Synchronization primitives can be faster with `SegmentQueueSynchronizer`

Nikita Koval, Hydra 2020

Kotlin

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- PhD student @ ITMO University
- Teaching concurrent programming course @ ITMO University

https://nkoval.com

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Writing concurrent code is painful...

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...that is why people use synchronization primitives.

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...that is why people use synchronization primitives.

Kotlin Coroutines should also provide them.

Locks and Semaphores

Mutex = **Mut**ual **Ex**clusion, at most 1 thread is in the critical section

Locks and Semaphores

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```
val m = Mutex()
```

`m.lock()`	`m.lock()`
`[critical section]`	`[critical section]`
`m.unlock()`	`m.unlock()`

Locks and Semaphores

Mutex = **Mut**ual **Ex**clusion, at most 1 thread is in the critical section

```
val m = Mutex()
```

Thread 1	Thread 2
m.lock() [critical section] m.unlock()	transfer the permit
	m.lock() [critical section] m.unlock()

Locks and Semaphores

Semaphore = at most **K** threads are in the critical section

```
Mutex = Semaphore(permits = 1)
```

Locks and Semaphores

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Semaphore algorithm is the start of this project!

Blocking Calls via `Future`

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  fun await(): T
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Blocking Calls via `Future`

Threads, coroutines, continuations… Need a simple abstraction!

```
interface Future<T> {
  fun await(): T
}
```

```
class FutureImmediate<T>(
  val res: T
) {
  fun await(): T = res
}
```

Blocking Calls via Future

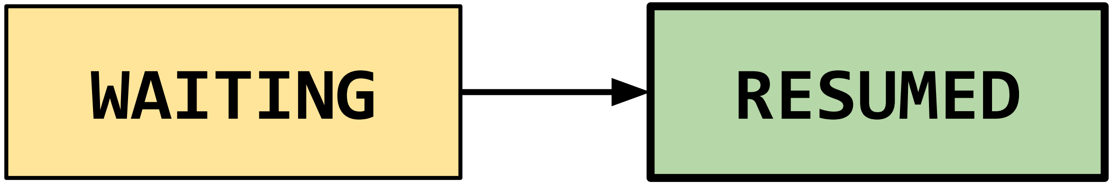
Threads, coroutines, continuations… Need a simple abstraction!

```
interface Future<T> {
  fun await(): T
}
```

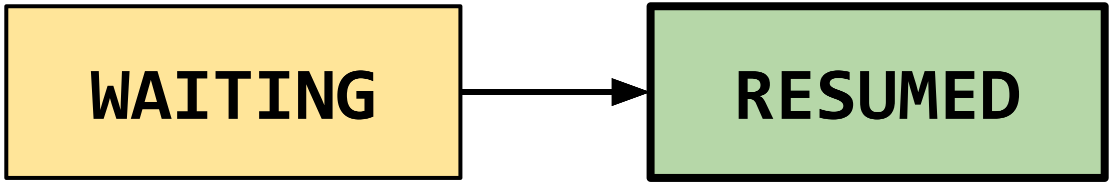
```
class FutureImmediate<T>(
  val res: T
) {
  fun await(): T = res
}
```

```
class FutureSuspended<T> {
  var state: T? = null

  fun await(): T {
    while (state == null) {}
    return state
  }

  fun complete(value: T) {
   state = value
  }
}
```

State Machine for `FutureSuspended`



State Machine for `FutureSuspended`



Further **`FutureSuspended`** updates will be shown via such diagrams

Semaphore API

```
class Semaphore(permits: Int) {
  fun acquire(): Unit
  fun release()
}
```

Semaphore API

```
class Semaphore(permits: Int) {
  fun acquire(): Future<Unit>
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Blocking by design

Straightforward Semaphore Implementation

```
class Semaphore(permits: Int) {
  var permits: Int = permits
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Straightforward Semaphore Implementation

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class Semaphore(permits: Int) {
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< 0 → # waiters

Straightforward Semaphore Implementation

```
class Semaphore(permits: Int) {
  var permits: Int = permits
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}
```

```
fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
  if p > 0:
    return FutureImmediate(Unit)
  else:
    return suspend()
}
```

Creates a new FutureSuspended and puts it into the waiting queue

Straightforward Semaphore Implementation

```
class Semaphore(permits: Int) {
  var permits: Int = permits
  ...
```

Retrieves the first waiter and completes it

```
fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
  if p > 0:
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  else:
    return suspend()
}
```

```
fun release() {
  val p = FAA(&permits, +1)
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  resume(Unit)
}
```
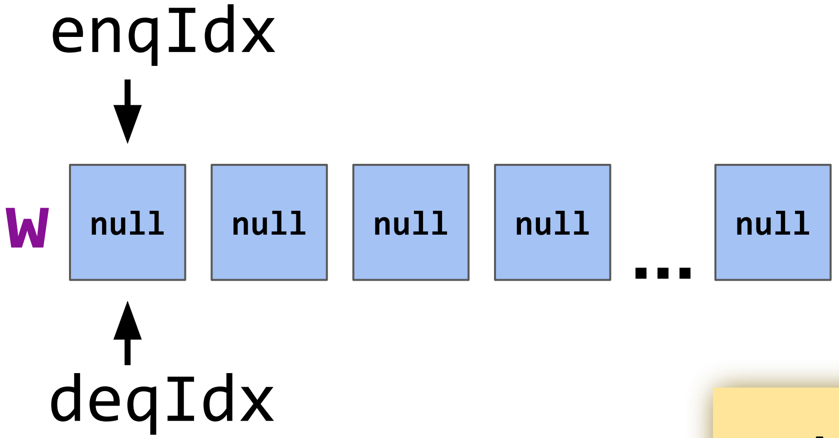
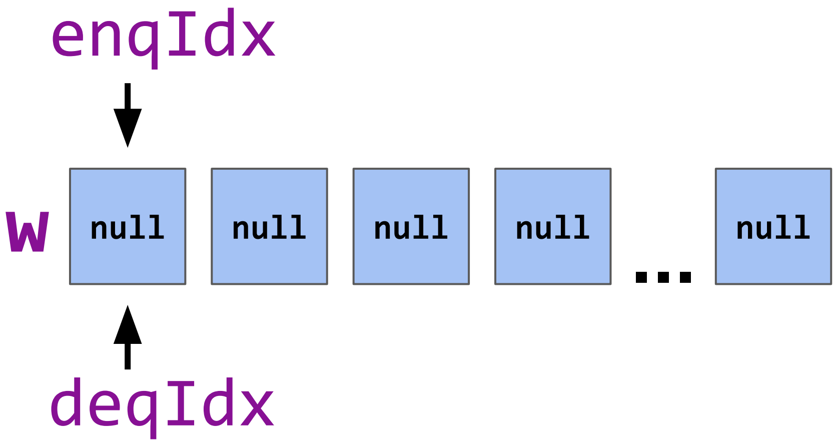

SegmentQueueSynchronizer



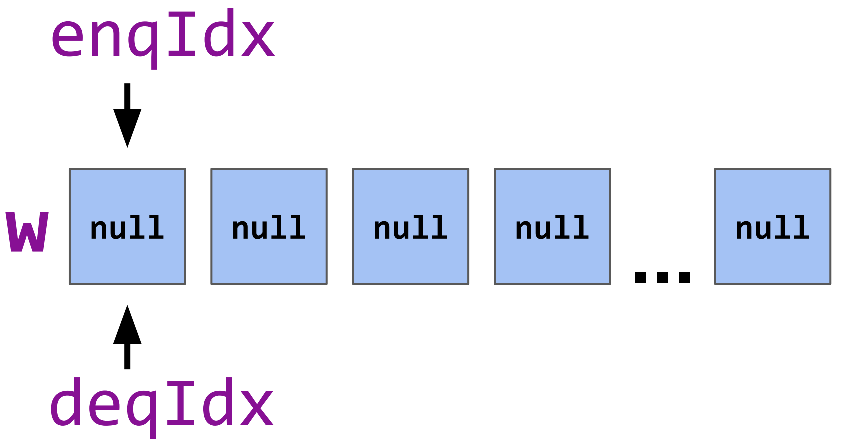
An infinite array with indices for the next addition and retrieval

SegmentQueueSynchronizer




```
fun suspend(): Future<T> {
  val f = FutureSuspended<T>()
  val i = FAA(&enqIdx, +1)
  // store f into w[i]
}
```

SegmentQueueSynchronizer

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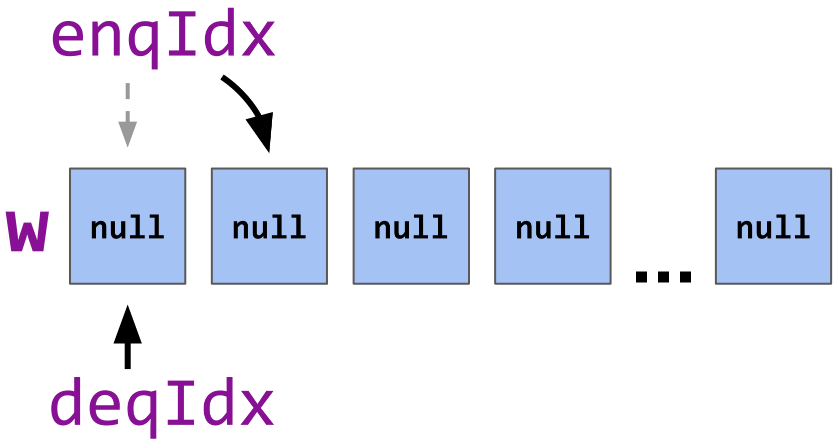


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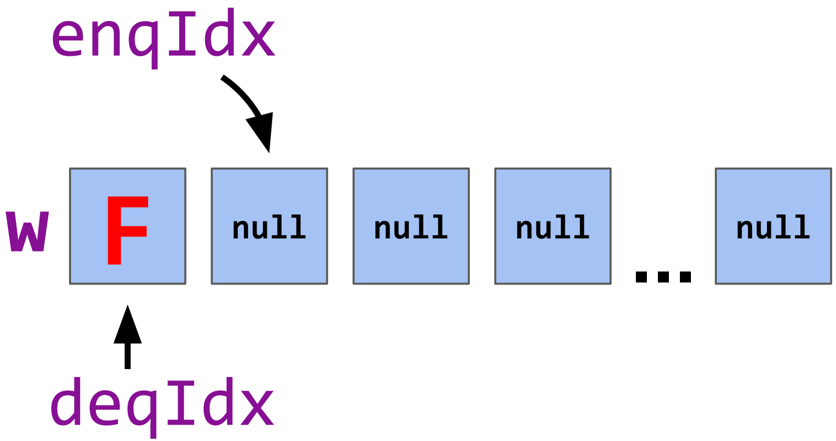


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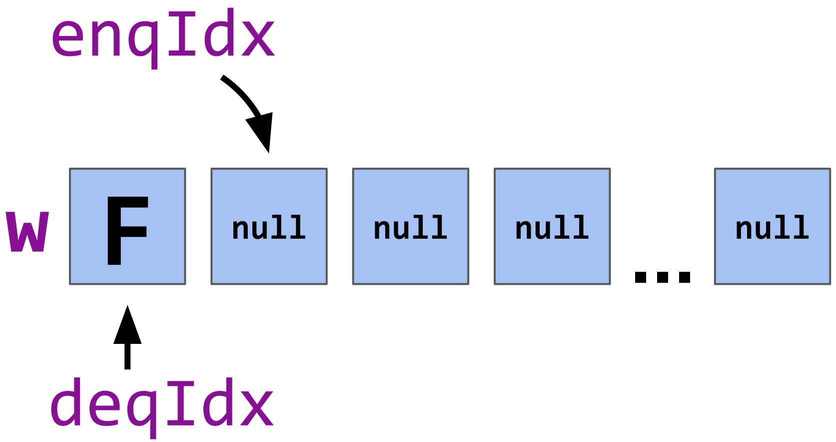
SegmentQueueSynchronizer




