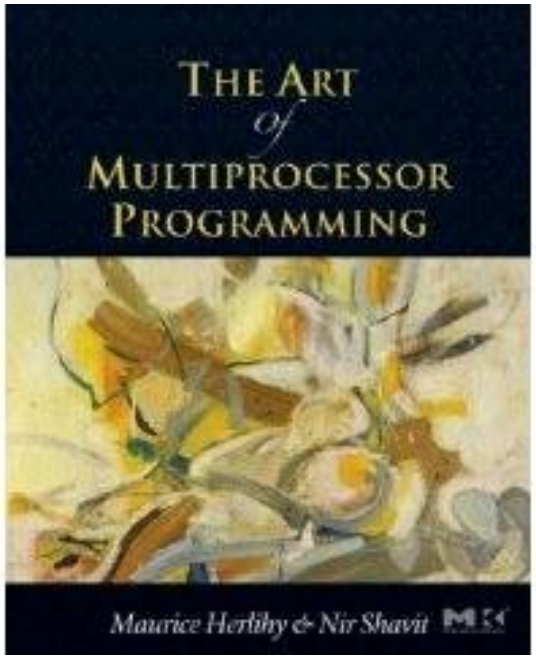
Department of Computer Science

COS 226

Chapter 11

Concurrent Stacks and Elimination

Acknowledgement



- Some of the slides are taken from the companion slides for “The Art of Multiprocessor Programming” by Maurice Herlihy & Nir Shavit

Stacks

- Methods
  - pop()
  - push(x)
- Last-in-First-out (LIFO) order

Concurrent Stacks

- Do stacks provide opportunity for concurrency?
  - push() and pop() calls access only the top of the stack
- However, stacks are not inherently sequential

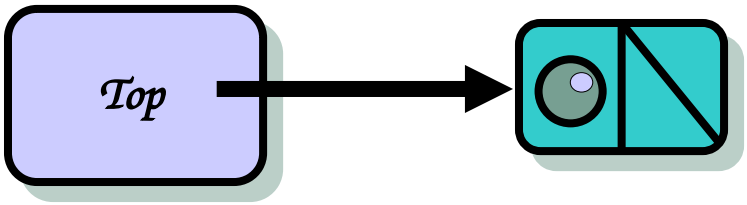
Lock-Free Stacks

- Linked-list implementation
- top field points to the first node
- pop() from an empty list throws an exception
- push() forms a new node

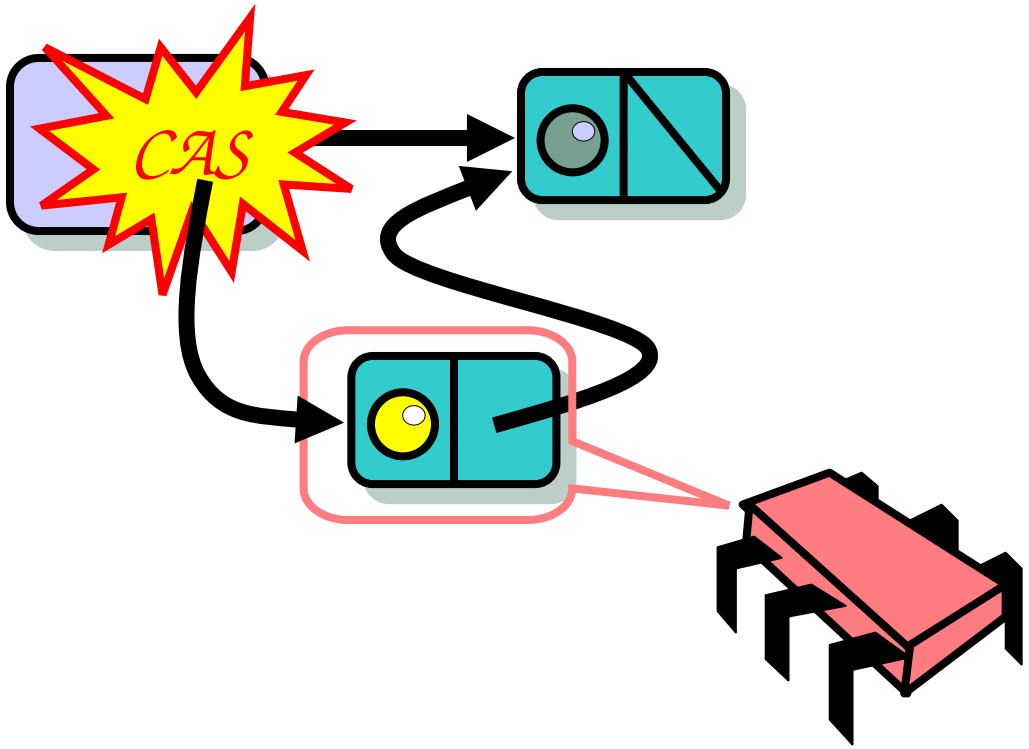
Lock-free Stacks

- Lock-free = atomic
- Use compareAndSet methods to change the link values in the list

