# ANNOUNCEMENTS

Project 2a: Graded – see Learn@UW; contact your TA if questions
Part 2b will be graded next week

**Exam 2: Monday 10/26 7:15 – 9:15 Ingraham B10**

- Covers all of Concurrency Piece (lecture and book)
  - Light on chapter 29, nothing from chapter 33
  - Very few questions from Virtualization Piece
- Multiple choice (fewer pure true/false)
- Look at two concurrency homeworks
- Questions from Project 2
- Goal: Sample questions available Friday evening

Tomorrow: No instructor office hours
Instead: Office hours in 1:45 – 2:45 in CS 2310 -- Come with questions!

Project 3: Only xv6 part; watch two videos early

- Due Wed 10/28
- **Create and handin specified user programs for testing**

Today's Reading: Chapter 32

UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

Andrea C. Arpaci-Dusseau
Remzi H. Arpaci-Dusseau

# CONCURRENCY BUGS

**Questions answered in this lecture:**

Why is concurrent programming difficult?

What type of concurrency bugs occur?

How to fix **atomicity bugs** (with locks)?

How to fix **ordering bugs** (with condition variables)?

How does **deadlock** occur?

How to prevent deadlock (with waitfree algorithms, grab all locks atomically, trylocks, and ordering across locks)?

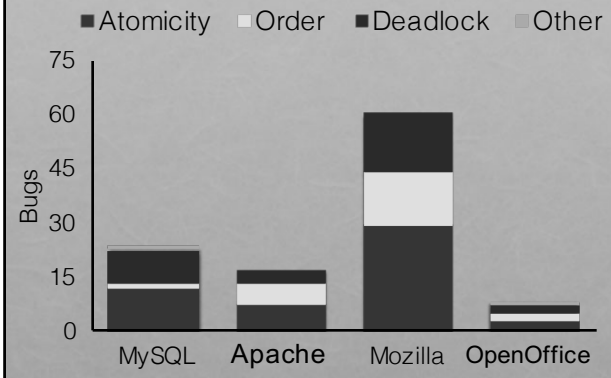
# CONCURRENCY IN MEDICINE: THERAC-25 (1980'S)

"The accidents occurred when the high-power electron beam was activated instead of the intended low power beam, and without the beam spreader plate rotated into place. Previous models had hardware interlocks in place to prevent this, but Therac-25 had removed them, depending instead on software interlocks for safety. The software interlock could fail due to a **race condition**."

"…in three cases, the injured patients **later died**."

Source: http://en.wikipedia.org/wiki/Therac-25

# CONCURRENCY STUDY FROM 2008




**Lu *etal.* Study:**

For four major projects, search for concurrency bugs among >500K bug reports. Analyze small sample to identify common types of concurrency bugs.

Source: http://pages.cs.wisc.edu/~shanlu/paper/asplos122-lu.pdf

# ATOMICITY: MYSQL

**Thread 1:**

```
if (thd->proc_info) {
   …
   fputs(thd->proc_info, …);
   …
}
```

**Thread 2:**

```
thd->proc_info = NULL;
```

What's wrong?

Test (thd->proc_info != NULL) and set (writing to thd->proc_info) should be atomic

# FIX ATOMICITY BUGS WITH LOCKS

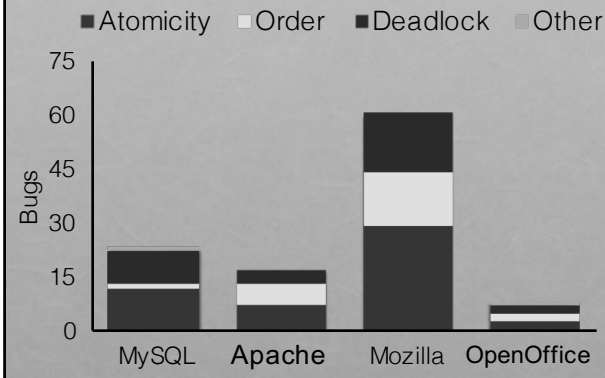
**Thread 1:**

```
pthread_mutex_lock(&lock);
if (thd->proc_info) {
   …
   fputs(thd->proc_info, …);
   …
}
pthread_mutex_unlock(&lock);
```

**Thread 2:**

```
pthread_mutex_lock(&lock);
thd->proc_info = NULL;
pthread_mutex_unlock(&lock);
```

# CONCURRENCY STUDY FROM 2008

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Source: http://pages.cs.wisc.edu/~shanlu/paper/asplos122-lu.pdf

# ORDERING: MOZILLA

**Thread 1:**

```
void init() {
  …
  mThread =
    PR_CreateThread(mMain, …);
  …
}
```

**Thread 2:**

```
void mMain(…) {
  …
  mState = mThread->State;
  …
}
```

What's wrong?

Thread 1 sets value of mThread needed by Thread2
How to ensure that reading MThread happens after mThread initialization?

