YSC3248: Parallel, Concurrent and Distributed Programming

Concurrent Stacks and Elimination

Last and This Lectures

- Queue
  - Bounded, blocking, lock-based
  - Unbounded, non-blocking, lock-free
- Stack
  - Unbounded, non-blocking lock-free
  - Elimination-backoff algorithm

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- Queue
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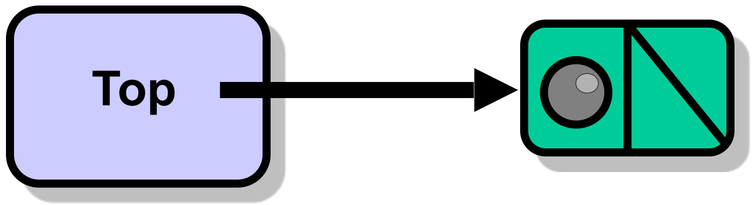
Demo:
Implementing and Testing Lock-Based Stack

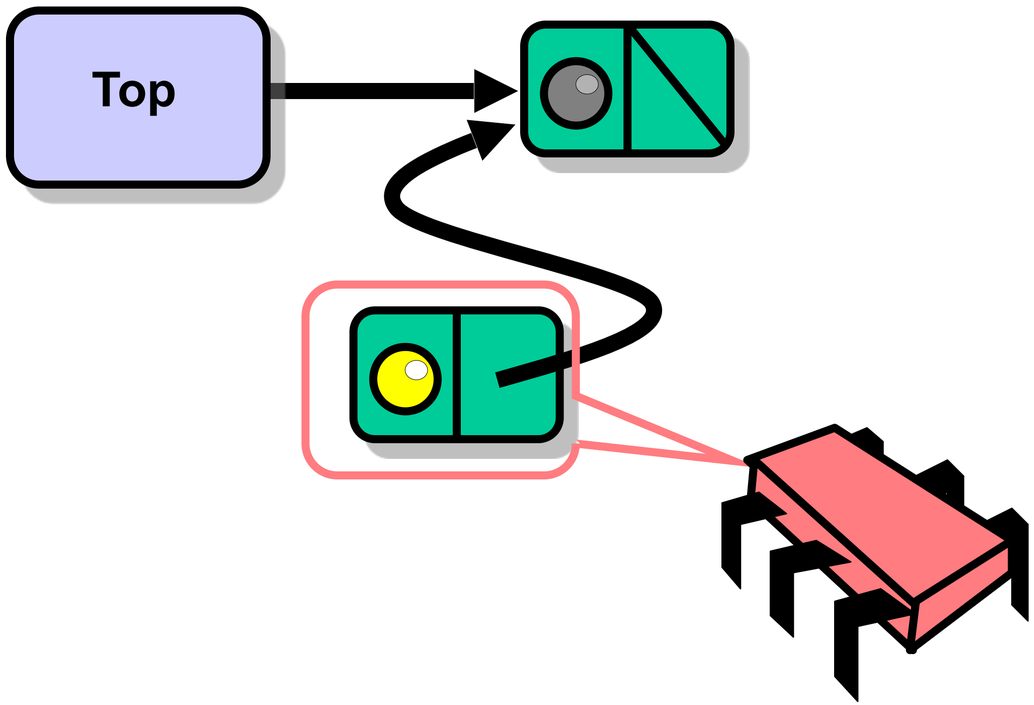
Concurrent Stack

- Methods
  - **push(x)**
  - **pop()**
- Last-in, First-out (LIFO) order
- Lock-Free!