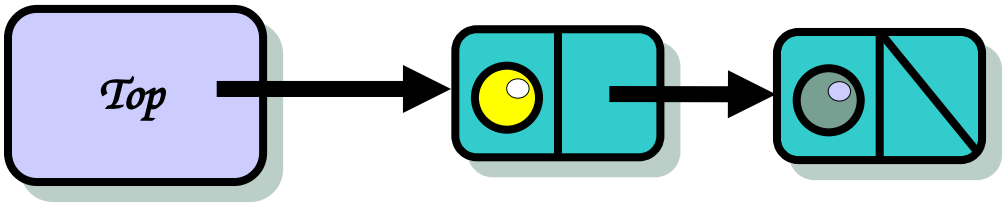
Empty Stack



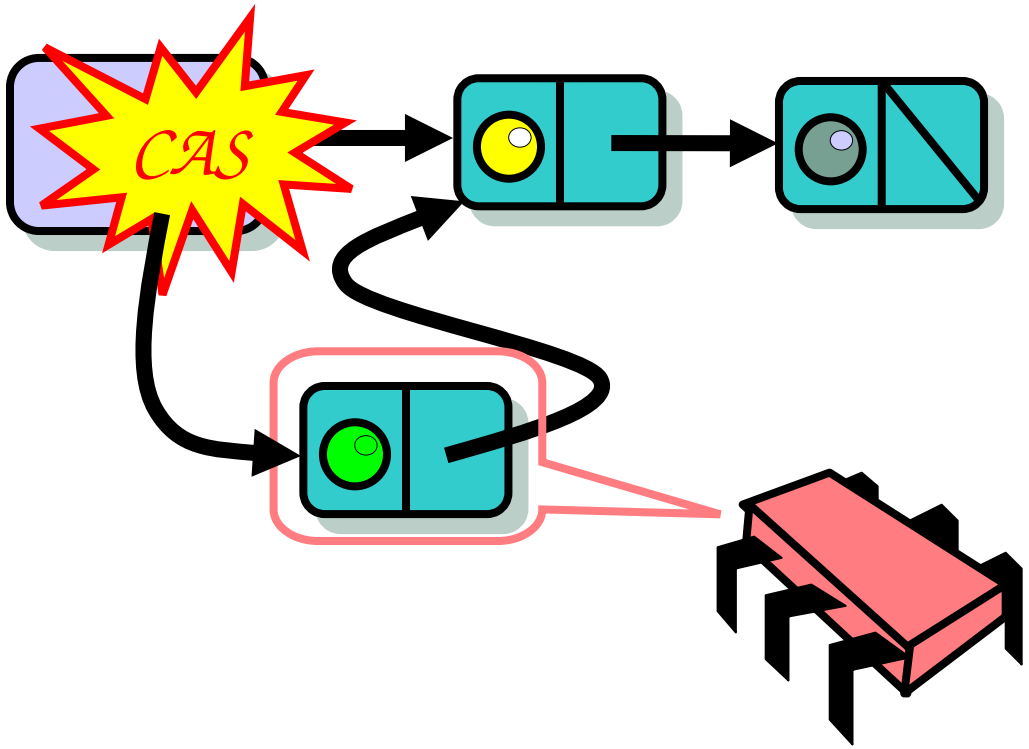
Push



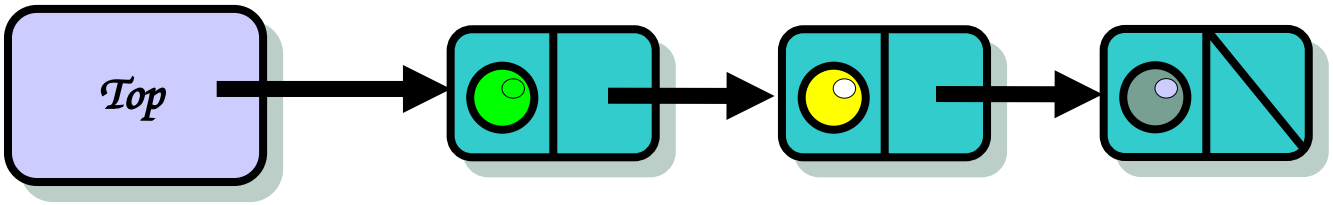
Push



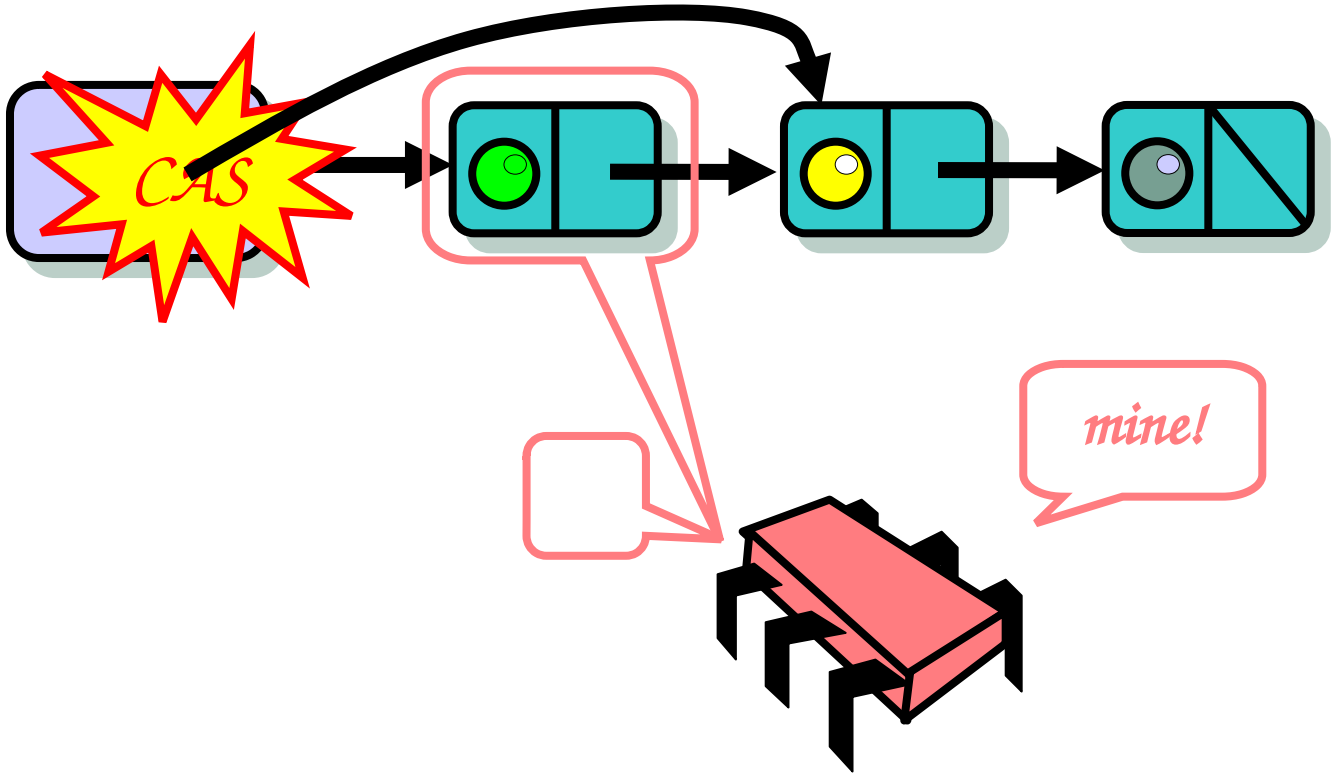
Push



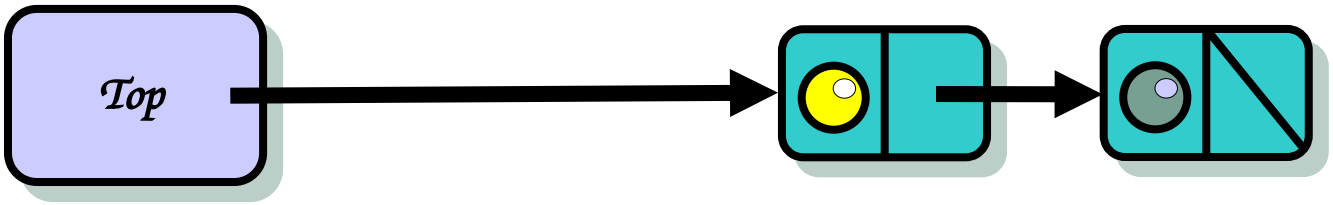
Stack



Pop



Pop



Lock-free Stack

```
public boolean tryPush(Node node){
    Node oldTop = top.get();
    node.next = oldTop;
    return(top.compareAndSet(oldTop, node))
 }
```

In what scenario will the tryPush return false?

Lock-free Stack

- If the compareAndSet returns a false it means that there is high contention
- In scenarios where there are high contention it is more effective to backoff and try again later

Lock-free Stack

```
public void push(T value) {
 Node node = new Node(value);
   while (true) {
     if (tryPush(node)) {
       return;
     } else backoff.backoff();
 }}
```

Lock-free Stack

```
public T pop() throws EmptyException {
   while (true) {
   Node returnNode = tryPop();
   if (returnNode != null)
   return returnNode.value;
   else
   backoff.backoff();
   }
}

protected Node tryPop() throws EmptyException {
   Node oldTop = top.get();
   if (oldTop == null)
   throw new EmptyException()
   Node newTop = oldTop.next;
   if (top.compareAndSet(oldTop, newTop))
   return oldTop;
   else
   return null;
}
```

Lock-free Stack

- Good
  - No locking
- Bad
  - Even with backoff, huge contention at top
  - In any case, no real parallelism

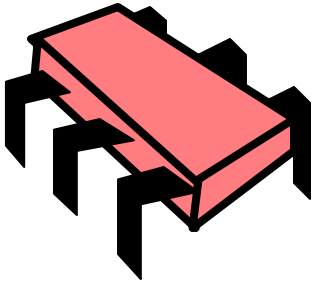
Lock-free Stack

- The LockFreeStack implementation scales poorly
  - Stack's top field is a source of contention
  - Sequential bottleneck
    - Method calls can proceed only one after the other
- Exponential Backoff alleviates contention, but does nothing for bottleneck

