a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

CPSC 213
Introduction to Computer Systems

Unit 2c
Synchronization

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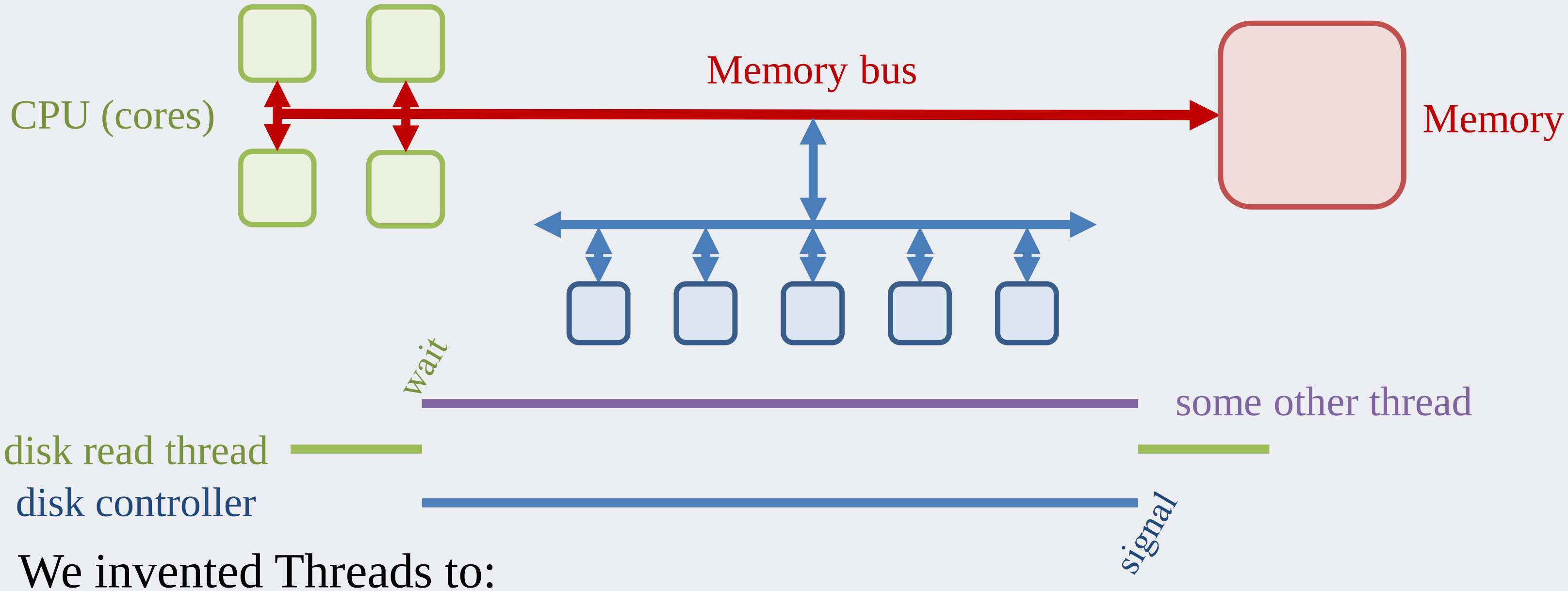
Announcements

- Google doc for lecture questions
  - See Piazza for link, section 102
  - https://docs.google.com/document/d/1G6hkekQS7mT9lFpP8AVftYao8vLRujIrRLAvOuX_07w/edit
  - Add your question anonymously (at the top)
  - Help answer questions too!

Overview

- Reading
  - text: 12.4-12.6, parts of 12.7
- Learning Goals
  - explain the relationship between concurrency, shared data, critical sections and mutual exclusion
  - use locks to guarantee mutual exclusion in C programs
  - identify race conditions in code
  - explain how to implement a *correct* and *efficient* spinlock
  - describe the difference between spinlocks (busy waiting) and blocking locks (blocking waiting) and identify conditions where each is favoured over the other
  - describe how blocking locks are implemented and how they use spinlocks
  - explain the difference between condition variables and monitors
  - describe why conditions are useful by giving an example of a situation where one would be used
  - use monitors and condition variables for synchronization in C programs
  - explain why it is necessary to associate a condition variable with a specific monitor and to require that the monitor be held before calling wait
  - explain how condition variables are implemented
  - describe why reader-writer monitors are useful and explain the constraints involved in their use
  - explain the difference between semaphores and monitors/condition variables
  - use semaphores for synchronization in C programs
  - explain how semaphores are implemented
  - describe what a deadlock is, how it can be caused, why it is bad, and how it can be avoided
  - give an example of the use of lock-free synchronization for updating a concurrent data structure and explain the benefit of this approach compared to using locks

Synchronization



- We invented Threads to:
  - **express parallelism** - do things at the same time on different processors
  - **manage asynchrony** - do something else while waiting for I/O controller
- But, now we have two problems related to controlling operation order
  - coordinating access to memory (variables) shared among multiple threads
  - control flow transfers among threads (wait until notified by another thread)
- **Synchronization** is the mechanism threads use to:
  - ensure mutual exclusion of critical sections
  - wait for and signal of the occurrence of events

Communicating through shared data

- There will be problems if:
  - threads share a data structure
  - operations involve multiple memory accesses
  - these accesses can be arbitrarily interleaved
- Example: a stack implemented as an array
  - suppose two threads accessing concurrently
  - what happens if both push? Both pop? 1 push, 1 pop?

