Mutual Exclusion

CS 475, Fall 2019
Concurrent & Distributed Systems

With material from Herlihy & Shavit, Art of Multiprocessor Programming

Review: Processes vs Threads

- Context Switching
  - Processor context: The minimal collection of values stored in the registers of a processor used for the execution of a series of instructions (e.g., stack pointer, addressing registers, program counter).
  - When switching processes, **all** of that data needs to get flushed out (by the OS)
- Threads share the same address space: no need to do this switch

Review: Threads in Java

```
public static void main(String[] args) throws InterruptedException {
 Thread t = new Thread(new Runnable() {
     @Override
     public void run() {
      //This code will now run in a new thread
       System.out.println("Hello from the thread!");
     }
   });
   t.start();
   System.out.println("Hello from main!”);
   t.join();
}
```

What is the output of this code?

#1 Hello from the thread!
Hello from main!

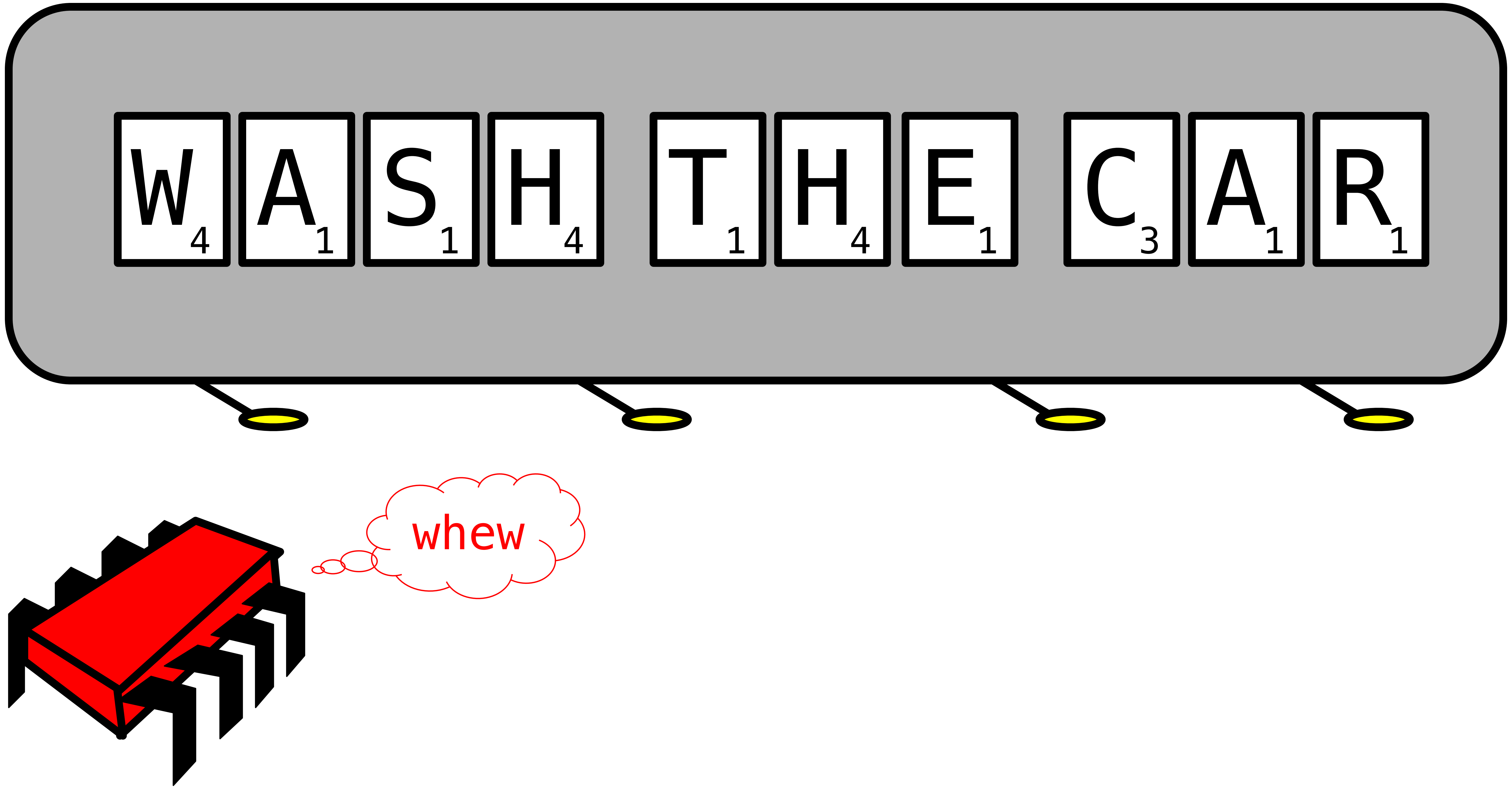
This is a race condition

#2 Hello from main!
Hello from the thread!