```
fun suspend(): Future<T> {
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  val i = FAA(&enqIdx, +1)
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```
fun resume(value: T) {
  val i = FAA(&deqIdx, +1)
  // complete the future
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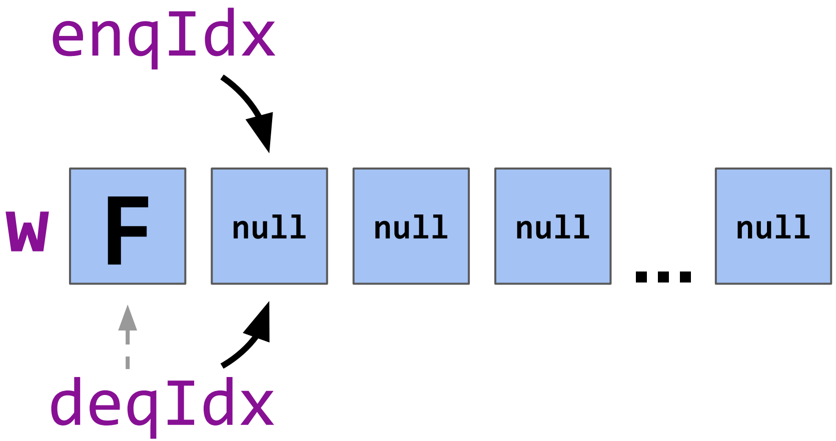
}
```

SegmentQueueSynchronizer

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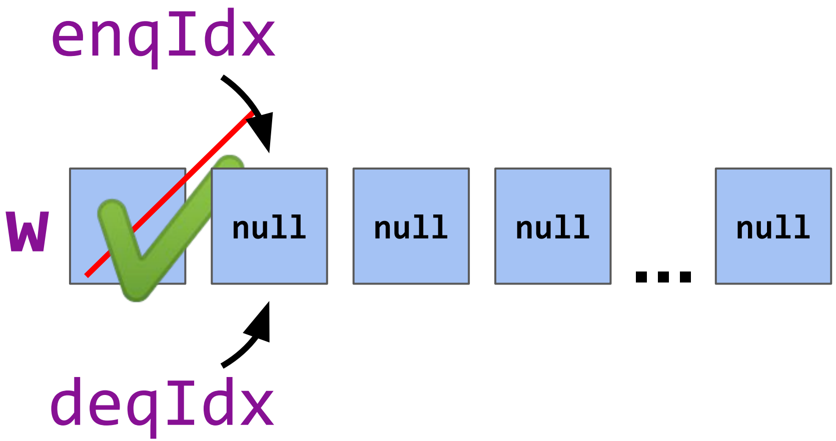


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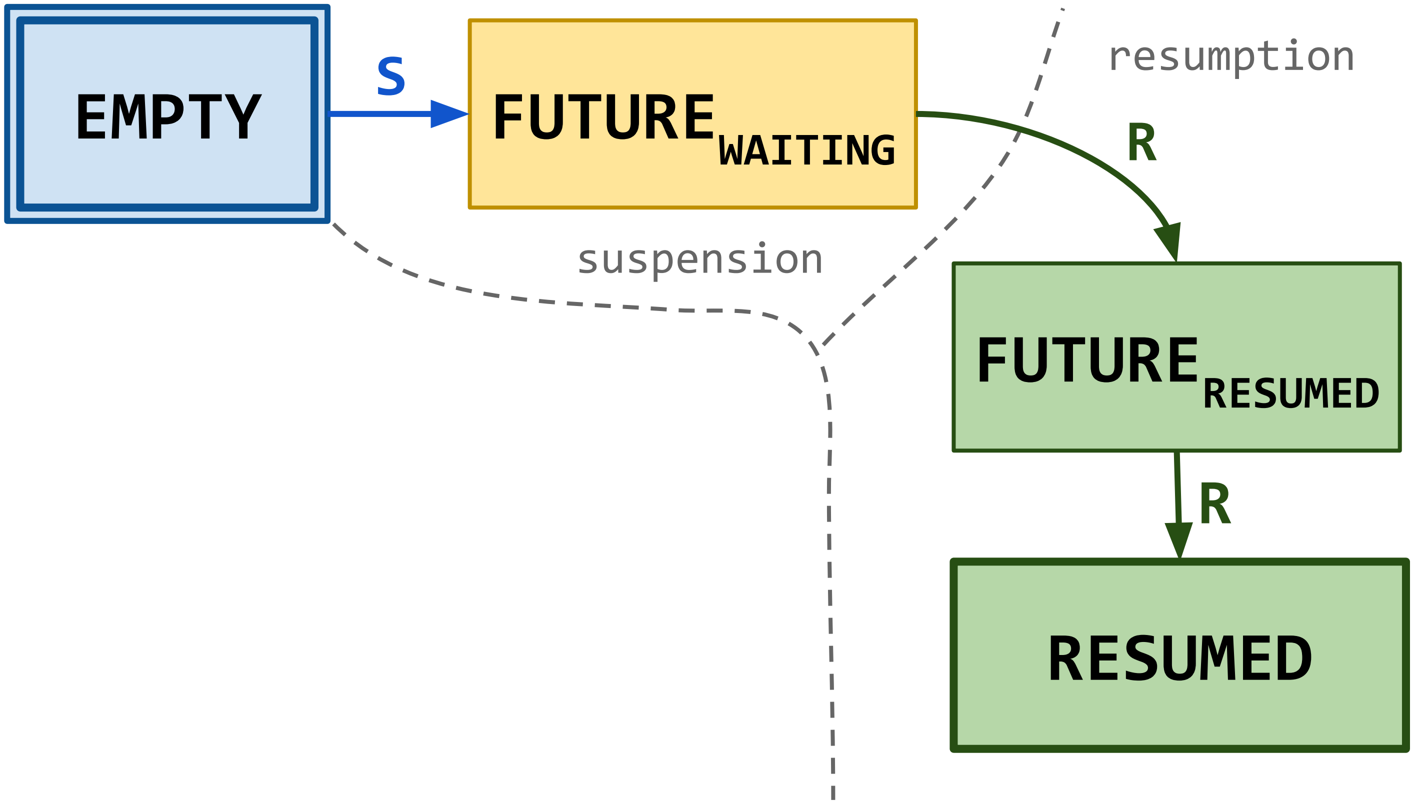
Cell Life-Cycle



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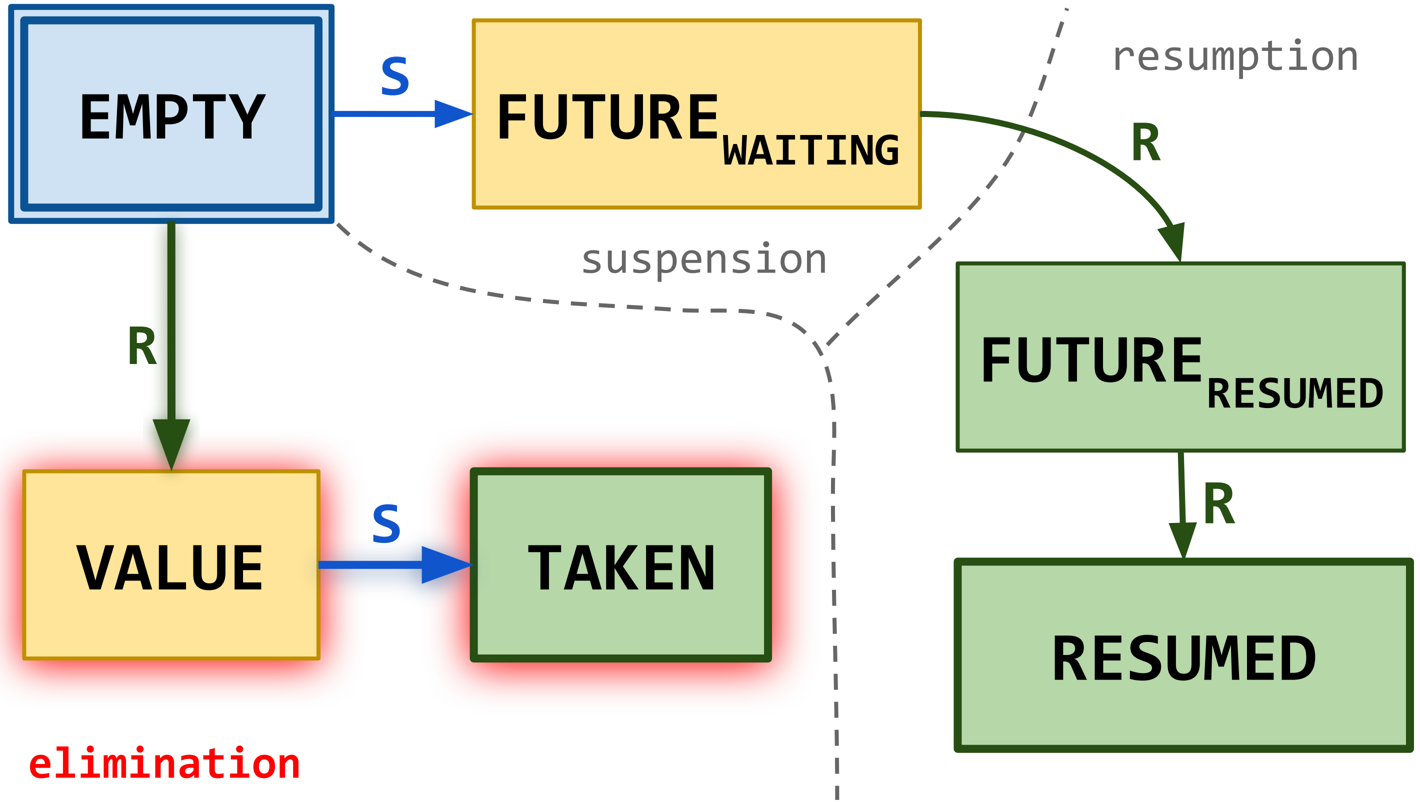
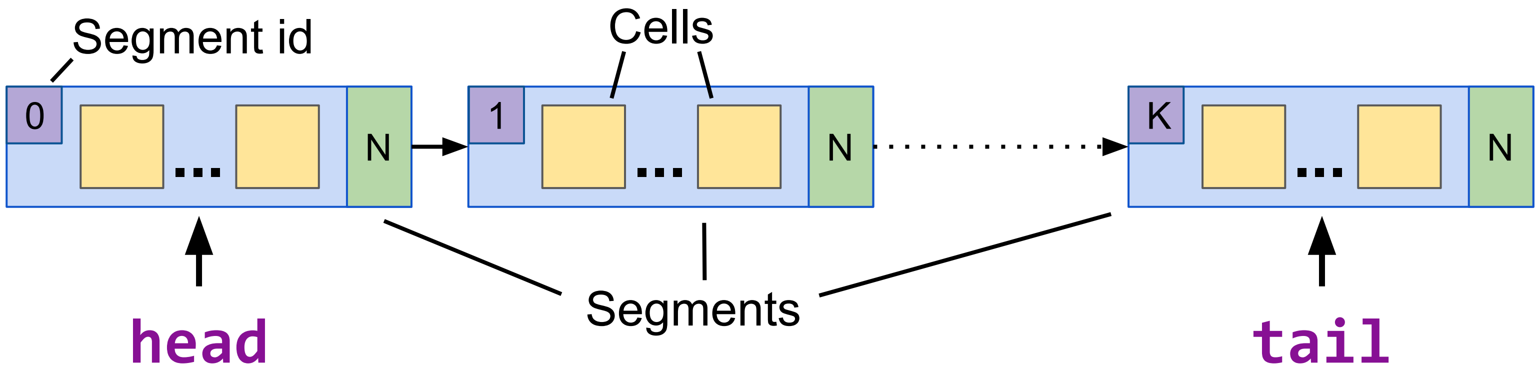


Infinite Array Implementation



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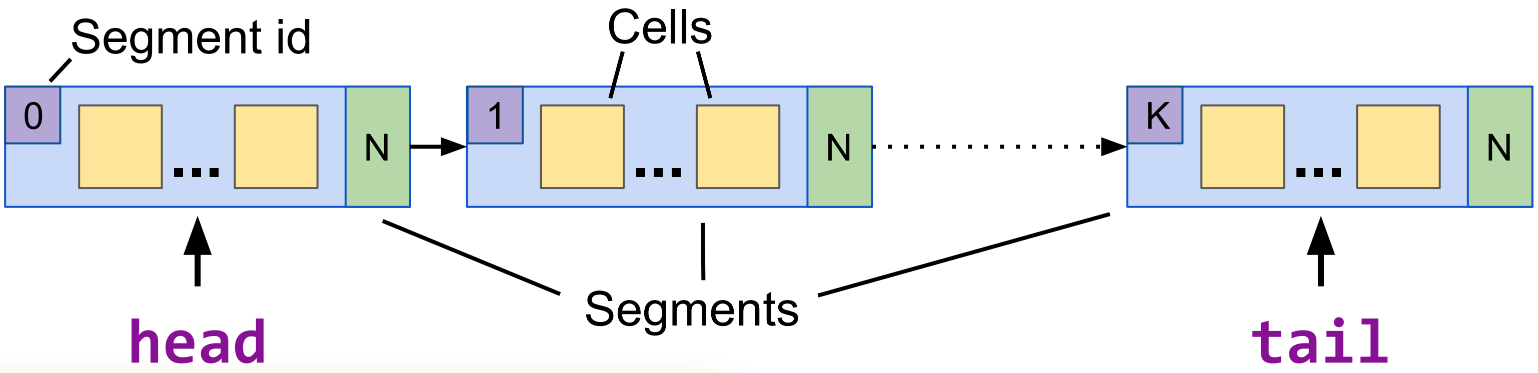
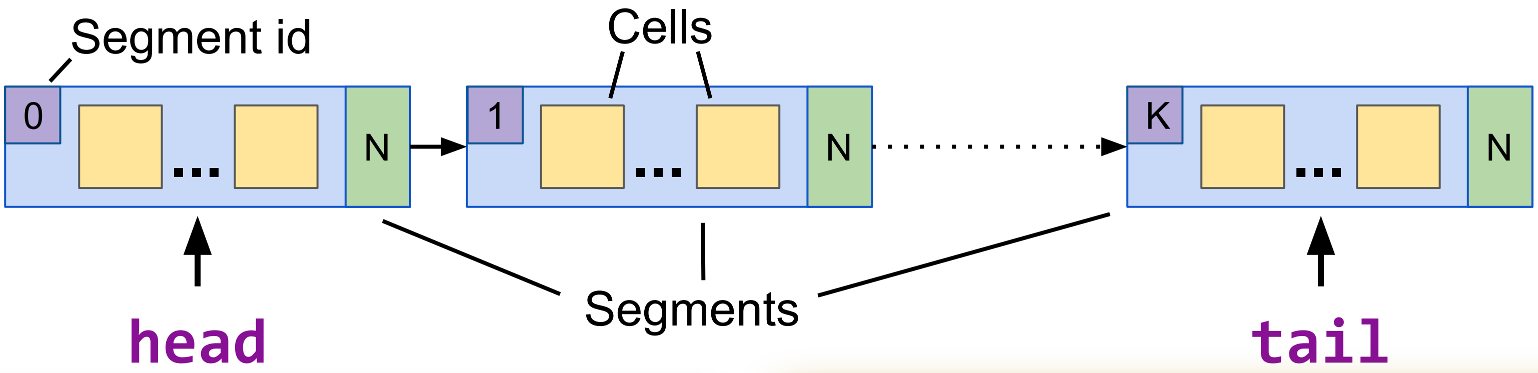



