# CS444/544
# Operating Systems II

Lecture 15

Lock and Synchronization (cont.)

Concurrency Bugs and Deadlock

5/22/2024

Acknowledgement: Slides drawn heavily from Yeongjin Jiang

Oregon State University

# Odds and Ends

- No lecture next Monday (5/27) – Memorial Day

- It is recommended to complete Part A by next lecture

# Part-A Result

```
dumbfork: OK (1.0s)
Part A score: 5/5
```

- You should get this OK before start exercise 8

- FAQ
  - What if dumbfork halts?
    - Check if your sched_yield()/env_run() is implemented correctly
    - curenv must set as ENV_RUNNABLE state if it is scheduled out…
  - What if I have a syscall error?
    - Check if your implementation returns the return value of the syscall correctly
    - Check syscall arguments and orders
    - There always be syscalls to SYS_getenvid and SYS_cputs

# CAUTION:
# You Will See LOTS of Page Faults in Part B

- What should I do if I see a page fault?

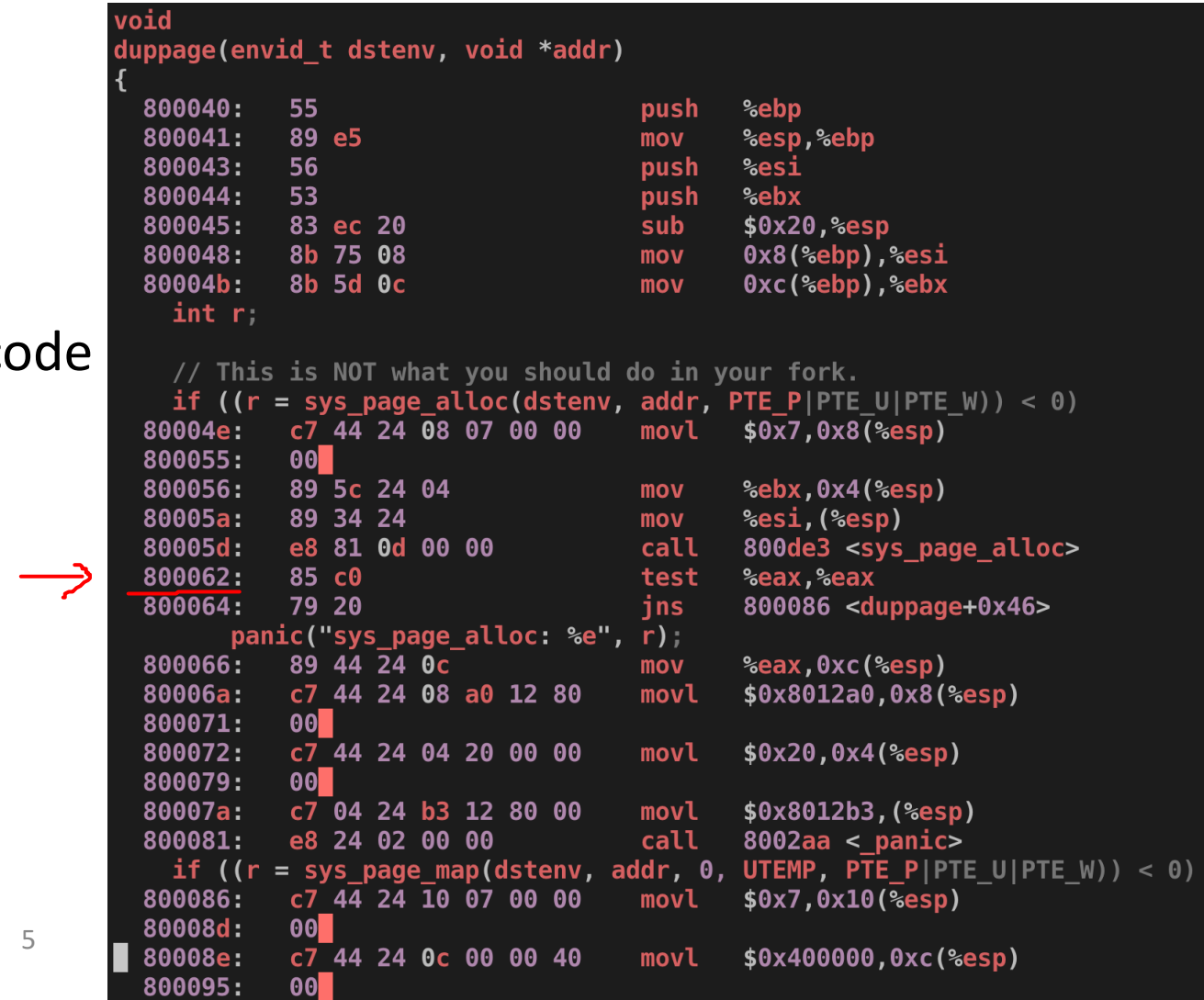
```
set_pgfault_handler(handler);
cprintf("%s\n", (char*)0xDeadBeef);
cprintf("%s\n", (char*)0xCafeBffe);
```

- Check information related to the fault
  - Check tf_eip (the origin of the fault)
  - Check fault_va (read cr2, rcr2())
    - You can reason a lot from this address, e.g., 0xcafebffe?
    - If it is 0, a null pointer dereference, check your impl!!!
  - Check error code (user/kernel, read/write, present?)

- Think about why this fault happens???

# How Can I Get the Code for User Exec?

- Read obj/user/xxxx.asm
- E.g., dumbfork:
  - You can match eip and the source code



```
void
duppage(envid_t dstenv, void *addr)
{
  800040:   55                      push   %ebp
  800041:   89 e5                   mov    %esp,%ebp
  800043:   56                      push   %esi
  800044:   53                      push   %ebx
  800045:   83 ec 20                sub    $0x20,%esp
  800048:   8b 75 08                mov    0x8(%ebp),%esi
  80004b:   8b 5d 0c                mov    0xc(%ebp),%ebx
    int r;

    // This is NOT what you should do in your fork.
    if ((r = sys_page_alloc(dstenv, addr, PTE_P|PTE_U|PTE_W)) < 0)
  80004e:   c7 44 24 08 07 00 00    movl   $0x7,0x8(%esp)
  800055:   00
  800056:   89 5c 24 04             mov    %ebx,0x4(%esp)
  80005a:   89 34 24                mov    %esi,(%esp)
  80005d:   e8 81 0d 00 00          call   800de3 <sys_page_alloc>
  800062:   85 c0                   test   %eax,%eax
  800064:   79 20                   jns    800086 <duppage+0x46>
        panic("sys_page_alloc: %e", r);
  800066:   89 44 24 0c             mov    %eax,0xc(%esp)
  80006a:   c7 44 24 08 a0 12 80    movl   $0x8012a0,0x8(%esp)
  800071:   00
  800072:   c7 44 24 04 20 00 00    movl   $0x20,0x4(%esp)
  800079:   00
  80007a:   c7 04 24 b3 12 80 00    movl   $0x8012b3,(%esp)
  800081:   e8 24 02 00 00          call   8002aa <_panic>
    if ((r = sys_page_map(dstenv, addr, 0, UTEMP, PTE_P|PTE_U|PTE_W)) < 0)
  800086:   c7 44 24 10 07 00 00    movl   $0x7,0x10(%esp)
  80008d:   00
  80008e:   c7 44 24 0c 00 00 40    movl   $0x400000,0xc(%esp)
  800095:   00
```

# Debugging Tips

- Check your traps. Recommend to print out some trap information whenever you got a trap…

```
static void
trap_dispatch(struct Trapframe *tf)
{
    // Handle processor exceptions.
    // LAB 3: Your code here.

    uint32_t envid;
    if (curenv == NULL) envid = 0;
    else envid = curenv->env_id;
    if (tf->tf_trapno == T_SYSCALL) {
        cprintf("Syscall from %p %s(%p, %p, %p, %p, %p) from "
                "eip %p\n",
                envid,
                stringtbl[tf->tf_regs.reg_eax],
                tf->tf_regs.reg_edx,
                tf->tf_regs.reg_ecx,
                tf->tf_regs.reg_ebx,
                tf->tf_regs.reg_edi,
                tf->tf_regs.reg_esi,
                tf->tf_eip);
    }
    else if (tf->tf_trapno == T_PGFLT) {
        cprintf("Page fault from %p from va %p eip %p\n",
                envid,
                rcr2(), tf->tf_eip);
    }
    else {
        cprintf("Trap from %p number %d from eip %p\n",
                envid,
                tf->tf_trapno, tf->tf_eip);
    }
```

