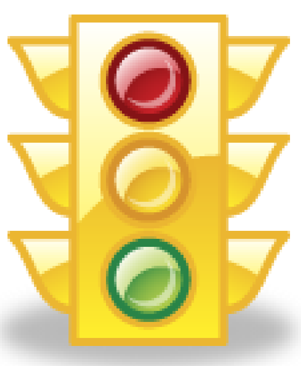
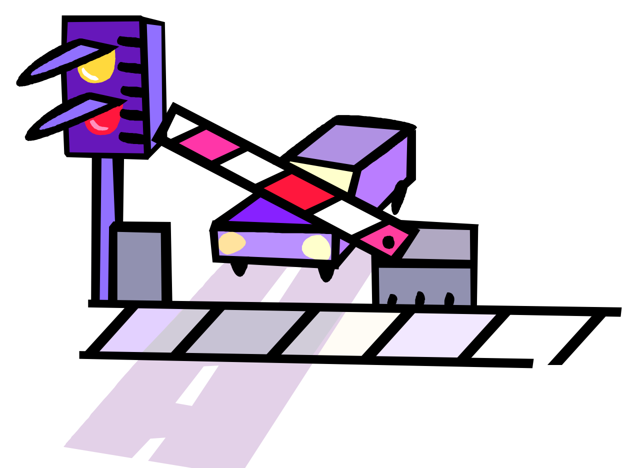
Synchronization and Semaphores





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Synchronization Primatives

- Counting Semaphores
  - Permit a limited number of threads to execute a section of the code
- Binary Semaphores - Mutexes
  - Permit only one thread to execute a section of the code
- Condition Variables
  - Communicate information about the state of shared data

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POSIX Semaphores

- Named Semaphores
  - Provides synchronization between unrelated process and related process as well as between threads
  - Kernel persistence
  - System-wide and limited in number
  - Uses **`sem_open`**
- Unnamed Semaphores
  - Provides synchronization between threads and between related processes
  - Thread-shared or process-shared
  - Uses **`sem_init`**

POSIX Semaphores

- Data type
  - Semaphore is a variable of type **`sem_t`**
- Include **`<semaphore.h>`**
- Atomic Operations

```
int sem_init(sem_t *sem, int pshared, unsigned
   value);
int sem_destroy(sem_t *sem);
int sem_post(sem_t *sem);
int sem_trywait(sem_t *sem);
int sem_wait(sem_t *sem);
```

Unnamed Semaphores

```
#include <semaphore.h>
int sem_init(sem_t *sem, int pshared, unsigned
    value);
```

- Initialize an unnamed semaphore
- Returns
  - 0 on success
  - -1 on failure, sets **errno**
- Parameters
  - **sem**:
    - Target semaphore
  - **pshared**:
    - 0: only threads of the creating process can use the semaphore
    - Non-0: other processes can use the semaphore
  - **value**:
    - Initial value of the semaphore

You cannot make a copy of a semaphore variable!!!

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Sharing Semaphores

- Sharing semaphores between threads within a process is easy, use **`pshared==0`**
- A non-zero **`pshared`** allows any process that can access the semaphore to use it
  - Places the semaphore in the global (OS) environment
  - Forking a process creates copies of any semaphore it has
    - Note: unnamed semaphores are not shared across unrelated processes

`sem_init` can fail

- On failure
  - `sem_init` returns -1 and sets `errno`

`errno`	cause
`EINVAL`	`Value > sem_value_max`
`ENOSPC`	Resources exhausted
`EPERM`	Insufficient privileges

```
sem_t semA;

if (sem_init(&semA, 0, 1) == -1)
  perror("Failed to initialize semaphore semA");
```

Semaphore Operations

```
#include <semaphore.h>
int sem_destroy(sem_t *sem);
```

- Destroy an semaphore
- Returns
  - 0 on success
  - -1 on failure, sets `errno`
- Parameters
  - `sem`:
    - Target semaphore
- Notes
  - Can destroy a `sem_t` only once
  - Destroying a destroyed semaphore gives undefined results
  - Destroying a semaphore on which a thread is blocked gives undefined results

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Semaphore Operations

```
#include <semaphore.h>
int sem_post(sem_t *sem);
```