```
fun suspend(): Future<T> {
  val t = tail
  val i = FAA(&enqIdx, +1)
  val s = findSegment(start = t,
                      id = i / M)
  moveTailForward(t)
  // w[i] is s[i % M]
}
```

Infinite Array Implementation

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  moveTailForward(t)
  // w[i] is s[i % M]
}
```

```
fun resume(value: T) {
  val t = head
  val i = FAA(&deqIdx, +1)
  val s = findSegment(start = t,
                      id = i / M)
  moveHeadForward(t)
  // w[i] is s[i % M]
}
```

Extend Semaphore with tryAcquire

```
fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
  if p > 0:
    return FutureImmediate(Unit)
  else:
    return suspend()
}
```

```
fun release() {
  val p = FAA(&permits, +1)
  if p >= 0: return
  resume(Unit)
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fun release() {
  val p = FAA(&permits, +1)
  if p >= 0: return
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}
```

```
fun tryAcquire(): Boolean = while(true) {
  val p = permits
  if p <= 0: return false
  if CAS(&permits, p, p - 1): return true
}
```

Is this `tryAcquire` correct?

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fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
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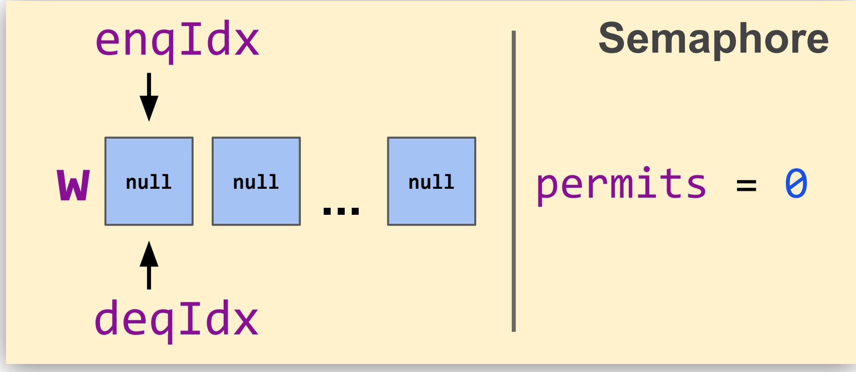


```
val s = Semaphore(1); s.acquire()
```

s.release() s.tryAcquire() s.acquire()	s.acquire(): 1. dec permits 2. suspend

Is this `tryAcquire` correct?

```
fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
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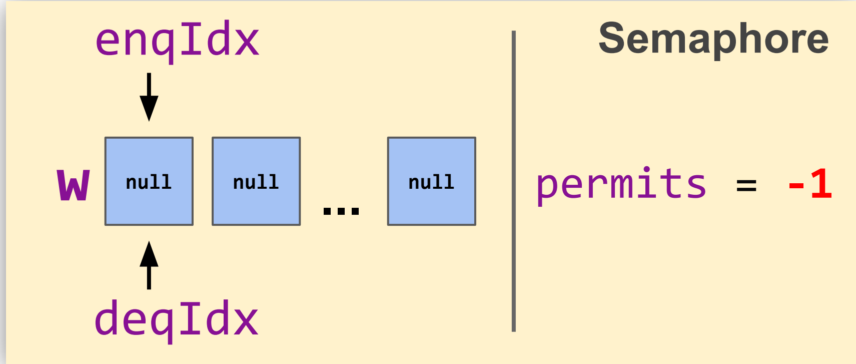


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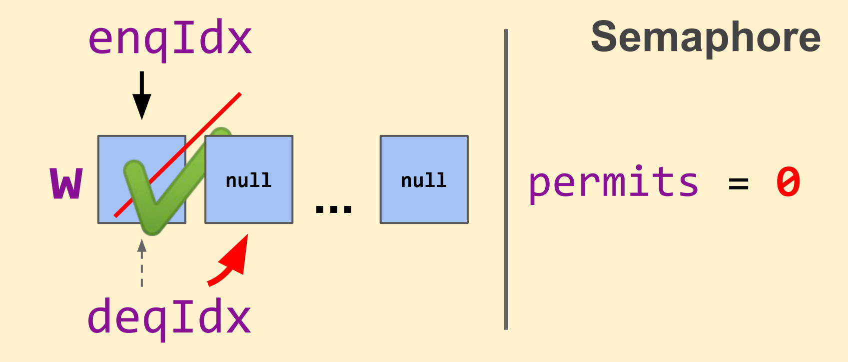


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val s = Semaphore(1); s.acquire()
```

s.release() :done s.tryAcquire() s.acquire()	s.acquire(): 1. dec permits 2. suspend

Is this `tryAcquire` correct?

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 }
}
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fun release() {
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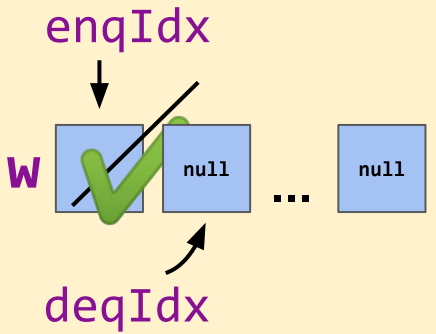
Semaphore



permits = 0

`val s = Semaphore(1); s.acquire()`

`s.release()` :done	`s.acquire():`
`s.tryAcquire()`:f	1. dec permits
`s.acquire()`	2. suspend

Is this `tryAcquire` correct?

```
fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
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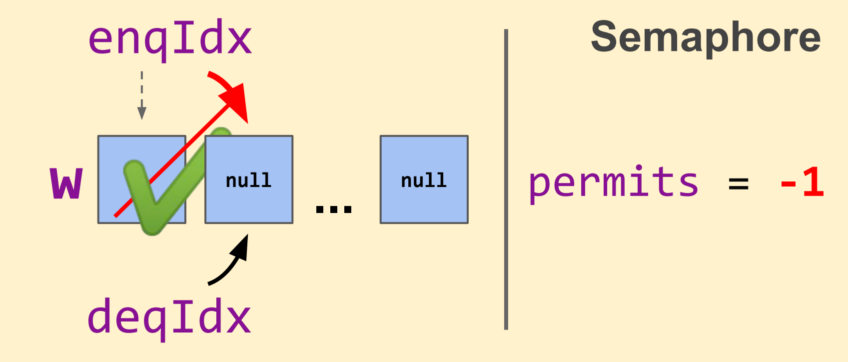
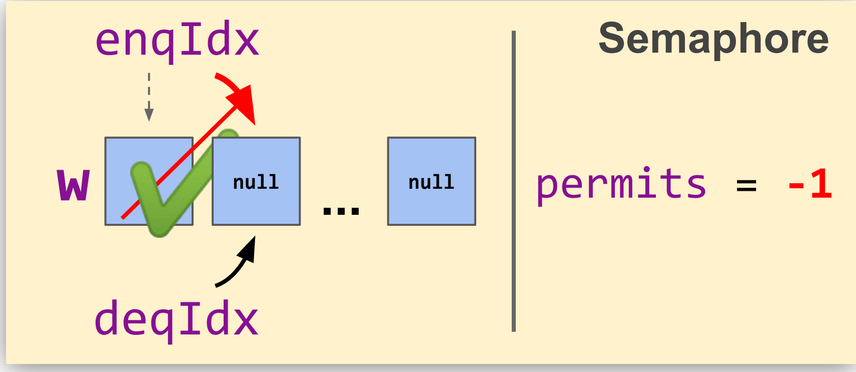



```
val s = Semaphore(1); s.acquire()
```

s.release() :done s.tryAcquire():f s.acquire() :done	s.acquire(): 1. dec permits 2. suspend

Is this `tryAcquire` correct?

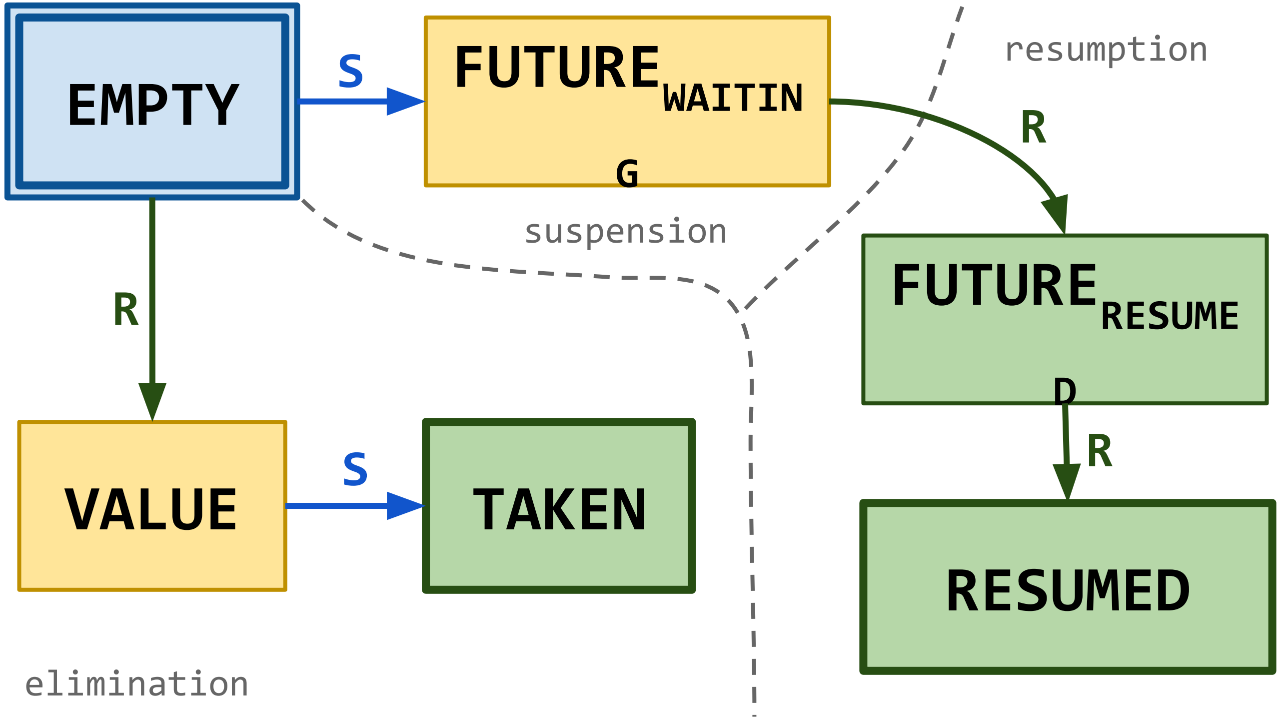
`release` was intended go give a permit to a concurrent **`acquire`**, but gave it to **`acquire`** that *happens after* it



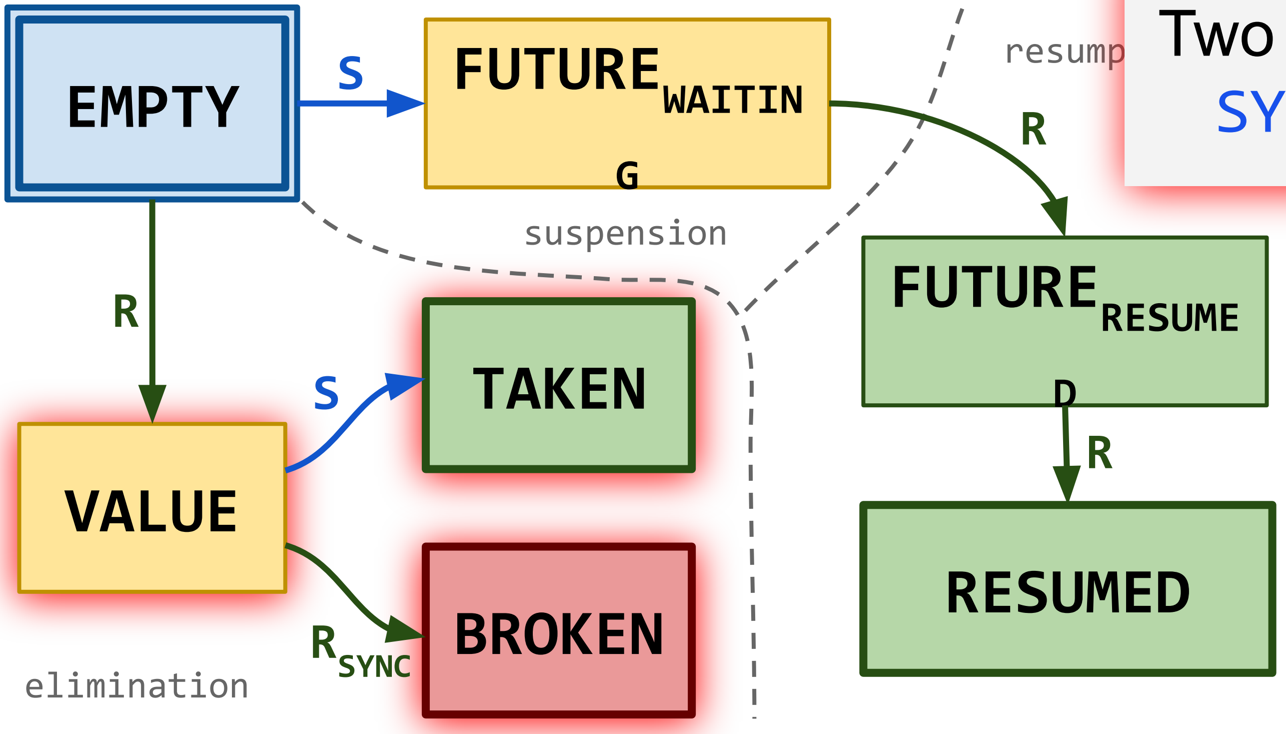

