CS 33

Multithreaded Programming II

Mutual Exclusion

Threads and Mutual Exclusion

Thread 1:

```
x = x+1;
 /*
   movl x,%eax
   incr %eax
   movl %eax,x
  */
```

Thread 2:

```
x = x+1;
 /*
   movl x,%eax
   incr %eax
   movl %eax,x
  */
```

Quiz 1

Suppose gcc produces the following code. Will it still be the case that x's value might not be incremented by 2?

a) yes
b) no

Thread 1:

```
x = x+1;
 /*
  incr x
 */
```

Thread 2:

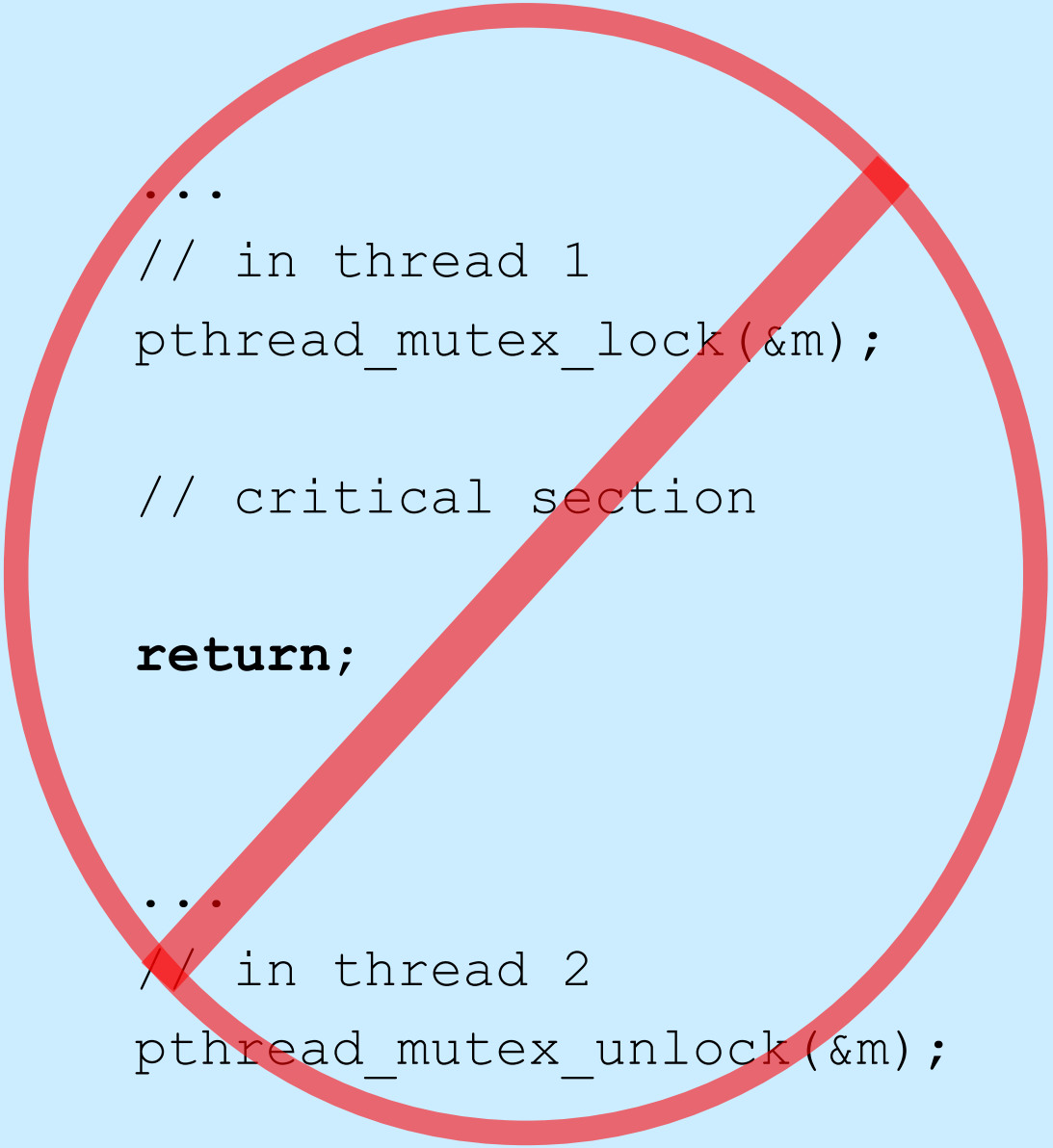
```
x = x+1;
 /*
