ECE/CS 5510 Multiprocessor Programming

Mutual Exclusion

Chapter 2, The Art of Multiprocessor Programming
(Maurice Herlihy & Nir Shavit)

Mutual Exclusion

- 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

Mutual Exclusion

In his 1965 paper E. W. Dijkstra wrote:

"Given in this paper is a solution to a problem which, to the knowledge of the author, has been an open question since at least 1962, irrespective of the solvability. [...] Although the setting of the problem might seem somewhat academic at first, the author trusts that anyone familiar with the logical problems that arise in computer coupling will appreciate the significance of the fact that this problem indeed can be solved."

Mutual Exclusion

- Formal problem definitions
- Solutions for 2 threads
- Solutions for *n* threads
- Fair solutions
- Inherent costs

Warning

- You will never use these protocols
  - Get over it
- You are advised to understand them
  - The same issues show up everywhere
  - Except hidden and more complex

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

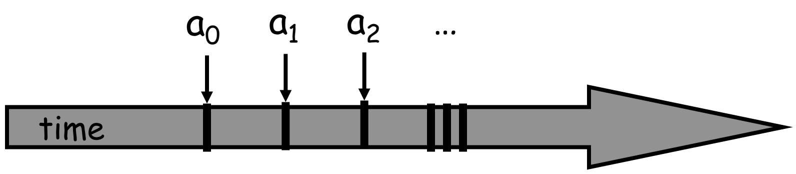
- "Absolute, true and mathematical time, of itself and from its own nature, flows equably without relation to anything external." (I. Newton, 1689)
- "Time is, like, Nature's way of making sure that everything doesn't happen all at once." (Anonymous, circa 1968)

Events

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

Threads

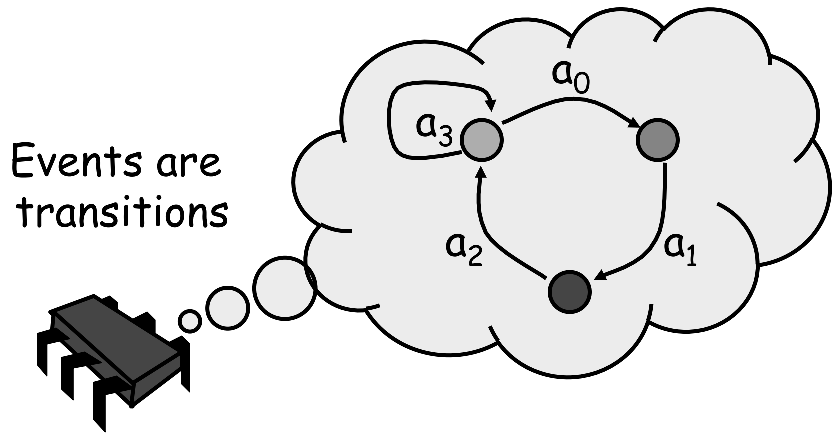
- A *thread* A is (formally) a sequence $a_0, a_1, \ldots$ of events
  - "Trace" model
  - Notation: $a_0 \rightarrow a_1$ indicates order



Example Thread Events

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

Threads are State Machines



States

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

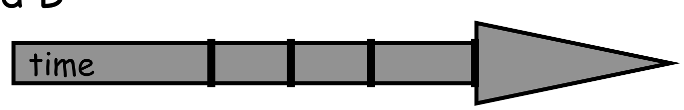
Concurrency

- Thread A

Concurrency

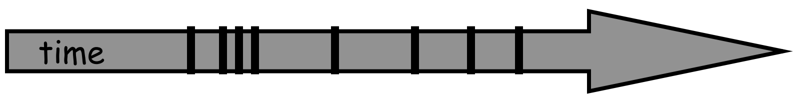
- Thread A

- Thread B



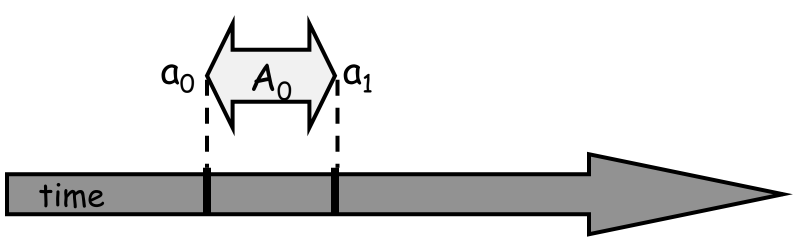
Interleavings

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

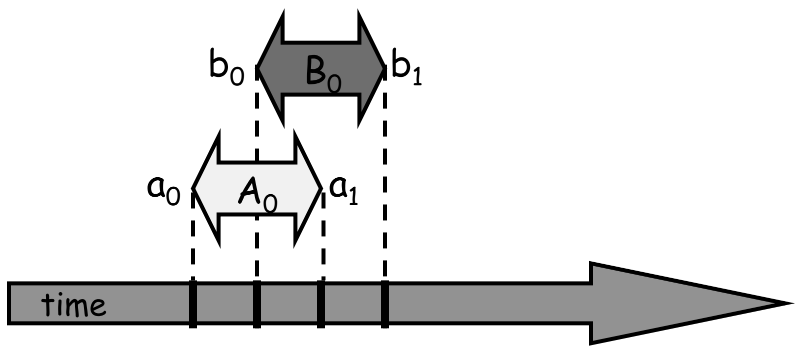


Intervals

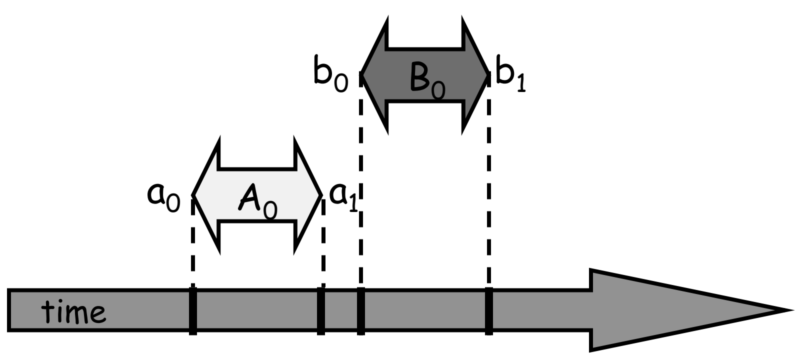
- An *interval* $A_0 = (a_0, a_1)$ is
  - Time between events a_0 and a_1



