

04 Monitors and Blocking Synchronisation

CS 6868: Concurrent Programming

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Our Focus

- **Keep trying**
 - “spin” or “busy-wait”
 - Good if delays are short
 - **Give up the processor**
 - Good if delays are long
 - Always good on uniprocessor
-
- Previous lecture*
- This lecture*

Lock-based queue (from lecture 3)

```
exception Full
exception Empty

type 'a t = {
    items : 'a option array;
    capacity : int;
    mutable head : int;
    mutable tail : int;
    lock : Mutex.t;
}

let create capacity =
{
    items = Array.make capacity None;
    capacity;
    head = 0;
    tail = 0;
    lock = Mutex.create ();
}
```

```
let deq q =
    Mutex.lock q.lock;
    Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
        (fun () ->
            if q.tail = q.head then
                raise Empty;
            match q.items.(q.head mod q.capacity) with
            | None ->
                assert false (* Should never happen *)
            | Some x ->
                q.items.(q.head mod q.capacity) <- None;
                q.head <- q.head + 1;
                x)
```

*deq raises **Empty** if the queue is empty*

Lock-based queue (from lecture 3)

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exception Full
exception Empty

type 'a t = {
    items : 'a option array;
    capacity : int;
    mutable head : int;
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let deq q =
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            | Some x ->
                q.items.(q.head mod q.capacity) <- None;
                q.head <- q.head + 1;
                x)
```

*deq raises **Empty** if the queue is empty*

How to wait till there is an element?

Spin-wait

```
exception Full
exception Empty

type 'a t = {
    items : 'a option array;
    capacity : int;
    mutable head : int;
    mutable tail : int;
    lock : Mutex.t;
}

let create capacity =
{
    items = Array.make capacity None;
    capacity;
    head = 0;
    tail = 0;
    lock = Mutex.create ();
}
```

```
let deq q =
    Mutex.lock q.lock;
    Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
        (fun () ->
            while q.tail = q.head do
                Mutex.unlock q.lock;
                Domain.cpu_relax ();
                Mutex.lock q.lock
            done;

            match q.items.(q.head mod q.capacity) with
            | None -> assert false (* Should never happen *)
            | Some x ->
                q.items.(q.head mod q.capacity) <- None;
                q.head <- q.head + 1;
                x)
```

Allow the `enq` operation to interleave

Downsides of Spin-wait

- Downside of spin-wait
 - Actively wasting CPU spin-waiting
 - On a multi-processor system, there may be other useful tasks to do
 - Waste a full time slice on a uniprocessor system
 - Assuming the OS does preemptive multi-threading every time slice
- What if we expect to wait for significant time?
 - Better to **block** until element is available in the queue.

Condition Variables

- Temporarily give up a critical section and **block**
 - Goes to sleep with the help of the OS; not using CPU actively
- Maybe signalled later to **wake up** the waiting threads
- Woken up thread **resumes** in the critical section
- Always associated with a **Mutex**
- Monitors = Mutex + Conditional Variables
 - Introduced in 1973 paper by Sir Tony Hoare
 - Same person who invented QuickSort and Program Logics

Condition Variables

(** Condition variables *)

type t

(** [create ()] creates and returns a new condition variable. *)

val create : unit -> t

(** [wait c m] atomically unlocks the mutex [m] and suspends the calling thread on the condition variable [c]. The thread will resume after being woken up via [signal] or [broadcast], at which point the mutex [m] is locked again before [wait] returns. *)

val wait : t -> Mutex.t -> unit

(** [signal c] wakes up one of the threads waiting on the condition variable [c], if there is one. If there are no threads waiting on [c], this call has no effect. *)

val signal : t -> unit

(** [broadcast c] wakes up all threads waiting on the condition variable [c]. If there are no threads waiting on [c], this call has no effect. *)

val broadcast : t -> unit

Blocking Queue

```
type 'a t = {
    items : 'a option array;
    capacity : int;
    mutable head : int;
    mutable tail : int;
    lock : Mutex.t;
    not_empty : Condition.t; (* Signaled when queue becomes non-empty *)
    not_full : Condition.t; (* Signaled when queue becomes non-full *)
}

let create capacity =
{
    items = Array.make capacity None;
    capacity;
    head = 0;
    tail = 0;
    lock = Mutex.create ();
    not_empty = Condition.create ();
    not_full = Condition.create ();
}
```

Blocking Queue

```
let deq q =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is empty *)
    while q.tail = q.head do
      Condition.wait q.not_empty q.lock
    done;

    match q.items.(q.head mod q.capacity) with
    | None -> assert false (* Should never happen *)
    | Some x ->
        q.items.(q.head mod q.capacity) <- None;
        q.head <- q.head + 1;
        (* Signal that queue is not full *)
        Condition.signal q.not_full;
        x)
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Blocking Queue

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Blocking Queue

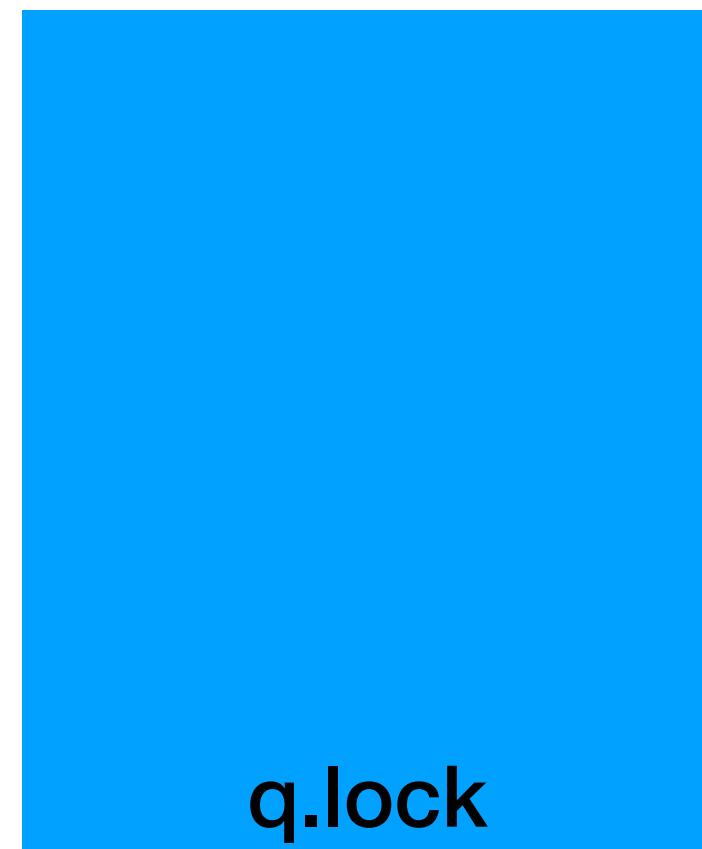
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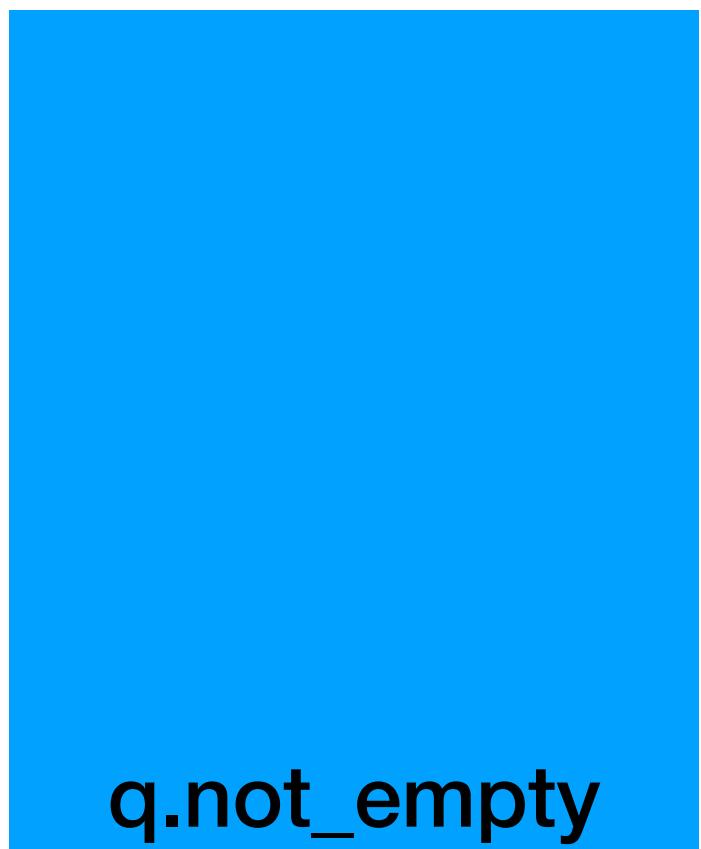
q = []

