)
13          ;       // spin-wait
14  }
15
16  void unlock(lock_t *lock) {
17      lock->flag = 0;
18  }
```


SPIN LOCK EVALUATION

- **Correctness:**
  - Spin locks guarantee: critical sections won't be executed simultaneously by (2) threads
- **Fairness:**
  - No fairness guarantee. Once a thread has a lock, nothing forces it to relinquish it…
- **Performance:**
  - Spin locks perform "busy waiting"
  - Spin locks are best for short periods of waiting
  - Performance is slow when multiple threads share a CPU
    - Especially for long periods

COMPARE AND SWAP

- Checks that the lock variable has the expected value FIRST, before changing its value
  - If so, make assignment
  - Return value at location
- Adds a comparison to TestAndSet
- Useful for wait-free synchronization
  - Supports implementation of shared data structures which can be updated atomically (*as a unit*) using the HW support CompareAndSwap instruction
  - Shared data structure updates become "wait-free"
  - Upcoming in Chapter 32

COMPARE AND SWAP

- Compare and Swap

```
1   int CompareAndSwap(int *ptr, int expected, int new) {
2       int actual = *ptr;
3       if (actual == expected)
4               *ptr = new;
5       return actual;
```

- Spin loc

```
3               ; // spin
4   }
```

1-core VM:
Count is correct, no deadlock

- X86 provides "`cmpxchgl`" compare-and-exchange instruction
  - `cmpxchg8b`
  - `cmpxchg16b`

TWO MORE "LOCK BUILDING" CPU INSTRUCTIONS

- Cooperative instructions used together to support synchronization on RISC systems
- No support on x86 processors
  - Supported by RISC: Alpha, PowerPC, ARM
- Load-linked (LL)
  - Loads value into register
  - Same as typical load
  - Used as a mechanism to track competition
- Store-conditional (SC)
  - Performs "mutually exclusive" store
  - Allows only one thread to store value

LL/SC LOCK

```
1   int LoadLinked(int *ptr) {
2       return *ptr;
3   }
4
5   int StoreConditional(int *ptr, int value) {
6       if (no one has updated *ptr since the LoadLinked to this address) {
7               *ptr = value;
8               return 1; // success!
9       } else {
10              return 0; // failed to update
11      }
12  }
```

- LL instruction loads pointer value (ptr)
- SC only stores if the load link pointer has not changed
- Requires HW support
  - C code is psuedo code

LL/SC LOCK - 2

```
1   void lock(lock_t *lock) {
2       while (1) {
3               while (LoadLinked(&lock->flag) == 1)
4                       ; // spin until it's zero
5               if (StoreConditional(&lock->flag, 1) == 1)
6                       return; // if set-it-to-1 was a success: all done
7                               otherwise: try it all over again
8       }
9   }
10
11  void unlock(lock_t *lock) {
12      lock->flag = 0;
13  }
```

- Two instruction lock

CHAPTER 29 – LOCK BASED DATA STRUCTTURES

OBJECTIVES

- Chapter 29
  - Concurrent Data Structures
  - Performance
  - Lock Granularity

LOCK-BASED CONCURRENT DATA STRUCTURES

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

COUNTER STRUCTURE W/O LOCK

- Synchronization weary --- not thread safe

```
1       typedef struct __counter_t {
2               int value;
3       } counter_t;
4
5       void init(counter_t *c) {
6               c->value = 0;
7       }
8
9       void increment(counter_t *c) {
10              c->value++;
11      }
12
13      void decrement(counter_t *c) {
14              c->value--;
15      }
16
17      int get(counter_t *c) {
18              return c->value;
19      }
```


CONCURRENT COUNTER

```
1       typedef struct __counter_t {
2               int value;
3               pthread_lock_t lock;
4       } counter_t;
5
6       void init(counter_t *c) {
7               c->value = 0;
8               Pthread_mutex_init(&c->lock, NULL);
9       }
10
11      void increment(counter_t *c) {
12              Pthread_mutex_lock(&c->lock);
13              c->value++;
14              Pthread_mutex_unlock(&c->lock);
15      }
16
```

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

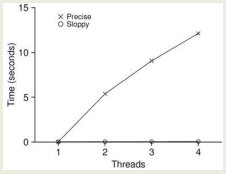
CONCURRENT COUNTER - 2

- Decrease counter
- Get value