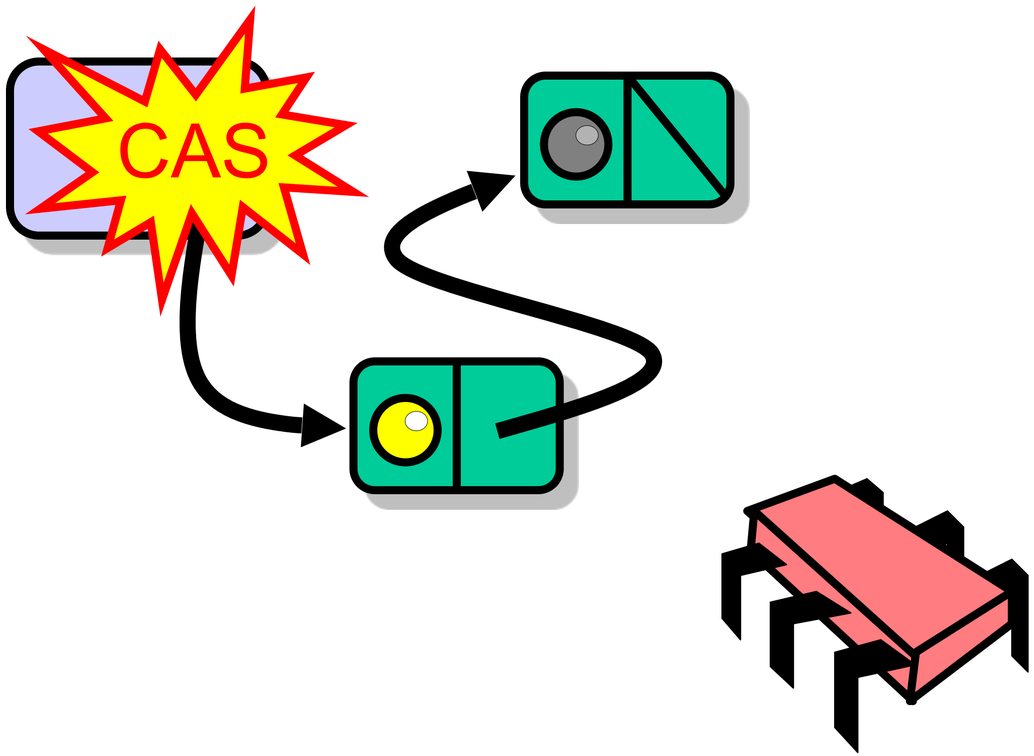
Empty Stack



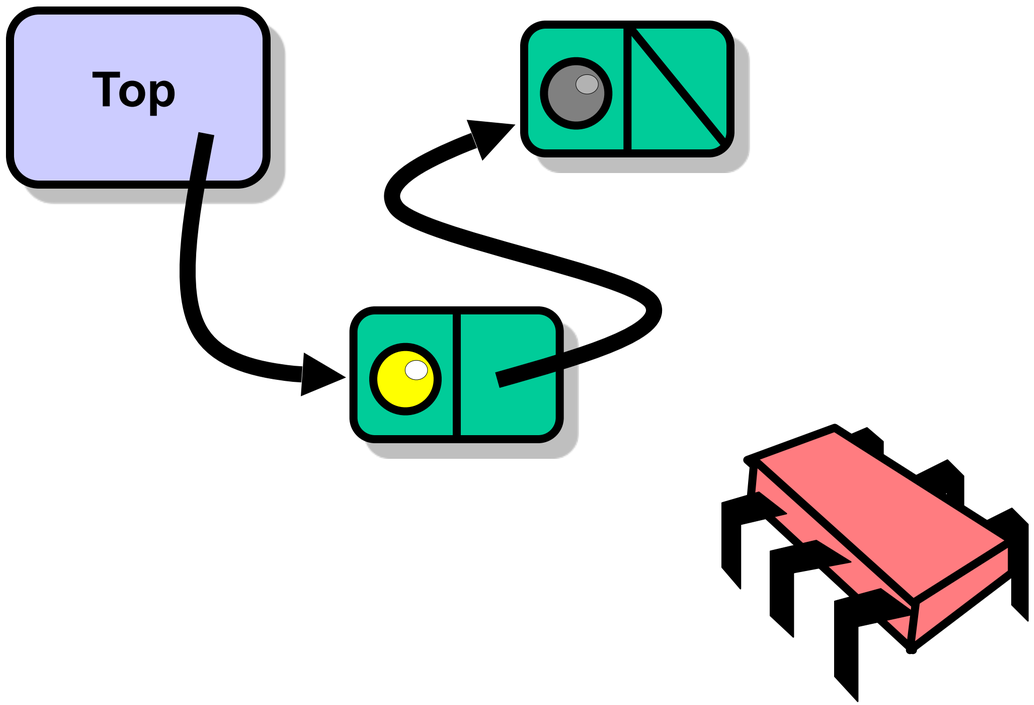
Push



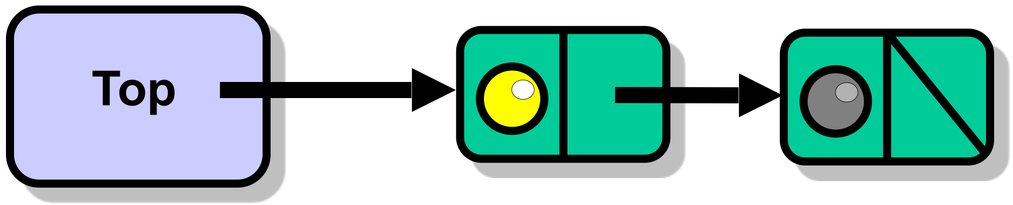
Push

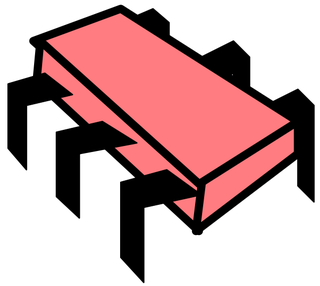


Push

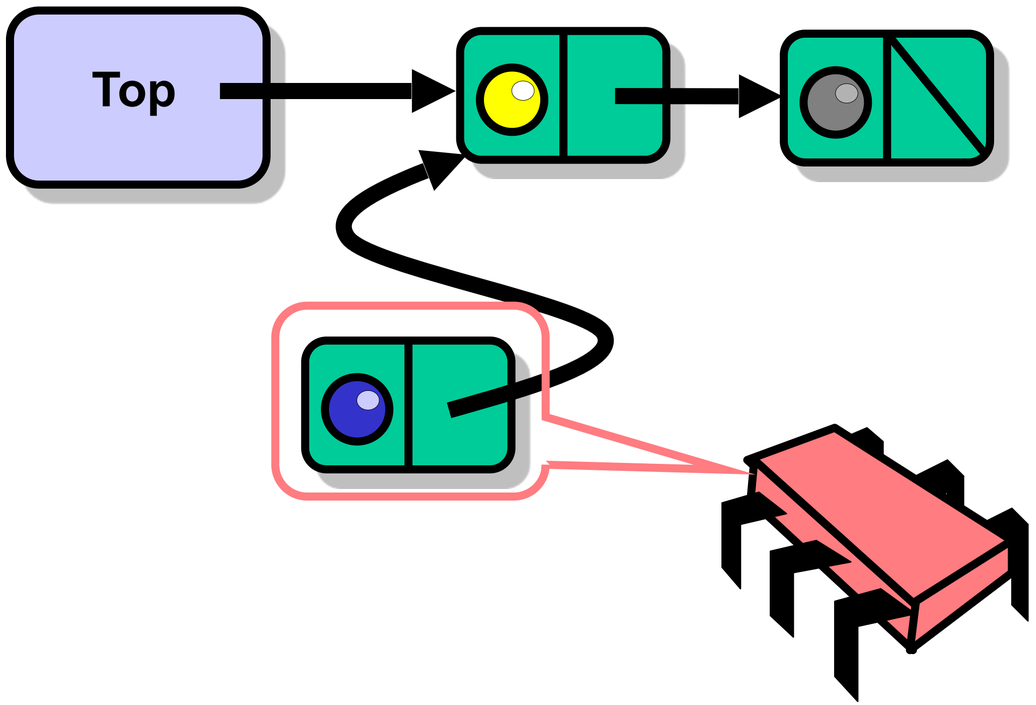


Push

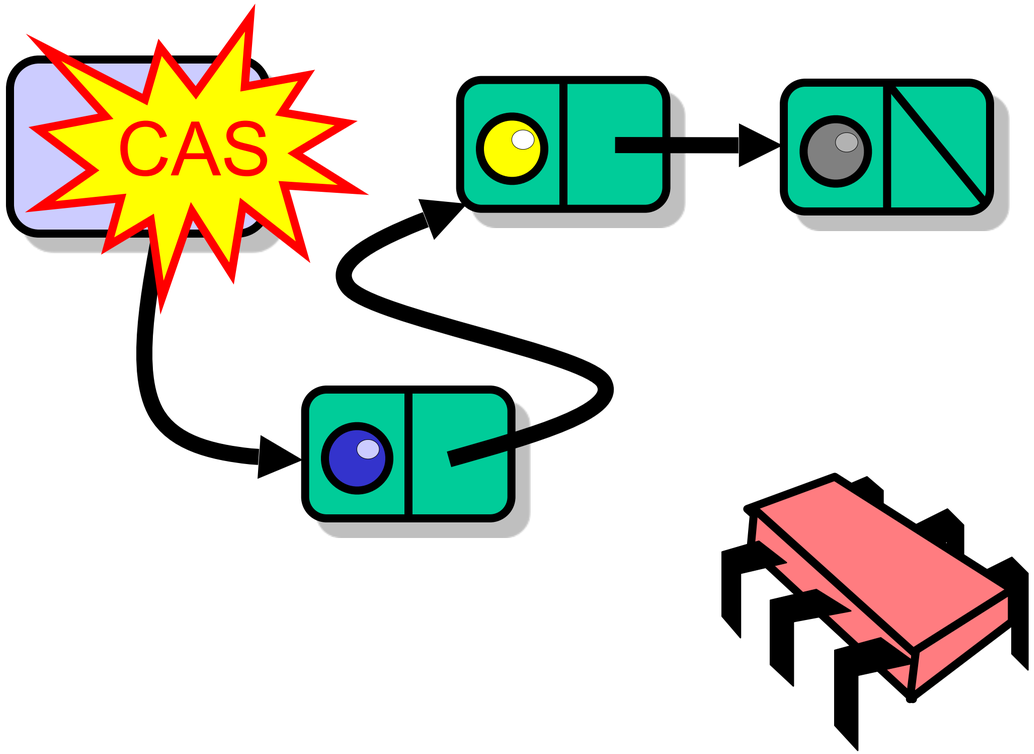




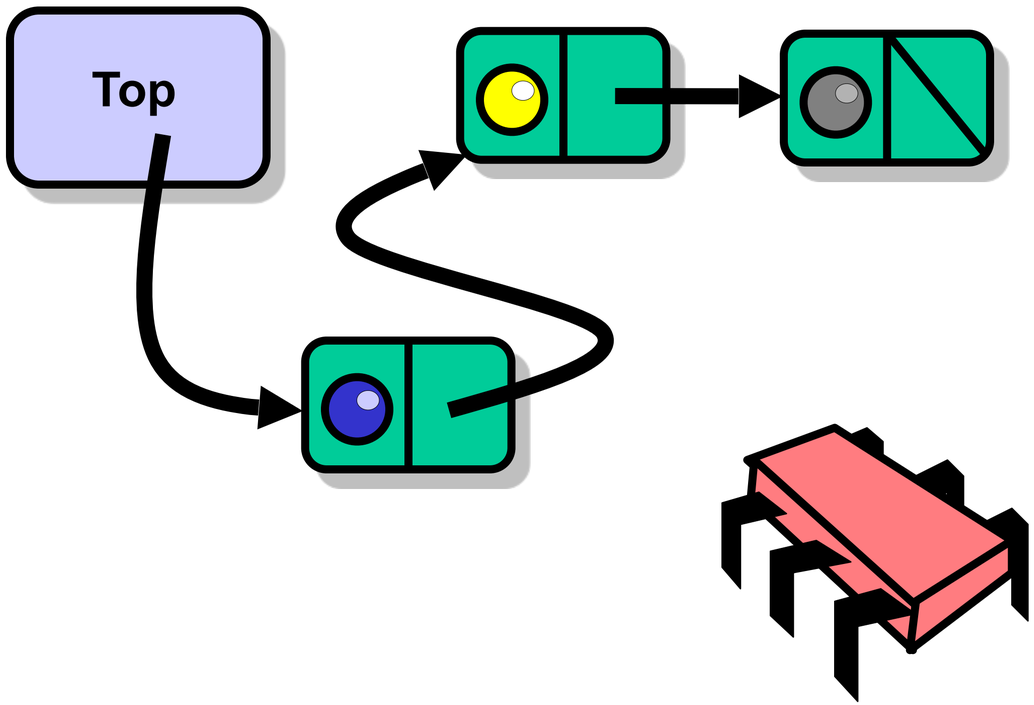
Push



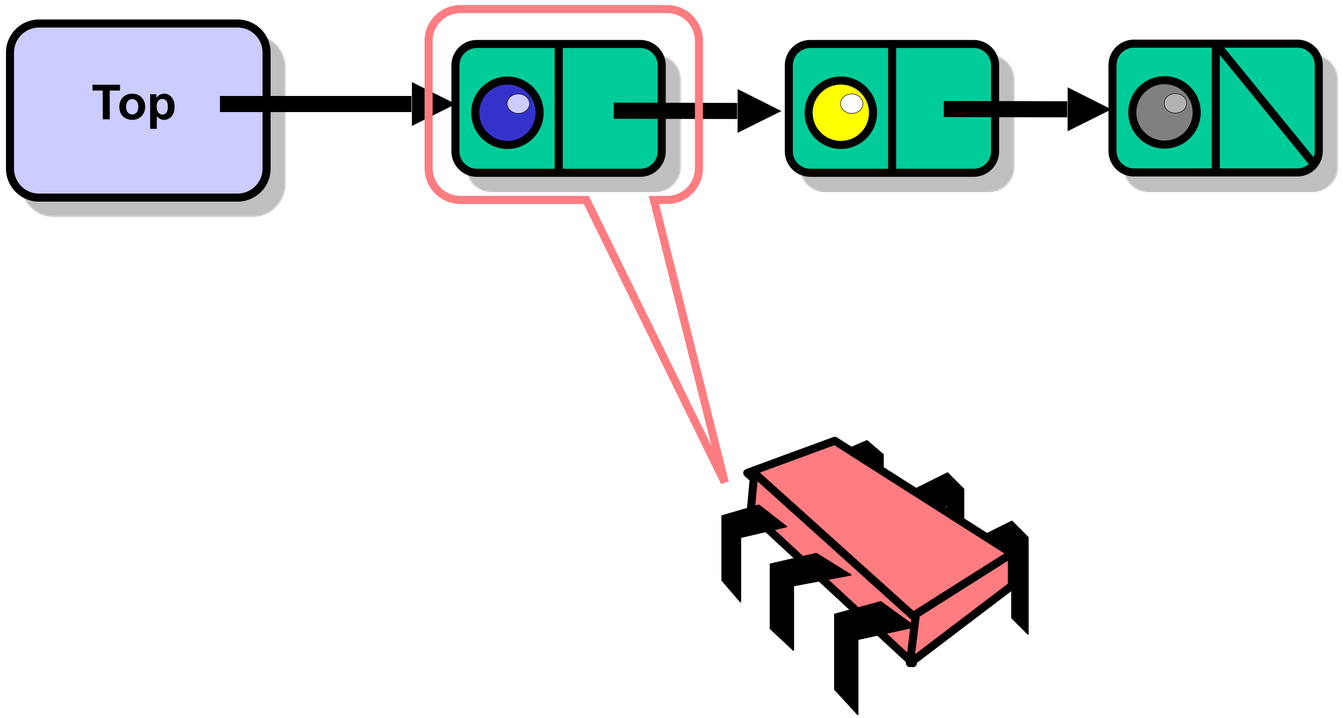
Push



Push



Pop



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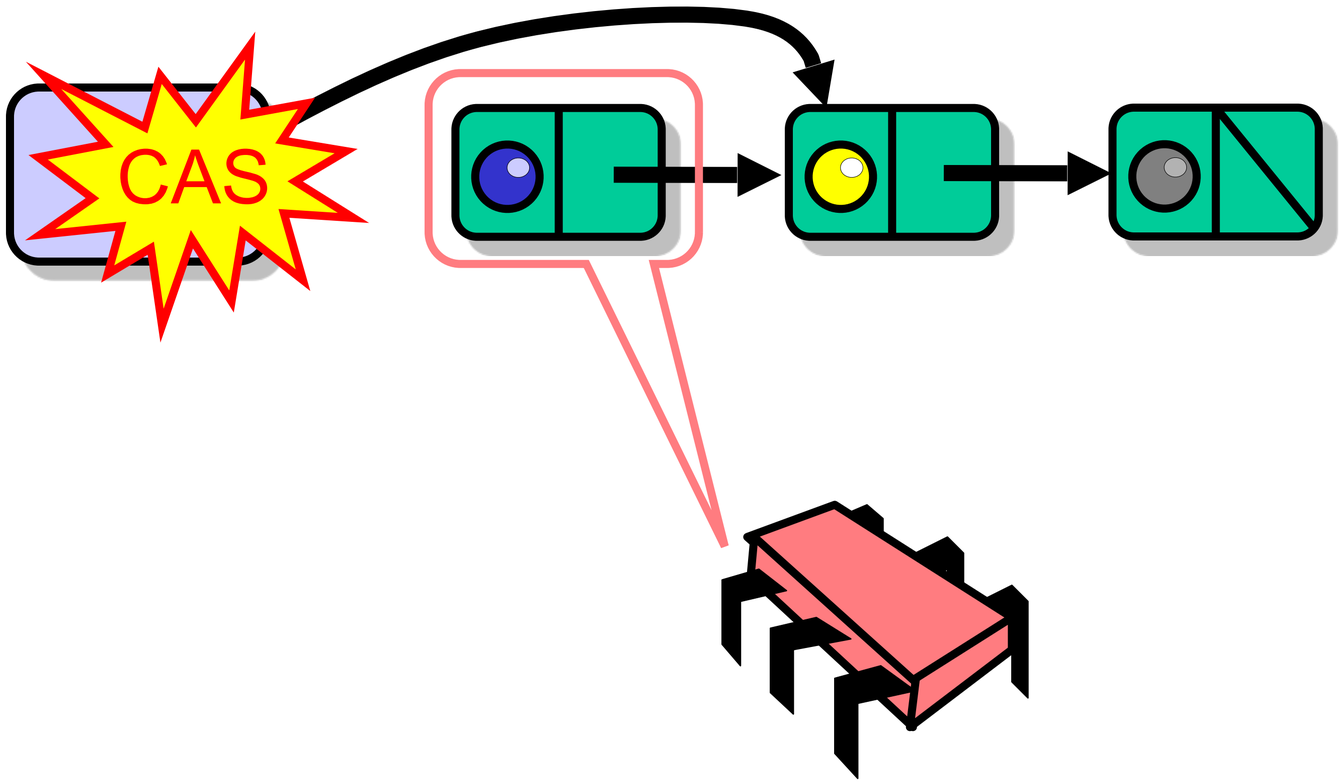

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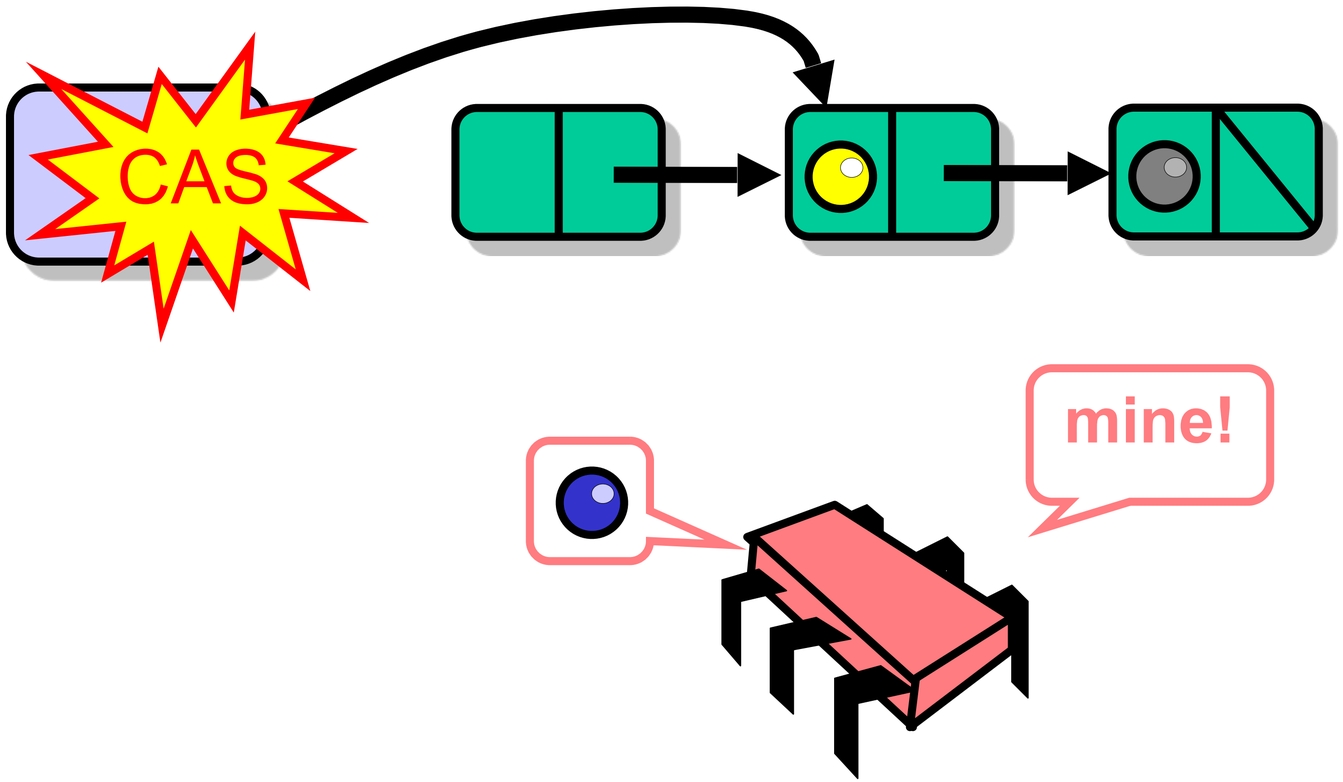
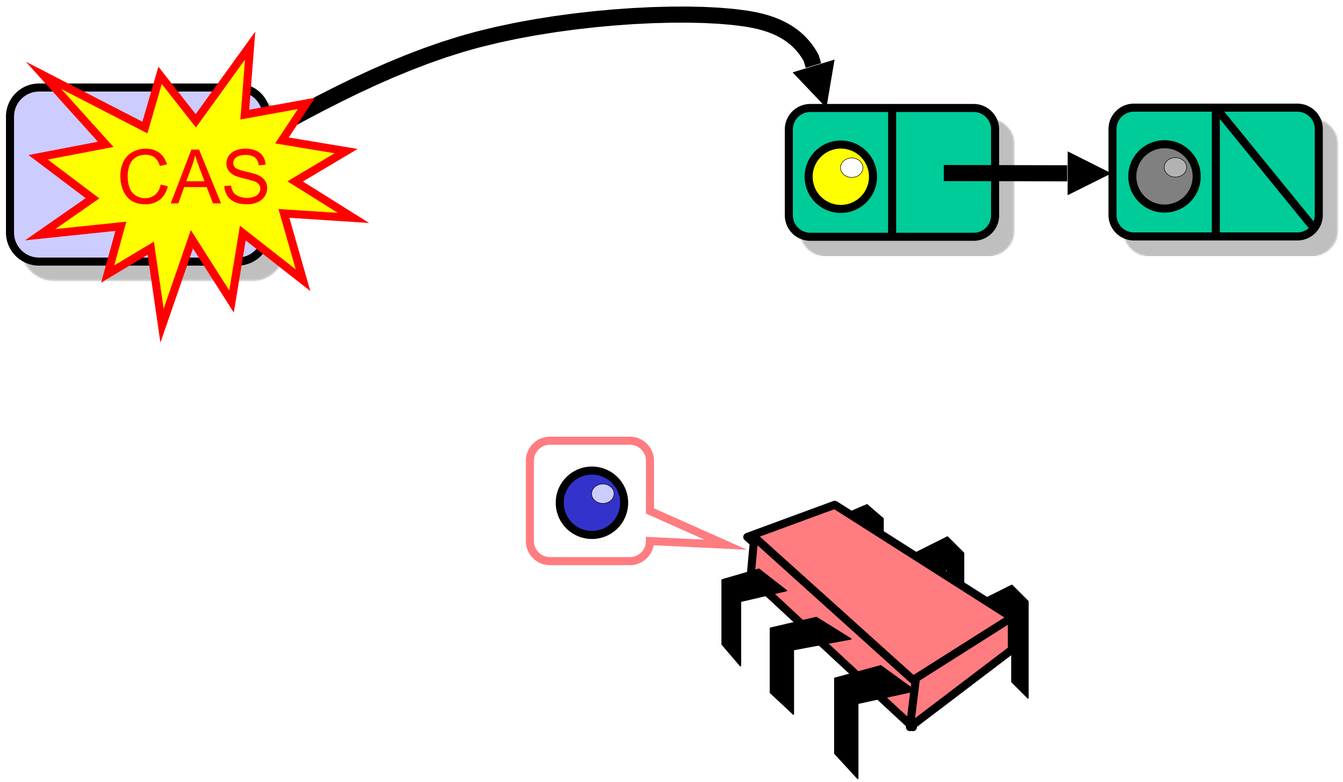
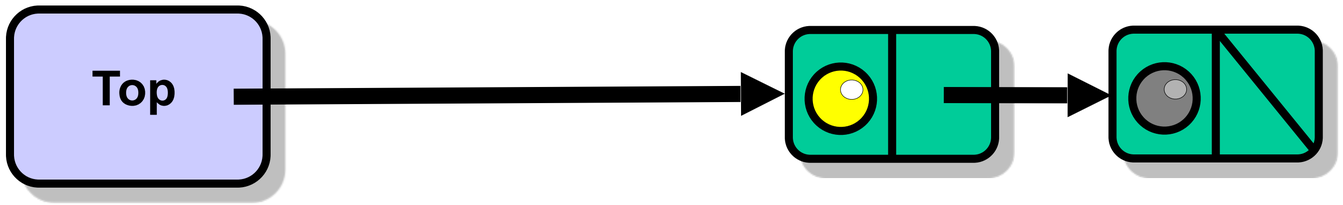
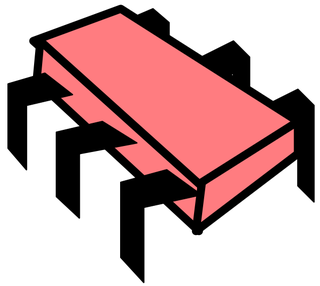