  incr x
 */
```

POSIX Threads Mutual Exclusion

```
pthread_mutex_t m =
      PTHREAD_MUTEX_INITIALIZER;
      // shared by both threads
int x; // ditto

  pthread_mutex_lock(&m);

  x = x+1;

  pthread_mutex_unlock(&m);
```

Correct Usage

```
pthread_mutex_lock(&m);

// critical section

pthread_mutex_unlock(&m);
```



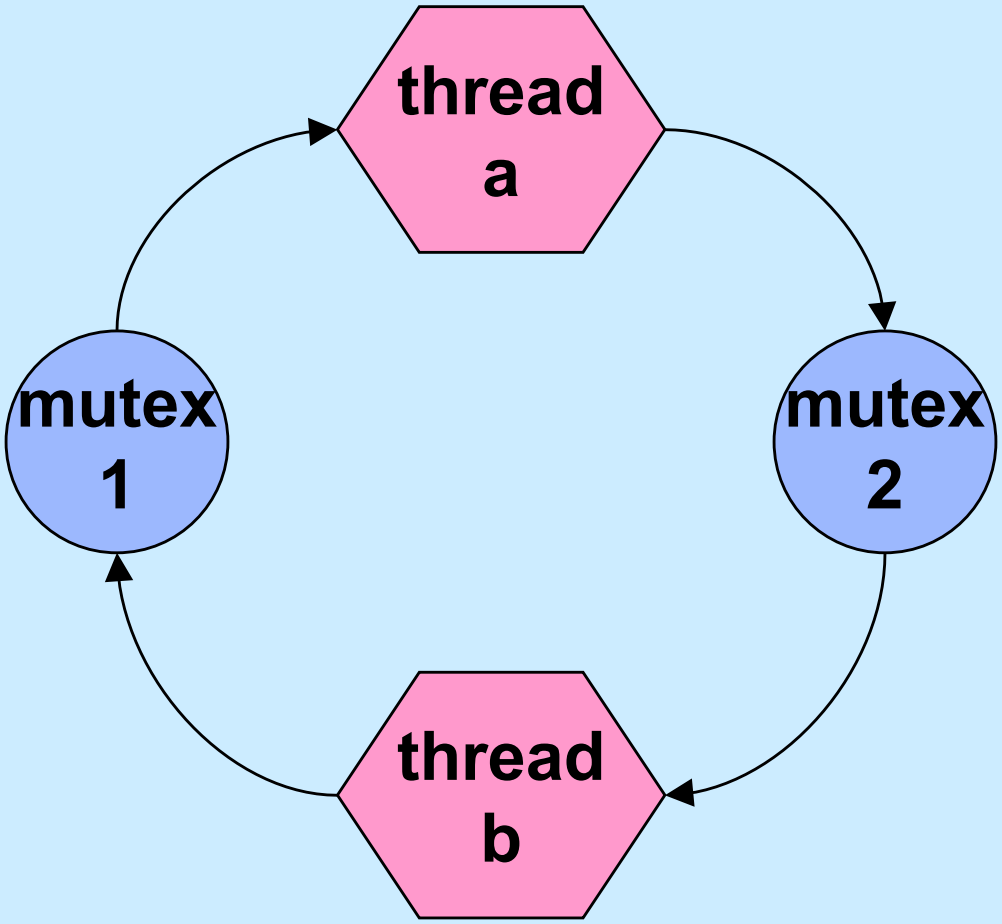
```
...
// in thread 1
pthread_mutex_lock(&m);

// critical section

return;


...
// in thread 2
pthread_mutex_unlock(&m);
```