Observation

- If a push() is immediately followed by a pop() the two operations cancel out and the stack does not change
- We can exploit this observation

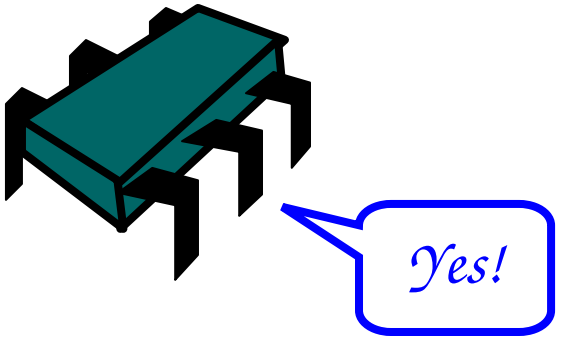
Observation



Push()

linearizable stack

Pop()



After an equal number of pushes and pops, stack stays the same

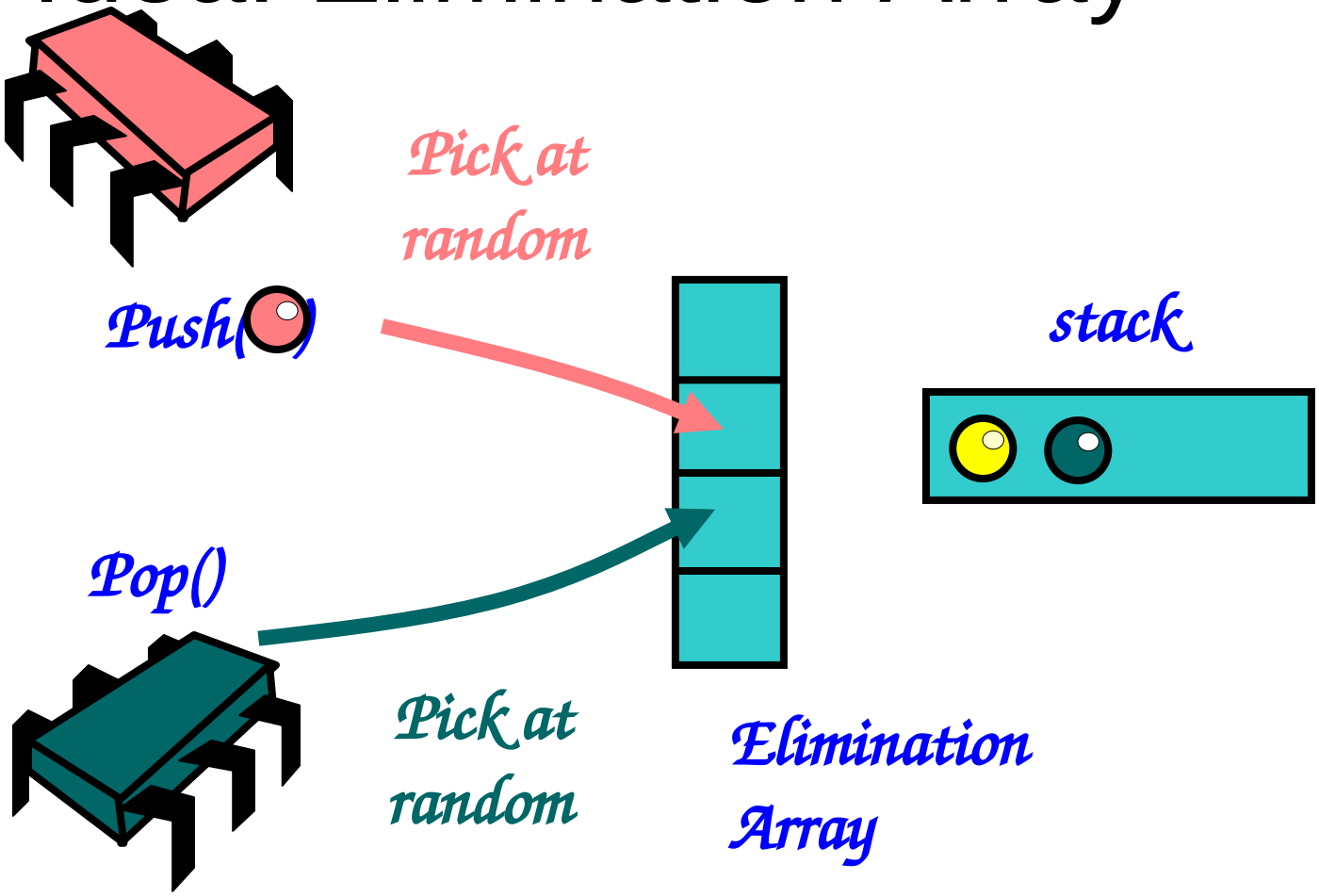
Elimination

- Cancel out concurrent pairs of pop() and push() method calls
- Thread calling push() exchanges value with thread calling pop()
- No modification to the stack needed
- The two calls *eliminate* one another