A push

1. if (n<4)

B push

2. if (n<4)
3. array[n] = i
4. n++;

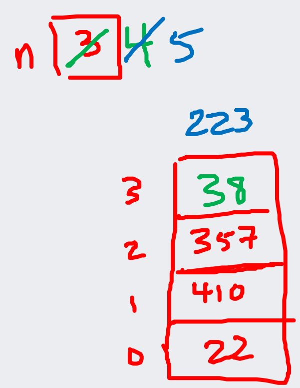
5. array[n] = i
6. n++

A

B

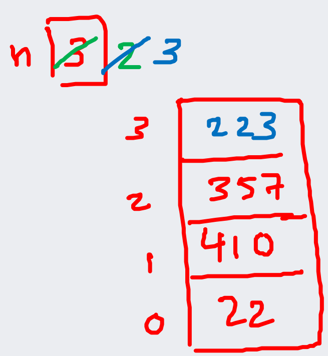
```
int n;
int array[4];

void push(i) {
  if (n < 4) {
    array[n] = i;
    n++;
  }
}

int pop() {
  if (n > 0) {
    n--;
    return array[n];
  } else
  return -1;
}
```

Both push



A pushes

B pops



return 357

The importance of mutual exclusion

- Shared data
  - data structure that could be accessed by multiple threads
  - typically, concurrent access to shared data is a bug
- Critical sections
  - sections of code that access shared data
- Race condition
  - simultaneous access to critical section by multiple threads (at least one updating)
  - conflicting operations on shared data structure are arbitrarily interleaved
  - unpredictable (non-deterministic) program behaviour – usually a (serious) bug
- Mutual exclusion
  - a mechanism implemented in software (with some special hardware support)
  - to ensure critical sections of a shared data item are executed by only one thread at a time
  - reading and writing should be handled differently (more about this later)

A linked-list stack

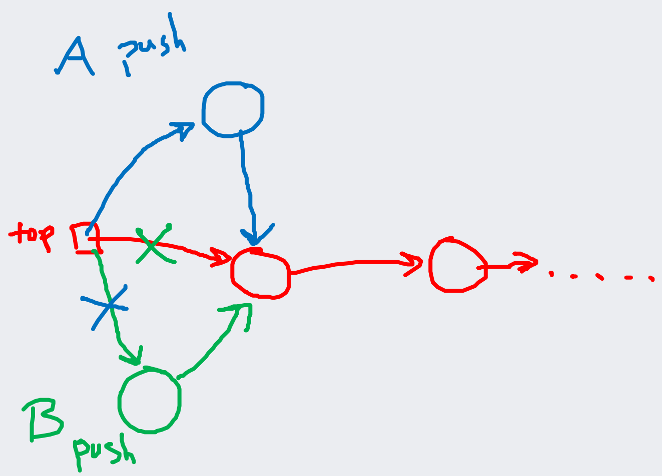
Still corrupting shared data

```
void push_st (struct SE* e) {
  e->next = top;
  top = e;
}
```

```
struct SE {
  struct SE* next;
};
struct SE* top = NULL;
```

```
void SE* pop_st () {
  struct SE* e = top;
  top = (top)? top->next: NULL;
  return e;
}
```

Still problems if both push? Both pop? 1 push, 1 pop?



Linked list stack

- Sequential/synchronous execution of repeated push/pop is OK…

```
void push_driver (long int n) {
  struct SE* e;
  while (n--)
    push (malloc (...) );
}
```

```
push_driver (n)
pop_driver  (n);
assert      (top == NULL);
```

```
void pop_driver (long int n) {
  struct SE* e;
  while (n--) {
    do {
      e = pop();
    }
    while (!e);
    free(e);
  }
}
```

Linked list stack

- …but concurrent execution doesn't always work

```
int main (void) {

  ...

  et = uthread_create(push_driver, num);
  dt = uthread_create(pop_driver, num);

  uthread_join(et, 0);
  uthread_join(dt, 0);

  assert (top == NULL);
}
```

Note: works for `uthread_init(1)` *without* pre-emption, but not guaranteed to work for `uthread_init(2)`

Linked list stack

The problem

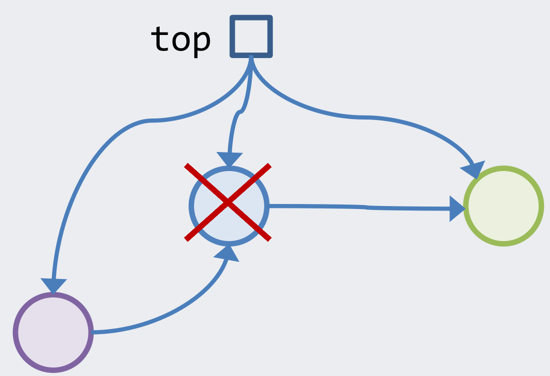
- Same situation as the array implementation
  - push and pop are critical sections on the shared stack
  - parallel execution leads to potential arbitrary interleaving of operations
  - sometimes, the interleaving corrupts the data structure

```c
void push_st (struct SE* e) {
  e->next = top;
  top = e;
}
```

```c
void SE* pop_st () {
  struct SE* e = top;
  top = (top)? top->next: NULL;
  return e;
}
```

Suppose the execution occurs as follows:

```
1. e->next = top
                  2. e = top
                  3. top = top->next
                  4. return e
                  5. free(e)
6. top = e
```



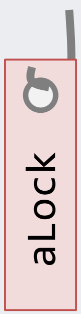
Mutual exclusion using locks

- lock semantics
  - a lock is either held by a thread, or available
  - at most one thread can hold a lock at a time
  - a thread attempting to acquire a lock that is already held is forced to wait
- lock primitives
  - `lock`   acquire lock, wait if necessary
  - `unlock`   release lock, allowing another thread to acquire if waiting

- Example: using locks on the shared stack

```
void push_cs (struct SE* e) {
  lock (&aLock);
    push_st(e);
  unlock (&aLock);
}
```

```
struct SE* pop_cs () {
  struct SE* e;
  lock (&aLock);
    e = pop_st();
  unlock (&aLock);

  return e;
}
```



Quick questions with locks

- What happens when…

```
void push_cs (struct SE* e) {
  lock (&aLock);
    push_st(e);
  unlock (&aLock);
}
```

```
struct SE* pop_cs () {
  struct SE* e;
  lock (&aLock);
    e = pop_st();
  unlock (&aLock);

  return e;
}
```

  - Thread A calls `push_cs` while thread B is executing in `push_cs`?

    → waits for lock to release → holds the lock

  - Thread A calls `push_cs` while thread B is executing in `pop_cs`?

    → waits for lock to release → holds the lock

  - What if `push_cs` and `pop_cs` use different locks?

    synchronization problems.

  - What if `push_cs` or `pop_cs` never call unlock?

    lock is held forever, other threads cannot proceed,

Implementing simple locks

- An initial attempt
  - use a shared global variable for synchronization
  - `lock` - loops until the variable is 0 and then sets it to 1
  - `unlock` - sets the variable to 0

```
int lock = 0;
```

```
void lock (int* lock) {
  while (*lock == 1) {}
  *lock = 1;
}
```

do nothing

claim the lock

```
void unlock (int* lock) {
  *lock = 0;
}
```

Will this work?