# Debugging Tips

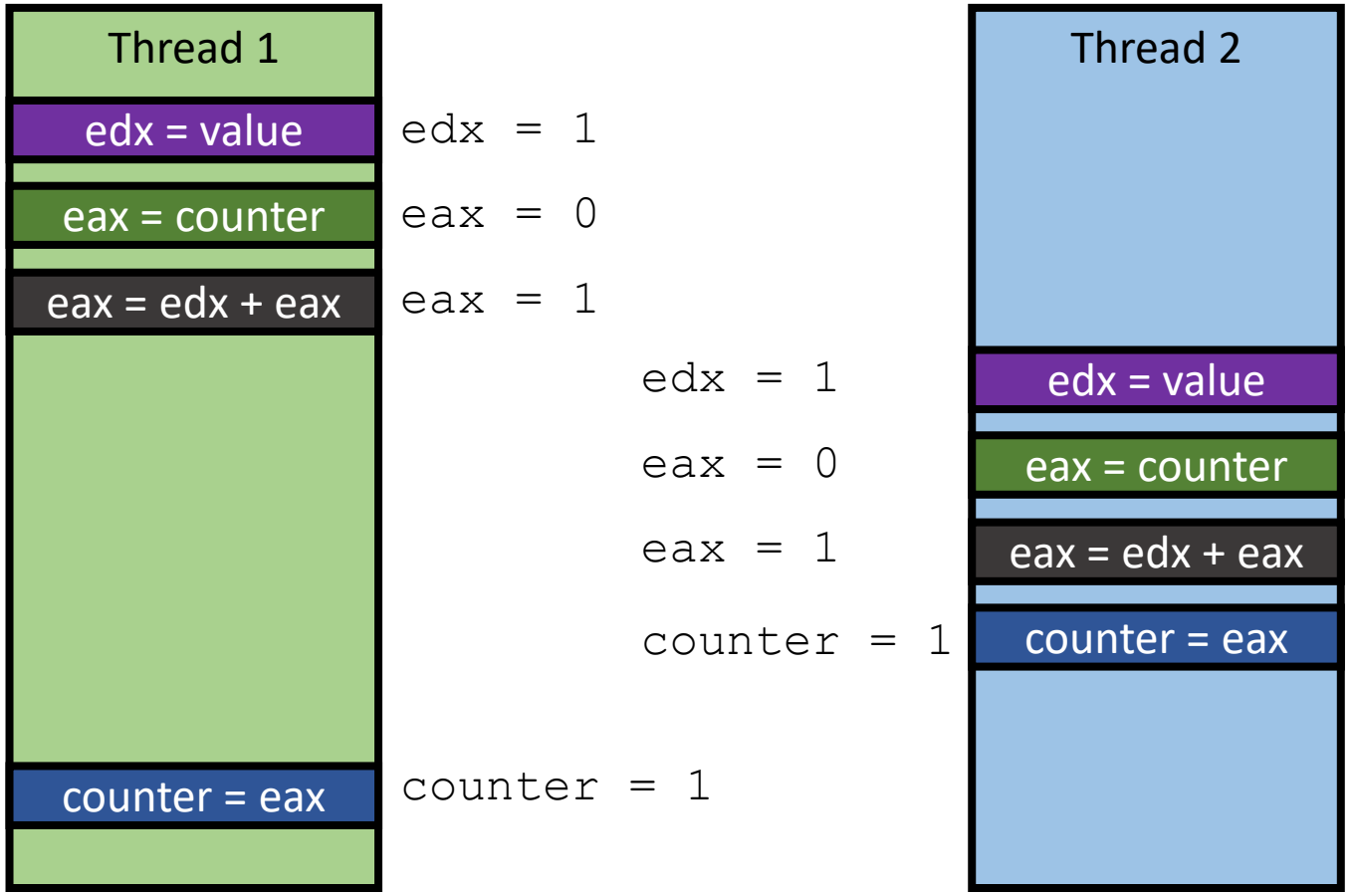
- Check your traps. Recommend to print out some trap information whenever you got a trap…

```
static void
trap_dispatch(struct Trapframe *tf)
{
    // Handle processor exceptions.
    // LAB 3: Your code here.

    uint32_t envid;
    if (curenv == NULL) envid = 0;
    else envid = curenv->env_id;
    if (tf->tf_trapno == T_SYSCALL) {
        cprintf("Syscall from %p %s(%p, %p, %p, %p, %p) from "
                "eip %p\n",
                envid,
                stringtbl[tf->tf_regs.reg_eax],
                tf->tf_regs.reg_edx,
                tf->tf_regs.reg_ecx,
```

```
[00000000] new env 00001000
Syscall from 0x1000 SYS_getenvid(0x0, 0x0, 0x0, 0x0, 0x0) from eip 0x800bdf
Syscall from 0x1000 SYS_cputs(0xeebfde88, 0x27, 0x0, 0x0, 0x0) from eip 0x800b4f
I am the parent.  Forking the child...
Syscall from 0x1000 SYS_page_alloc(0x1000, 0xeebff000, 0x7, 0x0, 0x0) from eip 0x800c23
Syscall from 0x1000 SYS_env_set_pgfault_upcall(0x0, 0x8012b9, 0x0, 0x0, 0x0) from eip 0x800d6f
Syscall from 0x1000 SYS_exofork(0x0, 0x8012b9, 0x0, 0x0, 0x0) from eip 0x800f77
[00001000] new env 00001001
Syscall from 0x1000 SYS_page_map(0x0, 0x200000, 0x1001, 0x200000, 0x805) from eip 0x800c76
Syscall from 0x1000 SYS_page_map(0x0, 0x200000, 0x0, 0x200000, 0x805) from eip 0x800c76
Trap from 0x1000 number 32 from eip 0x800c76
```

# Recap: Data Race Example

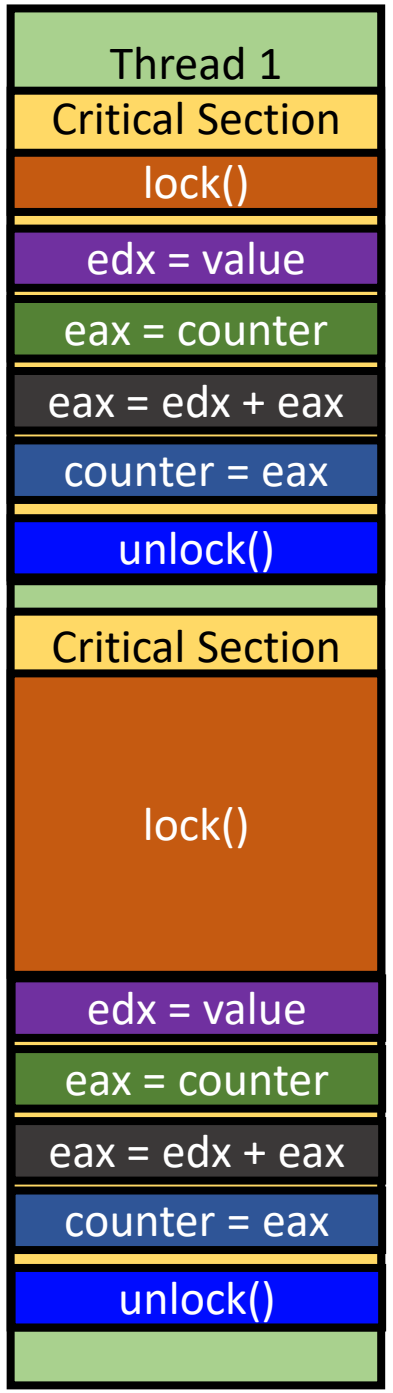
- counter += value
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
- Assume counter = 0 at start

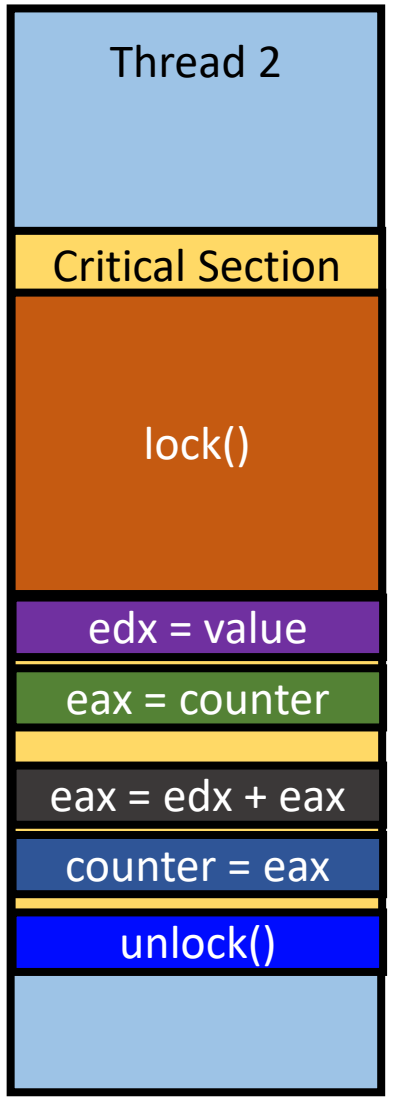



**Counter = 1, not 2!!!**

# Recap: Mutex

- Lock
  - Prevent others enter the critical section
- Unlock
  - Release the lock, let others acquire the lock
- counter += value
  - **`lock()`**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **`unlock()`**



