# Mutual Exclusion

CS 475, Spring 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: Processes vs Threads

- How threads and processes are similar
  - Each has its own logical control flow.
  - Each can run concurrently.
  - Each is context switched.
- How threads and processes are different
  - Threads share code and data, processes (typically) do not.
  - Threads are somewhat less expensive than processes.
  - Process control (creating and reaping) is (ballpark!) twice as expensive as thread control.

# 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!

# Review: Splitting up the work

- The problem: What if we have thousands of tasks to do simultaneously, should we make a new thread for each?
  - No (lots of overhead, probably too many threads)
- The answer: think about work as **tasks** and not **threads**
  - Threads will magically appear to do your tasks
  - Tasks -> **Runnable** and **Callable** objects
  - **ExecutorService** handles taking tasks and running them

# Today

- Mutual exclusion, formally
  - Definitions for time, ordering
  - Locks, and locking algorithms
- Reading: H&S 2.1-2.3
- Note: HW1 posted: https://www.jonbell.net/gmu-cs-475-spring-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

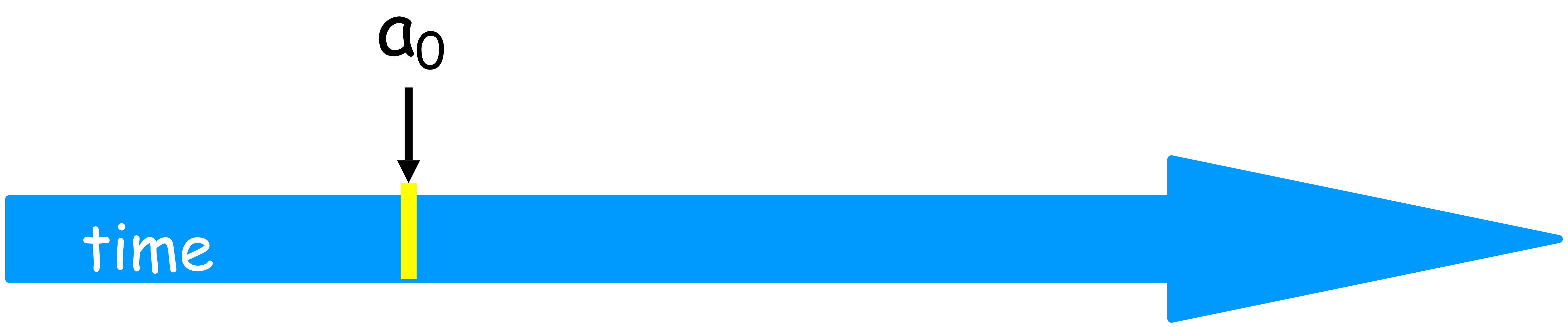
# Time

- “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)