Intervals may Overlap

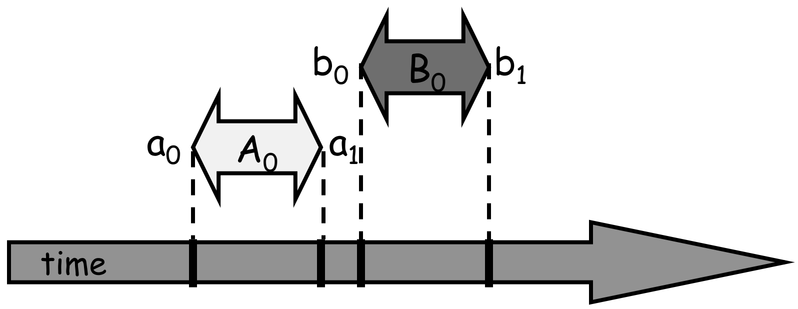


Intervals may be Disjoint

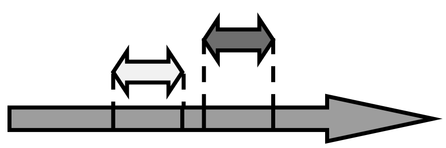


Precedence

Interval A_0 precedes interval B_0

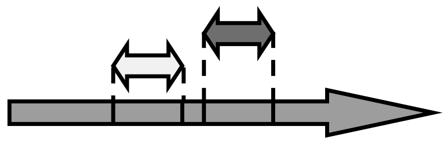


Precedence



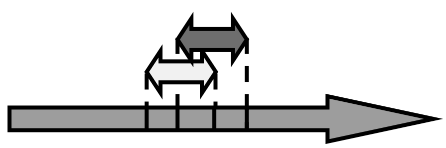
- Notation: $A_0 \rightarrow B_0$
- Formally,
  - End event of A_0 before start event of B_0
  - Also called "happens before" or "precedes"

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
  - "Totality"

Total order = partial order + totality

Repeated Events

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

a_0^k

k-th occurrence of event a_0

A_0^k

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();
}
```

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

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

Now, we will formalize properties that a good lock algorithm must exhibit

Mutual Exclusion

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

Mutual Exclusion

- 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

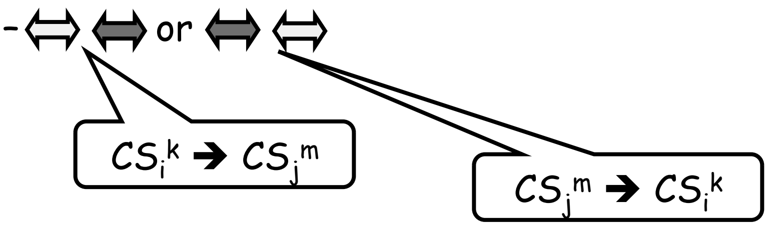
- Let CS_i^k ⟺ be thread i's k-th critical section execution
- And CS_j^m ⟺ be j's m-th execution
- Then either
  - ⟺ ⟺ or ⟺ ⟺

Mutual Exclusion

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

$CS_i^k \rightarrow CS_j^m$

Mutual Exclusion

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

Deadlock-Free

- If some thread calls **lock()**, then some thread will succeed, meaning:
- 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

- Note: starvation-freedom implies deadlock-freedom
  - So if former holds, no need to prove latter

Two-Thread vs *n* -Thread Solutions

- Two-thread solutions first
  - Illustrate most basic ideas
  - Fits on one slide
- Then n-Thread solutions

Two-Thread Conventions

```
class … implements Lock {
  …
  // thread-local index, 0 or 1
  public void lock() {
    int i = ThreadID.get();
    int j = 1 - i;
  …
  }
}
```

Two-Thread Conventions

```
class … implements Lock {
  …
  // thread-local index, 0 or 1
  public void lock() {
    int i = ThreadID.get();
    int j = 1 - i;
  …
  }
}
```

Henceforth: i is current thread, j is other thread

LockOne

```
class LockOne implements Lock {
private boolean[] flag =
                        new boolean[2];
public void lock() {
  flag[i] = true;
  while (flag[j]) {}
 }
```

LockOne

```
class LockOne implements Lock {
private boolean[] flag =
                        new boolean[2];
public void lock() {
  flag[i] = true;
  while (flag[j]) {}
 }
```

Set my flag

LockOne

```
class LockOne implements Lock {
private boolean[] flag =
                        new boolean[2];
public void lock() {
  flag[i] = true;
  while (flag[j]) {}
 }
```

Set my flag

Wait for other flag to go false

LockOne

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

}
```

Set my flag

LockOne Satisfies Mutual Exclusion

- Assume CS_A^j overlaps CS_B^k
- Consider each thread's last (j-th and k-th) read and write in the lock() method before entering
- Derive a contradiction

From the Code

- **$write_A$(flag[A]=true) → $read_A$(flag[B]==false) → CS_A**
- **$write_B$(flag[B]=true) → $read_B$(flag[A]==false) → CS_B**

```
class LockOne implements Lock {
…
public void lock() {
  flag[i] = true;
  while (flag[j]) {}
 }
```

From the Assumption

- **read_A(flag[B]==false) → write_B(flag[B]=true)**
- **read_B(flag[A]==false) → write_A(flag[A]=true)**

Combining

- Assumptions:
  - **read_A(flag[B]==false) → write_B(flag[B]=true)**
  - **read_B(flag[A]==false) → write_A(flag[A]=true)**
- From the code
  - **write_A(flag[A]=true) → read_A(flag[B]==false)**
  - **write_B(flag[B]=true) → read_B(flag[A]==false)**

Combining

- Assumptions:
  - $read_A(flag[B]==false) \rightarrow write_B(flag[B]=true)$
  - $read_B(flag[A]==false) \rightarrow write_A(flag[A]=true)$
- From the code
  - $write_A(flag[A]=true) \rightarrow read_A(flag[B]==false)$
  - $write_B(flag[B]=true) \rightarrow read_B(flag[A]==false)$

Combining

- Assumptions:
  - $read_A(flag[B]==false) \rightarrow write_B(flag[B]=true)$
  - $read_B(flag[A]==false) \rightarrow write_A(flag[A]=true)$
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Combining

- Assumptions:
  - $read_A(flag[B]==false) \rightarrow write_B(flag[B]=true)$
  - $read_B(flag[A]==false) \rightarrow write_A(flag[A]=true)$
- From the code
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  - $read_A(flag[B]==false) \rightarrow write_B(flag[B]=true)$
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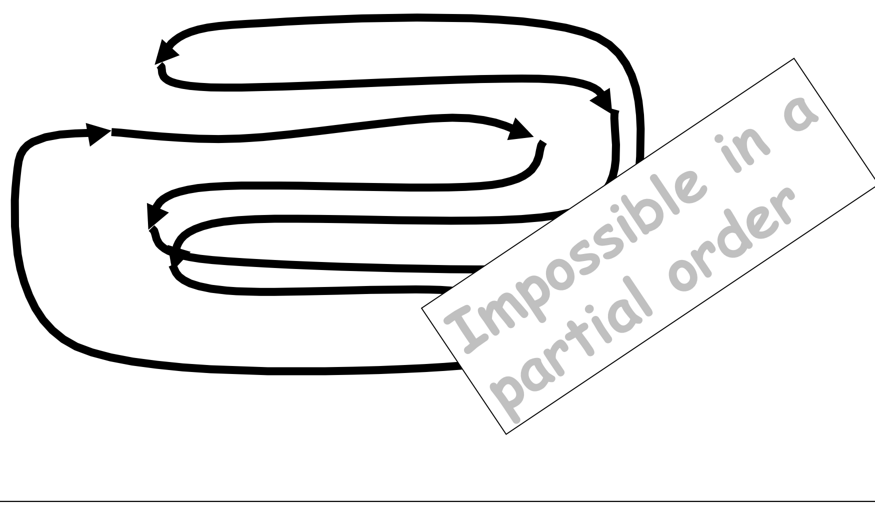
Combining