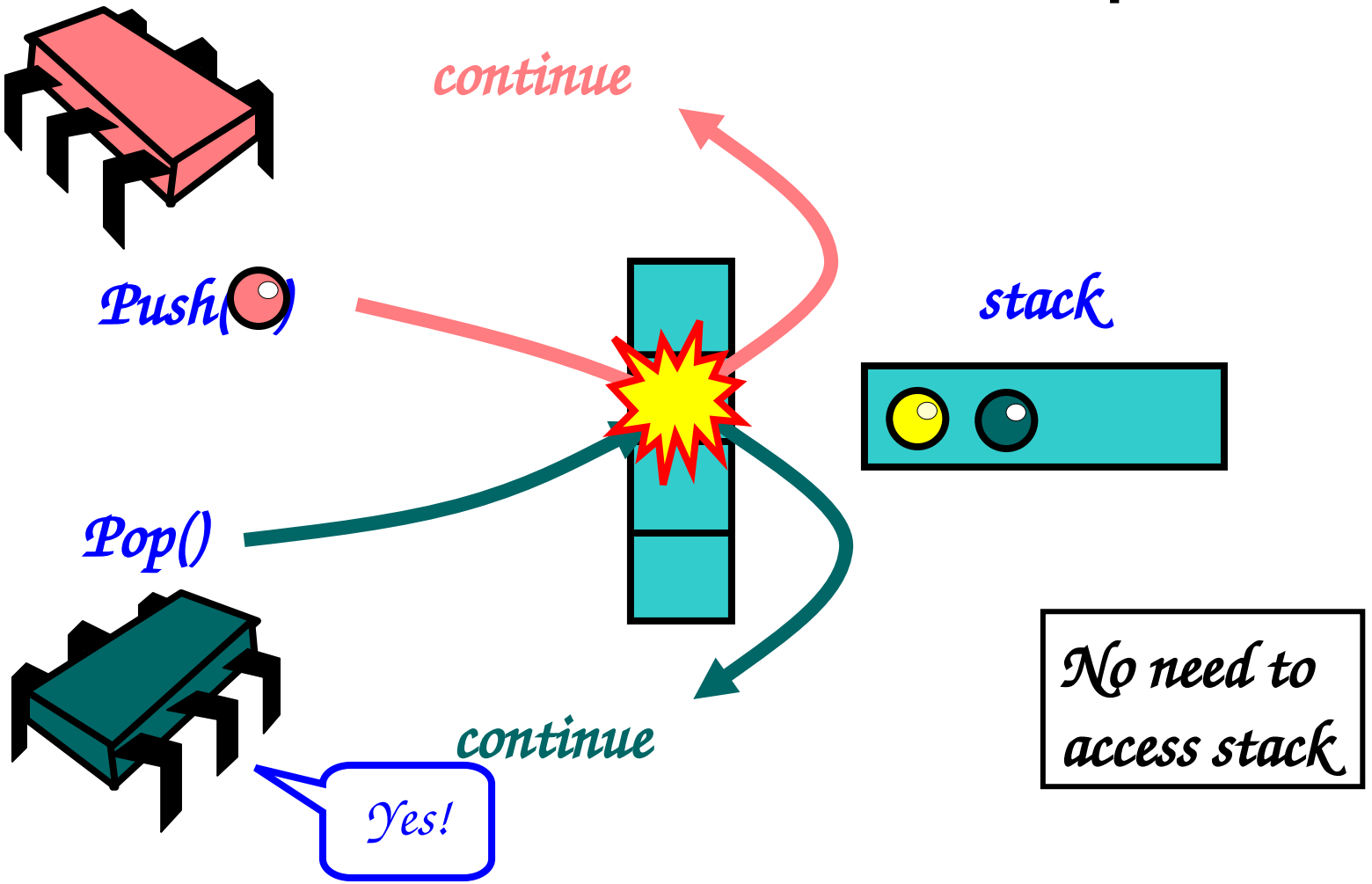
Elimination

- Idea:
  - Threads eliminate one another through an EliminationArray
  - Threads pick random array entries to try to meet complementary calls
  - Pairs of pop() and push() method calls that pick the same location exchange values and returns

Idea: Elimination Array



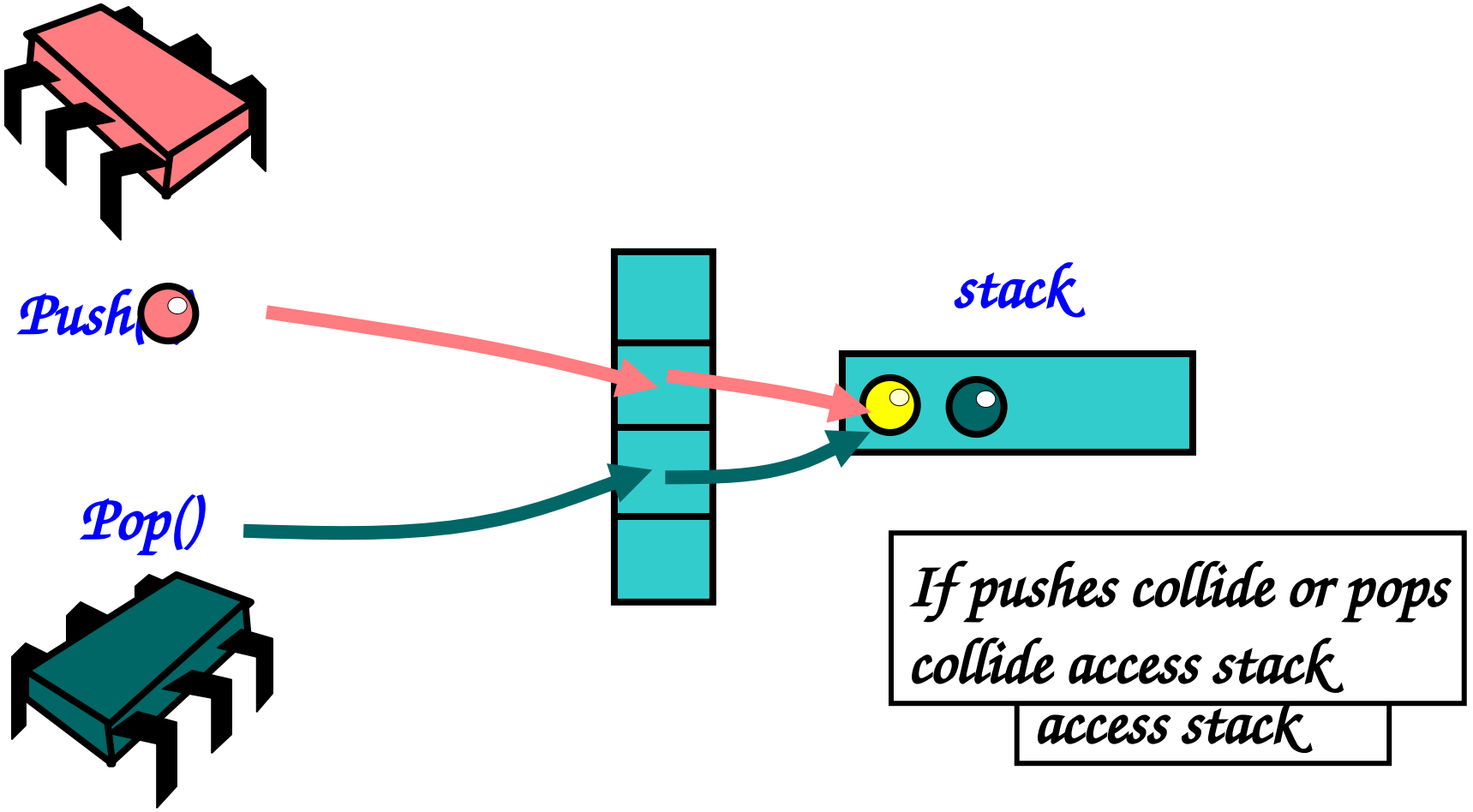
Push Collides With Pop



Elimination

- A thread whose call cannot be eliminated
  - Because it failed to find a partner (picked a wrong location) or
  - Picked a partner of the wrong type (pop() meeting a pop())
- Can either try again to eliminate at a new location or access the stack

No Collision



Elimination

- The EliminationArray can be used as a backoff scheme:
  - Each thread first access the Stack
  - If it fails (compareAndSet fails) it attempts to eliminate its call using the array instead of simply backing of
  - If it fails to eliminate, it access the Stack again
  - And so on…
- Called an EliminationBackoffStack

Elimination Backoff Stack

- Threads that push and pop should be allowed to cancel out
- However we must avoid a situation in which a thread can make an offer to more than one thread

Exchangers

- Object that allow exactly two threads (and no more) to rendezvous and exchange values
- The EliminationArray can be implemented as an array of Exchangers

LockFreeExchanger

- A LockFreeExchanger<T> object allows two threads to exchange values of type T
- If A calls exchange() with a and B calls exchange() with b, then A should return b and vice versa

LockFreeExchanger

- On a high level:
  - First thread arrives to write its values and spins until a second thread arrives
  - The second detects that the first is waiting, reads it value and signals the exchange
- The first thread may timeout if a second does not show up

LockFreeExchanger

- The exchanger has three possible states:
  - EMPTY
  - BUSY
  - WAITING
- AtomicStampedReference records the exchanger's state as an int stamp

LockFreeExhanger

- The exchanger reads the state of the AtomicStampedReference slot and proceeds as follows:

If EMPTY

- Thread tries to place item in slot and set state to WAITING
- If it was successful it spins waiting for another thread
- If another thread shows up, it will take the item, replace it with its own and set the state to BUSY
- The waiting state will take the item and reset the state to EMPTY

LockFreeExchanger

```
public class LockFreeExchanger {
  public T exchange(T myItem) {
     int[] stampholder = {EMPTY};
     while (true) {
       T yrItem = slot.get(stampHolder);
       int stamp = stampholder[0];
     switch(stamp) {
```

If EMPTY

```
case EMPTY: // slot is free
     if (slot.compareAndSet(yrItem, myItem, EMPTY,
WAITING)) {
     while (System.nanoTime() < timeBound){
       yrItem = slot.get(stampHolder);
       if (stampHolder[0] == BUSY) {
         slot.set(null, EMPTY);
         return yrItem;
       }}
     if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
      } else {
         yrItem = slot.get(stampHolder);
         slot.set(null, EMPTY);
         return yrItem;
     }
} break;
```