```
val s = Semaphore(1); s.acquire()
```

`s.release() :done`
`s.tryAcquire():f`
`s.acquire() :done`
	`s.acquire():`
	`1. dec permits`
	`2. suspend`

Extend Semaphore with tryAcquire



Extend Semaphore with tryAcquire



Two resume modes:
SYNC and ASYNC

Extend Semaphore with tryAcquire

```
class SegmentQueueSynchronizer<T> {
  // can fail on elimination
  fun resume(): Boolean { ... }

  // returns null on broken cell
  fun suspend(): Future<T>? { ... }
}
```

Extend Semaphore with tryAcquire

```
class SegmentQueueSynchronizer<T> {
  // can fail on elimination
  fun resume(): Boolean { ... }

  // returns null on broken cell
  fun suspend(): Future<T>? { ... }
}
```

```
fun acquire(): Future<Unit> {
  while(true) {
    val p = FAA(&permits, -1)
    if p > 0:
      return FutureImmediate(Unit)
    val f = suspend()
    if f != null: return f
  }
}
```

```
fun release() {
  while(true) {
    val p = FAA(&permits, +1)
    if p >= 0: return
    val done = resume(Unit)
    if done: return
  }
}
```

Cancellable `FutureSuspended`

- Cancellation (abortability) is natural for blocking primitives
- Moreover, it is a built-in feature in Kotlin Coroutines

Cancellable FutureSuspended

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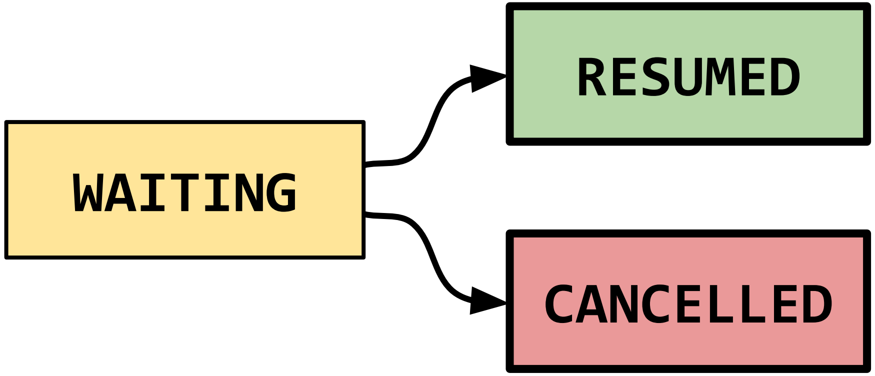
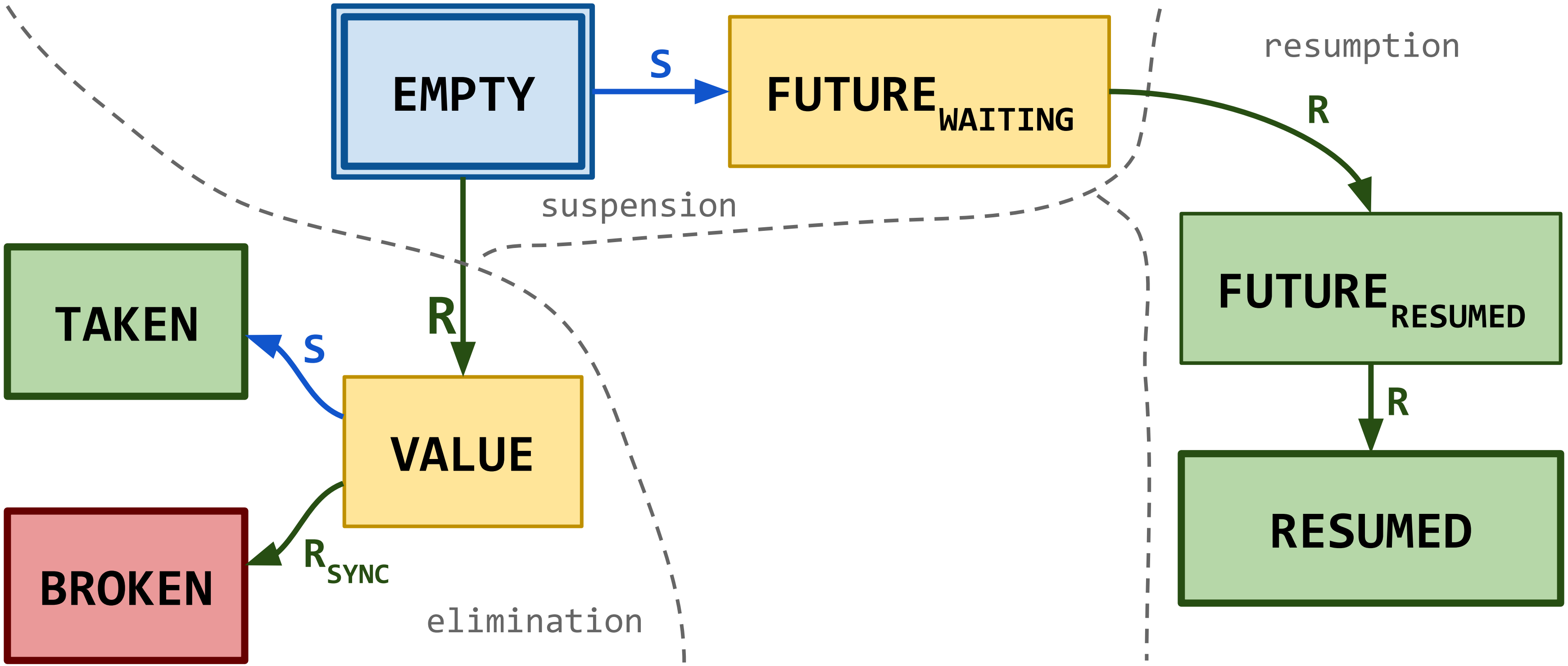
- Moreover, it is a built-in feature in Kotlin Coroutines

```
class FutureSuspended<T> {
  // returns ⊥ if cancelled
  fun await(): T? { ... }
  fun complete(value: T) { ... }
  fun cancel(): Boolean { ... }