deq q

D1



Critical Section



Waiting Area

Blocking Queue

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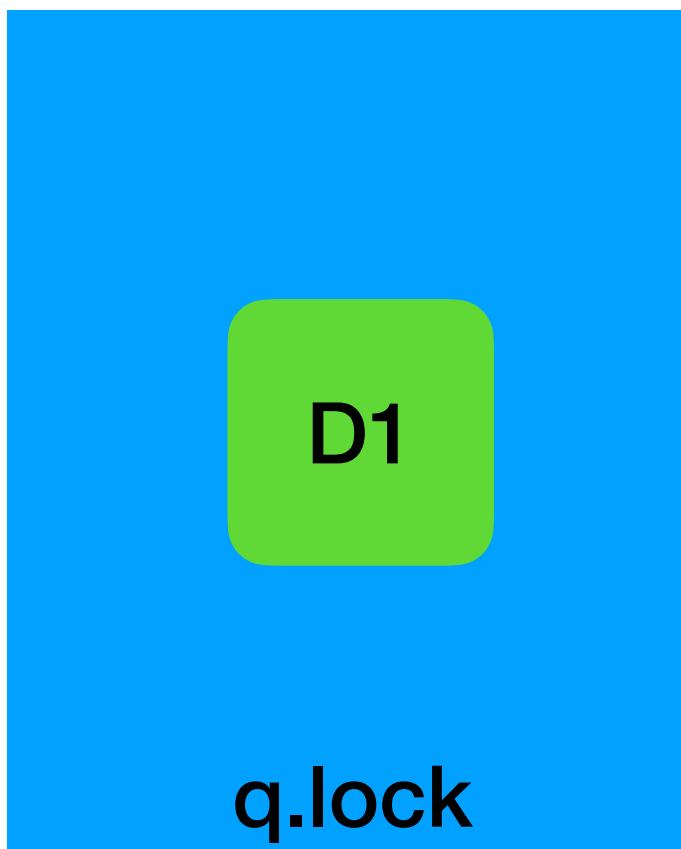
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        q.head <- q.head + 1;
        (* Signal that queue is not full *)
        Condition.signal q.not_full;
    x)
```

q = []

deq q

D1

q.lock



Critical Section



Waiting Area

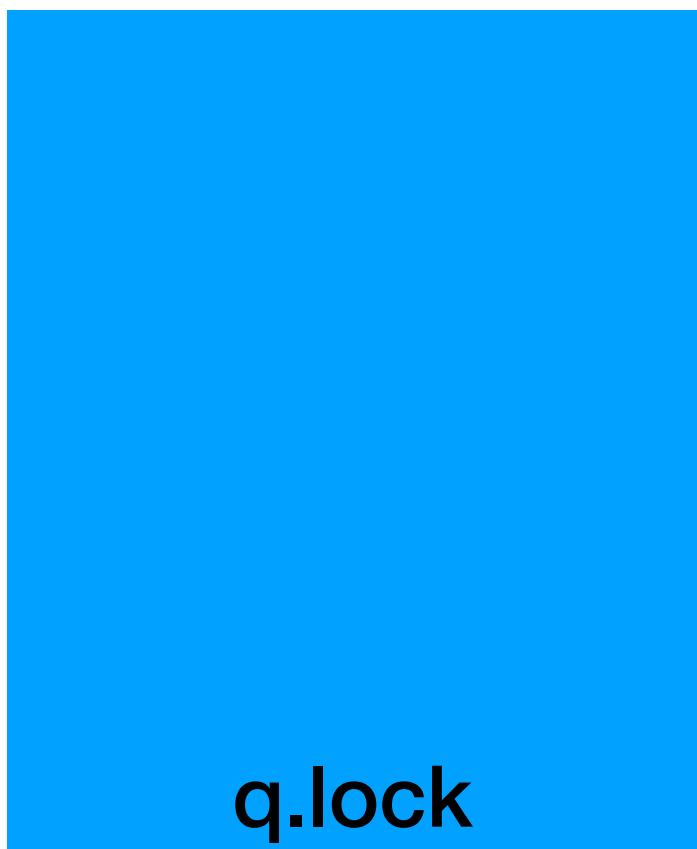
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deq q



Critical Section



Waiting Area

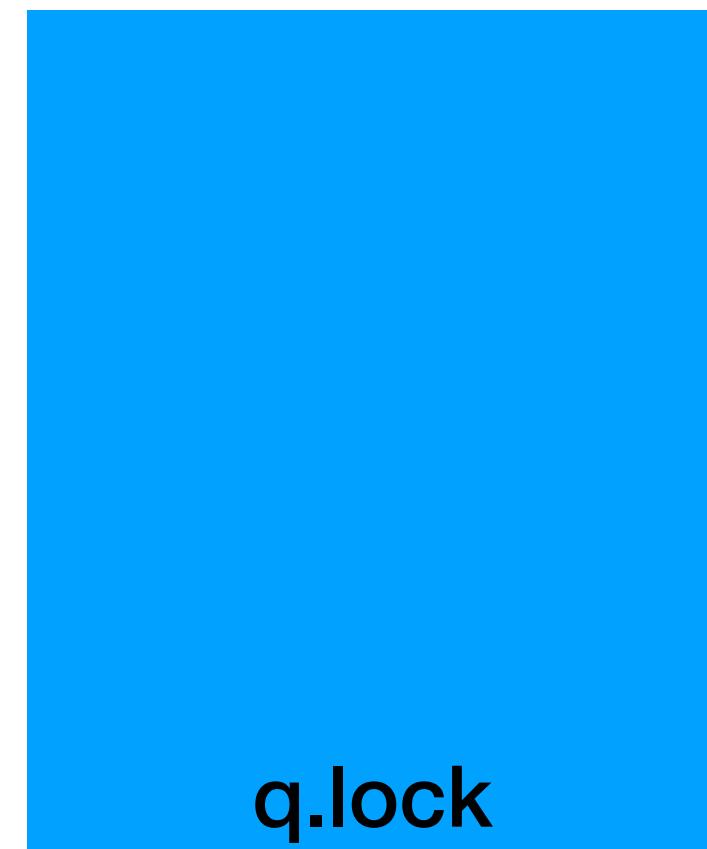
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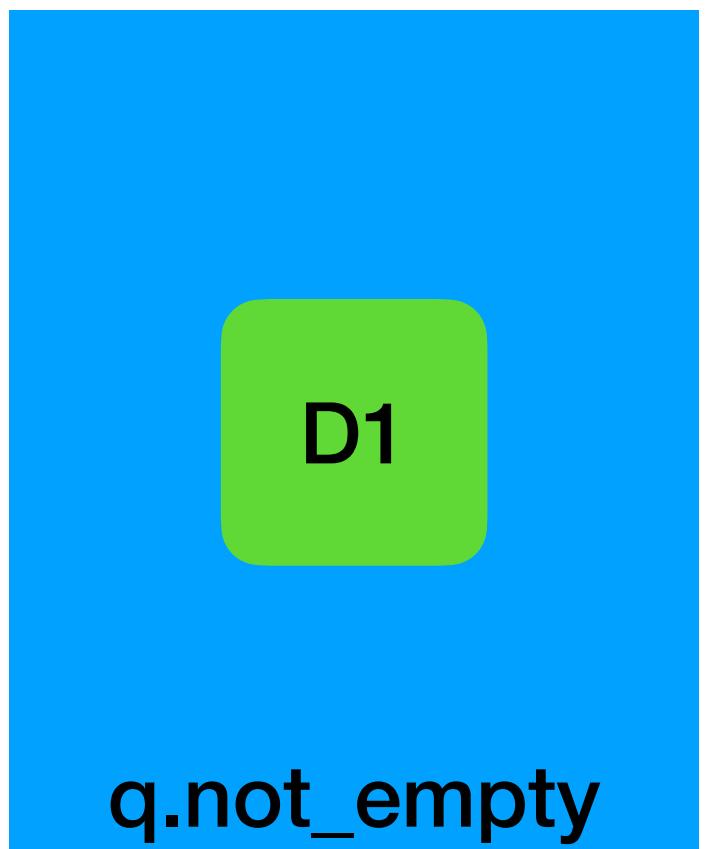
    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
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q = []



Critical Section