If EMPTY

```
case EMPTY: // slot is free
      if (slot.compareAndSet(yrItem, myItem, EMPTY,
WAITING)) {
      while (System.nanoTime() < timeBound){
        yrItem = slot.get(stampHolder);
        if (stampHolder[0] == BUSY) {
          slot.set(null, EMPTY);
          return yrItem;
        }}
      if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
```

Slot is free, try to insert myItem and change state to WAITING

```
          return yrItem;
      }
} break;
```

If EMPTY

```
case EMPTY: // slot is free
     if (slot.compareAndSet(yrItem, myItem, EMPTY,
WAITING)) {
     while (System.nanoTime() < timeBound){
       yrItem = slot.get(stampHolder);
       if (stampHolder[0] == BUSY) {
         slot.set(null, EMPTY);
         return yrItem;
       }}
     if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
         slot.set(null, EMPTY);
         return yrItem;
     }
} break;
```

Loop while still time left to attempt exchange

If EMPTY

```
case EMPTY: // slot is free
     if (slot.compareAndSet(yrItem, myItem, EMPTY,
WAITING)) {
     while (System.nanoTime() < timeBound){
       yrItem = slot.get(stampHolder);
       if (stampHolder[0] == BUSY) {
          slot.set(null, EMPTY);
          return yrItem;
        }}
     if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
```

Get item from slot and check if state changed to BUSY

```
          return yrItem;
     }
} break;
```

If EMPTY

```
case EMPTY: // slot is free
     if (slot.compareAndSet(yrItem, myItem, EMPTY,
WAITING)) {
     while (System.nanoTime() < timeBound){
       yrItem = slot.get(stampHolder);
       if (stampHolder[0] == BUSY) {
         slot.set(null, EMPTY);
         return yrItem;
       }}
     if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
      }
         yrItem = slot.get(stampHolder);
         slot.set(null, EMPTY);
         return yrItem;
     }
} break;
```

If successful reset slot state to EMPTY

If EMPTY

```
case EMPTY: // slot is free
     if (slot.compareAndSet(yrItem, myItem, EMPTY,
WAITING)) {
     while (System.nanoTime() < timeBound){
       yrItem = slot.get(stampHolder);
       if (stampHolder[0] == BUSY) {
         slot.set(null, EMPTY);
         return yrItem;
       }}
     if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
      } else {
         yrItem = slot.get(stampHolder);
         slot.set(null, EMPTY);
         return yrItem;
     }
} break;
```

and return item found in slot

If EMPTY

Otherwise we ran out of time, try to reset state to EMPTY, if successful time out

```
em, myItem, EMPTY,

timeBound){
lder);
      if (stampHolder[0] == BUSY) {
        slot.set(null, EMPTY);
        return yrItem;
      }}
    if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
      } else {
        yrItem = slot.get(stampHolder);
        slot.set(null, EMPTY);
        return yrItem;
    }
} break;
```

If EMPTY

```
( If reset failed, someone showed up after all, take                EMPTY,
\ that item
      while (System.nanoTime() < timeBound){
        yrItem = slot.get(stampHolder);
        if (stampHolder[0] == BUSY) {
          slot.set(null, EMPTY);
          return yrItem;
        }}
      if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
       } else {
          yrItem = slot.get(stampHolder);
          slot.set(null, EMPTY);
          return yrItem;
      }
} break;
```

If EMPTY

Set slot to EMPTY and return item found

```
WAITING)) {
     while (System.nanoTime() < timeBound){
       yrItem = slot.get(stampHolder);
       if (stampHolder[0] == BUSY) {
         slot.set(null, EMPTY);
         return yrItem;
       }}
     if (slot.compareAndSet(myItem, null, WAITING,
EMPTY)){throw new TimeoutException();
      } else {
         yrItem = slot.get(stampHolder);
         slot.set(null, EMPTY);
         return yrItem;
     }
} break;
```

If EMPTY

```
case EMPTY: // slot is free
     if (slot.compareAndSet(yrItem, myItem, EMPTY,
WAITING)) {
     while (System.nanoTime() < timeBound){
       yrItem = slot.get(stampHolder);
       if (stampHolder[0] == BUSY) {
         slot.set(null
         return yrItem
       }}
     if (slot.compareA
EMPTY)){throw new TimeoutException();
      } else {
         yrItem = slot.get(stampHolder);
         slot.set(null, EMPTY);
         return yrItem;
     }
} break;
```

If initial CAS failed then someone else changed state from EMPTY to WAITING so retry from start

If WAITING

- Some thread is waiting and the slot contains the item
- The thread takes the item and tries to replace it with its own by changing state from WAITING to BUSY
- It may fail if another thread succeeds or if the initial thread timeout
- If it does succeed it can return the item

If WAITING

```
case WAITING:
 if (slot.compareAndSet(yrItem, myItem, WAITING,
      BUSY))
   return yrItem;
 break;
```

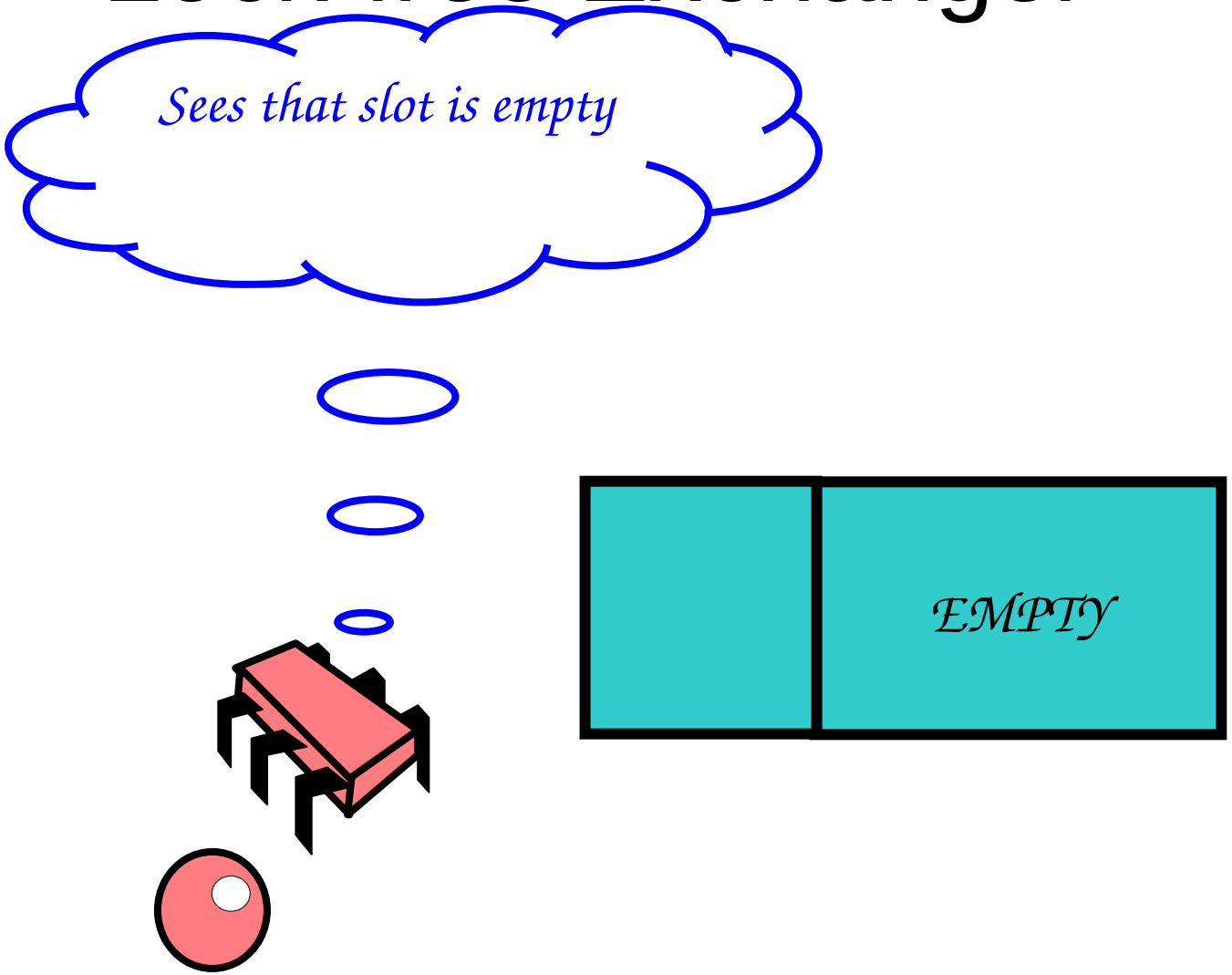
- Someone is waiting for an exchange, to try to CAS my item in and change state to BUSY
- If successful return that item, otherwise another thread got it