```
(Cont.)
17      void decrement(counter_t *c) {
18              Pthread_mutex_lock(&c->lock);
19              c->value--;
20              Pthread_mutex_unlock(&c->lock);
21      }
22
23      int get(counter_t *c) {
24              Pthread_mutex_lock(&c->lock);
25              int rc = c->value;
26              Pthread_mutex_unlock(&c->lock);
27              return rc;
28      }
```


CONCURRENT COUNTERS - PERFORMANCE

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



Traditional vs. sloppy counter
Sloppy Threshold (S) = 1024

Synchronized counter scales poorly.

PERFECT SCALING

- Achieve (N) performance gain with (N) additional resources
- Throughput:
- Transactions per second
- 1 core
- N = 100 tps
- 10 core
- N = 1000 tps

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?

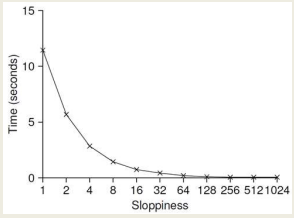
SLOPPY COUNTER - 2

- 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

CONCURRENT LINKED LIST - 1

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

```
1       // basic node structure
2       typedef struct __node_t {
3               int key;
4               struct __node_t *next;
5       } node_t;
6
7       // basic list structure (one used per list)
8       typedef struct __list_t {
9               node_t *head;
10              pthread_mutex_t lock;
11      } list_t;
12
13      void List_Init(list_t *L) {
14              L->head = NULL;
15              pthread_mutex_init(&L->lock, NULL);
16      }
17
(Cont.)
```

CONCURRENT LINKED LIST - 2

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

```
(Cont.)
18      int List_Insert(list_t *L, int key) {
19              pthread_mutex_lock(&L->lock);
20              node_t *new = malloc(sizeof(node_t));
21              if (new == NULL) {
22                      perror("malloc");
23                      pthread_mutex_unlock(&L->lock);
24              return -1; // fail
26              new->key = key;
27              new->next = L->head;
28              L->head = new;
29              pthread_mutex_unlock(&L->lock);
30              return 0; // success
31      }
(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.)
32
32      int List_Lookup(list_t *L, int key) {
33              pthread_mutex_lock(&L->lock);
34              node_t *curr = L->head;
35              while (curr) {
36                      if (curr->key == key) {
37                              pthread_mutex_unlock(&L->lock);
38                              return 0; // success
39                      }
40                      curr = curr->next;
41              }
42              pthread_mutex_unlock(&L->lock);
43              return -1; // failure
44      }
```


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

```
1       void List_Init(list_t *L) {
2               L->head = NULL;
3               pthread_mutex_init(&L->lock, NULL);
4       }
5
6       void List_Insert(list_t *L, int key) {
7               // synchronization not needed
8               node_t *new = malloc(sizeof(node_t));
9               if (new == NULL) {
10                      perror("malloc");
11                      return;
12              }
13              new->key = key;
14
15              // just lock critical section
16              pthread_mutex_lock(&L->lock);
17              new->next = L->head;
18              L->head = new;
19              pthread_mutex_unlock(&L->lock);
20      }
21
```


CCL – SECOND IMPLEMENTATION - 2

- Lookup

```
(Cont.)
22      int List_Lookup(list_t *L, int key) {
23              int rv = -1;
24              pthread_mutex_lock(&L->lock);
25              node_t *curr = L->head;
26              while (curr) {
27                      if (curr->key == key) {
28                              rv = 0;
29                              break;
30                      }
31                      curr = curr->next;
32              }
33              pthread_mutex_unlock(&L->lock);
34              return rv; // now both success and failure
35      }
```


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?

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

```
1       typedef struct __node_t {
2               int value;
3               struct __node_t *next;
4       } node_t;
5
6       typedef struct __queue_t {
7               node_t *head;
8               node_t *tail;
9               pthread_mutex_t headLock;
10              pthread_mutex_t tailLock;
11      } queue_t;
12
13      void Queue_Init(queue_t *q) {
14              node_t *tmp = malloc(sizeof(node_t));
15              tmp->next = NULL;
16              q->head = q->tail = tmp;
17              pthread_mutex_init(&q->headLock, NULL);
18              pthread_mutex_init(&q->tailLock, NULL);
19      }
20
(Cont.)
```


CONCURRENT QUEUE - 2

- Add to queue

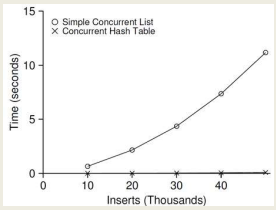
```
(Cont.)
21      void Queue_Enqueue(queue_t *q, int value) {
22              node_t *tmp = malloc(sizeof(node_t));
23              assert(tmp != NULL);
24
25              tmp->value = value;
26              tmp->next = NULL;
27
28              pthread_mutex_lock(&q->tailLock);
29              q->tail->next = tmp;
30              q->tail = tmp;
31              pthread_mutex_unlock(&q->tailLock);
32      }
(Cont.)
```


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