Pop



Pop





Lock-free Stack

```
class LockFreeStack[T] extends ConcurrentStack[T] {
  val top = new AtomicReference[Node](null)
  protected def tryPush(node: Node): Boolean = {
    val oldTop = top.get()
    node.next = oldTop
    top.compareAndSet(oldTop, node)
  }
  override def push(value: T): Unit = {
    val node = new Node(value)
    while (true) {
      if (tryPush(node))
        return
      else backoff.backoff()
    }}
```

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```

tryPush attempts to push a node

Lock-free Stack

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    }}
```

Read top value

Lock-free Stack

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  }
  override def push(value: T): Unit = {
    val node = new Node(value)
    while (true) {
      if (tryPush(node))
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      else backoff.backoff()
    }}
```

current top will be new node's successor

Lock-free Stack

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    val node = new Node(value)
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```

Try to swing top, return success or failure

Lock-free Stack

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    }}
```

Push calls tryPush

Lock-free Stack

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    val node = new Node(value)
    while (true) {
      if (tryPush(node))
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      else backoff.backoff()
    }}
```

Create new node

Lock-free Stack

```
class LockFreeStack[T] extends ConcurrentStack[T] {
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  }
  override def push(value: T): Unit = {
    val node = new Node(value)
    while (true) {
      if (tryPush(node))
        return
      else backoff.backoff()
    }}
```

If tryPush() fails, back off before retrying

Lock-free Stack

- Good
  - No locking
- Bad
  - Without GC, fear ABA
  - Without backoff, huge contention at top
  - In any case, no parallelism

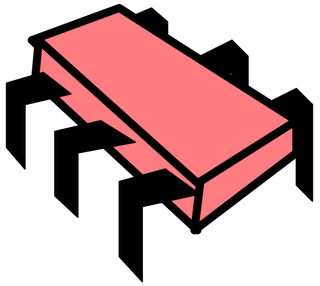
Big Question

- Are stacks *inherently* sequential?
- Reasons why
  - Every **pop()** call fights for top item
- Reasons why not
  - Stay tuned …

Elimination-Backoff Stack

- How to
  - “turn contention into parallelism”
- Replace familiar
  - **exponential backoff**
- With alternative
  - **elimination-backoff**

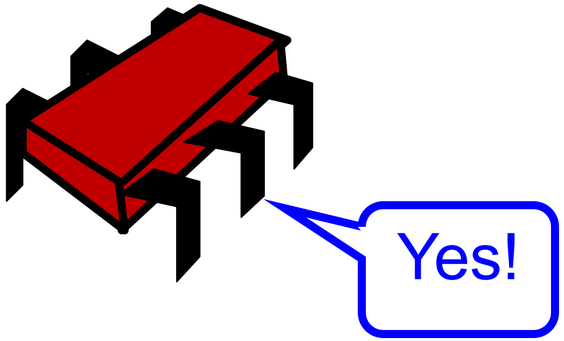
Observation



Push()

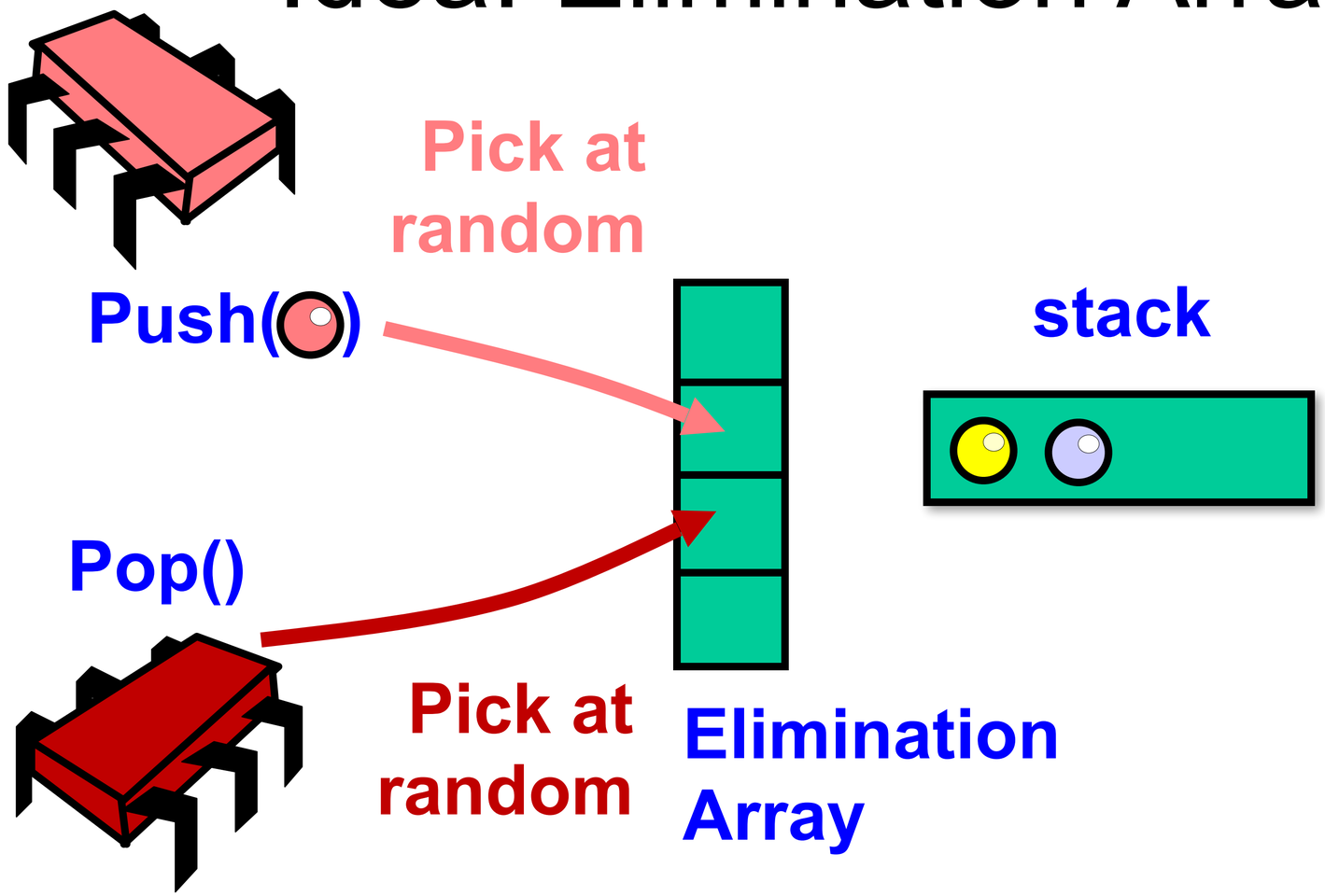
linearizable stack

Pop()