If BUSY

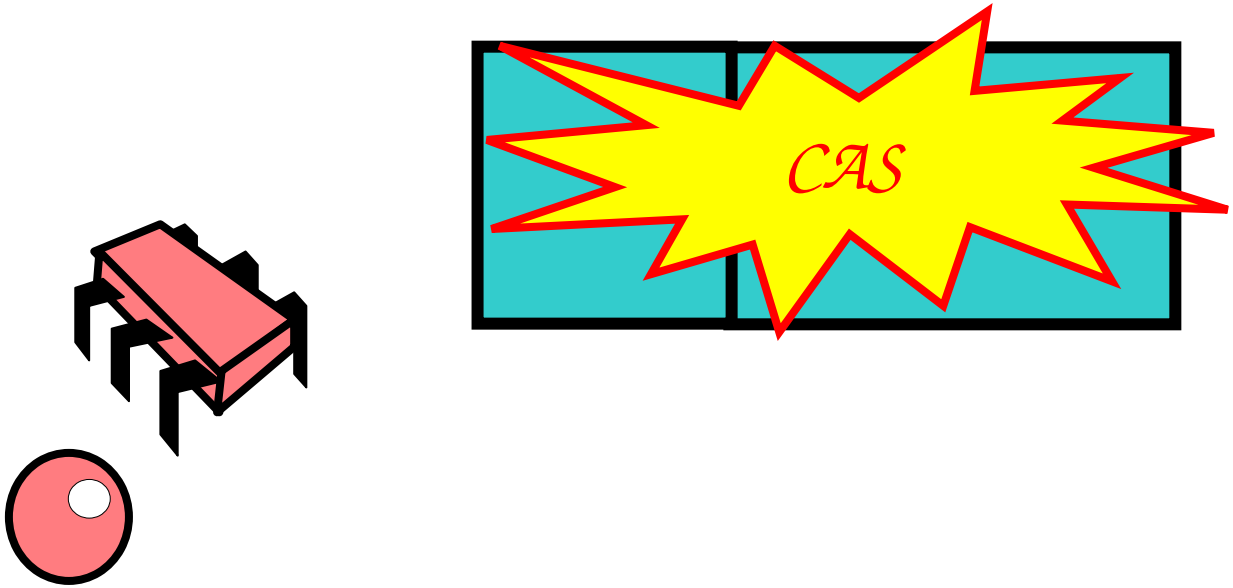
- If the state is BUSY then two other threads are currently using the slot for an exchange

```
case BUSY:
  break;
```