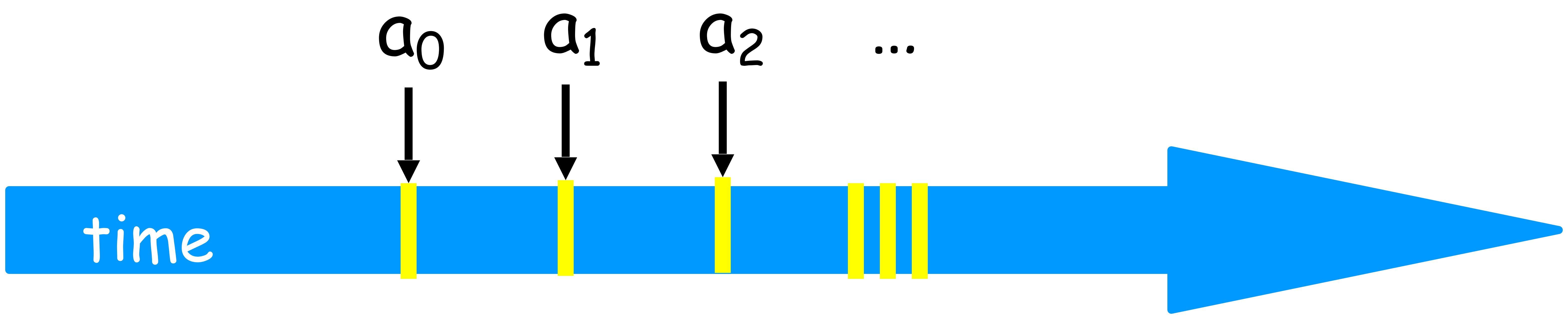
# Events

- 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

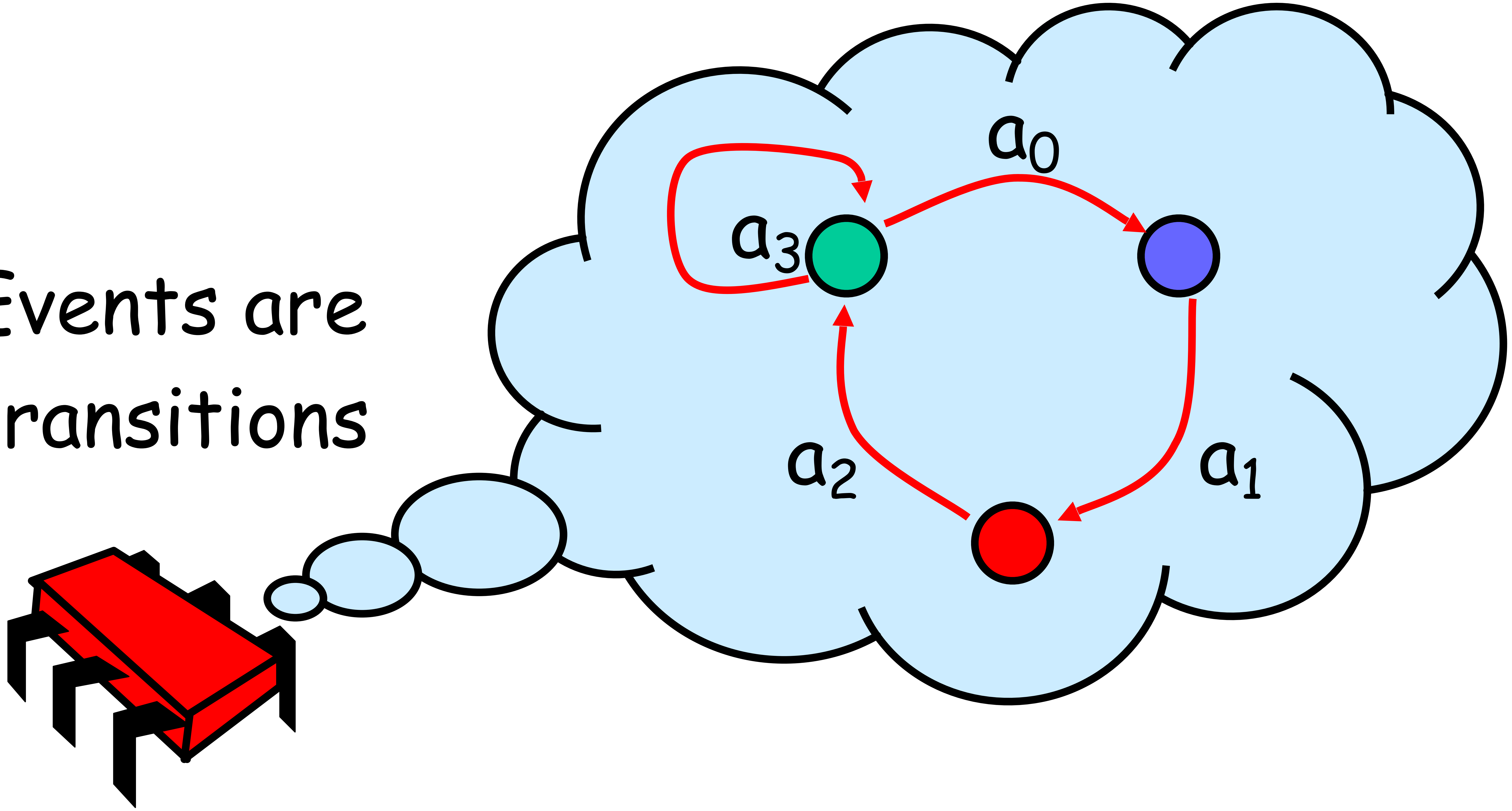