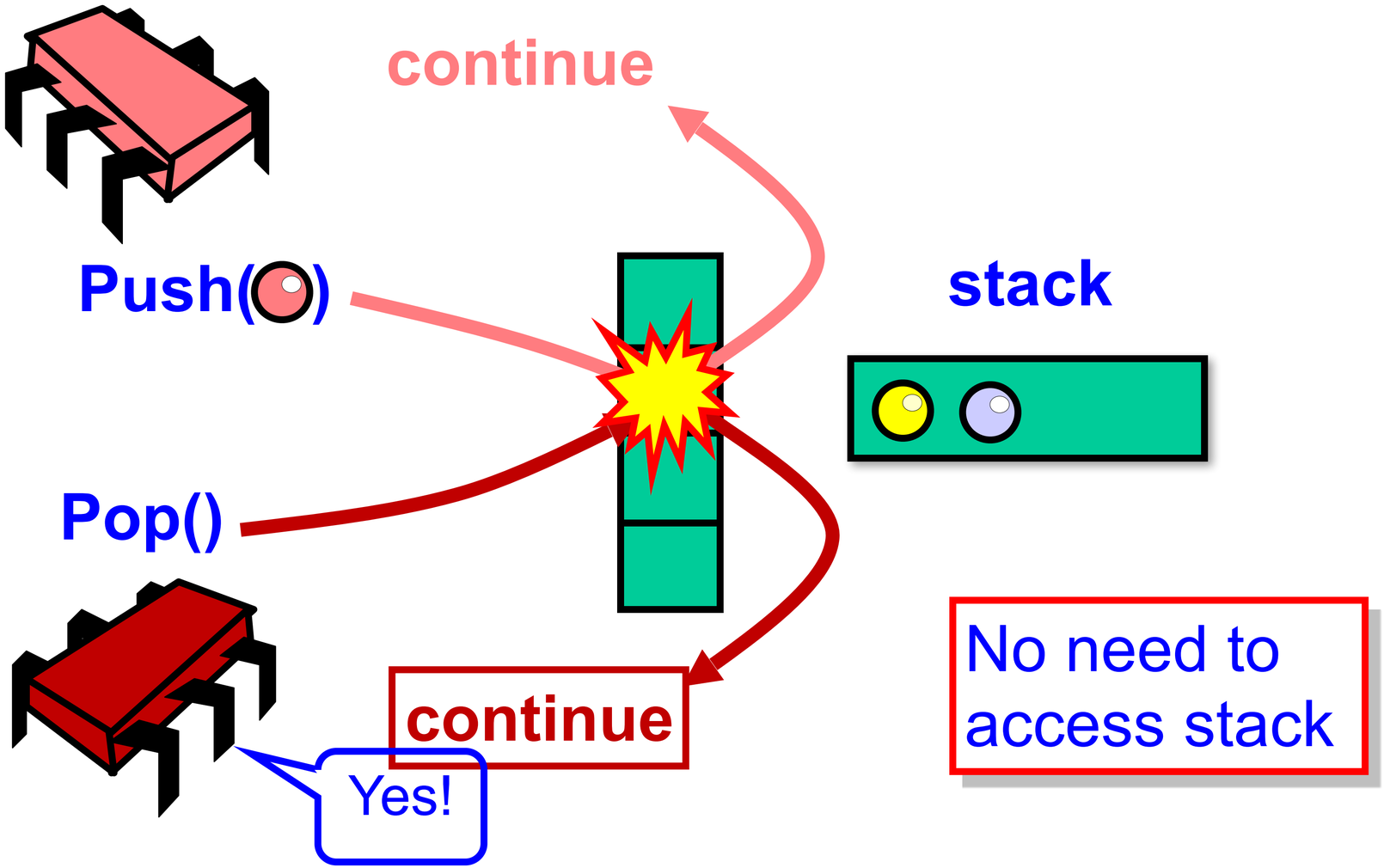


After an equal number of pushes and pops, stack stays the same

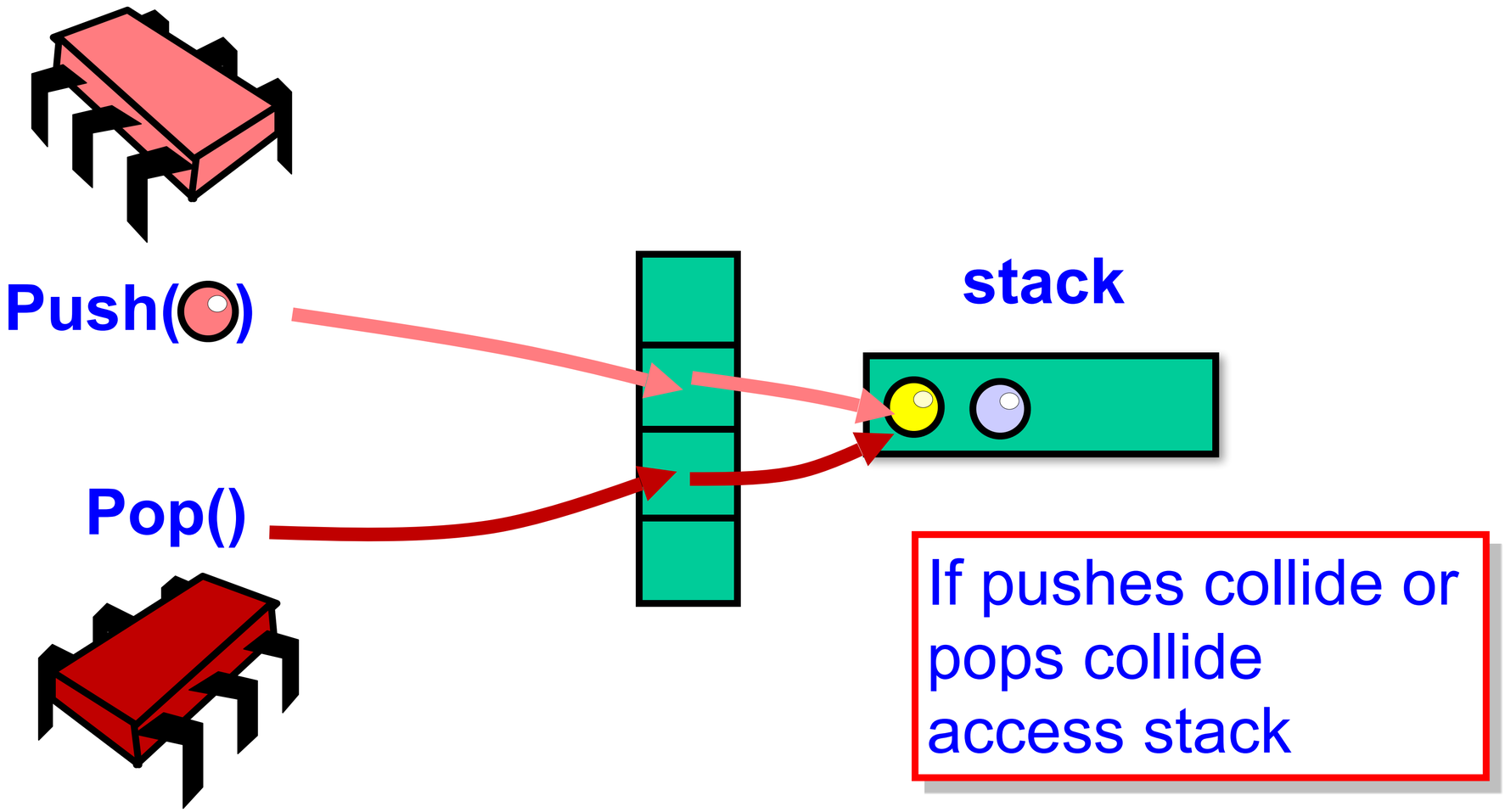
Idea: Elimination Array



Push Collides With Pop



No Collision

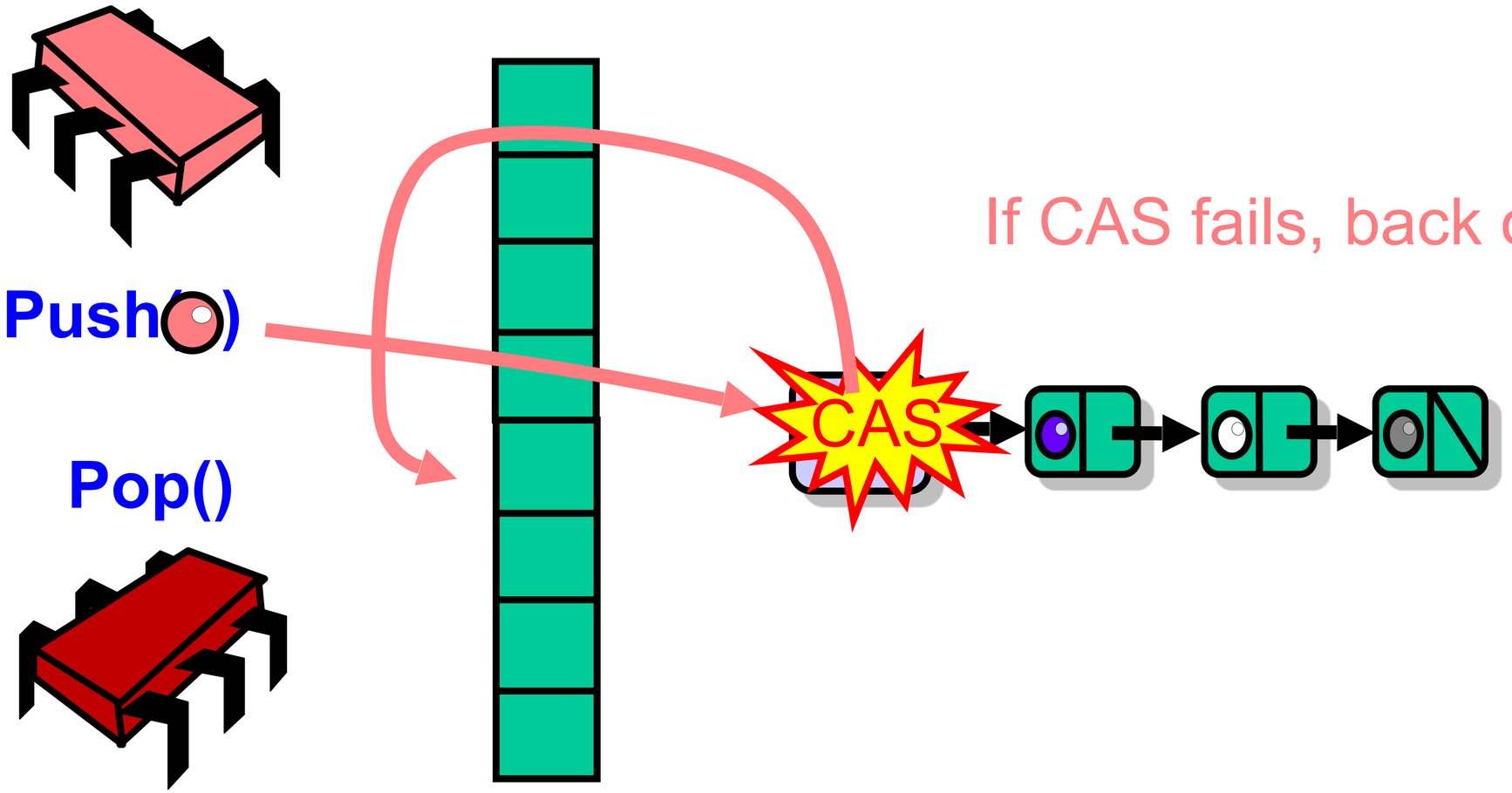


If pushes collide or pops collide access stack

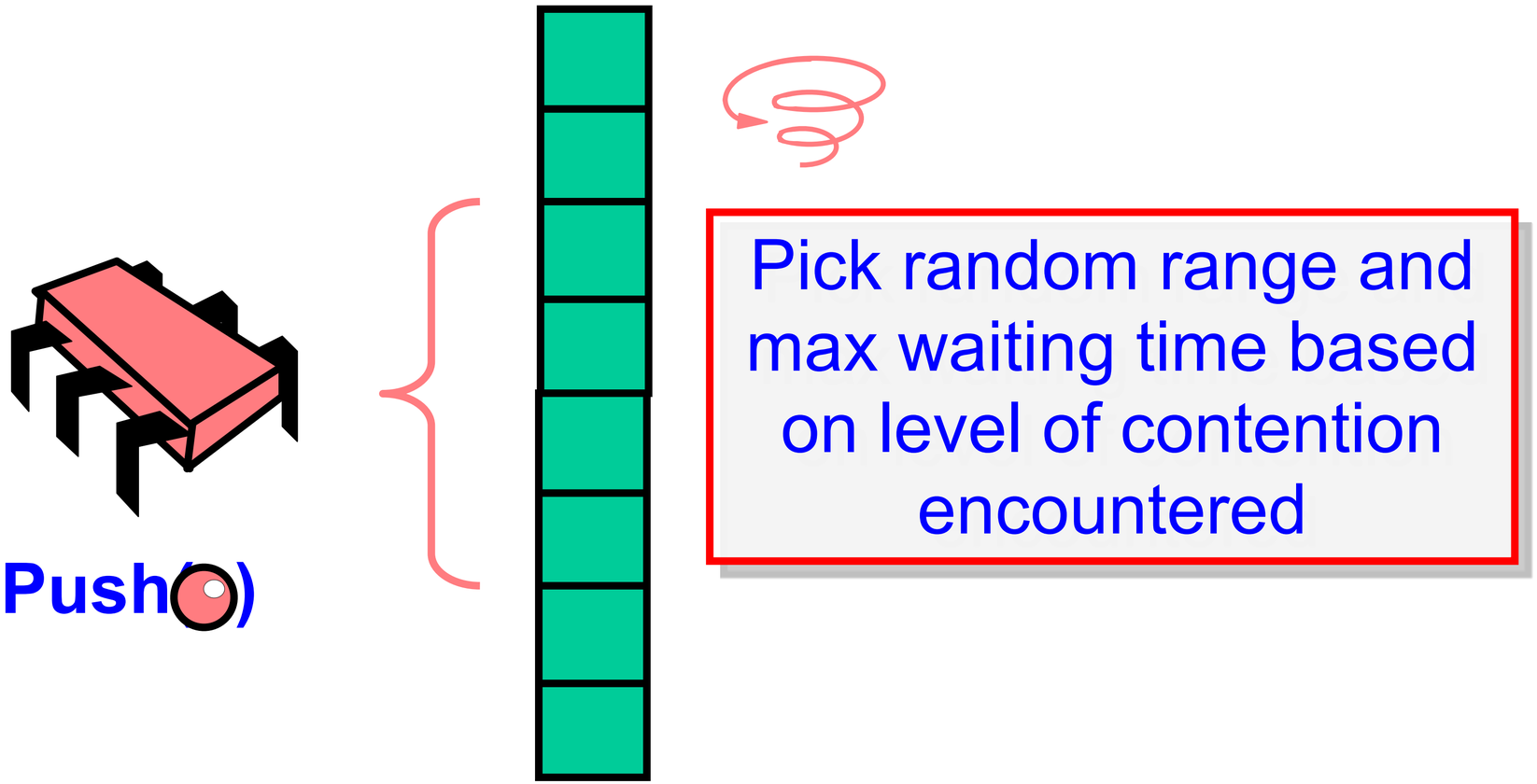
Elimination-Backoff Stack

- Lock-free stack + elimination array
- Access Lock-free stack,
  - If **uncontended**, apply operation
  - if **contended**, back off to elimination array and attempt elimination