- Assumptions:
  - $read_A(flag[B]==false) \rightarrow write_B(flag[B]=true)$
  - $read_B(flag[A]==false) \rightarrow write_A(flag[A]=true)$
- From the code
  - $write_A(flag[A]=true) \rightarrow read_A(flag[B]==false)$
  - $write_B(flag[B]=true) \rightarrow read_B(flag[A]==false)$

Cycle!



Deadlock Freedom

- LockOne Fails deadlock-freedom
  - Concurrent execution can deadlock

```
flag[i] = true;     flag[j] = true;
while (flag[j]){}   while (flag[i]){}
```

  - Sequential executions OK

LockTwo

```
public class LockTwo implements Lock {
 private int victim;
 public void lock() {
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```

LockTwo

```
public class LockTwo implements Lock {
 private int victim;
 public void lock() {
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```

Let other go first

LockTwo

```
public class LockTwo implements Lock {
 private int victim;
 public void lock() {
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```

Wait for permission

LockTwo

```
public class Lock2 implements Lock {
 private int victim;
 public void lock() {
  victim = i;
  while (victim == i) {};
 }

 public void unlock() {}
}
```

Nothing to do

LockTwo Claims

- Satisfies mutual exclusion
  - If thread **i** in CS
  - Then **victim == j**
  - Cannot be both 0 and 1
- Not deadlock free
  - Sequential execution deadlocks
  - Concurrent execution does not

```
public void LockTwo() {
  victim = i;
  while (victim == i) {};
 }
```

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

Peterson's Algorithm

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

Announce I'm interested

Defer to other

Peterson's Algorithm

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

Announce I'm interested

Defer to other

Wait while other interested & I'm the victim

Peterson's Algorithm

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

Announce I'm interested

Defer to other

Wait while other interested & I'm the victim

No longer interested

Mutual Exclusion

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

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

Cannot both be true

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

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

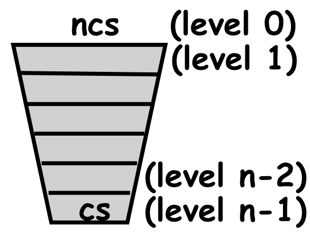
```
public void lock() {
  flag[i] = true;
  victim   = i;
  while (flag[j] && victim == i) {};
}

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

The Filter Algorithm for *n* Threads

There are ***n-1*** "waiting rooms" called levels

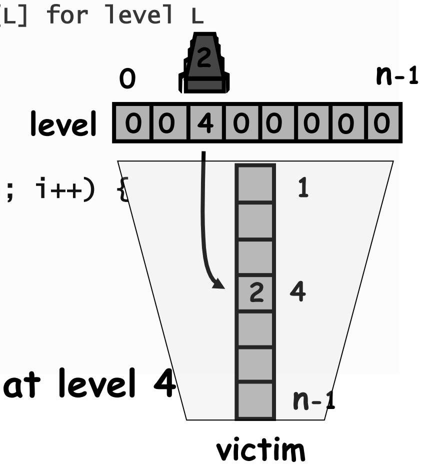
- At each level
  - At least one enters level
  - At least one blocked if many try
- Only one thread makes it through



Filter

```
class Filter implements Lock {
   int[] level;  // level[i] for thread i
   int[] victim; // victim[L] for level L

  public Filter(int n) {
     level  = new int[n];
     victim = new int[n];
     for (int i = 0; i < n; i++) {
         level[i] = 0;
     }}
   …
}
```



Thread 2 at level 4

Filter

```
class Filter implements Lock {
  …

  public void lock(){
    for (int L = 1; L < n; L++) {
      level[i]  = L;
      victim[L] = i;
      while ((∃ k != i level[k] >= L) &&
             victim[L] == i );
    }}
  public void unlock() {
    level[i] = 0;
  }}
```

Filter

```
class Filter implements Lock {
  …

  public void lock() {
    for (int L = 1; L < n; L++) {
      level[i]  = L;
      victim[L] = i;
      while ((∃ k != i) level[k] >= L) &&
             victim[L] == i);
    }}
  public void release(int i) {
    level[i] = 0;
  }}
```

One level at a time

Filter

```
class Filter implements Lock {
  …

  public void lock() {
    for (int L = 1; L < n; L++) {
      level[i]  = L;
      victim[L] = i;
      while ((∃ k != i) level[k] >= L) &&
             victim[L] == i)
    }}
  public void release(int i)
    level[i] = 0;
  }}
```

Announce intention to enter level L

Filter

```
class Filter implements Lock {
  int level[n];
  int victim[n];
  public void lock() {
    for (int L = 1; L < n; L++) {
      level[i]  = L;
      victim[L] = i;
      while ((∃ k != i) level[k] >= L) &&
             victim[L] == i);
    }}
  public void release(int i)
    level[i] = 0;
  }}
```

Give priority to anyone but me

Filter

Wait as long as someone else is at same or higher level, and I'm designated victim

```
  public void lock() {
    for (int L = 1; L < n; L++) {
      level[i]  = L;
      victim[L] = i;
      while ((∃ k != i) level[k] >= L) &&
             victim[L] == i);
    }}
  public void release(int i) {
    level[i] = 0;
  }}
```

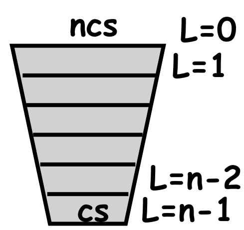
Filter

```
class Filter implements Lock {
  int level[n];
  int victim[n];
  public void lock() {
    for (int L = 1; L < n; L++) {
      level[i]  = L;
      victim[L] = i;
      while ((∃ k != i) level[k] >= L) &&
             victim[L] == i);
    }}
```

Thread **enters** level L when it completes the loop

Claim

- Start at level L=0
- At most n-L threads enter level L
- Mutual exclusion at level L=n-1



Proof is by induction on L

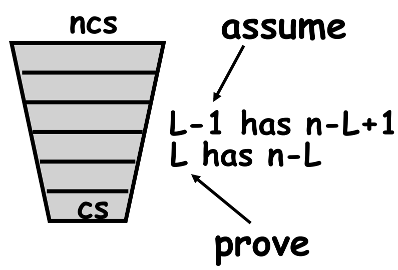
- Base case: L = 0
- From code inspection, n threads are at level L = 0

```
public void lock() {
 for (int L = 1; L < n; L++) {
   level[i] = L;
   victim[L]  = i;
   while ((∃ k != i) le
         && victim[L]
 }}
```