Waiting Area

Blocking Queue

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```

`q = []`

`enq q 0`

E1



Critical Section

D1



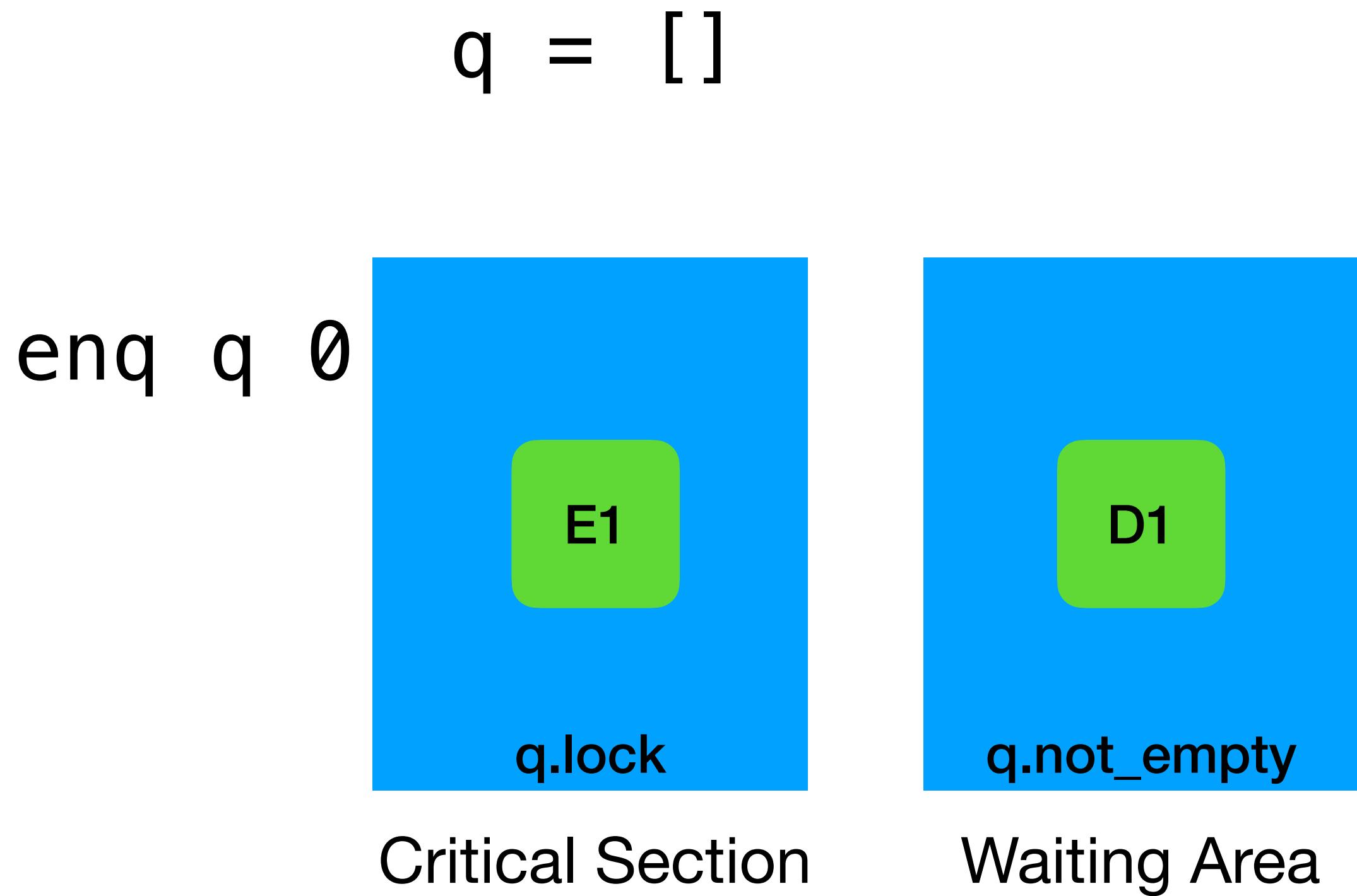
Waiting Area

Blocking Queue

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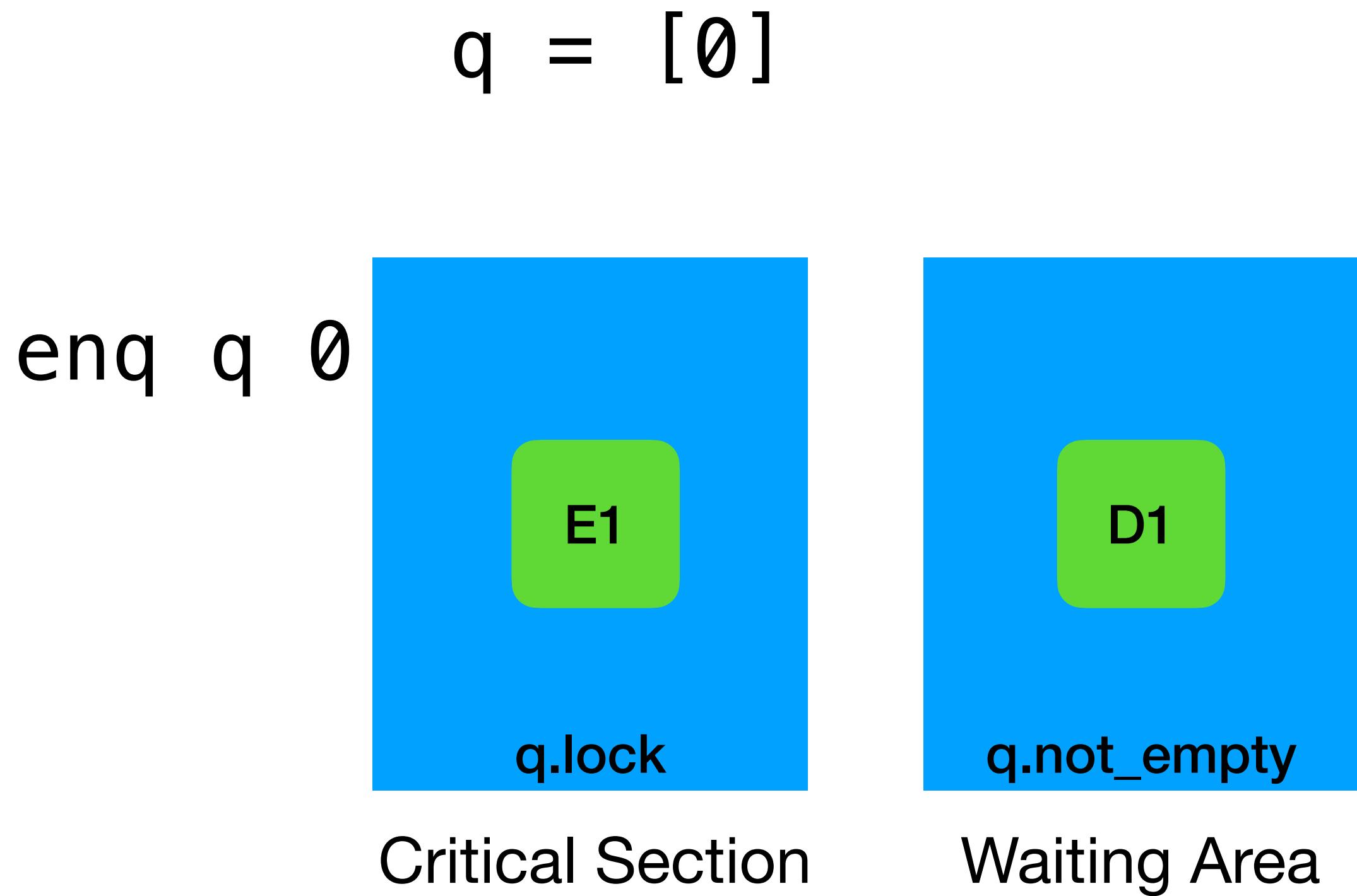


Blocking Queue

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      Condition.wait q.not_full q.lock
    done;

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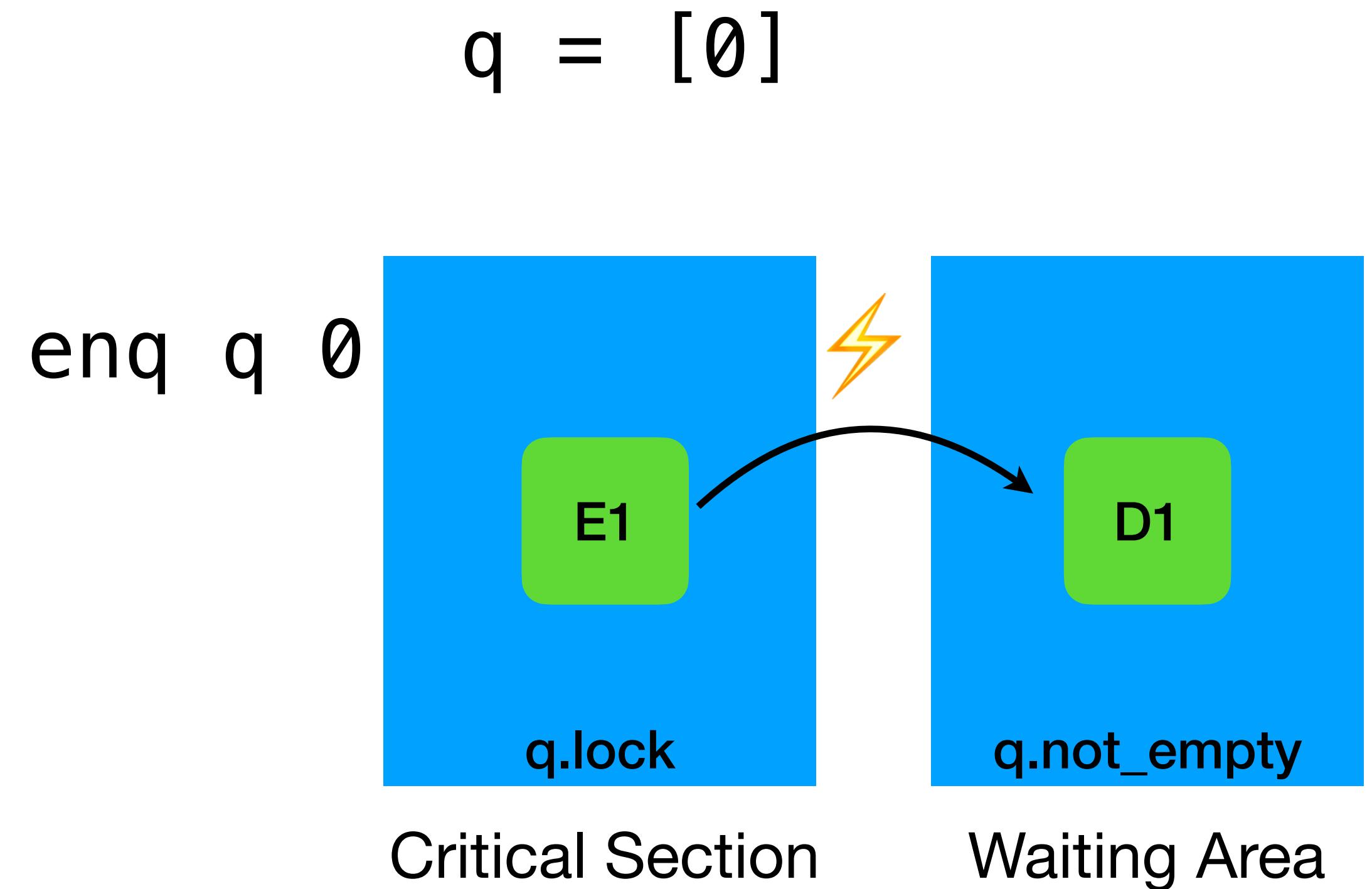


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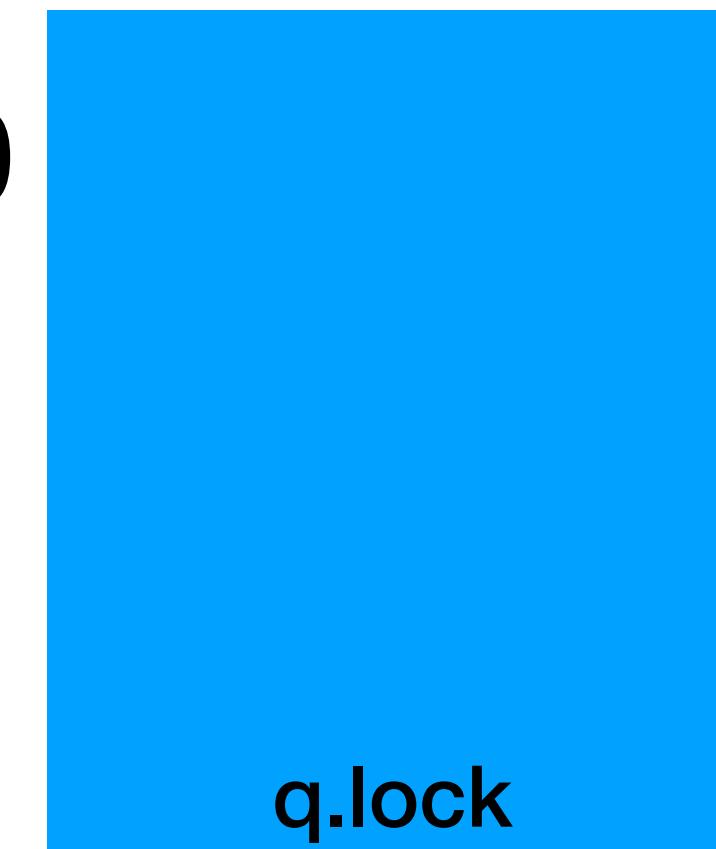
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    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;

    (* Signal that queue is not empty *)
    Condition.signal q.not_empty)
```