- Unlock a semaphore - same as signal
- Returns
  - 0 on success
  - -1 on failure, sets **`errno`** (**`== EINVAL`** if semaphore doesn't exist)
- Parameters
  - **`sem`**:
    - Target semaphore
    - sem > 0: no threads were blocked on this semaphore, the semaphore value is incremented
    - sem == 0: one blocked thread will be allowed to run

Semaphore Operations

```
#include <semaphore.h>
int sem_wait(sem_t *sem);
```

- Lock a semaphore
  - Blocks if semaphore value is zero
- Returns
  - 0 on success
  - -1 on failure, sets **errno** (**== EINTR** if interrupted by a signal)
- Parameters
  - **sem**:
    - Target semaphore
    - sem > 0: thread acquires lock
    - sem == 0: thread blocks

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Semaphore Operations

```
#include <semaphore.h>
int sem_trywait(sem_t *sem);
```

- Test a semaphore's current condition
  - Does not block
- Returns
  - 0 on success
  - -1 on failure, sets **errno** (**== AGAIN** if semaphore already locked)
- Parameters
  - **sem**:
    - Target semaphore
    - sem > 0: thread acquires lock
    - sem == 0: thread returns

Good Practices

```
int main(void)
{
    ...
    /* Initialize mutex */
    result = sem_init(&cnt_mutex, 0, 1);
    if (result < 0)
        exit(-1);

    ...

    /* Clean up the semaphore that we're done with */
    result = sem_destroy(&cnt_mutex);
    assert(result == 0);
}
```

Check for errors on each call

Clean up resources

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Why bother checking for errors?

- Without error handling, your code might
  - Crash rather than exiting gracefully
  - Keep working for a while, crash later
  - Sometimes fail randomly, but usually work fine
    - Hard to reproduce: even harder to debug
  - Fail when it might have recovered from the error cleanly!
- At a minimum, error handling converts a messy failure into a clean failure
  - Program terminates, but you know what caused it to terminate

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Some errors are recoverable

```
void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++) {
        while (sem_wait(&cnt_mutex) < 0)
            if (errno != EINTR)
                exit(-1);
        cnt++;
        if (sem_post(&cnt_mutex) <  0)
            exit(-1);
    }
}
```

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Back to the counter...

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <assert.h>

#define NUM_THREADS 2
#define ITERATIONS_PER_THREAD 50000

int cnt = 0;

void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++)
        cnt++;
}
```

How can we fix this using semaphores?

Example: bank balance

- Protect shared variable **balance** with a semaphore when used in:
  - **decshared**
    - Decrements current value of **balance**
  - **incshared**
    - increments the **balance**

Example: bank balance

```
int decshared() {
   while (sem_wait(&balance_sem) == -1)
      if (errno != EINTR)
         return -1;
   balance--;
   return sem_post(&balance_sem);
}

int incshared() {
   while (sem_wait(&balance_sem) == -1)
      if (errno != EINTR)
         return -1;
   balance++;
   return sem_post(&balance_sem);
}
```

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Example: bank balance

```
#include <errno.h>
#include <semaphore.h>

static int balance = 0;
static sem_t bal_sem;

int initshared(int val) {
   if (sem_init(&bal_sem, 0, 1) == -1)
      return -1;
   balance = val;
   return 0;
}
```

pshared

value

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Example: bank balance

```
int decshared() {
  while (sem_wait(&bal_sem)
             == -1)
    if (errno != EINTR)
      return -1;
  balance--;
  return sem_post(&bal_sem);
}
```

```
int incshared() {
  while (sem_wait(&bal_sem)
             == -1)
    if (errno != EINTR)
      return -1;
  balance++;
  return sem_post(&bal_sem);
}
```

Which one is going first?

Advanced Semaphores

```
int semget(key_t key, int nsems, int semflg);
```

- Get set of semaphores

```
int semop(int semid, struct sembuf *sops,
   unsigned int nsops);
```

- Atomically perform a user-defined array of semaphore operations on the set of semaphores

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Pthread Synchronization

- Two primitives
  - Mutex
    - Semaphore with maximum value 1
      - Locked
        - Some thread holds the mutex
      - Unlocked
        - No thread holds the mutex
  - Condition variable
    - Provides a shared signal
    - Combined with a mutex for synchronization

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Creating a mutex