```
1       #define BUCKETS (101)
2
3       typedef struct __hash_t {
4               list_t lists[BUCKETS];
5       } hash_t;
6
7       void Hash_Init(hash_t *H) {
8               int i;
9               for (i = 0; i < BUCKETS; i++) {
10                      List_Init(&H->lists[i]);
11              }
12      }
13
14      int Hash_Insert(hash_t *H, int key) {
15              int bucket = key % BUCKETS;
16              return List_Insert(&H->lists[bucket], key);
17      }
18
19      int Hash_Lookup(hash_t *H, int key) {
20              int bucket = key % BUCKETS;
21              return List_Lookup(&H->lists[bucket], key);
22      }
```

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/javase/7/docs/api/java/util/concurrent/atomic/package-summary.html

CHAPTER 30 – CONDITION VARIABLES

CONDITION VARIABLES

- There are many cases where a thread wants to wait for another thread before proceeding with execution
- Consider when a precondition must be fulfilled before it is meaningful to proceed …

CONDITION VARIABLES - 2

- Support a signaling mechanism to alert threads when preconditions have been satisfied
- Eliminate busy waiting
- Alert one or more threads to "consume" a result, or respond to state changes in the application
- Threads are placed on an **explicit queue** (FIFO) to wait for signals
- **Signal**: wakes one thread
  broadcast wakes all (ordering by the OS)

CONDITION VARIABLES - 3

- Condition variable

```
pthread_cond_t c;
```

  - Requires initialization
- Condition API calls

```
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);    // wait()
pthread_cond_signal(pthread_cond_t *c);                      // signal()
```

- wait() accepts a mutex parameter
  - Releases lock, puts thread to sleep
- signal()
  - Wakes up thread, awakening thread acquires lock

CONDITION VARIABLES - QUESTIONS

- **Why would we want to put waiting threads on a queue… why not use a stack?**
  - Queue (FIFO), Stack (LIFO)
  - Using condition variables eliminates busy waiting by putting threads to "sleep" and yielding the CPU.
- **Why do we want to not busily wait for the lock to become available?**
- A program has 10-threads, where 9 threads are waiting. The working thread finishes and broadcasts that the lock is available. **What happens next?**

MATRIX GENERATOR

Matrix generation example

Chapter 30
signal.c

MATRIX GENERATOR

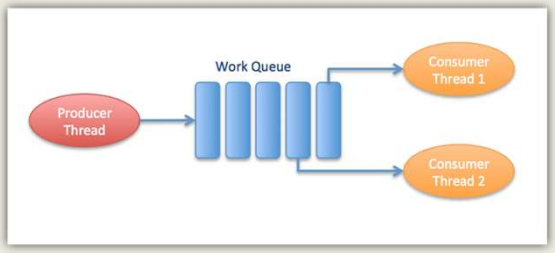
- The main thread, and worker thread (generates matrices) share a single matrix pointer.
- What would happen if we don't use a condition variable to coordinate exchange of the lock?
- Let's try "nosignal.c"

SUBTLE RACE CONDITION: WITHOUT A WHILE

```
1       void thr_exit() {
2               done = 1;
3               Pthread_cond_signal(&c);
4       }
5
6       void thr_join() {
7               if (done == 0)
8                       Pthread_cond_wait(&c);
9       }
```

- Parent thread calls thr_join() and executes the comparison
- The context switches to the child
- The child runs thr_exit() and signals the parent, but the parent is not waiting yet.
- **The signal is lost**
- The parent deadlocks

PRODUCER / CONSUMER



PRODUCER / CONSUMER

- **Producer**
  - Produces items – consider the child matrix maker
  - Places them in a buffer
    - Example: the buffer is only 1 element (single array pointer)
- **Consumer**
  - Grabs data out of the buffer
  - Our example: parent thread receives dynamically generated matrices and performs an operation on them
    - Example: calculates average value of every element (integer)
- Multithreaded web server example
  - Http requests placed into work queue; threads process

PRODUCER / CONSUMER - 2

- Producer / Consumer is also known as **Bounded Buffer**
- Bounded buffer
  - Similar to piping output from one Linux process to another
  - grep pthread signal.c | wc –l
  - Synchronized access:
    sends output from grep → wc as it is produced
  - File stream

PUT/GET ROUTINES

- Buffer is a one element shared data structure (int)
- Producer "puts" data
- Consumer "gets" data
- Shared data structure requires synchronization