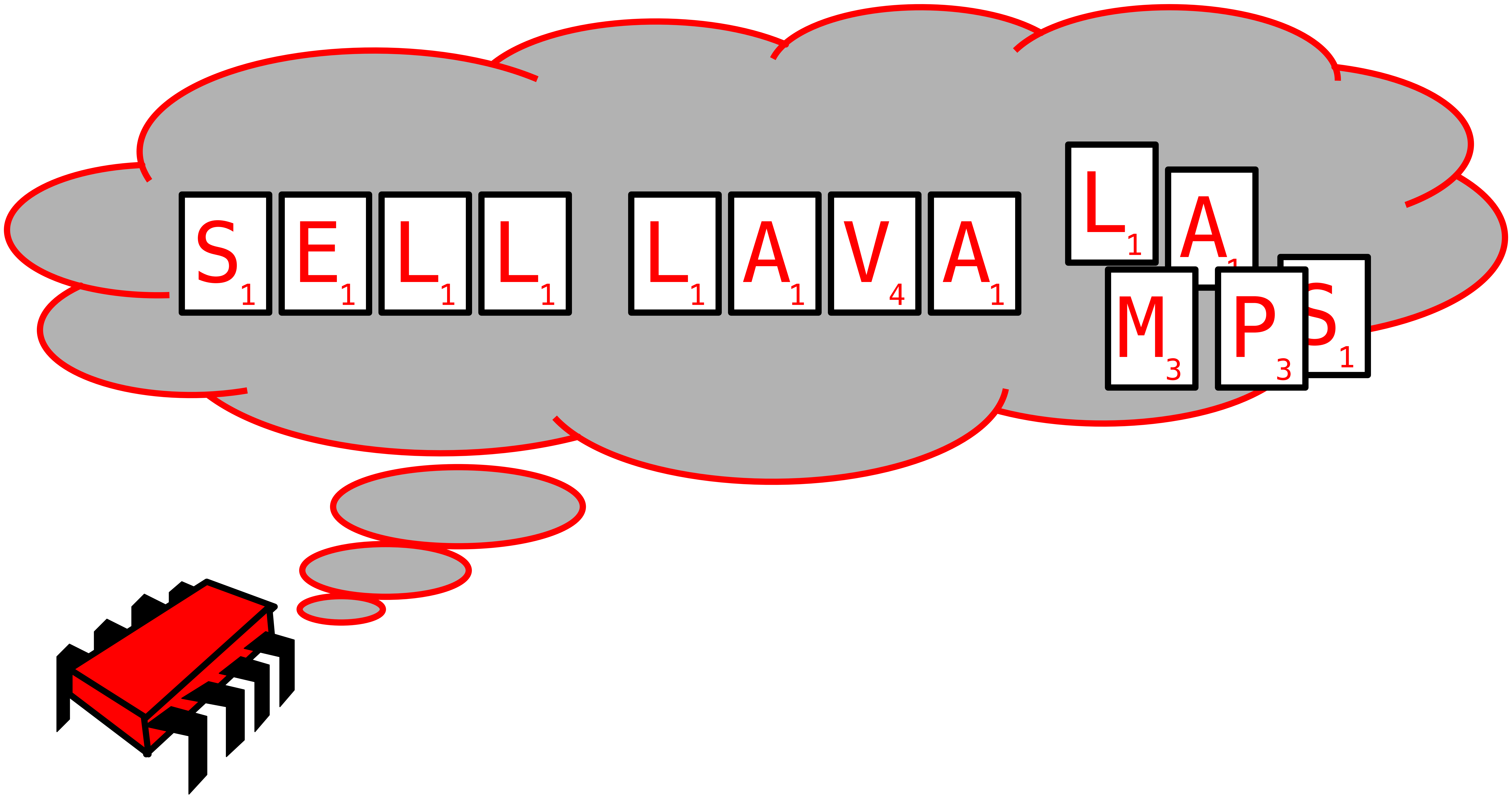
Producer/Consumer

- Alice and Bob can’t meet
  - Each has restraining order on other
  - So he puts food in the pond
  - And later, she releases the pets
- Avoid
  - Releasing pets when there’s no food
  - Putting out food if uneaten food remains

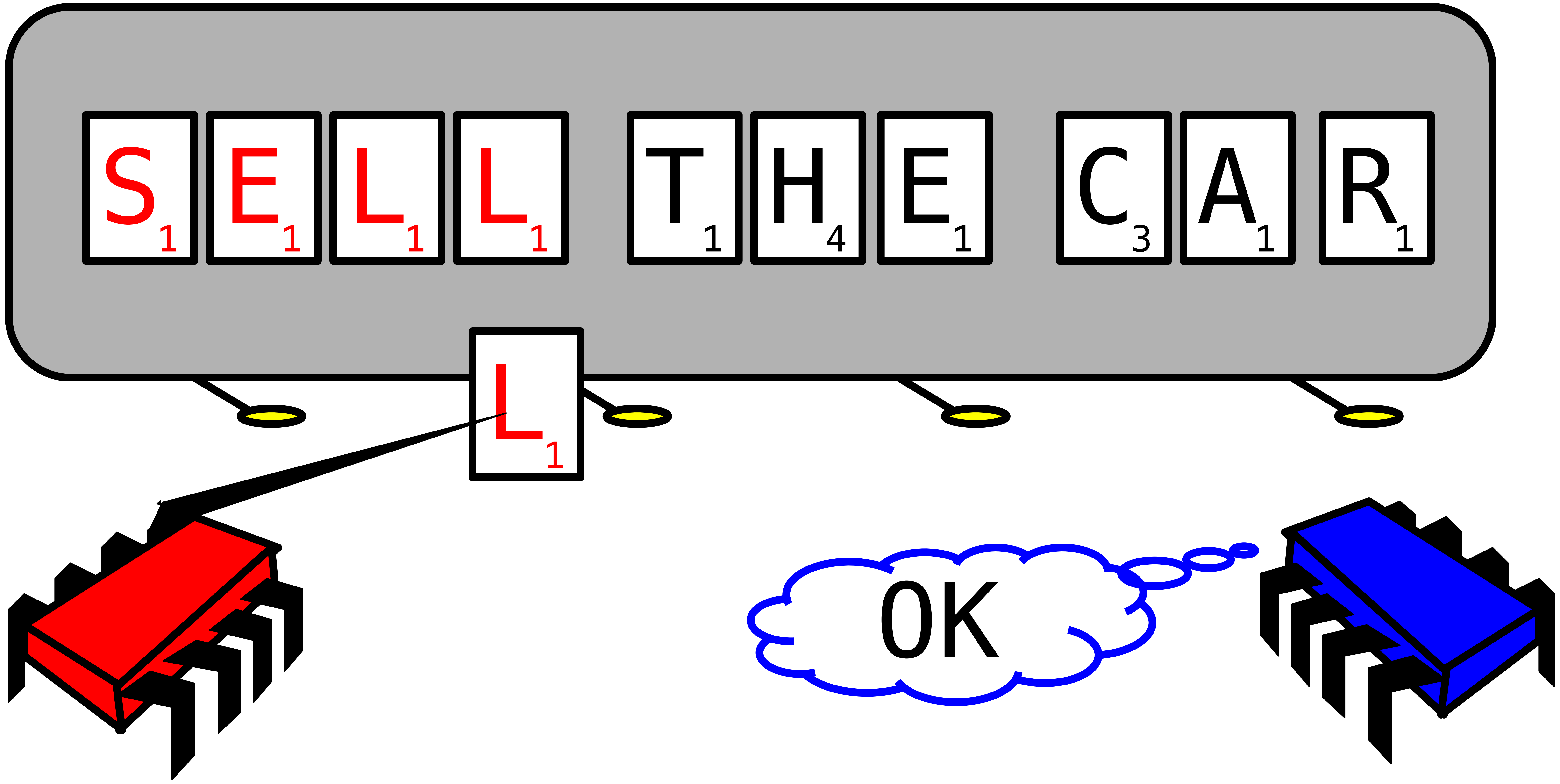
To post a message



Let's send another message



Uh-Oh



Readers/Writers

- Devise a protocol so that
  - Writer writes one letter at a time
  - Reader reads one letter at a time
  - Reader sees
    - Old message or new message
    - No mixed messages

Readers/Writers (continued)

- Easy with mutual exclusion
- But mutual exclusion requires waiting
  - One waits for the other
  - Everyone executes sequentially

Amdahl's Law

- Identifies performance gains from adding additional cores to an application that has both serial and parallel components
- S is serial portion
- N processing cores

$$speedup \leq \frac{1}{S + \frac{(1-S)}{N}}$$

- That is, if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times
- As N approaches infinity, speedup approaches 1 / S
- Serial portion of an application has disproportionate effect on performance gained by adding additional cores

Today

- Today we will try to formalize our understanding of mutual exclusion
  - We will also use the opportunity to show you how to argue about and prove various properties in an asynchronous concurrent setting
  - Reading: H&S 2.1-2.3
- Note: HW1 posted: https://www.jonbell.net/gmu-cs-475-fall-2019/homework-1/

Why is Concurrent Programming so Hard?