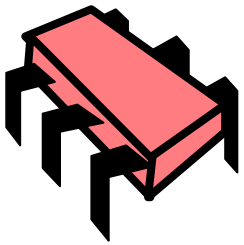
Lock-free Exchanger



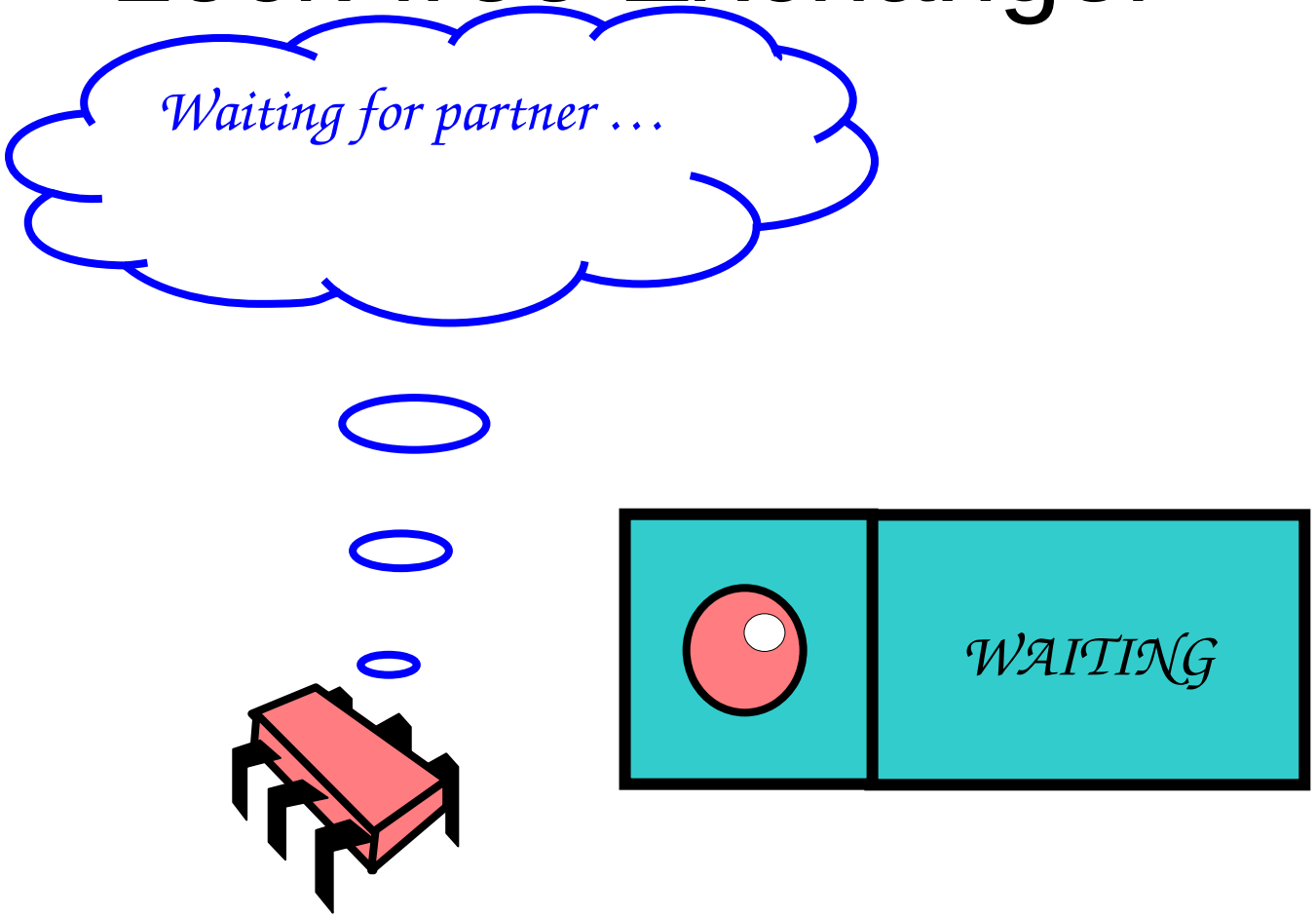
Lock-free Exchanger



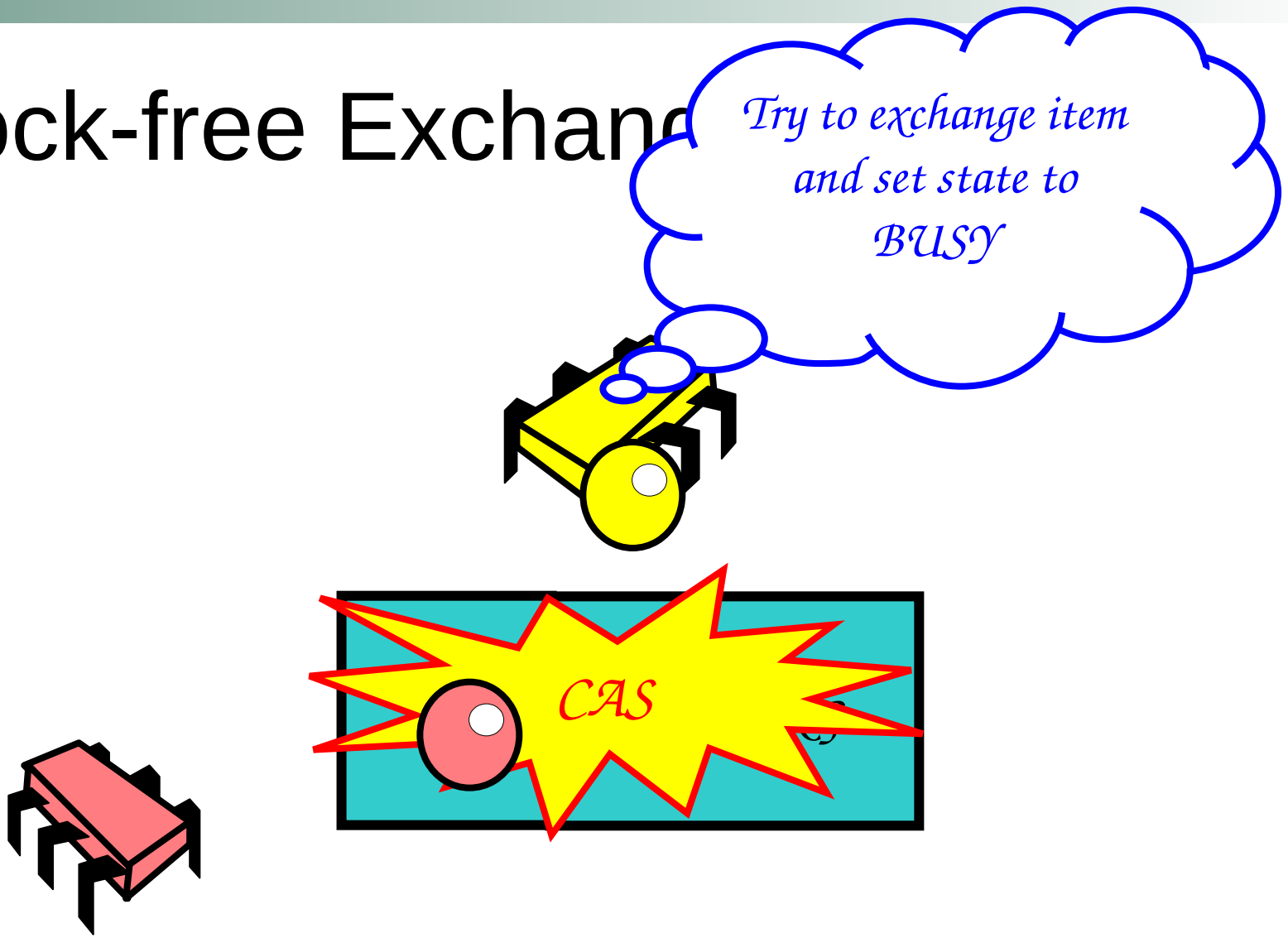
Lock-free Exchanger



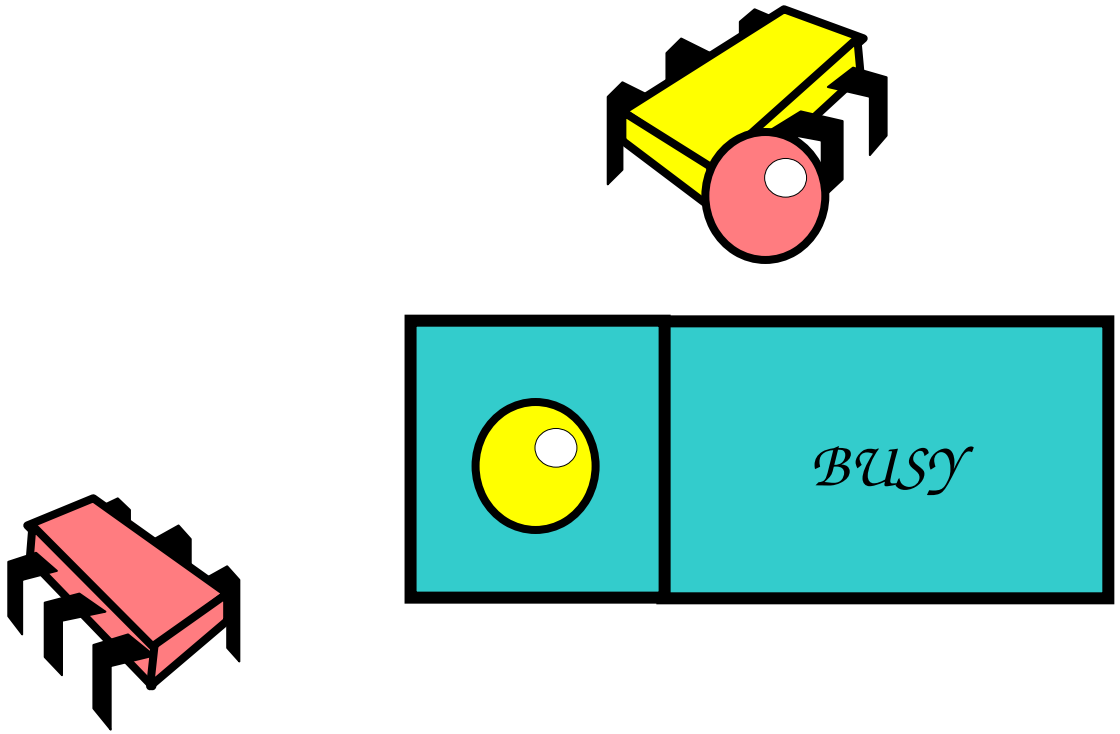
Lock-free Exchanger



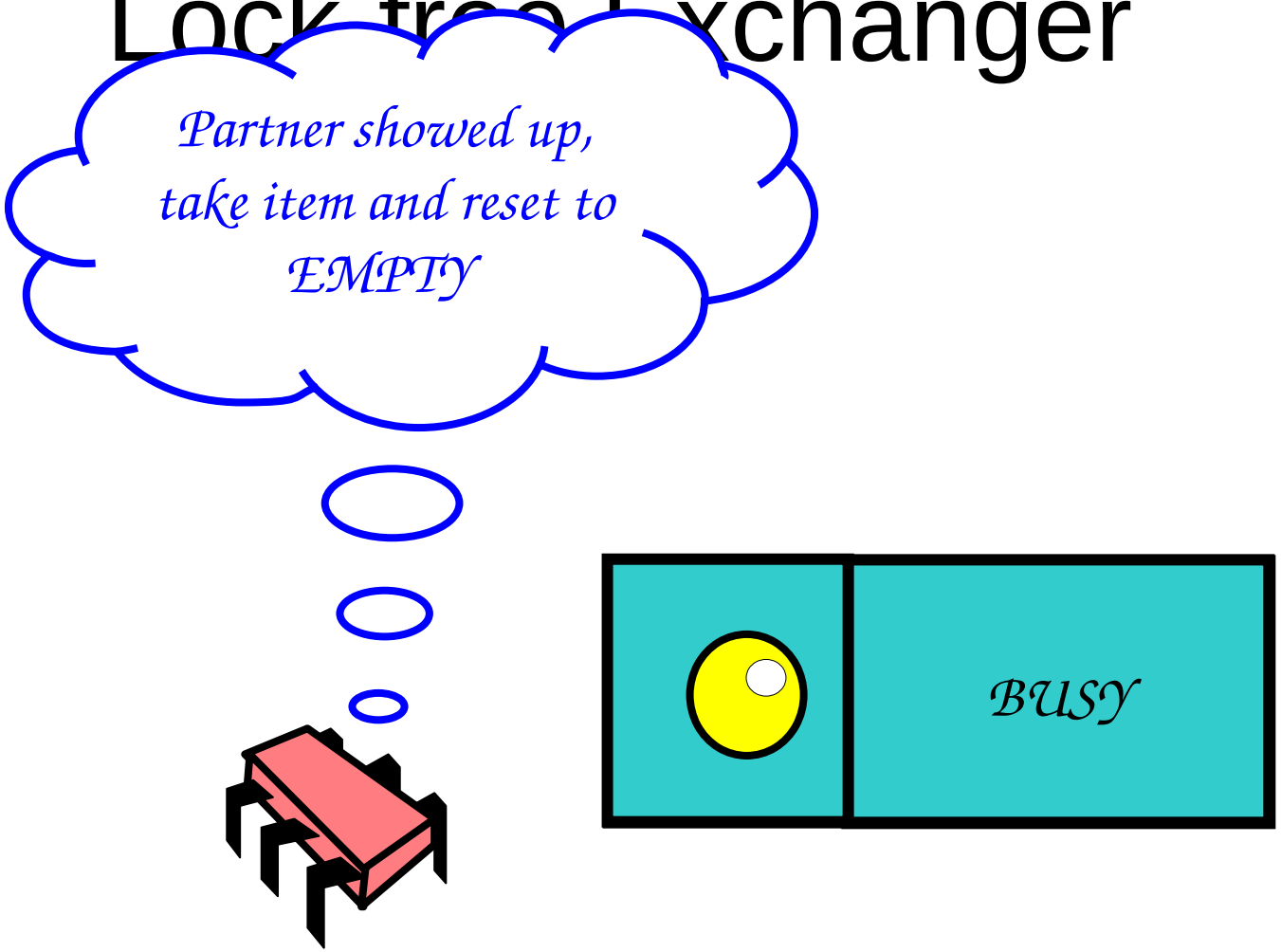
Lock-free Exchanc



Lock-free Exchanger



Lock-free Exchanger



Back to EliminationBackoffStack

- An EliminationArray is implemented as an array of Exchanger objects
- A thread attempting to perform an exchange picks an array entry at random and call that entry's exchange() method

EliminationBackoffStack

- Each thread first access the Stack
- If it fails, it attempts to eliminate its call using the array
  - It chooses a random array entry and calls exchange
- If it fails to eliminate due to:
  - Choosing an entry where the state is BUSY
  - Colliding with an unsuitable method call
- It accesses the Stack again
- And so on…

EliminationBackoffStack

```
 public void push(T value) {
  Node node = new Node(value);
    while (true) {
      if (tryPush(node)) {
        return;
      } else try {
        T otherValue =
         eliminationArray.visit(value);
        if (otherValue == null)
            return;
      } catch (TimeoutException e) {}
  }
}
```

EliminationBackoffStack

```
public void push(T value) {
 Node node = new Node(value);
   while (true) {
     if (tryPush(node)) {
       return;
     } else try {
       T otherValue =
        eliminationArray.visit(value);
       if (otherValue == null)
           return;
     } catch (TimeoutException e) {}
  }
}
```

First try to push element onto stack

Same method as **Lock-free Stack**

```
public boolean tryPush(Node node){
    Node oldTop = top.get();
    node.next = oldTop;
    return(top.compareAndSet(oldTop, node))
 }
```

Will return false if another thread succeeded = high contention

EliminationBackoffStack

```
public void push(T value) {
 Node node = new Node(value);
   while (true) {
     if (tryPush(node)) {
       return;
     } else try {
       T otherValue =
        eliminationArray.visit(value);
       if (otherValue == null)
           return;
     } catch (TimeoutException e) {}
  }
}
```

If high contention visit Elimination Array and try to eliminate call

EliminationBackoffStack

```
public void push(T value) {
 Node node = new Node(value);
   while (true) {
     if (tryPush(node)) {
       return;
     } else try {
       T otherValue =
        eliminationArray.visit(value);
       if (otherValue == null)