Taking Multiple Locks

```
proc1( ) {
  pthread_mutex_lock(&m1);
  /* use object 1 */
  pthread_mutex_lock(&m2);
  /* use objects 1 and 2 */
  pthread_mutex_unlock(&m2);
  pthread_mutex_unlock(&m1);
}
```

```
proc2( ) {
  pthread_mutex_lock(&m2);
  /* use object 2 */
  pthread_mutex_lock(&m1);
  /* use objects 1 and 2 */
  pthread_mutex_unlock(&m1);
  pthread_mutex_unlock(&m2);
}
```

Preventing Deadlock

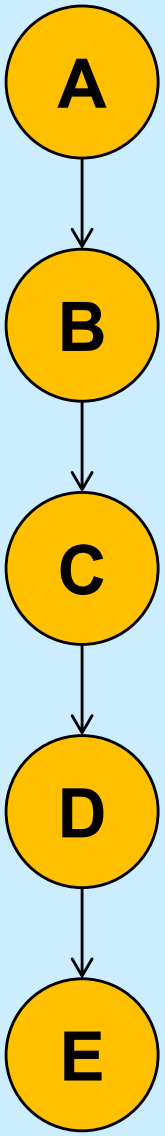


Taking Multiple Locks, Safely

```
proc1( ) {
  pthread_mutex_lock(&m1);
  /* use object 1 */
  pthread_mutex_lock(&m2);
  /* use objects 1 and 2 */
  pthread_mutex_unlock(&m2);
  pthread_mutex_unlock(&m1);
}
```

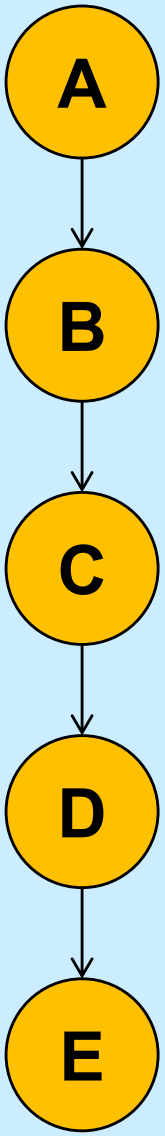
```
proc2( ) {
  pthread_mutex_lock(&m1);
  /* use object 1 */
  pthread_mutex_lock(&m2);
  /* use objects 1 and 2 */
  pthread_mutex_unlock(&m2);
  pthread_mutex_unlock(&m1);
}
```

Singly Linked List: Coarse-Grained




```
typedef struct node {
   int value;
   struct node *next;
} node_t;
pthread_mutex_t global_mutex;


void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&global_mutex);
  new->next = after->next;
  after->next = new;
  pthread_mutex_unlock(&global_mutex);
}
```

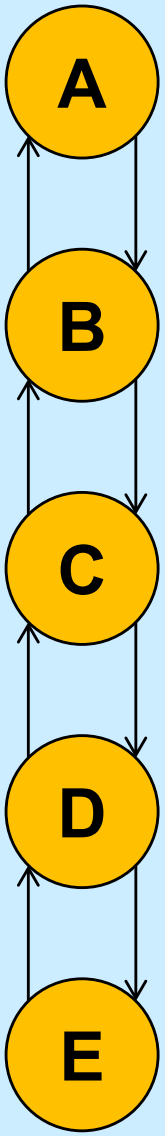

Singly Linked List: Fine-Grained




```
typedef struct node {
   pthread_mutex_t mutex;
   int value;
   struct node *next;
} node_t;
```

```
void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&after->mutex);
  new->next = after->next;
  after->next = new;
  pthread_mutex_unlock(&after->mutex);
}
```