Implementing simple locks

First attempt – problem!

- There is a race in the lock code
  - Suppose two threads both request a lock at (nearly) the same time

Thread A

```
void lock (int* lock) {
  while (*lock == 1) {}
  *lock = 1;
}
```

Thread B

```
void lock (int* lock) {
  while (*lock == 1) {}
  *lock = 1;
}
```

Suppose the execution occurs as follows:

Thread A	Thread B
`1. read *lock == 0, exit loop`	
	`2. read *lock == 0, exit loop`
`3. *lock = 1`	
`4. return with lock held`	
	`5. *lock = 1`
	`6. return with lock held`

Both threads think they hold the lock

Implementing simple locks

First attempt – bigger problems!

- The race exists even at the machine code level
  - two instructions are needed to acquire the lock
    - first, read to check that the lock is available
    - second, set the lock to held
  - but a read by another thread can check the lock before the first thread sets the hold

```
      ld  $lock, r1
      ld  $1,    r2

loop: ld  (r1),  r0
      beq r0,   free
      br  loop

free: st  r2,   (r1)
```

lock appears free

another thread reads lock

acquire lock

Thread A	Thread B
`ld (r1), r0`	
	`ld (r1), r0`
`st r2, (r1)`	
	`st r2, (r1)`

We need a way to read AND write a memory location with no possibility of interruption

Atomic memory exchange

- Atomicity
  - is a general property in systems
  - where a group of operations are performed as a single, indivisible unit

- Atomic memory exchange
  - one type of atomic memory instruction (there are other types)
  - group a load and store together atomically
  - exchanging the value of a register and a memory location

Name	Semantics	Assembly
atomic exchange	`r[v] ← m[r[a]]` `m[r[a]] ← r[v]`	`xchg (ra), rv`

Spinlock

- A spinlock is
  - a lock where the waiter *spins*, looping on memory reads until lock is acquired
  - also called a *busy-waiting* lock

- Implementation using atomic exchange
  - spin on atomic memory operation
    - that attempts to acquire lock while
    - atomically reading its old value

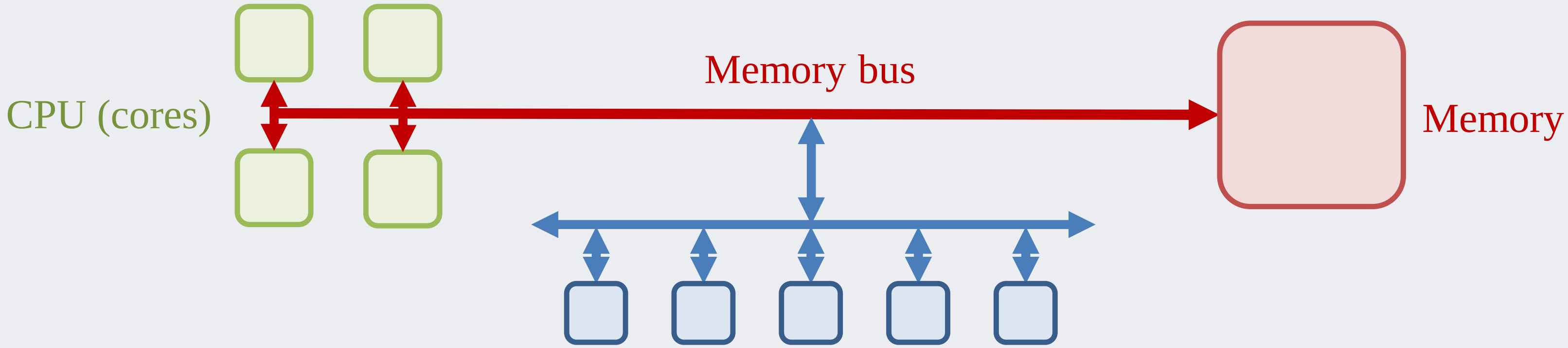
```
      ld   $lock, r1
      ld   $1,    r0
loop: xchg (r1),  r0   <- R/W
      beq  r0,  held
      br   loop
held: ...
```

Compare with:

```
      ld   $lock, r1
      ld   $1,    r2

loop: ld   (r1),  r0   R
      beq  r0,  free
      br   loop

free: st   r2,  (r1)   W
```

Problem: atomic exchange is EXPENSIVE

Implementing atomic exchange



- Cannot be implemented by CPU alone
  - must synchronize across multiple CPUs
    - accessing the same memory location at the same time

- Implemented by memory bus
  - memory bus synchronizes every CPU's access to memory
  - the two parts of the exchange (read + write) are coupled on bus
  - bus ensures that no other memory transaction can intervene
  - this instruction is much slower, with higher overhead than normal read/write

Speeding up spinlocks

- Spin first on normal read
  - normal reads are fast and efficient compared to exchange
  - use normal read in loop until lock appears free
  - when lock appears free, use exchange to try to grab it
  - if exchange fails, then go back to normal read

```
      ld   $lock, r1   # r1 = &lock
loop: ld   (r1),  r0   # r0 = lock
      beq  r0,   try   # goto try if lock == 0 (available)
      br   loop        # goto loop if lock != 0 (held)
try:  ld   $1, r0      # r0 = 1
      xchg (r1),  r0   # atomically swap r0 and lock
      beq  r0,  held   # goto held, if lock was 0 before swap
      br   loop        # try again if another thread holds lock
held: ...              # we now hold the lock
```

- Busy-waiting pros and cons
  - spinlocks are necessary and OK if spinner only waits a short time
  - But, using a spinlock to wait for a long time wastes CPU cycles

Blocking locks

- If a thread might wait for a long time
  - it should block so that other threads can run
  - it will then unblock when it becomes runnable, when
    - either the lock is unlocked, or an event is signaled

- Blocking locks for mutual exclusion
  - attempting to acquire a held lock blocks calling thread
    - blocked thread's TCB is stored on lock's waiting queue
  - when releasing lock, unblock a waiting thread if there is one
    - remove blocked thread from lock's waiting queue and place it on ready queue

- Blocking for event notification
  - wait by blocking, placing TCB on a waiting queue
  - signal a specific waiting queue by moving a thread to ready queue