# FIX ORDERING BUGS WITH CONDITION VARIABLES

**Thread 1:**

```
void init() {
    …

    mThread =
    PR_CreateThread(mMain,  …);

    pthread_mutex_lock(&mtLock);
    mtInit = 1;
    pthread_cond_signal(&mtCond);
    pthread_mutex_unlock(&mtLock);

    …
}
```

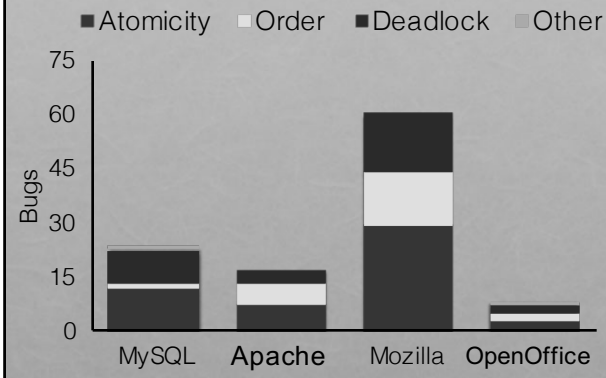
**Thread 2:**

```
void mMain(…) {
  …

  Mutex_lock(&mtLock);
  while (mtInit == 0)
    Cond_wait(&mtCond,  &mtLock);
  Mutex_unlock(&mtLock);

  mState = mThread->State;
  …
}
```

# CONCURRENCY STUDY FROM 2008

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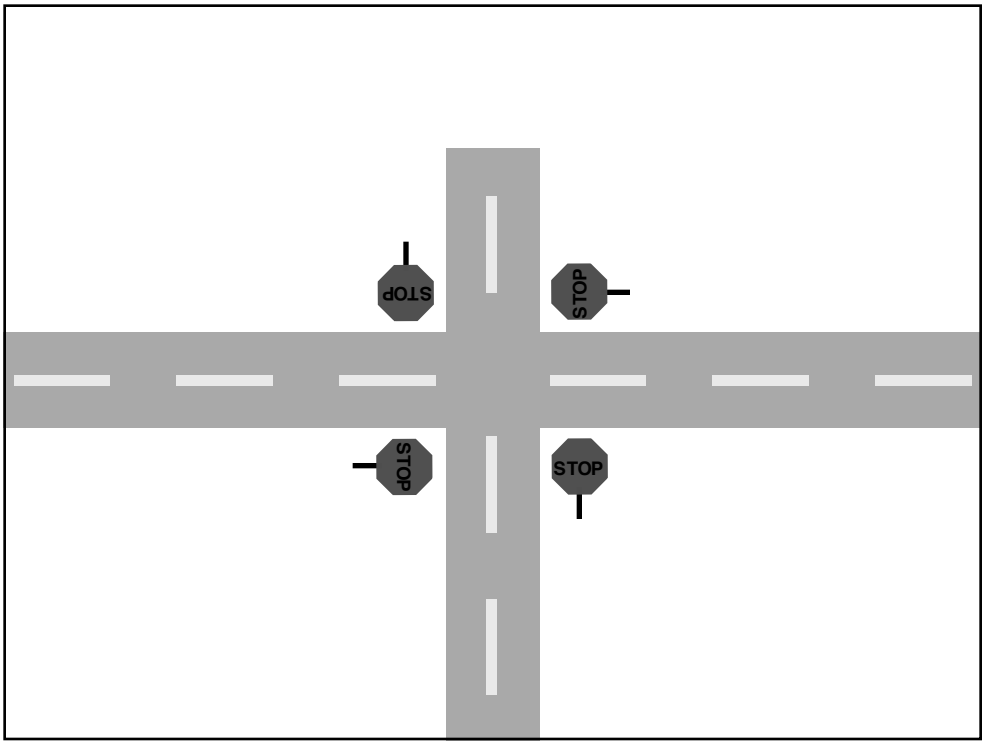
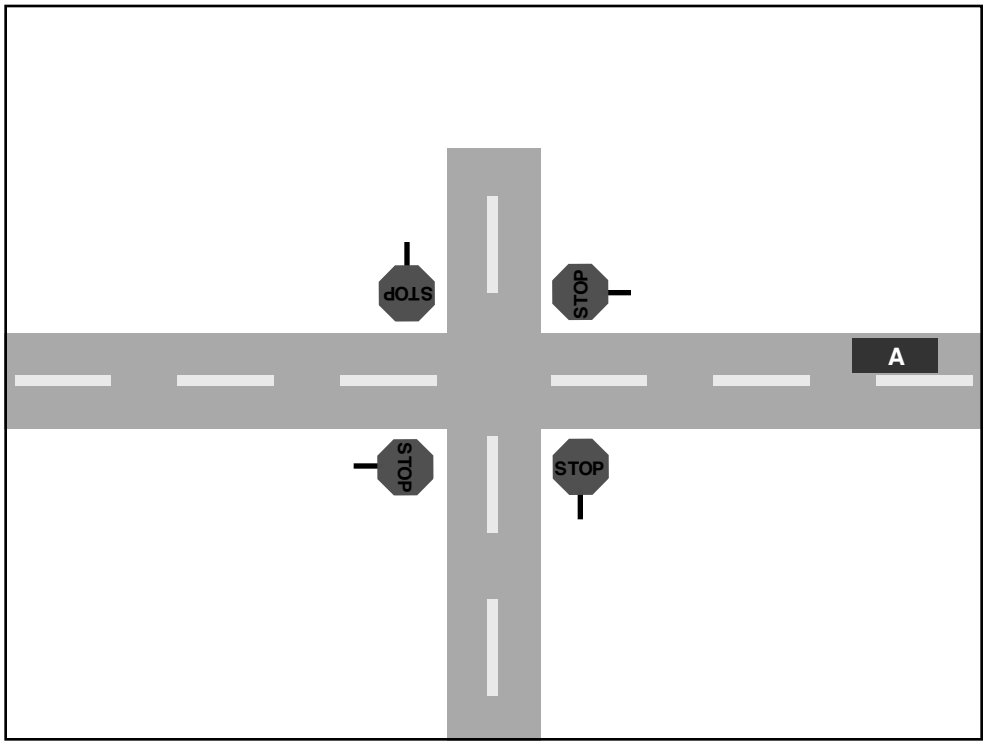
# DEADLOCK