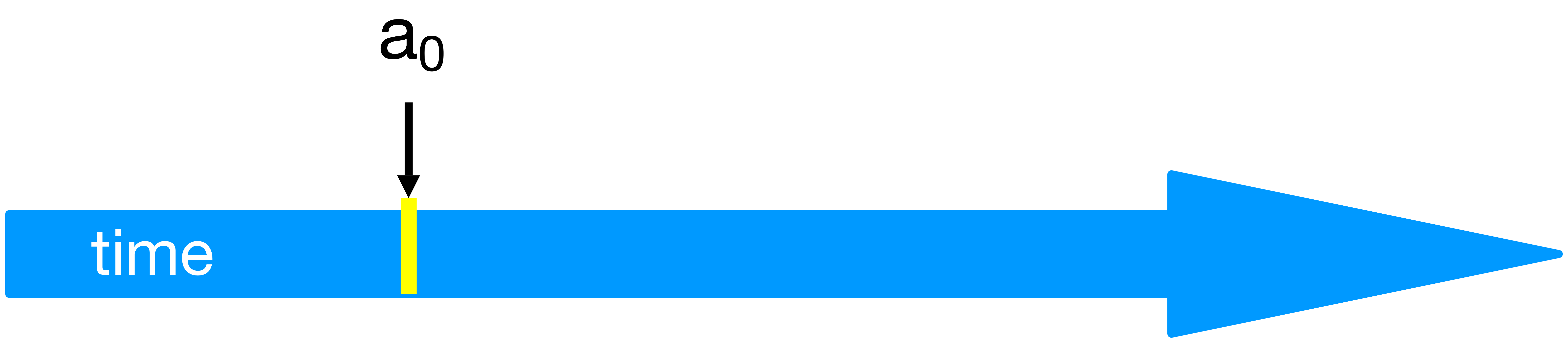
- Try preparing a seven-course banquet
  - By yourself
  - With one friend
  - With twenty-seven friends …
- Before we can talk about programs
  - Need a language
  - Describing time and concurrency

Time

- “Absolute, true and mathematical time, of itself and from its own nature, flows equably without relation to anything external.” (I. Newton, 1689)
- “Time is, like, Nature’s way of making sure that everything doesn’t happen all at once.” (Anonymous, circa 1968)

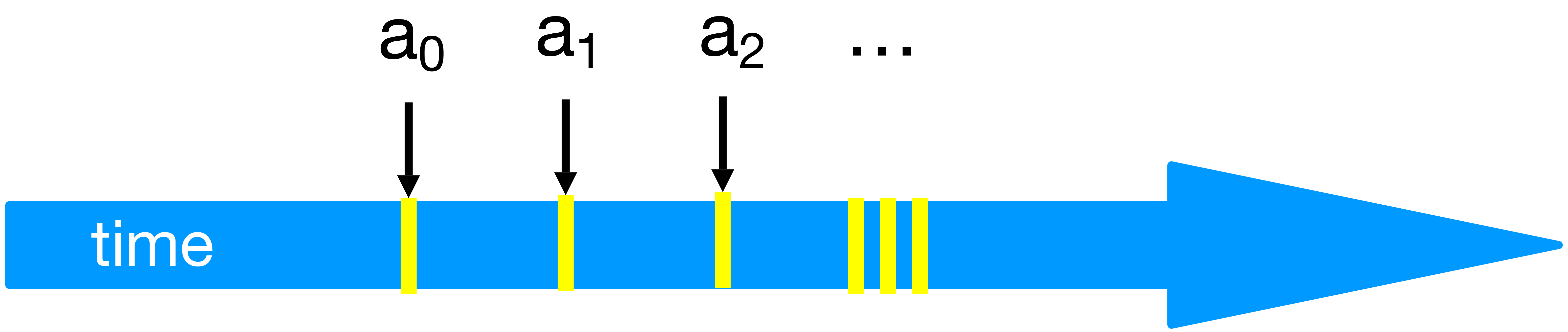
Events

- An event a_0 of thread A is
  - Instantaneous
  - No simultaneous events (break ties)



Threads

- A thread A is (formally) a sequence a_0, a_1, ... of events
  - "Trace" model
  - Notation: $a_0 \rightarrow a_1$ indicates order

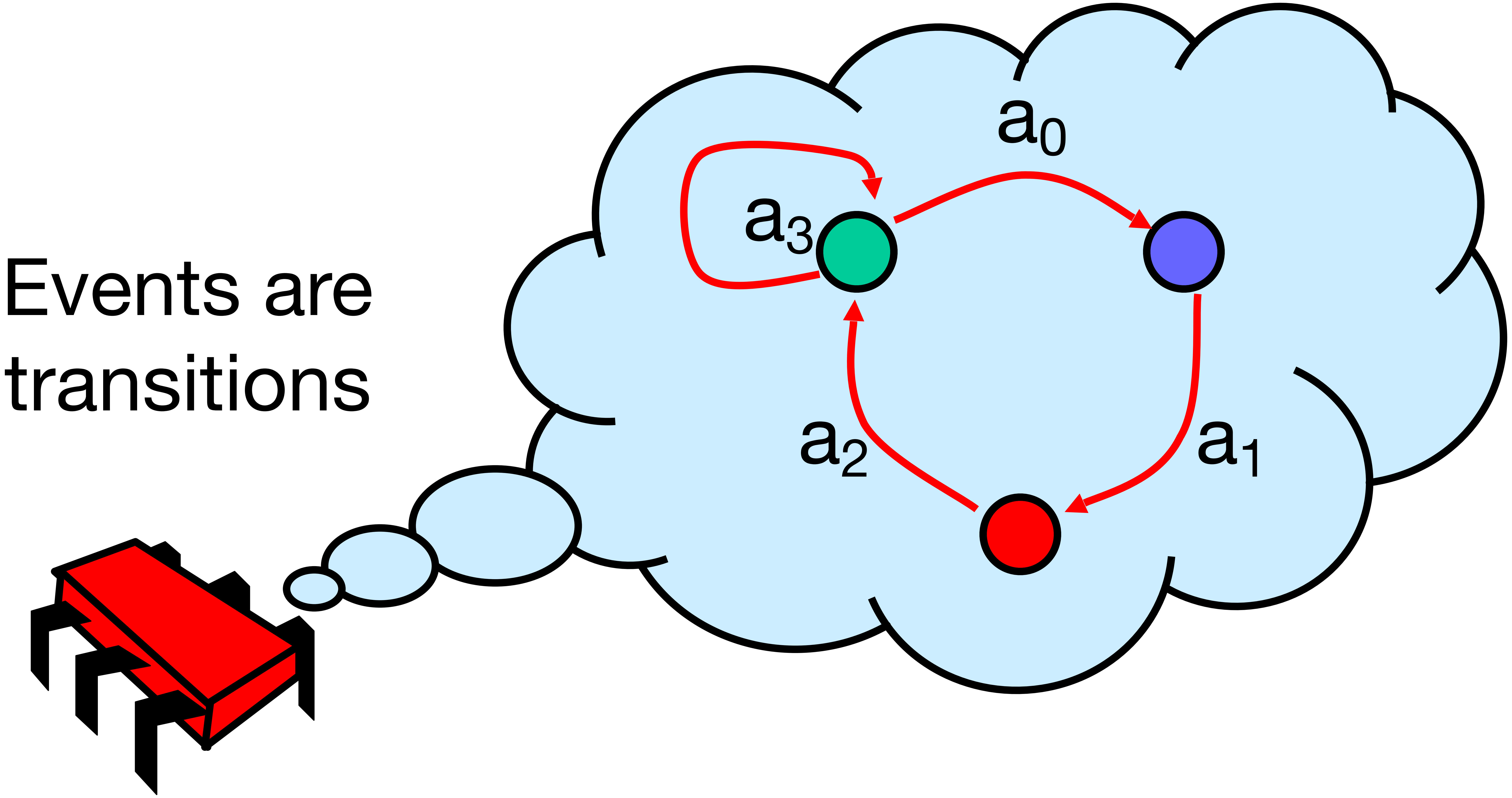


Example Thread Events

- Assign to shared variable
- Assign to local variable
- Invoke method
- Return from method
- Lots of other things …