# Example Thread Events

- 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

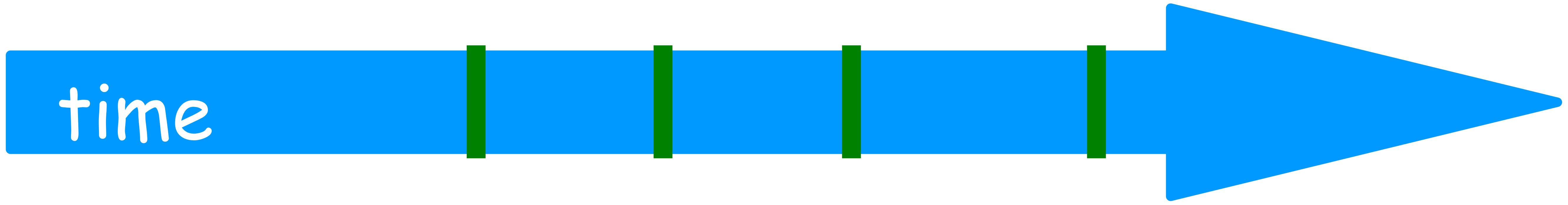
# Concurrency

- Thread A

# Concurrency

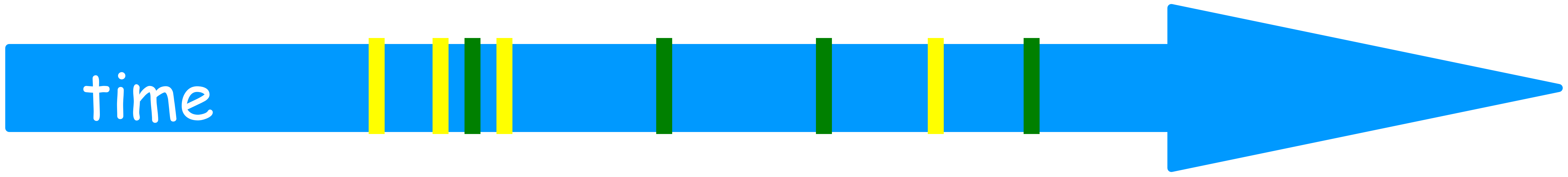