Deadlock: No progress can be made because two or more threads are waiting for the other to take some action and thus neither ever does

"Cooler" name: the **deadly embrace** (Dijkstra)




STOP
STOP
A
STOP
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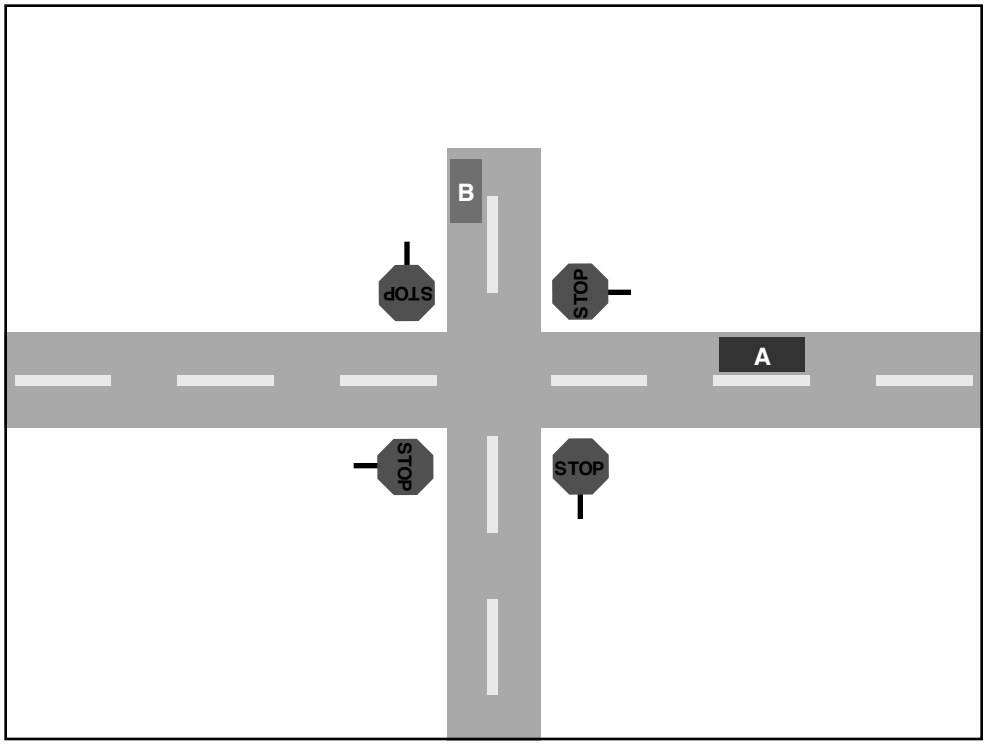