Threads are State Machines

Events are transitions



States

- Thread State
  - Program counter
  - Local variables
- System state
  - Object fields (shared variables)
  - Union of thread states

Concurrency

- Thread A

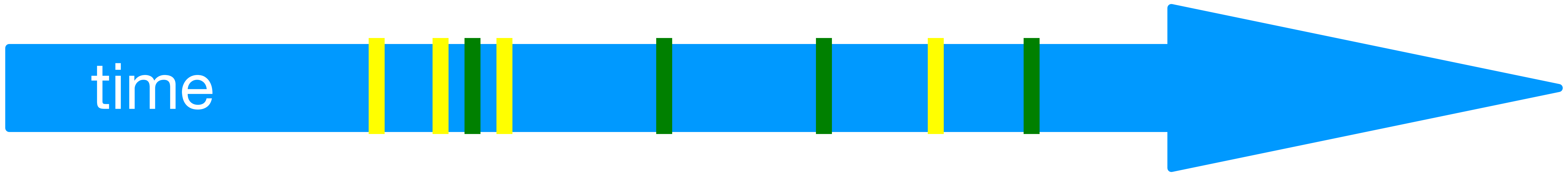
Concurrency

- Thread A

- Thread B

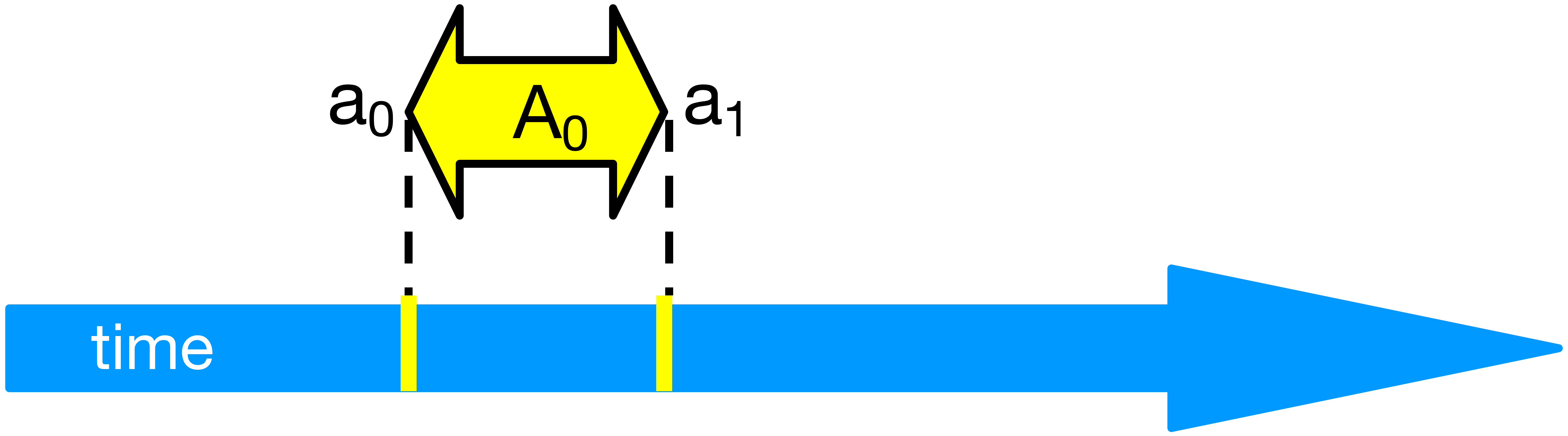
Interleavings

- Events of two or more threads
  - Interleaved
  - Not necessarily independent (why?)