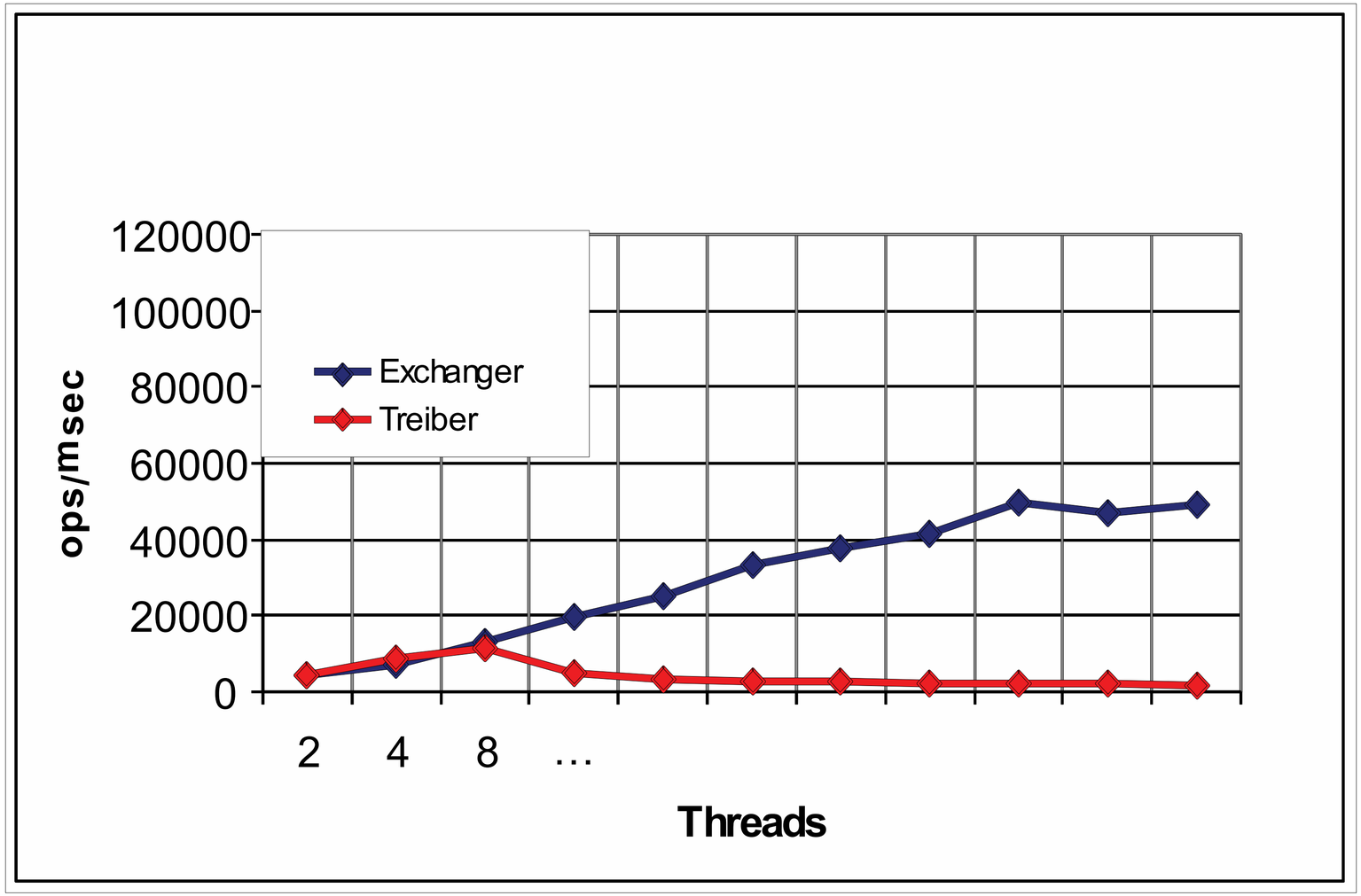
Elimination-Backoff Stack



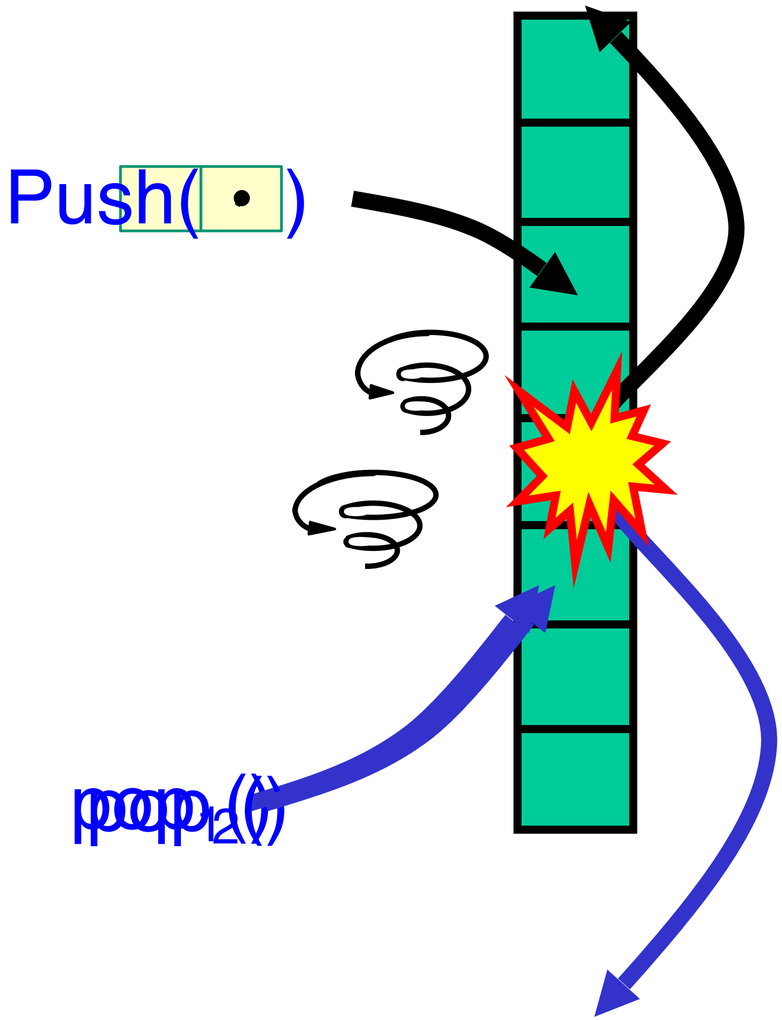
Dynamic Range and Delay



50-50, Random Slots

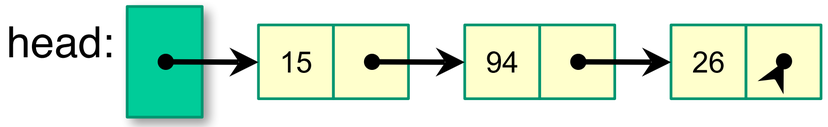


Asymmetric Rendevous

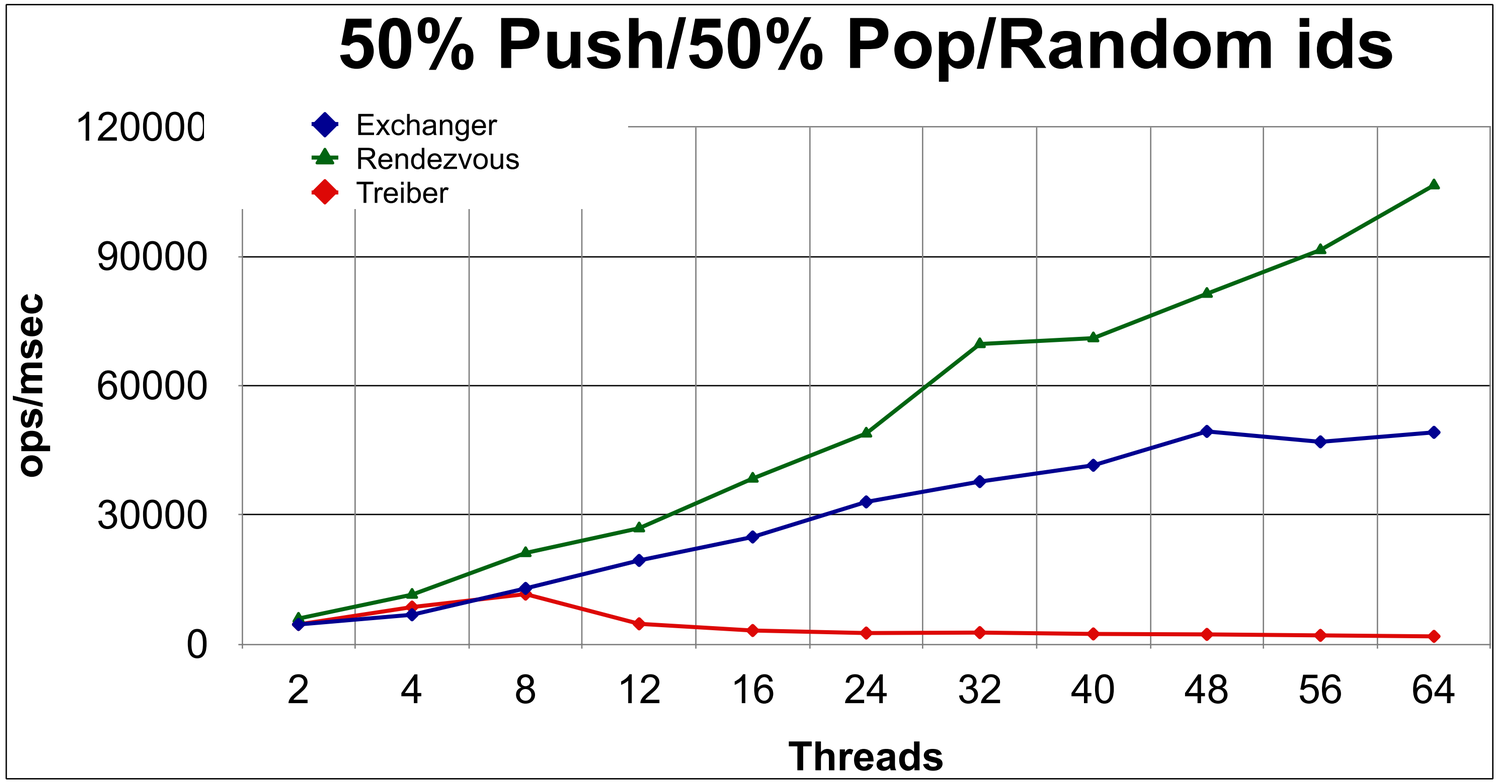


Pops find first vacant slot and spin.

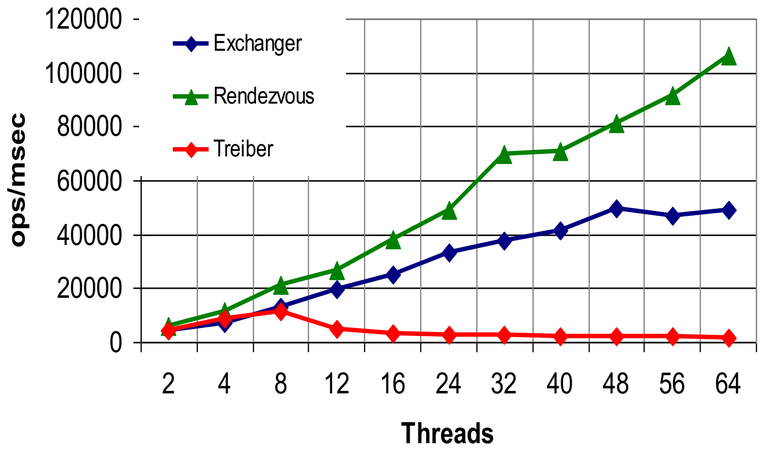
Pushes hunt for pops.