B
STOP
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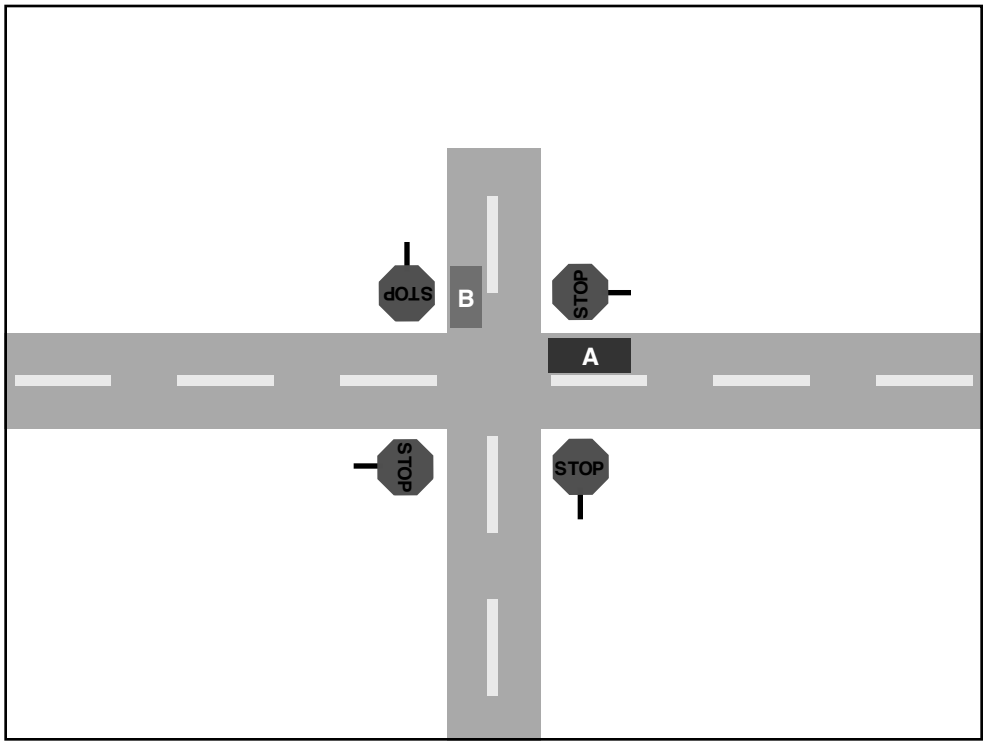
STOP
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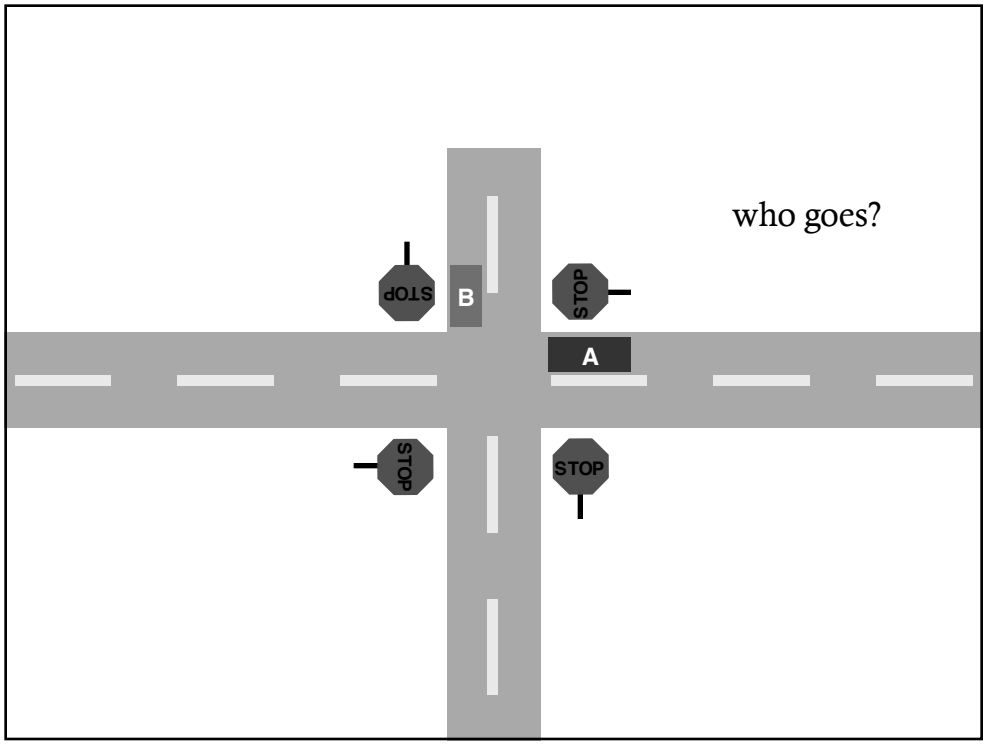
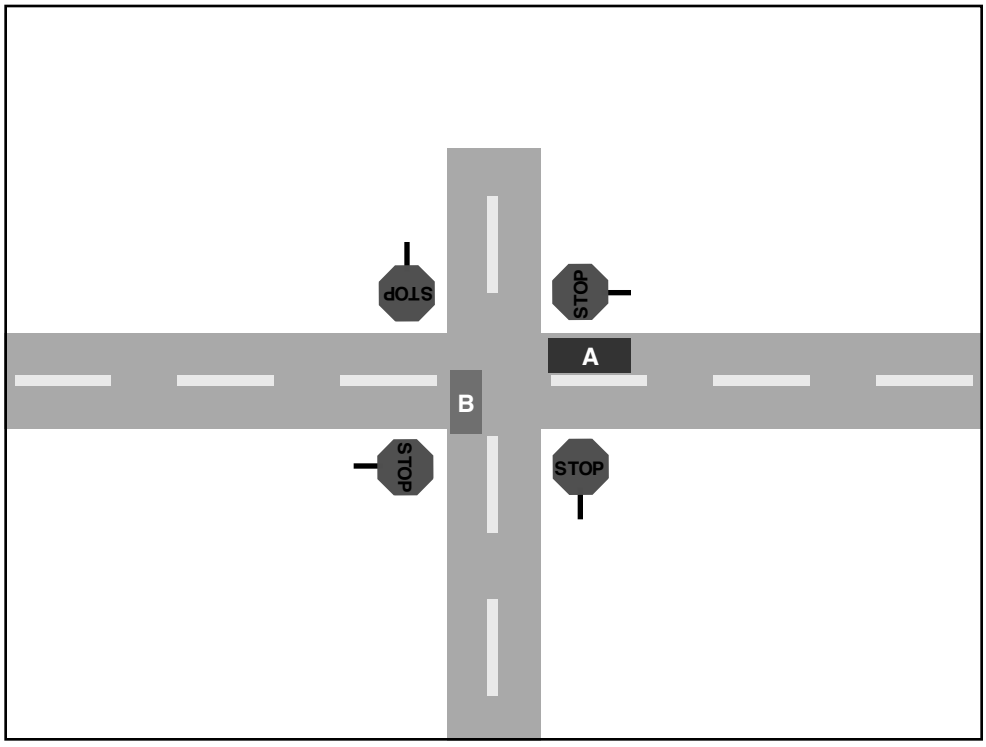