```
#include <pthread.h>
int pthread_mutex_init(pthread_mutex_t *mutex,
   const pthread_mutexattr_t *attr);
```

- Initialize a pthread mutex: the mutex is initially unlocked
- Returns
  - 0 on success
  - Error number on failure
    - **`EAGAIN:`** The system lacked the necessary resources; **`ENOMEM:`** Insufficient memory ; **`EPERM:`** Caller does not have privileges; **`EBUSY:`** An attempt to re-initialise a mutex; **`EINVAL:`** The value specified by attr is invalid
- Parameters
  - **`mutex`**: Target mutex
  - **`attr`**:
    - NULL: the default mutex attributes are used
    - Non-NULL: initializes with specified attributes

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Creating a mutex

- Default attributes
  - Use **PTHREAD_MUTEX_INITIALIZER**
    - Statically allocated
    - Equivalent to dynamic initialization by a call to **pthread_mutex_init()** with parameter **attr** specified as NULL
    - No error checks are performed

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Destroying a mutex

```
#include <pthread.h>
int pthread_mutex_destroy(pthread_mutex_t
    *mutex);
```

- Destroy a pthread mutex
- Returns
  - 0 on success
  - Error number on failure
    - **EBUSY:** An attempt to re-initialise a mutex; **EINVAL:** The value specified by attr is invalid
- Parameters
  - **mutex**: Target mutex

Locking/unlocking a mutex

```
#include <pthread.h>
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_trylock(pthread_mutex_t
    *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

- Returns
  - 0 on success
  - Error number on failure
    - **EBUSY:** already locked; **EINVAL:** Not an initialised mutex; **EDEADLK:** The current thread already owns the mutex; **EPERM:** The current thread does not own the mutex

Simple Example

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

static pthread_mutex_t my_lock =
    PTHREAD_MUTEX_INITIALIZER;

void *mythread(void *ptr) {
   long int i,j;
   while (1) {

     pthread_mutex_lock (&my_lock);

     for (i=0; i<10; i++) {
       printf ("Thread %d\n", int) ptr);
       for (j=0; j<50000000; j++);
     }

     pthread_mutex_unlock (&my_lock);
     for (j=0; j<50000000; j++);
   }
}
```

```
int main (int argc, char *argv[]) {
   pthread_t thread[2];

   pthread_create(&thread[0], NULL,
    mythread, (void *)0);

   pthread_create(&thread[1], NULL,
    mythread, (void *)1);

   getchar();
}
```

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Condition Variables

- Goal: Wait for a specific event to happen
  - Event depends on state shared with multiple threads
- Solution: condition variables
  - “Names” an event
  - Internally, is a queue of threads waiting for the event
- Basic operations
  - Wait for event
  - Signal occurrence of event to one waiting thread
  - Signal occurrence of event to all waiting threads
- Signaling, not mutual exclusion
  - Condition variable is intimately tied to a mutex

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Condition Variables

- Allows threads to synchronize based upon the actual value of data
- Without condition variables
  - Threads continually poll to check if the condition is met
- Signaling, not mutual exclusion
  - A mutex is needed to synchronize access to the shared data
- Each condition variable is associated with a single mutex
  - Wait atomically unlocks the mutex and blocks the thread
  - Signal awakens a blocked thread

Creating a Condition Variable

- Similar to pthread mutexes

```
int pthread_cond_init(pthread_cond_t *cond, const
    pthread_condattr_t *attr);
int pthread_cond_destroy(pthread_cond_t *cond);

pthread_cond_t cond = PTHREAD_COND_INITIALIZER;
```

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Using a Condition Variable

- Waiting
  - Block on a condition variable.
  - Called with **mutex** locked by the calling thread
  - Atomically release **mutex** and cause the calling thread to block on the condition variable
  - On return, **mutex** is locked again

```
int pthread_cond_wait(pthread_cond_t *cond,
   pthread_mutex_t *mutex);
int pthread_cond_timedwait(pthread_cond_t *cond,
   pthread_mutex_t *mutex, const struct timespec
   *abstime);
```

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Using a Condition Variable

- Signaling

```
int pthread_cond_signal(pthread_cond_t *cond);
```

  - unblocks at least one of the blocked threads

```
int pthread_cond_broadcast(pthread_cond_t *cond);
```

  - unblocks all of the blocked threads

- Signals are not saved
  - Must have a thread waiting for the signal or it will be lost

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Condition Variable: Why do we need the mutex?