  fun handleCancellation() {
    // TODO: Implement me, please!
  }
}
```



Cancellation Support in the Cell Life-Cycle



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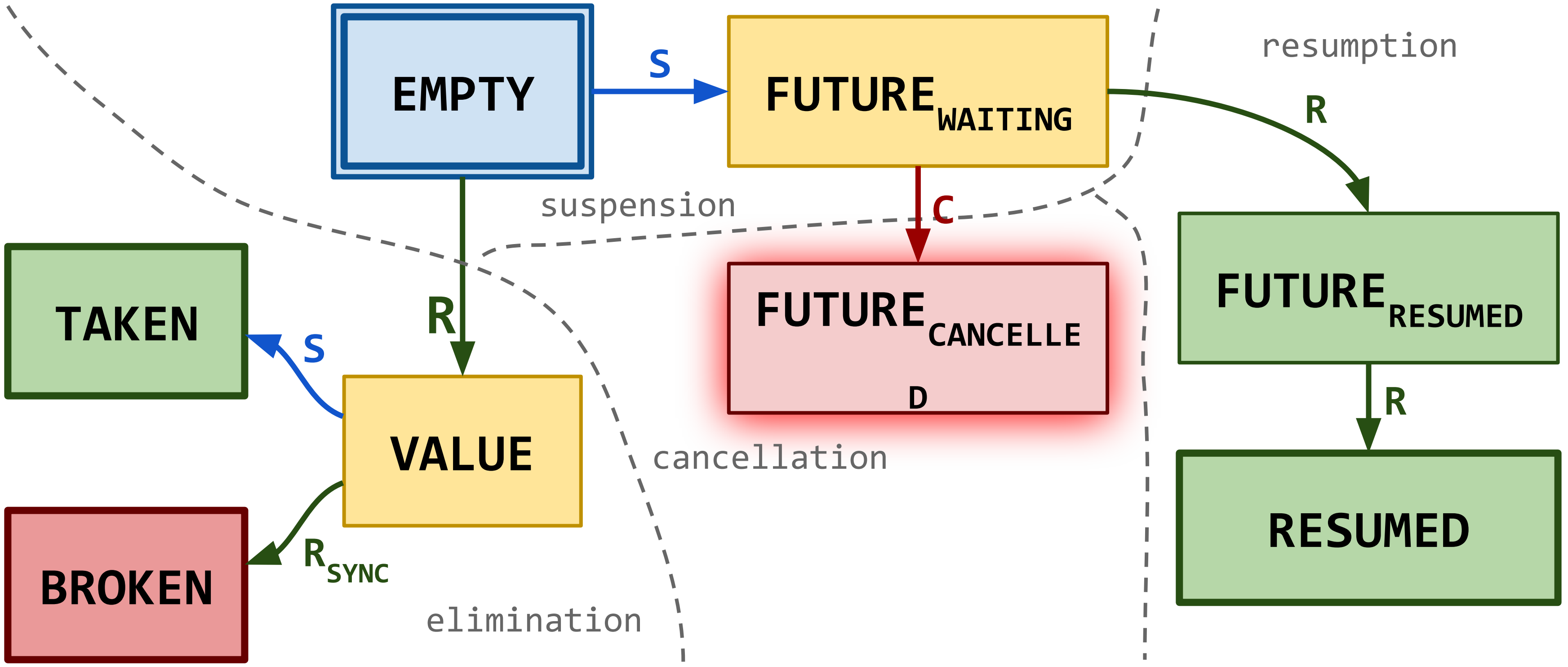

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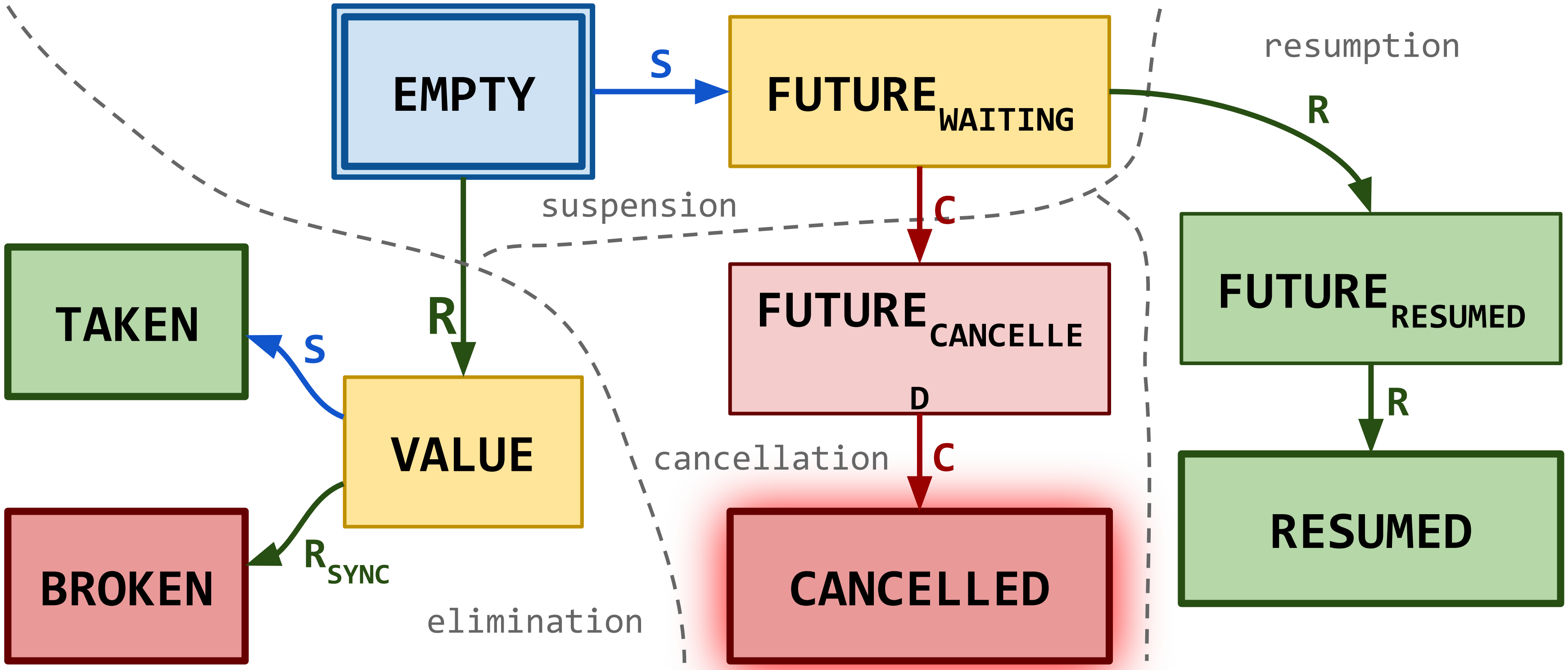
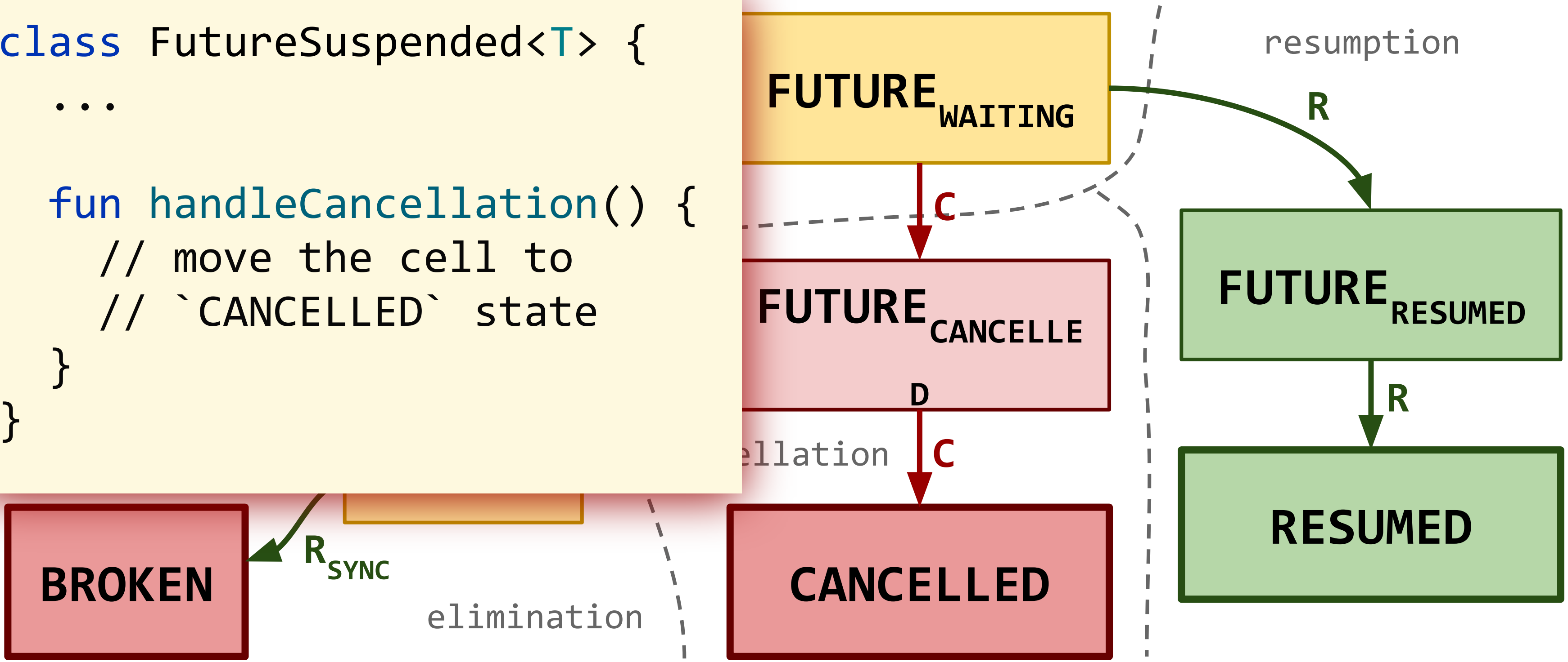


Cancellation Support in the Cell Life-Cycle

```
class FutureSuspended<T> {
  ...

  fun handleCancellation() {
    // move the cell to
    // `CANCELLED` state
  }
}
```

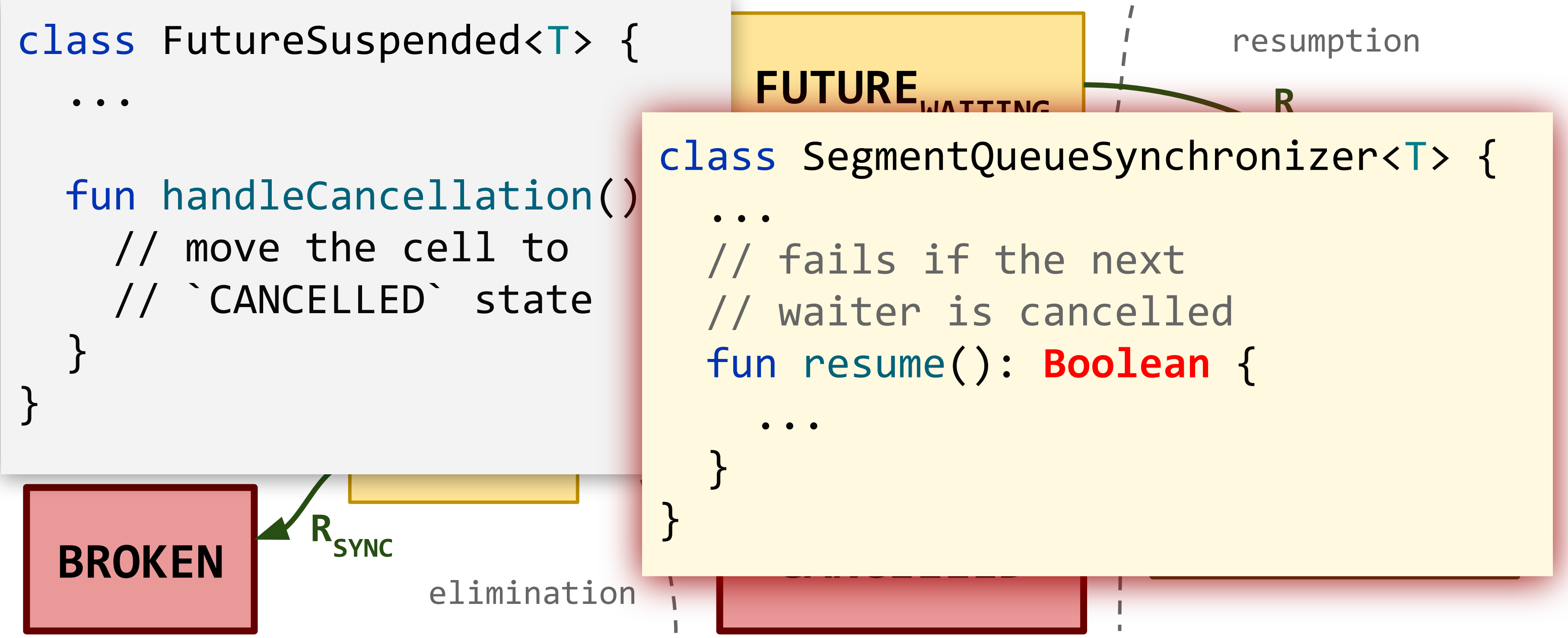


Cancellation Support in the Cell Life-Cycle

```
class FutureSuspended<T> {
  ...

  fun handleCancellation()
    // move the cell to
    // `CANCELLED` state
  }
}
```

```
class SegmentQueueSynchronizer<T> {
  ...
  // fails if the next
  // waiter is cancelled
  fun resume(): Boolean {
    ...
  }
}
```



Cancellation Support in General

- `handleCancellation` moves the cell state to `CANCELLED` to avoid memory leaks
- Can we remove the cells themselves for the same reason?

Cancellation Support and Memory Leaks

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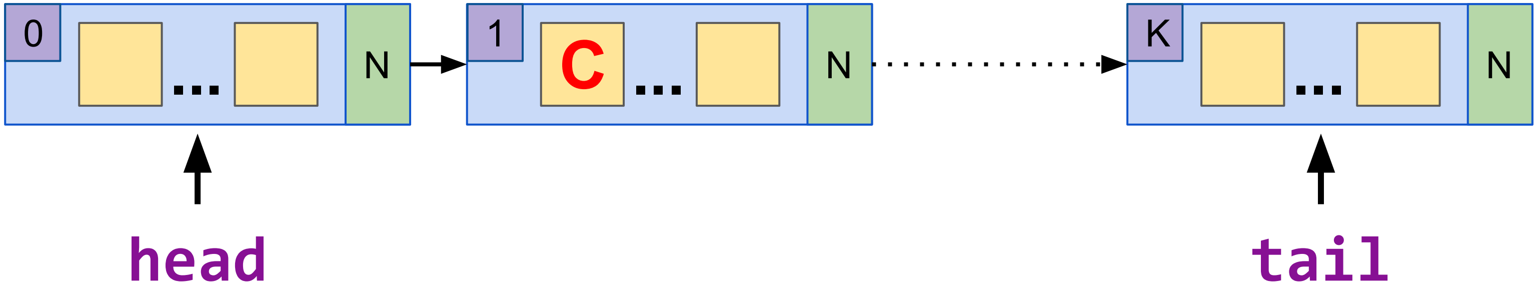

Cancellation Support and Memory Leaks

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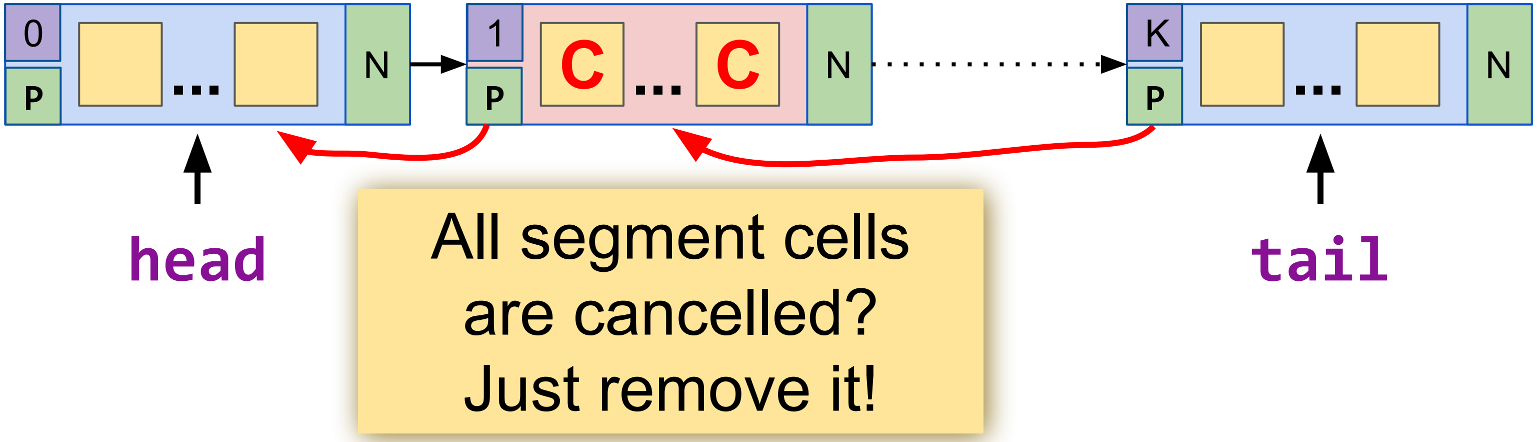

Semaphore with Cancellation

Our implementation is already correct!