Monitors and condition variables

- MUTual EXclusion plus inter-thread synchronization
  - introduced by Tony Hoare and Per Brinch Hansen, circ. 1974
  - basis for synchronization primitives in Unix, Java, etc.
- Monitor / Mutex
  - blocking lock to guarantee mutual exclusion
  - monitor operations were enter and exit
  - typically called a **mutex** (or just a lock), with operations `lock` and `unlock`
- Condition variable
  - allows threads to synchronize with each other
  - **wait** blocks until a subsequent signal operation on the variable
  - **signal** unblocks waiter
  - **broadcast** unblocks all waiters
  - can only be accessed from inside of a monitor (i.e. with mutex held)

Uthreads mutex and condition

```
struct uthread_mutex;
typedef struct uthread_mutex* uthread_mutex_t;
struct uthread_cond;
typedef struct uthread_cond*  uthread_cond_t;
uthread_mutex_t uthread_mutex_create        ();
void            uthread_mutex_lock          (uthread_mutex_t);
void            uthread_mutex_lock_readonly (uthread_mutex_t);
void            uthread_mutex_unlock        (uthread_mutex_t);
void            uthread_mutex_destroy       (uthread_mutex_t);
uthread_cond_t  uthread_cond_create         (uthread_mutex_t);
void            uthread_cond_wait           (uthread_cond_t);
void            uthread_cond_signal         (uthread_cond_t);
void            uthread_cond_broadcast      (uthread_cond_t);
void            uthread_cond_destroy        (uthread_cond_t);
```

Using conditions

- Basic formulation
  - one thread acquires mutex and may wait for a condition to be established

```
uthread_mutex_lock (aMutex);
  while (!aDesiredState)
    uthread_cond_wait (aCond);
  aDesiredState = 0;
uthread_mutex_unlock (aMutex);
```

condition for acquiring lock

wait blocks the thread, release the lock

do whatever you need

  - another thread acquires mutex, establishes condition and signals waiter, if there is one

```
uthread_mutex_lock (aMutex);
  aDesiredState = 1;
  uthread_cond_signal (aCond);
uthread_mutex_unlock (aMutex);
```

set the available condition (for others)

wakes up a waiter

`wait` releases the mutex and blocks thread

- before waiter blocks, it atomically releases mutex to allow other threads to acquire it
- when wait unblocks, it re-acquires mutex, waiting/blocking to enter if necessary
- note: other threads may have acquired mutex between wait call and return

Using conditions

- **`signal`** awakens at most one thread
  - waiter does not run until signaler releases the mutex explicitly
  - a third thread could intervene and acquire mutex before waiter
  - waiter must then re-check wait condition
  - if no threads are waiting, then calling signal has no effect

Recheck condition after wakeup

```
lock (aMutex);
  while (!aDesiredState)
    wait (aCond);
  aDesiredState = 0;
unlock (aMutex);
```

Don't assume condition is still true

```
lock (aMutex);
  if (!aDesiredState)
    wait (aCond);
  aDesiredState = 0;
unlock (aMutex);
```

- **`broadcast`** awakens all threads
  - may wake up too many
  - that's OK since threads re-check wait condition and re-wait if necessary

```
lock (aMutex);
  aDesiredCondition += n;
  broadcast (aCond);
unlock (aMutex);
```

```
lock (aMutex);
  while (!aDesiredCondition)
    wait (aCond);
  aDesiredCondition--;
unlock (aMutex);
```

Event ordering exercise

IC_11_29 – order_starter.c

- Suppose we have two threads running concurrently
  - `t0` prints `"a"`
  - `t1` prints `"b"`
- We want to ensure the output is always `"ab"`, in that order
  - How?
    - add a mutex, condition, and a desired state variable (see earlier slides)