$q = [\emptyset]$

enq q \emptyset

E1



Critical Section



Waiting Area
q.not_empty

Subtleties – Recheck condition for spurious wakeups

```
let enq q x =
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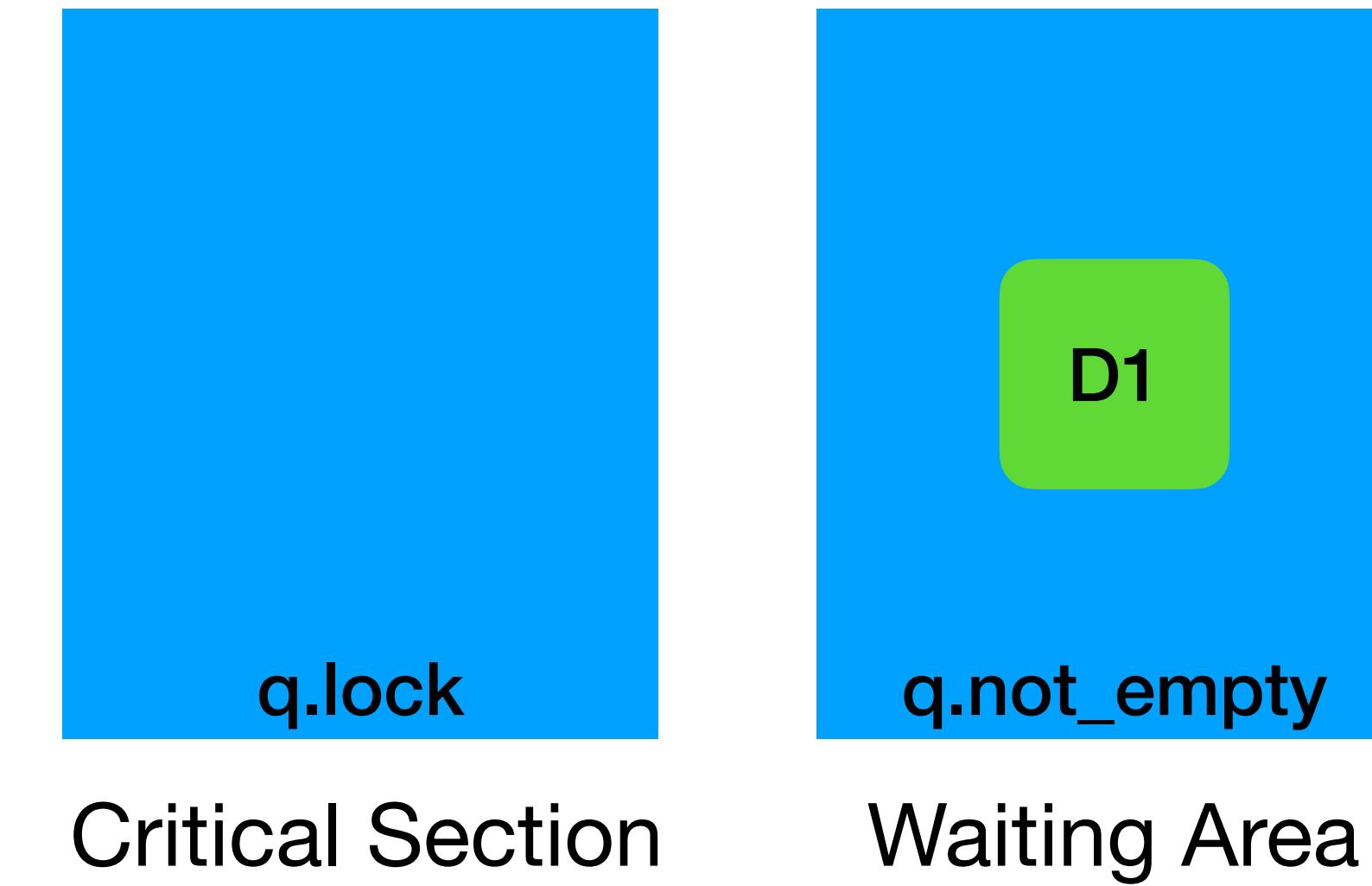
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```

Spurious wakeups possible

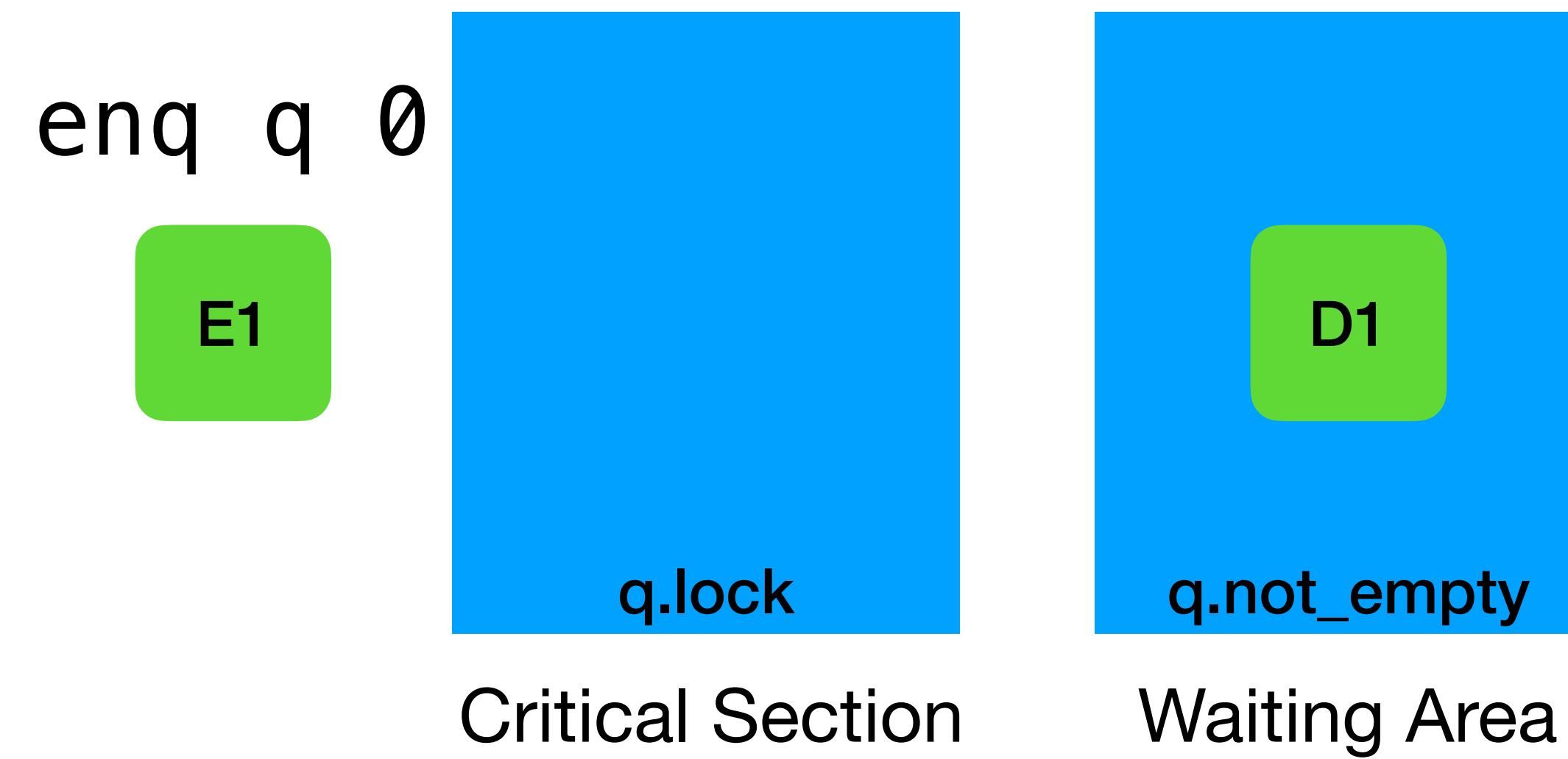
Subtleties – Recheck condition for concurrency

`q = []`



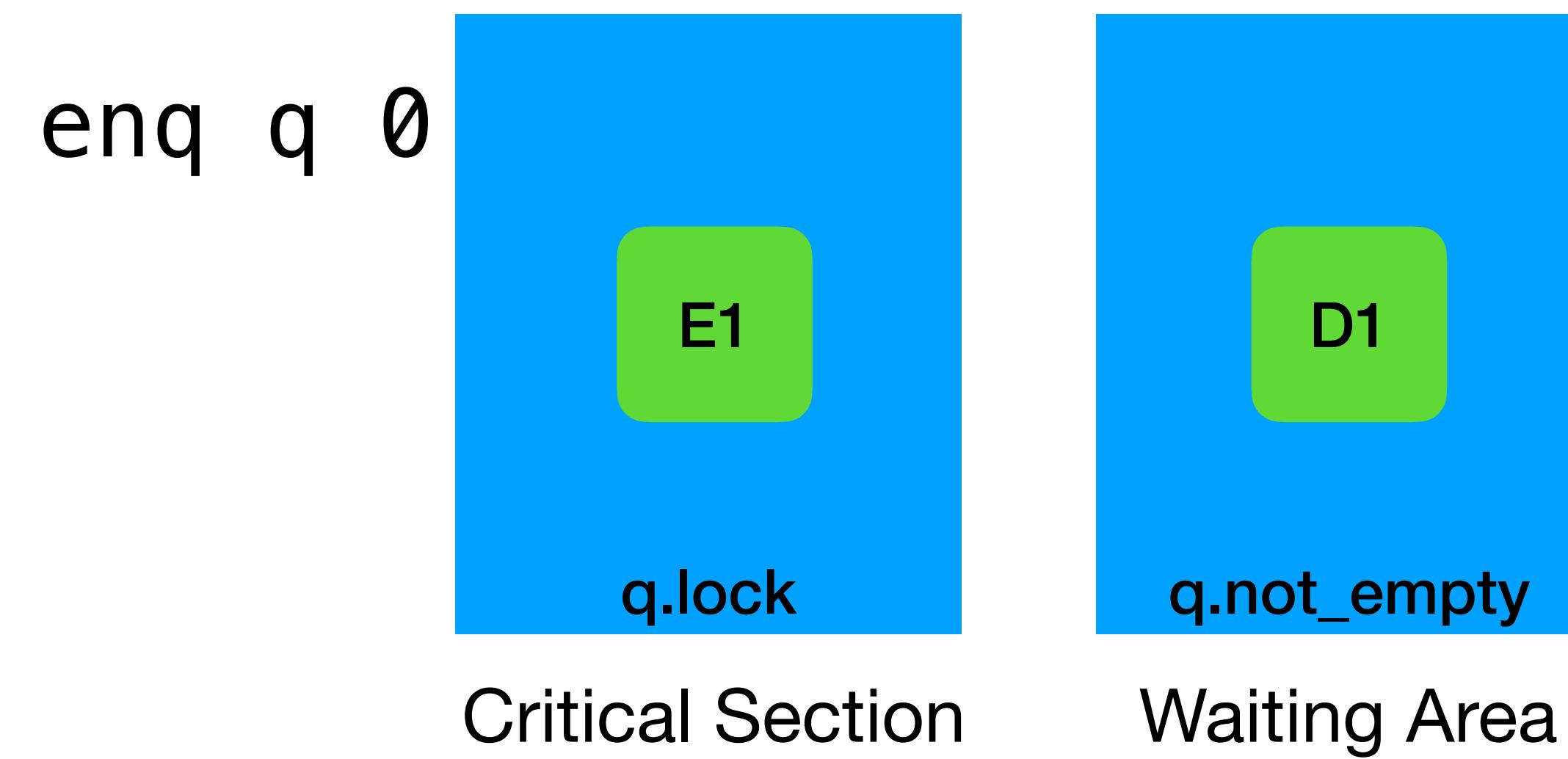