```
fun acquire(): Future<Unit> {
  while(true) {
    val p = FAA(&permits, -1)
    if p > 0:
      return FutureImmediate(Unit)
    val f = suspend()
    if f != null: return f
  }
}
```

```
fun release() {
  while(true) {
    val p = FAA(&permits, +1)
    if p >= 0: return
    // can fail due to cancellation,
    // adjusted `permits` then
    val done = resume(Unit)
    if done: return
  }
}
```

Semaphore with Cancellation

is already correct!

`release` works in linear in the number of cancelled acquisitions.

Can we improve this?

```
fun ac
  whil
    va
    if

    val f = suspend()
    if f != null: return f
  }
}
```

```
fun release() {
  while(true) {
    val p = FAA(&permits, +1)
    if p >= 0: return
    // can fail due to cancellation,
    // adjusted `permits` then
    val done = resume(Unit)
    if done: return
  }
}
```

Smart Cancellation

Straightforward logic for `Semaphore`:

- Increment the permits counter on cancellation
- Skip cancelled cells in **`resume`**

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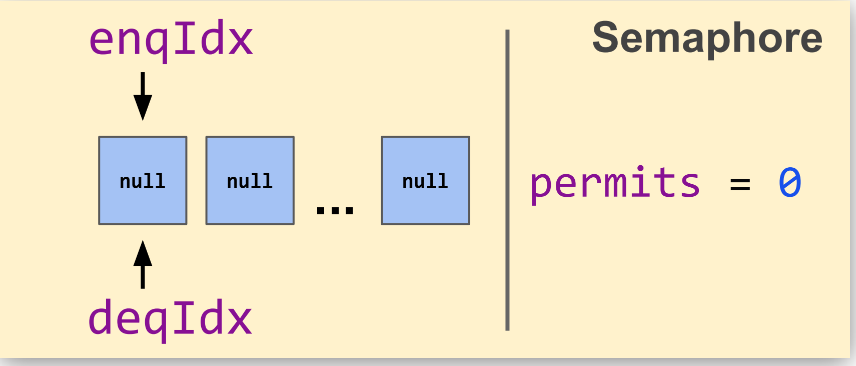


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val s = Semaphore(1); s.acquire()
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s.release()	f = s.acquire() f.cancel(): 1. mark cancelled 2. inc permits

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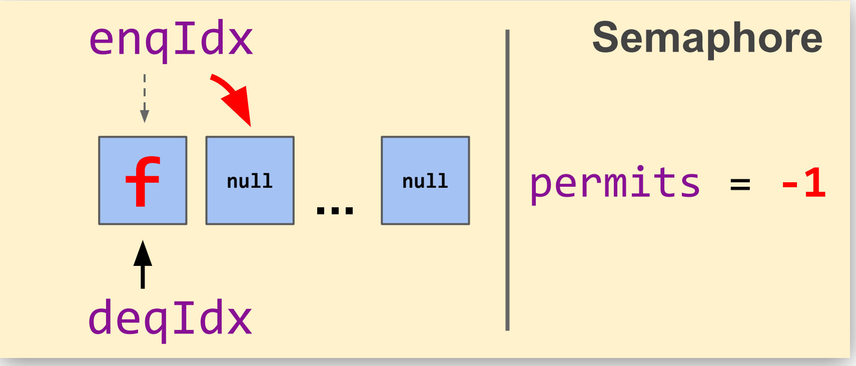


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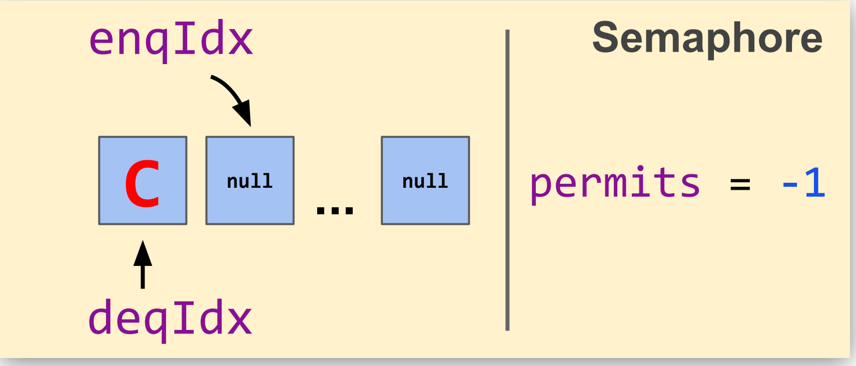


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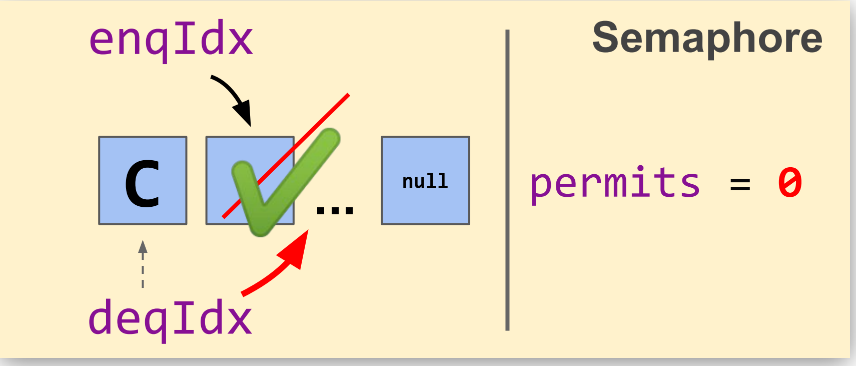


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```
s.release()
```

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```
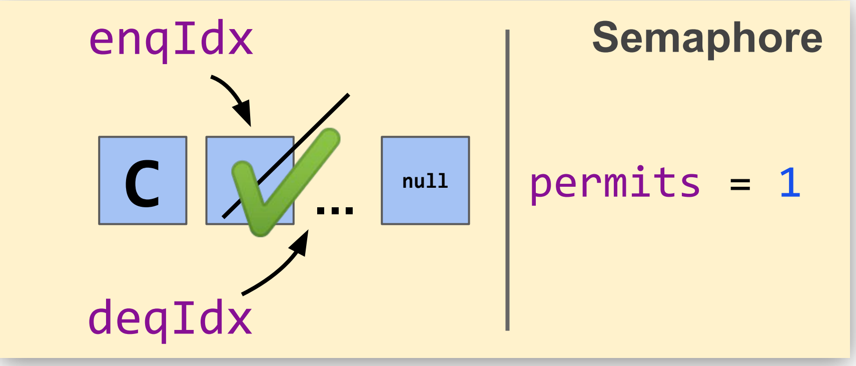

Smart Cancellation

`resume` in **`release`** had to be refused due to the lack of waiters

Straightforward logic for `Semaphore`:

- Increment the permits counter on cancellation
- Skip cancelled cells in **`resume`**

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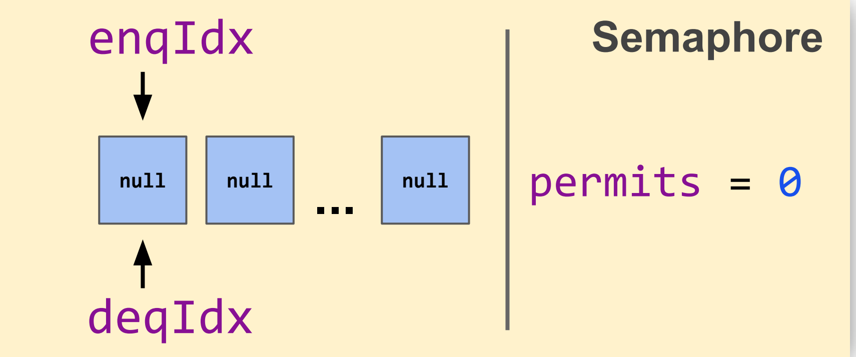
Increment the permits counter on cancellation, and decide whether to cancel the cell or refuse the corresponding **`resume`**.

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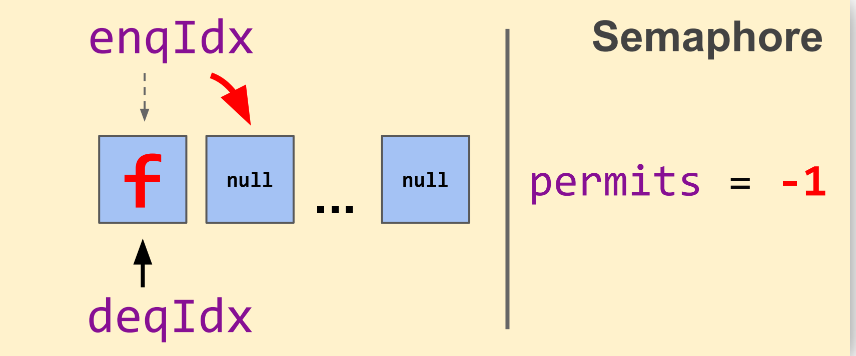


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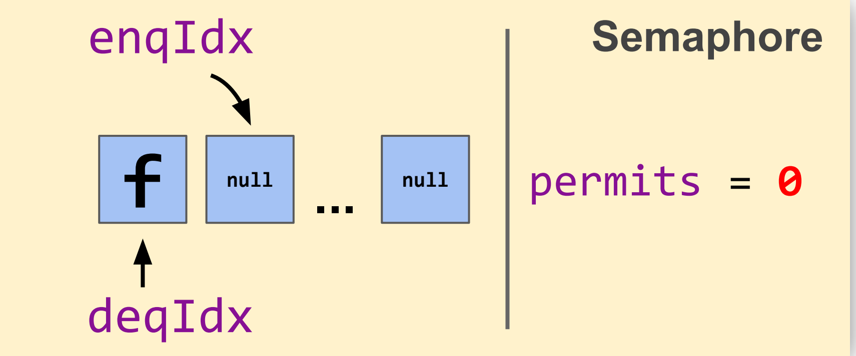


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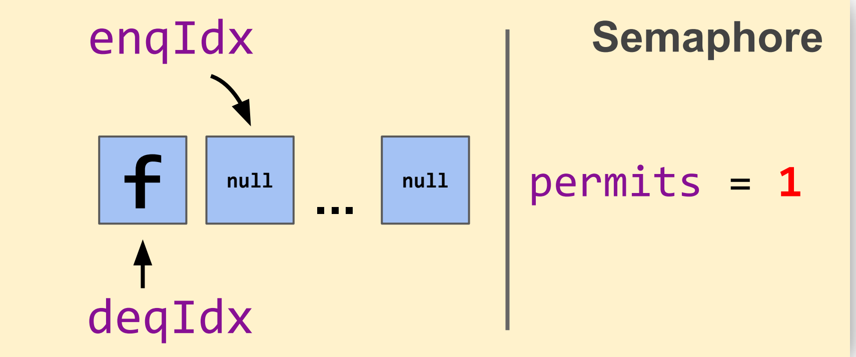


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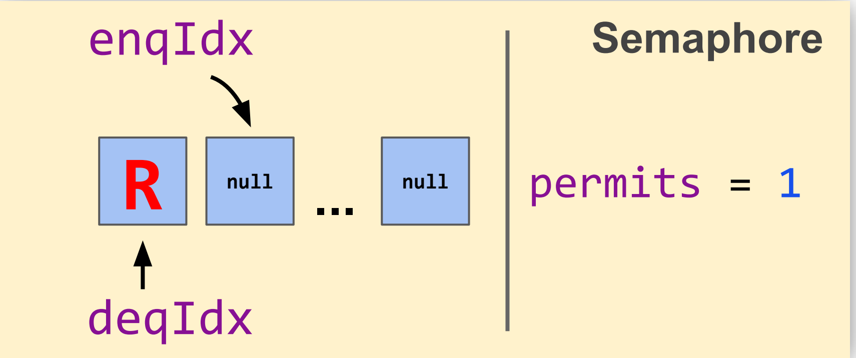