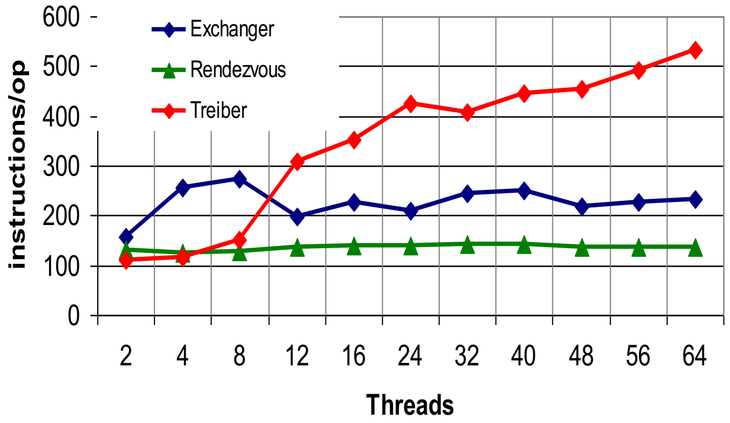
Asymmetric vs. Symmetric



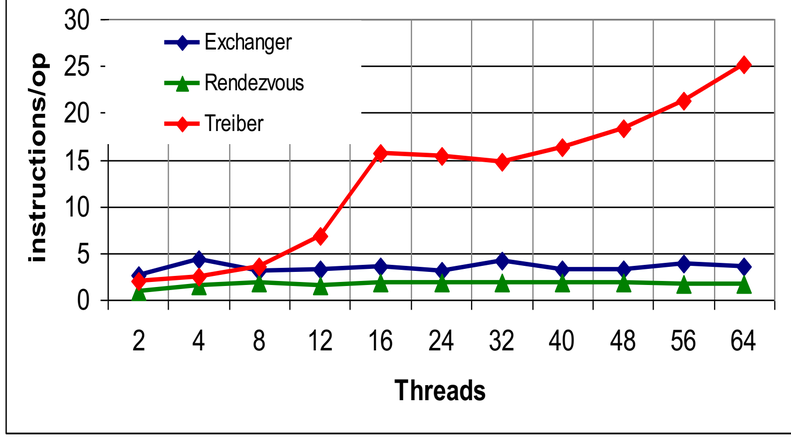
50% Push/50% Pop/Random ids



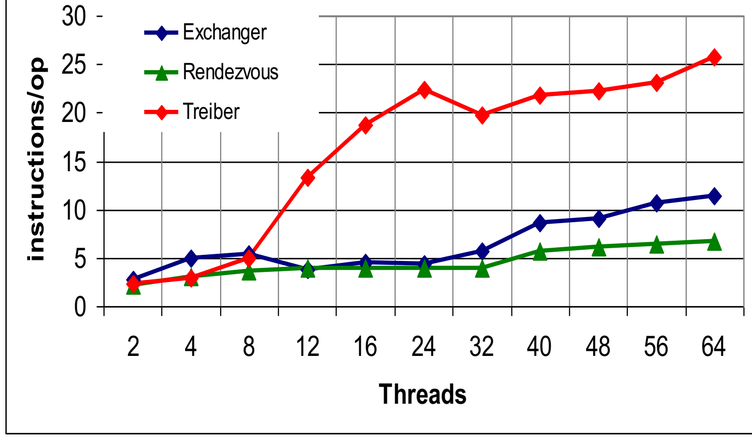
(a) Instructions/op



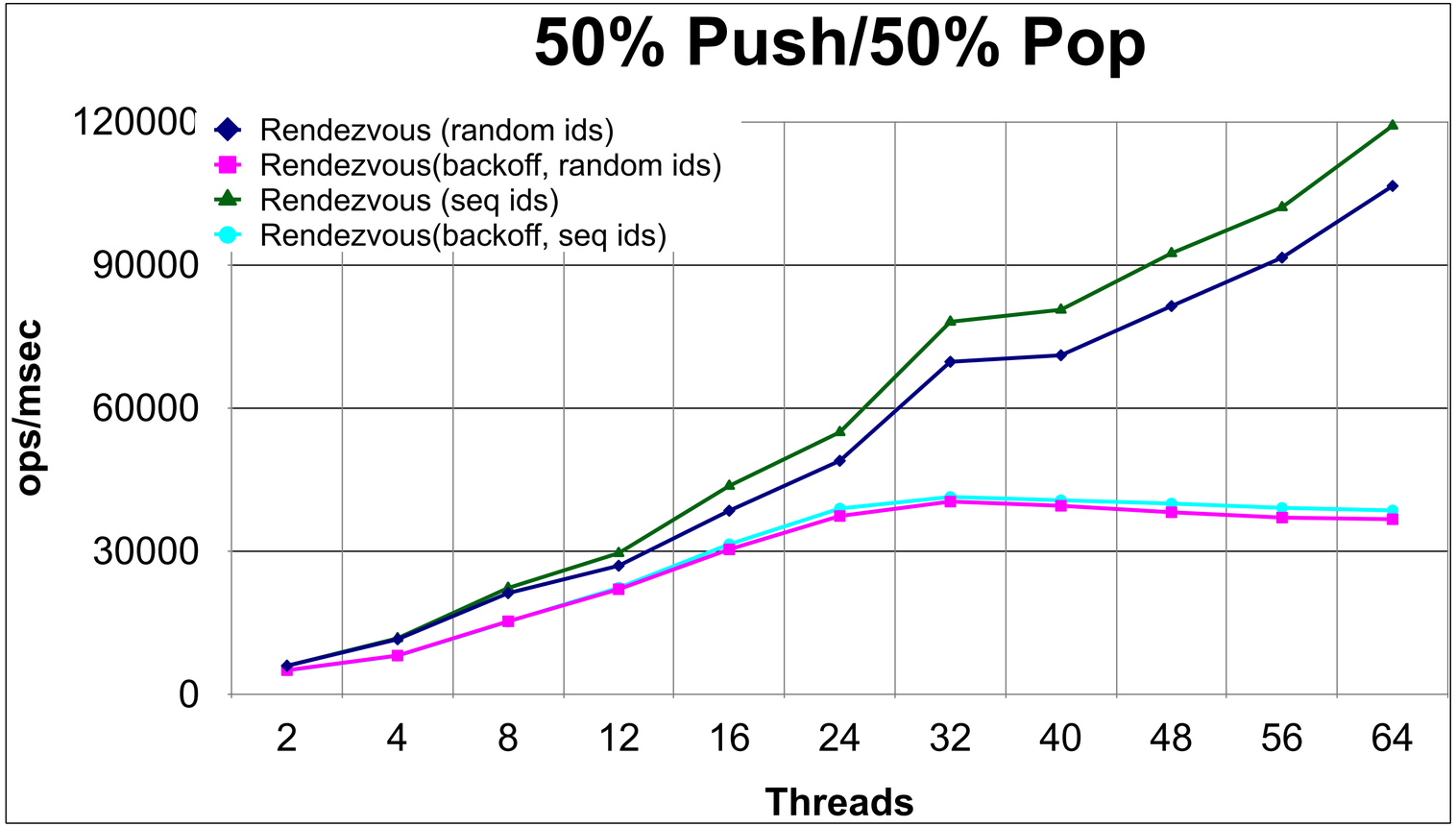
(c) CAS/op



(b) Cache misses/op



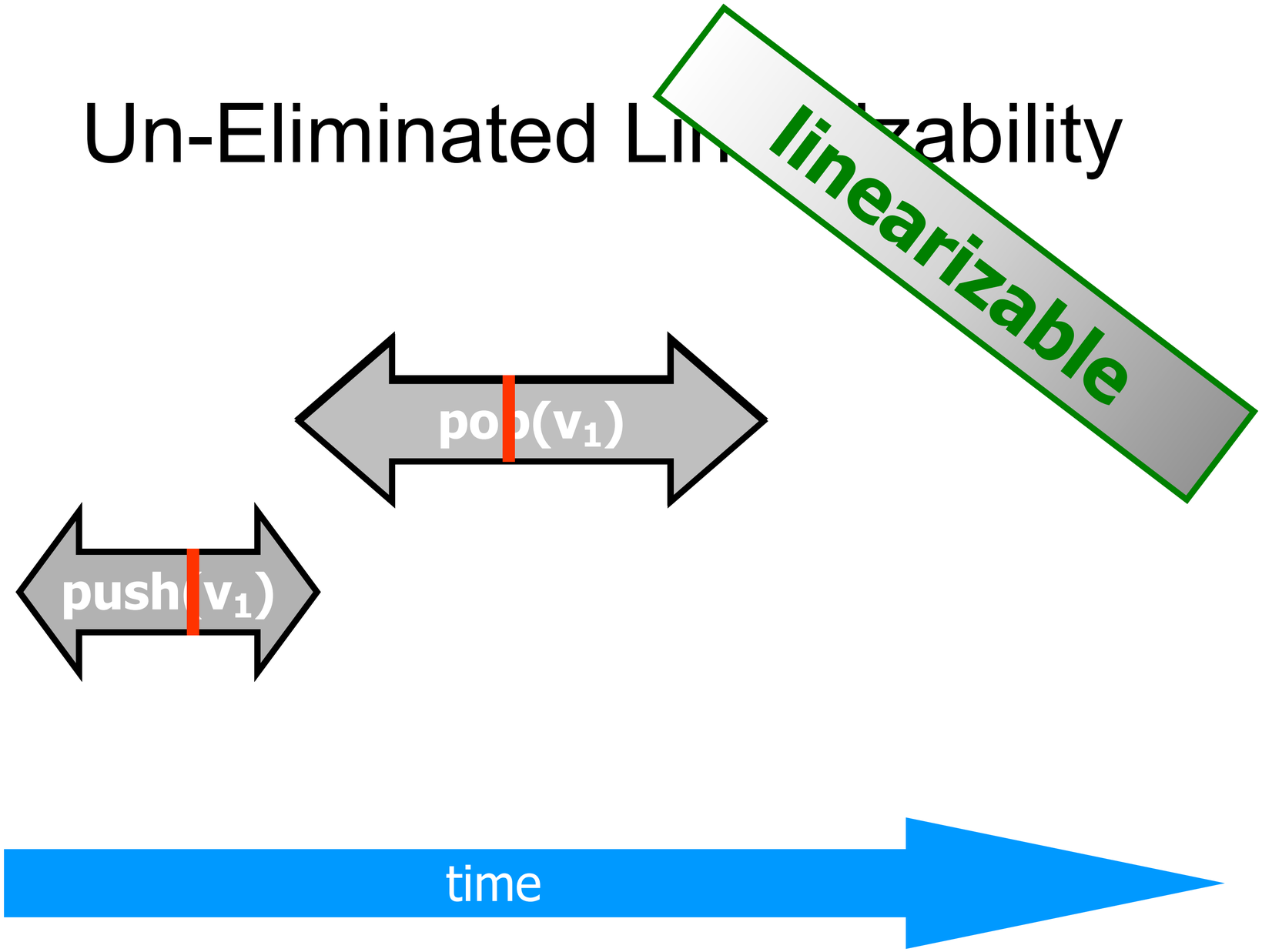
Effect of Backoff and Slot Choice



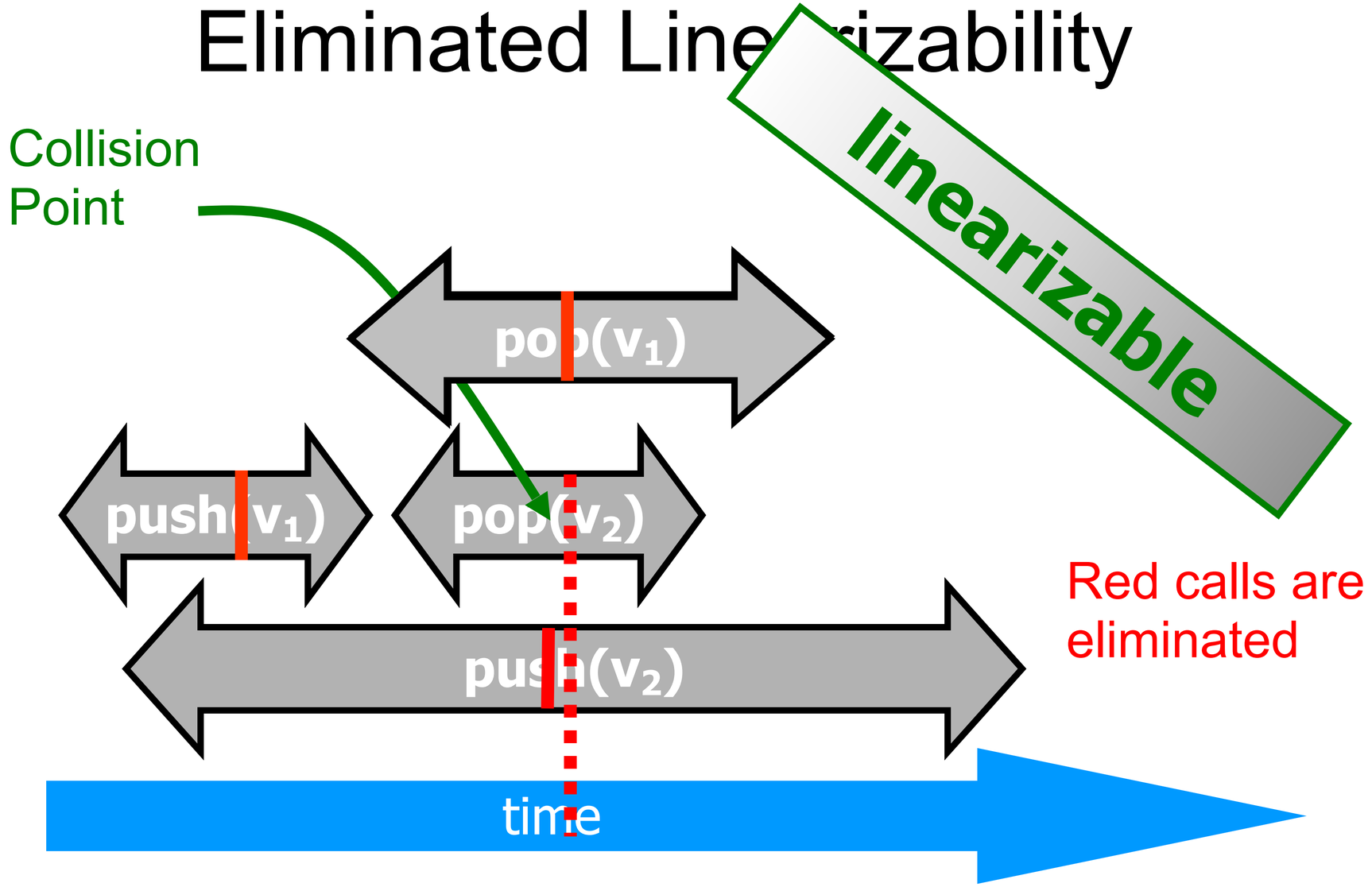
Linearizability

- **Un-eliminated calls**
  - **linearized as before**
- **Eliminated calls:**
  - **linearize pop() immediately after matching push()**
- **Combination is a linearizable stack**

Un-Eliminated Linearizability



Eliminated Linearizability



Backoff Has Dual Effect

- Elimination introduces parallelism
- Backoff to array cuts contention on lock-free stack
- Elimination in array cuts down number of threads accessing lock-free stack

Elimination Array

```
class EliminationArray[T: ClassTag] {
  val duration = 10
  private val size = ...
  val exchangers = Array.fill(size)(new Exchanger[T])
  val random = new Random()

  def visit(value: T, range: Int): T = {
    val slot = random.nextInt(range)
    exchangers(slot).exchange(value, duration)
  }
}
```

Elimination Array

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    val slot = random.nextInt(range)
    exchangers(slot).exchange(value, duration)
  }
}
```

An array of *Exchangers*

Digression: A Lock-Free Exchanger

```
class Exchanger[T] {

  val slot = new AtomicStampedReference[T](null, 0)

  def exchange(myItem: T,
               timeout: Long,
               unit: TimeUnit): T = { ... }
}
```

A Lock-Free Exchanger

```
class Exchanger[T] {

  val slot = new AtomicStampedReference[T](null, 0)

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}
```

Atomically modifiable reference + status

Atomic Stamped Reference

- AtomicStampedReference class
  - Java.util.concurrent.atomic package
- In C or C++:

Extracting Reference & Stamp

```
def get(stampHolder: Array[Int]): T
```

Extracting Reference & Stamp

```
def get(stampHolder: Array[Int]): T
```

Returns stamp at array index 0

Returns reference to object of type T

Exchanger Status

```
val EMPTY = 0
val WAITING = 1
val BUSY = 2
```

Exchanger Status

```
val EMPTY = 0
val WAITING = 1
val BUSY = 2
```

Nothing yet

Exchange Status

```
val EMPTY = 0
val WAITING = 1
val BUSY = 2
```

Nothing yet

One thread is waiting for rendez-vous

Exchange Status

```
val EMPTY = 0
val WAITING = 1
val BUSY = 2
```

Nothing yet

One thread is waiting for rendez-vous

Other threads busy with rendez-vous

The Exchange

```
def exchange(myItem: T, timeout: Long): T = {
  val timeBound = System.nanoTime() + timeout
  val stapmholder = Array(EMPTY)
  while (true) {
    if (System.nanoTime() > timeBound)
      throw new TimeoutException
    var yrItem = slot.get(stapmholder)
    stapmholder(0) match {
      case EMPTY => ...     // slot is free
      case WAITING => ...   // someone waiting for me
      case BUSY => ...      // others exchanging
    }
  }
}
```

The Exchange

```
def exchange(myItem: T, timeout: Long) : T = {
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  val stapmholder = Array(EMPTY)
  while (true) {
    if (System.nano
      throw new TimeoutException
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      case EMPTY => ...     // slot is free
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      case BUSY => ...      // others exchanging
    }
  }
}
```

Item and timeout

The Exchange

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    }
  }
}
```

Array holds status

The Exchange

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def exchange(myItem: T, timeout: Long): T = {
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    }
  }
}
```

Loop until timeout

The Exchange

```
def exchange(myItem: T, timeout: Long): T = {
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      case WAITING => ...   // someone waiting for me
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    }
  }
}
```

Get other's item and status

The Exchange

An *Exchanger* has three possible states