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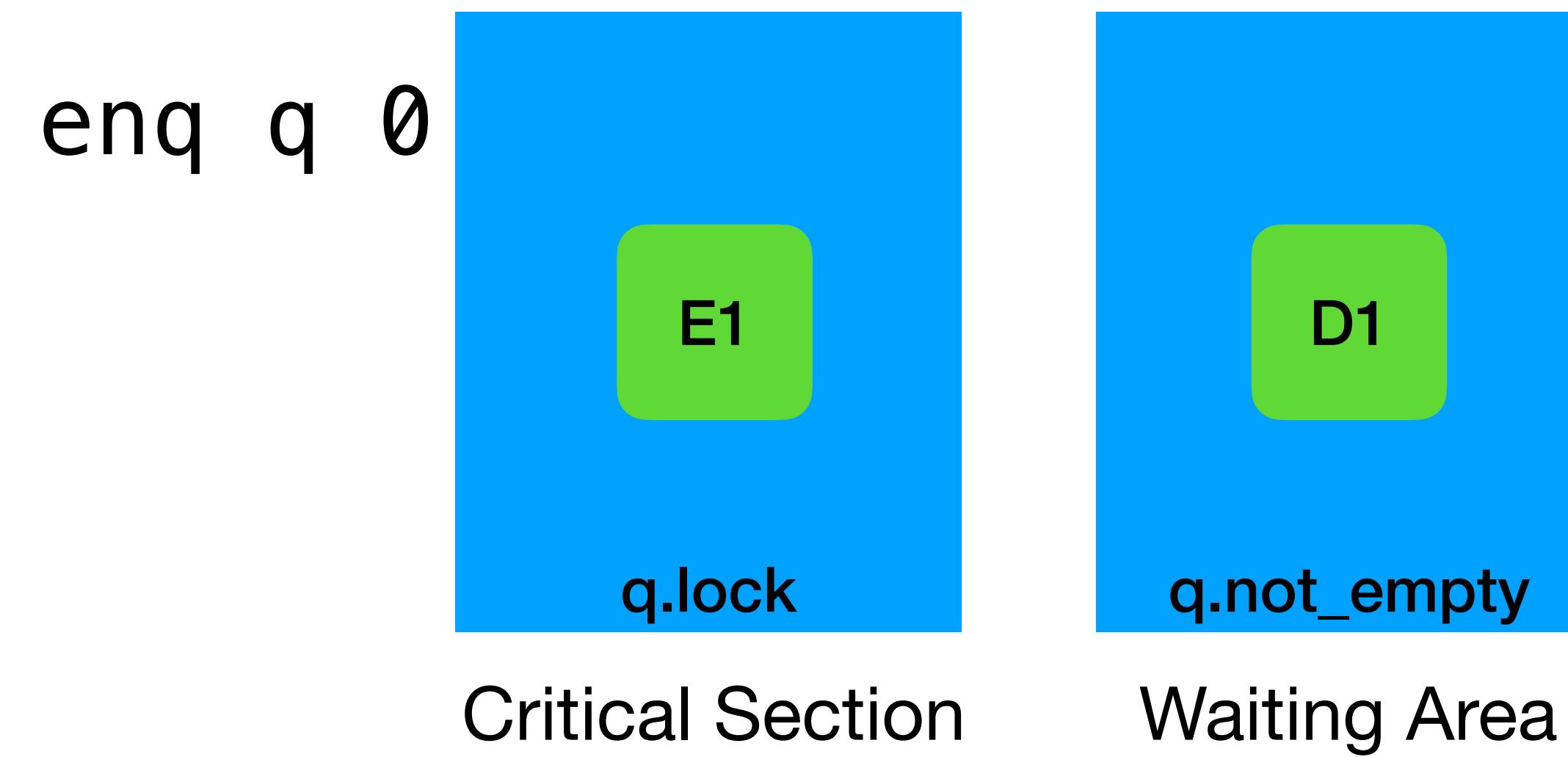
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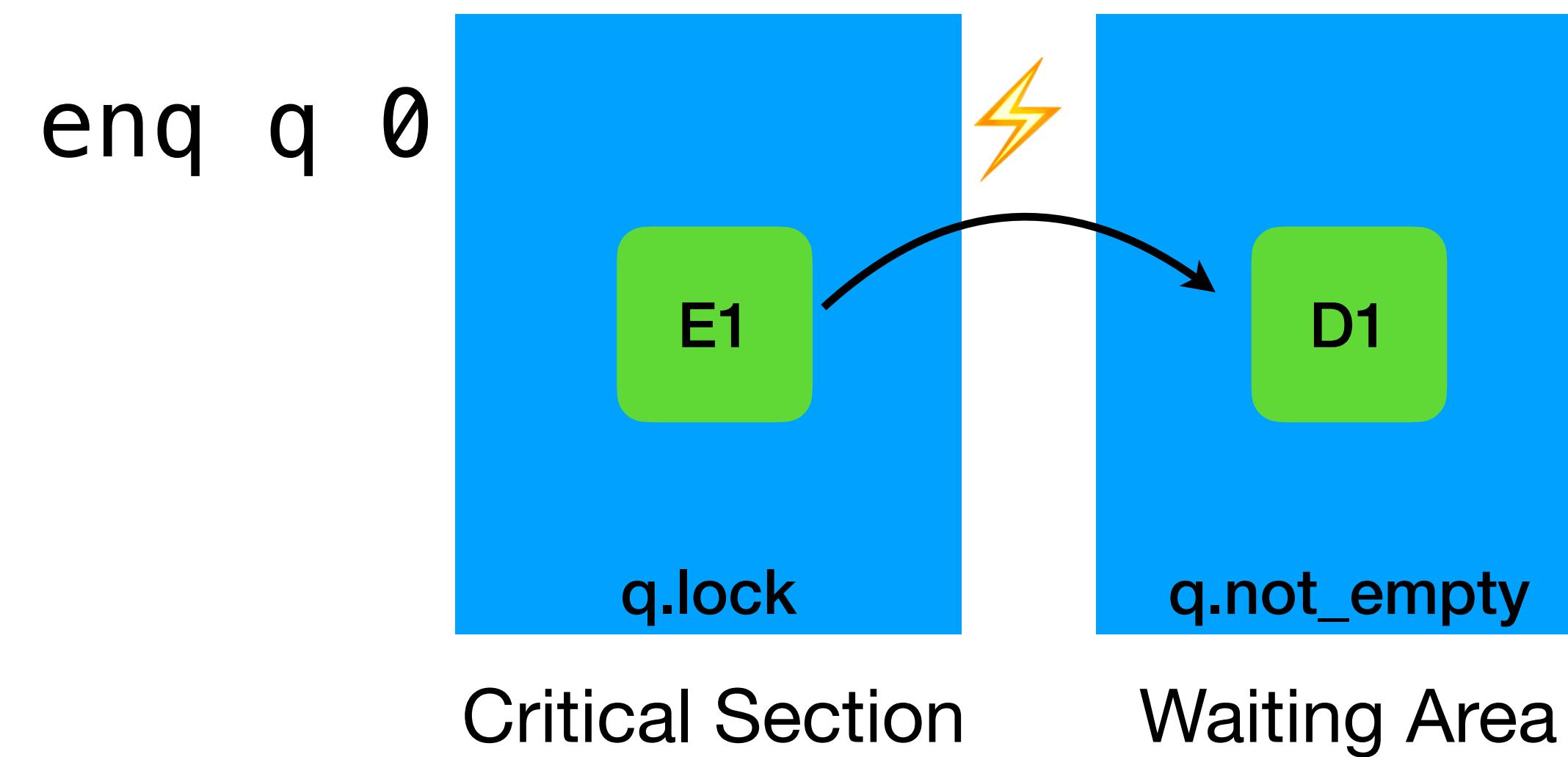
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$q = [\emptyset]$



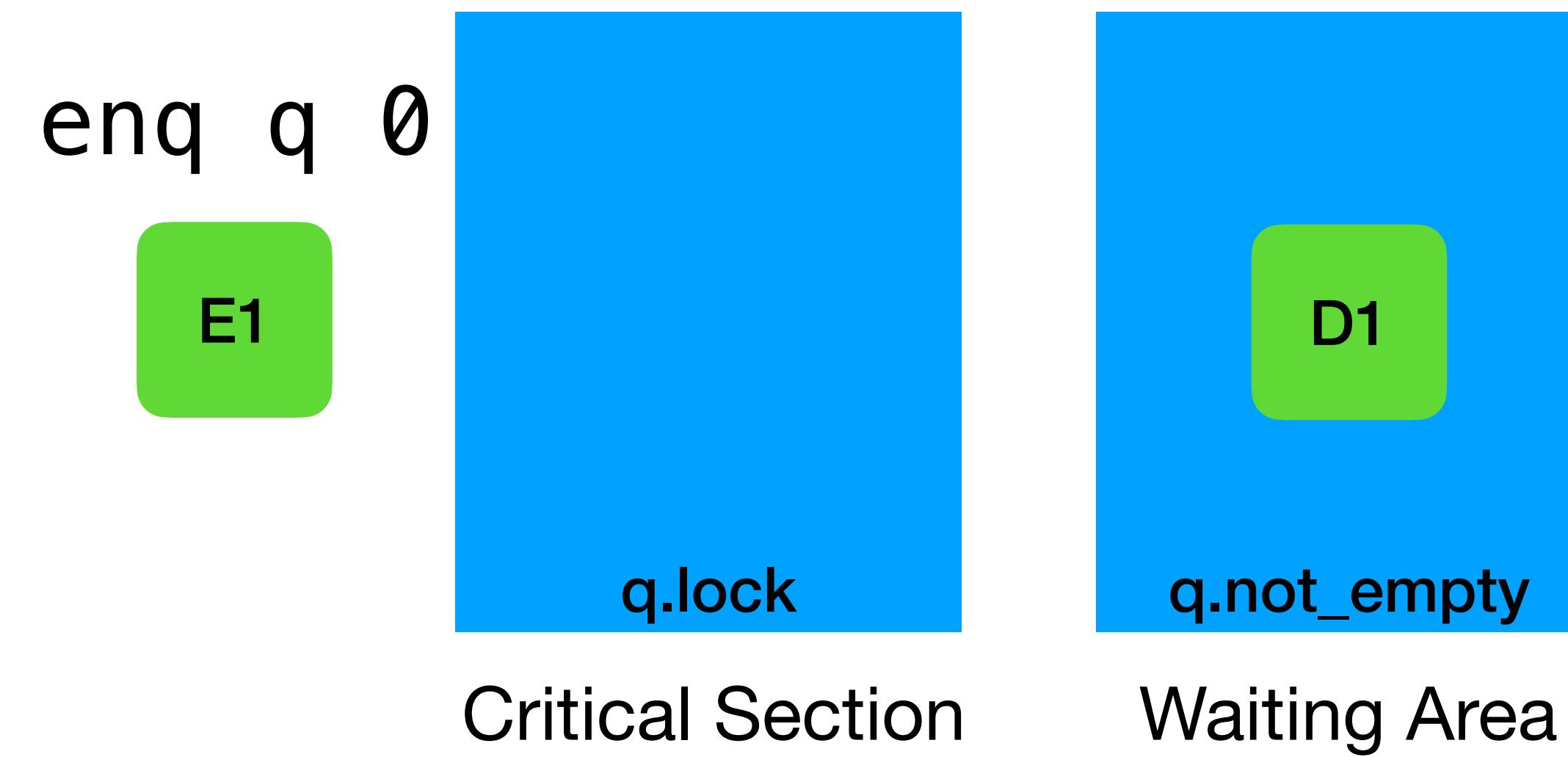
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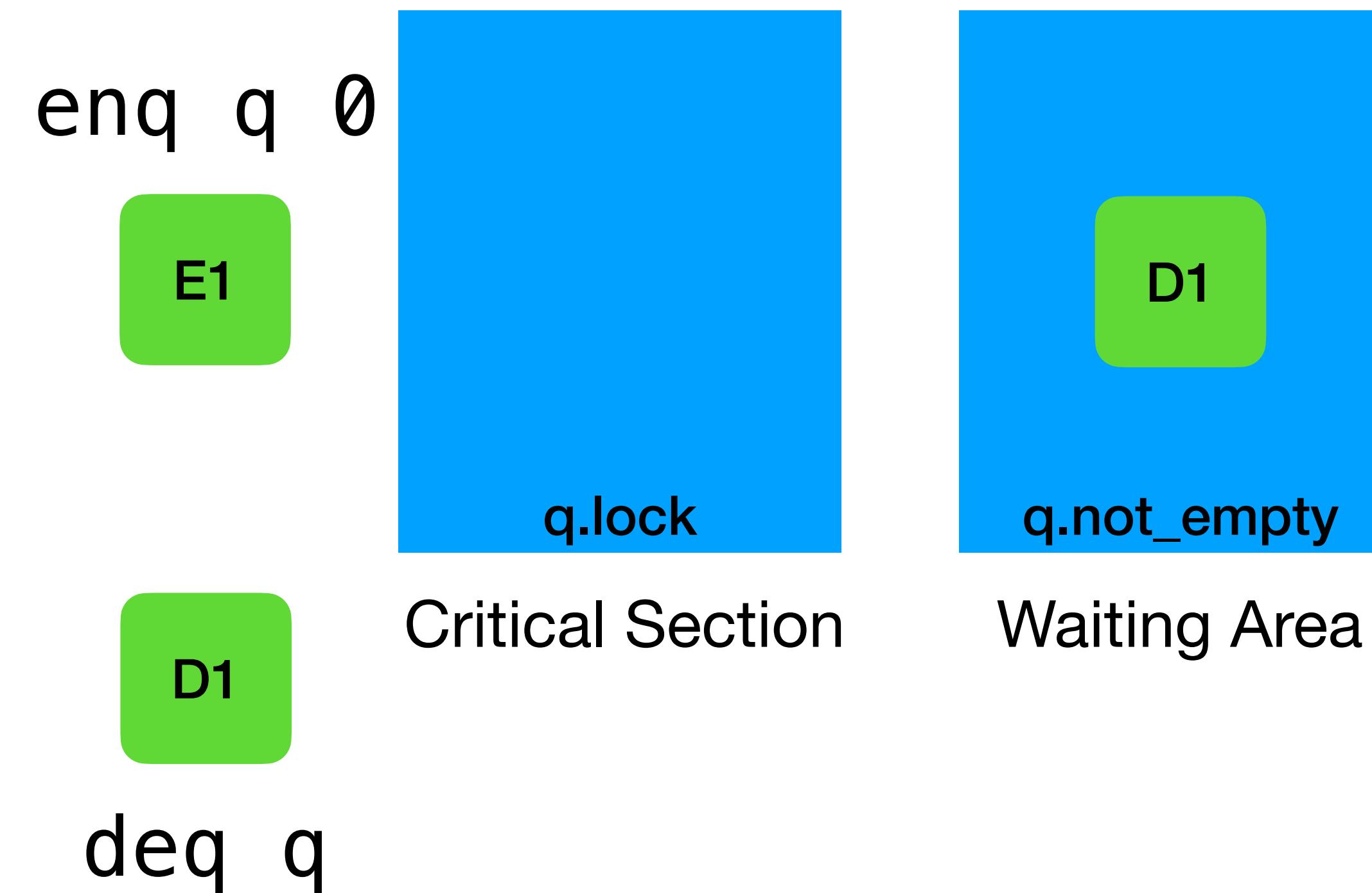
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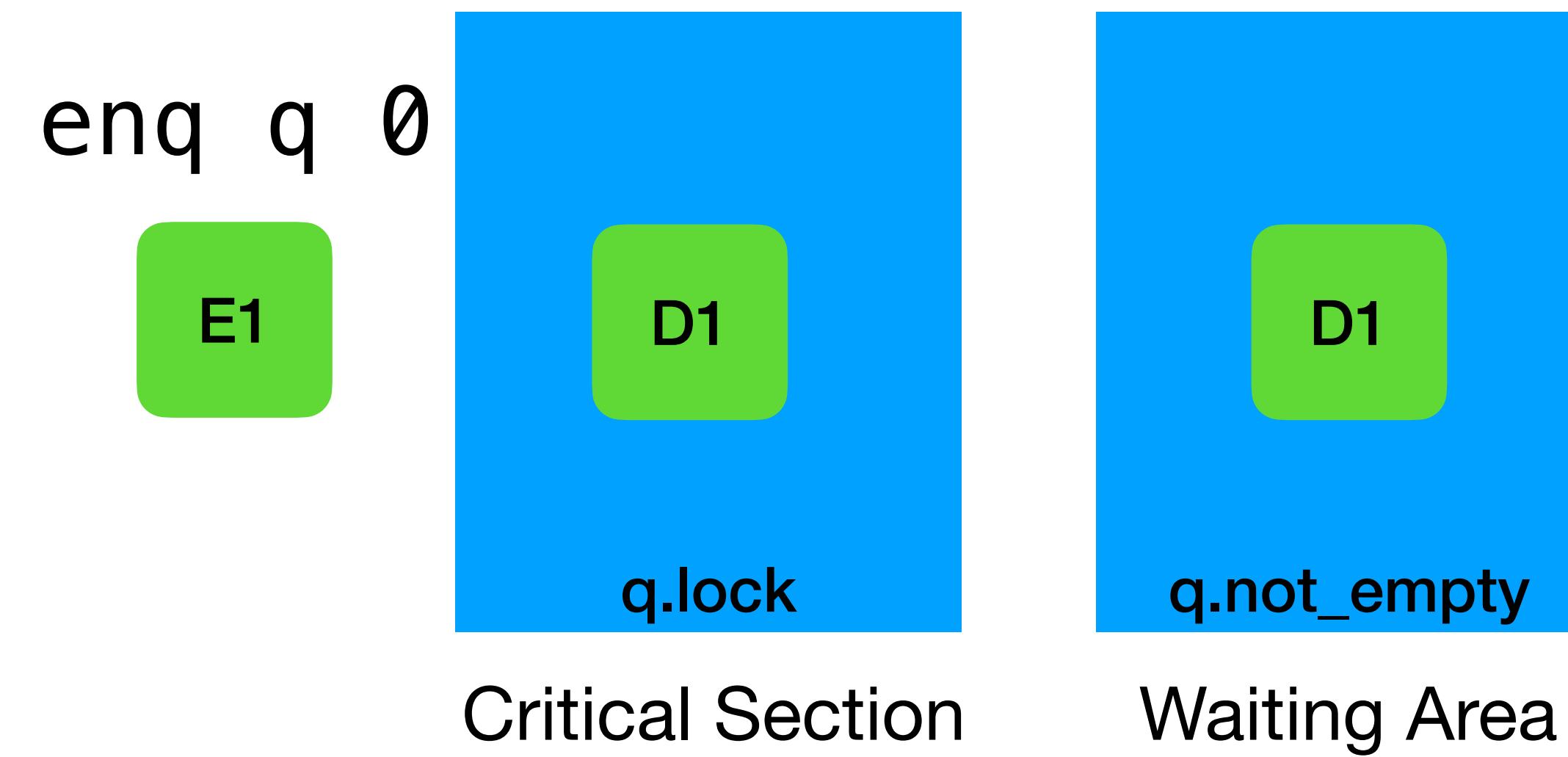
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Subtleties – Recheck condition for concurrency