who goes?
STOP
B
STOP
A
STOP
STOP


STOP
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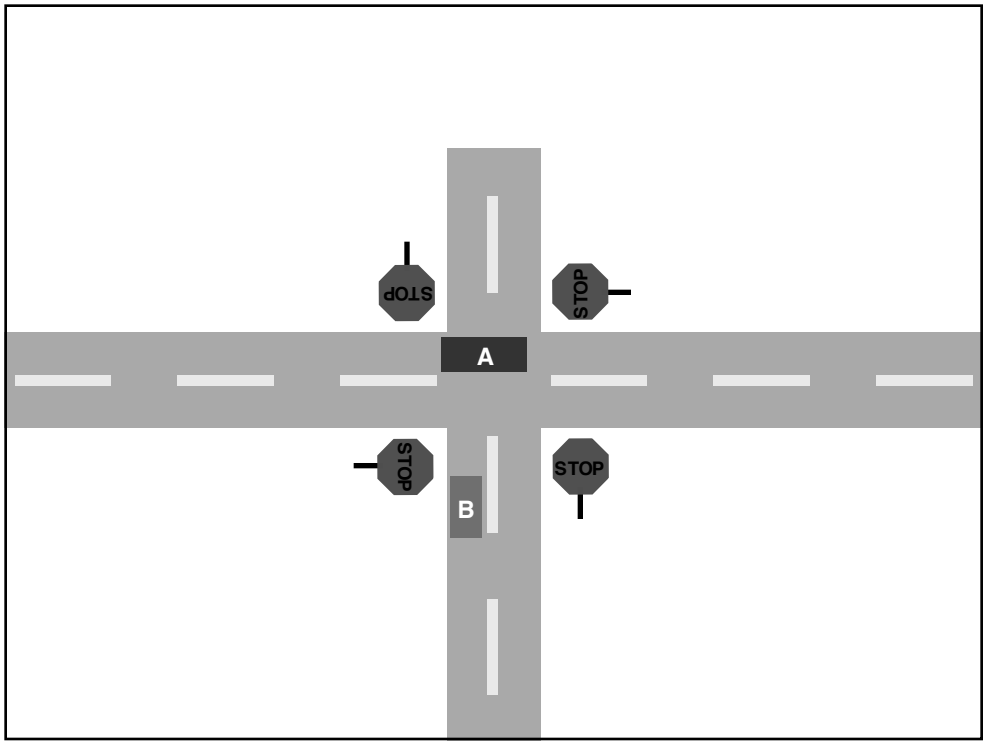
STOP
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A