- Thread A


- Thread B



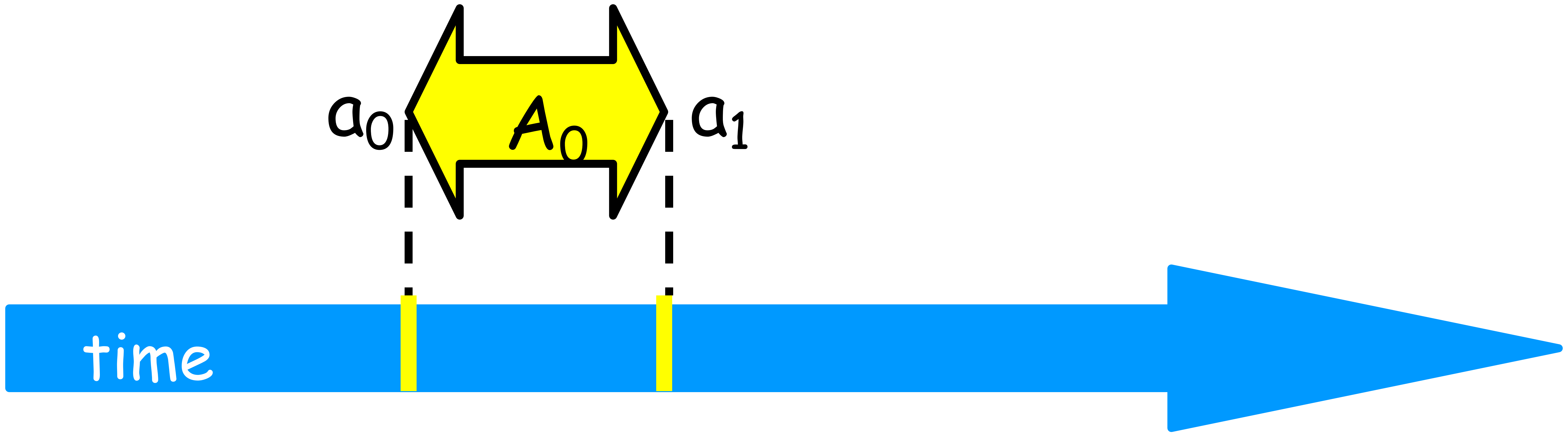
# Interleavings

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