# Spinlock Examples

- unzip lock-example-master.zip
- Run 30 threads, each count upto 10000

- Build code
  - $ make

```
os2 ~/cs444/s21/lock-example-master 146% make
gcc -o lock lock.c -std=c99 -g -Wno-implicit-function-declaration -O2 -lpthread
```

# Summary

- 5 Lock implementations
  - Naïve lock (bad_lock, not working)
  - xchg lock (test-and-set, slow)
  - cmpxchg lock (a fake test and test-and-set, still slow)
  - Software test and hardware test-and-set (fast!)
  - Hardware test-and-set with exponential backoff (**faster!**)

- Performance check
  - Total execution time
  - L1-dcache-load-misses
  - Compare the performance to pthread_mutex

# lock-example

```
if (LLL_MUTEX_TRYLOCK (mutex) != 0)
  {
    int cnt = 0;
    int max_cnt = MIN (max_adaptive_count (),
                       mutex->__data.__spins * 2 + 10);
    do
      {
        if (cnt++ >= max_cnt)
          {
            LLL_MUTEX_LOCK (mutex);
            break;
          }
        atomic_spin_nop ();
      }
    while (LLL_MUTEX_TRYLOCK (mutex) != 0);
```

If the lock variable is not 0

Spins * 2 + 10… exp backoff!

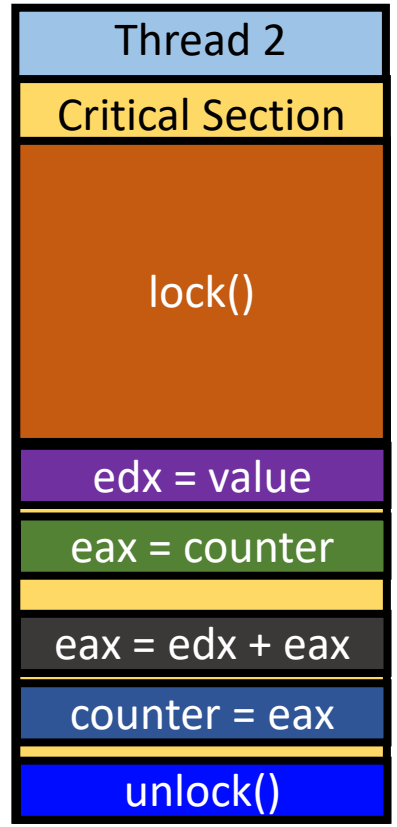
```
#define atomic_spin_nop() __asm ("pause")
```

Check if the lock variable is 0…

# Lock is Slow

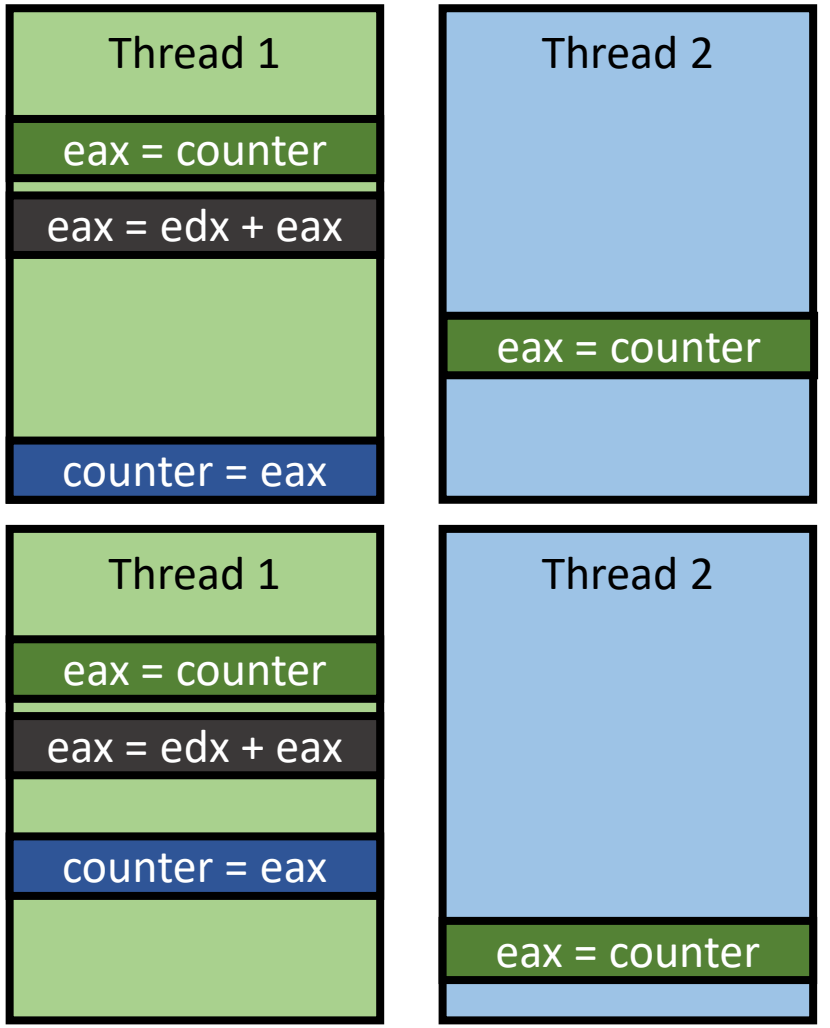
- Run While() internally
- Can block other threads
- We need to determine when and where to use lock

```
void
xchg_lock(volatile uint32_t *lock) {
    while(xchg(lock, 1));
}

void
xchg_unlock(volatile uint32_t *lock) {
    xchg(lock, 0);
}
```



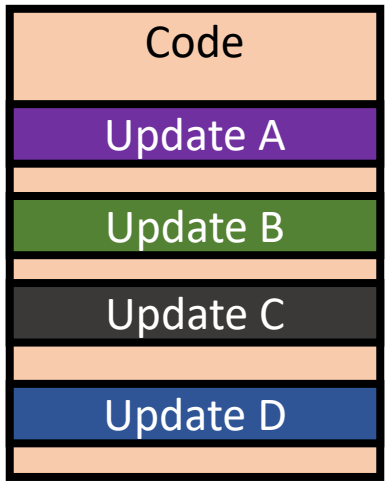
# When Do We Need to Use a Lock?

- Write must be finished before the next load
- Many writers and one reader
  - Yes… many writers..
- Two writers and two readers
  - Yes, two writers…
- One writer and many readers
  - Not always if there is only one writer

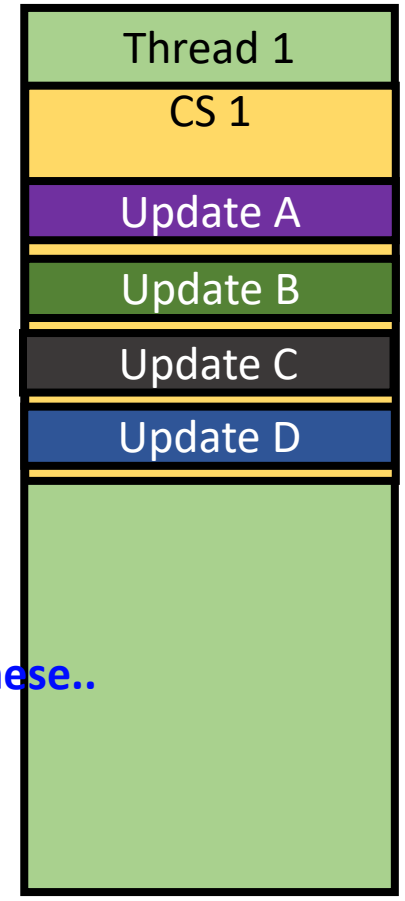


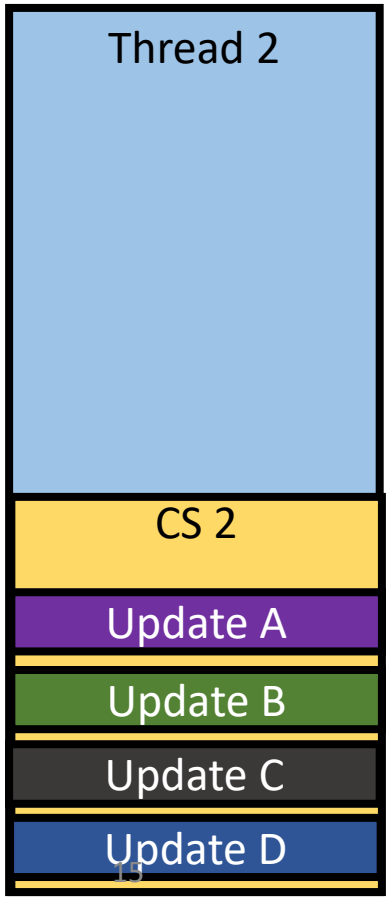
# Where Do We Need to Put a Lock?