Video streaming with threads

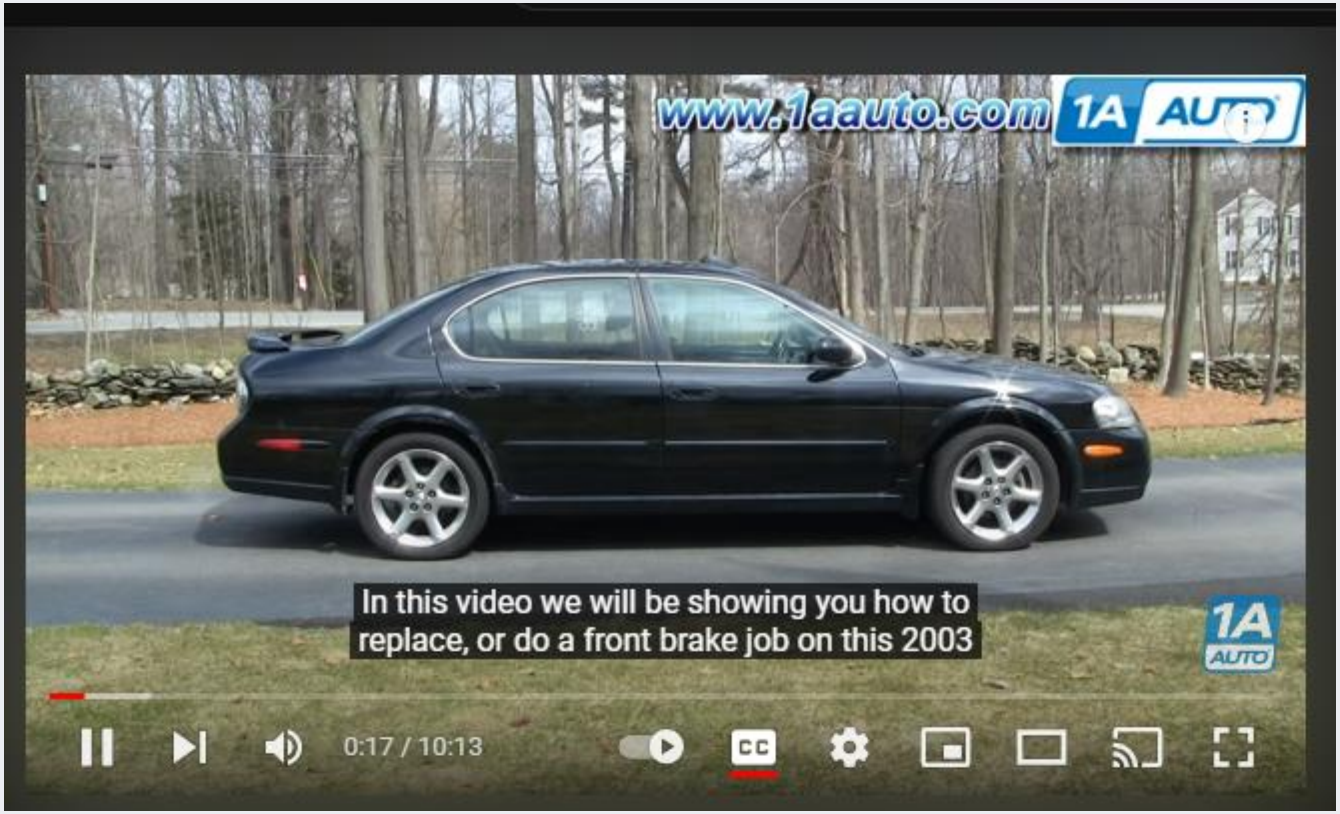


Image credit: https://www.youtube.com/@1AAuto

Video streaming with threads

- General problem
  - video playback has two parts: (1) fetch/decode and (2) playback
  - fetch has variable latency and so we need a buffer
    - Sometimes you can fetch faster than playback rate
    - but, other times there are long delays
    - buffer hides the delays by fetching ahead of playback position when possible
- Bounded buffer and two independent threads
  - finite buffer of the next few video frames to play
  - maximum size is N
  - goal: keep buffer at least 50% full (or some other threshold of our choosing)
- Producer thread
  - fetch frame from network and put them in buffer
- Consumer thread
  - fetch frame from buffer, decode them and send them to video driver
- How are Producer and Consumer connected?
  - advantage of this approach is that they are largely decoupled; each has a separate job
  - but, it's the consumer that decides when the producer should run

Video streaming with threads

Step 1 – requesting frames

```
struct video_frame;
#define N 100
struct video_frame buf[N];
int buf_length = 0;
int buf_pcur   = 0;
int buf_ccur   = 0;

uthread_mutex_t mx;
uthread_cond_t  need_frames;
```

```
void producer() {
  while (1) {
    uthread_lock (mx);
      while (buf_length < N) {
        buf [pcur] =  get_next_frame();
        buf_pcur   =  (pcur + 1) % N;
        buf_length += 1;
      }
      uthread_cond_wait (need_frames);
    uthread_unlock (mx);
  }
}
```

```
void consumer() {
  while (1) {
    uthread_lock (mx);
      assert (buf_length > 0);
      show_frame (buf [buf_ccur]);
      buf_ccur   =  (buf_ccur + 1) % N;
      buf_length -= 1;
      if (buf_length == N/2)
         uthread_cond_signal (need_frames);
    uthread_unlock (mx);
  }
}
```

Video streaming with threads

Step 2 – delivering frames

```
struct video_frame;
#define N 100
struct video_frame buf[N];
int buf_length = 0;
int buf_pcur   = 0;
int buf_ccur   = 0;

uthread_mutex_t mx;
uthread_cond_t  need_frames;
uthread_cond_t  have_frame;
```

```
void producer() {
  uthread_lock (mx);
    while (1) {
      while (buf_length < N) {
        buf [pcur] =  get_next_frame();
        buf_pcur   =  (pcur + 1) % N;
        buf_length += 1;
        uthread_cond_signal (have_frame);
      }
      uthread_cond_wait (need_frames);
    }
  uthread_unlock (mx);
}
```

```
void consumer() {
  uthread_lock (mx);
    while (1) {
      while (buf_length == 0)
        uthread_cond_wait (have_frame);
      show_frame (buf [buf_ccur]);
      buf_ccur   =  (buf_ccur + 1) % N;
      buf_length -= 1;
      if (buf_length < N/2)
        uthread_cond_signal (need_frames);
    }
  uthread_unlock (mx);
}
```

Video streaming with threads

Full version

```
struct video_frame;
#define N 100
struct video_frame buf[N];
int buf_length = 0;
int buf_pcur   = 0;
int buf_ccur   = 0;

uthread_mutex_t mx;
uthread_cond_t  need_frames;
uthread_cond_t  have_frame;
uthread_cond_t  show_next_frame;
```

```
void producer() {
  uthread_lock (mx);
    while (1) {
      while (buf_length < N) {
        buf [pcur] =  get_next_frame();
        buf_pcur   =  (pcur + 1) % N;
        buf_length += 1;
        uthread_cond_signal (have_frame);
      }
      uthread_cond_wait (need_frames);
    }
  uthread_unlock (mx);
}
```

```
void consumer() {
  uthread_lock (mx);
    while (1) {
      uthread_cond_wait (show_next_frame);
      while (buf_length == 0);
        uthread_cond_wait (have_frame);
      show_frame (buf [buf_ccur]);
      buf_ccur   =  (buf_ccur + 1) % N;
      buf_length -= 1;
      if (buf_length < N/2)
        uthread_cond_signal (need_frames);
    }
  uthread_unlock (mx);
}
```

Final note:
show_next_frame will be signaled every time a new frame is required for the video driver; e.g. every 1/30 s

Producer and Consumer threads

General template

```
int canGoFlag = 1;
uthread_mutex_t mx;
uthread_cond_t canGoCond;
```

Producer (P)

```
uthread_mutex_lock(mx);
    uthread_cond_signal(canGoCond);
    canGoFlag = 1;
uthread_mutex_unlock(mx);
```

Consumer (C)

```
uthread_mutex_lock(mx);
    while (canGoFlag == 0)
        uthread_cond_wait(canGoCond);
    canGoFlag = 0;
uthread_mutex_unlock(mx);
```

- Key invariant: C does not complete until it is able to change `canGoFlag` from 0 to 1
    - so, if `canGoFlag` is 0, it waits for P to set it to 1
    - This waiting behaviour is achieved by P waiting on and C signaling the same condition

iClicker 2c.1

```
int canGoFlag = 1;
uthread_mutex_t mx;
uthread_cond_t canGoCond;
```

Producer (P)

```
uthread_mutex_lock(mx);
    uthread_cond_signal(canGoCond);
    canGoFlag = 1;
uthread_mutex_unlock(mx);
```

Consumer (C)

```
uthread_mutex_lock(mx);
    while (canGoFlag == 0)
        uthread_cond_wait(canGoCond);
    canGoFlag = 0;
uthread_mutex_unlock(mx);
```

```
void uthread_cond_wait (uthread_cond_t cond) {
  assert (cond->mutex->holder == uthread_self ());
  uthread_enqueue (&cond->waiter_queue, uthread_self());
  uthread_mutex_unlock (cond->mutex);
  uthread_block();
  uthread_mutex_lock (cond->mutex);
}
```

What would happen if `cond_wait` didn't unlock and lock as it does?