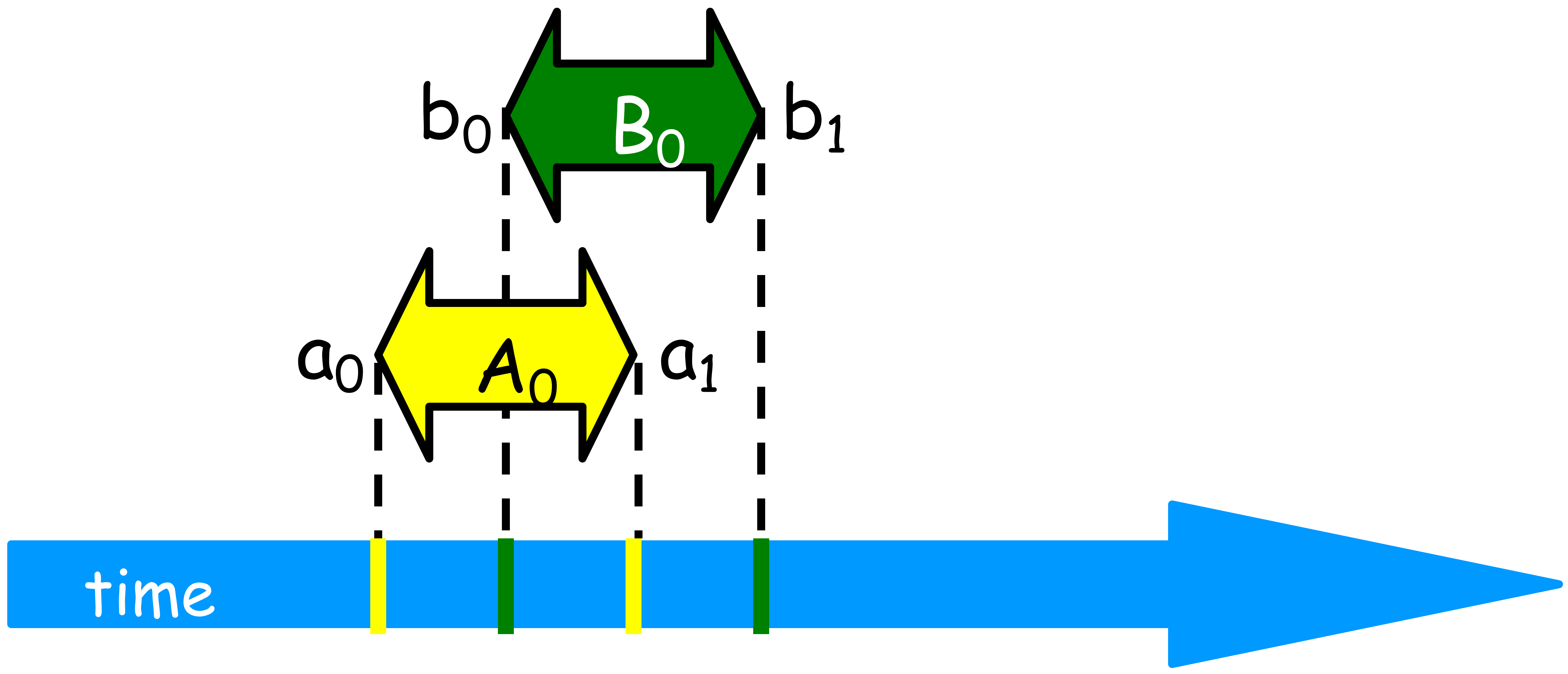


# Intervals

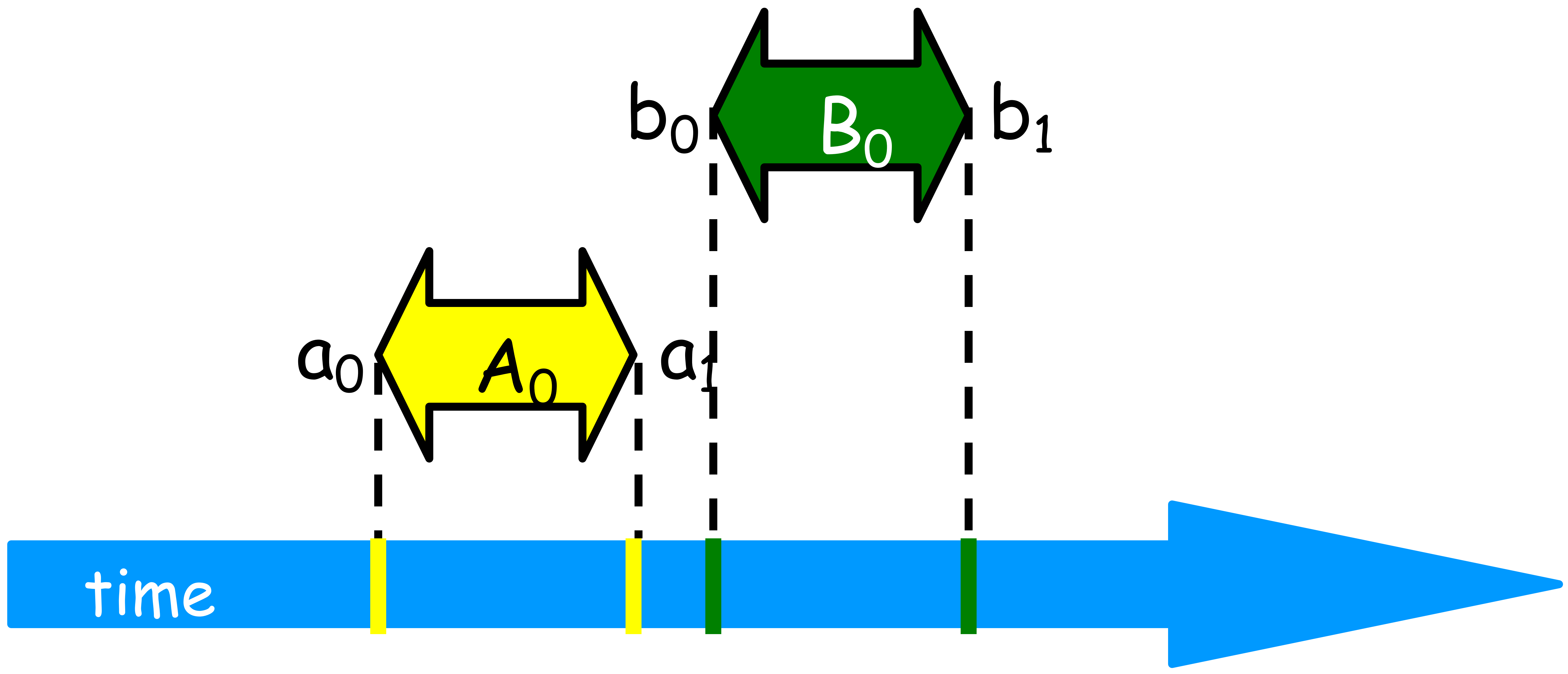
- An interval $A_0 = (a_0, a_1)$ is
  - Time between events $a_0$ and $a_1$