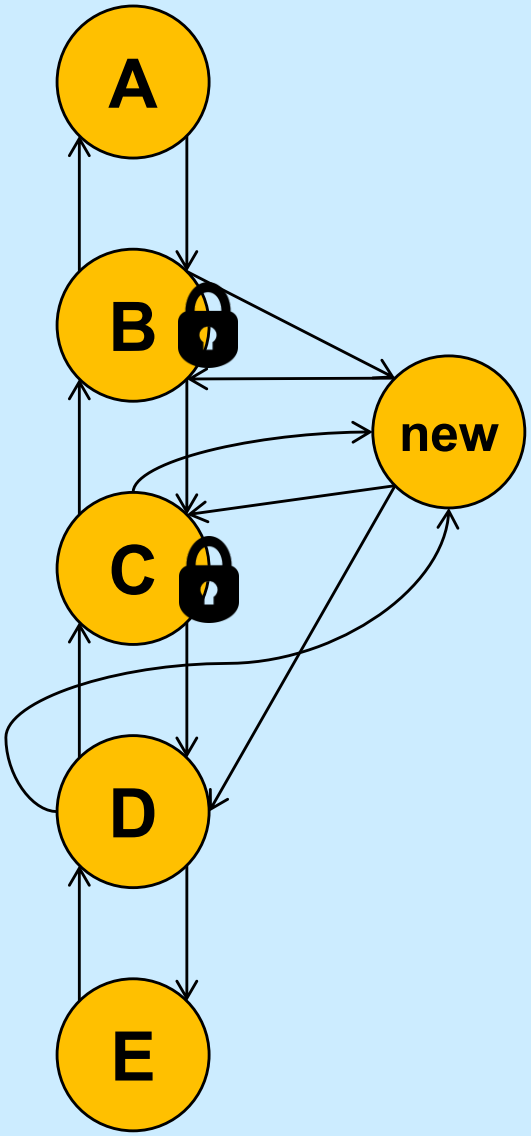
Doubly Linked List




```
void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&after->mutex);
  after->next->prev = new;
  new->next = after->next;
  new->prev = after;
  after->next = new;
  pthread_mutex_unlock(&after->mutex);
}
```

```
void delete(node_t *old) {
  pthread_mutex_lock(&old->mutex);
  old->prev->next = old->next;
  old->next->prev = old->prev;
  pthread_mutex_unlock(&old->mutex);
}
```

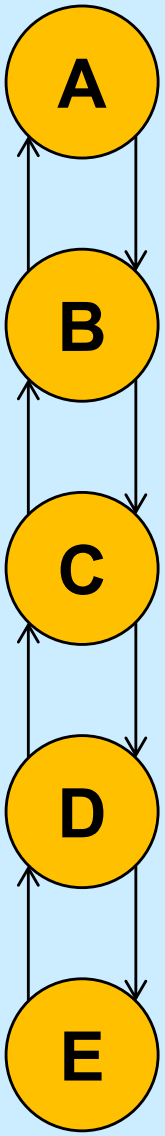
Doesn't Work ...




```
void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&after->mutex);
  after->next->prev = new;
  new->next = after->next;
  new->prev = after;
  after->next = new;
  pthread_mutex_unlock(&after->mutex);
}
```

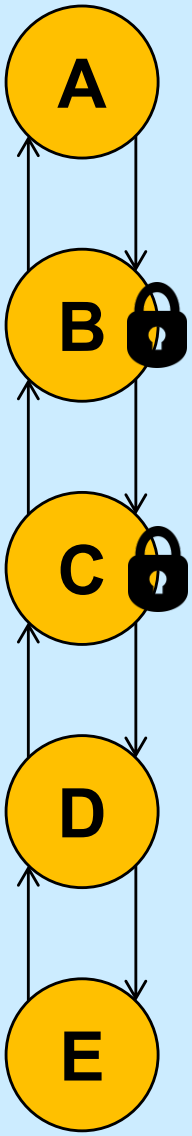
```
void delete(node_t *old) {
  pthread_mutex_lock(&old->mutex);
  old->prev->next = old->next;
  old->next->prev = old->prev;
  pthread_mutex_unlock(&old->mutex);
}
```

Doubly Linked List, Attempt 2



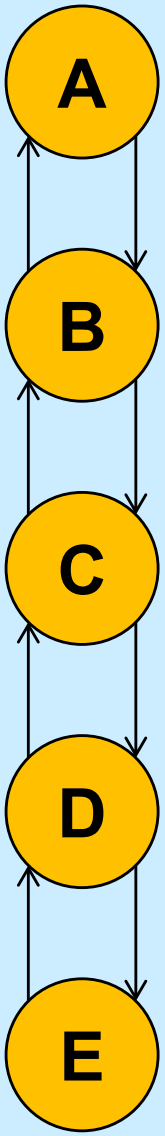

```
void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&after->mutex);
  pthread_mutex_lock(&after->next->mutex);
  after->next->prev = new;
  new->next = after->next;
  new->prev = after;
  after->next = new;
  pthread_mutex_unlock(&new->next->mutex);
  pthread_mutex_unlock(&after->mutex);
}

void delete(node_t *old) {
  pthread_mutex_lock(&old->mutex);
  pthread_mutex_lock(&old->prev->mutex);
  pthread_mutex_lock(&old->next->mutex);
  old->prev->next = old->next;
  old->next->prev = old->prev;
  pthread_mutex_unlock(&old->next->mutex);
  pthread_mutex_unlock(&old->prev->mutex);
  pthread_mutex_unlock(&old->mutex);
}
```


