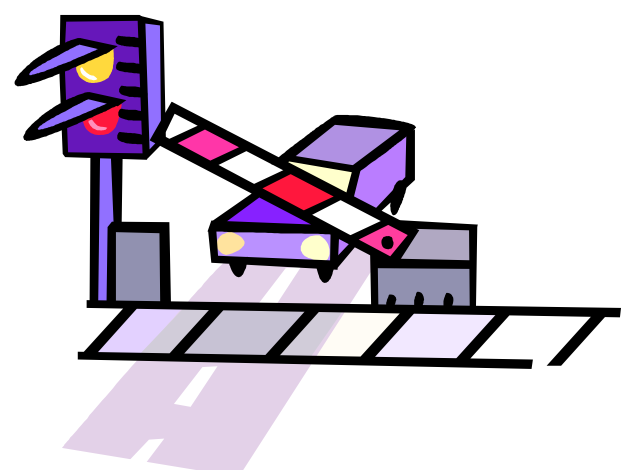
Synchronization



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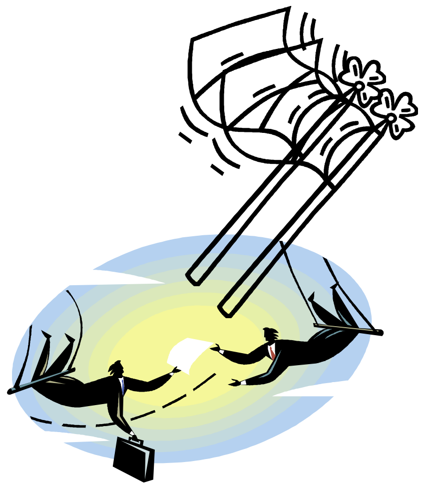
Software-based Mutual Exclusion

- Would a software-based solution work?

Two Flag and Turn Mutual Exclusion



```
int owner[2]={false, false};
int turn;
…
owner[my_process_id] = true;
turn = other_process_id;
while (owner[other_process_id] and
          turn == other_process_id) {
    /* wait your turn */
}
access shared variables;
owner[my_process_id] = false;
…
```

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Two Flag and Turn Mutual Exclusion

```
int owner[2]={false, false};
int turn;
…
owner[my_process_id] = true;
turn = other_process_id;
while (owner[other_process_id] and
            turn == other_process_id) {
    /* wait your turn */
}
access shared variables;
owner[my_process_id] = false;
…
```

```
owner[0] = false true
owner[1] = false true
turn = 0  1  0
```

Progress and mutual exclusion!

Peterson's Solution

Are we done?

- Peterson's algorithm works
  - It guarantees mutual exclusion
  - no thread can monopolize use of shared resource, because each thread has to give an opportunity to the other thread by setting "turn=other_process_id" before each attempt to enter its critical section
- But….

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In case you test Peterson sol.

- If everything worked...

```
$ ./peterson
Final value: 100000
```

```
Output
---------------------------------------
mcaccamo$ ./peterson
Final value: 100000
mcaccamo$ ./peterson
Final value: 100000
mcaccamo$ ./peterson
Final value: 99999
mcaccamo$ ./peterson
Final value: 100000
```

I am confused…

The perilous landscape of relaxed memory multicores

- Required assumptions for correctness of Peterson's alg.:
  - We consider only two threads
  - **[Topic for computer architecture class]** CPU does not perform memory operations in an out-of-order fashion. The programmer needs to rely on strict ordering for the memory operations within a thread.
    - Guess what… x86 performs the following re-ordering:

    Loads may be reordered with older stores to different locations

    ➔ **Peterson's algorithm is broken on x86. Test it yourself…..**

- Problem: software-based solutions are slow

➔ Solution: leverage CPU atomic operations like test-and-set

Hardware support for mutual exclusion

- We need hardware support: an atomic operation like test-and-set is needed to implement mutual exclusion.

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TestAndSet function

```
int TestAndSet(int* plock) atomic {
   int initial;
   initial = *plock;
   *plock = 1;
   return initial;
}
```

atomic = *executed in a single shot without any interruption*

Note: this pseudo-code only serves to help explain the behavior of test-and-set; atomicity requires explicit hardware support and hence can't be implemented as a simple C function.

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TestAndSet function

```
volatile long lock = 0; // lock is initially set to free

// Calling TestAndSet(&lock) sets lock to 1 and returns the old value of lock.
// So, if lock is zero, then TestAndSet(&lock) returns zero and sets lock to
// one. This means the lock has been succesfully acquired.  On the other hand,
// if the lock had already been set to one by another process or thread,
// then 1 would be returned. This would indicate to the caller that the lock
// is already being held by another process or thread.

// This code is gcc/linux/intel x86 specific.
long TestAndSet (volatile long * lock) {
        long retval;
        // Atomically exchange value of register %0 with lock. The
        // atomicity of xchg is what guarantees that at most one
        // process or thread can be holding the lock at any point in time.
        __asm__ __volatile__ (
                "movl  $0x1, %0  \n"
                "xchg  %0, (%1)  \n"
                : "=&r"(retval) : "r"(lock) : "memory" );

        return retval;
}
```

TestAndSet function

- `int TestAndSet(int *lock)`
  - **Pros**:
    - Very fast to entry to unlocked region
    - Guarantees safety & progress
  - **Cons**:
    - Wastes CPU cycles if used with busy waiting (spin lock)
    - Extremely high memory (i.e., bus) traffic if used with busy waiting
- TestAndSet can be used to implement higher-level synchronization constructs.

