[537] Concurrency Bugs

Chapter 32

Tyler Harter

10/22/14

Review Semaphores

CV's vs. Semaphores

CV rules of thumb:
- Keep state in addition to CV's
- Always do wait/signal with lock held
- Whenever you acquire a lock, recheck state

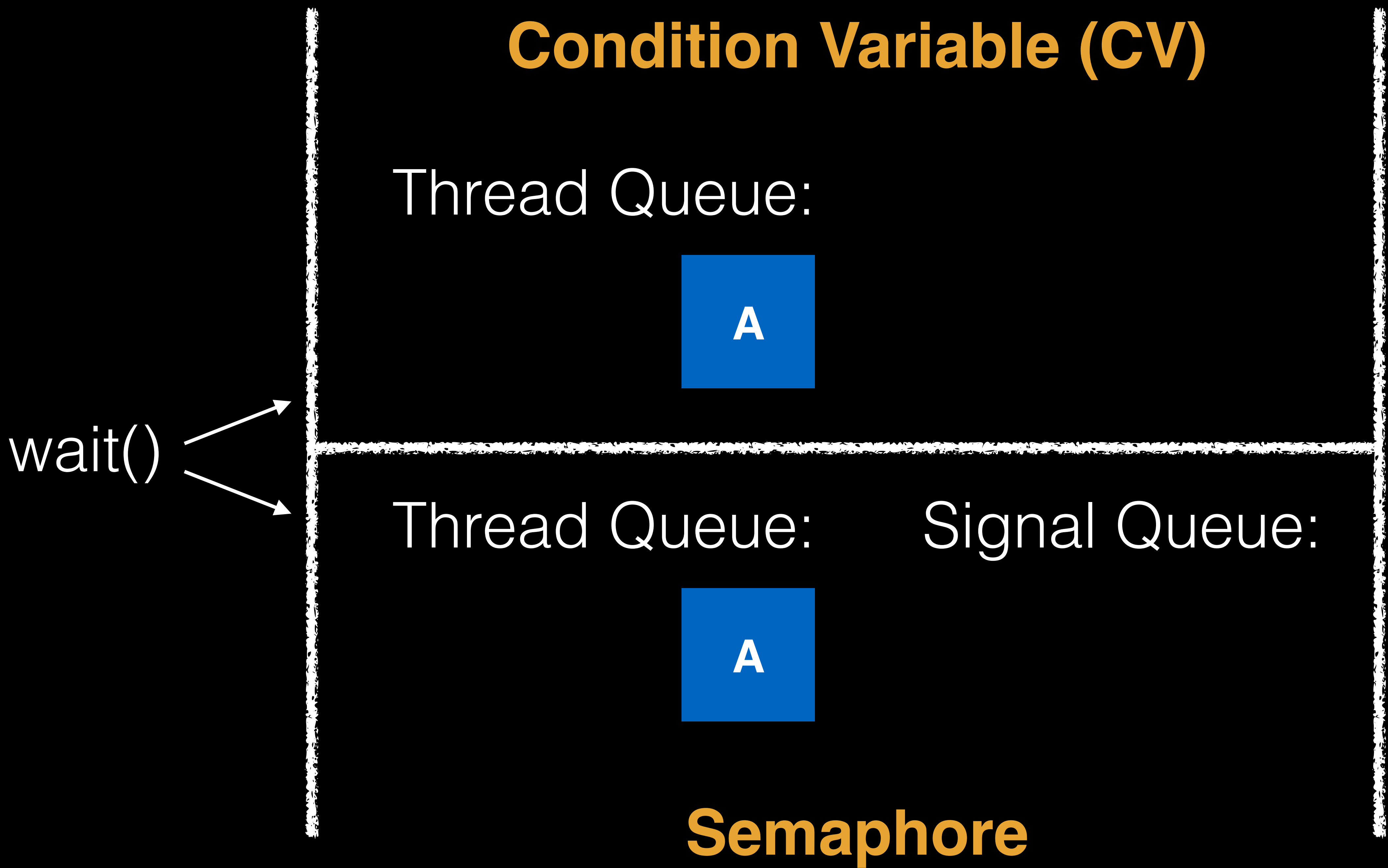
How do semaphores eliminate these needs?

Condition Variable (CV)

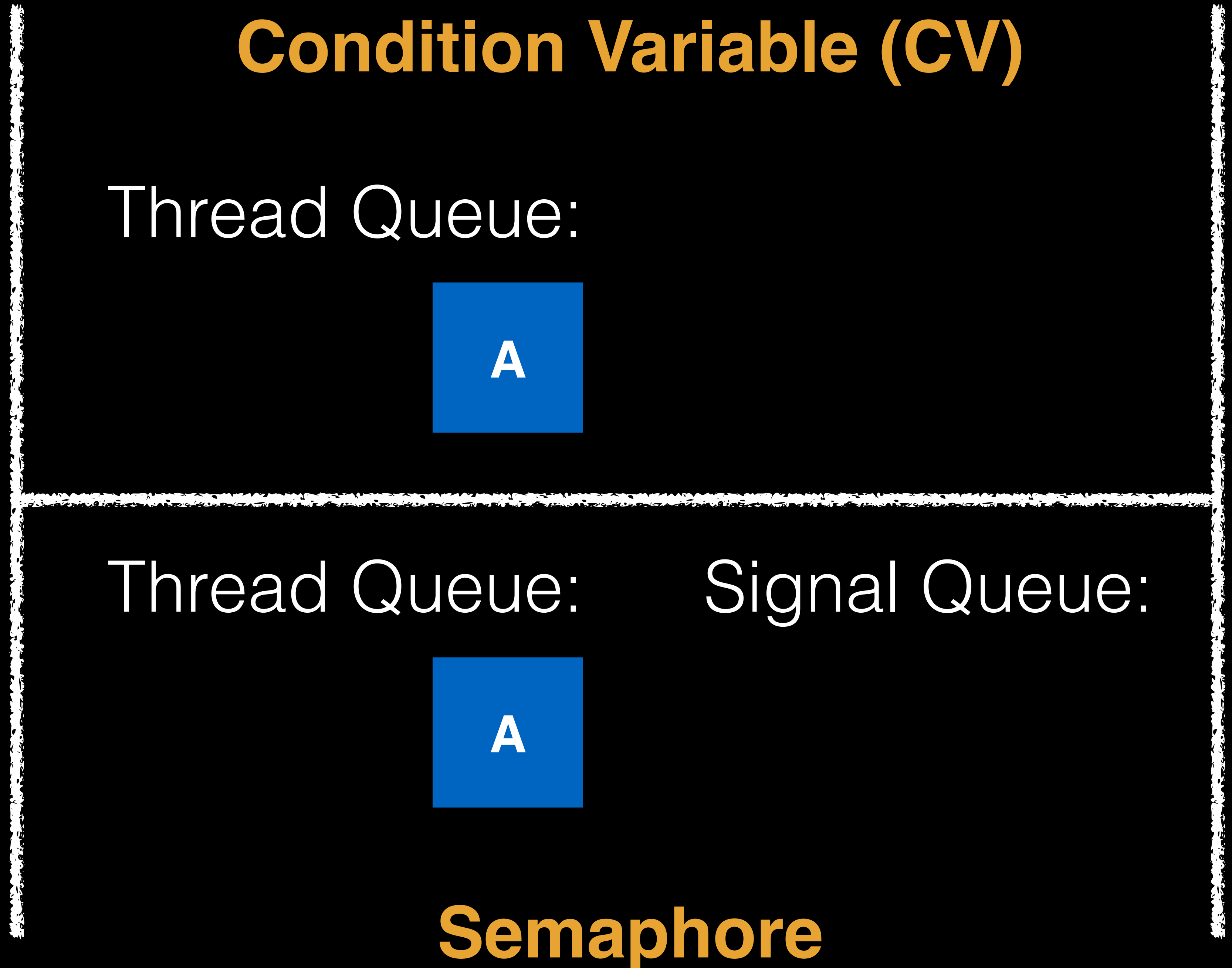
Thread Queue:

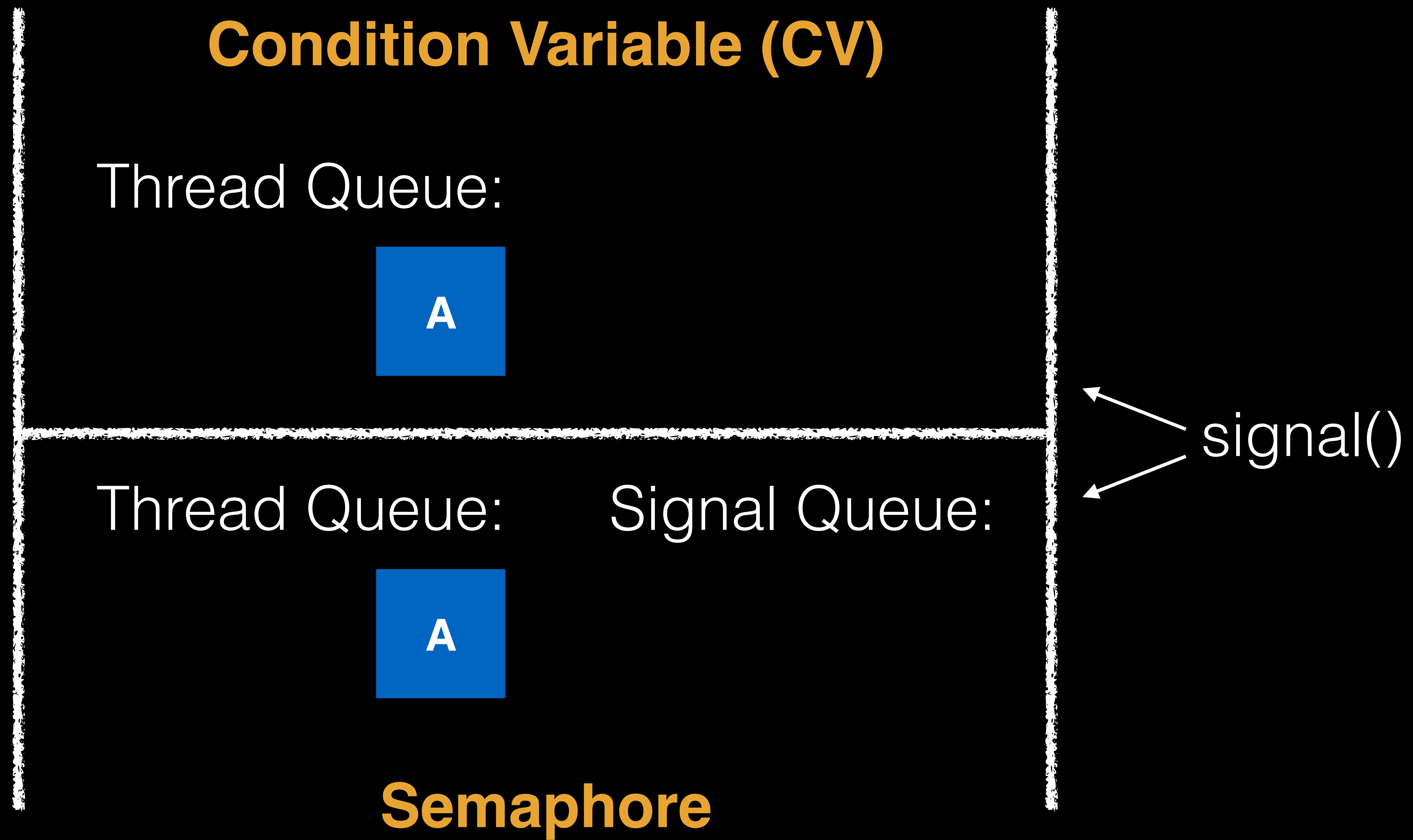
Thread Queue: Signal Queue:

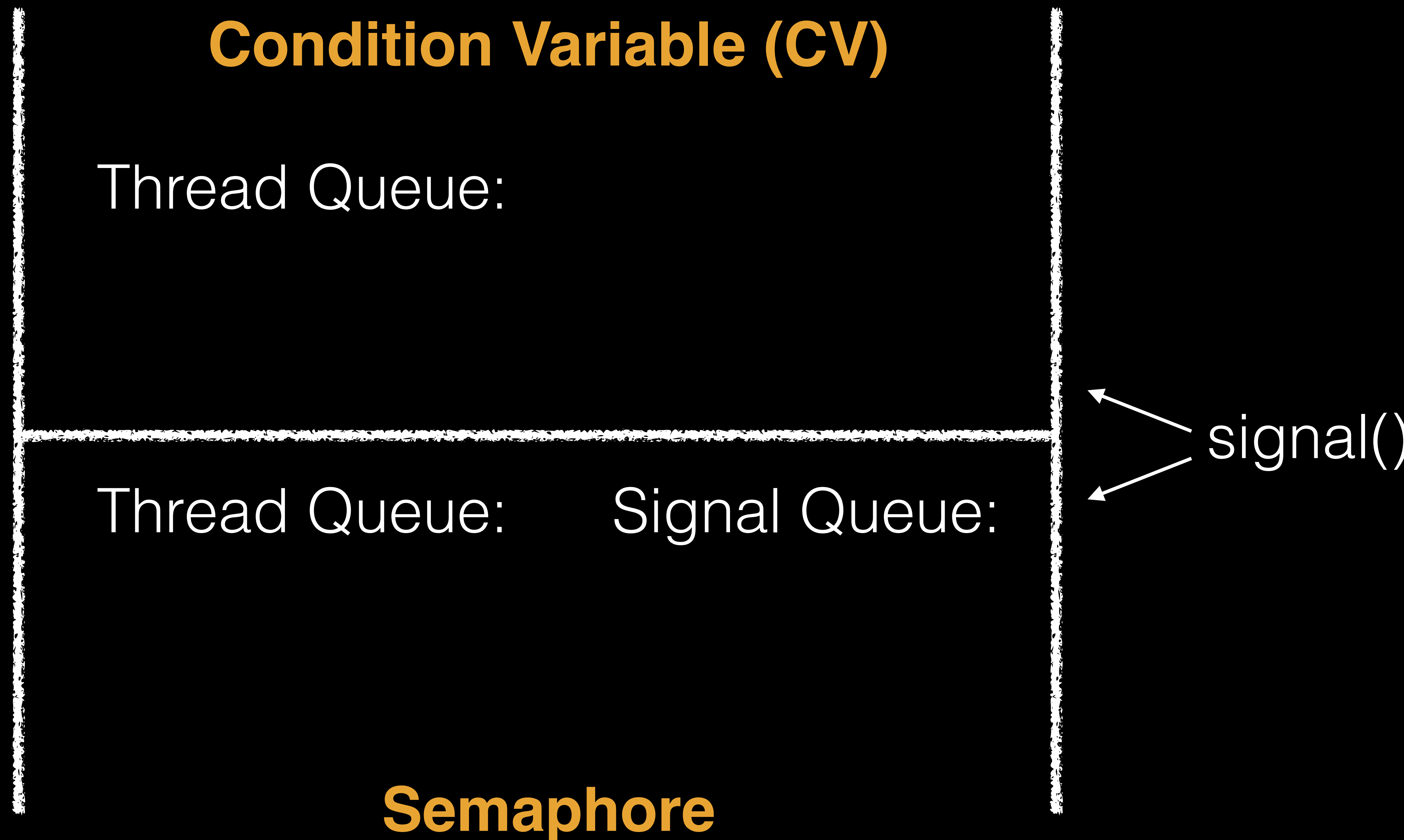
Semaphore



Condition Variable (CV)
Thread Queue:
A
wait()
Thread Queue:
Signal Queue:
A
Semaphore


Condition Variable (CV)
Thread Queue:
A
Thread Queue:
Signal Queue:
A
Semaphore


Condition Variable (CV)
Thread Queue:
A
signal()
Thread Queue:
Signal Queue:
A
Semaphore