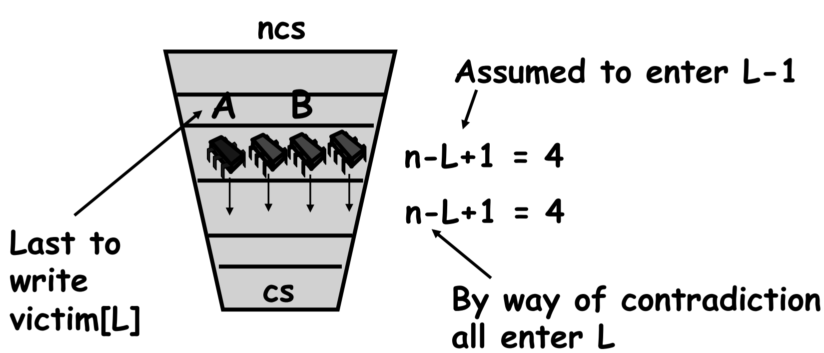
```
public Filter(int n) {
  …
  for (int i = 0; i < n; i++) {
        level[i] = 0;
  }}
  …
```

Induction Hypothesis

- No more than n-L+1 at level L-1
- Induction step: by contradiction
- Assume all at level L-1 enter level L
- A is last to write victim[L]
- B is any other thread at level L



Proof Structure



Show that A must have seen B in level[L] and since victim[L] == A could not have entered

From the Code

(1) $\text{write}_B(\text{level}[B]=L) \rightarrow \text{write}_B(\text{victim}[L]=B)$

```
public void lock() {
 for (int L = 1; L < n; L++) {
   level[i] = L;
   victim[L]  = i;
   while ((∃ k != i) level[k] >= L)
          && victim[L] == i) {};
   }}
```

From the Code

(2) $\text{write}_A(\text{victim}[L]=A) \rightarrow \text{read}_A(\text{level}[B])$

```
public void lock() {
 for (int L = 1; L < n; L++) {
   level[i] = L;
   victim[L]  = i;
   while ((∃ k != i) level[k] >= L)
          && victim[L] == i) {};
   }}
```

By Assumption

(3) $write_B$(victim[L]=B)➔$write_A$(victim[L]=A)

By assumption, *A* is the last thread to write **victim[L]**

Combining Observations

(1) $write_B$(level[B]=L)➔$write_B$(victim[L]=B)

(3) $write_B$(victim[L]=B)➔$write_A$(victim[L]=A)

(2) $write_A$(victim[L]=A)➔$read_A$(level[B])

Combining Observations

(1) $\text{write}_B(\text{level}[B]=L) \rightarrow$ $\boxed{}$

(3) $\text{write}_B(\text{victim}[L]=B) \rightarrow \text{write}_A(\text{victim}[L]=A)$

(2) $\boxed{} \rightarrow \text{read}_A(\text{level}[B])$

```
public void lock() {
 for (int L = 1; L < n; L++) {
   level[i]  = L;
   victim[L] = i;
   while ((∃ k != i) level[k] >= L)
          && victim[L] == i) {};
   }}
```


Combining Observations

(1) $\text{write}_B(\text{level}[B]=L) \rightarrow$ $\boxed{}$

(3) $\text{write}_B(\text{victim}[L]=B) \rightarrow \text{write}_A(\text{victim}[L]=A)$

(2) $\boxed{} \rightarrow \text{read}_A(\text{level}[B])$

Thus, A read level[B] ≥ L,
A was last to write victim[L],
so it could not have entered level L!

No Starvation

- Filter Lock satisfies properties:
  - Just like Peterson Alg at any level
  - So no one starves
- But what about fairness?
  - Threads can be overtaken by others
  - E.g., thread A which called lock() earlier than B may write to victim[L] later than B

Bounded Waiting

- Want stronger fairness guarantees
- Thread not “overtaken” too much
- Need to adjust definitions ….

Bounded Waiting

- Divide `lock()` method into 2 parts:
  - Doorway interval:
    - Written D_A (for thread A)
    - always finishes in finite steps (no waiting!)
  - Waiting interval:
    - Written W_A (for thread A)
    - may take unbounded steps

r-Bounded Waiting

- For threads A and B:
  - If $D_A^k \rightarrow D_B^j$
    - A's k-th doorway precedes B's j-th doorway
  - Then $CS_A^k \rightarrow CS_B^{j+r}$
    - A's k-th critical section precedes B's (j+r)-th critical section
    - B cannot overtake A by more than r times
- First-come-first-served means r = 0.

Can we define bounded waiting without doorway/waiting intervals?

Fairness Again

- Filter Lock satisfies properties:
  - No one starves
  - But very weak fairness
    - Not **r-**bounded for any r!
  - That's pretty lame…

Bakery Algorithm

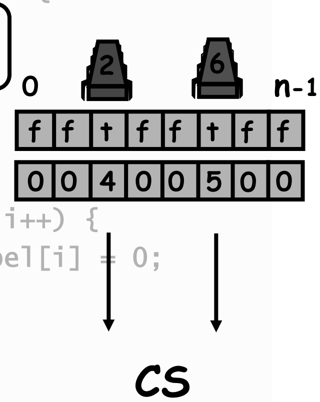
- Provides First-Come-First-Served
- How?
  - Take a "number"
  - Wait until lower numbers have been served
- Lexicographic order
  - (a,i) > (b,j)
    - If a > b, or a = b and i > j

Bakery Algorithm

```
class Bakery implements Lock {
   boolean[] flag;
   Label[] label;
  public Bakery (int n) {
    flag  = new boolean[n];
    label = new Label[n];
    for (int i = 0; i < n; i++) {
       flag[i] = false; label[i] = 0;
    }
  }
 …
```


Bakery Algorithm

```
class Bakery implements Lock {
   boolean[] flag;
   Label[] label;
  public Bakery (int n) {
    flag  = new boolean[n];
    label = new Label[n];
    for (int i = 0; i < n; i++) {
       flag[i] = false; label[i] = 0;
    }
  }
 …
```

Bakery Algorithm

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while ( (∃ k != i) flag[k]
            && (label[i],i) > (label[k],k));
 }
```

Bakery Algorithm

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
            && (label[i],i) > (label[k],k));
 }
```

Doorway

Bakery Algorithm

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

I'm interested

Bakery Algorithm

Take increasing label (read labels in some arbitrary order)

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

Threads read labels asynchronously, and in arbitrary order: set of labels seen before picking a new one may have never been in memory at the same time