- What will happen if a critical section is too big?



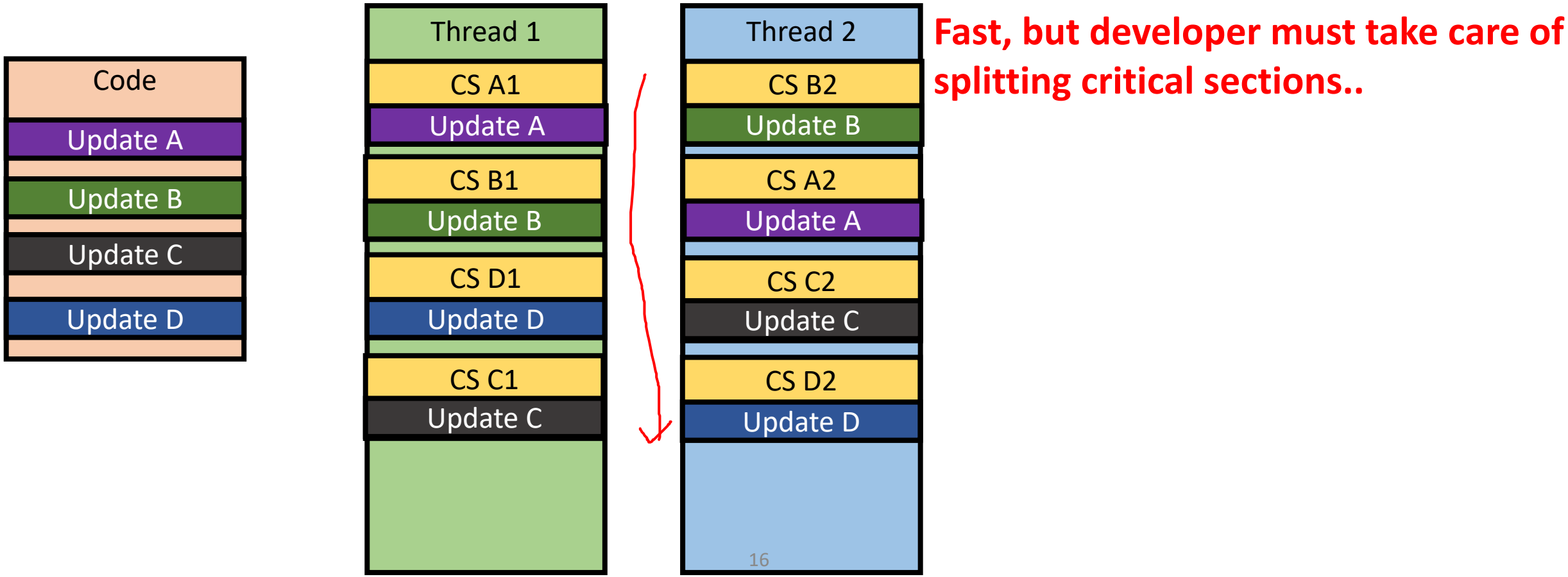

**Four independent variables**
**Require a lock on updating these..**




**Wasting time for waiting for all**

# Small Critical Sections




**Fast, but developer must take care of splitting critical sections..**

# General Practice

- Use lock only if it is required
  - Determine the case when you do not need a lock
    - Atomic read
    - Only one writer
- Use a small critical section
  - Critical section prohibits concurrent execution
  - Determine where do we share a variable
  - Wrap only the code that updates the shared variable
- Looks simple, but sometimes it’s difficult

# Concurrency Bugs

- Code does not have a bug when it runs with single thread could have a bug when it runs with multiple threads
  - Multiple cores, etc.

- What are the types of concurrency bugs?
  - Atomicity
  - Ordering
  - Deadlock

# Atomicity

Read

```
1   Thread 1::
2   if (thd->proc_info) {
3     ...
4     fputs(thd->proc_info, ...);
5     ...
6   }
7
8   Thread 2::
9   thd->proc_info = NULL;
```

Time of check

Time of use

Write!

**Time-of-check-to-time-of-use bug**

**TOCTTOU**

# Atomicity: Use Lock

```
1   pthread_mutex_t proc_info_lock = PTHREAD_MUTEX_INITIALIZER;
2
3   Thread 1::
4   pthread_mutex_lock(&proc_info_lock);
5   if (thd->proc_info) {
6     ...
7     fputs(thd->proc_info, ...);
8     ...
9   }
10  pthread_mutex_unlock(&proc_info_lock);
11
12  Thread 2::
13  pthread_mutex_lock(&proc_info_lock);
14  thd->proc_info = NULL;
15  pthread_mutex_unlock(&proc_info_lock);
```

Time of check

Time of use

Update!

In critical section, NO UPDATE
Do not have TOCTTOU!

This will also block other threads that run line 5 while thread 2 updates thd->proc_info..

# Ordering: Mozilla – Order 1

```
1   Thread 1::
2   void init() {
3       ...
4       mThread = PR_CreateThread(mMain, ...);
5       ...
6   }
7
8   Thread 2::
9   void mMain(...) {
10      ...
11      mState = mThread->State;
12      ...
13  }
```

# Ordering: Mozilla – Order 2

```
8    Thread 2::
9    void mMain(...) {
10       ...
11       mState = mThread->State;
12       ...
13   }
```

Not Initialized…

```
1    Thread 1::
2    void init() {
3       ...
4       mThread = PR_CreateThread(mMain, ...);
5       ...
6    }
```

# How Can We Resolve the Ordering Issue?

- Use locks and conditional variables to force a specific ordering…
- pthread_cond_wait(cond, lock)
  - Set cond = 0
  - You will release the lock
  - Wait until cond == 1
  - Acquire the lock again
- pthread_cond_signal(cond)
  - cond = 1

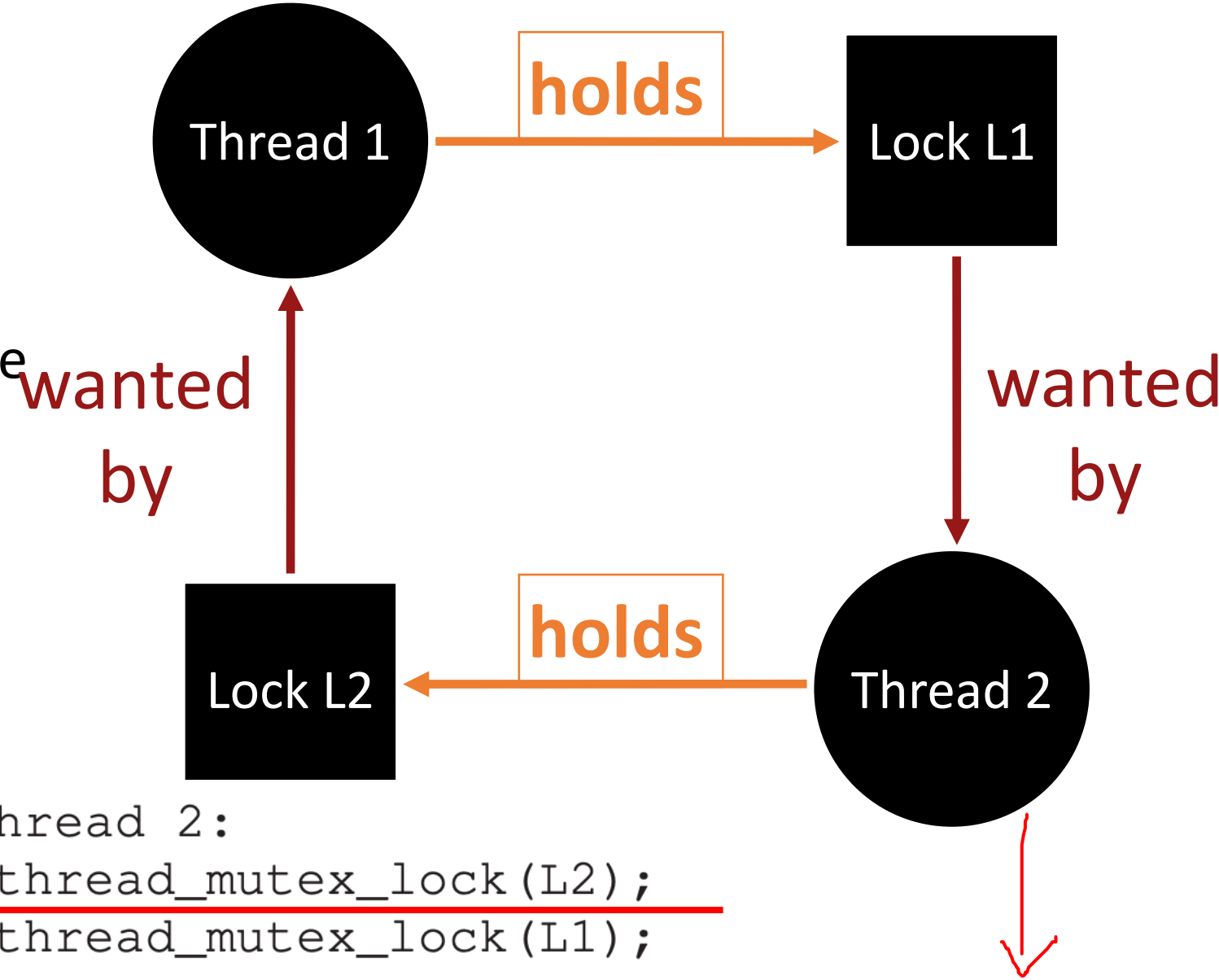
```
5   Thread 1::
6   void init() {
7       ...
8       mThread = PR_CreateThread(mMain, ...);
9
10      // signal that the thread has been created...
11      pthread_mutex_lock(&mtLock);
12      mtInit = 1;
13      pthread_cond_signal(&mtCond);
14      pthread_mutex_unlock(&mtLock);
15      ...
16  }
17
18  Thread 2::
19  void mMain(...) {
20      ...
21      // wait for the thread to be initialized...
22      pthread_mutex_lock(&mtLock);
23      while (mtInit == 0)
24          pthread_cond_wait(&mtCond, &mtLock);
25      pthread_mutex_unlock(&mtLock);
26
27      mState = mThread->State;
28      ...
29  }
```