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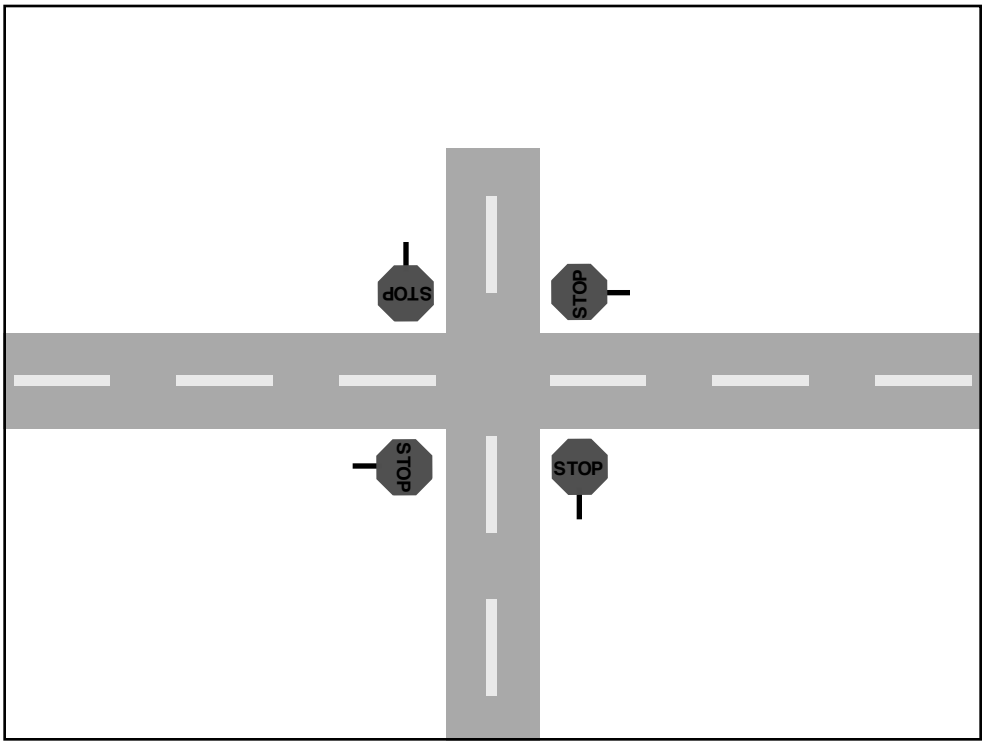
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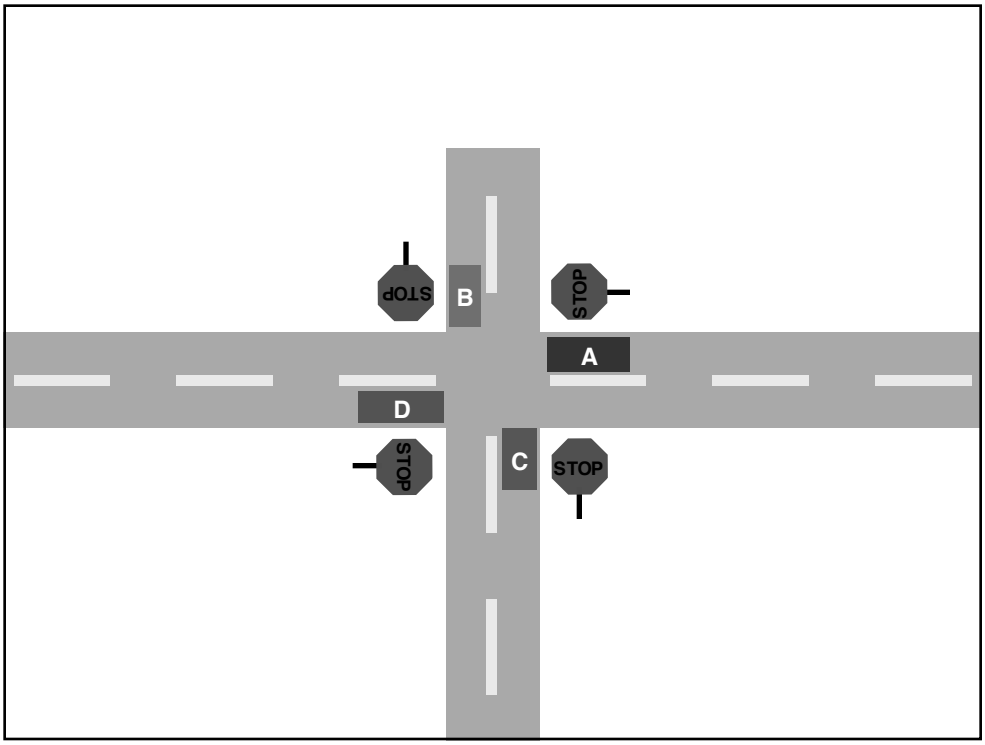
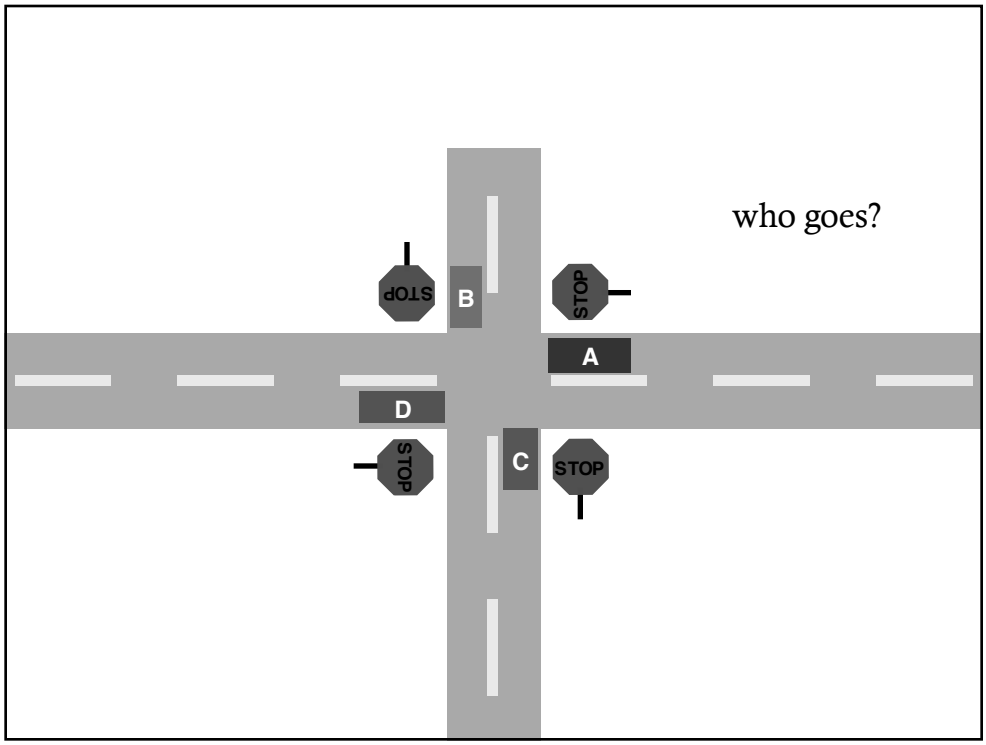