```
1       int buffer;
2       int count = 0;    // initially, empty
3
4       void put(int value) {
5               assert(count == 0);
6               count = 1;
7               buffer = value;
8       }
9
10      int get() {
11              assert(count == 1);
12              count = 0;
13              return buffer;
14      }
```


PRODUCER / CONSUMER - 3

- Producer adds data
- Consumer removes data (busy waiting)
- **Will this code work (spin locks) with 2-threads?**
  1. Producer 2. Consumer

```
1       void *producer(void *arg) {
2               int i;
3               int loops = (int) arg;
4               for (i = 0; i < loops; i++) {
5                       put(i);
6               }
7       }
8
9       void *consumer(void *arg) {
10              int i;
11              while (1) {
12                      int tmp = get();
13                      printf("%d\n", tmp);
14              }
15      }
```


PRODUCER / CONSUMER - 3

- The shared data structure needs synchronization!

```
1       cond_t cond;
2       mutex_t mutex;
3
4       void *producer(void *arg) {
5           int i;
6           for (i = 0; i < loops; i++) {
7               Pthread_mutex_lock(&mutex);            // p1
8               if (count == 1)                        // p2
9                   Pthread_cond_wait(&cond, &mutex);  // p3
10              put(i);                                // p4
11              Pthread_cond_signal(&cond);            // p5
12              Pthread_mutex_unlock(&mutex);          // p6
13          }
14      }
15
16      void *consumer(void *arg) {
17          int i;
18          for (i = 0; i < loops; i++) {
19              Pthread_mutex_lock(&mutex);            // c1
```

Producer

PRODUCER/CONSUMER - 4

```
20              if (count == 0)                        // c2
21                  Pthread_cond_wait(&cond, &mutex);  // c3
22              int tmp = get();                       // c4
23              Pthread_cond_signal(&cond);            // c5
24              Pthread_mutex_unlock(&mutex);          // c6
25              printf("%d\n", tmp);
26          }
27      }
```

Consumer

- This code as-is works with just:
  - (1) Producer
  - (1) Consumer
- If we scale to (2+) consumer's it fails
  - How can it be fixed ?

EXECUTION TRACE: NO WHILE, 1 PRODUCER, 2 CONSUMERS

- Two threads

Legend
c1/p1- lock
c2/p2- check var
c3/p3- wait
c4- put()
p4- get()
c5/p5- signal
c6/p6- unlock

T_{c1}	State	T_{c2}	State	T_p	State	Count	Comment
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
Sleep			Ready	p1	Running	0	
Sleep			Ready	p2	Running	0	
Sleep			Ready	p4	Running	1	Buffer now full
Ready			Ready	p5	Running	1	T_{c1} awoken
Ready			Ready	p6	Running	1	
Ready			Ready	p1	Running	1	
Ready			Ready	p2	Running	1	
Ready			Ready	p3	Sleep	1	Buffer full; sleep
Ready	c1		Running		Sleep	1	T_{c2} sneaks in ...
Ready	c2		Running		Sleep	1	
Ready	c4		Running		Sleep	0	... and grabs data
Ready	c5		Running		Ready	0	T_p awoken
Ready	c6		Running		Ready	0	
c4	Running		Ready		Ready	0	Oh oh! No data

PRODUCER/CONSUMER SYNCHRONIZATION

- When producer threads awake, they do not check if there is any data in the buffer…
  - Need while, not if
- What if T_p puts a value, wakes T_{c1} whom consumes the value
- Then T_p has a value to put, but T_{c1}'s signal on &cond wakes T_{c2}
- There is nothing for T_{c2} consume, so T_{c2} sleeps
- T_{c1}, T_{c2}, and T_p all sleep forever
- T_{c1} needs to wake T_p to T_{c2}

EXECUTION TRACE: WHILE, 1 CONDITION, 1 PRODUCER, 2 CONSUMERS

Legend
c1/p1- lock
c2/p2- check var
c3/p3- wait
c4- put()
p4- get()
c5/p5- signal
c6/p6- unlock

T_{c1}	State	T_{c2}	State	T_p	State	Count	Comment
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Running		Sleep		Sleep	1	Recheck condition
c4	Running		Sleep		Sleep	0	T_{c1} grabs data
c5	Running		Ready		Sleep	0	Oops! Woke T_{c2}

EXECUTION TRACE – 2 WHILE, 1 CONDITION, 1 PRODUCER, 2 CONSUMERS

- T_{c2} runs, no data to consume

Legend
c1/p1- lock
c2/p2- check var
c3/p3- wait
c4- put()
p4- get()
c5/p5- signal
c6/p6- unlock

T_{c1}	State	T_{c2}	State	T_p	State	Count	Comment
...	...	...	...	...	...	...	(cont.)
c6	Running		Ready		Sleep	0	
c1	Running		Ready		Sleep	0	
c2	Running		Ready		Sleep	0	
c3	Sleep		Ready		Sleep	0	Nothing to get
	Sleep	c2	Running		Sleep	0	
	Sleep	c3	Sleep		Sleep	0	Everyone asleep ...

TWO CONDITIONS

- Use two condition variables: empty & full
  - One condition handles the producer
  - the other the consumer