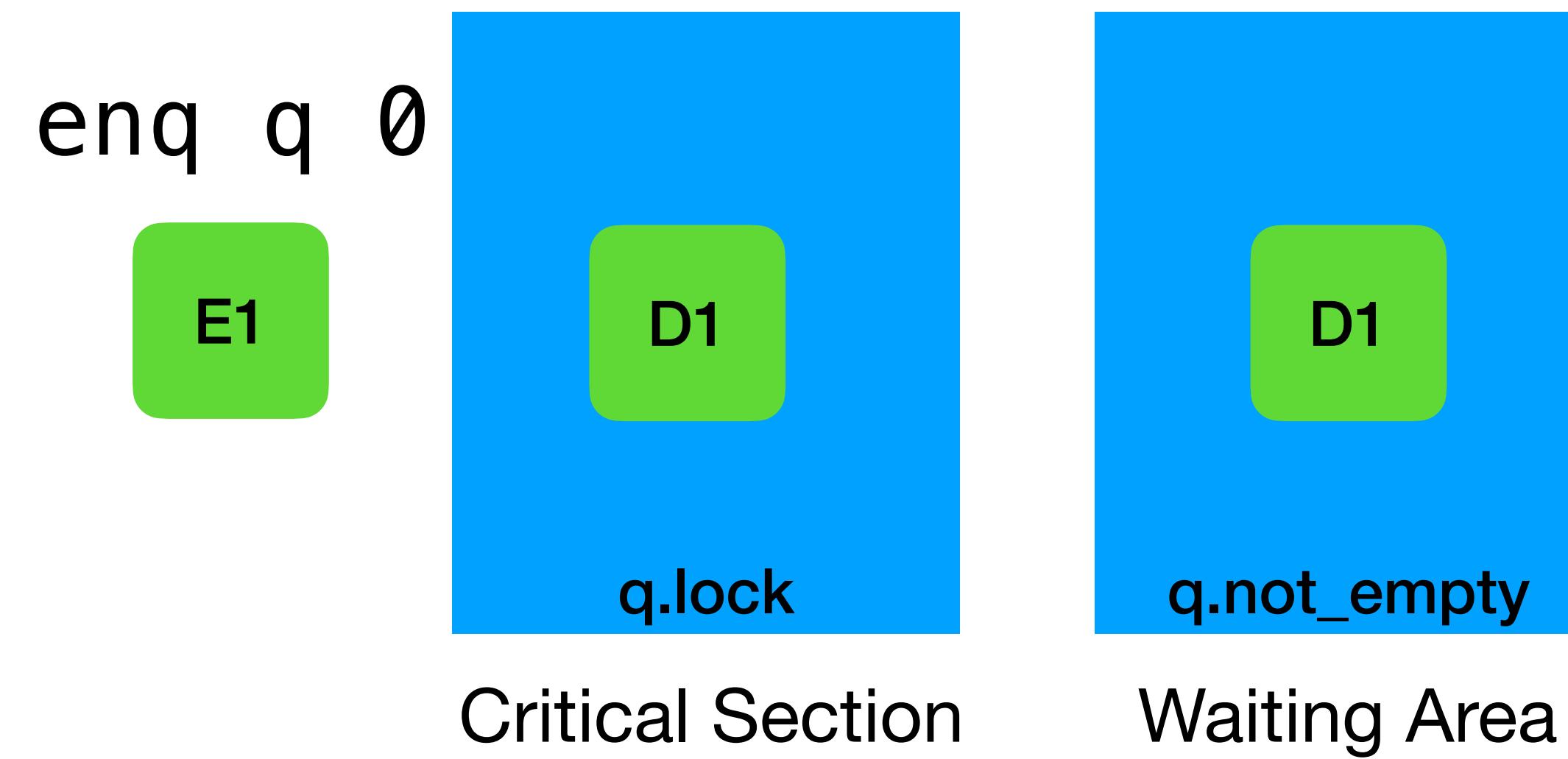
$q = [\emptyset]$



deq q

Subtleties – Recheck condition for concurrency

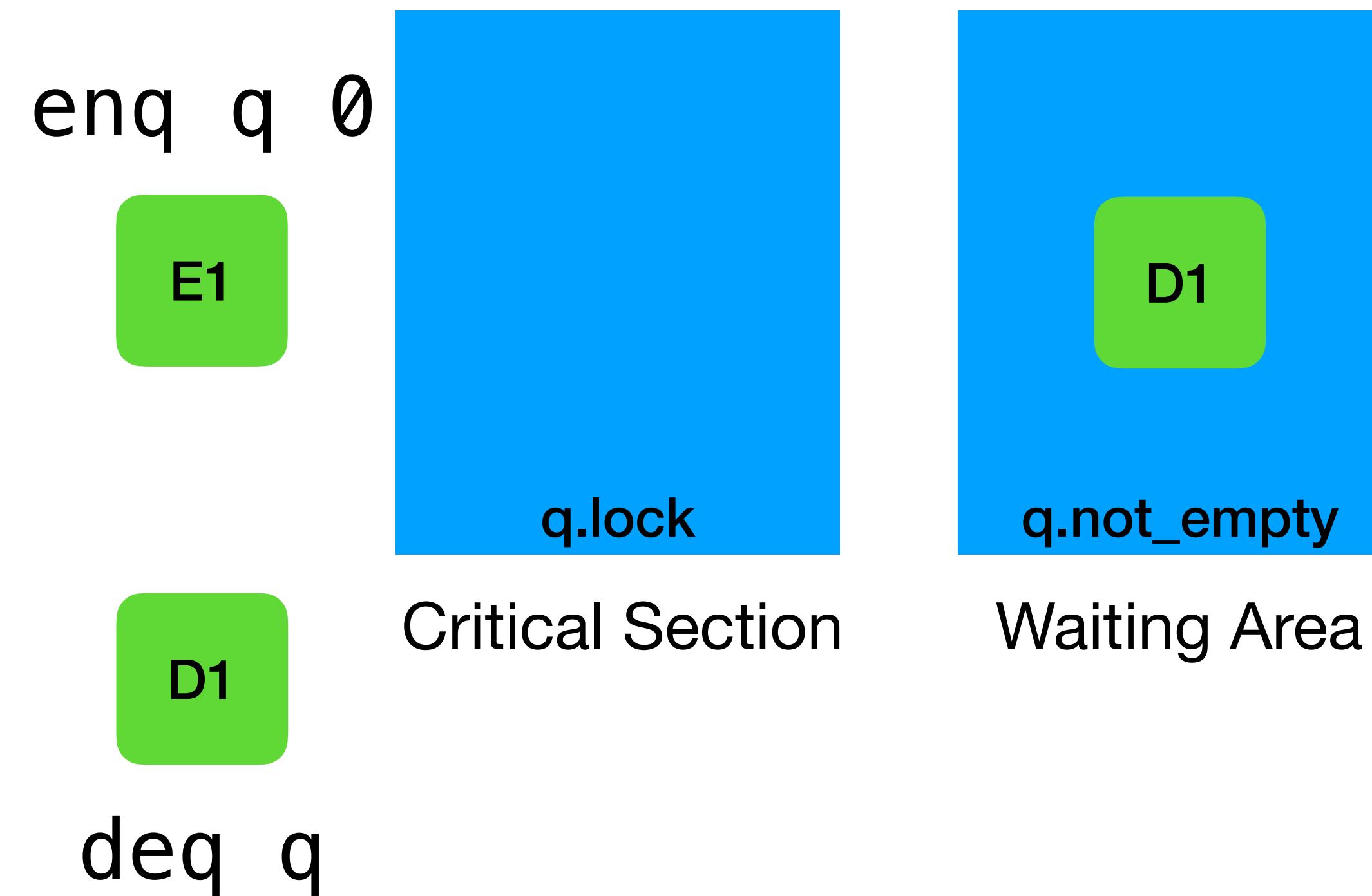
$q = []$



$deq\ q$

Subtleties – Recheck condition for concurrency

$q = []$



Subtleties – Lost-wakeup Problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;

    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;

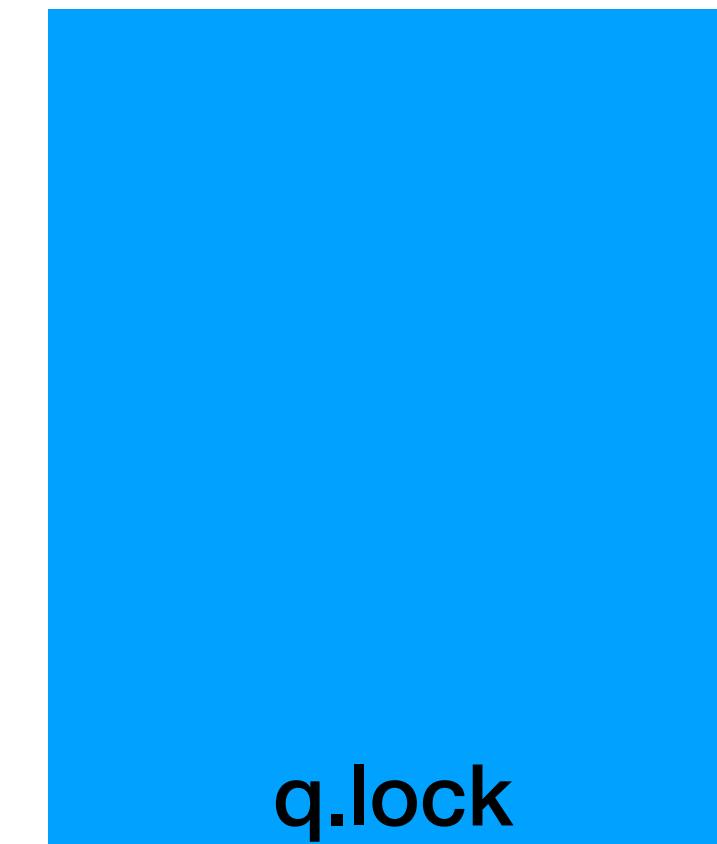
    (* Signal that queue is not empty *)
    Condition.signal q.not_empty)
```