# Intervals may Overlap

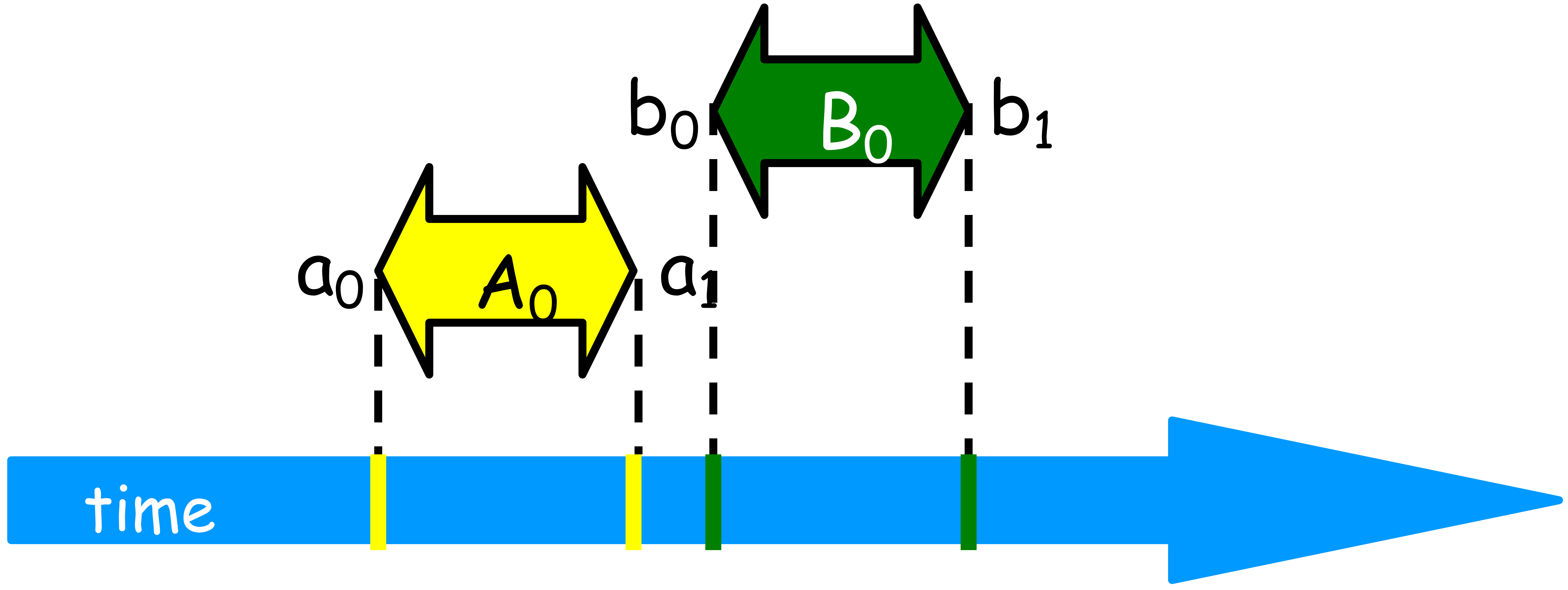


# Intervals may be Disjoint

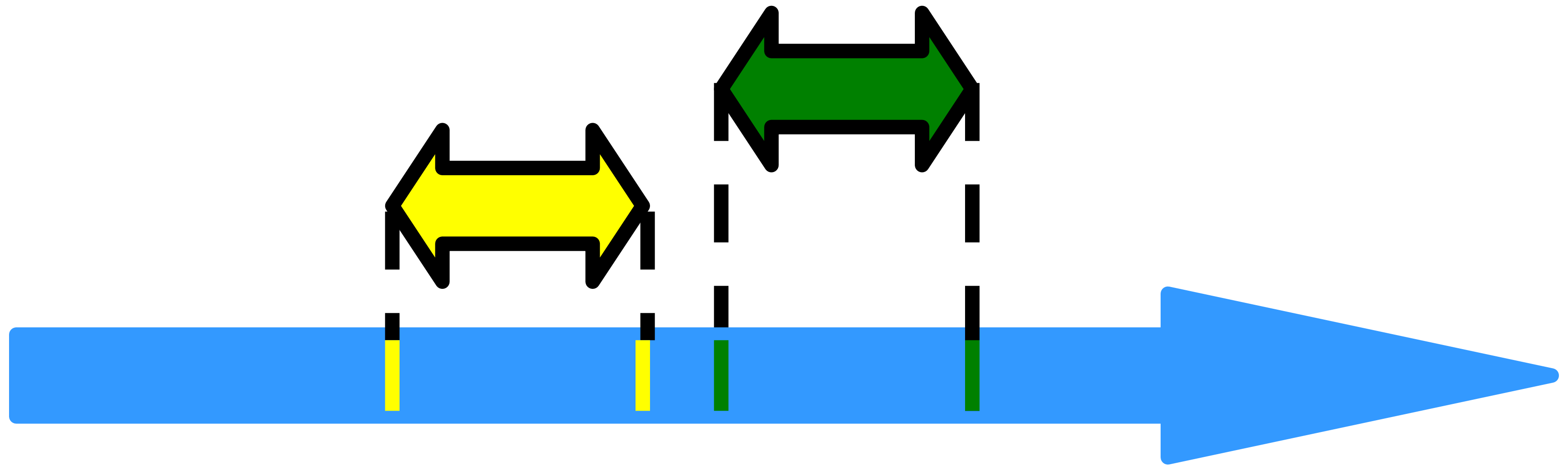


# Precedence

Interval $A_0$ precedes interval $B_0$

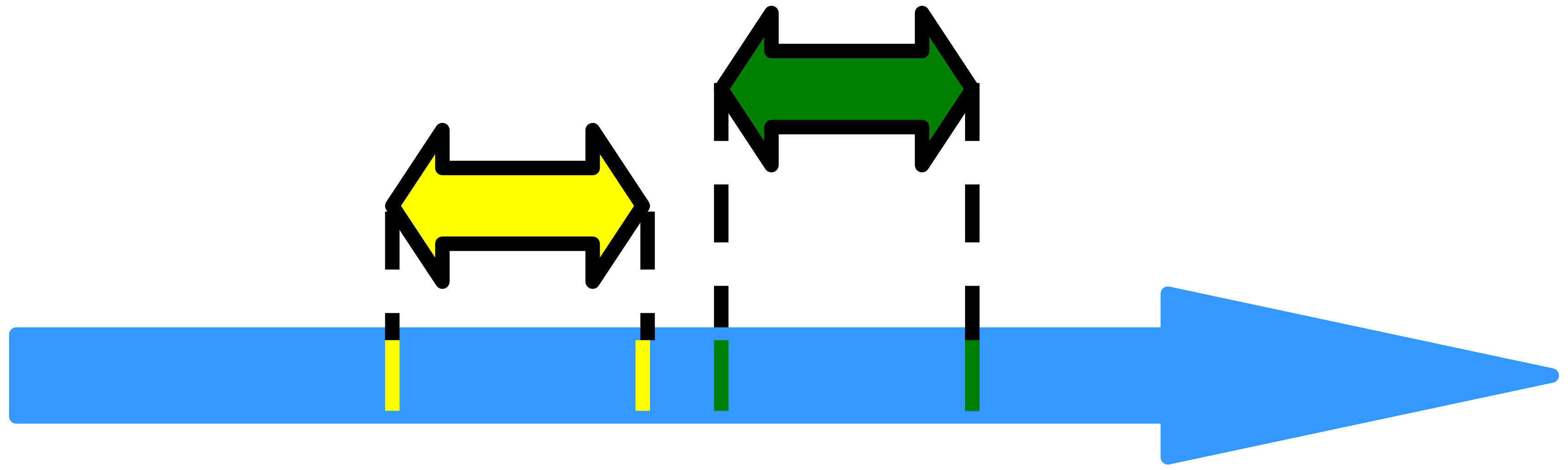


# Precedence



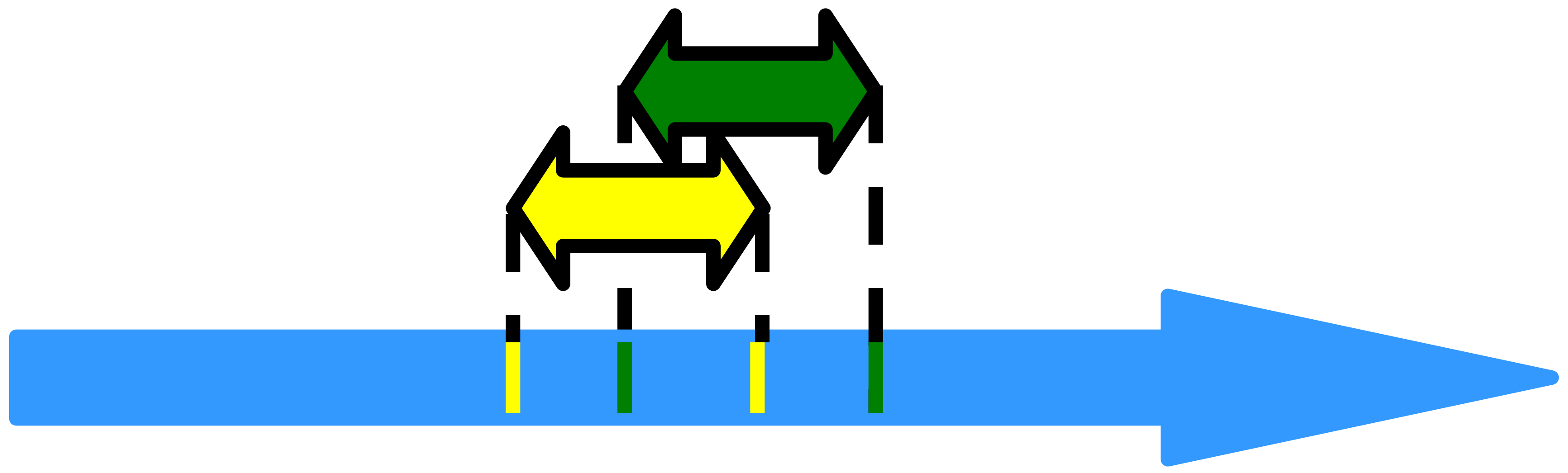
- Notation: $A_0 \rightarrow B_0$
- Formally,
  - End event of $A_0$ before start event of $B_0$
  - Also called “happens before” or “precedes”

# 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

# Repeated Events

```
while (mumble) {
  a0; a1;
}
```

$a_0^k$

$A_0^k$

k-th occurrence of event $a_0$

k-th occurrence of interval $A_0 = (a_0, a_1)$

# 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();
}
```

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public interface Lock {

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acquire lock

# Locks (Mutual Exclusion)