Sends Signal..

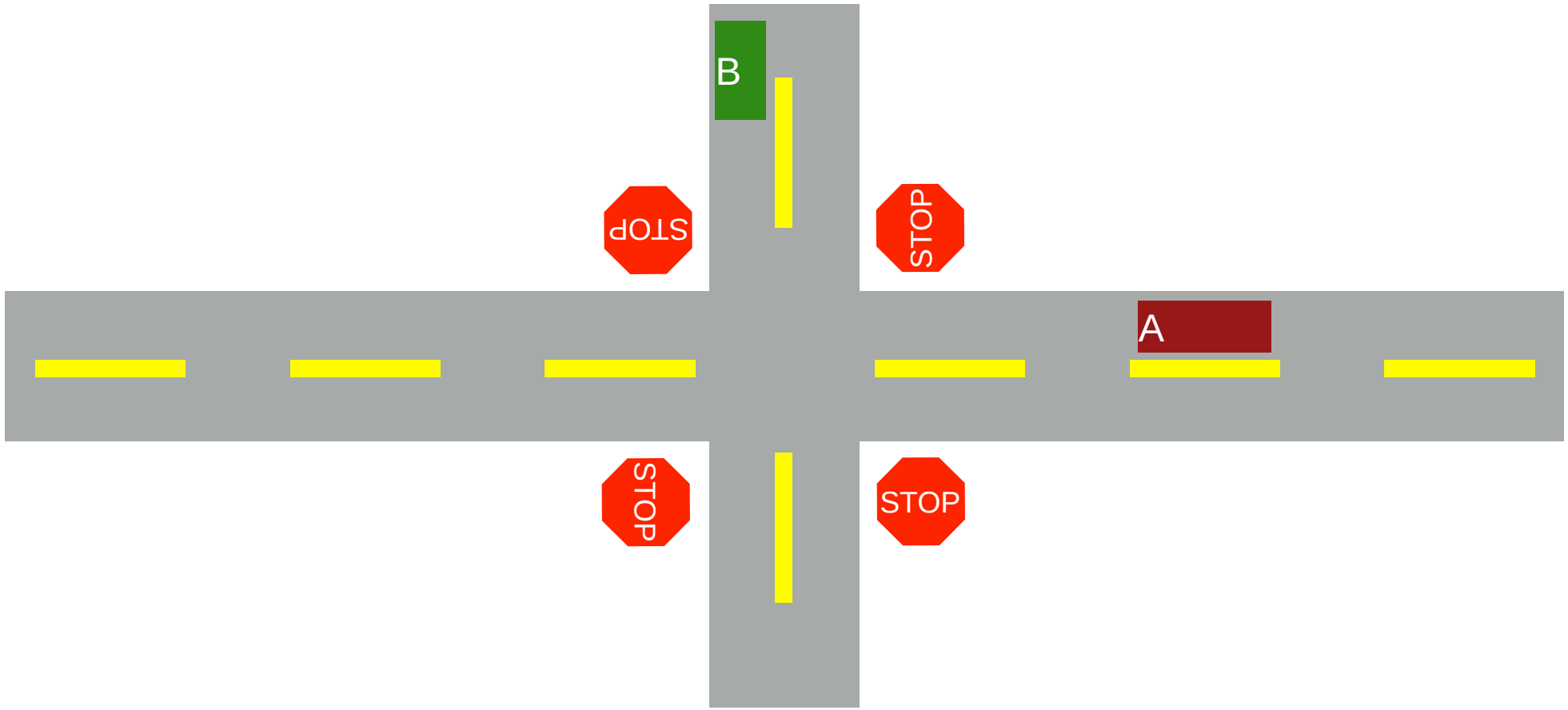
Waits condition..