Condition Variable (CV)
Thread Queue:
signal()
Thread Queue:
Signal Queue:
Semaphore

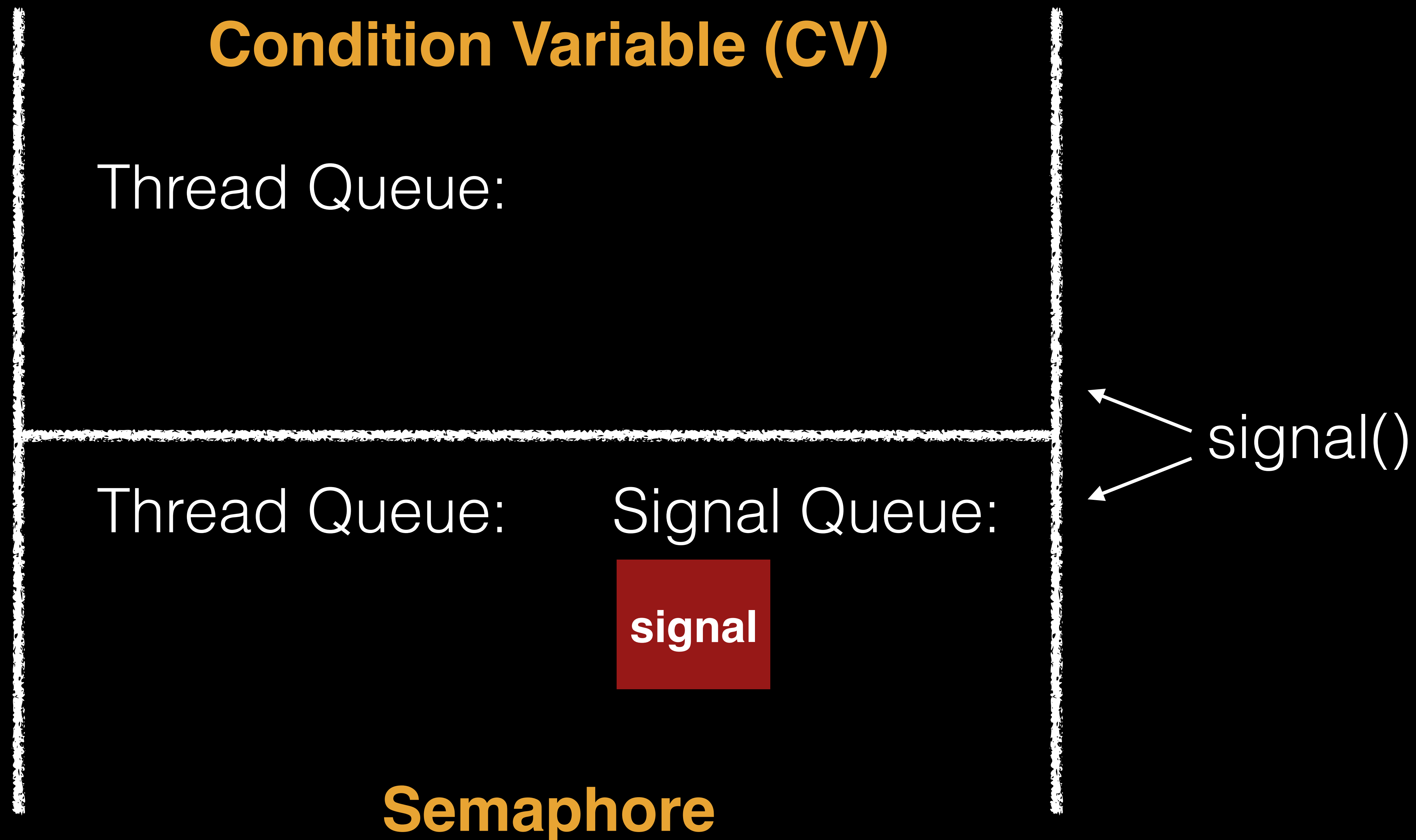
Condition Variable (CV)

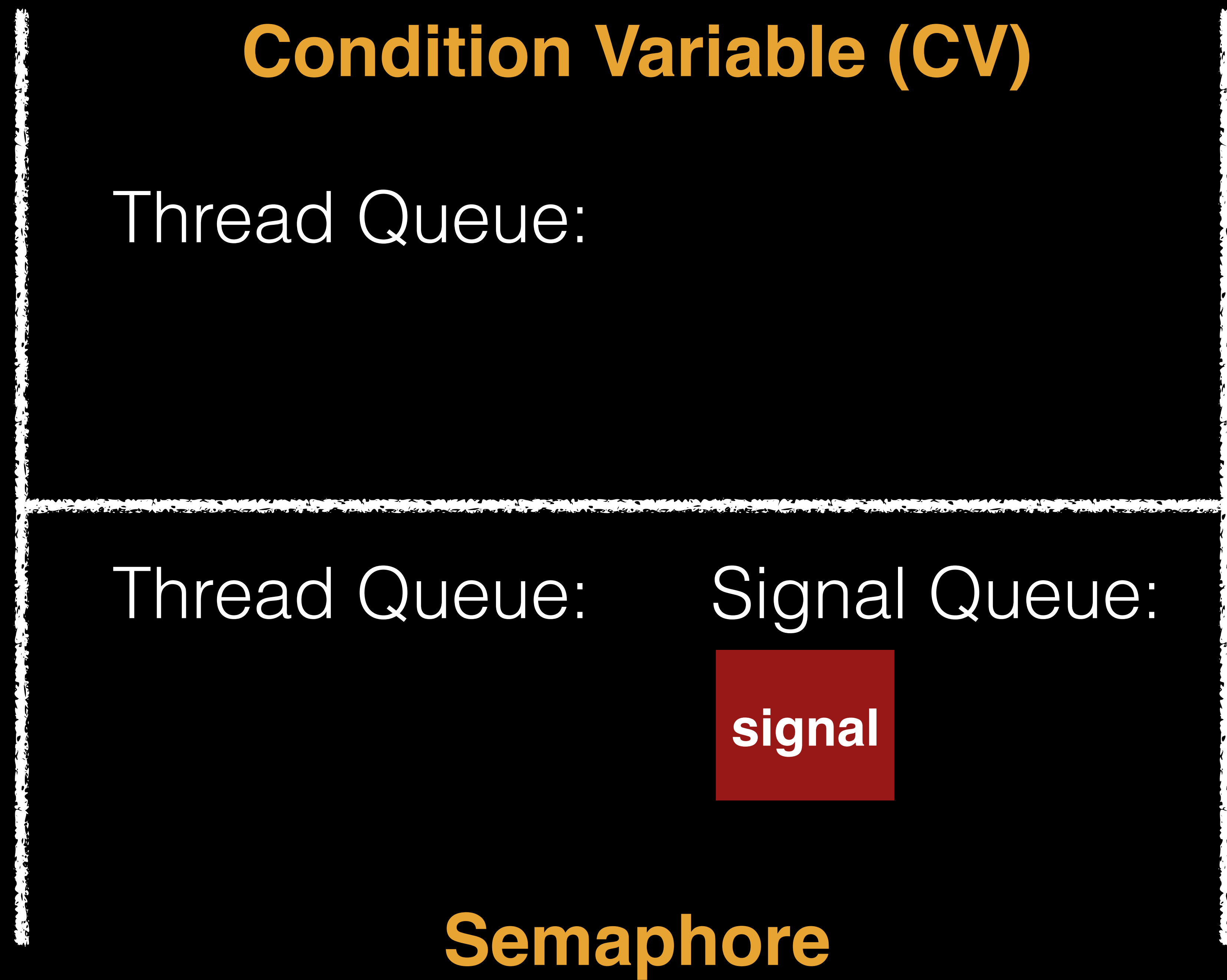
Thread Queue:

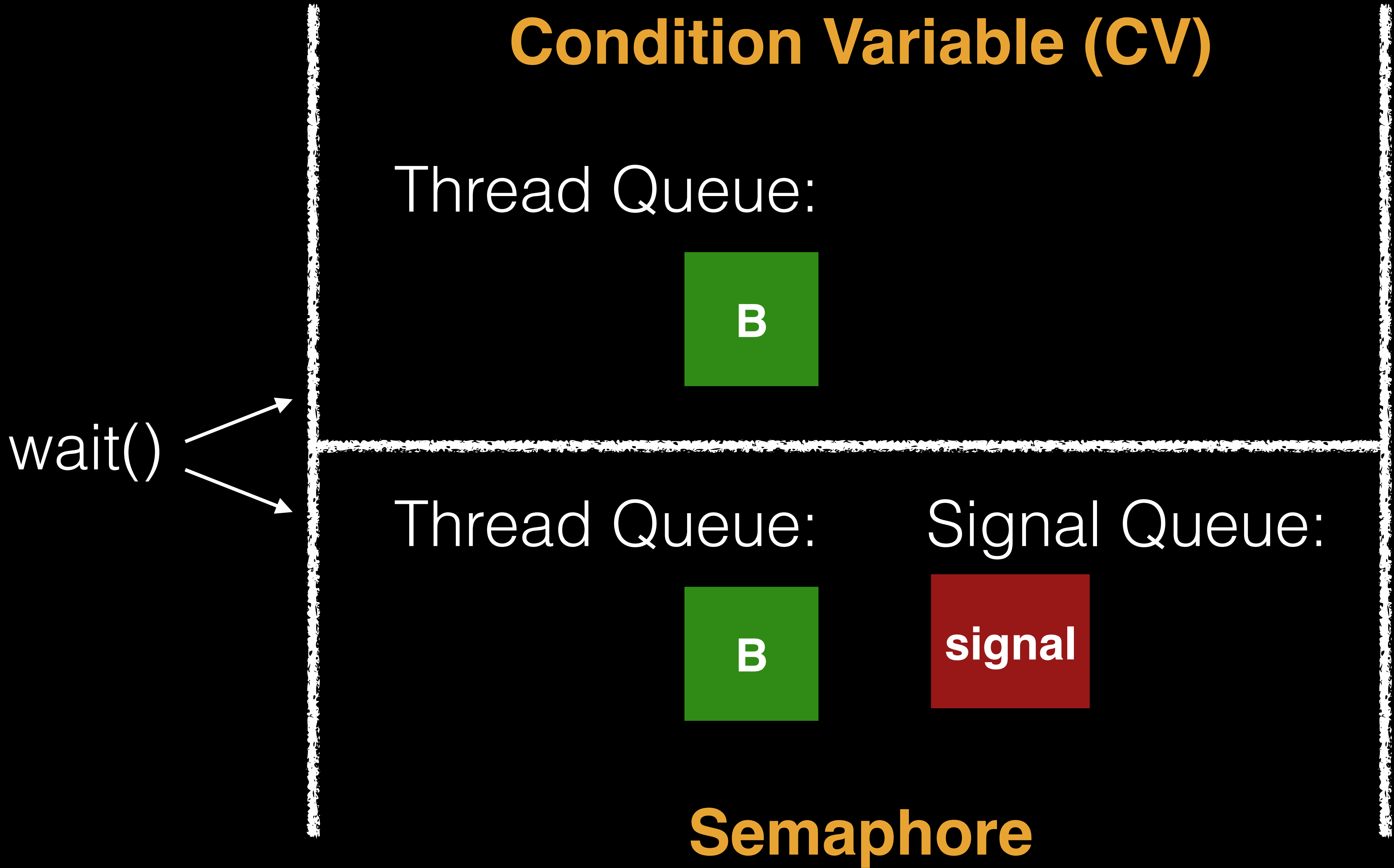
Thread Queue:

Signal Queue:

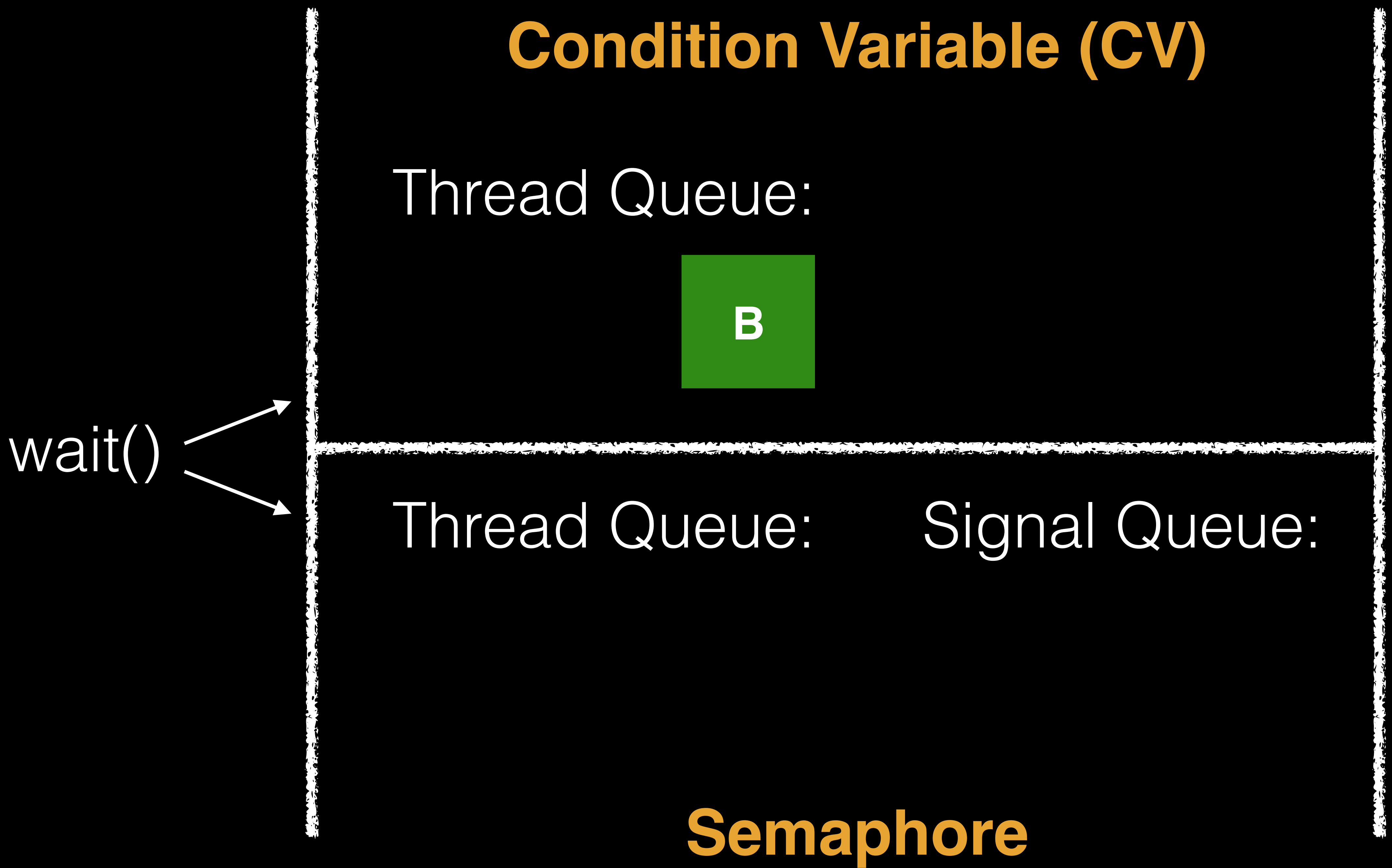
Semaphore

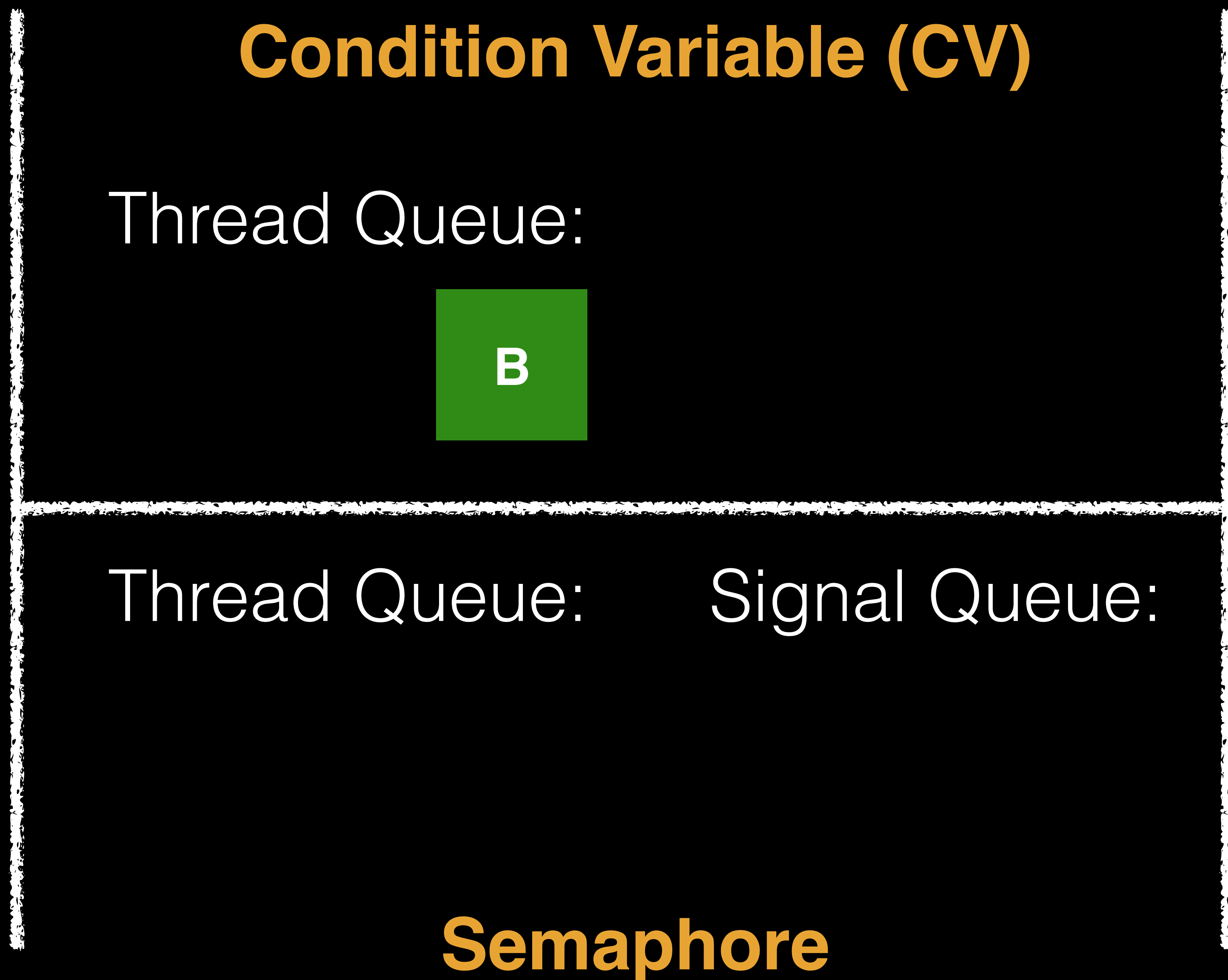

Condition Variable (CV)
Thread Queue:
signal()
Thread Queue:
Signal Queue:
signal
Semaphore

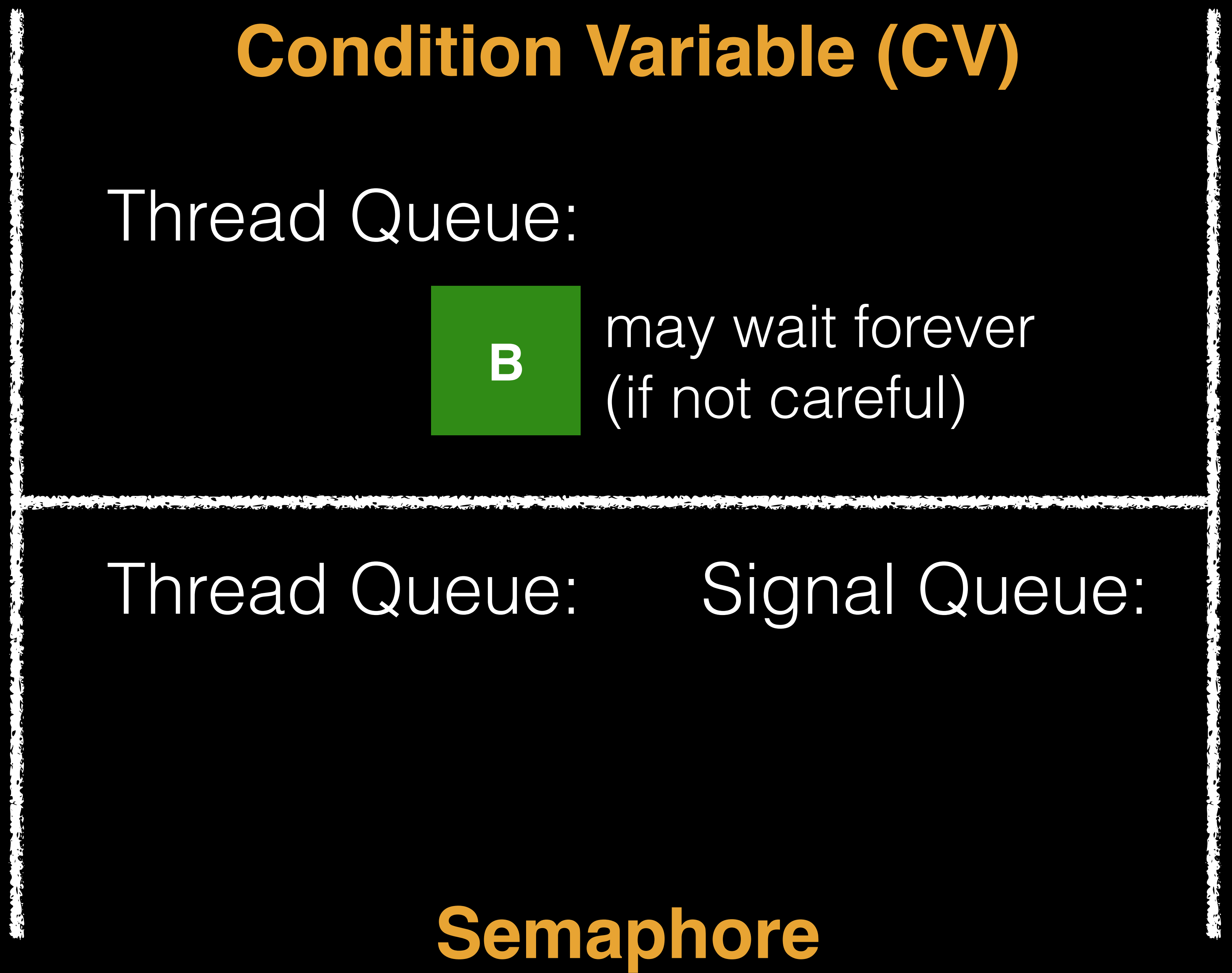

Condition Variable (CV)
Thread Queue:
Thread Queue:
Signal Queue:
signal
Semaphore

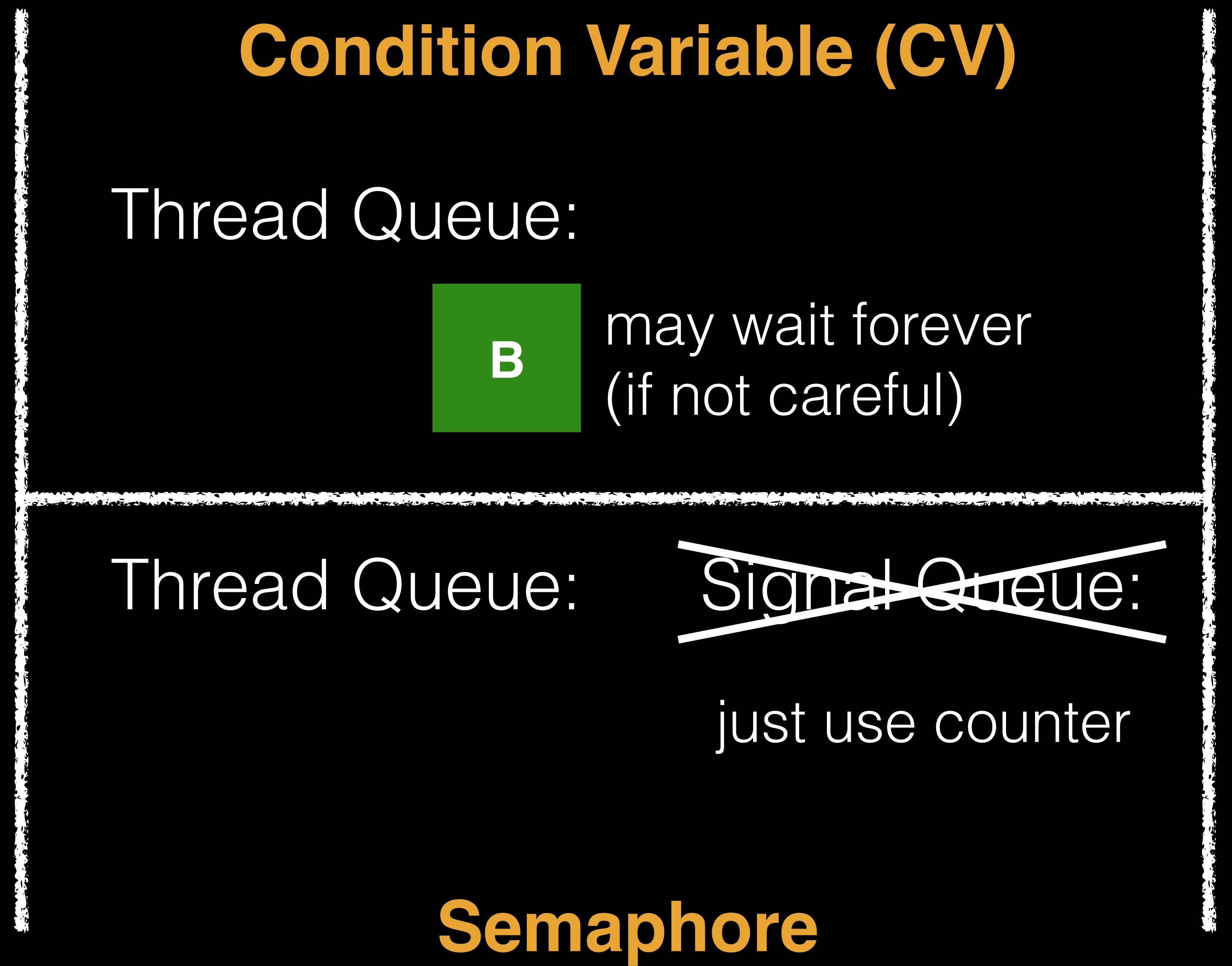


Condition Variable (CV)
Thread Queue:
B
wait()
Thread Queue:
Signal Queue:
B
signal
Semaphore


Condition Variable (CV)
Thread Queue:
B
wait()
Thread Queue:
Signal Queue:
Semaphore


Condition Variable (CV)
Thread Queue:
B
Thread Queue:
Signal Queue:
Semaphore


Condition Variable (CV)
Thread Queue:
B
may wait forever
(if not careful)
Thread Queue:
Signal Queue:
Semaphore


Condition Variable (CV)
Thread Queue:
B
may wait forever
(if not careful)
Thread Queue:
~~Signal Queue:~~
just use counter
Semaphore

Join w/ CV

```
int done = 0;
mutex_t m = MUTEX_INIT;
cond_t c = COND_INIT;
void *child(void *arg) {
    printf("child\n");
    Mutex_lock(&m);
    done = 1;
    cond_signal(&c);
    Mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    pthread_t c;
    printf("parent: begin\n");
    Pthread_create(c, NULL, child, NULL);
    Mutex_lock(&m);
    while(done == 0)
        Cond_wait(&c, &m);
    Mutex_unlock(&m);
    printf("parent: end\n");
}
```

Join w/ CV

```
int done = 0;
mutex_t m = MUTEX_INIT;
cond_t c = COND_INIT;
void *child(void *arg) {
    printf("child\n");
    Mutex_lock(&m);
    done = 1;
    cond_signal(&c);
    Mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    pthread_t c;
    printf("parent: begin\n");
    Pthread_create(c, NULL, child, NULL);
    Mutex_lock(&m);
    while(done == 0)
        Cond_wait(&c, &m);
    Mutex_unlock(&m);
    printf("parent: end\n");
}
```

extra state and mutex

locks around state/signal

while loop for checking state

Join w/ CV

```
int done = 0;
mutex_t m = MUTEX_INIT;
cond_t c = COND_INIT;
void *child(void *arg) {
    printf("child\n");
    Mutex_lock(&m);
    done = 1;
    cond_signal(&c);
    Mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    pthread_t c;
    printf("parent: begin\n");
    Pthread_create(c, NULL, child, NULL);
    Mutex_lock(&m);
    while(done == 0)
        Cond_wait(&c, &m);
    Mutex_unlock(&m);
    printf("parent: end\n");
}
```

Join w/ Semaphore

```
sem_t s;
void *child(void *arg) {
    printf("child\n");
    sem_post(&s);
}

int main(int argc, char *argv[]) {
    sem_init(&s, 0);
    pthread_t c;
    printf("parent: begin\n");
    Pthread_create(c, NULL, child, NULL);
    sem_wait(&s);
    printf("parent: end\n");
}
```

Semaphore Uses

For the following init's, what might the use be?

(a) sem_init(&s, **0**);

(b) sem_init(&s, **1**);

(c) sem_init(&s, **N**);

Producer/Consumer

How many semaphores do we need?

Producer/Consumer

How many semaphores do we need?

```
Sem_init(&empty, max); // max are empty
Sem_init(&full, 0);    // 0 are full
Sem_init(&mutex, 1);   // mutex
```

Producer/Consumer

```
void *producer(void *arg) {
  for (int i = 0; i < loops; i++) {
    Sem_wait(&empty);
    Sem_wait(&mutex);
    do_fill(i);
    Sem_post(&mutex);
    Sem_post(&full);
  }
}
```

```
void *consumer(void *arg) {
  while (1) {
    Sem_wait(&full);
    Sem_wait(&mutex);
    tmp = do_get();
    Sem_post(&mutex);
    Sem_post(&empty);
    printf("%d\n", tmp);
  }
}
```

Producer/Consumer

```c
void *producer(void *arg) {
  for (int i = 0; i < loops; i++) {
    Sem_wait(&empty);
    Sem_wait(&mutex);
    do_fill(i);
    Sem_post(&mutex);
    Sem_post(&full);
  }
}
```

```c
void *consumer(void *arg) {
  while (1) {
    Sem_wait(&full);
    Sem_wait(&mutex);
    tmp = do_get();
    Sem_post(&mutex);
    Sem_post(&empty);
    printf("%d\n", tmp);
  }
}
```

Mutual Exclusion

Producer/Consumer

```
void *producer(void *arg) {
  for (int i = 0; i < loops; i++) {
    Sem_wait(&empty);
    Sem_wait(&mutex);
    do_fill(i);
    Sem_post(&mutex);
    Sem_post(&full);
  }
}
```

```
void *consumer(void *arg) {
  while (1) {
    Sem_wait(&full);
    Sem_wait(&mutex);
    tmp = do_get();
    Sem_post(&mutex);
    Sem_post(&empty);
    printf("%d\n", tmp);
  }
}
```

Signaling

Concurrency Bugs

Concurrency in Medicine: Therac-25

"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**."