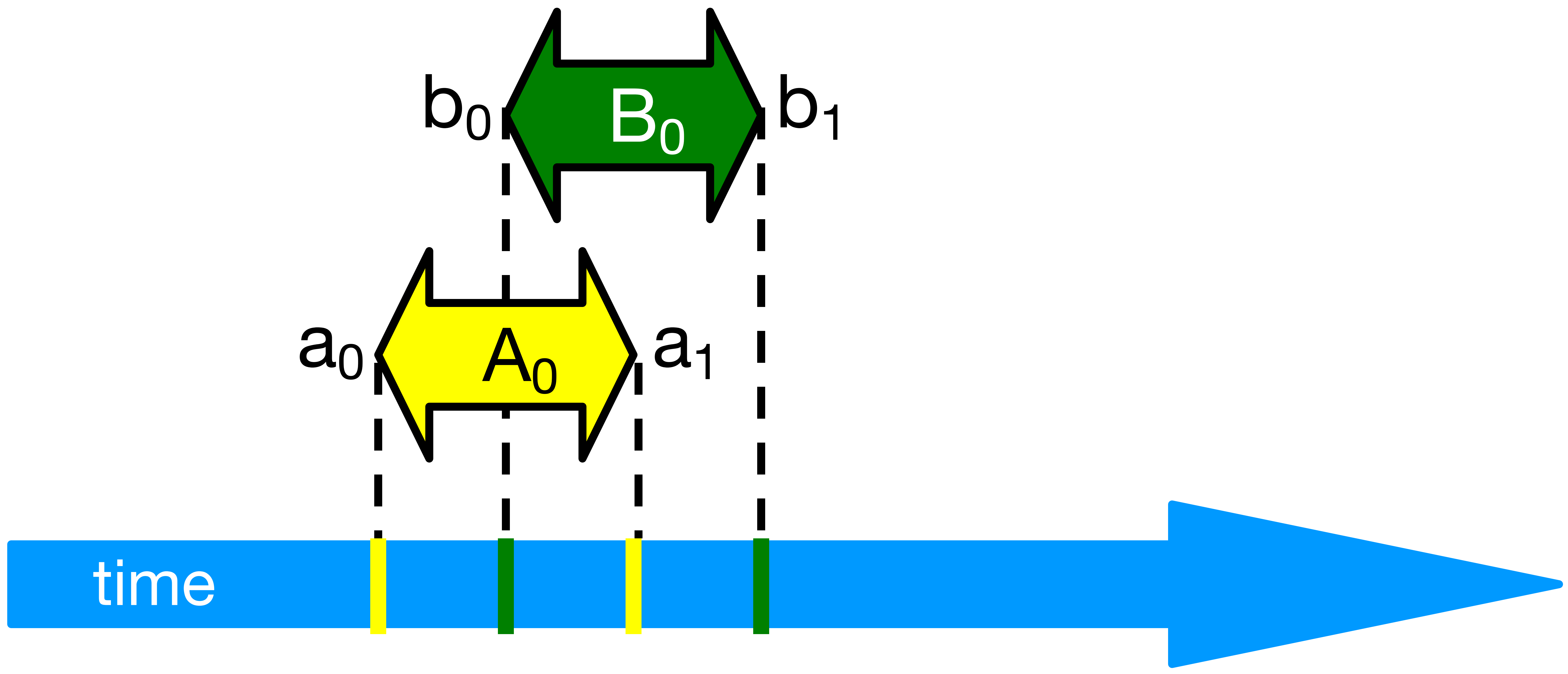


Intervals

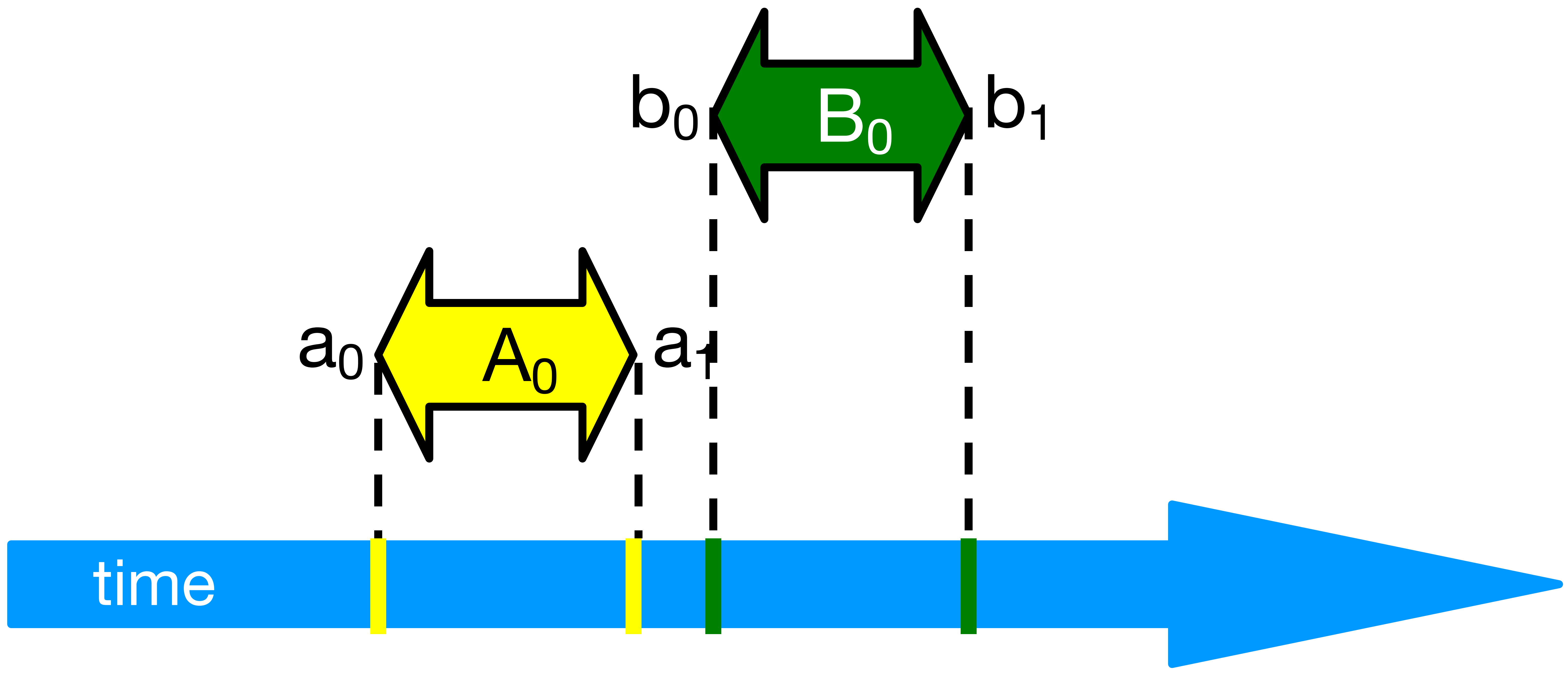
- An interval $A_0 = (a_0, a_1)$ is
  - Time between events a_0 and a_1