Doesn't Work ...



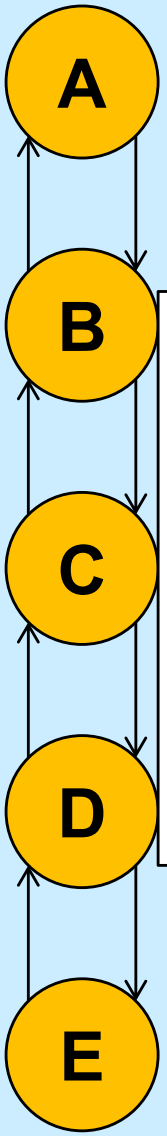

```
void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&after->mutex);
  pthread_mutex_lock(&after->next->mutex);
  after->next->prev = new;
  new->next = after->next;
  new->prev = after;
  after->next = new;
  pthread_mutex_unlock(&new->next->mutex);
  pthread_mutex_unlock(&after->mutex);
}

void delete(node_t *old) {
  pthread_mutex_lock(&old->mutex);
  pthread_mutex_lock(&old->prev->mutex);
  pthread_mutex_lock(&old->next->mutex);
  old->prev->next = old->next;
  old->next->prev = old->prev;
  pthread_mutex_unlock(&old->next->mutex);
  pthread_mutex_unlock(&old->prev->mutex);
  pthread_mutex_unlock(&old->mutex);
}
```


Doubly Linked List, Attempt 3




```
void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&after->mutex);
  pthread_mutex_lock(&after->next->mutex);
  after->next->prev = new;
  new->next = after->next;
  new->prev = after;
  after->next = new;
  pthread_mutex_unlock(&new->next->mutex);
  pthread_mutex_unlock(&after->mutex);
}

void delete(node_t *old) {
  pthread_mutex_lock(&old->prev->mutex);
  pthread_mutex_lock(&old->mutex);
  pthread_mutex_lock(&old->next->mutex);
  old->prev->next = old->next;
  old->next->prev = old->prev;
  pthread_mutex_unlock(&old->next->mutex);
  pthread_mutex_unlock(&old->mutex);
  pthread_mutex_unlock(&old->prev->mutex);
}
```


Doubly Linked List, Attempt 3



Not a quiz!

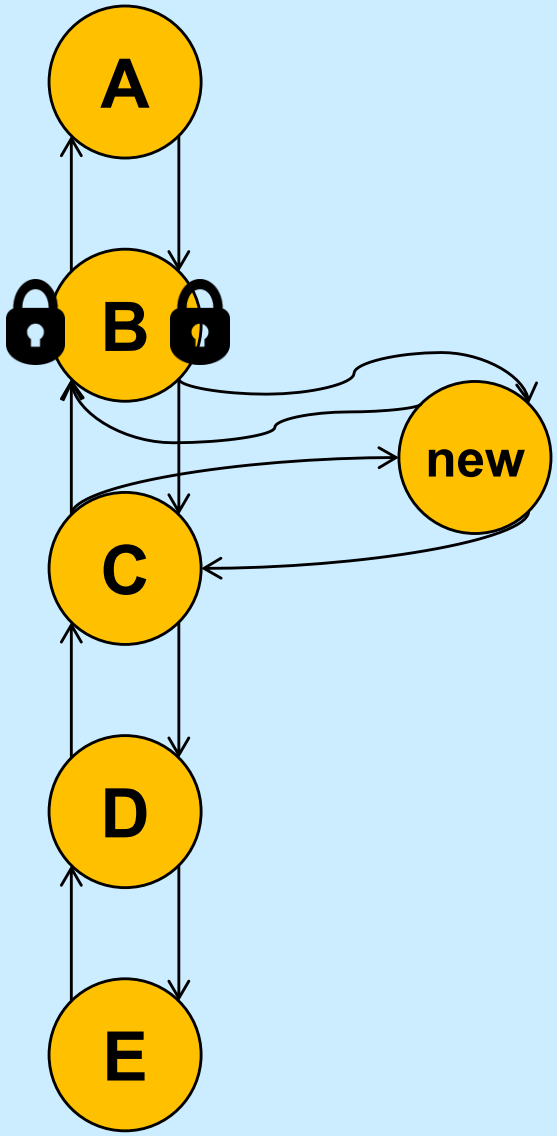
Does this work?