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

Concurrency in Medicine: Therac-25

“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 in Medicine: Therac-25

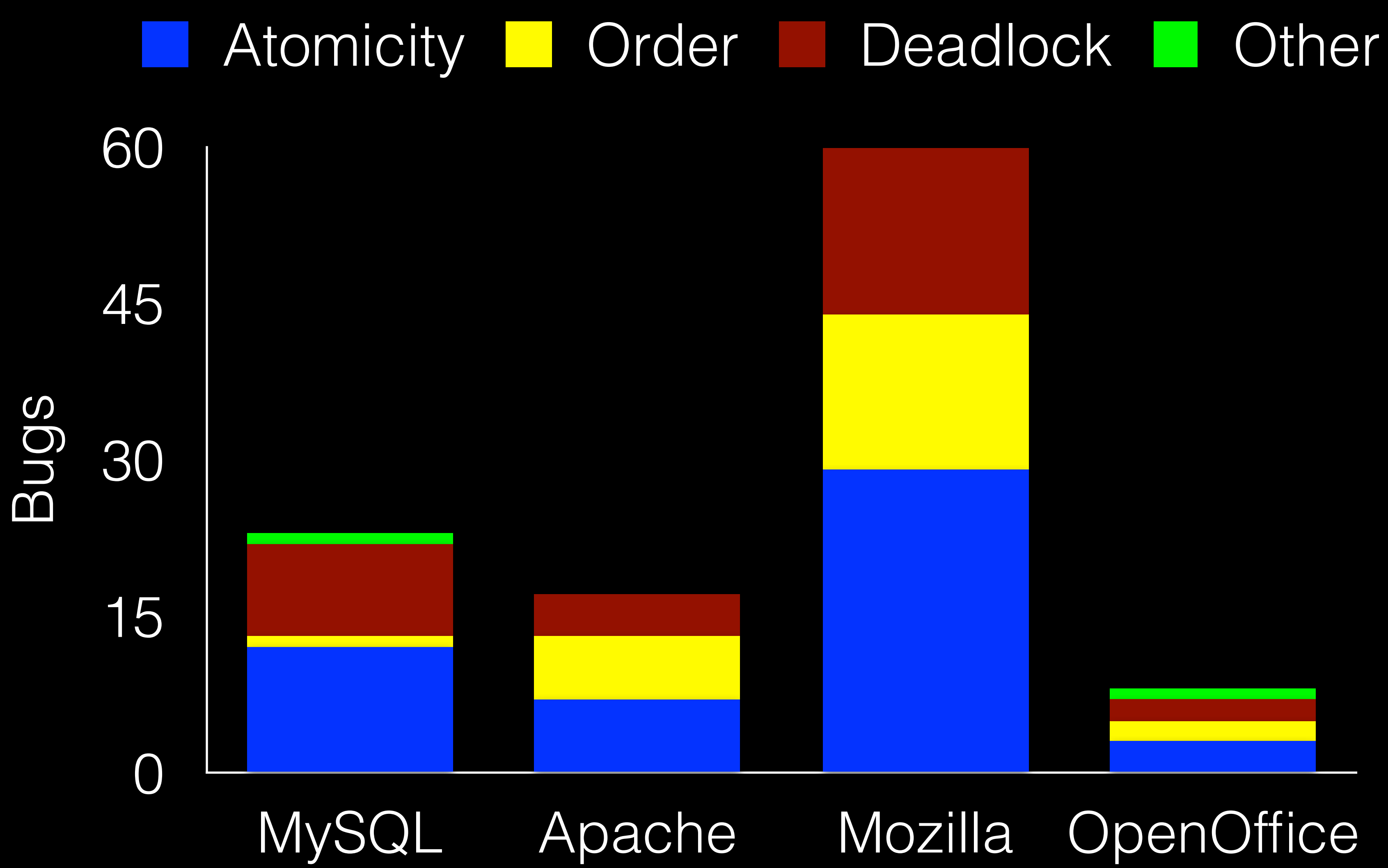
“The accidents occurred when the high-power electron beam was activated instead of the intended low power beam, and without the beam spreader plate rotated into place. Previous models had hardware interlocks in place to prevent this, but Therac-25 had removed them, depending instead on software interlocks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

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

Getting concurrency right can sometimes save lives!

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

Concurrency Bugs are Common and Various

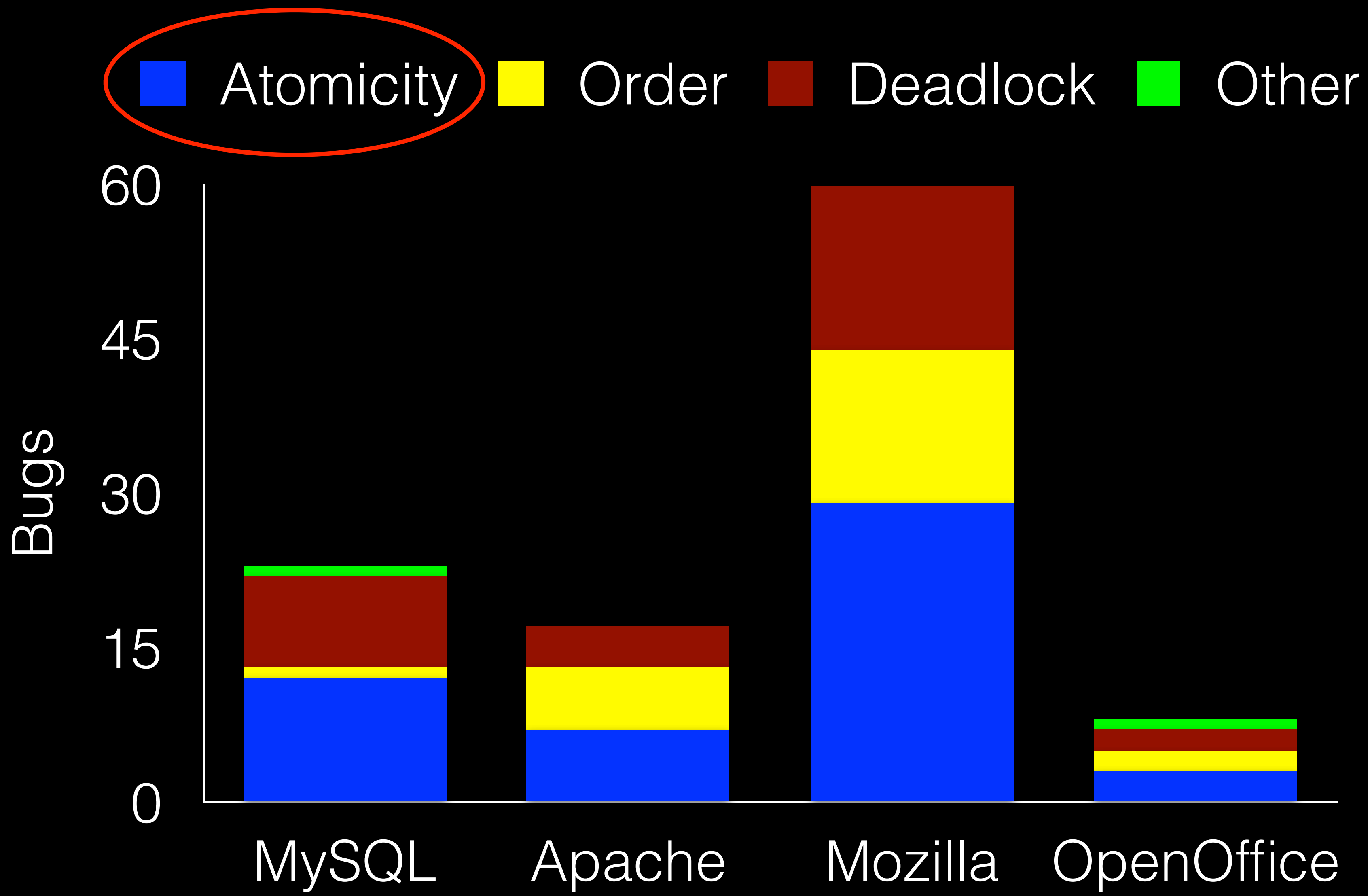


Lu *etal.* Study:

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

Concurrency Bugs are Common and Various



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?

Atomicity: MySQL

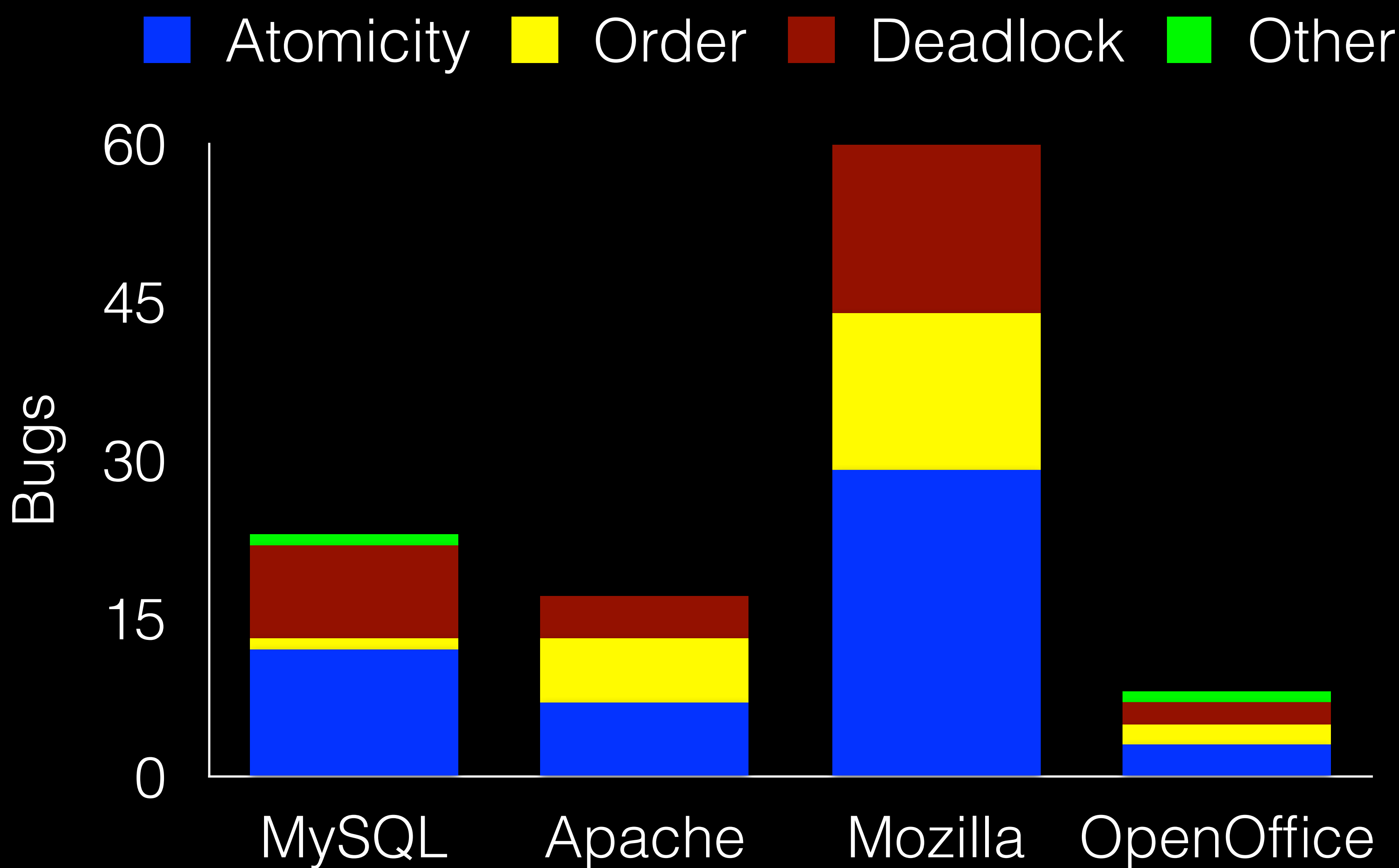
Thread 1:

```
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 Bugs are Common and Various

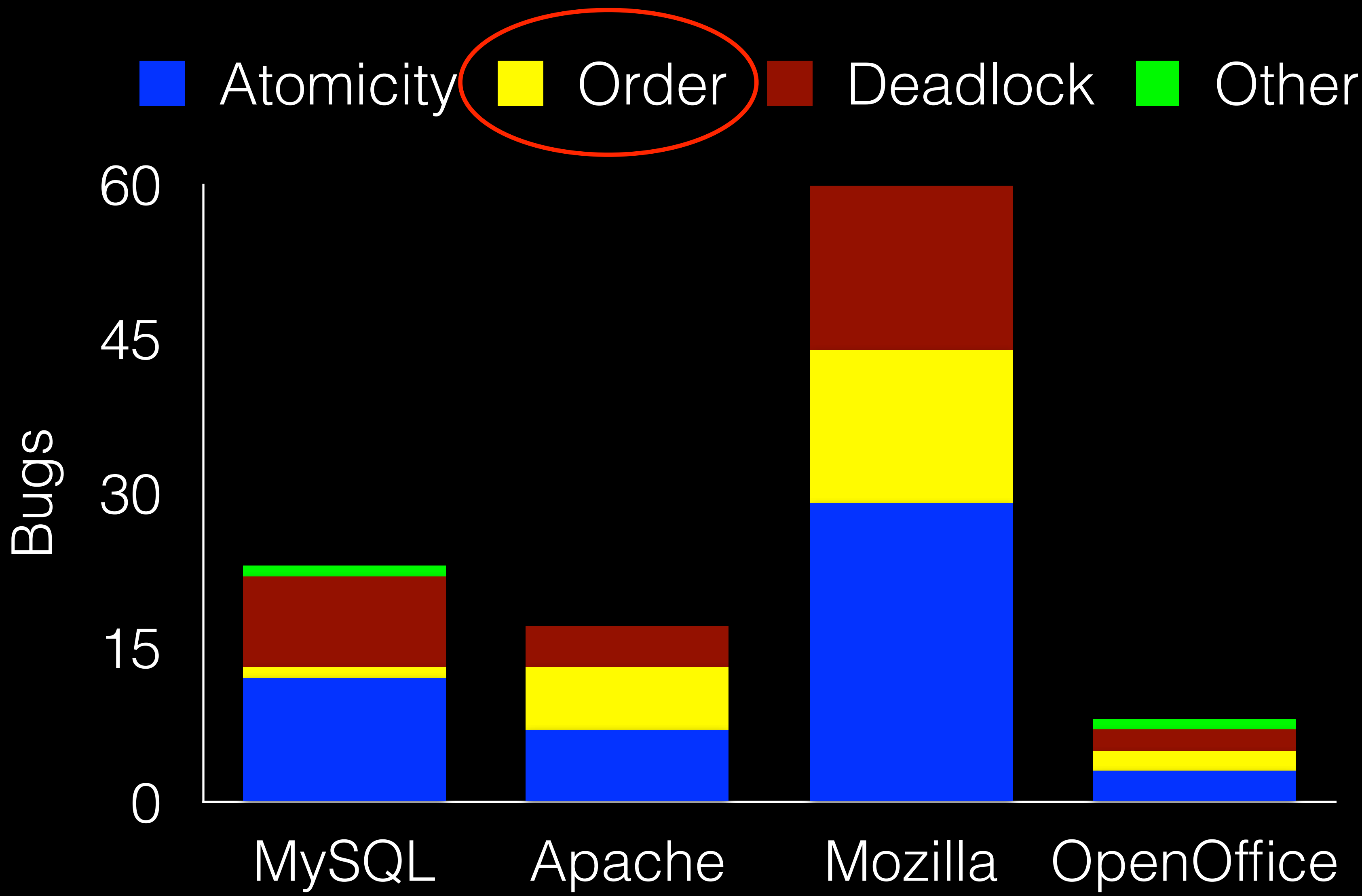


Lu *etal.* Study:

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

Concurrency Bugs are Common and Various



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

Ordering: Mozilla

Thread 1:

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

Thread 2:

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

Ordering: Mozilla

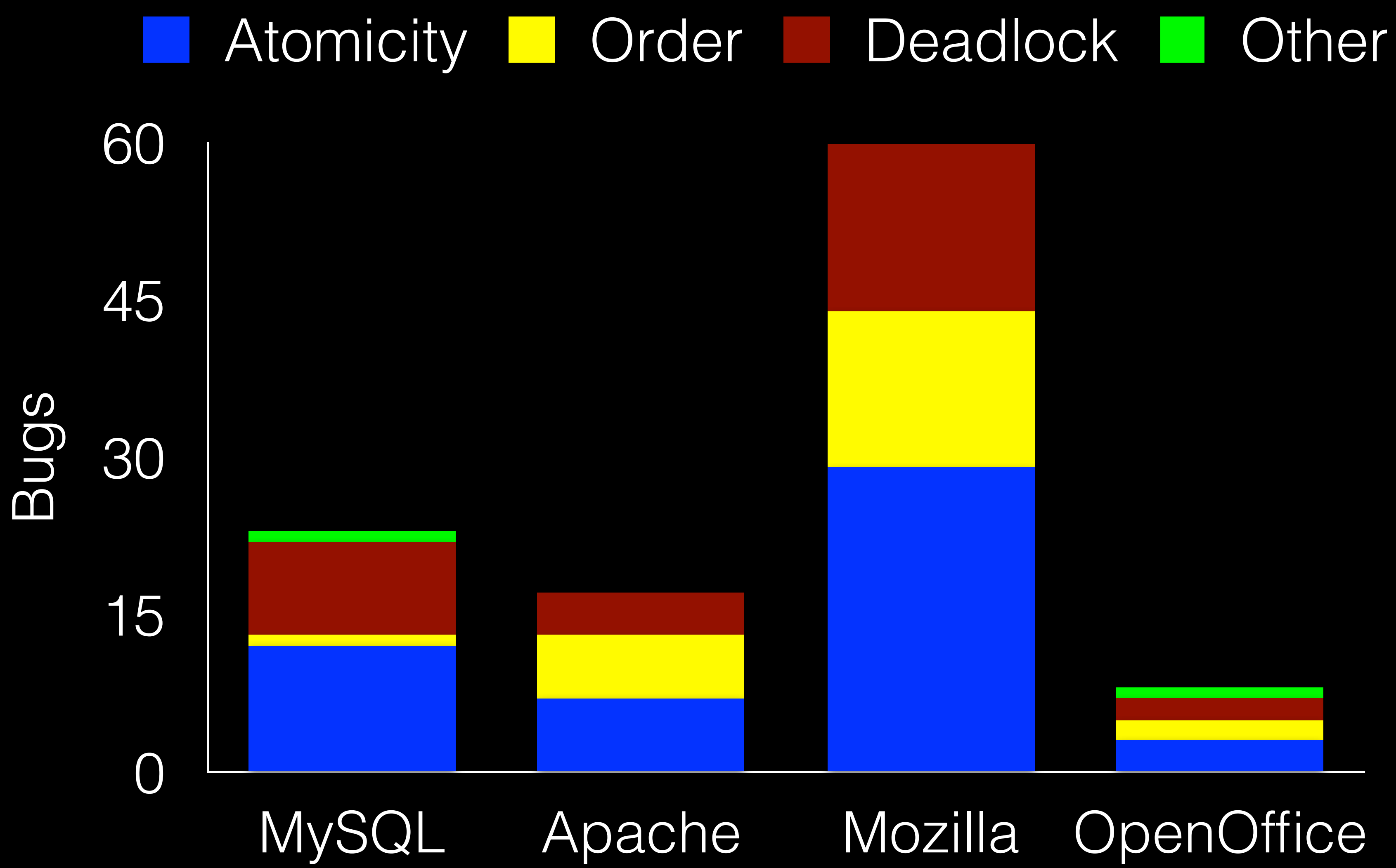
Thread 1:

```
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 Bugs are Common and Various

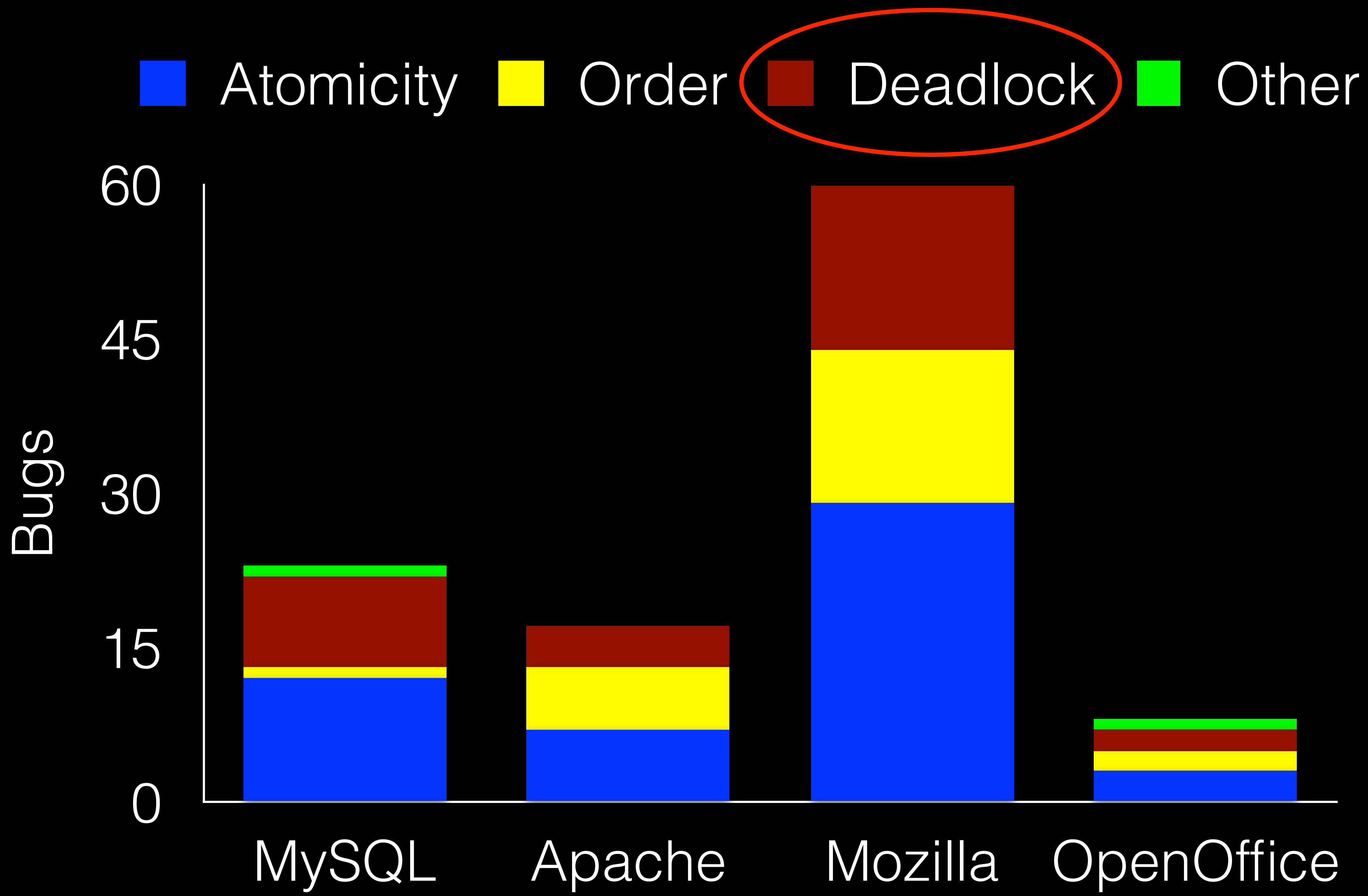


Lu *etal.* Study:

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

Concurrency Bugs are Common and Various



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.

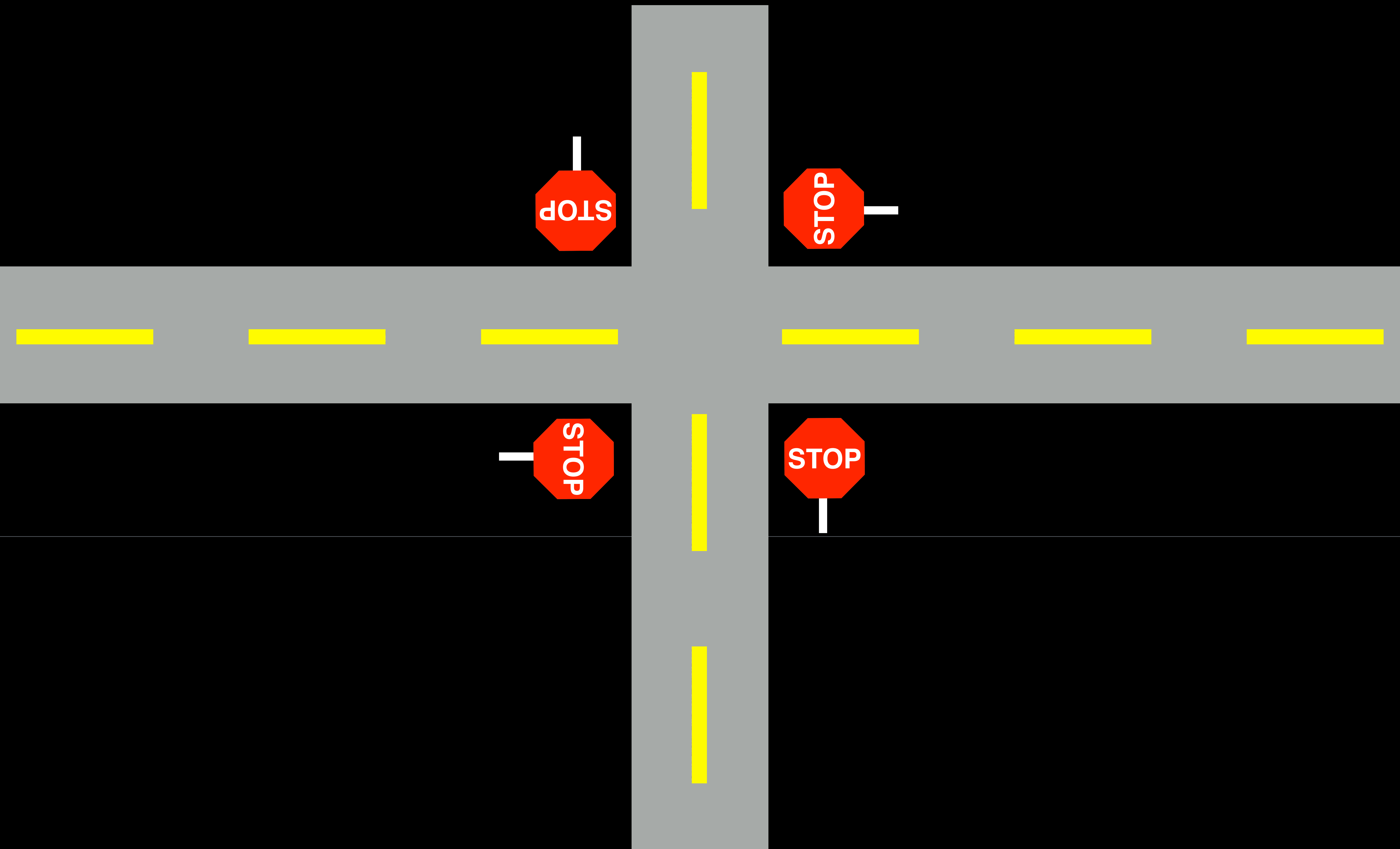
Source: http://pages.cs.wisc.edu/~shanlu/paper/asplos122-lu.pdf