```
pthread_mutex_lock(&mutex);                    /* lock mutex */
while (!predicate) {                           /* check predicate */

  pthread_cond_wait(&condvar, &mutex);
                                               /* go to sleep - recheck
                                                  pred on awakening */
}
pthread_mutex_unlock(&mutex);                  /* unlock mutex */
```

```
pthread_mutex_lock(&mutex);                    /* lock the mutex       */
predicate=1;                                   /* set the predicate    */
pthread_cond_broadcast(&condvar);              /* wake everyone up     */
pthread_mutex_unlock(&mutex);                  /* unlock the mutex     */
```

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Condition Variable: No mutex!

```
pthread_mutex_lock(&mutex);                 /* lock mutex */
while (!predicate) {                        /* check predicate      */
  pthread_mutex_unlock(&mutex);             /* unlock mutex         */
  pthread_cond_wait(&condvar);              /* go to sleep - recheck
                                               pred on awakening    */
  pthread_mutex_lock(&mutex);               /* lock mutex           */
}
pthread_mutex_unlock(&mutex);               /* unlock mutex         */
```

What can happen here?

```
pthread_mutex_lock(&mutex);                 /* lock the mutex       */
predicate=1;                                /* set the predicate    */
pthread_cond_broadcast(&condvar);           /* wake everyone up     */
pthread_mutex_unlock(&mutex);               /* unlock the mutex     */
```

Condition Variable: Why do we need the mutex?

- Separating the condition variable from the mutex
  - Thread goes to sleep when it shouldn't
  - Problem
    - **`pthread_mutex_unlock()`** and **`pthread_cond_wait()`** are not guaranteed to be atomic
- Joining condition variable and mutex
  - Call to **`pthread_cond_wait()`** unlocks the mutex
  - UNIX kernel can guarantee that the calling thread will not miss the broadcast

Condition Variable: Why do we need the while loop?

- Why not just use an **if** statement?

```
while (items_in_buffer == 0) {
   cond_wait(&item_available, &m);
...
```

```
if (items_in_buffer == 0) {
   cond_wait(&item_available, &m);
...
```

Using a Condition Variable: Challenges

- Call **`pthread_cond_signal()`** before calling **`pthread_cond_wait()`**
  - Logical error – waiting thread will not catch the signal
- Fail to lock the mutex before calling **`pthread_cond_wait()`**
  - May cause it NOT to block
- Fail to unlock the mutex after calling **`pthread_cond_signal()`**
  - May not allow a matching **`pthread_cond_wait()`** routine to complete (it will remain blocked).

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Example without Condition Variables

```
int data_avail = 0;
pthread_mutex_t data_mutex =
    PTHREAD_MUTEX_INITIALIZER;

void *producer(void *) {
    pthread_mutex_lock(&data_mutex);

    <Produce data>
    <Insert data into queue;>
    data_avail=1;

    pthread_mutex_unlock(&data_mutex);
}
```

Example without Condition Variables

```
void *consumer(void *) {
   while( !data_avail );  /* do nothing */

   pthread_mutex_lock(&data_mutex);

   <Extract data from queue;>
   if (queue is empty)
      data_avail = 0;

   pthread_mutex_unlock(&data_mutex);
   <Consume Data>
}
```

Busy Waiting!

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Example with Condition Variables

```
int data_avail = 0;
pthread_mutex_t data_mutex = PTHREAD_MUTEX_INITIALIZER;
pthread_cont_t data_cond = PTHREAD_COND_INITIALIZER;

void *producer(void *) {
   pthread_mutex_lock(&data_mutex);
   <Produce data>
   <Insert data into queue;>
   data_avail = 1;

   pthread_cond_signal(&data_cond);
   pthread_mutex_unlock(&data_mutex);
}
```

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Example with Condition Variables

Mutex solution