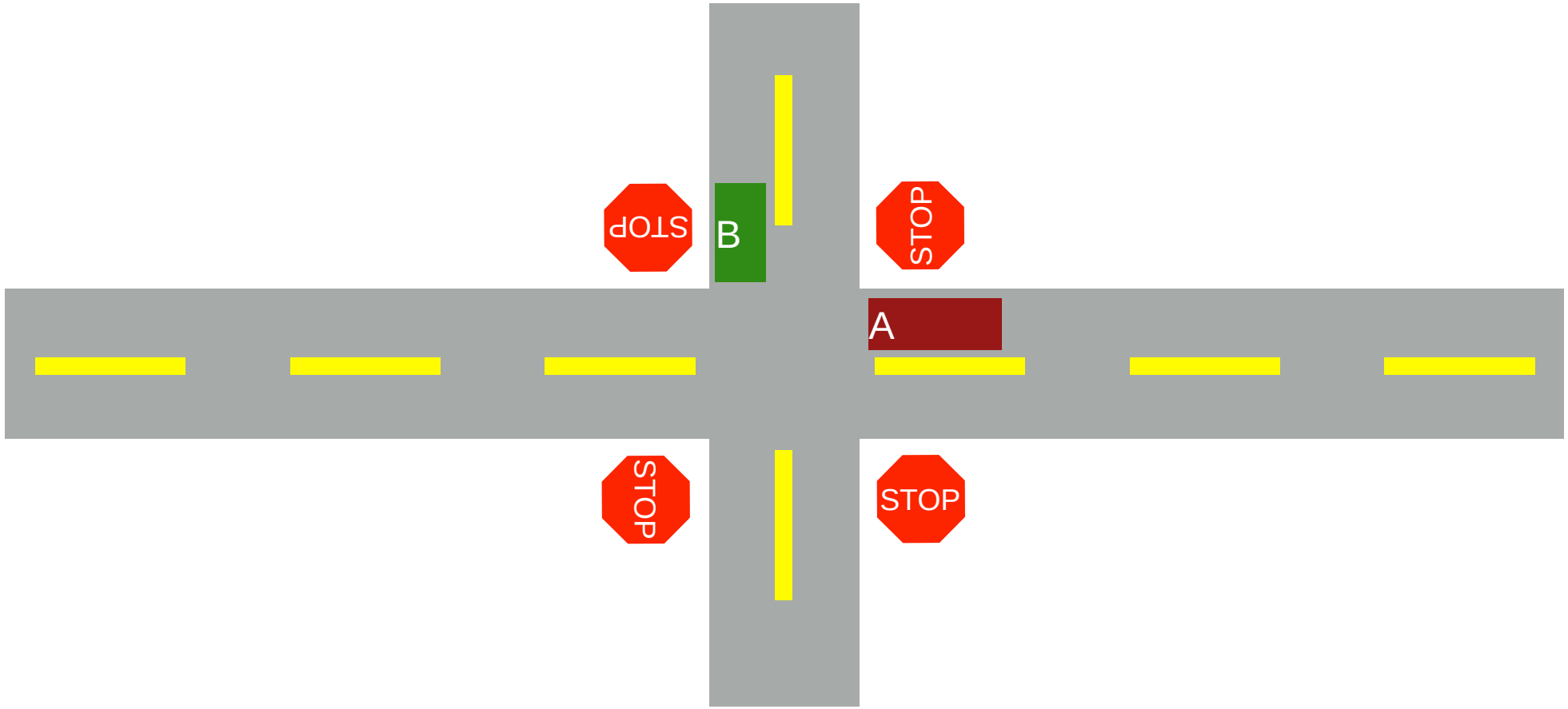
# Deadlock

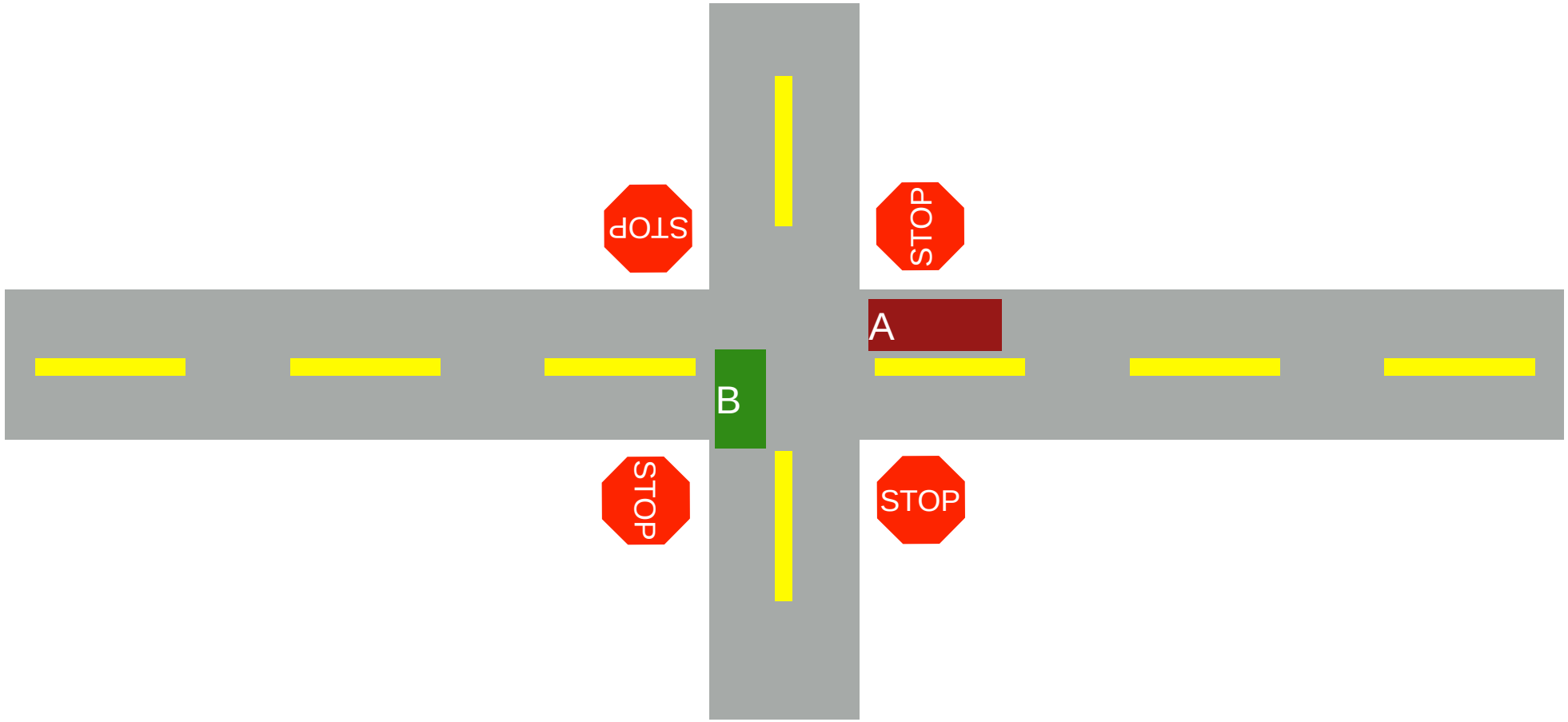
- Two or more threads are waiting for the other to take some actions thus neither makes any progress