Intervals may Overlap

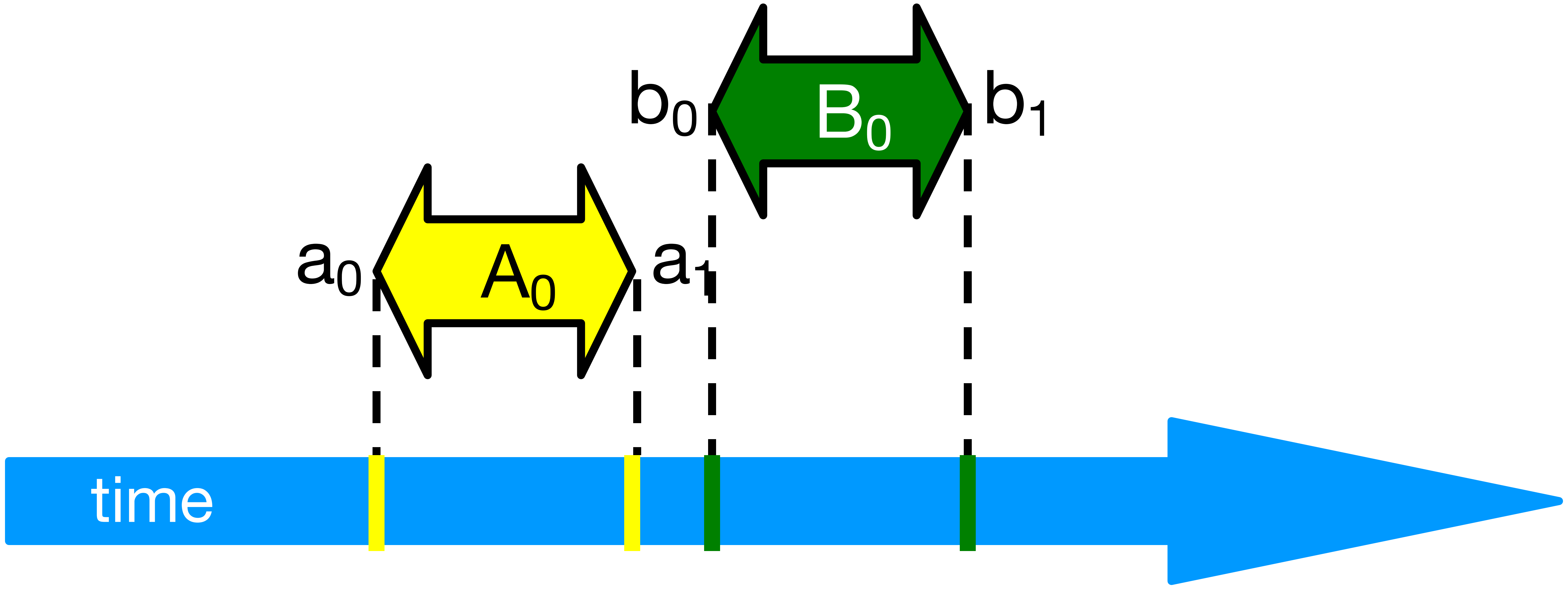


Intervals may be Disjoint

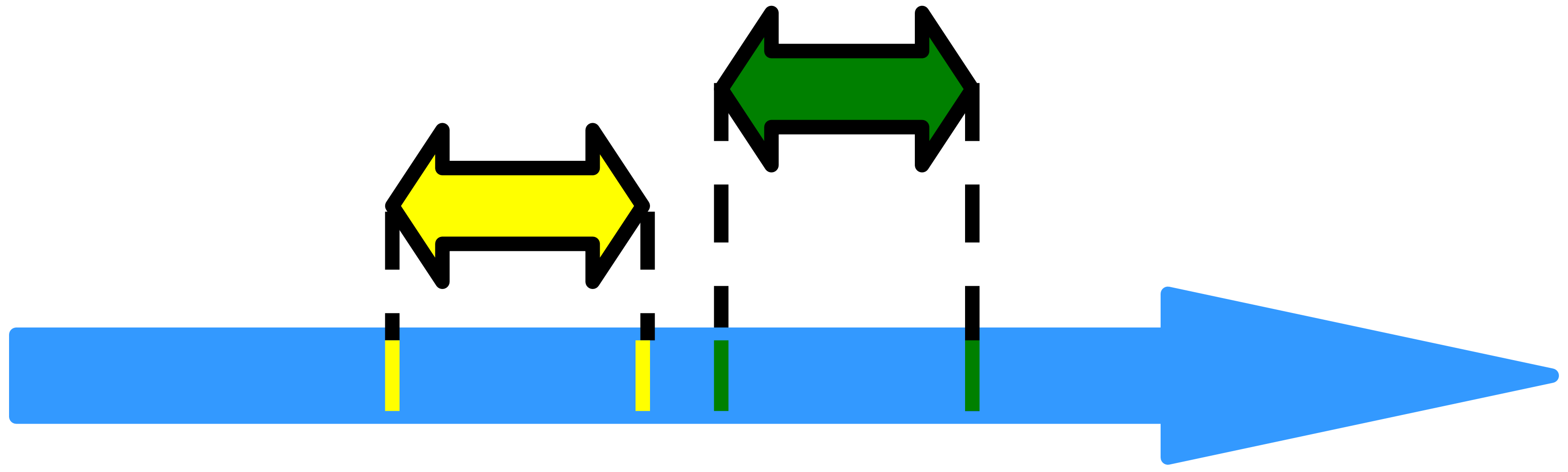


Precedence

Interval A_0 precedes interval B_0

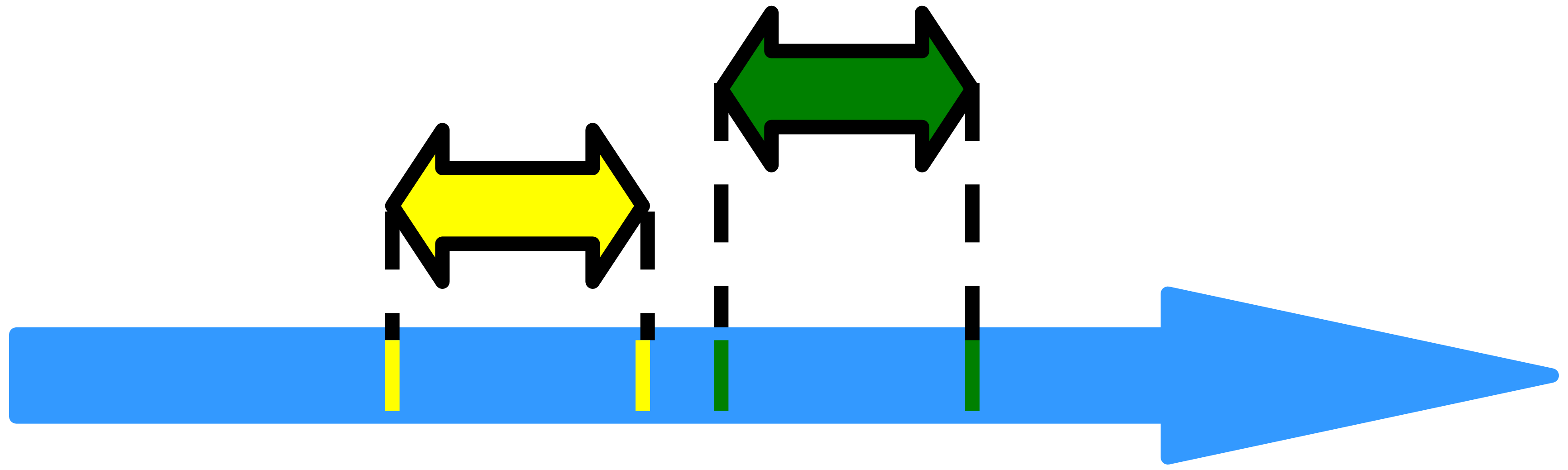


Precedence



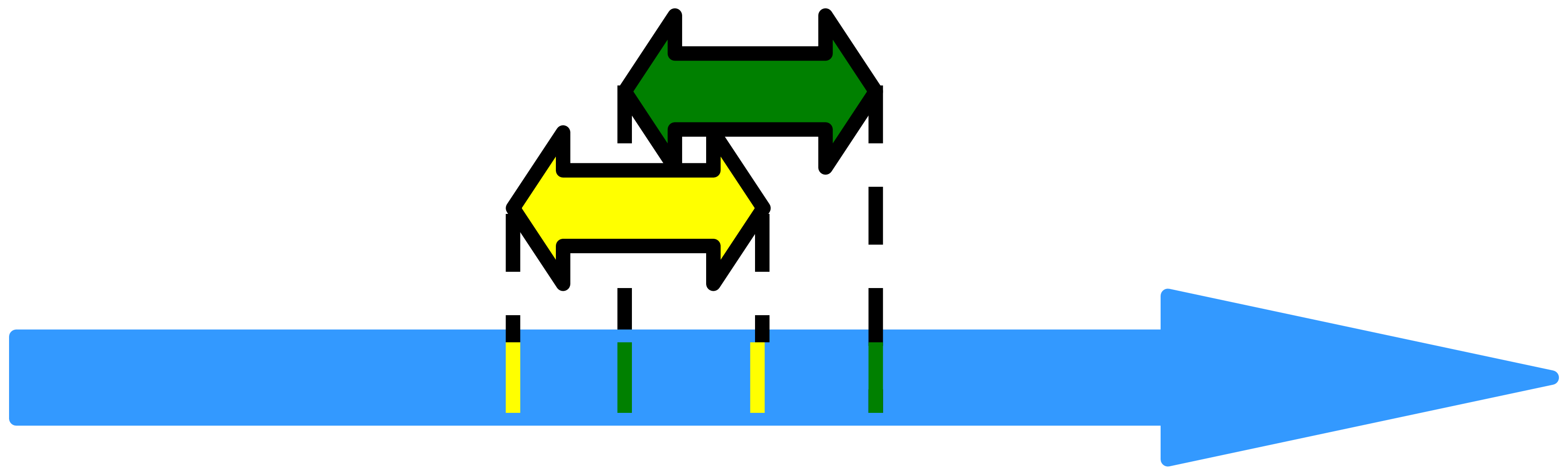
- Notation: $A_0 \rightarrow B_0$
- Formally,
  - End event of A_0 before start event of B_0
  - Also called “happens before” or “precedes”
- Informally,
  - Alice can’t look at the billboard while Bob is changing the letters

Precedence Ordering



- Remark: $A_0 \rightarrow B_0$ is just like saying
  - 1066 AD ➔ 1492 AD,
  - Middle Ages ➔ Renaissance,
- Oh wait,
  - what about **this week** vs **this month**?