           return;
     } catch (TimeoutException e) {}
  }
}
```

If push method returns null, exchange was succesful

EliminationBackoffStack

```
 public void push(T value) {
  Node node = new Node(value);
    while (true) {
      if (tryPush(node)) {
        return;
      } else try {
        T otherValue =
         eliminationArray.visit(value);
        if (otherValue == null)
            return;
      } catch (TimeoutException e) {}
  }
}
```

If not, try again

EliminationBackoffStack

```
public T pop() throws EmptyException {
  while (true) {
  Node returnNode = tryPop();
  if (returnNode != null)
  return returnNode.value;
  else try {
  T otherValue =
            eliminationArray.visit(null);
  if (otherValue != null)
  return otherValue;
  } catch (TimeoutException e) {}
  }
}
```

EliminationBackoffStack

```
public T pop() throws EmptyException {
  while (true) {
  Node returnNode = tryPop();
  if (returnNode != null)
  return returnNode.value;
  else try {
  T otherValue =
              eliminationArray.visit(null);
  if (otherValue != null)
  return otherValue;
  } catch (TimeoutException e) {}
  }
}
```

First try to pop element from stack

Same method as **Lock-free Stack**

```
protected Node tryPop() throws EmptyException
  {
  Node oldTop = top.get();
  if (oldTop == null)
  throw new EmptyException()
  Node newTop = oldTop.next;
  if (top.compareAndSet(oldTop, newTop))
  return oldTop;
  else
  return null;
}
```

Return null if failed due to high contention

EliminationBackoffStack

```
public T pop() throws EmptyException {
  while (true) {
  Node returnNode = tryPop();
  if (returnNode != null)
  return returnNode.value;
  else try {
  T otherValue =
              eliminationArray.visit(null);
  if (otherValue != null)
  return otherValue;
  } catch (TimeoutException e) {}
  }
}
```

Attempt to eliminate – add null to elimination array

EliminationBackoffStack

```
public T pop() throws EmptyException {
  while (true) {
  Node returnNode = tryPop();
  if (returnNode != null)
  return returnNode.value;
  else try {
  T otherValue =
              eliminationArray.visit(null);
  if (otherValue != null)
  return otherValue;
  } catch (TimeoutException e) {}
  }
}
```

Successful exchange for pop method if non-null value returned

Performance

- At low levels of contention the performance of EliminationBackoffStack is comparable to LockFreeStack
- However at high contention the number of successful eliminations will increase, allowing more operations to complete in parallel