```
def exchange(x: T, timeout: Long, tunit: TimeUnit): T = {
  val timeBound = System.nanoTime() + timeout
  val stapmholder = Array(EMPTY)
  while (true) {
    if (System.nanoTime() > timeBound)
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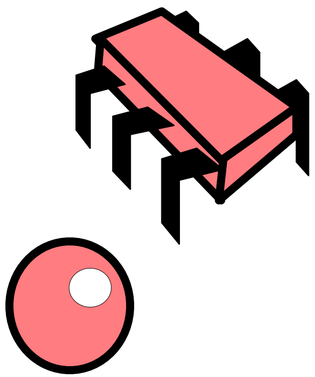
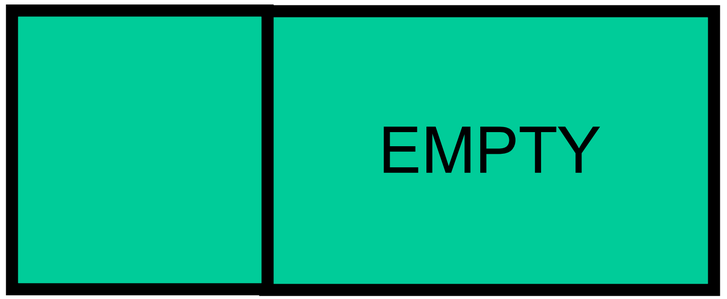
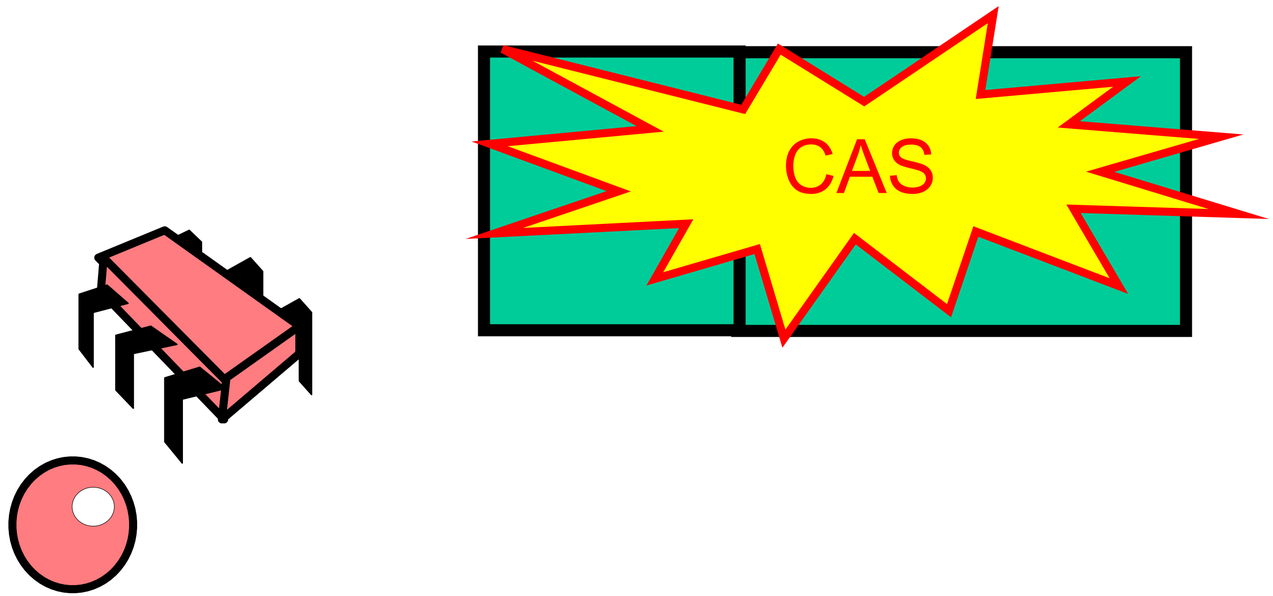
  }
}
```

Lock-free Exchanger

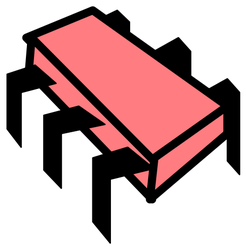


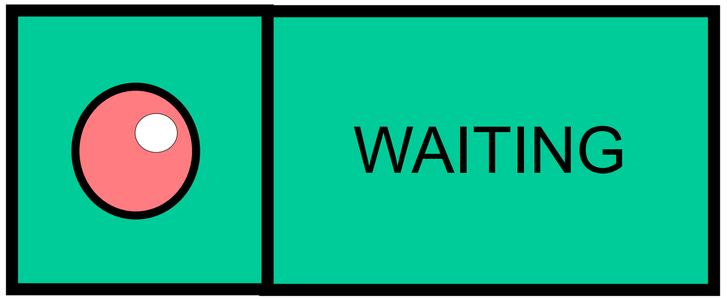


Lock-free Exchanger

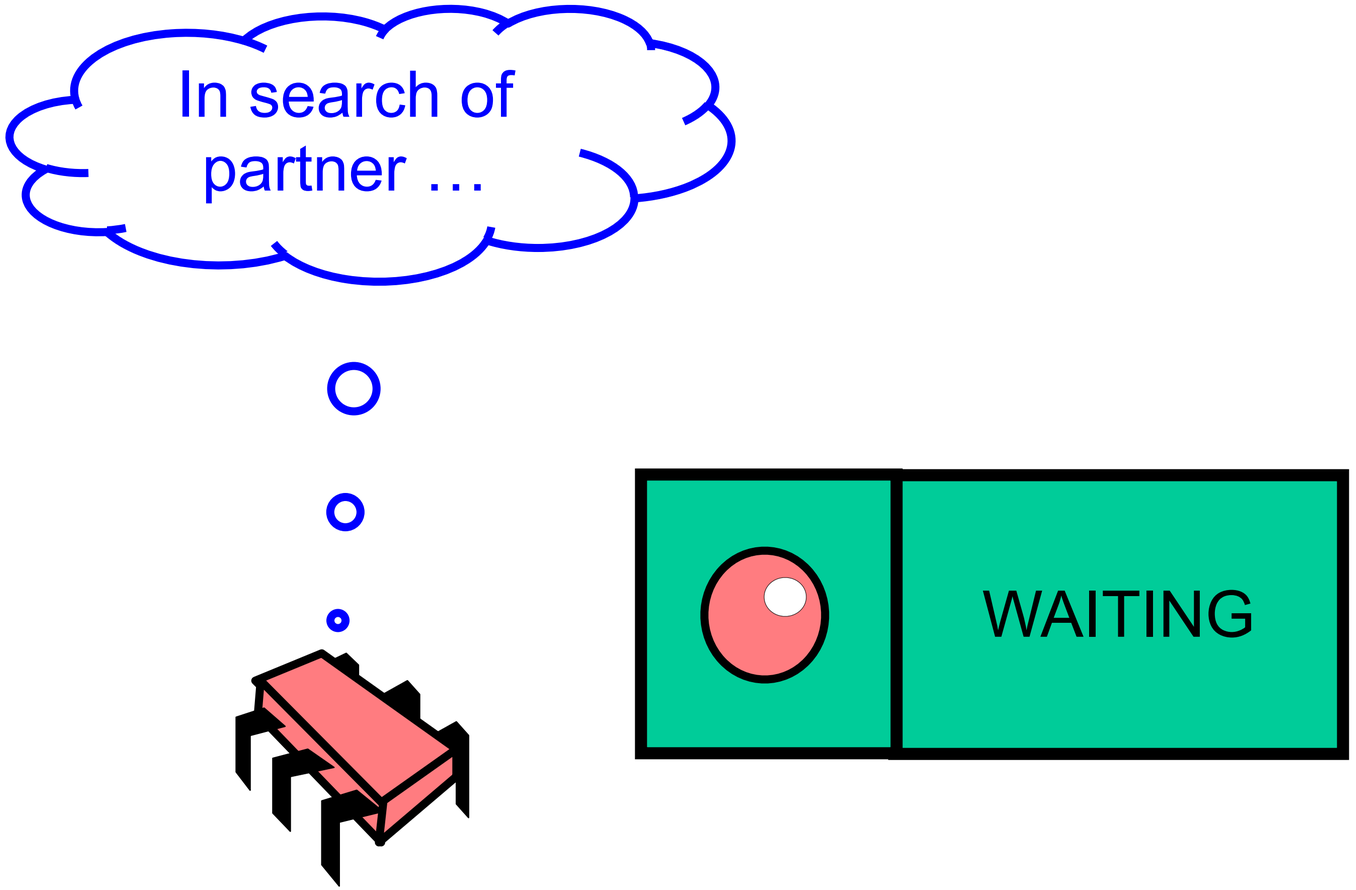


Lock-free Exchanger

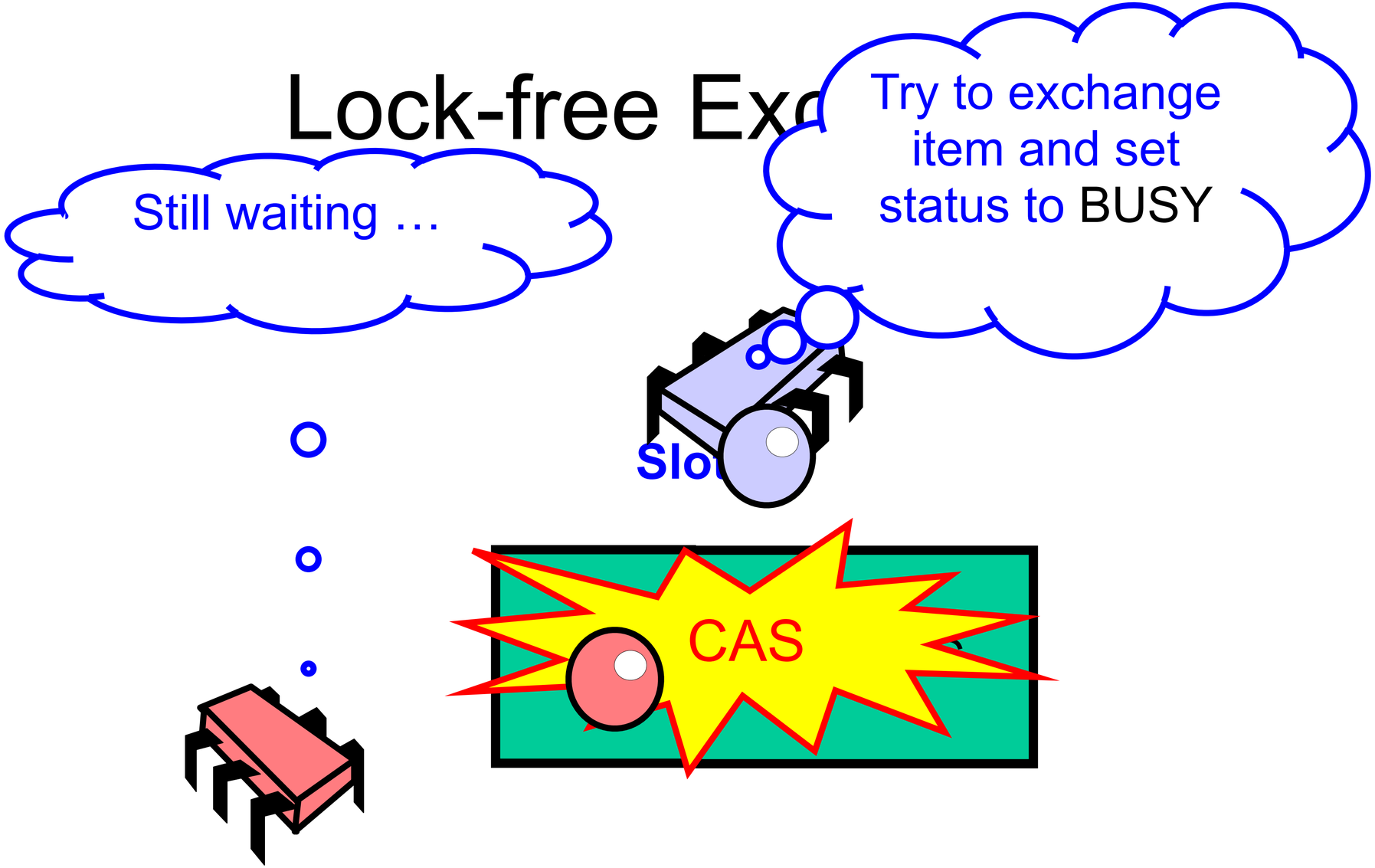




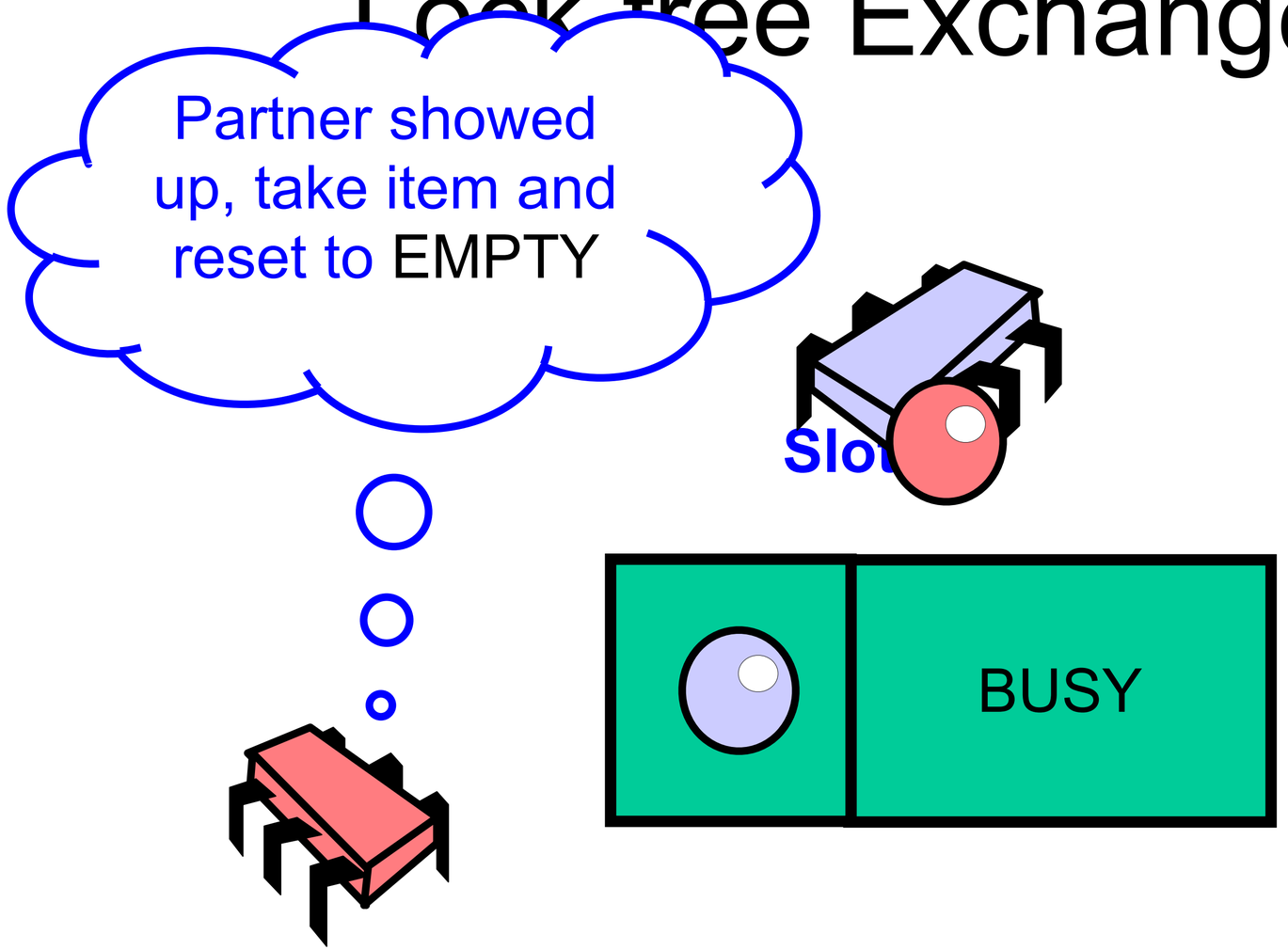
Lock-free Exchanger



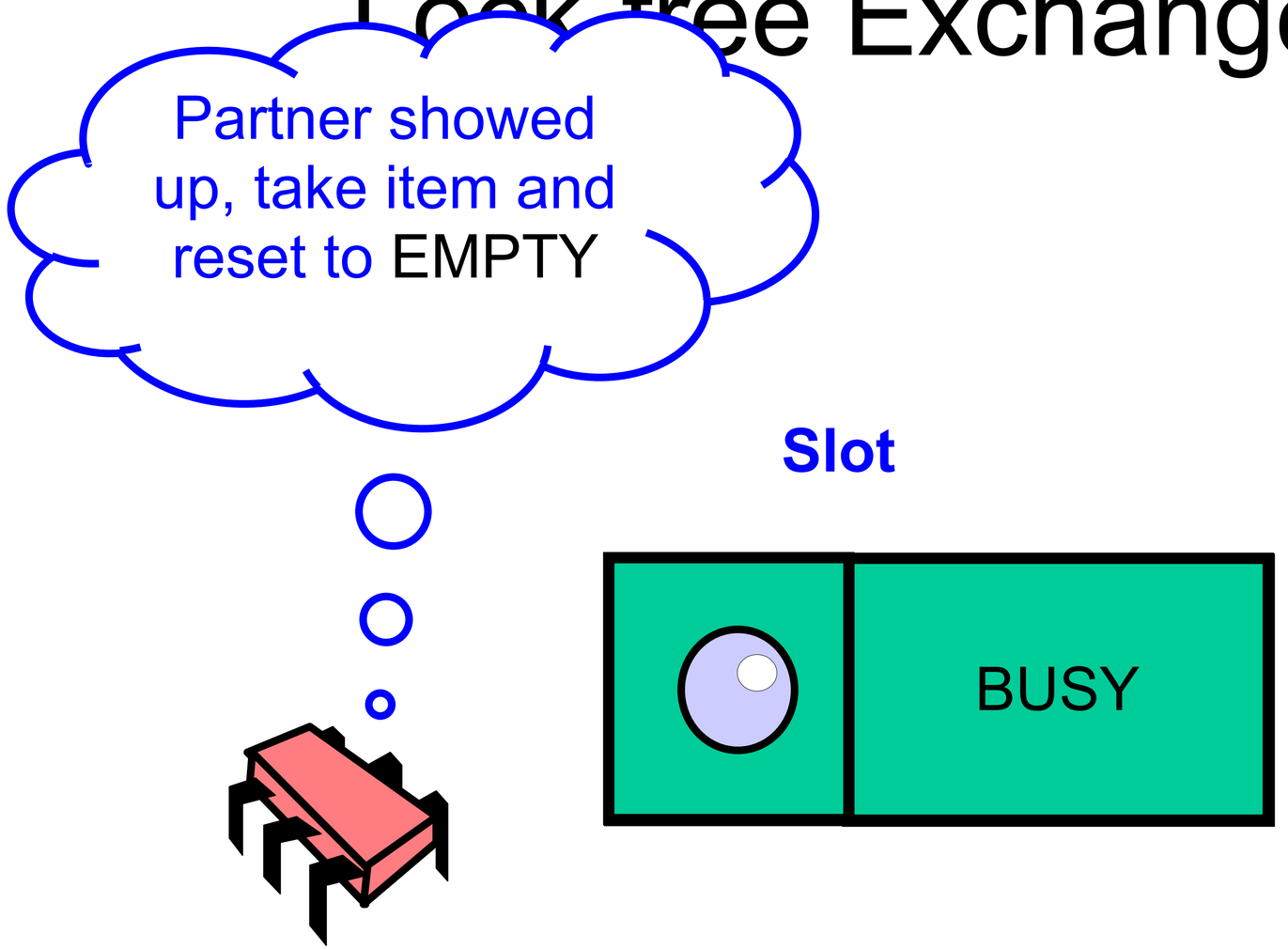
Lock-free Exc



Lock-free Exchanger



Lock-free Exchanger



Can start skipping from here if running out of time

Exchanger State EMPTY