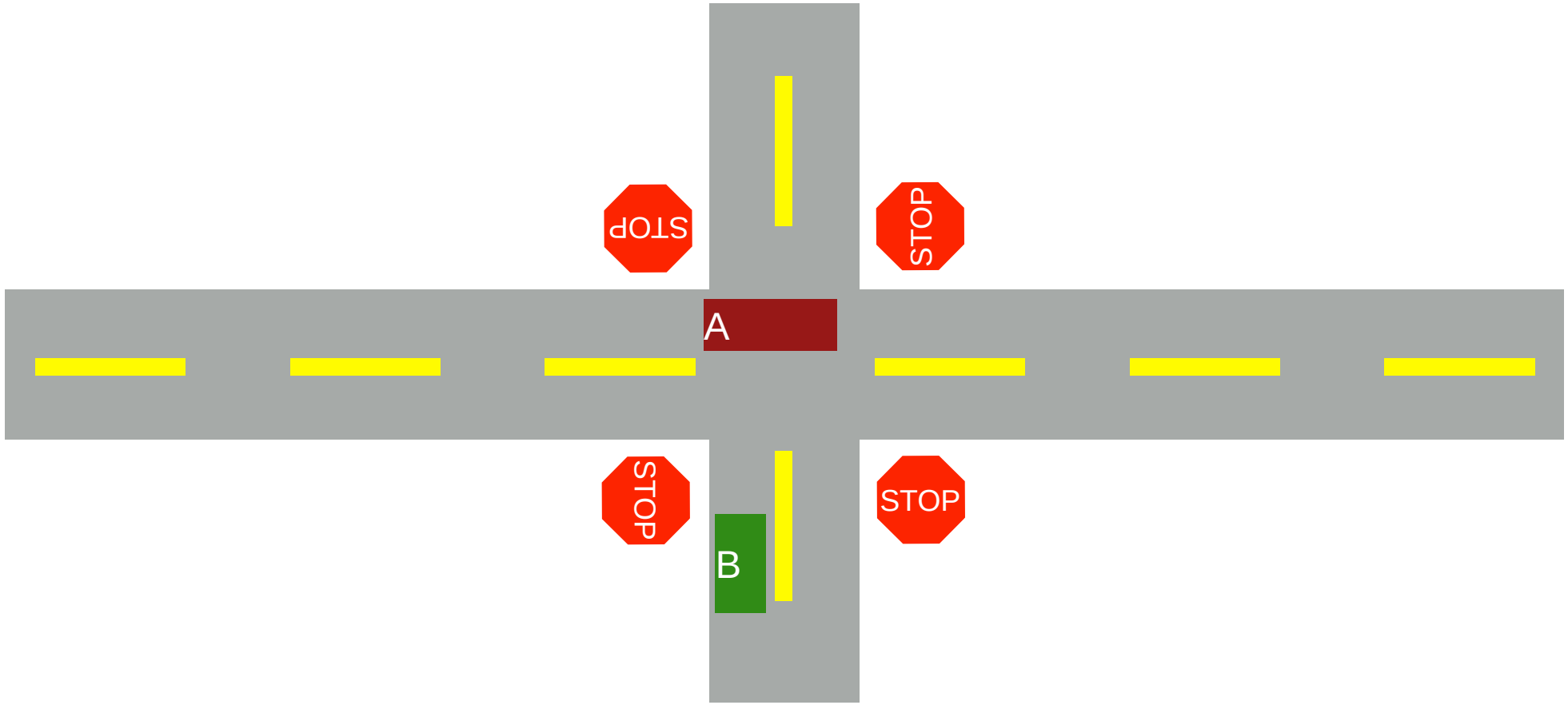


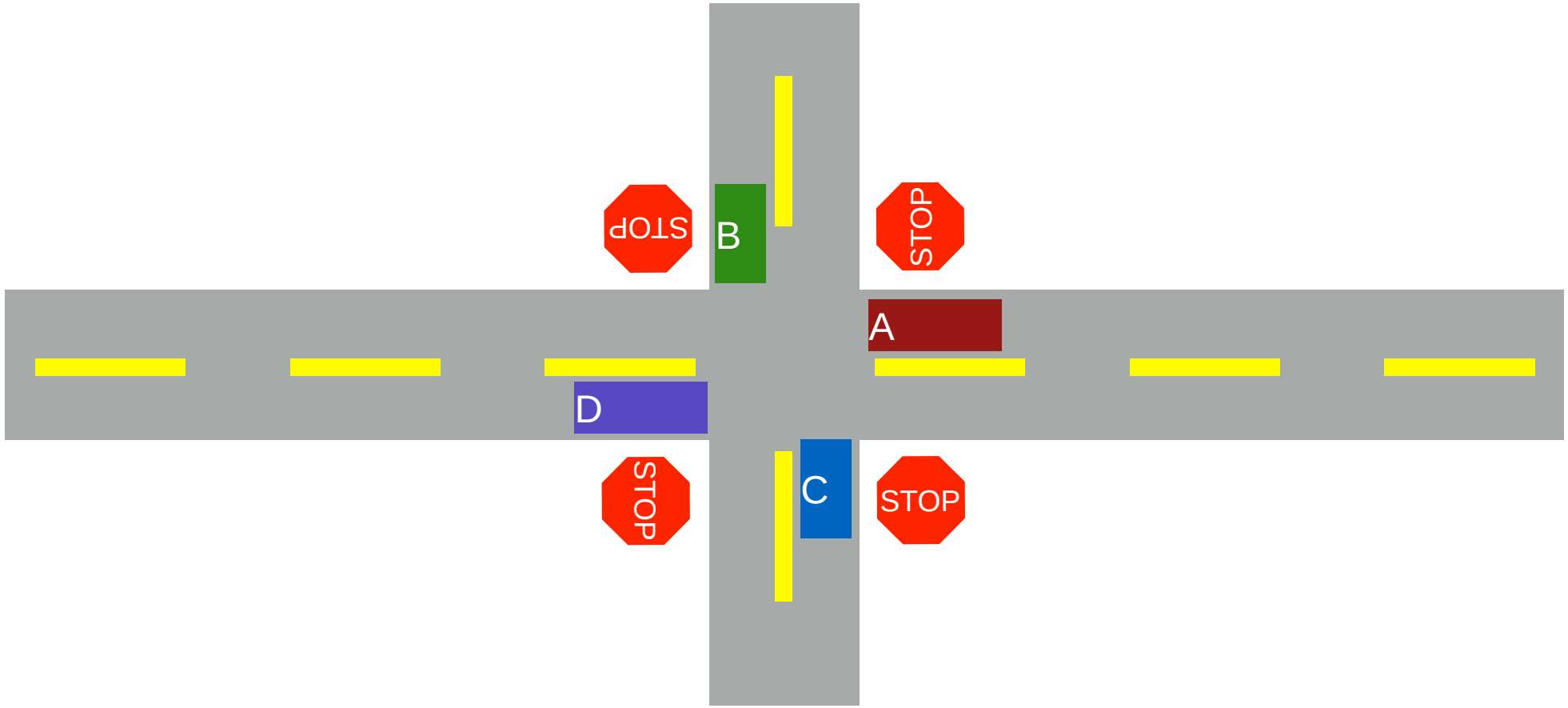

```
Thread 1:                    Thread 2:
pthread_mutex_lock(L1);      pthread_mutex_lock(L2);
pthread_mutex_lock(L2);      pthread_mutex_lock(L1);
```