```
public interface Lock {

public void lock();

public void unlock();
}
```

acquire lock

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

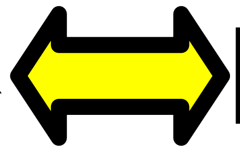
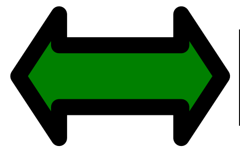
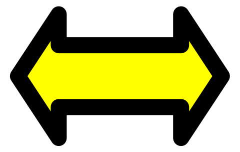
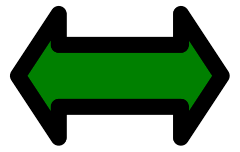
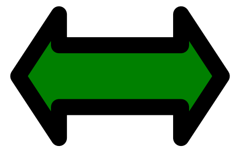
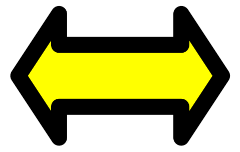
# Mutual Exclusion, Formally

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

# Mutual Exclusion, Formally

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

$CS_i^k \rightarrow CS_j^m$

# 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
  - ⟺ ⟺ or ⟺ ⟺

$CS_i^k \rightarrow CS_j^m$

$CS_j^m \rightarrow CS_i^k$

**Aka: it is guaranteed that one critical section happens before the other**

# 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{}`
- Plus…
  - `Lock` API… `lock.lock()`, `lock.unlock()`
  - The *preferred* way

# Live programming: Locks

# Synchronized methods in Java

```
public synchronized static void increment()
{
    i = i + 1;
}
```

Result: Before entering `increment()`, thread gets a lock on the Class object of `increment()`

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```java
public synchronized static void increment()
{
    i = i + 1;
}
```

Result: Before entering `increment()`, thread gets a lock on the Class object of `increment()`

```java
public synchronized static void incrementOther()
{
    j = j + 1;
}
```

Result: Before entering `incrementOther()`, thread gets a lock on the Class object of `incrementOther()`

**Problem?**

# Synchronized blocks in Java

- Can also use *any* object as that monitor

```
static Object someObject = new Object();
public static void increment()
{
    synchronized(someObject){
        i = i + 1;
    }
}
static Object someOtherObject = new Object();
public static void incrementOther()
{
    synchronized(someOtherObject){
        j = j + 1;
    }
}
```

Now, two different threads could call `increment()` and `incrementOther()` at the same time

# Live programming: Synchronized

# Implementing Locks: Peterson's Algorithm

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

# Peterson's Algorithm

Announce I'm interested

```
public void lock() {
 flag[i] = true;
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Wait while other interested & I'm the victim

# Peterson's Algorithm

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flag[i] = false;
}
```

Announce I'm interested

Defer to other

Wait while other interested & I'm the victim

No longer interested

# 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;
}
```

# Locking Granularity

- BIG design question in writing concurrent programs: how many locks should you have?
- Example: Distributed filesystem
  - It would be *correct* to block all clients from reading *any* file, when one client writes a file
  - However, this would not be performant at all!
  - It would be much better to instead lock on *individual files*
- *More locks -> more complicated semantics and tricky to avoid deadlocks, races*

# 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

# Example

- Ten processors
- 60% concurrent, 40% sequential
- How close to 10-fold speedup?

# Example

- Ten processors
- 60% concurrent, 40% sequential
- How close to 10-fold speedup?

$$\text{Speedup}=2.17=\frac{1}{1-0.6+\frac{0.6}{10}}$$

# Example

- Ten processors
- 80% concurrent, 20% sequential
- How close to 10-fold speedup?

$$\text{Speedup}=3.57=\frac{1}{1-0.8+\frac{0.8}{10}}$$

# Example

- Ten processors
- 90% concurrent, 10% sequential
- How close to 10-fold speedup?

$$\text{Speedup}=5.26=\frac{1}{1-0.9+\frac{0.9}{10}}$$

# Example

- Ten processors
- 99% concurrent, 01% sequential
- How close to 10-fold speedup?

$$\text{Speedup}=9.17=\frac{1}{1-0.99+\frac{0.99}{10}}$$

# The Moral

- Making good use of our multiple processors (cores) means
- Finding ways to effectively parallelize our code
  - Minimize sequential parts
  - Reduce idle time in which threads **wait** without
- This will be a constant theme throughout the course!

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