A. nothing; it's fine either way
B. it might mean that C would return when it shouldn't
C. it might mean that P would not be able to signal it correctly
D. P will never be able to signal C under any circumstances
E. I am not sure

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```
int canGoFlag = 1;
uthread_mutex_t mx;
uthread_cond_t canGoCond;
```

Producer (P)

```
uthread_mutex_lock(mx);
    uthread_cond_signal(canGoCond);
    canGoFlag = 1;
uthread_mutex_unlock(mx);
```

Consumer (C)

```
uthread_mutex_lock(mx);
    while (canGoFlag == 0)
        uthread_cond_wait(canGoCond);
    canGoFlag = 0;
uthread_mutex_unlock(mx);
```

Why not this? (CX)

```
uthread_mutex_lock(mx);
    if (canGoFlag == 0)
        uthread_cond_wait(canGoCond);
    canGoFlag = 0;
uthread_mutex_unlock(mx);
```

Suppose P and CX are the only threads accessing the mutex. Which statement is correct?

A. CX always works
B. CX never works
C. CX works if and only if there is a single P thread
D. CX works if and only if there is a single CX thread
E. I am not sure

P1

3. acquires mutex
4. sets condition =1, signals
5. release mutex

CX

1. check condition, sees 0
2. waits release mutex

6. wakes up, attempt to acquire mutex
7. fails, goes back to sleep

9. wakes up due to signal, acquires mutex
10. proceeds as if condition==1 ✓
11. sets condition = 0
12. release mutex

P2

6. acquires mutex
7. sets condition to 1, signals
8. release mutex

P

1. check condition, sees 0
2. wait, release mutex

3. acquires mutex
4. sets condition = 1, signal
5. release mutex

Cx1

3. wakes up, attempt to get mutex
4. fails, goes back to sleep

7. wake up, acquires mutex
8. proceed as if condition == 1 ?
9. release mutex

Cx2

3. acquires mutex
4. checks condition, sees 1
5. proceeds, sets condition = 0
6. releases mutex

suppose there is a signal

Beer for everyone!

- Beer pitcher is a shared data structure with:
  - `glasses`: amount of beer left, in glasses (`int`)
  - `pour()`: pours one glass from pitcher (reduces beer left by `1`)
  - `refill()`: adds more beer to pitcher (increases beer left by `N`)

- Implementation goal
  - synchronize access to pitcher
  - pouring from empty pitcher requires waiting for it to be refilled
  - filling pitcher releases waiting threads

Beer drinking implementation

Static declaration

```
struct BeerPitcher {
  int              glasses;
  uthread_mutex_t mx;
  uthread_cond_t  hasBeer;
};
```

can do these with global variables

Create and initialize instance

```
void foo() {
  struct BeerPitcher* p = malloc(sizeof(struct BeerPitcher));
  p->glasses = 0;
  p->mx      = uthread_mutex_create();
  p->hasBeer = uthread_cond_create(p->mx);
  ...
}
```

Beer drinking implementation

Pouring a glass

```
void pour (struct BeerPitcher* p) {
  uthread_mutex_lock (p->mx);
    while (p->glasses == 0)
      uthread_cond_wait (p->hasBeer);
    p->glasses -= 1;
  uthread_mutex_unlock (p->mx);
}
```

similar layout to threaded consumer

loop signal vs broadcast

decide by how many waiters vs.

how much resource

Refilling the pitcher (pitcher has unlimited capacity)

```
void refill (struct BeerPitcher* p, int n) {
  uthread_mutex_lock (p->mx);
    p->glasses += n;
    for (int i = 0; i < n; i++)
      uthread_cond_signal (p->hasBeer);
  uthread_mutex_unlock (p->mx);
}
```

or `uthread_cond_broadcast`

Signal and mutex race

The mutex in action!

```
void pour (struct BeerPitcher* p) {
  uthread_mutex_lock (p->mx);
    while (p->glasses == 0)
      uthread_cond_wait (p->hasBeer);
    p->glasses -= 1;
  uthread_mutex_unlock (p->mx);
}
```

pour

```
void refill (struct BeerPitcher* p, int n) {
  uthread_mutex_lock (p->mx);
    p->glasses += n;
    for (int i = 0; i < n; i++)
      uthread_cond_signal (p->hasBeer);
  uthread_mutex_unlock (p->mx);
}
```

pour

Thread A

1. `pour` acquires mutex
2. sees `glasses == 0`
3. waits, releasing mutex

Thread B

4. `refill` acquires mutex
5. sets `glasses = 1`
6. signals condition
7. releases mutex

race to get mutex

Thread A

8a. tries to acquire mutex
9a. fails, waits on mutex

Thread C

8c. `pour` acquires mutex
9. sets `glasses = 0`
10. releases mutex

Thread A

11. acquires mutex
12. sees `glasses == 0`, again
13. waits, releasing mutex

Beer for everyone, forever!

Extending the beer pouring example

- What if we want to refill automatically?
  - a pitcher has capacity `maxGlasses` and current volume `glasses`
  - pouring removes one glass if there is enough beer, and waits otherwise
  - refilling loops forever, waiting for pitcher to be empty, and when it is, it refills the pitcher to its full capacity and awakens any pourers

Static declaration

```
struct BeerPitcher {
  int              glasses;
  int              maxGlasses;
  uthread_mutex_t mx;
  uthread_cond_t  hasBeer;
  uthread_cond_t  isEmpty;
};
```

and an appropriate instantiation and initialization

Automatic refills

```
void pour (struct BeerPitcher* p) {
  uthread_mutex_lock (p->mx);
    while (p->glasses == 0)
      uthread_cond_wait (p->hasBeer);
    p->glasses -= 1;
    if (p->glasses == 0)
      uthread_cond_signal (p->isEmpty)
  uthread_mutex_unlock (p->mx);
}
```

same as before

NEW!