Deadlock

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

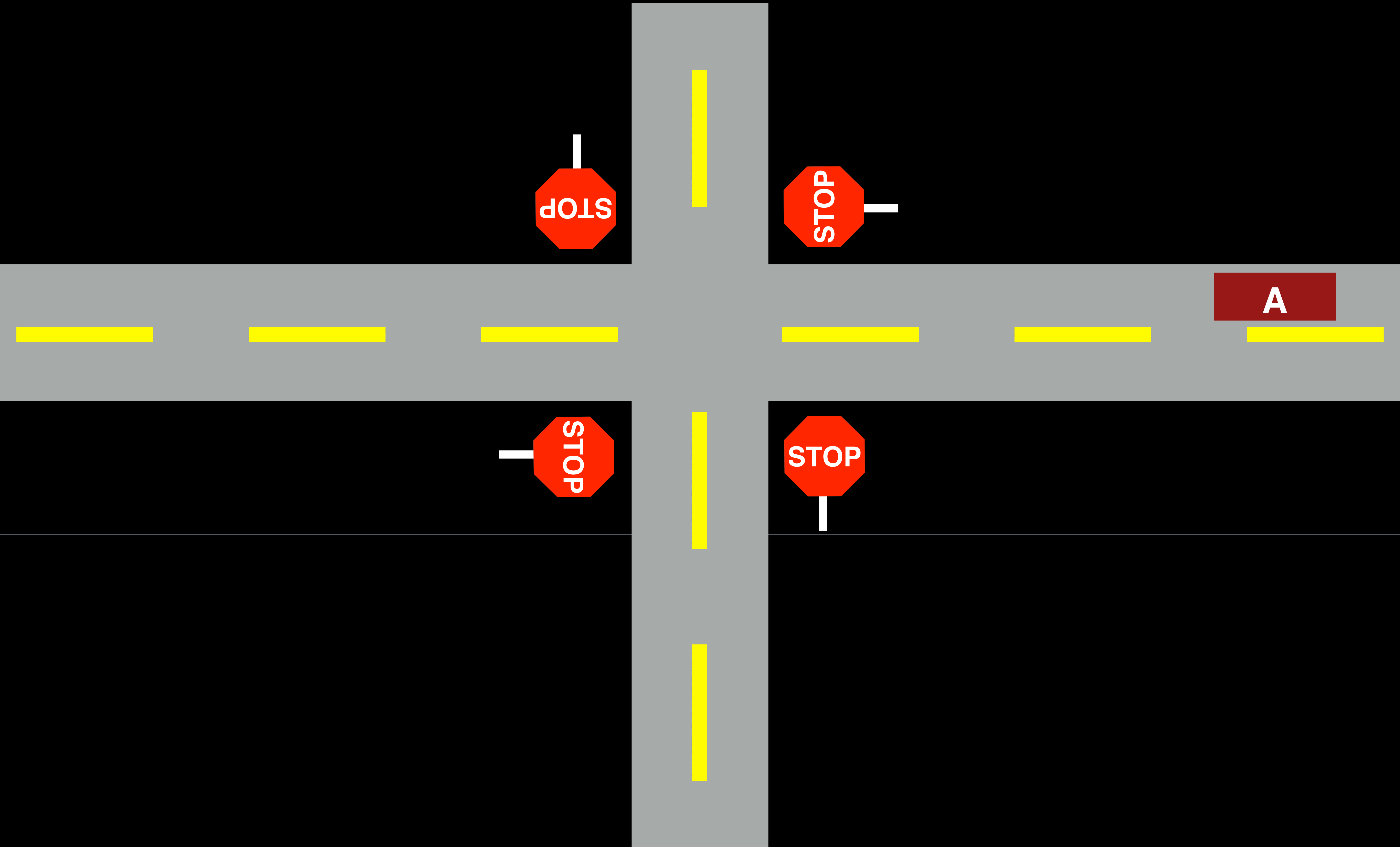
Deadlock

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



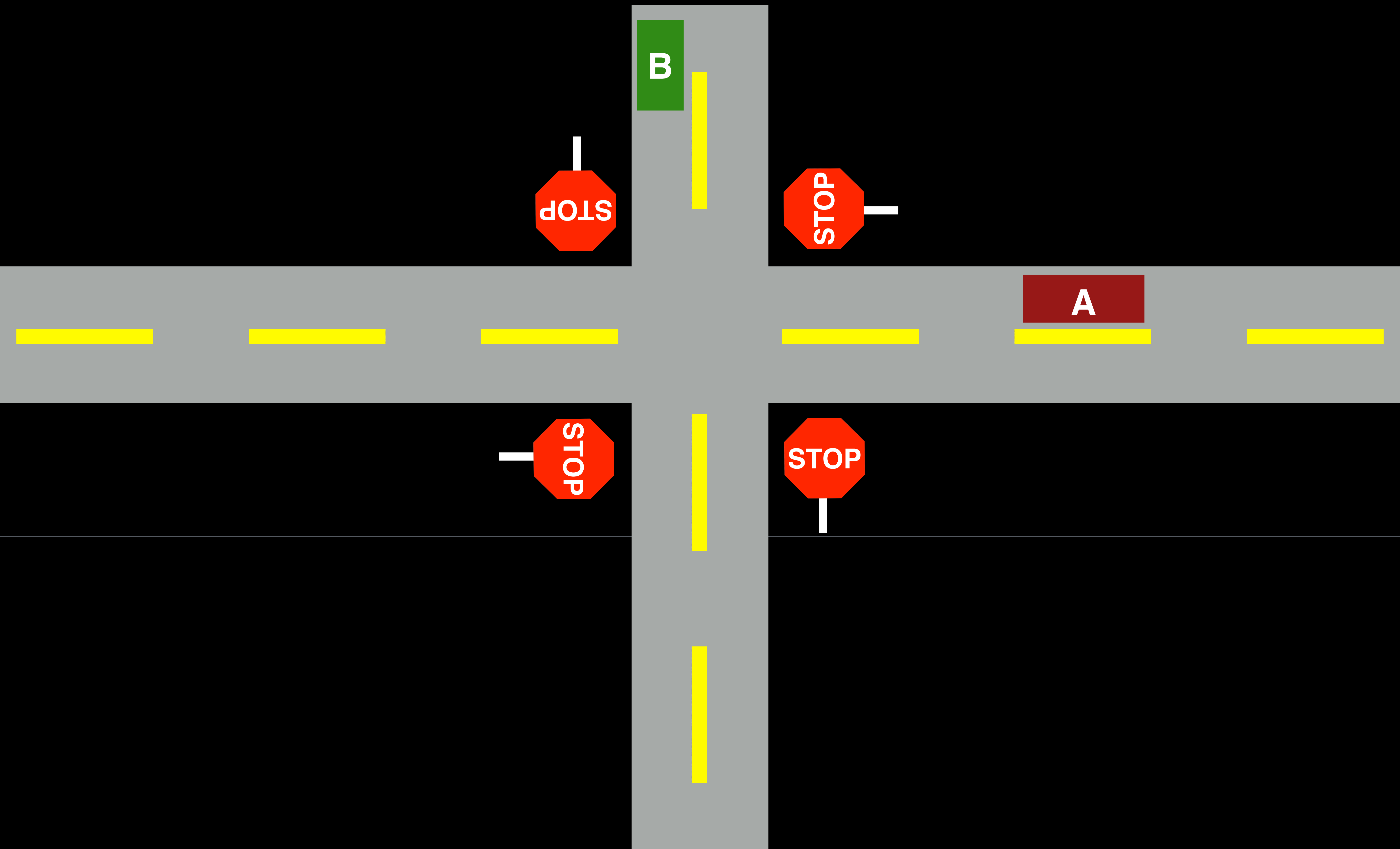
Deadlock

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



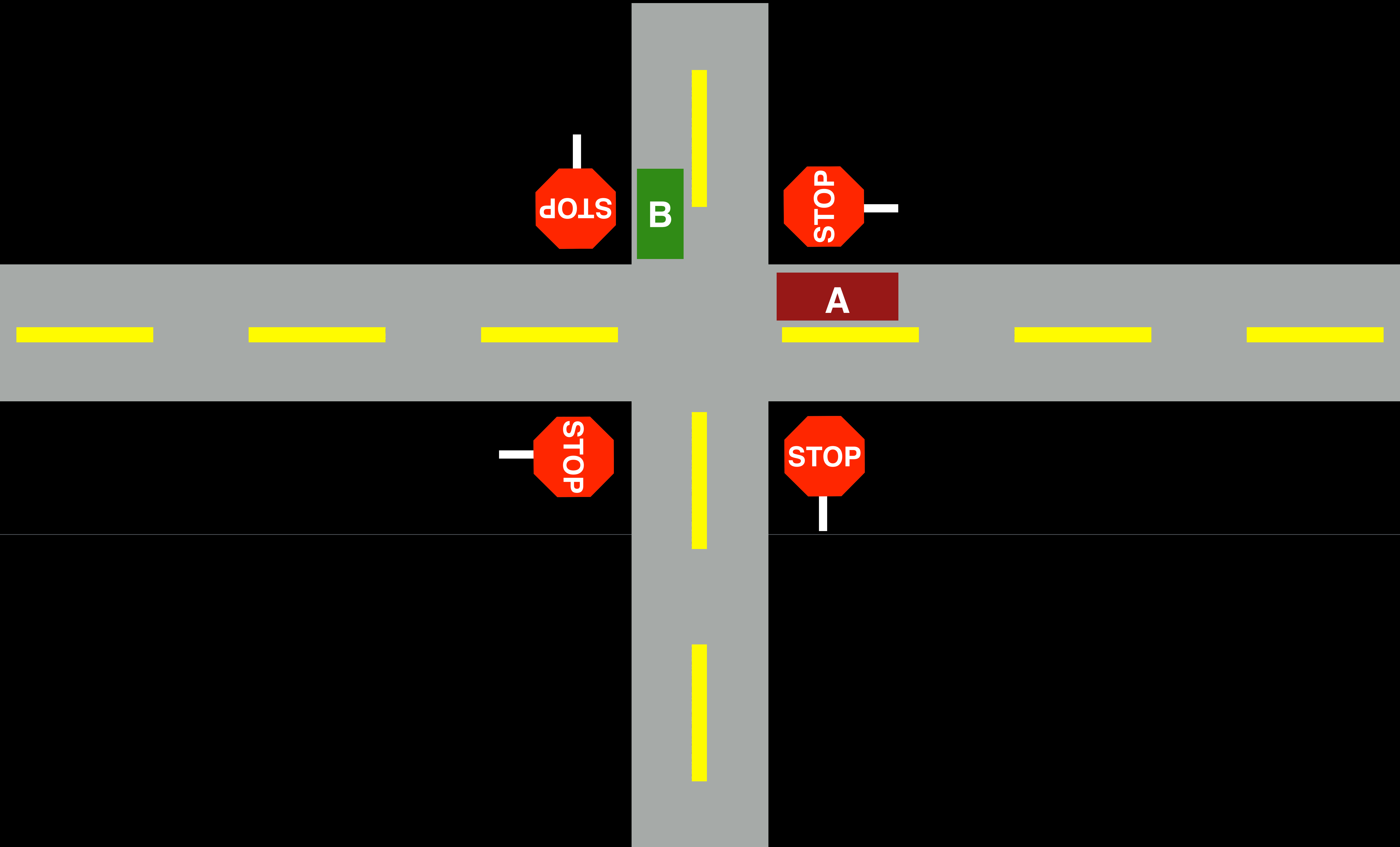
Deadlock

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



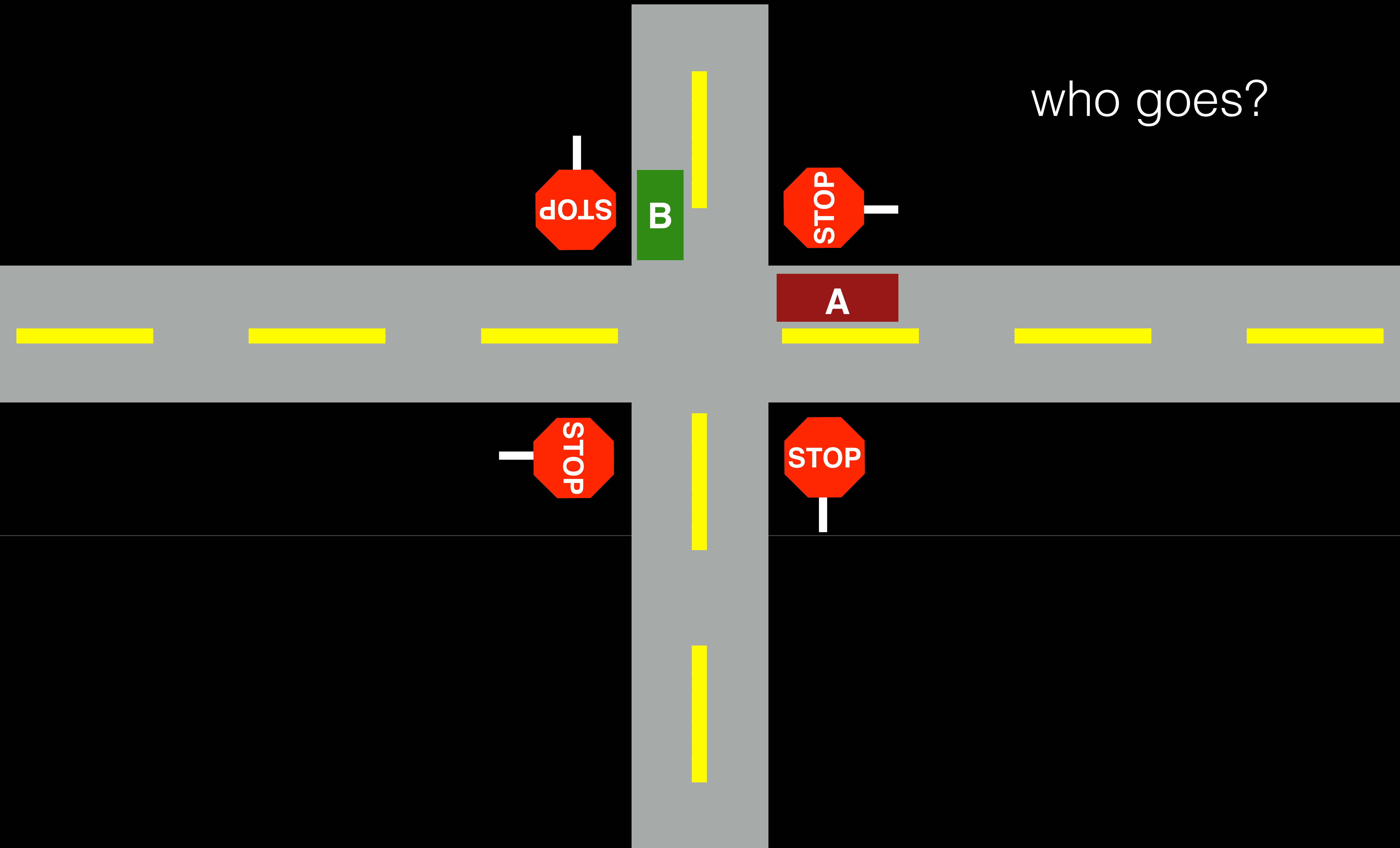
Deadlock

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



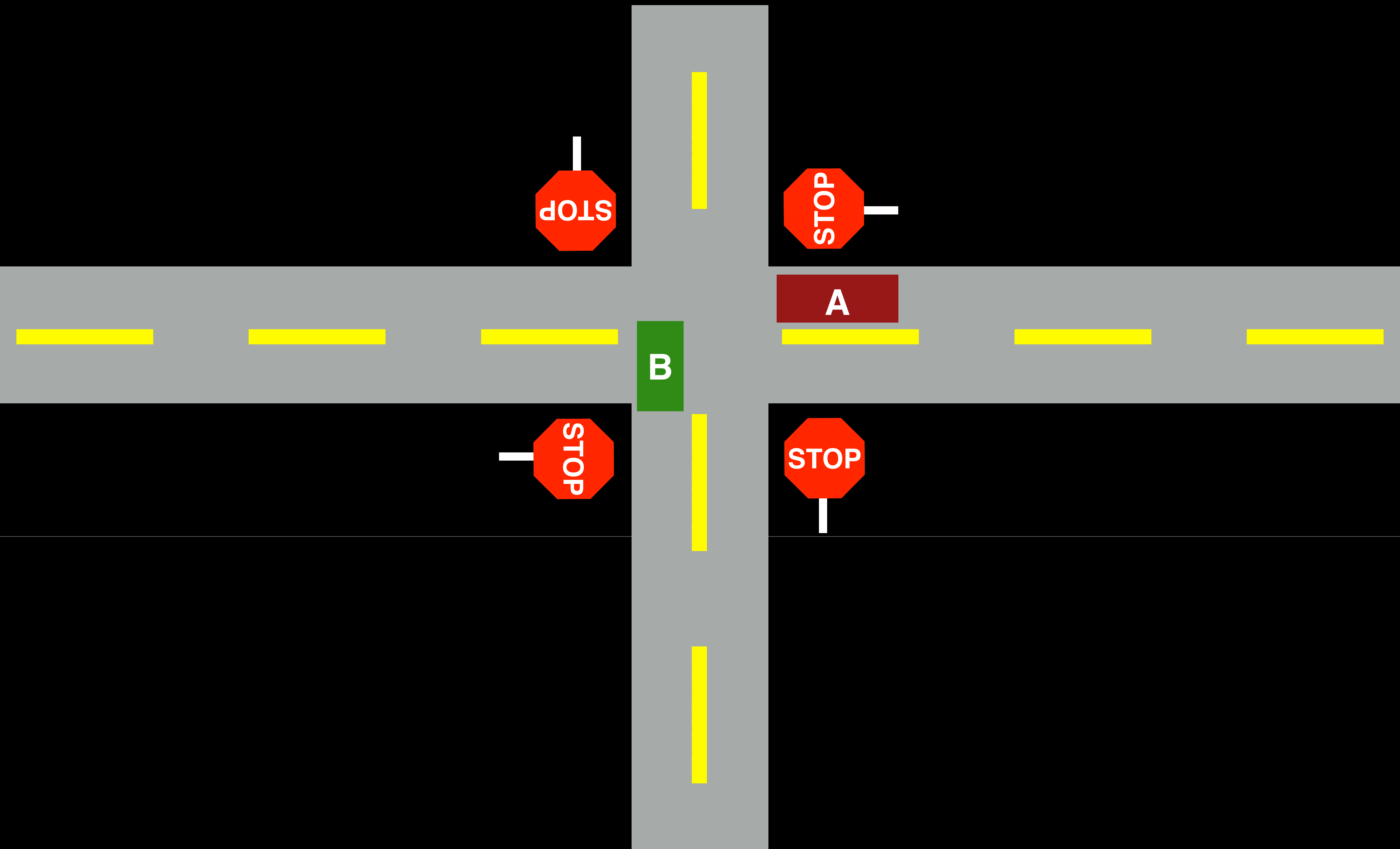
Deadlock

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



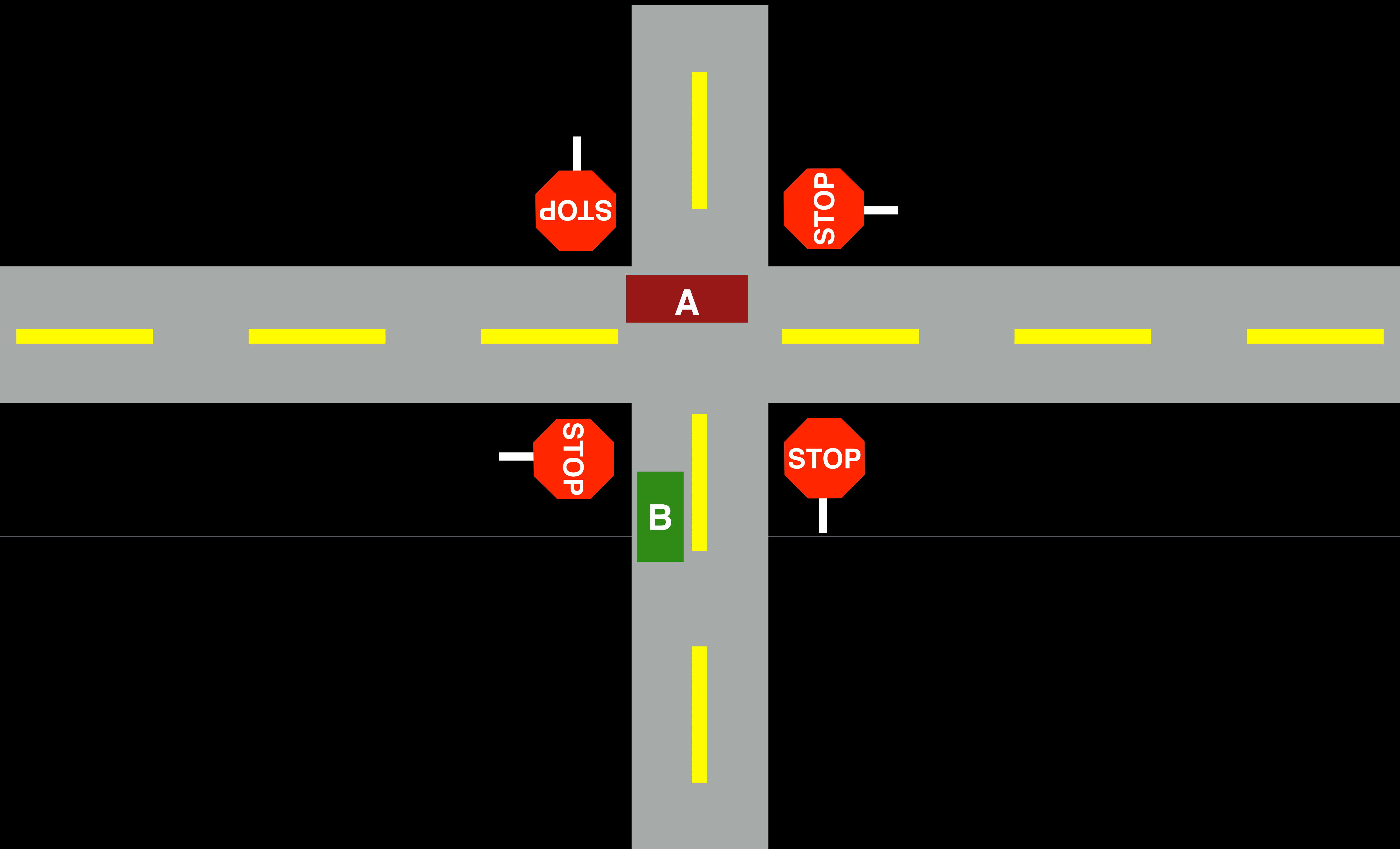
Deadlock

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



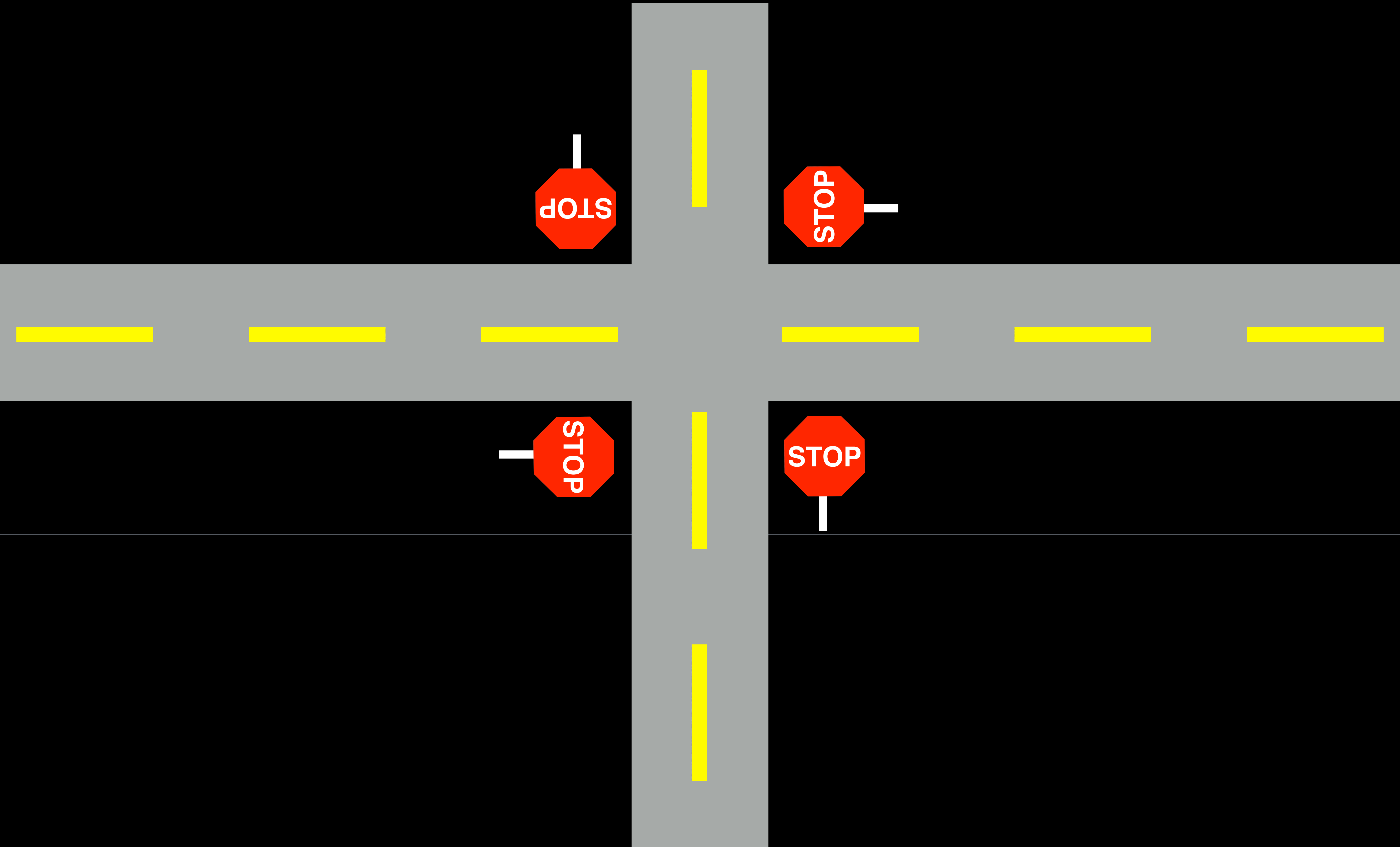
Deadlock

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



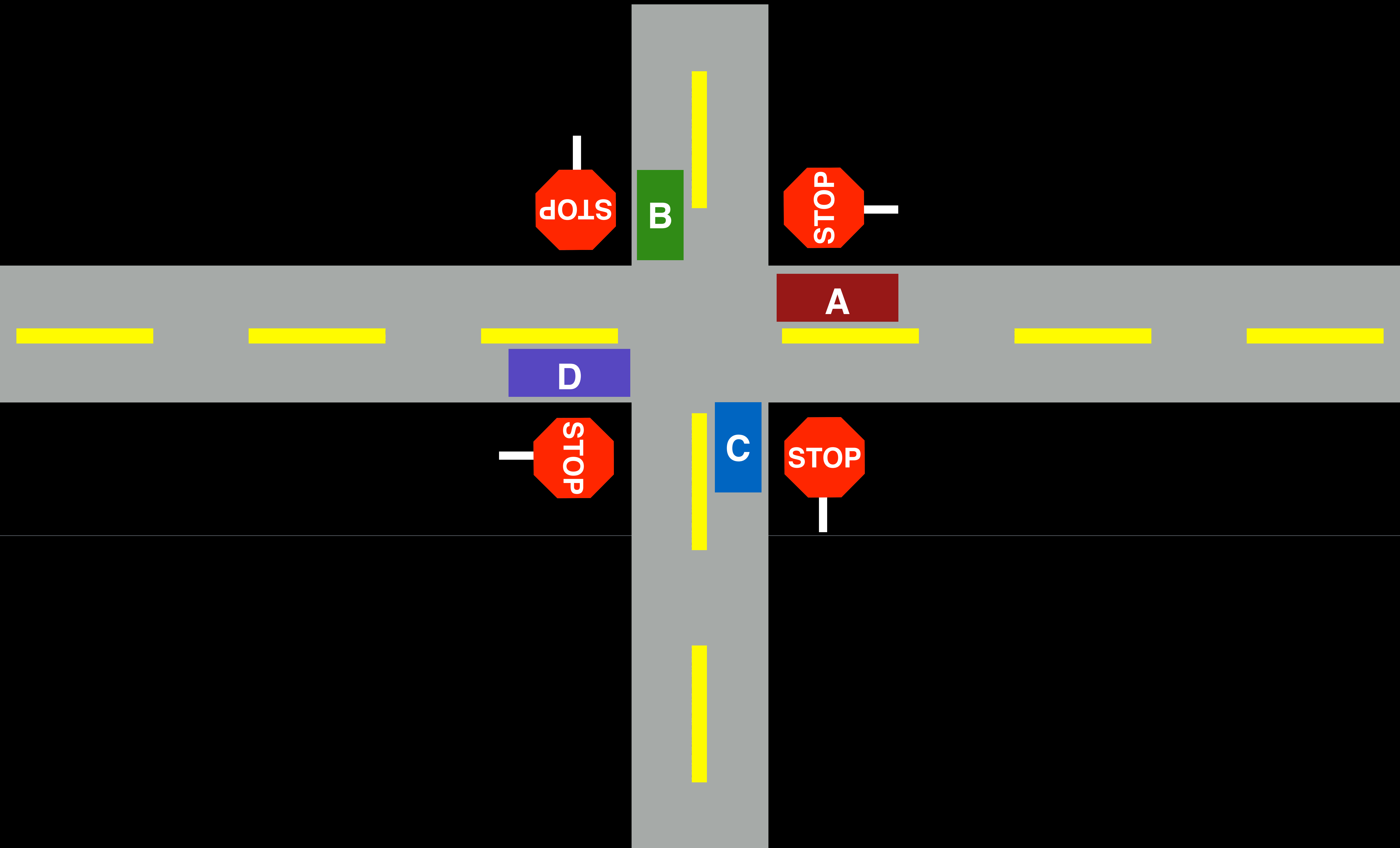
Deadlock

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



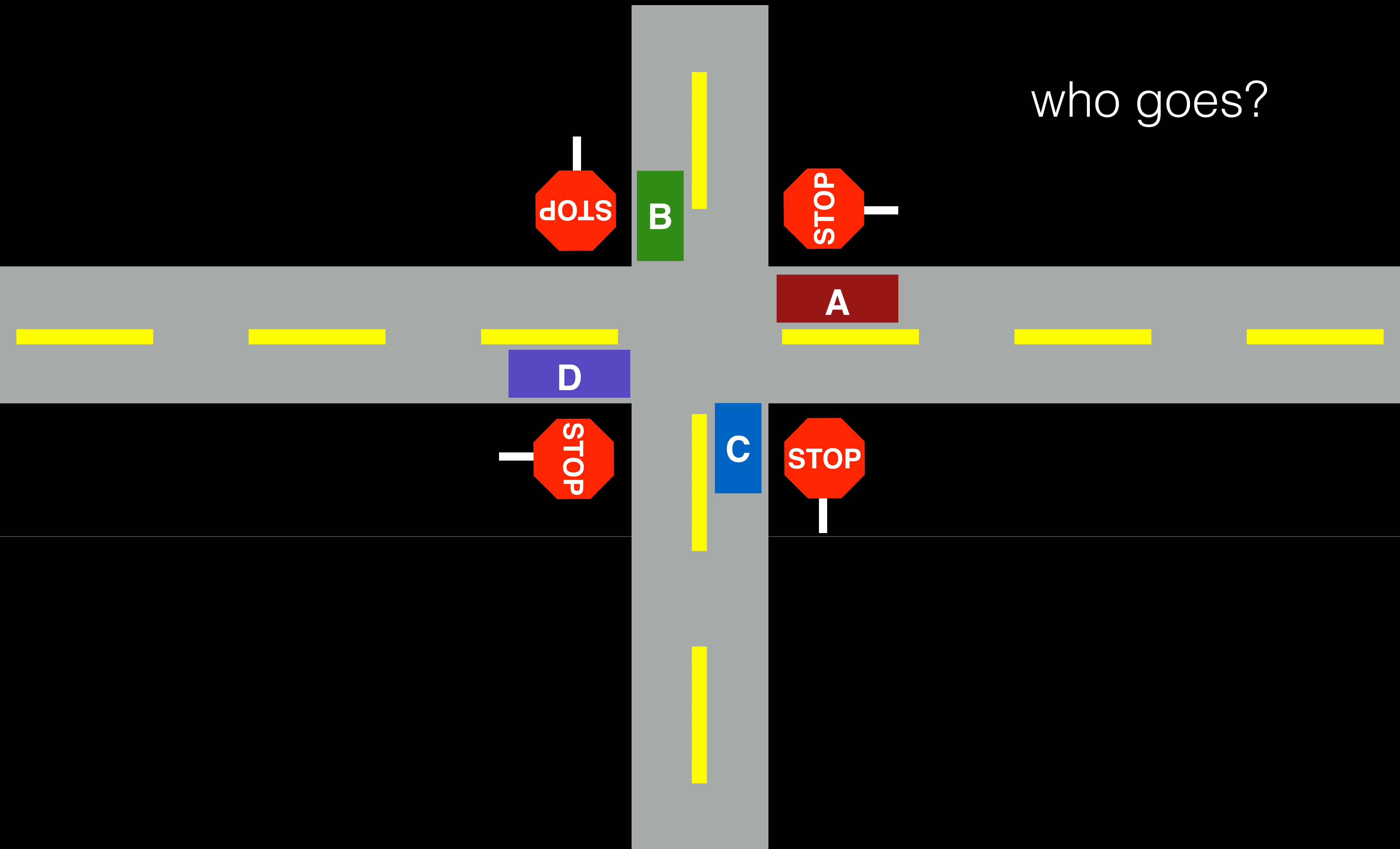
Deadlock

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



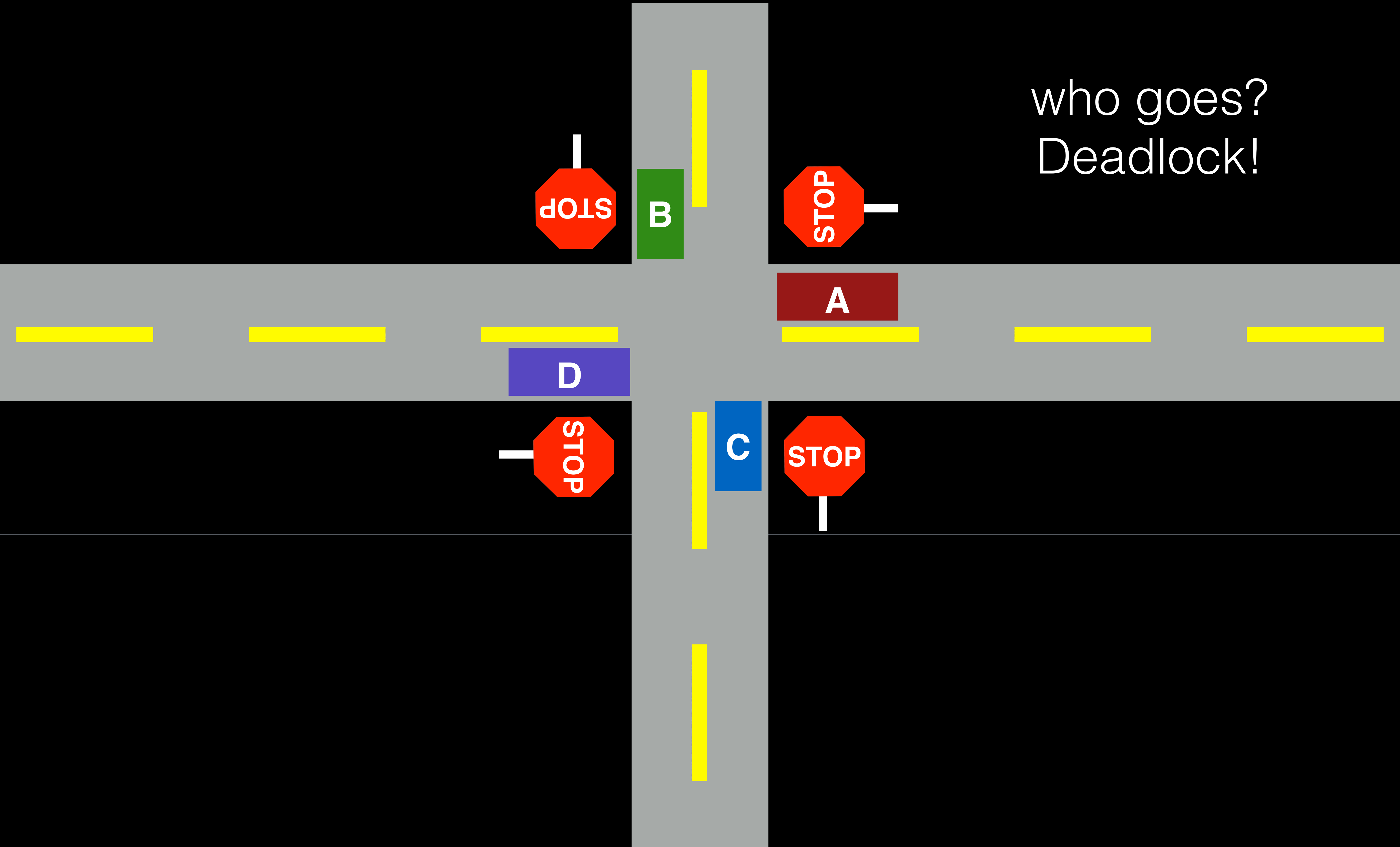
Deadlock

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



Deadlock

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



who goes?
Deadlock!

Boring Code Example

Thread 1 [RUNNING]:

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

Thread 2 [RUNNABLE]:

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

Boring Code Example

Thread 1 [RUNNING]:

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

Thread 2 [RUNNABLE]:

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

Boring Code Example

Thread 1 [RUNNABLE]:

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

Thread 2 [RUNNING]:

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

Boring Code Example

Thread 1 [RUNNABLE]:

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

Thread 2 [RUNNING]:

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

Boring Code Example

Thread 1 [RUNNING]:

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

Thread 2 [RUNNABLE]:

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

Boring Code Example

Thread 1 [SLEEPING]:

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

Thread 2 [RUNNABLE]:

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

Boring Code Example

Thread 1 [SLEEPING]:

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

Thread 2 [RUNNING]:

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

Boring Code Example

Thread 1 [SLEEPING]:

lock(&A);
lock(&B)

Thread 2 [SLEEPING]:

lock(&B);
lock(&A)

Boring Code Example