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 1. inc permits
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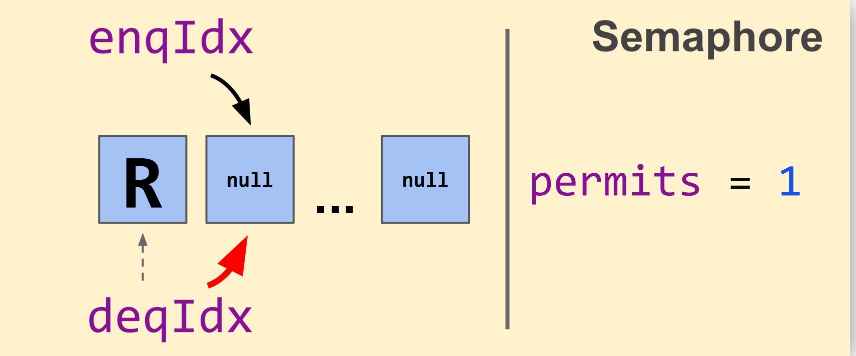
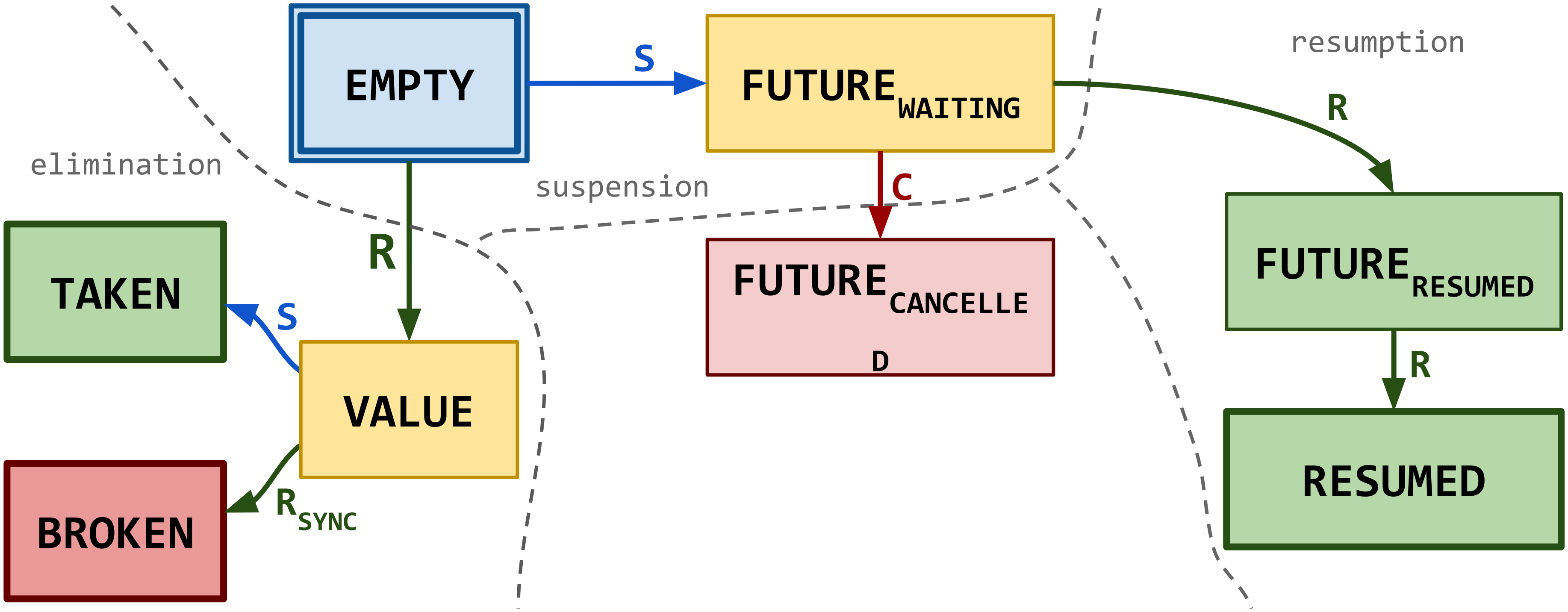


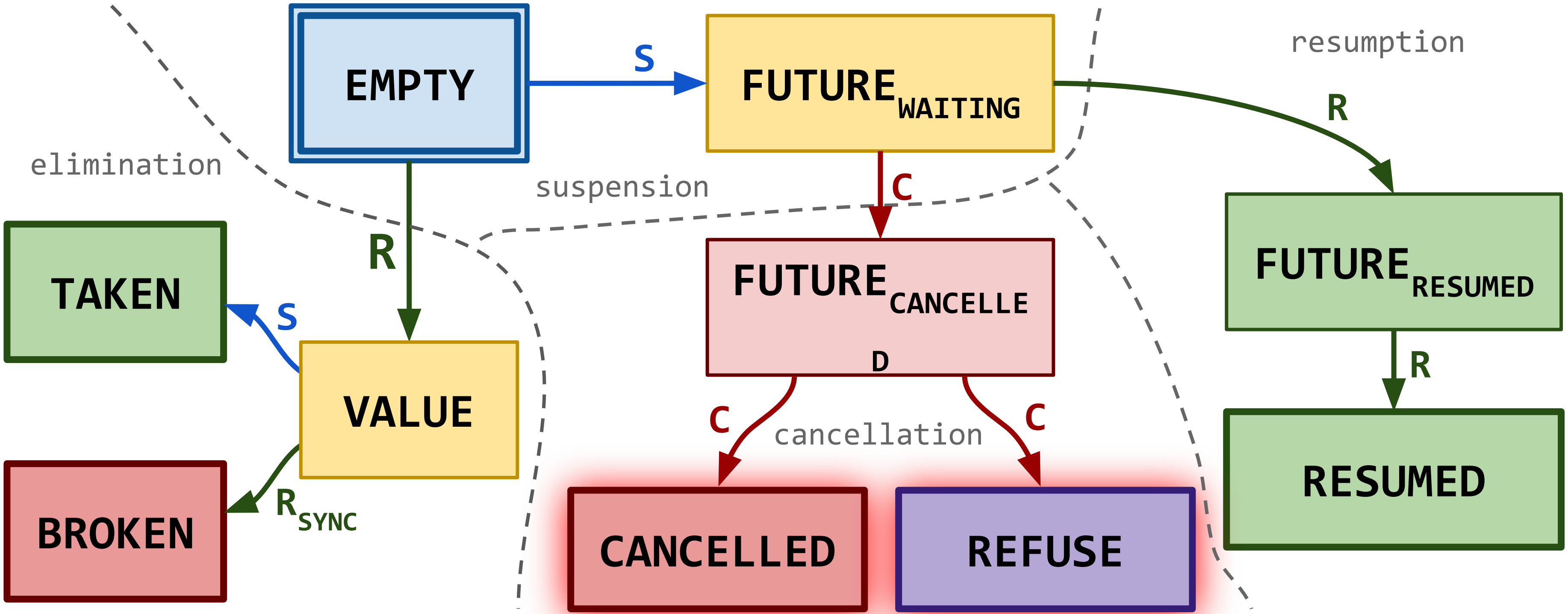

```
val s = Semaphore(1); s.acquire()
```

s.release():	f = s.acquire()
1. inc permits	f.cancel():
2. resume :refused	1. inc permits
	2. mark cancelled or refuse resume

Smart Cancellation and Cell Life-Cycle



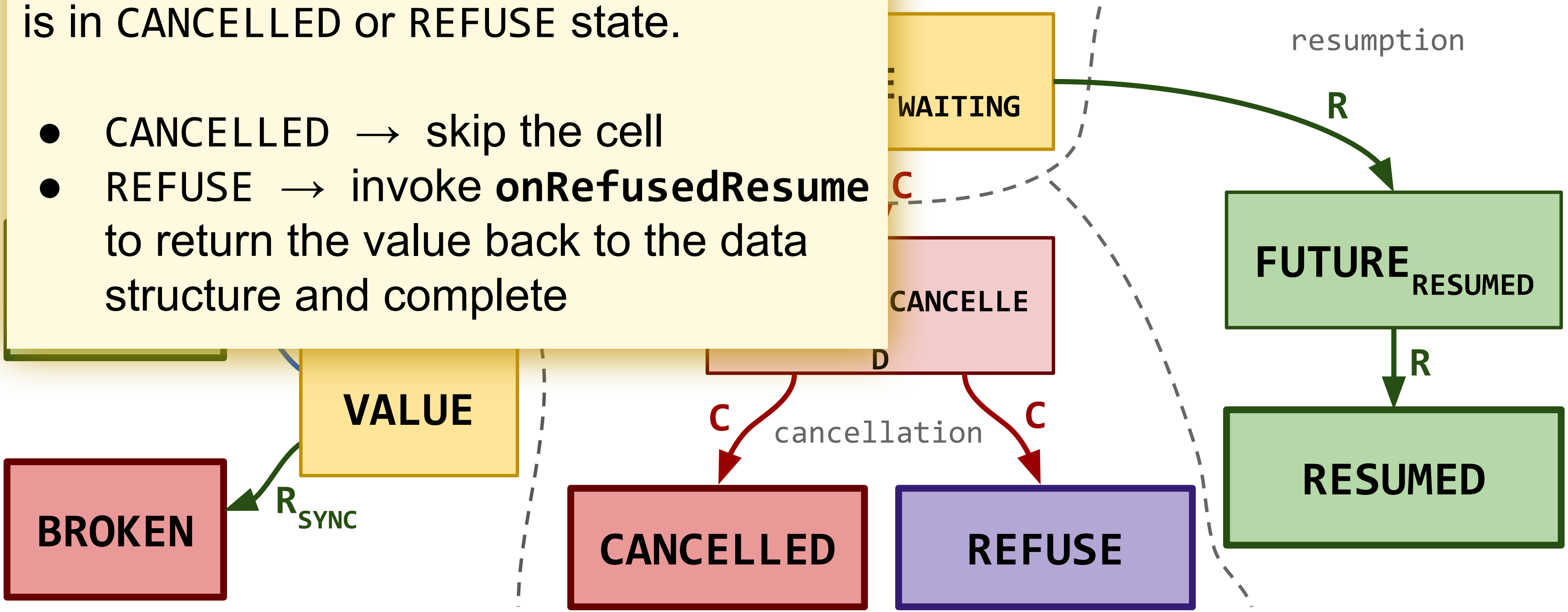
Smart Cancellation and Cell Life-Cycle



Smart Cancellation and Cell Life-Cycle

`resume` waits in a spin-loop until the cell is in `CANCELLED` or `REFUSE` state.

- `CANCELLED` → skip the cell
- `REFUSE` → invoke **`onRefusedResume`** to return the value back to the data structure and complete

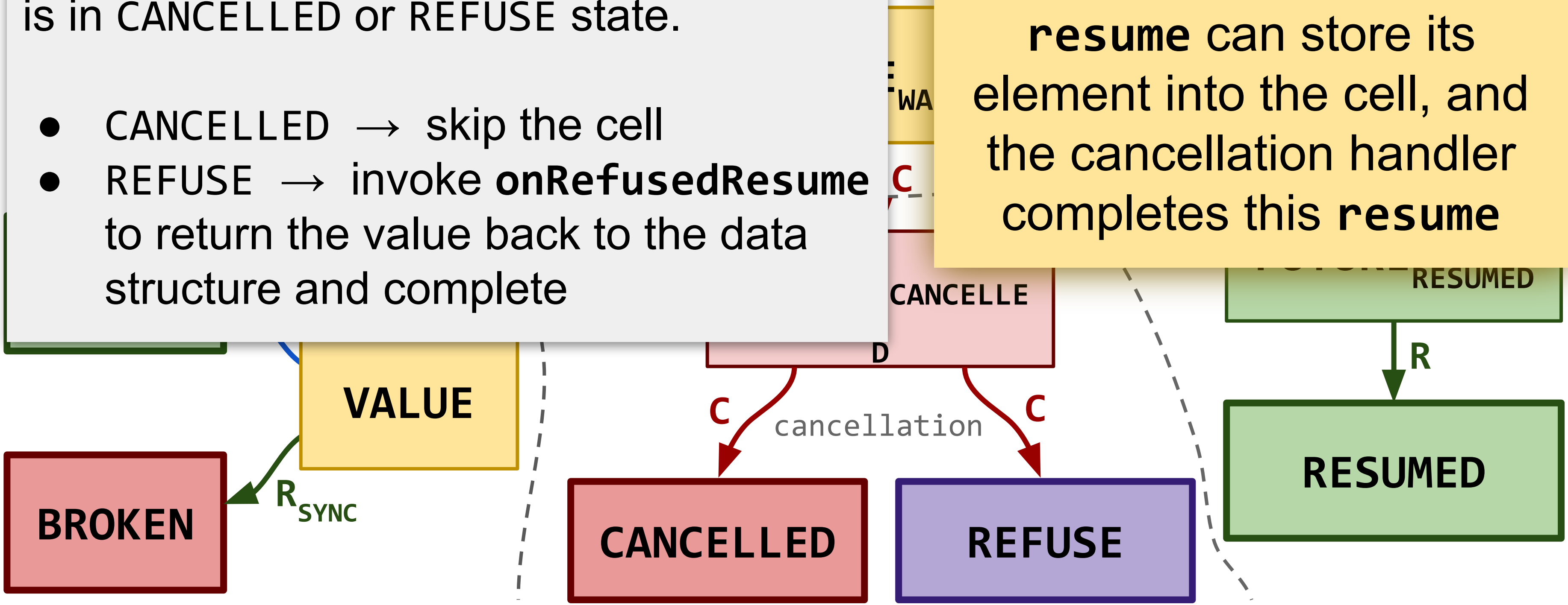


Smart Cancellation and Cell Life-Cycle

`resume` waits in a spin-loop until the cell is in CANCELLED or REFUSE state.