STOP
B
STOP
A
D
STOP
C
STOP


who goes?
STOP
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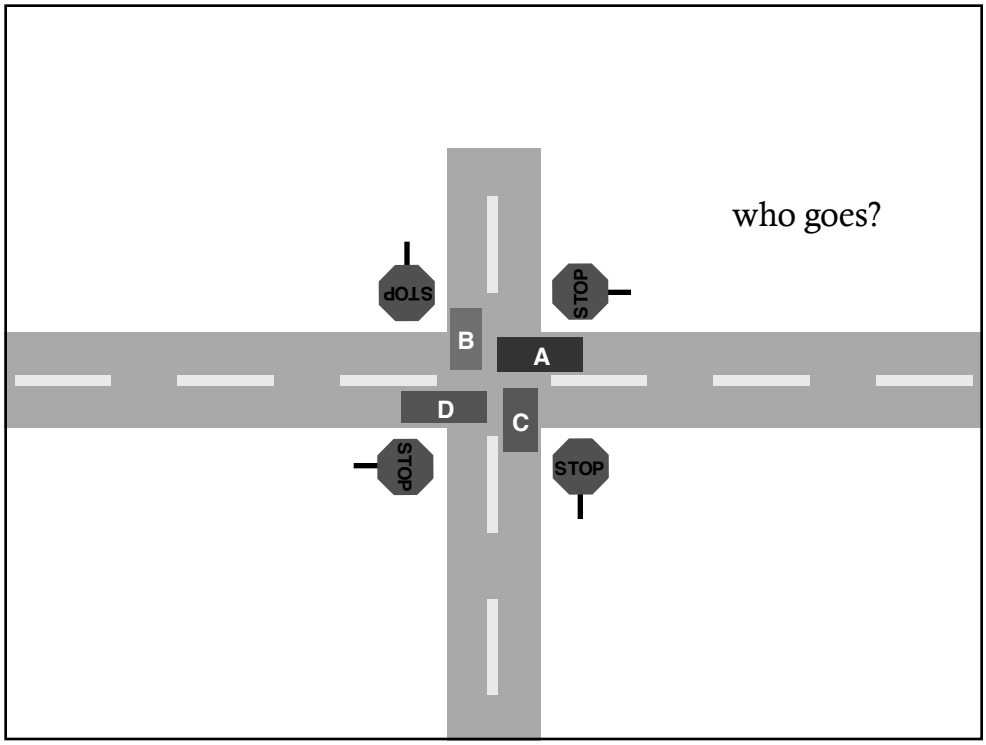
who goes?
STOP
STOP
B
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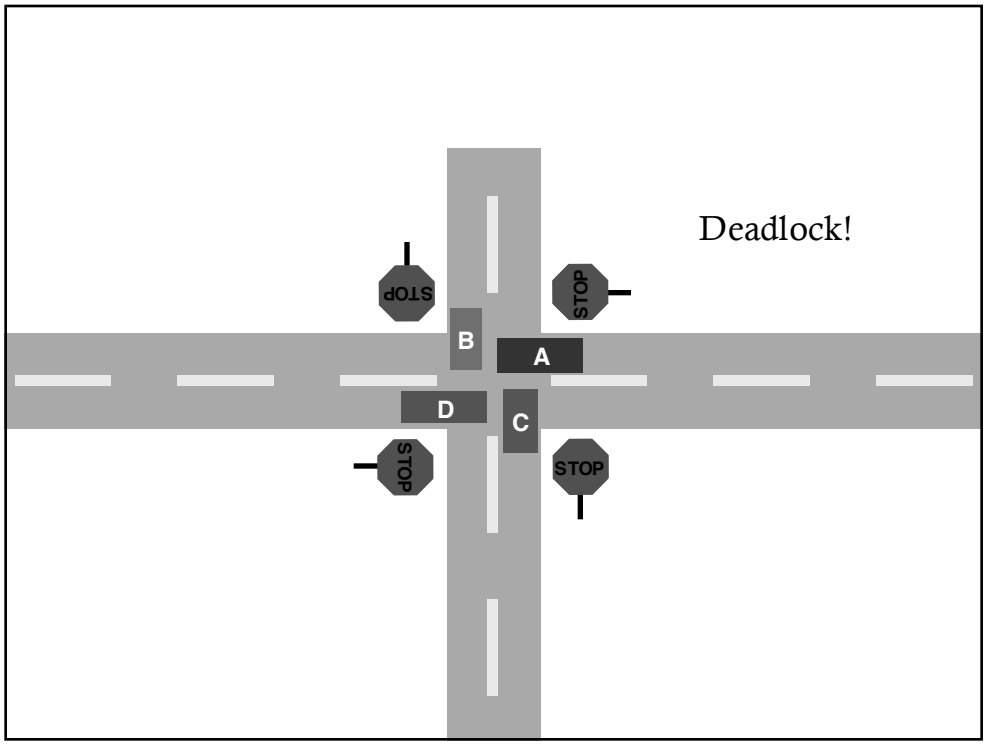
D
C
STOP
STOP




# CODE EXAMPLE

Thread 1:

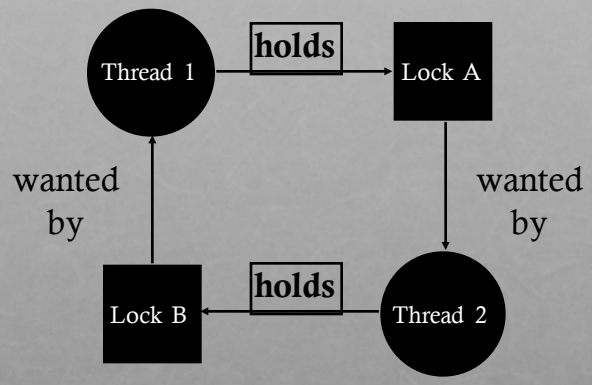
```
lock(&A);
lock(&B);
```

Thread 2:

```
lock(&B);
lock(&A);
```

Can deadlock happen with these two threads?

# CIRCULAR DEPENDENCY




# FIX DEADLOCKED CODE

Thread 1:

```
lock(&A);
lock(&B);
```

Thread 2:

```
lock(&B);
lock(&A);
```

How would you fix this code?

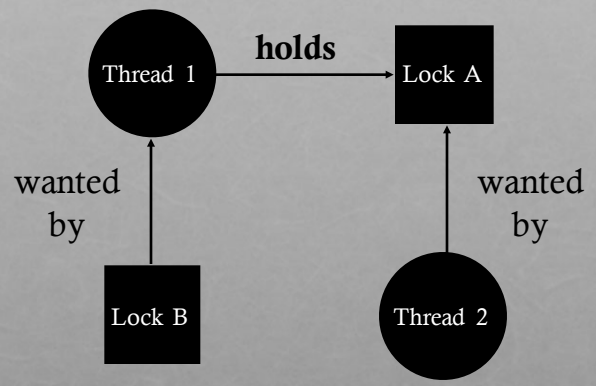
Thread 1

```
lock(&A);
lock(&B);
```

Thread 2

```
lock(&A);
lock(&B);
```

# NON-CIRCULAR DEPENDENCY (FINE)




# WHAT'S WRONG?

```
set_t *set_intersection (set_t *s1, set_t *s2) {
      set_t *rv = Malloc(sizeof(*rv));
      Mutex_lock(&s1->lock);
      Mutex_lock(&s2->lock);
      for(int i=0; i<s1->len; i++) {
            if(set_contains(s2, s1->items[i])
                  set_add(rv, s1->items[i]);
      Mutex_unlock(&s2->lock);
      Mutex_unlock(&s1->lock);
}
```