Bakery Algorithm

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

Someone is interested

Bakery Algorithm

```
class Bakery implements Lock {
  boolean flag[n];
  int label[n];

 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

Someone is interested

With lower (label,i) in lexicographic order

Here also, threads read labels asynchronously, and in arbitrary order: set of labels seen before concluding on thread k's presence/absence may have never been in memory at the same time

Bakery Algorithm

```
class Bakery implements Lock {

    …

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

Bakery Algorithm

```
class Bakery implements Lock {

    …

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

No longer interested

labels are always increasing

No Deadlock

- There is always one thread with earliest label (i.e., unique least label/id pair)
- Ties are impossible (why?)

First-Come-First-Served

- If $D_A \rightarrow D_B$ then A's label is smaller
- And:
  - $write_A(flag[A]) \rightarrow write_A(label[A]) \rightarrow read_B(label[A]) \rightarrow write_B(label[B]) \rightarrow read_B(flag[A])$
- So B is locked out while flag[A] is true

```
class Bakery implements Lock {

public void lock() {
  flag[i]  = true;
  label[i] = max(label[0],
               …,label[n-1])+1;
  while (∃k flag[k]
            && (label[i],i) >
  (label[k],k));
 }
```

DF + FCFS = SF

Mutual Exclusion

- Suppose A and B in CS together
- Suppose A has a lower (label[A],A)
- When B entered, it must have seen
  - flag[A] is *false*, or
  - (label[A],A) > (label[B],B)

```
class Bakery implements Lock {

public void lock() {
  flag[i]  = true;
  label[i] = max(label[0],
                 …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) >
  (label[k],k));
 }
```

Mutual Exclusion

- Labels are strictly increasing so
- B must have seen flag[A] == false

Mutual Exclusion

- Labels are strictly increasing so
- B must have seen flag[A] == false
- $\text{Labeling}_B \rightarrow \text{read}_B(\text{flag}[A]) \rightarrow \text{write}_A(\text{flag}[A]) \rightarrow \text{Labeling}_A$

```
class Bakery implements Lock {

public void lock() {
  flag[i]  = true;
  label[i] = max(label[0],
                 …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

Mutual Exclusion

- Labels are strictly increasing so
- B must have seen flag[A] == false
- $\text{Labeling}_B \rightarrow \text{read}_B(\text{flag}[A]) \rightarrow \text{write}_A(\text{flag}[A]) \rightarrow \text{Labeling}_A$
- Which contradicts the assumption that A has a lower (label[A],A)

Bakery Y2^{32}K Bug

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

Bakery Y2^{32}K Bug

```
class Bakery implements Lock {
  …
 public void lock() {
  flag[i]  = true;
  label[i] = max(label[0], …,label[n-1])+1;
  while (∃k flag[k]
           && (label[i],i) > (label[k],k));
 }
```

Mutex breaks if `label[i]` overflows

FCFS also doesn't hold

Does Overflow Actually Matter?

- Yes
  - Y2K
  - 18 January 2038 (Unix `time_t` rollover)
  - 16-bit counters
- No
  - 64-bit counters
- Maybe
  - 32-bit counters

Timestamps

- Label variable is really a timestamp
- Need ability to
  - Read others' timestamps
  - Compare them
  - Generate a later timestamp
- Can we do this without overflow?

Timestamps

- Label variable is really a timestamp
- Need ability to
  - Read others' timestamps
  - Compare them
  - Generate a later timestamp
- Can we do this without overflow?
- Can we do this without waiting?

The Good News

- One can construct a
  - Wait-free (no mutual exclusion)
  - Concurrent
  - Timestamping system
  - That never overflows

The Bad News

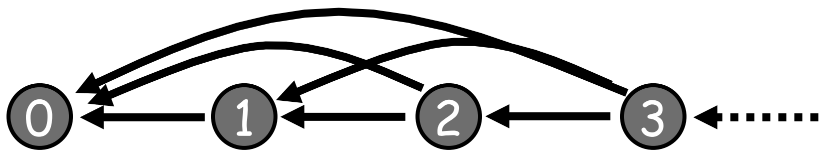
- One can construct a
  - Wait-free (no mutual exclusion)
  - Concurrent

    This part is hard
  - Timestamping system
  - That never overflows

Instead …

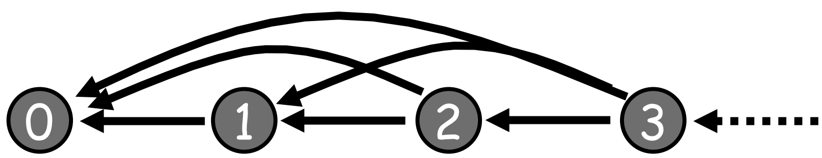
- We construct a Sequential timestamping system
  - Same basic idea
  - But simpler
- Uses mutex to read & write atomically
- No good for building locks
  - But useful anyway

Precedence Graphs



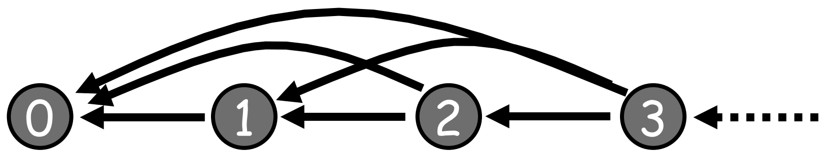
- Timestamps form directed graph
- Edge x to y
  - Means x is later timestamp
  - We say x dominates y

Unbounded Counter Precedence Graph

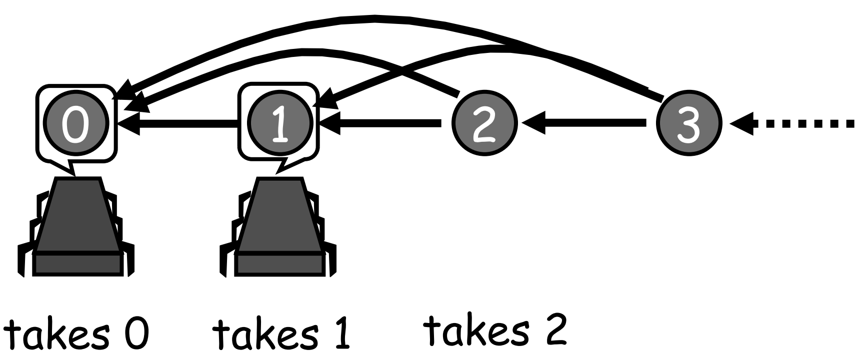


- Timestamping = move tokens on graph
- Atomically
  - read others' tokens
  - move mine
- Ignore tie-breaking for now