a) yes

b) no

```
void add_after(node_t *after, node_t *new) {
  pthread_mutex_lock(&after->mutex);
  pthread_mutex_lock(&after->next->mutex);
  after->next->prev = new;
  new->next = after->next;
  new->prev = after;
  after->next = new;
  pthread_mutex_unlock(&new->next->mutex);
  pthread_mutex_unlock(&after->mutex);
}

void delete(node_t *old) {
  pthread_mutex_lock(&old->prev->mutex);
  pthread_mutex_lock(&old->mutex);
  pthread_mutex_lock(&old->next->mutex);
  old->prev->next = old->next;
  old->next->prev = old->prev;
  pthread_mutex_unlock(&old->next->mutex);
  pthread_mutex_unlock(&old->mutex);
  pthread_mutex_unlock(&old->prev->mutex);
}
```


Doubly Linked List

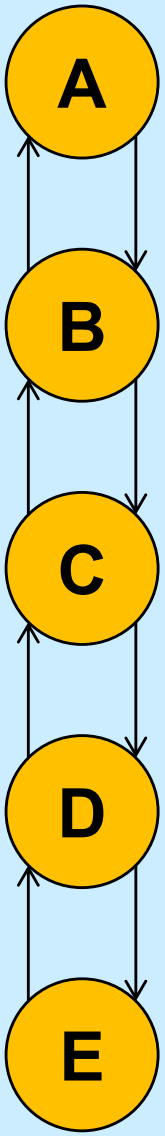


More Machinery ...

```
proc1( ) {
  pthread_mutex_lock(&m1);
  /* use object 1 */
  pthread_mutex_lock(&m2);
  /* use objects 1 and 2 */
  pthread_mutex_unlock(&m2);
  pthread_mutex_unlock(&m1);
}
```

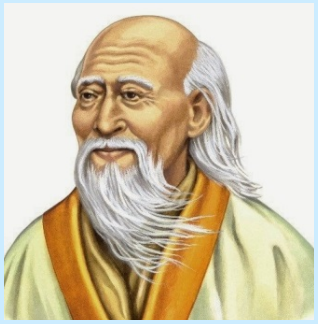
```
proc2( ) {
  while (1) {
    pthread_mutex_lock(&m2);

    if (!pthread_mutex_trylock(&m1))
      break;
    pthread_mutex_unlock(&m2);
   }

   /* use objects 1 and 2 */

   pthread_mutex_unlock(&m1);
   pthread_mutex_unlock(&m2);
}
```

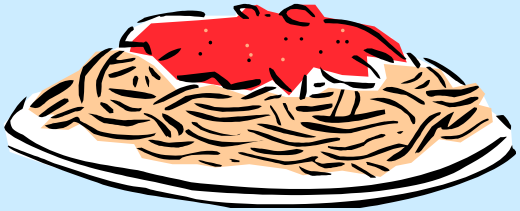
Doubly Linked List

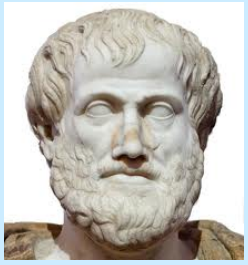



```
void delete(node_t *old) {
  while(1) {
    pthread_mutex_lock(&old->mutex);
    if (pthread_mutex_trylock(&old->prev->mutex) != 0) {
      pthread_mutex_unlock(&old->mutex);
      continue;
    }
    break;
  }
  pthread_mutex_lock(&old->next->mutex);
  old->prev->next = old->next;
  old->next->prev = old->prev;
  pthread_mutex_unlock(&old->next->mutex);
  pthread_mutex_unlock(&old->mutex);
  pthread_mutex_unlock(&old->prev->mutex);
}
```