# ENCAPSULATION

Modularity can make it harder to see deadlocks

**Thread 1:**

```
rv = set_intersection(setA,
                      setB);
```

**Thread 2:**

```
rv = set_intersection(setB,
                      setA);
```

Solution?

```
if (m1 > m2) {
    // grab locks in high-to-low address order
    pthread_mutex_lock(m1);
    pthread_mutex_lock(m2);
} else {
    pthread_mutex_lock(m2);
    pthread_mutex_lock(m1);
}
```

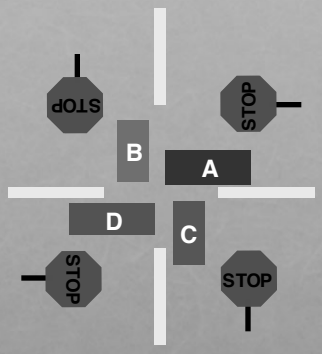
Any other problems?

Code assumes m1 != m2 (not same lock)

# DEADLOCK THEORY

Deadlocks can only happen with these four conditions:

- mutual exclusion
- hold-and-wait
- no preemption
- circular wait




Eliminate deadlock by eliminating any one condition

# MUTUAL EXCLUSION

Def:

Threads claim exclusive control of resources that they require (e.g., thread grabs a lock)

# WAIT-FREE ALGORITHMS

Strategy: Eliminate locks!

Try to replace locks with atomic primitive:

int CompAndSwap(int *addr, int expected, int new)
Returns 0: fail, 1: success

```
void add (int *val, int amt) {
    Mutex_lock(&m);
    *val += amt;
    Mutex_unlock(&m);
}
```

```
void add (int *val, int amt) {
    do {
        int old = *value;
    } while(!CompAndSwap(val, ??, old+amt);
}
```

?? → old

# WAIT-FREE ALGORITHMS: LINKED LIST INSERT

Strategy: Eliminate locks!

int CompAndSwap(int *addr, int expected, int new)
Returns 0: fail, 1: success

```
void insert (int val) {
    node_t *n = Malloc(sizeof(*n));
    n->val = val;
    lock(&m);
    n->next = head;
    head = n;
    unlock(&m);
}
```

```
void insert (int val) {
    node_t *n = Malloc(sizeof(*n));
    n->val = val;
    do {
        n->next = head;
    } while (!CompAndSwap(&head,
            n->next, n));
}
```

# DEADLOCK THEORY

Deadlocks can only happen with these four conditions:

- mutual exclusion
- hold-and-wait
- no preemption
- circular wait

Eliminate deadlock by eliminating any one condition

# HOLD-AND-WAIT

Def:

Threads hold resources allocated to them (e.g., locks they have already acquired) while waiting for additional resources (e.g., locks they wish to acquire).

# ELIMINATE HOLD-AND-WAIT

Strategy: Acquire all locks atomically **once**

Can release locks over time, but cannot acquire again until all have been released

How to do this? Use a meta lock, like this:

```
lock(&meta);
lock(&L1);
lock(&L2);
…
unlock(&meta);

// Critical section code

unlock(…);
```

Disadvantages?

Must know ahead of time which locks will be needed
Must be conservative (acquire any lock possibly needed)
Degenerates to just having one big lock

# DEADLOCK THEORY

Deadlocks can only happen with these four conditions:

- mutual exclusion
- hold-and-wait
- no preemption
- circular wait

Eliminate deadlock by eliminating any one condition

# NO PREEMPTION

Def:

Resources (e.g., locks) cannot be forcibly removed from threads that are holding them.

# SUPPORT PREEMPTION

Strategy: if thread can't get what it wants, release what it holds

```
top:
      lock(A);
      if (trylock(B) == -1) {
            unlock(A);
            goto top;
      }
      …
```

Disadvantages?

Livelock:
no processes make progress, but the state of involved processes constantly changes
Classic solution: Exponential back-off

# DEADLOCK THEORY

Deadlocks can only happen with these four conditions:

- mutual exclusion
- hold-and-wait
- no preemption
- circular wait

Eliminate deadlock by eliminating any one condition

# CIRCULAR WAIT

Def:

There exists a circular chain of threads such that each thread holds a resource (e.g., lock) being requested by next thread in the chain.

# ELIMINATING CIRCULAR WAIT

Strategy:

- decide which locks should be acquired before others
- if A before B, never acquire A if B is already held!
- document this, and write code accordingly

Works well if system has distinct layers

# LOCK ORDERING IN LINUX

*In linux-3.2.51/include/linux/fs.h*

```
/* inode->i_mutex nesting subclasses for the lock
 * validator:
 * 0: the object of the current VFS operation
 * 1: parent
 * 2: child/target
 * 3: quota file
 * The locking order between these classes is
 * parent -> child -> normal -> xattr -> quota
 */
```

# SUMMARY

When in doubt about correctness, better to limit concurrency (i.e., add unneccessary lock)

Concurrency is hard, encapsulation makes it harder!

Have a strategy to avoid deadlock and stick to it

Choosing a lock order is probably most practical