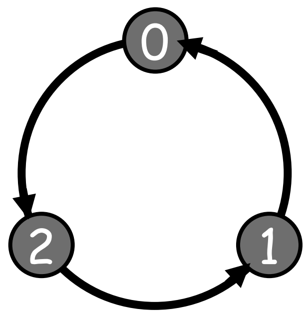
Unbounded Counter Precedence Graph



Unbounded Counter Precedence Graph

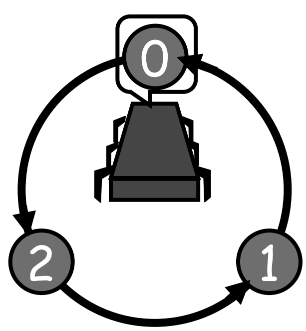


Two-Thread Bounded Precedence Graph

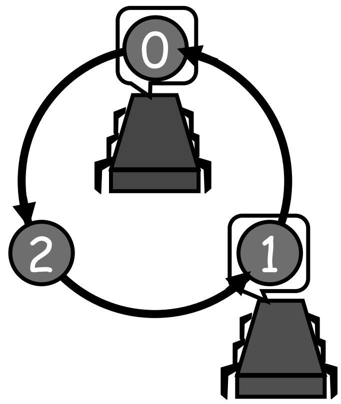


Edges define the ordering: 0 < 1; 1 < 2; 2 < 0

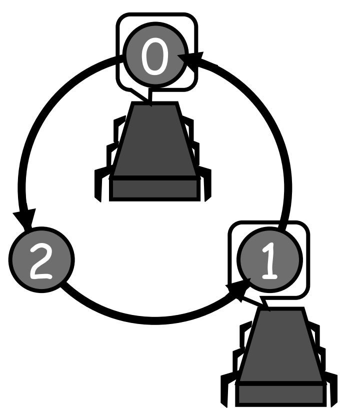
Two-Thread Bounded Precedence Graph



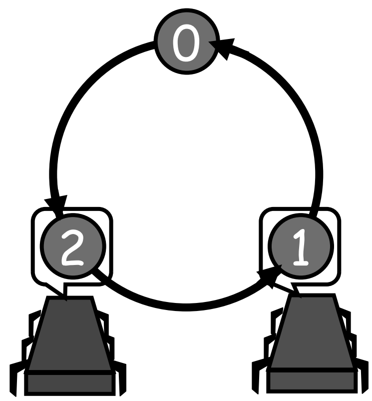
Two-Thread Bounded Precedence Graph



Two-Thread Bounded Precedence Graph

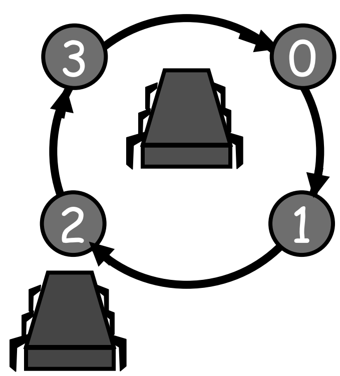


Two-Thread Bounded Precedence Graph T^2

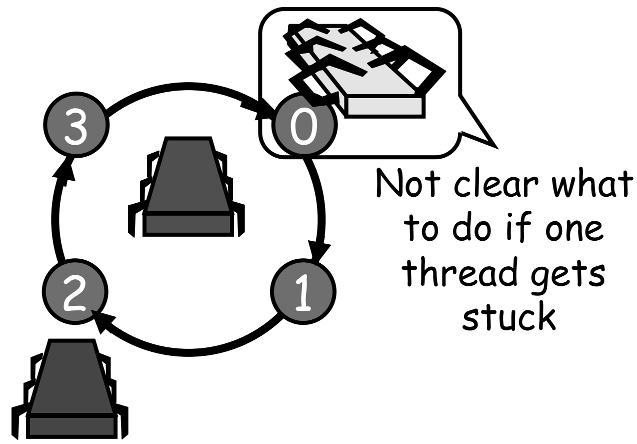


and so on …

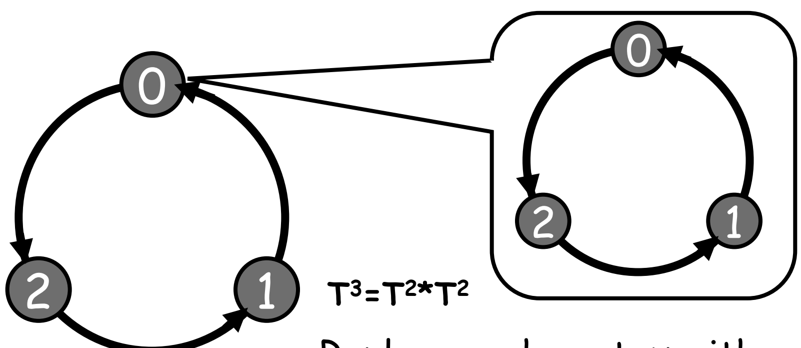
Three-Thread Bounded Precedence Graph?



Three-Thread Bounded Precedence Graph?