```
case EMPTY =>
  if (slot.compareAndSet(yrItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound) {
      yrItem = slot.get(stapmholder)
      if (stapmholder(0) == BUSY) {
         slot.set(null, EMPTY)
         return yrItem
      }
    }
    if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
      throw new TimeoutException
    } else {
      yrItem = slot.get(stapmholder)
      slot.set(null, EMPTY)
      return yrItem
    }}
```

Exchanger State EMPTY

```
case EMPTY =>
  if (slot.compareAndSet(yrItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound) {
      yrItem = slot.get(stapmholder)
      if (stapmholder(0) == BUSY) {
        slot.set(null, EMPTY)
        return yrI
      }
    }
    if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
      throw new TimeoutException
    } else {
      yrItem = slot.get(stapmholder)
      slot.set(null, EMPTY)
      return yrItem
    }}
```

Try to insert *myItem* and change state to *WAITING*

Exchanger State EMPTY

```
case EMPTY =>
  if (slot.compareAndSet(yrItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound) {
      yrItem = slot.get(stapmholder)
      if (stapmholder(0) == BUSY) {
        slot.set(null, EMPTY)
        return yrItem
      }
    }
    if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
      throw new
    } else {
      yrItem = slot.get(stapmholder)
      slot.set(null, EMPTY)
      return yrItem
    }}
```

Spin until either
myItem is taken or timeout

Exchanger State EMPTY

```
case EMPTY =>
  if (slot.compareAndSet(yrItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound) {
      yrItem = slot.get(stapmholder)
      if (stapmholder(0) == BUSY) {
        slot.set(null, EMPTY)
        return yrItem
      }
    }
    if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
      throw new TimeoutException
    } else {
      yrItem = slot.get(stapmholder)
      slot.set(null, EMPTY)
      return yrItem
    }}
```

myItem was taken,
so return *yrItem*
that was put in its place

Exchanger State EMPTY

Otherwise we ran out of time, try to reset status to EMPTY and time out

```
if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
  throw new TimeoutException
```

Exchanger State EMPTY

```
case EMPTY =>
  if (slot.compareAndSet(yrItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound) {
      yrItem = slot.get(stapmholder)
      if (stapmholder(0) == BUSY) {
        slot
        return yrIte
      }
    }
    if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
      throw new TimeoutException
    } else {
      yrItem = slot.get(stapmholder)
      slot.set(null, EMPTY)
      return yrItem
    }}
```

If reset failed,
someone showed up after all,
so take that item

Exchanger State EMPTY

```
case EMPTY =>
  if (slot.compareAndSet(yrItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound) {
      yrItem = slot.get(stapmholder)
      if (stapmholder(0) == BUSY) {
        slot.set(null, EMPTY)
        return yrItem
      }
    }
    if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
      throw new TimeoutException
    } else {
      yrItem = slot.get(stapmholder)
      slot.set(null, EMPTY)
      return yrItem
    }}
```

Clear slot and take that item

Exchanger State EMPTY

```
case EMPTY =>
  if (slot.compareAndSet(yrItem, myItem, EMPTY, WAITING)) {
    while (System.nanoTime() < timeBound) {
      yrItem = slot.get(stapmholder)
      if (stapmholder(0) == BUSY) {
        slot.
        retur
      }
    }
    if (slot.compareAndSet(myItem, null, WAITING, EMPTY)) {
      throw new TimeoutException
    } else {
      yrItem = slot.get(stapmholder)
      slot.set(null, EMPTY)
      return yrItem
    }}
```

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

States WAITING and BUSY

```
case WAITING =>
  if (slot.compareAndSet(yrItem, myItem, WAITING, BUSY)) {
    return yrItem
  }
case BUSY =>
case x =>
  throw new Exception("Cannot happen")
```

States WAITING and BUSY

```
case WAITING =>
  if (slot.compareAndSet(yrItem, myItem, WAITING, BUSY)) {
    return yrItem
  }
case BUSY =>
case x =>
  throw new Exception("Cannot happen")
```

someone is waiting to exchange,
so try to CAS my item in
and change state to BUSY

States WAITING and BUSY

```
case WAITING =>
  if (slot.compareAndSet(yrItem, myItem, WAITING, BUSY)) {
    return yrItem
  }
case BUSY =>
case x =>
  throw new Exception("Cannot happen")
```

If successful, return other's item,
otherwise someone else took it,
so try again from start

States WAITING and BUSY

```
case WAITING =>
  if (slot.compareAndSet(yrItem, myItem, WAITING, BUSY)) {
    return yrItem
  }
case BUSY =>
case x =>
  throw new Exception("Cannot happen!")
```

If BUSY,
other threads exchanging,
so start again

The Exchanger Slot

- Exchanger is lock-free
- Because the only way an exchange can fail is if others repeatedly succeeded or no-one showed up
- The slot we need does not require symmetric exchange

Stop skipping

Back to the Stack: the Elimination Array

```
class EliminationArray[T: ClassTag] {
  ...
  def visit(value: T, range: Int): T = {
    val slot = random.nextInt(range)
    exchanger(slot).exchange(value, duration)
  }
}
```

Elimination Array

```
class EliminationArray[T: ClassTag] {
  ...
  def visit(value: T, range: Int): T = {
    val slot = random.nextInt(range)
    exchanger(slot).exchange(value, duration)
  }
}
```

visit the elimination array with fixed value and range

Elimination Array

```
class EliminationArray[T: ClassTag] {
  ...
  def visit(value: T, range: Int): T = {
    val slot = random.nextInt(range)
    exchanger(slot).exchange(value, duration)
  }
}
```

Pick a random array entry

Elimination Array

```
class EliminationArray[T] {
  ...
  def visit(value: T, range: Int): T = {
    val slot = random.nextInt(range)
    exchanger(slot).exchange(value, duration)
  }
}
```

Exchange value or time out

Elimination Stack Push

```
override def push(value: T): Unit = {
  ...
  while (true) {
    if (tryPush(node))
      return
    else try {
      val otherValue =
        eliminationArray.visit(value, rangePolicy.getRange)
      if (otherValue == null)
        return
  }
}
```

Elimination Stack Push

```
override def push(value: T): Unit = {
  ...
  while (true) {
    if (tryPush(node))
      return
    else try {
      val otherValue =
        eliminationArray.visit(value, rangePolicy.getRange)
      if (otherValue == null)
        return
  }
}
```

First, try to push

Elimination Stack Push

```
override def push(value: T): Unit = {
  ...
  while (true) {
    if (tryPush(node))
      return
    else try {
      val otherValue =
        eliminationArray.visit(value, rangePolicy.getRange)
      if (otherValue == null)
        return
  }
}
```

If I failed, backoff & try to eliminate

Elimination Stack Push

```
override def push(value: T): Unit = {
  ...
  while (true) {
    if (tryPush(node))
      return
    else try {
      val otherValue =
        eliminationArray.visit(value, rangePolicy.getRange)
      if (otherValue == null)
        return
  }
}
```

Value pushed and range to try

Elimination Stack Push

```
override def push(value: T): Unit = {
  ...
  while (true) {
    if (tryPush(node))
      return
    else try {
      val otherValue =
        eliminationArray.visit(value, rangePolicy.getRange)
      if (otherValue == null)
        return
    }
  }
```

Only `pop()` leaves null,
so elimination was successful

Elimination Stack Push

```
override def push(value: T): Unit = {
  ...
  while (true) {
    if (tryPush(node))
      return
    else try {
      val otherValue =
        eliminationArray.visit(value, rangePolicy.getRange)
      if (otherValue == null)
        return
    }
  }
```

Otherwise, retry **`push()`** on lock-free stack

Elimination Stack Pop

```
override def pop(): T = {
  while (true) {
    val returnNode = tryPop()
    if (returnNode != null) {
      return returnNode.value
    } else try {
      val otherValue =
        eliminationArray.visit(null, rangePolicy.getRange)
      if (otherValue != null) {
        return otherValue
      }
    }
  }}
```

Elimination Stack Pop

If value not null, other thread is a **`push()`**, so elimination succeeded

```
override def pop(): T = {
  while (true) {
    if (returnNode != null) {
      return returnNode.value
    } else try {
      val otherValue =
        eliminationArray.visit(null, rangePolicy.getRange)
      if (otherValue != null) {
        return otherValue
      }
    }
  }}
```

Demo: Benchmarking Stacks

Summary

- We saw both lock-based and lock-free implementations of
- queues and stacks
- Don’t be quick to declare a data structure inherently sequential
  - Linearizable stack is not inherently sequential (though it is in the worst case)
- ABA is a real problem, pay attention