Note that we signal all the time, not just when the queue transitions from empty to non-empty

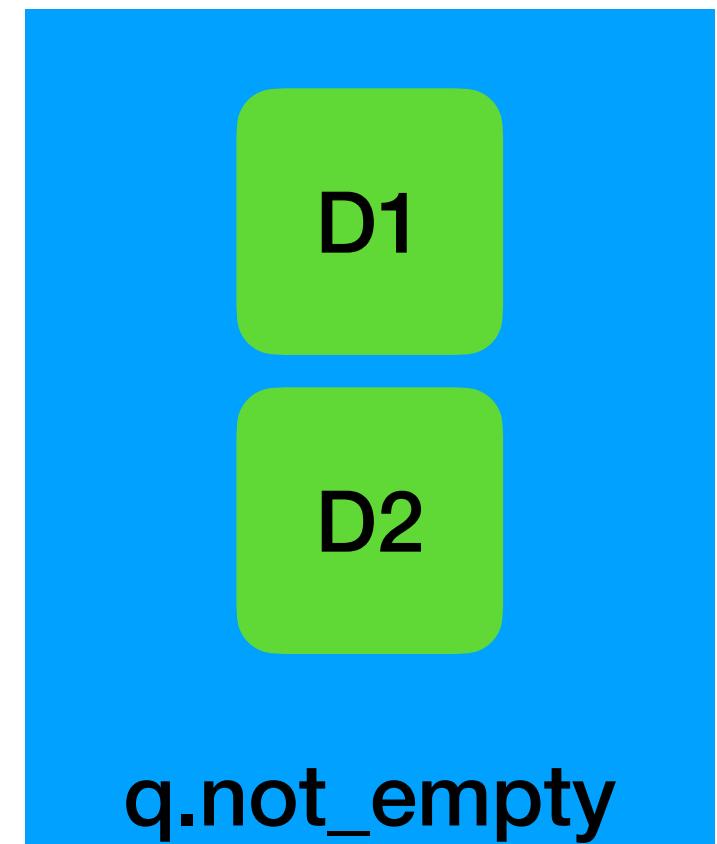
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    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in
    (* Add element *)
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    q.tail <- q.tail + 1;
    (* Signal that queue is not empty *)
    if must_signal then
      Condition.signal q.not_empty)
```

q = []



Critical Section



Waiting Area

Subtleties – Lost-wakeup Problem

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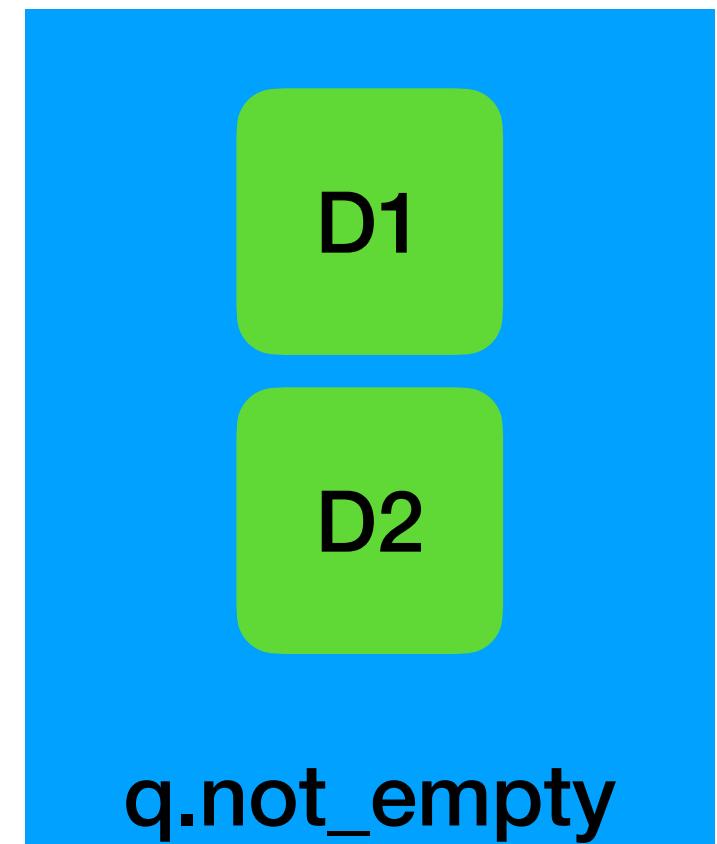
q = []

enq q 0

E1



Critical Section



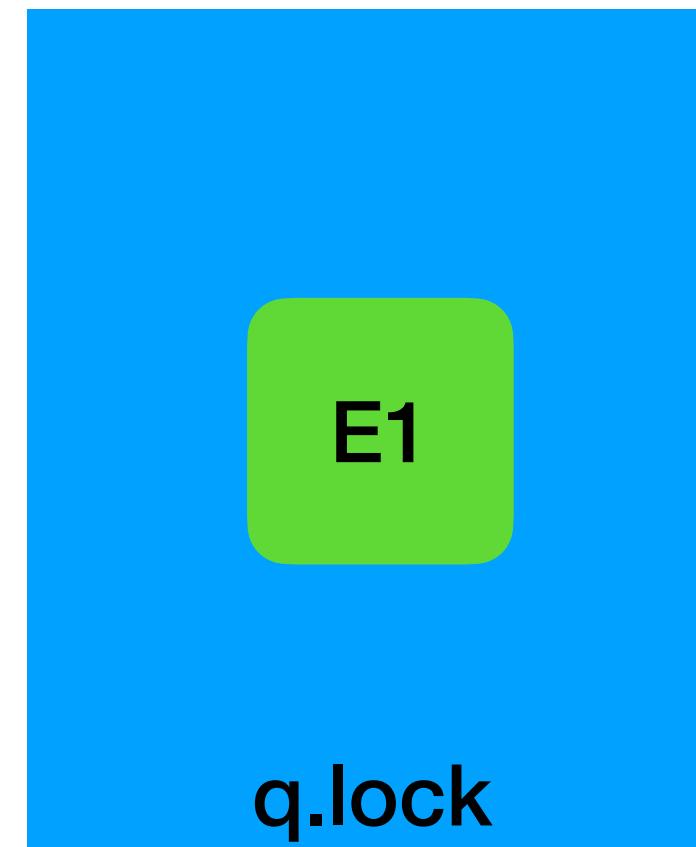
Waiting Area

Subtleties – Lost-wakeup Problem

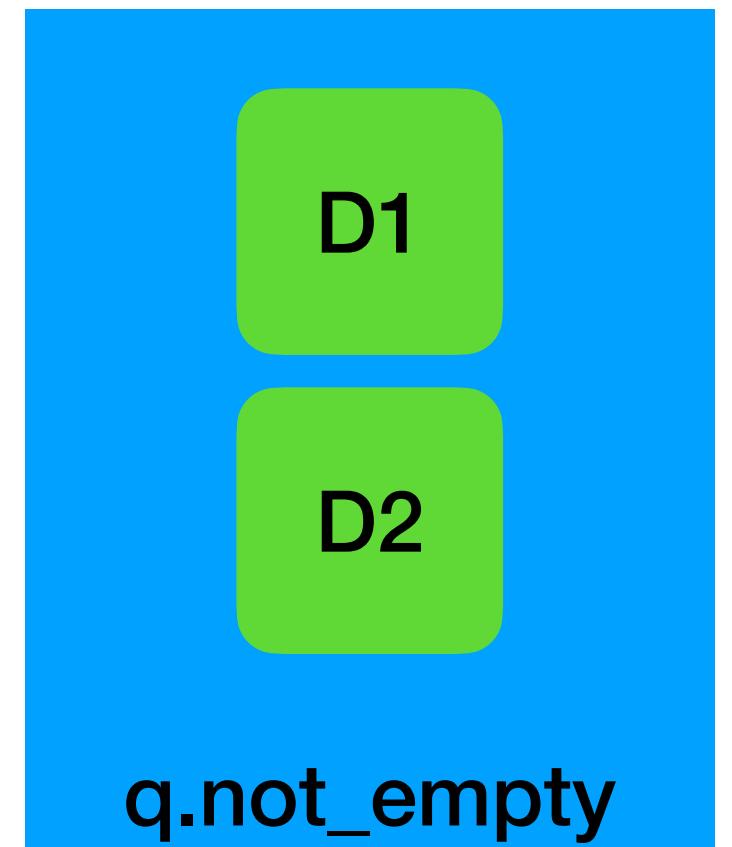
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    (* Signal that queue is not empty *)
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      Condition.signal q.not_empty)
```

q = []