```
void refill (struct BeerPitcher* p) {
  uthread_mutex_lock (p->mx);
    while (1) {
      while (p->glasses > 0)
        uthread_cond_wait (p->isEmpty);
      p->glasses += p->maxGlasses;
      for (int i = 0; i < n; i++)
        uthread_cond_signal (p->hasBeer);
    }
  uthread_mutex_unlock (p->mx);
}
```

max Glasses

} or broadcast

Back to disk reads

- Suppose we write an asynchronous disk read
  - and we want to block/wait with conditions

```
void read (char* buf, int nbytes, int blockno) {

    scheduleRead (buf, nbytes, blockno);
  uthread_mutex_lock(mx);
    uthread_cond_wait(disk_op_complete);
  uthread_mutex_unlock(mx);
}
```

something might happen here.

```
void readCompleteCalledByISR () {
  uthread_mutex_lock(mx);
    uthread_signal(disk_op_complete);
  uthread_mutex_unlock(mx);
}
```

If it takes a long time, disk_op_complete may signal before wait is called

- Wait-signal race problem:
  - wait condition check / trigger and wait are not atomic
  - signal could occur before wait, thus waiter could miss signal and never wake up

- Solution:
  - Ensure that condition check / trigger and wait are atomic
  - So that wait is ordered before signal

Reader-writer monitors

- If we classify critical sections as:
  - reader — it only reads the shared data
  - writer — it updates the shared data
  - then we can weaken the mutual exclusion constraint
    - writers require exclusive access to the monitor
    - but a group of readers can access monitor concurrently

- Reader-writer monitors
  - monitor states: free, held for reading, or held for writing by a single writer
  - If held for reading, multiple readers can access simultaneously
    - but, we will need to know how many readers are accessing, and when they are done

Reader-writer monitors

Operations

- `mutex_lock()`: lock for writing
  - only acquires lock if it is free
  - sets state to held for writing
- `mutex_lock_read_only()`:
  - if lock is free, set its state to held for reading
  - increments a reader count
- `mutex_unlock()`:
  - if held for writing, set state to free
  - if held for reading, decrement reader count
    - if reader count reaches zero, set state to free

Fair access to reader-writer lock

- Policy question
  - if monitor state is held for reading and…
    - Thread A calls `mutex_lock()`, and blocks while waiting for monitor to be free
    - Thread B calls `mutex_lock_read_only()`
  - What should we do?

- Option 1 – disallow new readers while a writer is waiting
  - affects a thread that could be running but now must wait
  - provides fair access to monitor (writer may have been waiting longer)
- Option 2 – allow new readers while a writer is waiting
  - increases concurrency, allows more threads to run
  - writer may need to wait for a long time to get access (starvation)

- Solution
  - tradeoffs, may depend on application

Semaphores

- Introduced by Edsger Dijkstra (THE System, ~1968)

- A semaphore is a non-negative atomic counter
  - any attempt to make counter negative will block the calling thread
  - No operation to read value; only to change it

- `P(s)` (or wait):
  - From Dutch: *prober te verlagen* – "try lowering"
  - atomically blocks until $s > 0$, then decrements s

- `V(s)` (or signal):
  - From Dutch: *verhogen* – "to increase"
  - atomically increase s, and unblock threads waiting in `P` as appropriate

UThread semaphores

```
struct uthread_sem;
typedef struct uthread_sem* uthread_sem_t;

uthread_sem_t uthread_sem_create  (int initial_value);
void          uthread_sem_destroy (uthread_sem_t);
void          uthread_sem_wait    (uthread_sem_t);
void          uthread_sem_signal  (uthread_sem_t);
```

Note that there is no broadcast!

Drinking beer with semaphores

- Use semaphore to store number of glasses held by pitcher
  - set initial value to empty (zero) when creating it

```
uthread_sem_t glasses = uthread_sem_create (0);
```

- Pour and refill no longer require a monitor
  - since the semaphore atomically changes the counter already

```
void pour () {
  uthread_sem_wait (glasses);
}
```

atomically decrement if it can.
otherwise sleep.
try again after waking up.

```
void refill (int n) {
  for (int i = 0; i < n; i++);
    uthread_sem_signal (glasses);
}
```

each signal increments by 1

Implementing monitors using semaphores

- Implementing a mutex using semaphores:
  - create semaphore with initial value 1 (free)
  - lock is `P()` / wait
  - unlock is `V()` / signal()

- Implementing condition variables using semaphores:
  - Difficult!
    - In condition variables, signal without wait will be ignored / no effect
    - In semaphores, signal can unlock a future wait
  - Further reading: *Andrew D. Birrell. "Implementing Condition Variables with Semaphores", 2003.*

Example: semaphore for disk read

- Asynchronous read request

```
void read (char* buf, int nbytes, int blockno) {
  scheduleRead(buf, nbytes, blockno);
  uthread_sem_wait(readComplete);
  ... // handle data
}
```

interruptions here are ok

- Read completion (called by disk ISR)

```
void onReadComplete() {
  uthread_sem_signal(readComplete);
}
```

No critical section, no wait-signal race problem

Ordering threads using semaphores

- If thread B must wait for thread A to finish
  - Initialize semaphore to 0, i.e. `uthread_sem_t b = uthread_sem_create(0);`
  - Thread A: `uthread_sem_signal(b);`
  - Thread B: `uthread_sem_wait(b);`

Compare with PL activity IC_11_29 (slide 25)

- If both threads need to wait for each other (rendezvous)
  - Initialize two semaphores with 0
  - Thread A:

```
uthread_sem_signal(a);
uthread_sem_wait(b);
```

wait
signal

  - Thread B:

```
uthread_sem_signal(b);
uthread_sem_wait(a);
```

wait
signal

What happens if the order of wait and signal are reversed for either (or both) threads?

Problems with concurrency

- Race condition
  - competing, unsynchronized access to shared variable
    - from multiple threads
    - at least one of the threads is attempting to update the variable
  - solved with synchronization
    - guaranteeing mutual exclusion for competing accesses
    - but the language does not help you see what data might be shared – can be very hard

- Deadlock
  - multiple competing actions wait for each other, preventing any to complete

Systems with multiple mutexes

- We have already seen this with semaphores
- Consider a system with two mutexes: `a` and `b`