```
1   cond_t empty, full;
2   mutex_t mutex;
3
4   void *producer(void *arg) {
5       int i;
6       for (i = 0; i < loops; i++) {
7           Pthread_mutex_lock(&mutex);
8           while (count == 1)
9               Pthread_cond_wait(&empty, &mutex);
10          put(i);
11          Pthread_cond_signal( &full);
12          Pthread_mutex_unlock(&mutex);
13      }
14  }
15
```


FINAL PRODUCER/CONSUMER

- Change buffer from int, to int buffer[MAX]
- Add indexing variables

```
1   int buffer[MAX];
2   int fill = 0;
3   int use = 0;
4   int count = 0;
5
6   void put(int value) {
7       buffer[fill] = value;
8       fill = (fill + 1) % MAX;
9       count++;
10  }
11
12  int get() {
13      int tmp = buffer[use];
14      use = (use + 1) % MAX;
15      count--;
16      return tmp;
17  }
```


FINAL P/C - 2

```
1   cond_t empty, full
2   mutex_t mutex;
3
4   void *producer(void *arg) {
5       int i;
6       for (i = 0; i < loops; i++) {
7           Pthread_mutex_lock(&mutex);              // p1
8           while (count == MAX)                     // p2
9               Pthread_cond_wait(&empty, &mutex);   // p3
10          put(i);                                  // p4
11          Pthread_cond_signal (&full);             // p5
12          Pthread_mutex_unlock(&mutex);            // p6
13      }
14  }
15
16  void *consumer(void *arg) {
17      int i;
18      for (i = 0; i < loops; i++) {
19          Pthread_mutex_lock(&mutex);              // c1
20          while (count == 0)                       // c2
21              Pthread_cond_wait( &full, &mutex);   // c3
22          int tmp = get();                         // c4
```


FINAL P/C - 3

```
(Cont.)
23              Pthread_cond_signal (&empty);            // c5
24              Pthread_mutex_unlock(&mutex);            // c6
25              printf("%d\n", tmp);
26          }
27      }
```

- Producer: only sleeps when buffer is full
- Consumer: only sleeps if buffers are empty

COVERING CONDITIONS

- A condition that covers ***all*** cases (conditions):
- Excellent use case for **pthread_cond_broadcast**
- Consider memory allocation:
  - When a program deals with huge memory allocation/deallocation on the heap
  - Access to the heap must be managed when memory is scarce

  PREVENT: Out of memory:
  - queue requests until memory is free

  - Which thread should be woken up?

COVERING CONDITIONS - 2

```
1   // how many bytes of the heap are free?
2   int bytesLeft = MAX_HEAP_SIZE;
3
4   // need lock and condition too
5   cond_t c;
6   mutex_t m;
7
8   void *
9   allocate(int size) {
10      Pthread_mutex_lock(&m);
11      while (bytesLeft < size)
12          Pthread_cond_wait(&c, &m);
13      void *ptr = ...;                    // get mem from heap
14      bytesLeft -= size;
15      Pthread_mutex_unlock(&m);
16      return ptr;
17  }
18
19  void free(void *ptr, int size) {
20      Pthread_mutex_lock(&m);
21      bytesLeft += size;
22      Pthread_cond_signal(&c);        //
23      Pthread_mutex_unlock(&m);
24  }
```

Check available memory

Broadcast

COVER CONDITIONS - 3

- Broadcast awakens all blocked threads requesting memory
- Each thread evaluates if there's enough memory: (bytesLeft < size)
  - Reject: requests that cannot be fulfilled- go back to sleep
    - *Insufficient memory*
  - Run: requests which **can** be fulfilled
    - with newly available memory!
- **Overhead**
  - Many threads may be awoken which can't execute

QUESTIONS