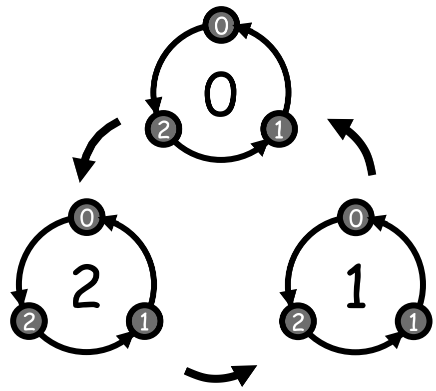
Graph Composition



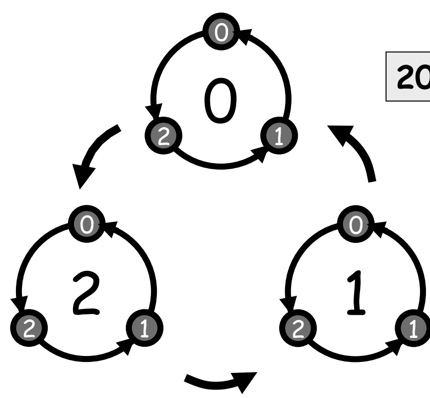
$T^3 = T^2 * T^2$

Replace each vertex with a copy of the graph

Three-Thread Bounded Precedence Graph T^3

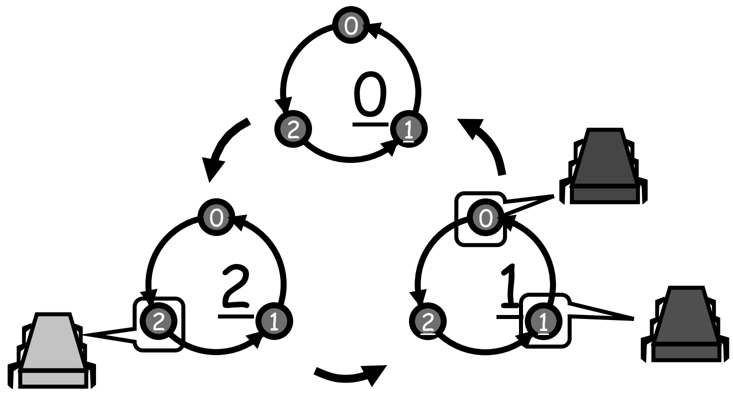


Three-Thread Bounded Precedence Graph T^3



20 < 02 < 12

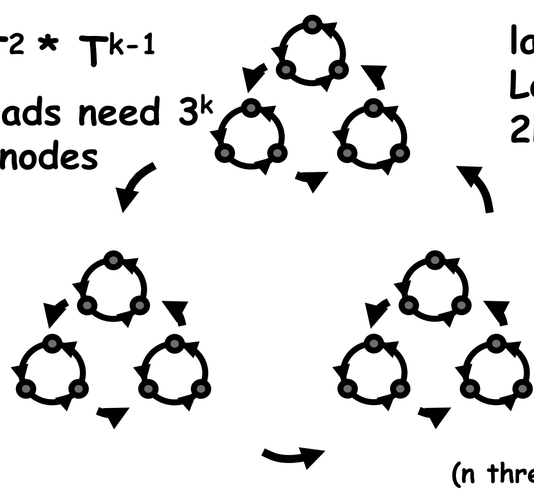
Three-Thread Bounded Precedence Graph T^3



In General

$T^k = T^2 * T^{k-1}$

K threads need 3^k nodes



label size = $\text{Log}_2(3^k)$ = 2k

(n threads need a max label size of 2n bits)

Deep Philosophical Question

- The Bakery Algorithm is
  - Succinct,
  - Elegant, and
  - Fair.
- Q: So why isn't it practical?
- A: Well, you have to read N distinct variables

Shared Memory

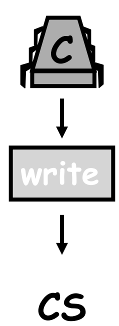
- Shared read/write memory locations called Registers (historical reasons)
- Come in different flavors
  - Multi-Reader-Single-Writer (`Flag[]`)
  - Multi-Reader-Multi-Writer (**Victim**`[]`)
  - Not that interesting: SRMW and SRSW

Theorem

At least N MRSW (multi-reader/ single-writer) registers are needed to solve deadlock-free mutual exclusion.

N registers like Flag[]…

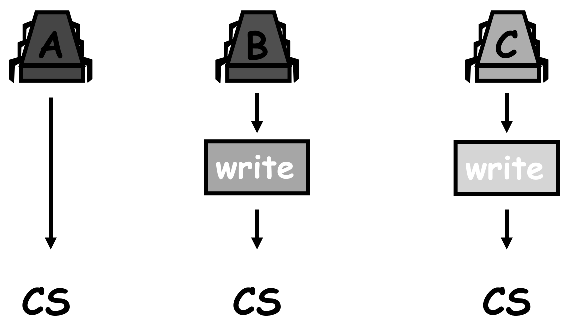
Proving Algorithmic Impossibility



- To show no algorithm exists:
  - assume by way of contradiction one does,
  - in our case assume an alg for deadlock free mutual exclusion using < N registers
  - show a bad execution that violates properties

Proof: Need N-MRSW Registers

Each thread must write to some register



…can't tell whether A is in critical section

Upper Bound

- Bakery algorithm
  - Uses 2N MRSW registers
- So the bound is (pretty) tight
- But what if we use MRMW registers?
  - Like **victim[]** ?

Bad News Theorem

At least N MRMW multi-reader/ multi-writer registers are needed to solve deadlock-free mutual exclusion.

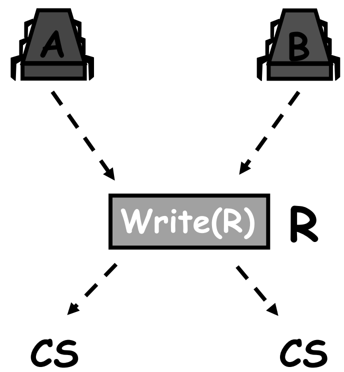
(So multiple writers don't help)

Theorem (First 2-Threads)

Theorem: Deadlock-free mutual exclusion for 2 threads requires at least 2 multi-reader multi-writer registers

Proof: assume one register suffices and derive a contradiction

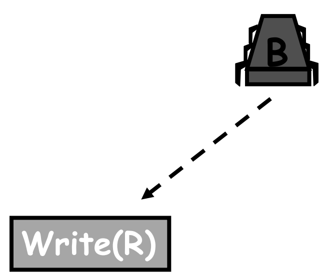
Two Thread Execution



- Threads run, reading and writing R
- Deadlock free so at least one gets in

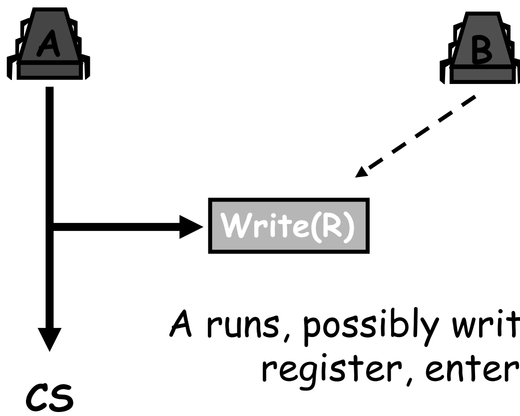
Covering State for One Register Always Exists

Before poising to write, B has read register and concluded that CS is empty



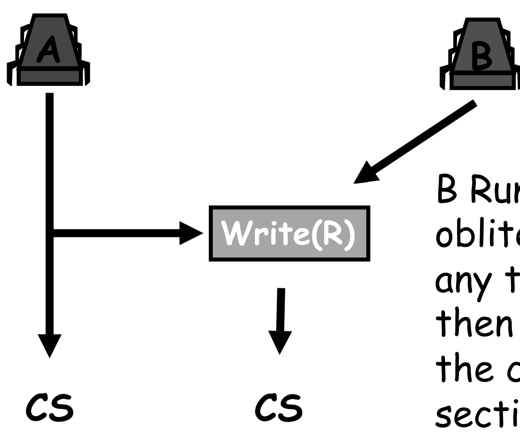
In any mutual exclusion protocol, B has to write to the register before entering CS, so stop it just before