Precedence Ordering



- Never true that A ➔ A
- If A ➔B then not true that B ➔A
- If A ➔B & B ➔C then A ➔C
- Funny thing: A ➔B & B ➔A might both be false!

Partial Orders

(you may know this already)

- Irreflexive:
  - Never true that A ➔ A
- Antisymmetric:
  - If A ➔ B then not true that B ➔ A
- Transitive:
  - If A ➔ B & B ➔ C then A ➔ C

Total Orders

(you may know this already)

- Also
  - Irreflexive
  - Antisymmetric
  - Transitive
- Except that for every distinct A, B,
  - Either A ➔ B or B ➔ A

Implementing a Counter

```
public class Counter {
  private long value;

  public long getAndIncrement() {
    temp  = value;
    value = temp + 1;
    return temp;
  }
}
```

Make these steps indivisible using locks

Locks (Mutual Exclusion)

```
public interface Lock {

 public void lock();

 public void unlock();
}
```

Locks (Mutual Exclusion)

```
public interface Lock {

 public void lock();

 public void unlock();
}
```

acquire lock

Locks (Mutual Exclusion)

```
public interface Lock {

 public void lock();        acquire lock

 public void unlock();      release lock
}
```

Using Locks

```
public class Counter {
  private long value;
  private Lock lock;
  public long getAndIncrement() {
   lock.lock();
   try {
    int temp = value;
    value = value + 1;
   } finally {
     lock.unlock();
   }
   return temp;
  }}
```

Using Locks

```
public class Counter {
  private long value;
  private Lock lock;
  public long getAndIncrement() {
   lock.lock();
   try {
    int temp = value;
    value = value + 1;
   } finally {
     lock.unlock();
   }
   return temp;
  }}
```

acquire Lock

Using Locks

```
public class Counter {
  private long value;
  private Lock lock;
  public long getAndIncrement() {
   lock.lock();
   try {
    int temp = value;
    value = value + 1;
   } finally {
    lock.unlock();
   }
   return temp;
  }}
```

Release lock
(no matter what)

Using Locks

```
public class Counter {
  private long value;
  private Lock lock;
  public long getAndIncrement() {
   lock.lock();
   try {
    int temp = value;
    value = value + 1;
   } finally {
     lock.unlock();
   }
   return temp;
  }}
```

Critical section

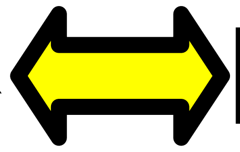
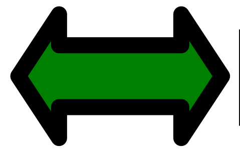
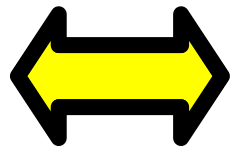
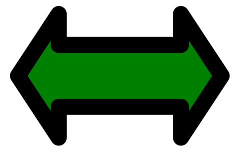
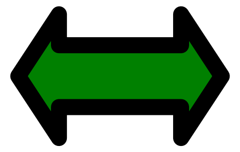
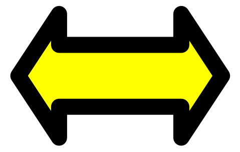
Mutual Exclusion, Formally

- Let $CS_i^k \Longleftrightarrow$ be thread i's k-th critical section execution

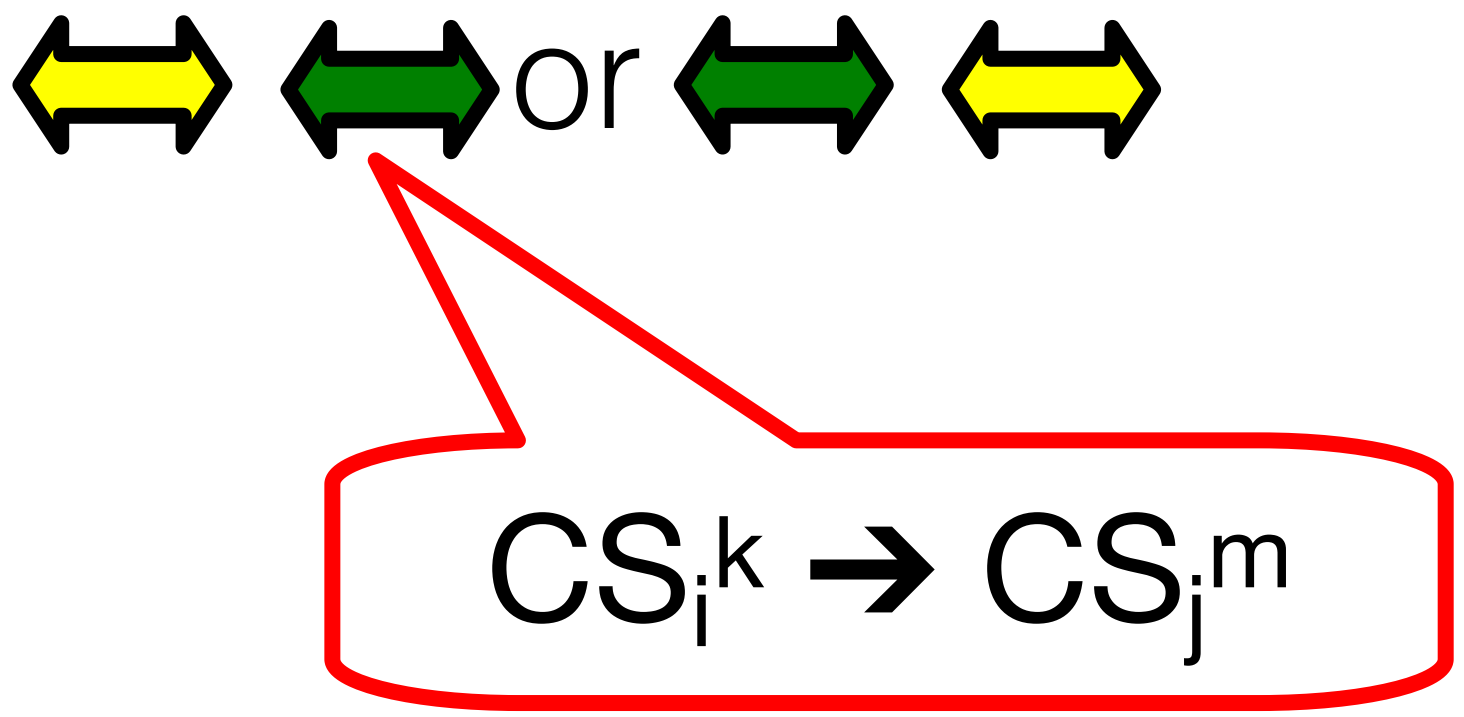
Mutual Exclusion, Formally

- Let CS_i^k $\Longleftrightarrow$ be thread i's k-th critical section execution
- And CS_j^m $\Longleftrightarrow$ be thread j's m-th critical section execution