- CANCELLED → skip the cell
- REFUSE → invoke **`onRefusedResume`** to return the value back to the data structure and complete

In order not to wait, **`resume`** can store its element into the cell, and the cancellation handler completes this **`resume`**



Smart Cancellation for Semaphore

```
fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
  if p > 0:
    return FutureImmediate(Unit)
  else:
    return suspend()
}
```

```
fun release() {
  val p = FAA(&permits, +1)
  if p >= 0: return
  resume(Unit)
}
```

```
resume_mode      = ASYNC
```

Smart Cancellation for Semaphore

```
fun acquire(): Future<Unit> {
  val p = FAA(&permits, -1)
  if p > 0:
    return FutureImmediate(Unit)
  else:
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}
```

```
fun release() {
  val p = FAA(&permits, +1)
  if p >= 0: return
  resume(Unit)
}
```

```
resume_mode        = ASYNC
cancellation_mode = SMART
```

```
// true - CANCELLED, false - REFUSE
fun onCancellation(): Boolean {
  val p = FAA(&permits, +1)
  // return `true` if there are
  // waiters in the queue, or
  // `false if` `resume` on this
  // cell should be refused.
  return p < 0
}
```

Evaluation

- Google Cloud machine with 96 CPUs
- Comparison against standard Java implementations:
  - `j.u.c.Semaphore` and `j.u.c.ReentrantLock`

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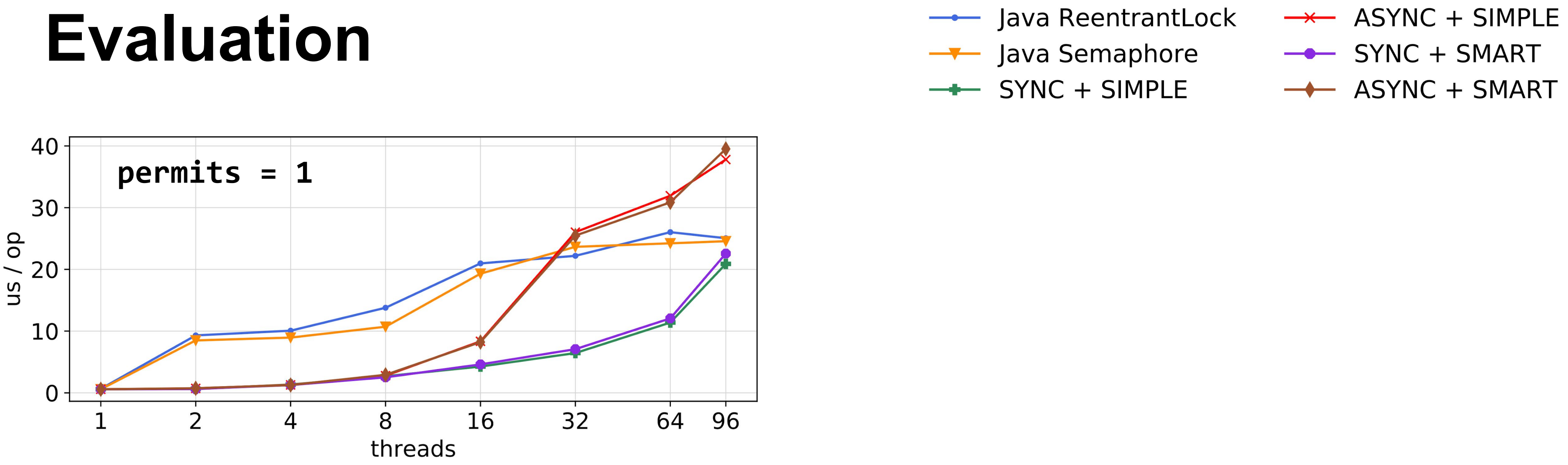
```
fun operation() {
    semaphore.acquire()
    doSomeGeomDistrWork()
    semaphore.release()
}
```

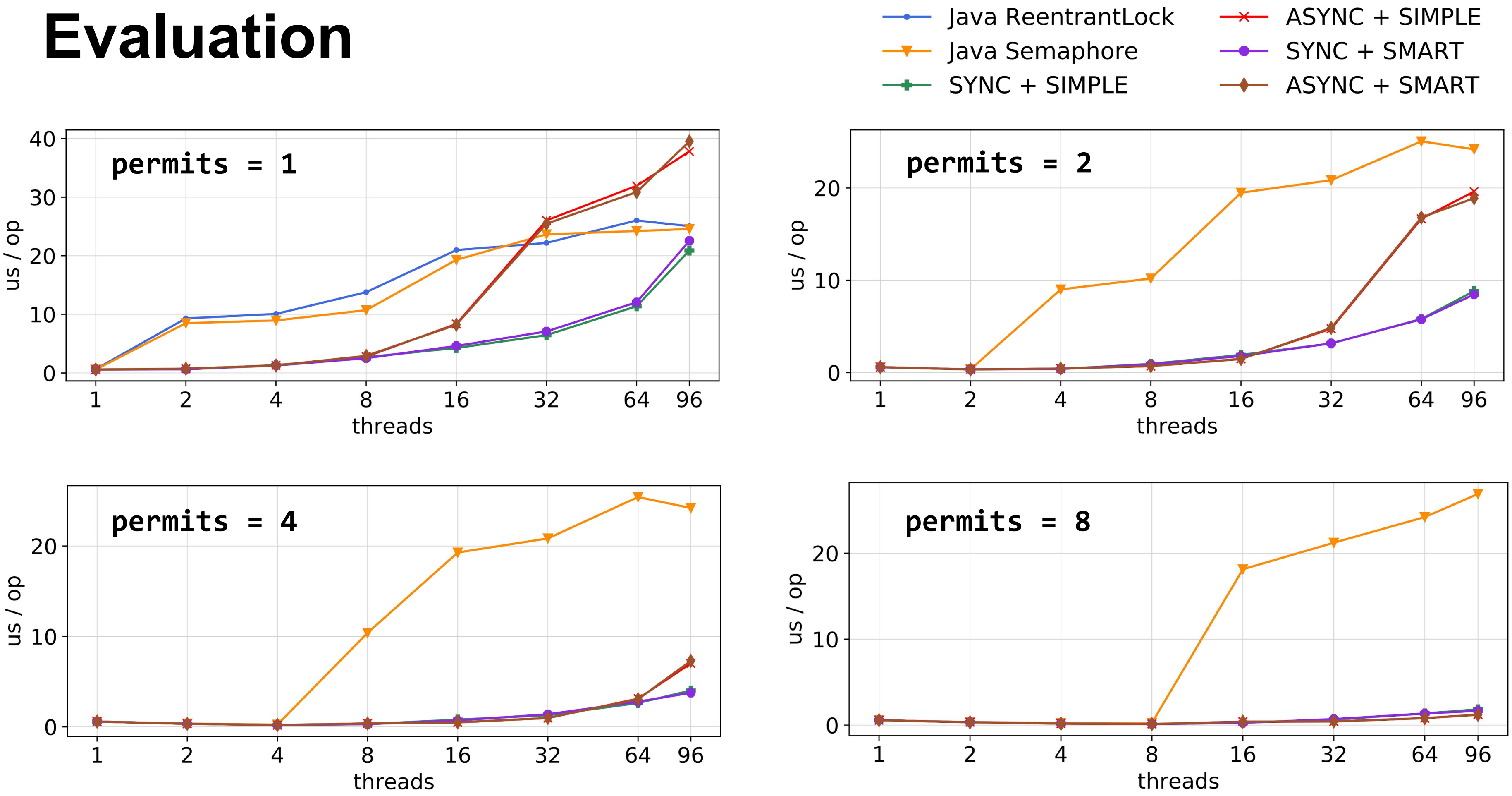
Let's run this code on different numbers of threads!

Evaluation



Java ReentrantLock
Java Semaphore
SYNC + SIMPLE
ASYNC + SIMPLE
SYNC + SMART
ASYNC + SMART
permits = 1
us / op
threads
0
10
20
30
40
1
2
4
8
16
32
64
96

Evaluation



Java ReentrantLock
Java Semaphore
SYNC + SIMPLE
ASYNC + SIMPLE
SYNC + SMART
ASYNC + SMART
permits = 1
permits = 2
permits = 4
permits = 8
us / op
threads
1
2
4
8
16
32
64
96
0
10
20
30
40

Let's use `SegmentQueueSynchronizer` for primitives other than `Semaphore`!

CountDownLatch

Allows to wait until several operations are completed

```
class CountDownLatch(count: Int) {

  fun countDown() { ... }

  fun await(): Future<Unit> { ... }
}
```

CountDownLatch

```
resume_mode       = ASYNC
cancellation_mode = SIMPLE
```

```
class CountDownLatch(count: Int) {
  val count = count
  val waiters = 0
  ...
}
```

CountDownLatch

```
resume_mode       = ASYNC
cancellation_mode = SIMPLE
```

```
class CountDownLatch(count: Int) {
  val count = count
  val waiters = 0
  ...
}
```

```
fun countDown() {
  val c = FAA(&count, -1)
  if c <= 0: resumeWaiters()
}
```

CountDownLatch

```
resume_mode       = ASYNC
cancellation_mode = SIMPLE
```

```
class CountDownLatch(count: Int) {
  val count = count
  val waiters = 0
  ...
}
```

```
fun countDown() {
  val c = FAA(&count, -1)
  if c <= 0: resumeWaiters()
}

fun resumeWaiters() = while (true) {
  val w = waiters
  if w & DONE_BIT != 0: return
  if CAS(&waiters, w, w & DONE_BIT) {
    repeat(w) { resume(Unit) }
  }
}
```

CountDownLatch

```
resume_mode       = ASYNC
cancellation_mode = SIMPLE
```

```
class CountDownLatch(count: Int) {
  val count = count
  val waiters = 0
  ...
}
```

```
fun await(): Future<Unit> {
   if count <= 0:
     return FutureImmediate(Unit)
   val w = FAA(&waiters, +1)
   if w & DONE_BIT != 0:
     return FutureImmediate(Unit)
   return suspend()
}
```

```
fun countDown() {
  val c = FAA(&count, -1)
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}

fun resumeWaiters() = while (true) {
  val w = waiters
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CountDownLatch

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  ...
}
```

```
fun aw
   if
     return FutureImmediate(Unit)
   val w = FAA(&waiters, +1)
   if w & DONE_BIT != 0:
     return FutureImmediate(Unit)
   return suspend()
}
```

```
fun countDown() {
  val c = FAA(&count, -1)
  if c <= 0: resumeWaiters()
```

```
) {
```

```
  if CAS(&waiters, w, w & DONE_BIT) {
    repeat(w) { resume(Unit) }
  }
}
```

Can we use smart cancellation here?

CountDownLatch

```
resume_mode       = ASYNC
cancellation_mode = SMART
```

```
fun await(): Future<Unit> {
   if count <= 0:
     return FutureImmediate(Unit)
   val w = FAA(&waiters, +1)
   if w & DONE_BIT != 0:
     return FutureImmediate(Unit)
   return suspend()
}
```

```
fun onCancellation() {
  val w = FAA(&waiters, -1)
  // cancelled or refuse resume?
  return w & DONE_BIT == 0
}
```

```
fun countDown() {
  val c = FAA(&count, -1)
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}

fun resumeWaiters() = while (true) {
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  if w & DONE_BIT != 0: return
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  }
}
```

Pools

```
resume_mode       = ASYNC
cancellation_mode = NO
```

```
class BlockingPool() {
  // < 0 => # waiters
  var elements = 0
  ...
}
```

Pools

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resume_mode       = ASYNC
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```

```
class BlockingPool() {
  // < 0 => # waiters
  var elements = 0
  ...
}
```

```
fun put(element: T) {
  val e = FAA(&elements, 1)
  if e < 0 {
    resume(element)
  } else {
     insertIntoPool(element)
  }
}
```

Pools

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  val e = FAA(&elements, 1)
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  }
}
```

```
fun retrieve(): Future<T> {
   val e = FAA(&elements, -1)
   if (e > 0) {
     val elem = retrieveFromPool()
     return FutureImmediate(elem)
   } else {
     return suspend()
   }
}
```

Pools

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`insertIntoPool` and **`retrieveFromPool`** can use any data structure under the hood, e.g. queue, stack, or just bag.

Pools

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resume_mode       = ASYNC
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```

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class BlockingPool() {
  // < 0 => # waiters
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  ...
}
```

Smart cancellation mode can be used here as well

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fun put(element: T) {
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`insertIntoPool` and **`retrieveFromPool`** can use any data structure under the hood, e.g. queue, stack, or just bag.

Conclusion and Links

- Fair synchronization primitives can be simple and fast
- Stronger guarantees ⇒ more complicated code

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- Kotlin Coroutines project
  github.com/Kotlin/kotlinx.coroutines
- The experiments (`sqs-experiments` branch)
  github.com/Kotlin/kotlinx.coroutines/tree/sqs-experiments
- My website: nkoval.com

Questions?