Dining Philosophers Problem







Practical Issues with Mutexes

- Used a lot in multithreaded programs
  - speed is really important
    - » shouldn't slow things down much in the success case
  - checking for errors slows things down (a lot)
    - » thus errors aren't checked by default

Set Up

```
int pthread_mutex_init(pthread_mutex_t *mutexp,
    pthread_mutexattr_t *attrp)

int pthread_mutex_destroy(pthread_mutex_t *mutexp)

int pthread_mutexattr_init(pthread_mutexattr_t *attrp)

int pthread_mutexattr_destroy(pthread_mutexattr_t *attrp)
```


Stupid (i.e., Common) Mistakes ...

```
pthread_mutex_lock(&m1);
pthread_mutex_lock(&m1);
  // really meant to lock m2 ...
```

```
pthread_mutex_lock(&m1);
  ...
pthread_mutex_unlock(&m2);
  // really meant to unlock m1 ...
```

Runtime Error Checking

```
pthread_mutexattr_t err_chk_attr;
pthread_mutexattr_init(&err_chk_attr);
pthread_mutexattr_settype(&err_chk_attr,
       PTHREAD_MUTEX_ERRORCHECK);

pthread_mutex_t mut1;
pthread_mutex_init(&mut1, &err_chk_attr);

pthread_mutex_lock(&mut1);

if (pthread_mutex_lock(&mut1) == EDEADLK)
  fprintf(stderr, "error caught at runtime\n");

if (pthread_mutex_unlock(&mut2) == EPERM)
  fprintf(stderr, "another error: you didn't lock it!\n");
```

Example

```
void InsertList(val_t v) {
  list_t *new = (list_t *)malloc(sizeof(list_t));
  new->val = v;
  pthread_mutex_lock(&m);
  new->next = head;
  head = new;
  pthread_mutex_unlock(&m);
}
```

```
InsertList(val);
```

thread 1

```
InsertList(val);
```

thread 2

Example

```
void InsertList(val_t v) {
  list_t *new = (list_t *)malloc(sizeof(list_t));
  new->val = v;
  pthread_mutex_lock(&m);
  new->next = head;
  head = new;
  pthread_mutex_unlock(&m);
}
```

```
InsertList(val);
```

thread 1

```
InsertList(val);
```

thread 2

```
InsertList(val);
InsertList(mustBeNext);
```

thread 3

Example

```
void InsertList(val_t v) {
  list_t *new = (list_t *)malloc(sizeof(list_t));
  new->val = v;
  pthread_mutex_lock(&m);
  new->next = head;
  head = new;
  pthread_mutex_unlock(&m);
}
```

```
InsertList(val);
```

thread 1

```
InsertList(val);
```

thread 2

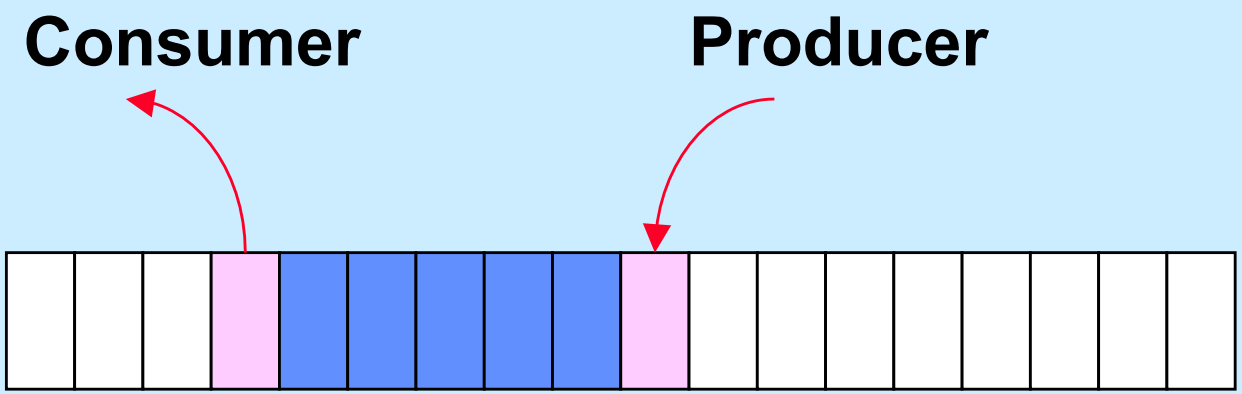
```
pthread_mutex_lock(&m);
InsertList(val);
InsertList(mustBeNext);
pthread_mutex_unlock(&m);
```