```
while( !data_avail );  /* do nothing */
```

```
void *consumer(void *) {
   pthread_mutex_lock(&data_mutex);
   while( !data_avail ) {
      /* sleep on condition variable*/
      pthread_cond_wait(&data_cond, &data_mutex);
   }
   /* woken up */
   <Extract data from queue;>
   if (queue is empty)
      data_avail = 0;
   pthread_mutex_unlock(&data_mutex);
   <Consume Data>
}
```

No Busy Waiting!

More Complex Example

- Master thread
  - Spawns a number of concurrent slaves
  - Waits until all of the slaves have finished to exit
  - Tracks current number of slaves executing
- A mutex is associated with count and a condition variable with the mutex

Example

```
#include <stdio.h>
#include <pthread.h>

#define NO_OF_PROCS  4

typedef struct _SharedType {
  int count;                   /* number of active slaves */
  pthread_mutex_t lock;        /* mutex for count */
  pthread_cond_t done;         /* sig. by finished slave */
} SharedType, *SharedType_ptr;

SharedType_ptr shared_data;
```

Example: Main

```
main(int argc, char **argv) {
  int res;
  /* allocate shared data */
  if ((sh_data = (SharedType *)
    malloc(sizeof(SharedType))) ==
    NULL) {
      exit(1);
  }
  sh_data->count = 0;

  /* allocate mutex */
  if ((res =
    pthread_mutex_init(&sh_data-
    >lock, NULL)) != 0) {
     exit(1);
  }
```

```
/* allocate condition var */
  if ((res =
    pthread_cond_init(&sh_data-
    >done, NULL)) != 0) {
     exit(1);
  }
  /* generate number of slaves
    to create */
  srandom(0);
  /* create up to 15 slaves */
  master((int) random()%16);
}
```

Example: Main

```
main(int argc, char **argv) {
  int res;
  /* allocate shared data */
  if ((sh_data = (SharedType *)
    malloc(sizeof(SharedType))) ==
    NULL) {
      exit(1);
  }
  sh_data->count = 0;
```

```
pthread_mutex_t data_mutex =
PTHREAD_MUTEX_INITIALIZER;
```

```
pthread_cont_t data_cond =
PTHREAD_COND_INITIALIZER;
```

```
  /* generate number of slaves
     to create */
  srandom(0);
  /* create up to 15 slaves */
  master((int) random()%16);
}
```

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Example: Master

```
master(int nslaves) {
  int i;
  pthread_t id;
  for (i = 1; i <= nslaves; i +=
    1) {
    pthread_mutex_lock(&sh_data-
    >lock);
    /* start slave and detach */
    shared_data->count += 1;
    pthread_create(&id, NULL,
      (void* (*)(void *))slave,
      (void *)sh_data);
    pthread_mutex_unlock(&sh_data-
    >lock);
  }
  pthread_mutex_lock(&sh_data-
    >lock);

  while (sh_data->count != 0)
    pthread_cond_wait(&sh_data-
    >done, &sh_data->lock);

  pthread_mutex_unlock(&sh_data-
    >lock);

  printf("All %d slaves have
    finished.\n", nslaves);
  pthread_exit(0);
}
```

Example: Slave

```
void slave(void *shared) {
  int i, n;
  sh_data = shared;
  printf("Slave.\n", n);
  n = random() % 1000;

  for (i = 0; i < n; i+= 1)
    Sleep(10);

  /* mutex for shared data */
  pthread_mutex_lock(&sh_data->lock);

  /* dec number of slaves */
  sh_data->count -= 1;

  /* done running */
  printf("Slave finished %d cycles.\n", n);

  /* signal that you are done working */
  pthread_cond_signal(&sh_data->done);

  /* release mutex for shared data */
  pthread_mutex_unlock(&sh_data->lock);
}
```

Semaphores vs. CVs

Semaphore

- Integer value (>=0)
- Wait does not always block
- Signal either releases thread or inc's counter
- If signal releases thread, both threads continue afterwards

Condition Variables

- No integer value
- Wait always blocks
- Signal either releases thread or is lost
- If signal releases thread, only one of them continue

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Next: Dining Philosophers

- N philosophers and N forks
  - Philosophers eat/think
  - Eating needs 2 forks
  - Pick one fork at a time