```
void foo() {
  uthread_mutex_lock   (a);
  uthread_mutex_unlock (a);
}
```

```
void bar() {
  uthread_mutex_lock   (b);
  uthread_mutex_unlock (b);
}
```

```
void x() {
  uthread_mutex_lock   (a);
    bar();
  uthread_mutex_unlock (a);
}
```

```
void y() {
  uthread_mutex_lock   (b);
    foo();
  uthread_mutex_unlock (b);
}
```

Any problems so far?

What if `x` calls foo?

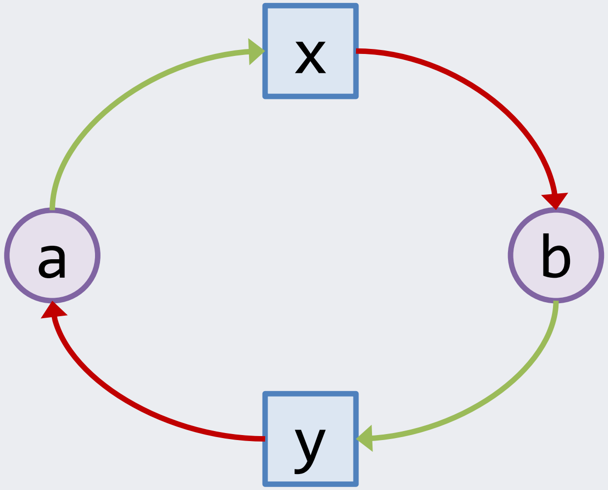
What about now?

OK if a single thread runs x, or y

but threads for x and y at the same time will deadlock

Waiter graph can show deadlocks

- Waiter graph
  - edge from lock to thread, if lock is HELD by thread
  - edge from thread to lock, if thread is WAITING for lock
  - a cycle indicates deadlock




```
void foo() {
  uthread_mutex_lock   (a);
  uthread_mutex_unlock (a);
}
```

```
void bar() {
  uthread_mutex_lock   (b);
  uthread_mutex_unlock (b);
}
```

```
void x() {
  uthread_mutex_lock   (a);
    bar();
  uthread_mutex_unlock (a);
}
```

```
void y() {
  uthread_mutex_lock   (b);
    foo();
  uthread_mutex_unlock (b);
}
```

The dining philosophers problem

- Formulated by Edsger Dijkstra around 1965 as an exam problem

- Description:
  - 5 philosophers sit at a round table with one fork placed in between each
    - so there is a fork to the left and right of each philosopher

  - each philosopher is either eating, or thinking
    - if eating, they are not thinking, and while thinking, they are not eating
    - they never speak to each other

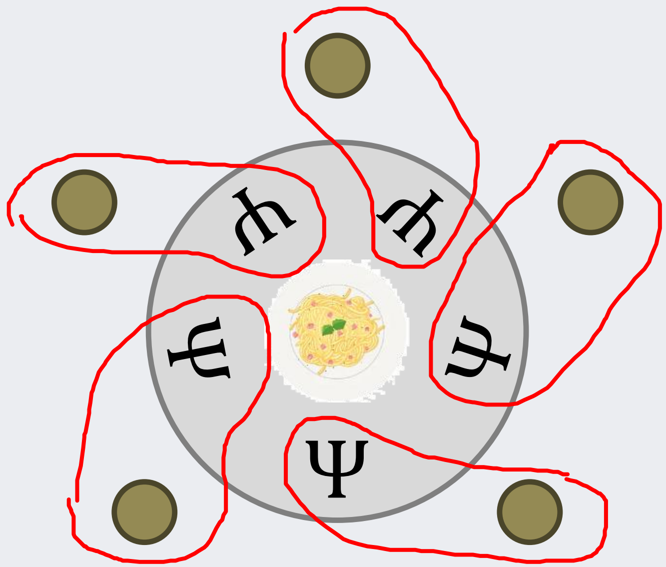
  - a large bowl of spaghetti in the middle of the table requires 2 forks to serve
    - if a philosopher wants to eat, he grabs his 2 adjacent forks to do so
    - if another philosopher is using the fork, then the other must wait

The dining philosophers problem

Deadlock

- Assume that philosophers always start with the left fork

- Also assume that all philosophers decide to start eating at the same time
  - Everyone is able to get the left fork
  - But everyone waits for the right fork
  - DEADLOCK



The dining philosophers problem

Livelock

- Assume that, if philosophers can't get the second fork, they release the first fork, then wait on the second
  - if all of them do this at the same time, they will now hold the right fork
  - but none can proceed because they can't get the left fork

- If the process is repeated, and all philosophers are synchronized
  - Philosophers will repeatedly get one fork at a time
  - All are busy (never idle waiting), but still are unable to eat
  - LIVELOCK
    - threads respond to actions by other threads, but other threads also respond the same way
    - nobody can make progress

Avoiding deadlock

- Don't use multiple threads
  - you'll have many idle CPU cores and write asynchronous code
- Don't use shared variables
  - if threads don't access shared data, no need for synchronization
- Don't use locks
  - for example, use atomic data structures and lock-free synchronization
- Use only one lock at a time
  - deadlock is not possible unless thread holding a lock waits (requires 2 sync variables)
- Organize locks into precedence hierarchy
  - each lock is assigned a unique precedence number
  - before thread X acquires a lock i, it must hold all higher precedence locks
  - ensures that any thread holding i can not be waiting for X
- Detect and destroy
  - if you can't avoid deadlock, detect when it has occurred
  - break deadlock by terminating threads (e.g., sending them an exception)

Synchronization summary

- Spinlock
  - one acquirer at a time, busy-wait until acquired
  - need atomic read-write memory operation, implemented in hardware
  - use for locks held for short periods (or when minimal lock contention)
- Mutex and Condition Variables
  - blocking locks, stop thread while it is waiting
  - mutex guarantees mutual exclusion
  - condition variables wait/signal provides control transfer among threads
- Semaphores
  - blocking atomic counter, stop thread if counter would go negative
  - introduced to coordinate asynchronous resource use
  - can be used to implement a mutex or condition variable (nearly the same semantics)
    - other uses include: turnstiles, thread ordering, and rendezvous
- Problems, problems, problems
  - race conditions to be avoided using synchronization
  - deadlock/livelock to be avoided using synchronization carefully