thread 3

Creating Recursive Mutexes

```
pthread_mutexattr_t recursive_attr;
pthread_mutexattr_init(&recursive_attr);
pthread_mutexattr_settype(&recursive_attr,
      PTHREAD_MUTEX_RECURSIVE);

pthread_mutex_t mut;
pthread_mutex_init(&mut, &recursive_attr);
pthread_mutex_lock(&mut);
if (pthread_mutex_lock(&mut) == EDEADLK)
  // won't happen -- mutex is recursive
  ;
pthread_mutex_unlock(&mut);  // decrements lock count
pthread_mutex_unlock(&mut);  // really unlocks it
```

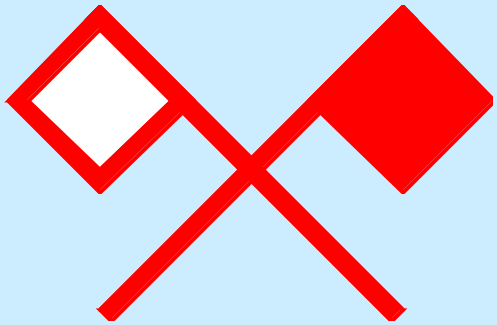
Producer-Consumer Problem



Guarded Commands

```
when (guard) [
  /*
     once the guard is true, execute this
     code atomically
   */

  ...

]
```


Semaphores



- **P(S) operation:**

```
when (S > 0) [
    S = S - 1;
]
```

- **V(S) operation:**

```
[S = S + 1;]
```

Quiz 2

```
semaphore S = 1;
int count = 0;

void proc( ) {
   P(S);
   count++;
   ...
   count--;
   V(S);
}
```

The function proc is called concurrently by n threads. What's the maximum value that count will take on?

a) 1
b) 2
c) n
d) indeterminate

- **P(S) operation:**

```
when (S > 0) [
   S = S - 1;
]
```

- **V(S) operation:**

```
[S = S + 1;]
```

Producer/Consumer with Semaphores

```
Semaphore empty = BSIZE;
Semaphore occupied = 0;
int nextin = 0;
int nextout = 0;
```

```
void Produce(char item) {
  P(empty);
  buf[nextin] = item;
  if (++nextin >= BSIZE)
    nextin = 0;
  V(occupied);
}
```

```
char Consume( ) {
  char item;
  P(occupied);
  item = buf[nextout];
  if (++nextout >= BSIZE)
    nextout = 0;
  V(empty);
  return item;
}
```

POSIX Semaphores

```
#include <semaphore.h>

int sem_init(sem_t *semaphore, int pshared, int init);
int sem_destroy(sem_t *semaphore);
int sem_wait(sem_t *semaphore);
    /* P operation */
int sem_trywait(sem_t *semaphore);
    /* conditional P operation */
int sem_post(sem_t *semaphore);
    /* V operation */
```


Producer-Consumer with POSIX Semaphores

```
sem_init(&empty, 0, BSIZE);
sem_init(&occupied, 0, 0);
int nextin = 0;
int nextout = 0;
```

```
void produce(char item) {

  sem_wait(&empty);
  buf[nextin] = item;
  if (++nextin >= BSIZE)
    nextin = 0;
  sem_post(&occupied);
}
```

```
char consume( ) {
  char item;
  sem_wait(&occupied);
  item = buf[nextout];
  if (++nextout >= BSIZE)
    nextout = 0;
  sem_post(&empty);
  return item;
}
```