Thread 1 [SLEEPING]:

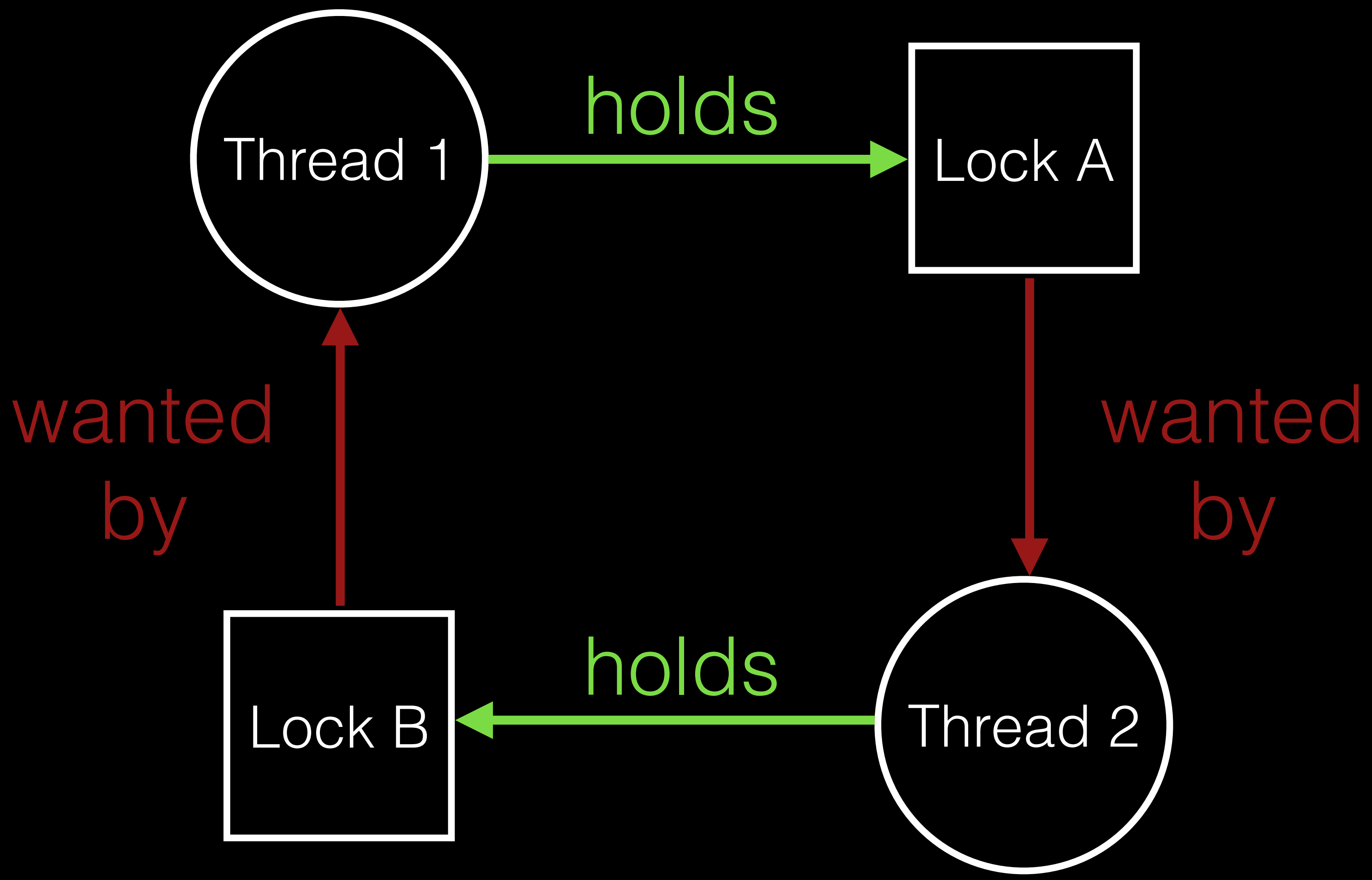
```
lock(&A);
lock(&B)
```

Thread 2 [SLEEPING]:

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

Deadlock!

Circular Dependency



Boring Code Example

Thread 1 [RUNNING]:

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

Thread 2 [RUNNABLE]:

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

Boring Code Example

Thread 1 [RUNNING]:

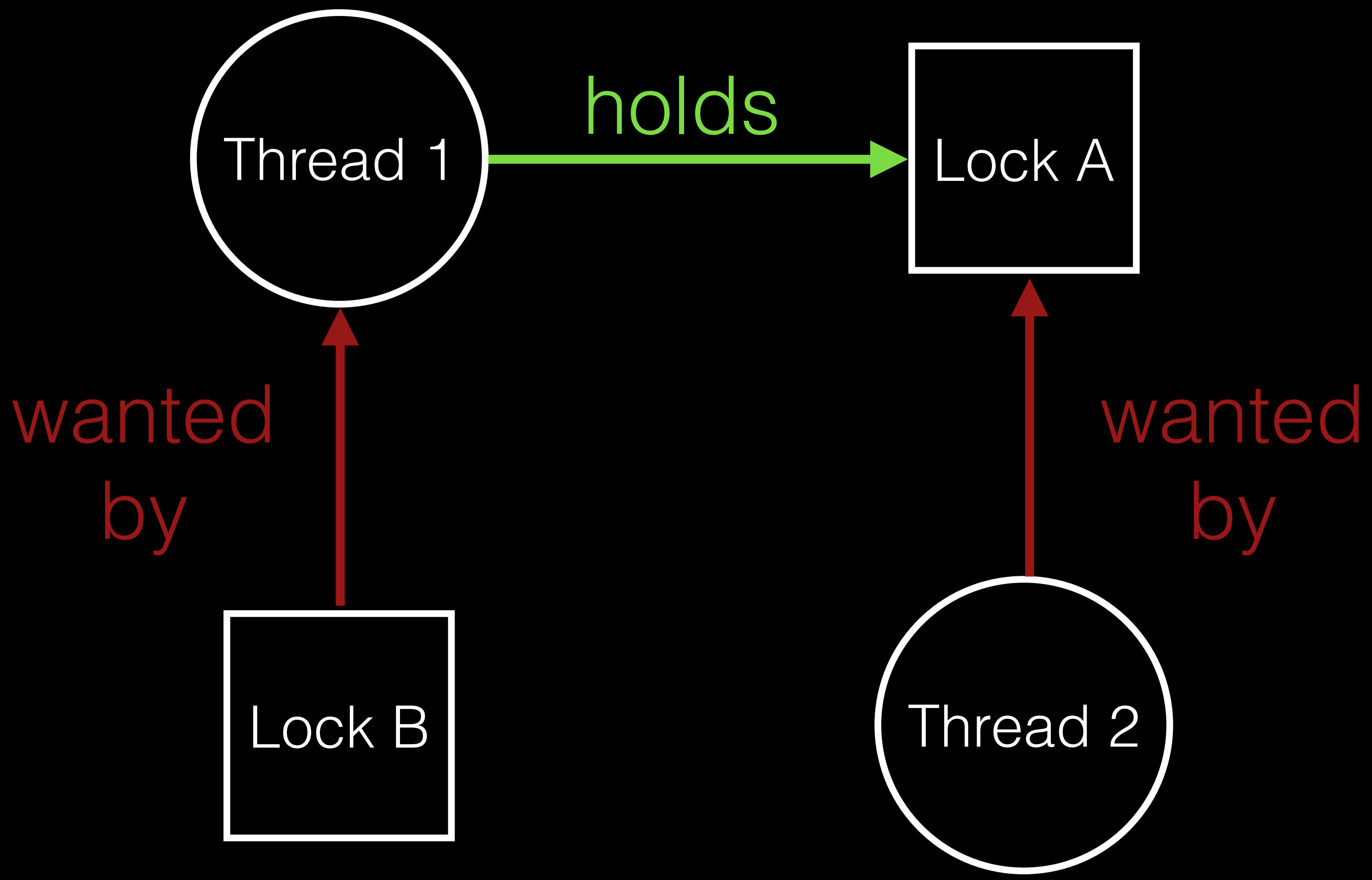
```
lock(&A);
lock(&B)
```

Thread 2 [RUNNABLE]:

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

Can't deadlock.

Non-circular Dependency (fine)



What's Wrong?

```
set_t *set_union (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_union(setA, setB);
```

Thread 2:

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

Encapsulation

Modularity can make it harder to see deadlocks.

Thread 1:

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

Thread 2:

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

Solutions?

Deadlock Theory

Deadlocks can only happen with these four conditions:

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

Deadlock Theory

Deadlocks can only happen with these four conditions:
- mutual exclusion
- hold-and-wait
- no preemption
- circular wait

Eliminate deadlock by eliminating one condition.

Deadlock Theory

Deadlocks can only happen with these four conditions:

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

Eliminate deadlock by eliminating 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 lock use.

Assume we have:
int CompAndSwap(int *addr, int expected, int new)
0: fail, 1: success

```
void add_v1(int *val, int amt) {
    Mutex_lock(&m);
    *val += amt;
    Mutex_unlock(&m);
}
```

```
void add_v2(int *val, int amt) {
    do {
        int old = *value;
    } while(!CompAndSwap(val, old, old+amt);
}
```

Wait-Free Algorithms

Strategy: eliminate lock use.

Assume we have:

int CompAndSwap(int *addr, int expected, int new)

eliminate the lock!

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

Wait-Free Algorithms

Strategy: eliminate lock use.

Assume we have:

int CompAndSwap(int *addr, int expected, int new)

```
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 one condition.

Deadlock Theory

Deadlocks can only happen with these four conditions:

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

Eliminate deadlock by eliminating 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**
(cannot acquire again until all have been released).

For this, use a meta lock, like this:

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

Eliminate Hold-and-Wait

Strategy: acquire all locks atomically **once**
(cannot acquire again until all have been released).

For this, use a meta lock, like this:

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

Discuss:

- how should unlock work?
- disadvantages?

Deadlock Theory

Deadlocks can only happen with these four conditions:
- mutual exclusion
- hold-and-wait
- no preemption
- circular wait

Eliminate deadlock by eliminating one condition.

Deadlock Theory

Deadlocks can only happen with these four conditions:

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

Eliminate deadlock by eliminating one condition.

No preemption

Def:

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

Support Preemption

Strategy: if we can't get what we want, release what we have.

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

Support Preemption

Strategy: if we can't get what we want, release what we have.

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

Discuss:

- disadvantages?

Support Preemption

Strategy: if we can't get what we want, release what we have.

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

Discussis:

- disadvantages? (livelock)

Deadlock Theory

Deadlocks can only happen with these four conditions:
- mutual exclusion
- hold-and-wait
- no preemption
- circular wait

Eliminate deadlock by eliminating one condition.

Deadlock Theory

Deadlocks can only happen with these four conditions:

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

Eliminate deadlock by eliminating 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

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
 */
```

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
 */
```

Linux lockdep Module

Idea:
- track order in which locks are acquired
- give warning if circular

Extremely useful for debugging!

Example Output

==
[INFO: possible circular locking dependency detected]
3.1.0rc4test00131g9e79e3e #2

insmod/1357 is trying to acquire lock:
(lockC){+.+...}, at: [<ffffffffa000d438>] pick_test+0x2a2/0x892
[lockdep_test]

but task is already holding lock:
(lockB){+.+...}, at: [<ffffffffa000d42c>] pick_test+0x296/0x892
[lockdep_test]

Source: http://www.linuxplumbersconf.org/2011/ocw/sessions/153

Summary

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.

When possible, avoid concurrent solutions altogether!

Announcements

Office hours: 1pm in office.

p3a due Friday.

Start **p3b**!

Thursday discussion: hand back and discuss **test**.