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Back to the counter example

compile with gcc -m32 –lpthread -o test test.c

```c
#include <stdio.h>
#include <pthread.h>
#define NUM_THREADS 2

// lock is initially set to free
volatile long lock = 0;

int cnt = 0;

void * worker( void *ptr ) {
  int i;
  for (i = 0; i < 50000; i++) {
    // spin until it locks
    while(TestAndSet(&lock)) {};
    // locked in mutual exclusion
    cnt++;
    lock = 0; // lock is released }
  }
  pthread_exit(NULL);
}
```

```c
int main(void) {
   pthread_t threads[NUM_THREADS];
   int i, res;

   for (i=0; i < NUM_THREADS; i++) {
     res=pthread_create(&threads[i],
                  NULL, worker, NULL);
   }
   for (i=0; i < NUM_THREADS; i++) {
     res=pthread_join(threads[i],NULL);
   }
    /* Print result */
    printf("Final value: %d\n", cnt);
```

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Simple implementation of P(s)

- P(s) and V(s) need to execute atomically.
- How can I implement them?
- **Solution**: use TestAndSet!

```
#include <sched.h>
typedef struct SEMAPHORE {
  volatile long lock;
  volatile long sem;
} semaphore;
```

Simple implementation of a semaphore without a queue of blocked threads

```
void P(semaphore *p) {
 while(1){
  while(TestAndSet(&p->lock))
        sched_yield();
  // locked in mutual exclusion
  if (p->sem > 0) {
    p->sem--;
    p->lock = 0;//lock is released
    break; // entering crit. sec.
  }
  p->lock = 0; //lock is released
  sched_yield(); //relinquish CPU
 }
}
```

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Simple implementation of V(s)

- How can I implement V(s)?
- **Solution**: use TestAndSet!

```
void V(semaphore *p) {
  while(TestAndSet(&p->lock))
        sched_yield();

  // locked in mutual exclusion
  p->sem++;
  p->lock = 0; //lock is released
}
```

Back to the counter example: solution with primitives P & V

```
#include <stdio.h>
#include <pthread.h>
#include <sched.h>
#define NUM_THREADS 2

semaphore s = {.lock =0, .sem =1};
int cnt = 0;

void * worker( void *ptr ) {
  int i;
  for (i = 0; i < 50000; i++) {
    P(&s);
    cnt++; // critical section
    V(&s);
  }
  pthread_exit(NULL);
}
```

```
int main(void) {
   pthread_t threads[NUM_THREADS];
   int i, res;

   for (i=0; i < NUM_THREADS; i++) {
     res=pthread_create(&threads[i],
              NULL, worker, NULL);
   }
   for (i=0; i < NUM_THREADS; i++) {
     res=pthread_join(threads[i],NULL);
   }
    /* Print result */
    printf("Final value: %d\n", cnt);
}
```

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Synchronization Primatives

- Pthread mutex
  - Permits only one thread to execute a critical section
- Posix Semaphore
  - Permits up to a limited number of threads to execute a critical section
- Pthread condition variable
  - Wait for event
  - Signal occurrence of event to one waiting thread
  - Broadcast occurrence of event to all waiting threads

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Creating a mutex

```
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

```
int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

- Destroy a pthread mutex
- Returns
  - 0 on success
  - Error number on failure
    - `EBUSY:` Mutex is locked by a thread; `EINVAL:` The value specified by mutex is invalid
- Parameters
  - `mutex`: Target mutex

Locking/unlocking a mutex

```
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:` Mutex is already locked; `EINVAL:` The value specified by mutex is invalid; `EDEADLK:` The current thread already owns the mutex; `EPERM:` The current thread does not hold a lock on mutex.

➔ If a signal is delivered to a thread while that thread is waiting for a mutex, when the signal handler returns, the wait resumes. **pthread_mutex_lock**() does not return **EINTR**!

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Back to the counter example: solution with pthread_mutex

```
#include <stdio.h>
#include <pthread.h>
#define NUM_THREADS 2

pthread_mutex_t mutex =
        PTHREAD_MUTEX_INITIALIZER;
int cnt = 0;

void * worker( void *ptr ) {
  int i;
  for (i = 0; i < 50000; i++) {
    pthread_mutex_lock(&mutex);
    cnt++; // critical section
    pthread_mutex_unlock(&mutex);
  }
  pthread_exit(NULL);
}
```

```
int main(void) {
   pthread_t threads[NUM_THREADS];
   int i, res;

   for (i=0; i < NUM_THREADS; i++) {
     res=pthread_create(&threads[i],
              NULL, worker, NULL);
   }
   for (i=0; i < NUM_THREADS; i++) {
     res=pthread_join(threads[i],NULL);
   }
   /* Print result */
   printf("Final value: %d\n", cnt);
}
```

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