Mutual Exclusion, Formally

- Let CS_i^k  be thread i's k-th critical section execution
- And CS_j^m  be thread j's m-th critical section execution
- Then either
  -   or  

Mutual Exclusion, Formally

- Let CS_i^k be thread i's k-th critical section execution
- And CS_j^m be thread j's m-th execution
- Then either
  - 

Mutual Exclusion, Formally

- Let CS_i^k be thread i's k-th critical section execution
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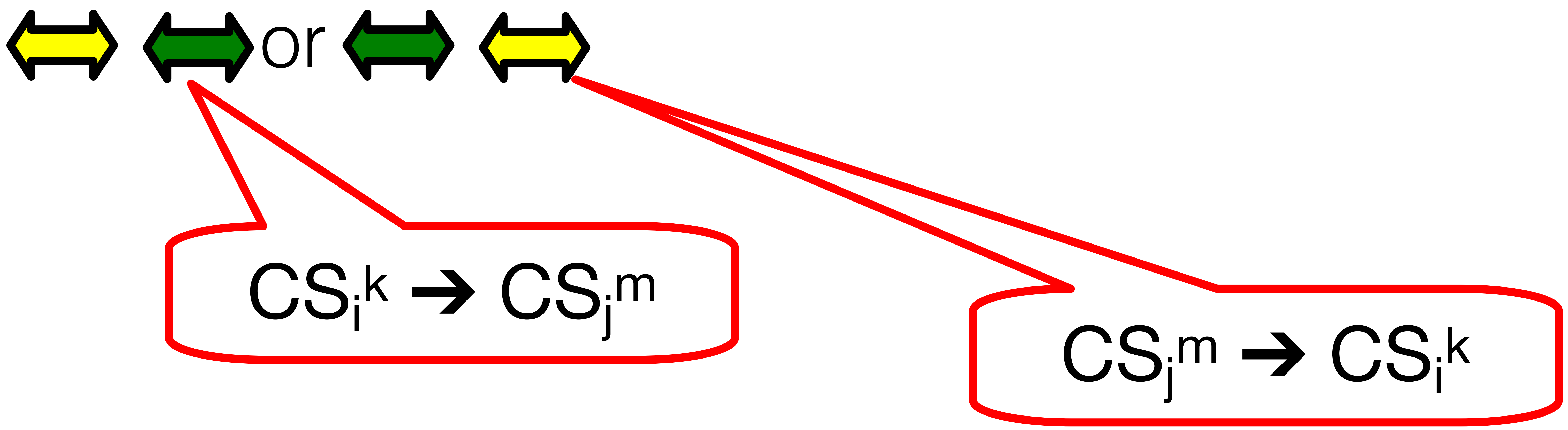
  - 

Aka: it is guaranteed that one critical section happens before the other (NOT concurently)

Deadlock-Free

- If some thread calls **lock()**
  - And never returns
  - Then other threads must complete **lock()** and **unlock()** calls infinitely often
- System as a whole makes progress
  - Even if individuals starve

Starvation-Free

- If some thread calls lock()
  - It will eventually return
- Individual threads make progress

Locking in Java

- Most locks are *reentrant*: if you hold it, and ask for it again, you don't have to wait (because you already have it)
- Basic primitives:
  - `synchronized{}`
  - We will come back to in next few weeks
- Plus…
  - `Lock` API… `lock.lock()`, `lock.unlock()`
  - The *preferred* way

How to Implement a Lock?

- Note - we will ONLY discuss how to implement mutual exclusion locks for *two* threads
  - *n*-Thread solutions exist too, they just take somewhat longer to explain (see book if curious)
- Note - It's unlikely you will ever implement a mutual exclusion lock. But, they provide a great example to understand how to write concurrent algorithms

Peterson's Algorithm

```
public void lock() {
 flag[i] = true;
 victim  = i;
 while (flag[j] && victim == i) {};
}
public void unlock() {
 flag[i] = false;
}
```

Where `i` is the index of the current thread, `j` is the index of the other thread

Peterson’s Algorithm

Announce I’m interested

```
public void lock() {
 flag[i] = true;
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Announce I'm interested

Defer to other

Where `i` is the index of the current thread, `j` is the index of the other thread

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Announce I'm interested

Defer to other

Wait while other interested & I'm the victim

Where `i` is the index of the current thread, `j` is the index of the other thread

Peterson's Algorithm

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public void lock() {
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 }
public void unlock() {
 flag[i] = false;
}
```

Announce I'm interested

Defer to other

Wait while other interested & I'm the victim

No longer interested

Where `i` is the index of the current thread, `j` is the index of the other thread

Peterson's Alg: Mutual Exclusion

```
public void lock() {
  flag[i] = true;
  victim  = i;
  while (flag[j] && victim == i) {};
```

- If thread **1** in critical section,
  - `flag[1]=true`,
  - `victim = 0`
- If thread **0** in critical section,
  - `flag[0]=true`,
  - `victim = 1`

Cannot both be true, hence yes: it is safe!

Peterson's Alg: Deadlock Free

```
public void lock() {
  …
  while (flag[j] && victim == i) {};
```

- Thread blocked
  - only at `while` loop
  - only if it is the victim
- One or the other must not be the victim

Peterson's Alg: Starvation Free

- Thread `i` blocked only if `j` repeatedly re-enters so that

  `flag[j] == true` and `victim == i`

- When `j` re-enters
  - it sets `victim` to `j`.
  - So `i` gets in

```
public void lock() {
  flag[i] = true;
  victim    = i;
  while (flag[j] && victim == i) {};
}

public void unlock() {
  flag[i] = false;
}
```

Introducing HW1

https://www.jonbell.net/gmu-cs-475-fall-2019/homework-1/

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Peterson's Algorithm

Thread 0	Thread 1
i=0	i=1
j=1	j=0

```
public void lock() {
 flag[i] = true;
 victim  = i;
 while (flag[j] && victim == i) {};
}
public void unlock() {
 flag[i] = false;
}
```

Victim:

flag[0]:

flag[1]:

Peterson's Algorithm

```
true
true
false
false
0
0
1
1
```

Thread 0 wants lock, Thread 1 doesn't have or want it

Thread 0 wants lock, Thread 1 has it already

Thread 1 wants lock, Thread 0 wants it also

Thread 0 ⟶

Thread 1 ⟶