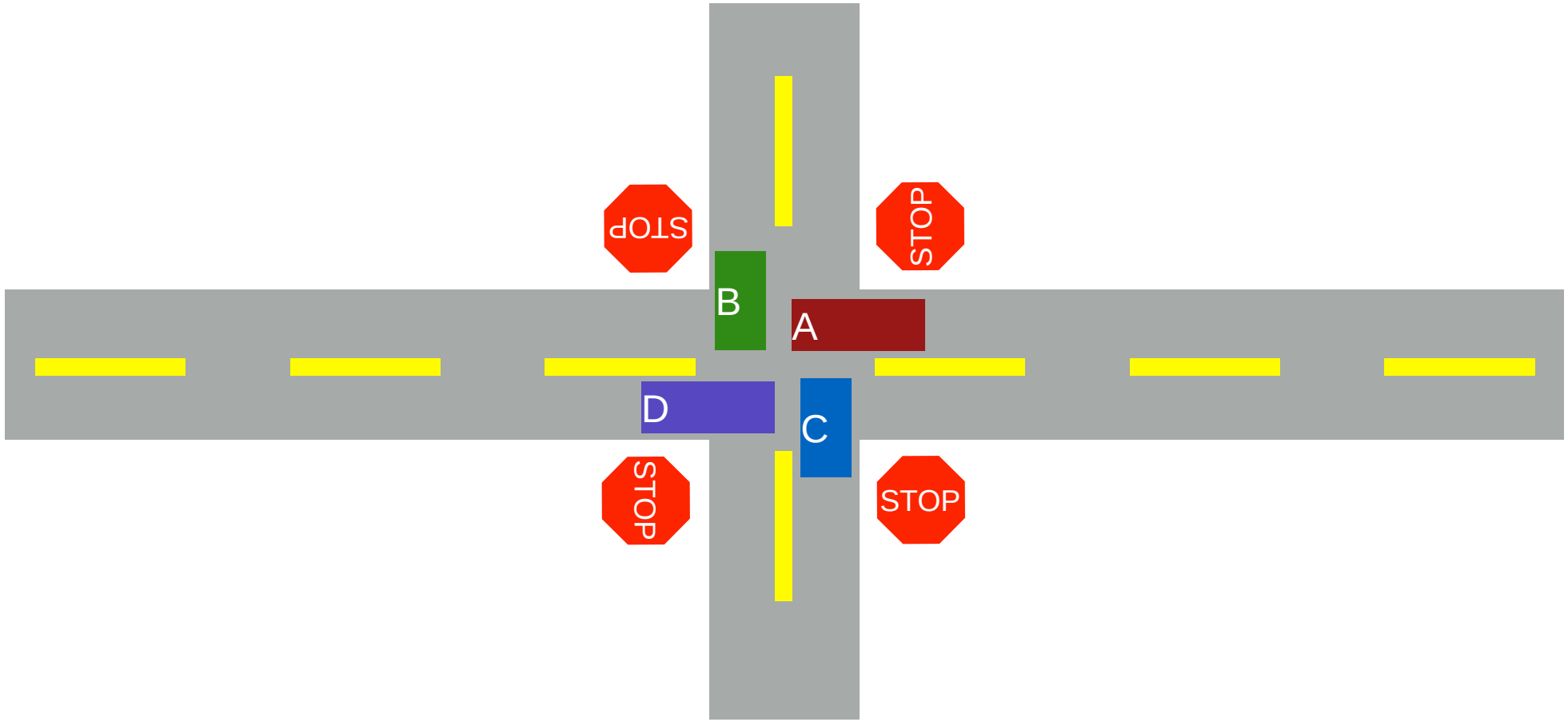

B
STOP
STOP
A
STOP
STOP


STOP
B
STOP
A
STOP
STOP

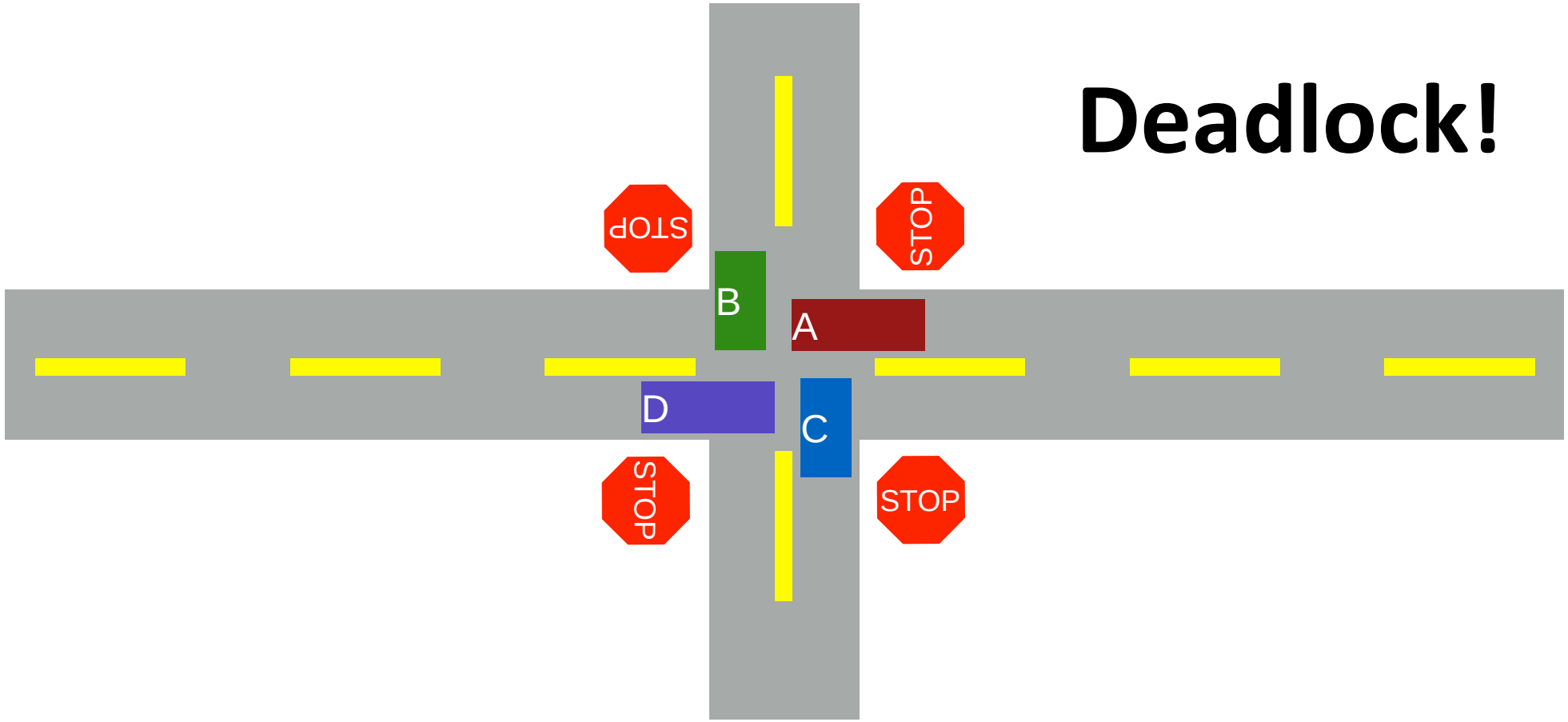

STOP
STOP
A
B
STOP
STOP


STOP
STOP
A
STOP
STOP
B


STOP
B
STOP
A
D
STOP
C
STOP

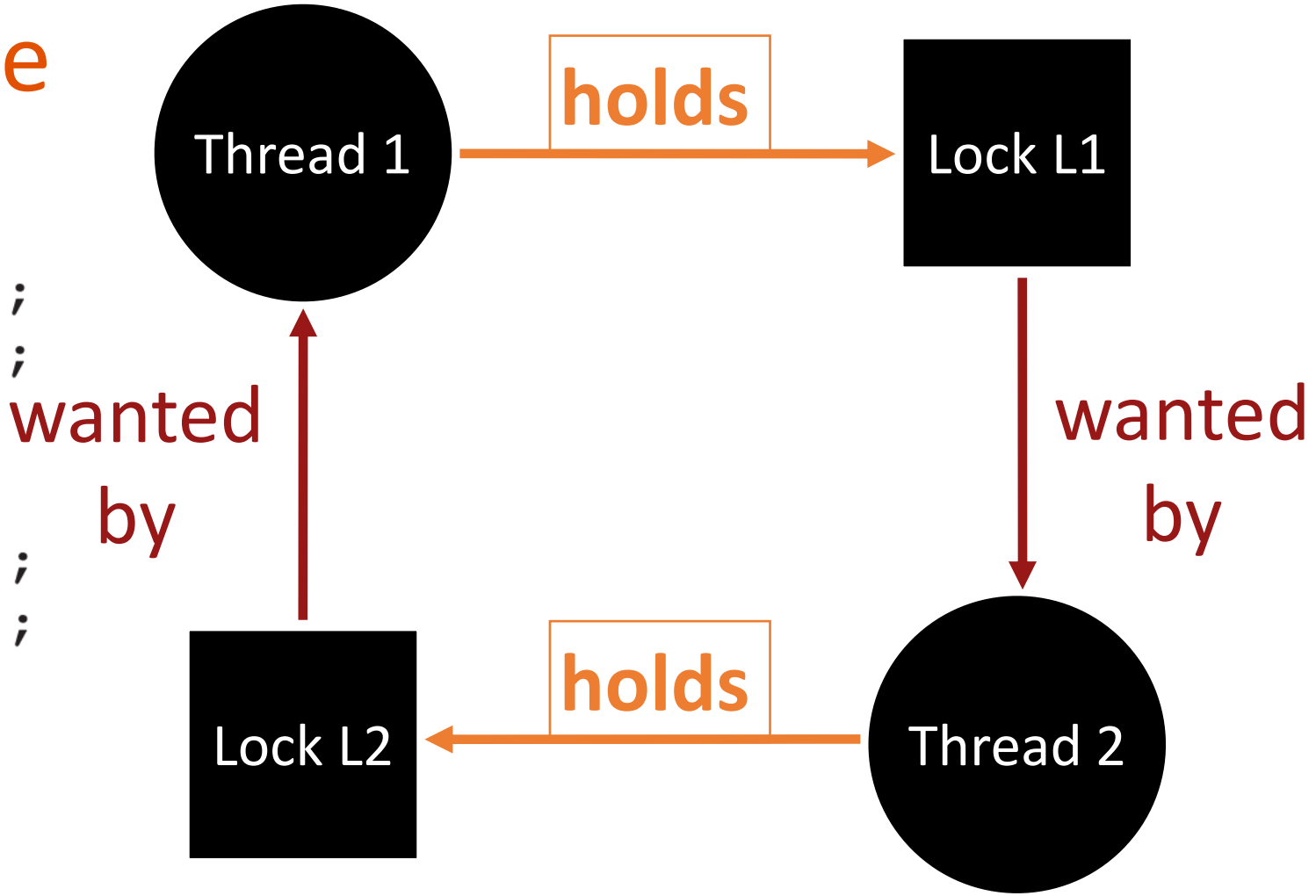

STOP
STOP
B
A
D
C
STOP
STOP

# Deadlock!



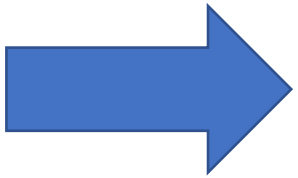
# Deadlock: Example

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```



# How Can We Resolve Circular Dependency

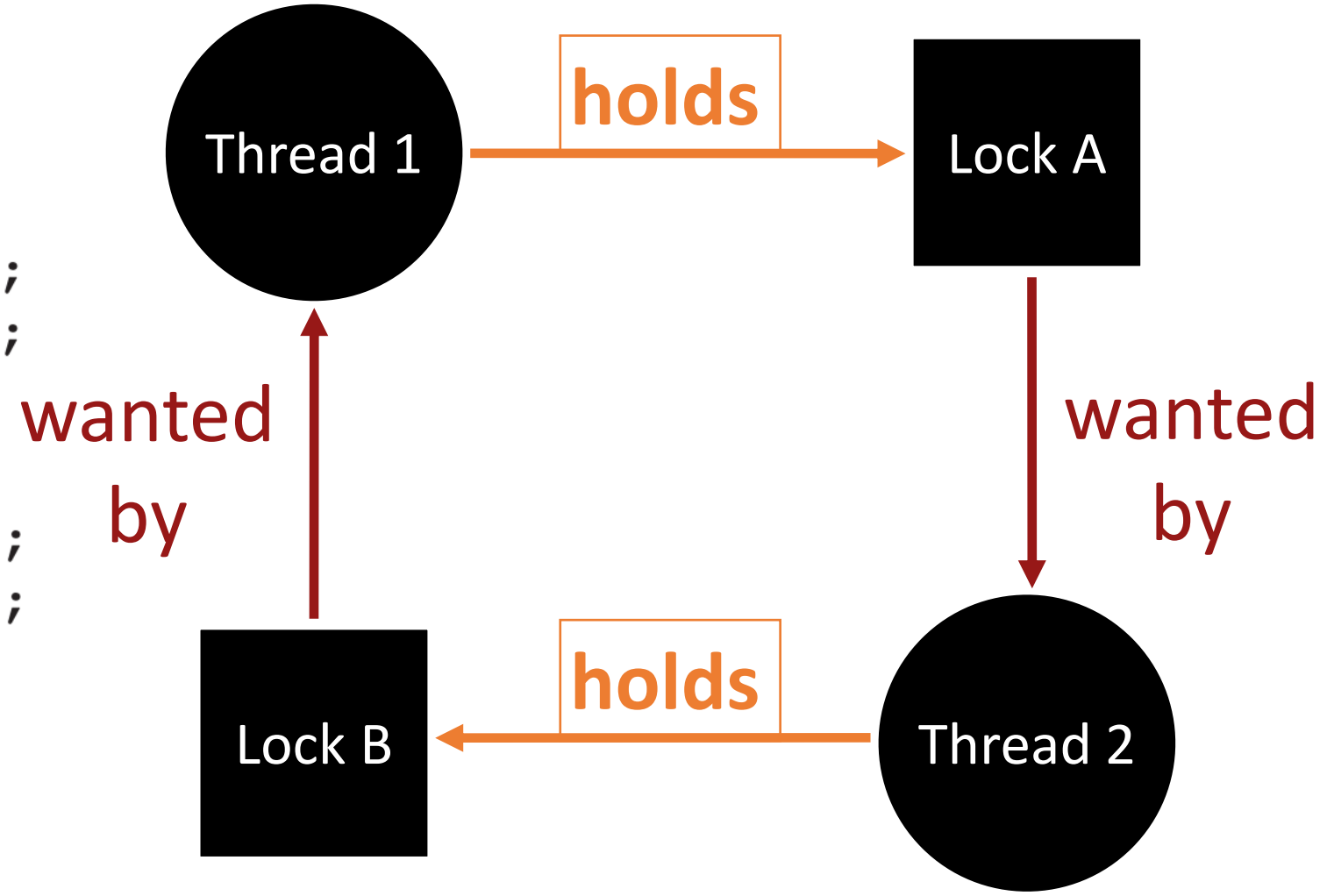
```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```



```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
```

# Circular Dependency

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```



# Non-Circular Dependency

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
```

```
Thread 2:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
```