Proof: Assume Cover of 1



A runs, possibly writes to the register, enters CS

Proof: Assume Cover of 1

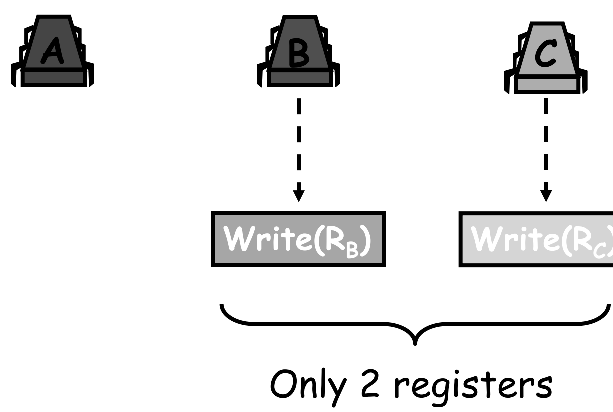


B Runs, first obliterating any trace of A, then also enters the critical section

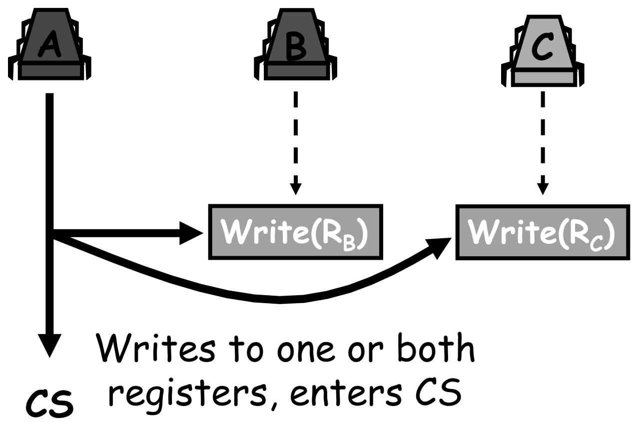
Theorem

Deadlock-free mutual exclusion for 3 threads requires at least 3 multi-reader multi-writer registers

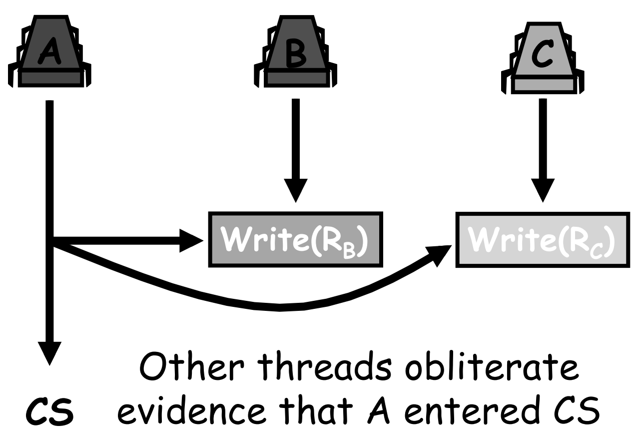
Proof: Assume Cover of 2



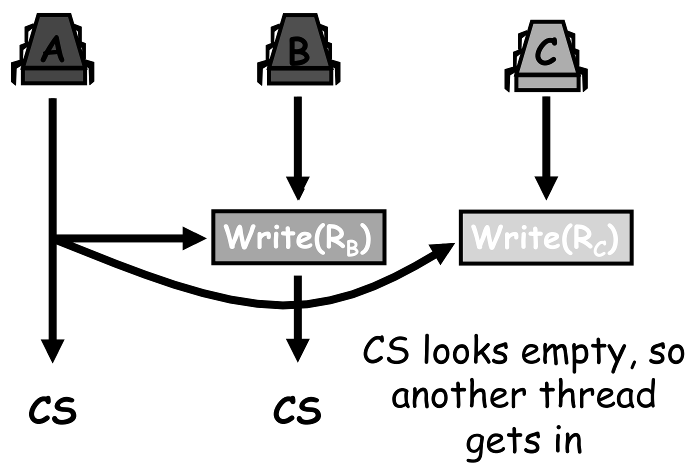
Run A Solo



Obliterate Traces of A



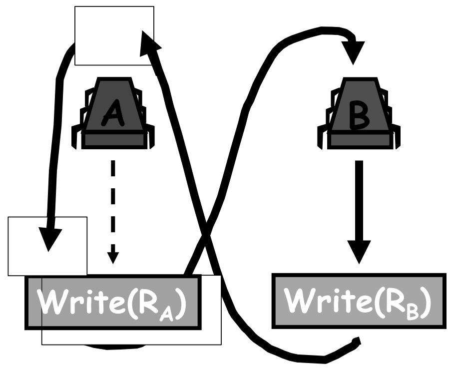
Mutual Exclusion Fails



Proof Strategy

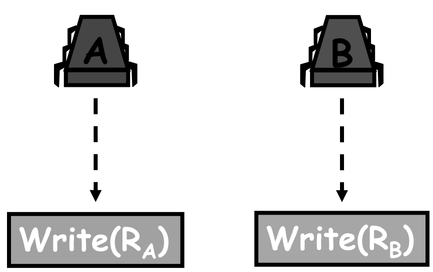
- Proved: a contradiction starting from a covering state for 2 registers
- Claim: a covering state for 2 registers is reachable from any state where CS is empty

Covering State for Two



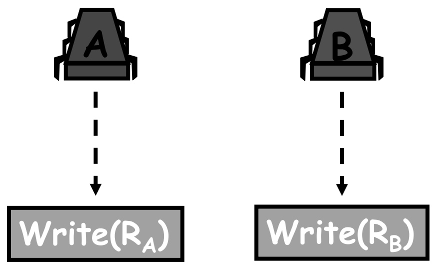
- If we run B through CS 3 times, B must return twice to cover some register, say R_B

Covering State for Two



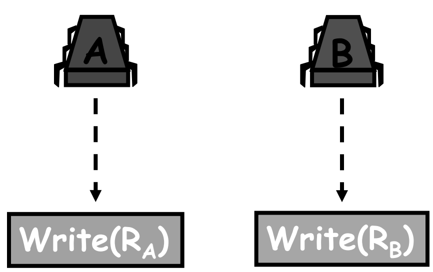
- Start with B covering register R_B for the 1st time
- Run A until it is about to write to uncovered R_A
  - A must write to R_A (inconsistent state if it <u>only</u> writes to R_B)
- Are we done?

Covering State for Two



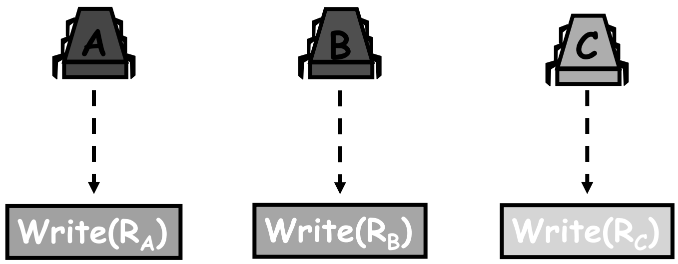
- NO! A could have written to R_B
- So CS no longer looks empty

Covering State for Two



- Run B obliterating traces of A in R_B
- Run B again until it is about to write to R_B
- Now we are done

Inductively We Can Show



- There is a covering state
  - Where k threads not in CS cover k distinct registers
  - Proof follows when k = N-1

Summary of Lecture

- In the 1960's many incorrect solutions to starvation-free mutual exclusion using RW-registers were published…
- Today we know how to solve FIFO N thread mutual exclusion using 2N RW-Registers

Summary of Lecture

- N RW-Registers inefficient
  - Because writes "cover" older writes
- Need stronger hardware operations
  - that do not have the "covering problem"
- In next lectures - understand what these operations are…