enq q 0



Critical Section



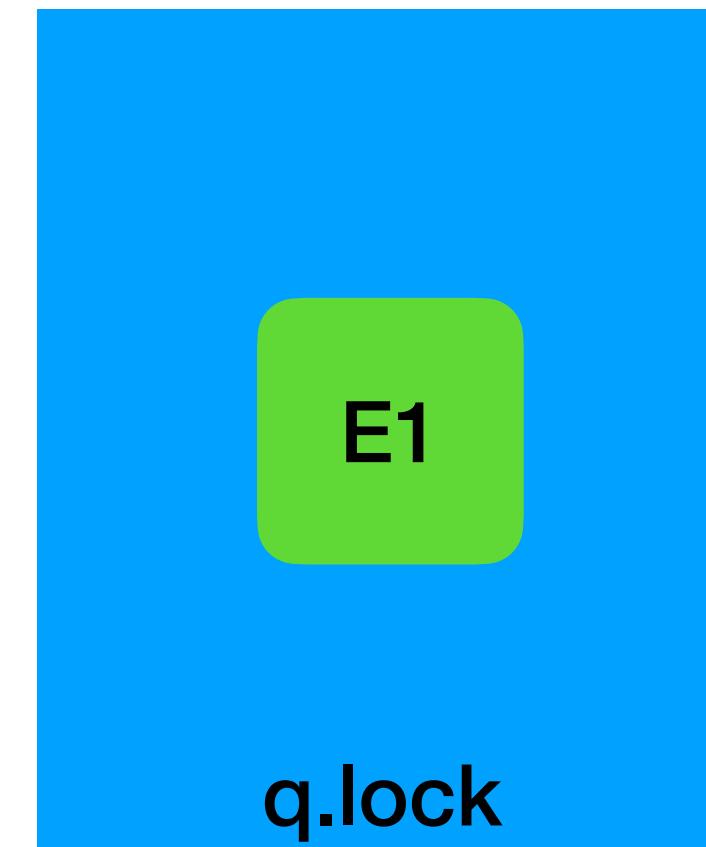
Waiting Area

Subtleties – Lost-wakeup Problem

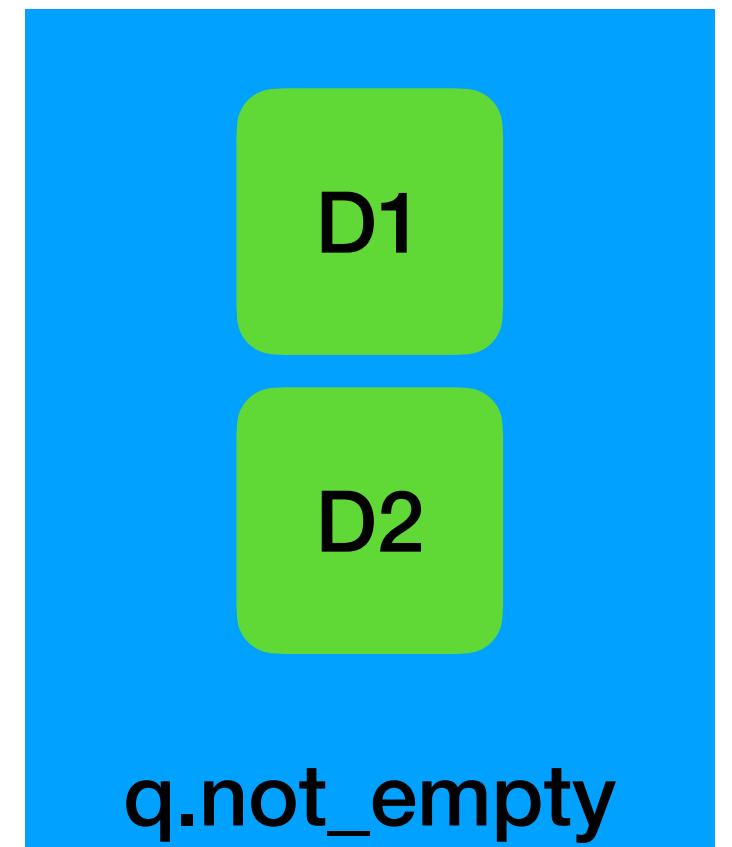
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```

q = []

enq q 0



Critical Section



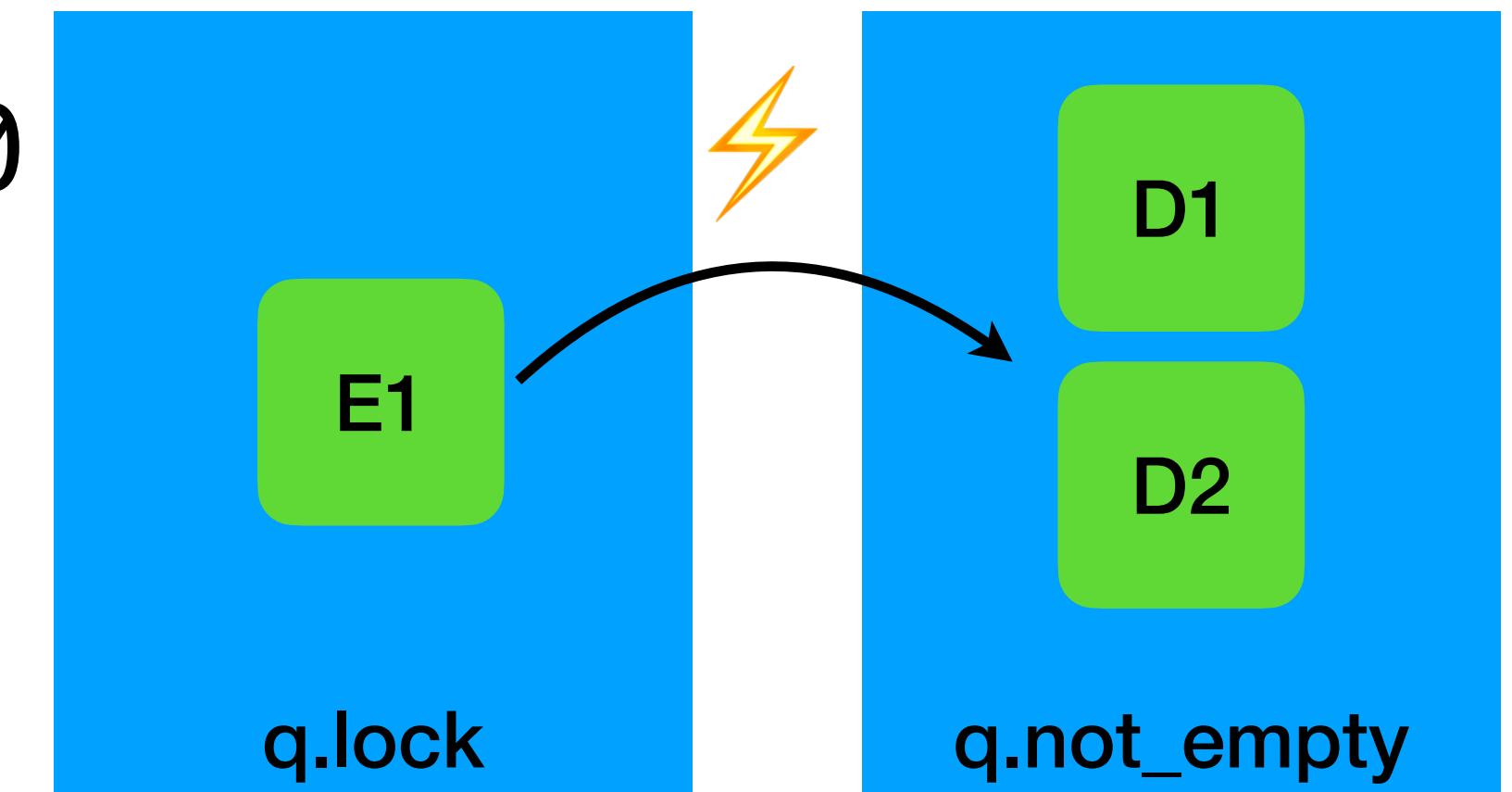
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    (* Signal that queue is not empty *)
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```

$q = [0]$

enq q 0



Critical Section

Waiting Area

Subtleties – Lost-wakeup Problem

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    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in
      (* Add element *)
      q.items.(q.tail mod q.capacity) <- Some x;
      q.tail <- q.tail + 1;
    (* Signal that queue is not empty *)
    if must_signal then
      Condition.signal q.not_empty)
```

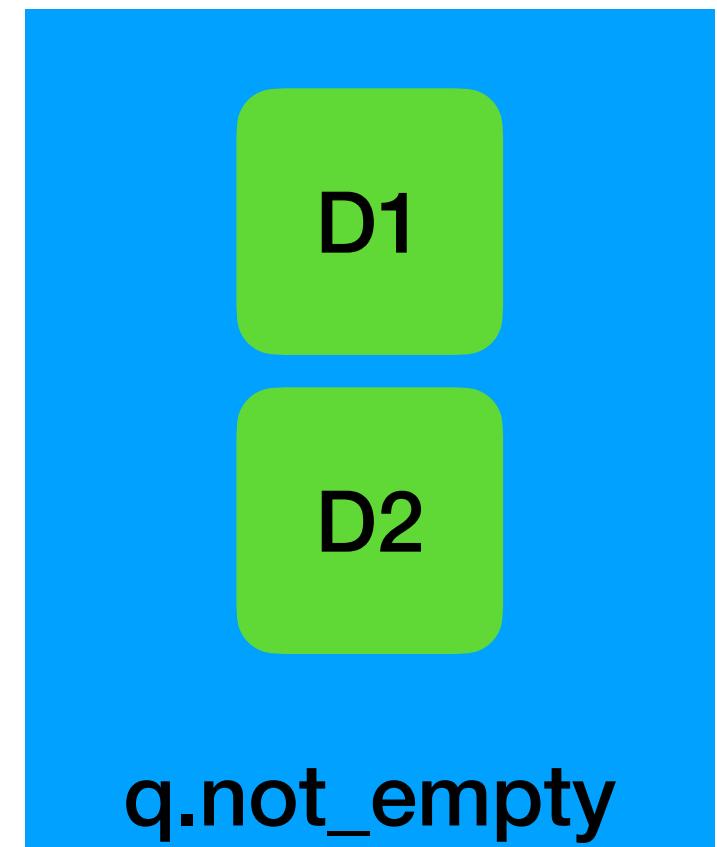
$q = [\emptyset]$

enq q 0

E1



Critical Section



Waiting Area

Subtleties – Lost-wakeup Problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in
    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;
    (* Signal that queue is not empty *)
    if must_signal then
      Condition.signal q.not_empty)
```

q = [0]

enq q 0

E1

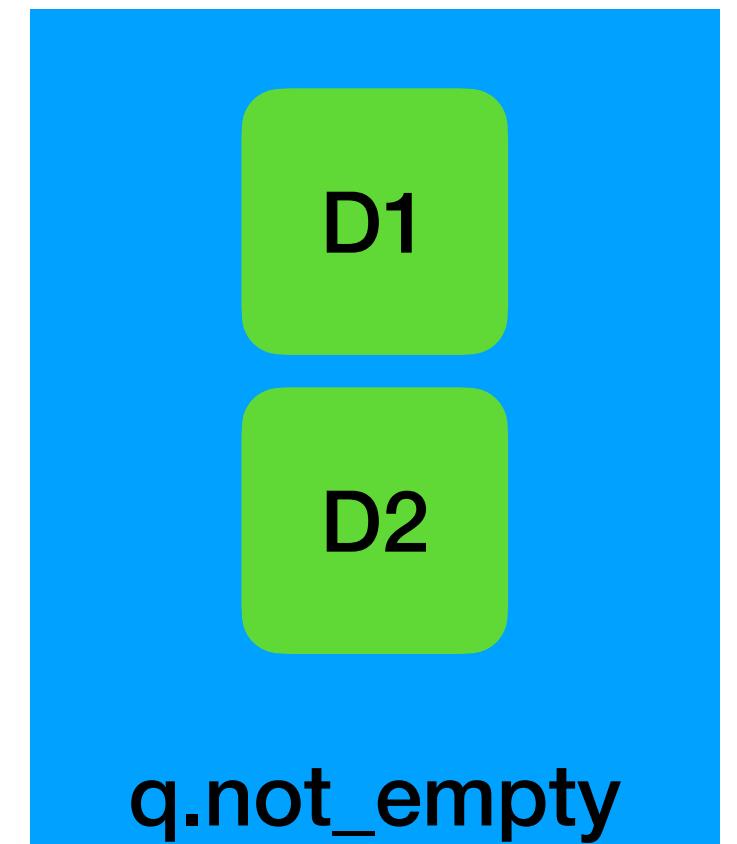
q.lock

E2

enq q 1



Critical Section

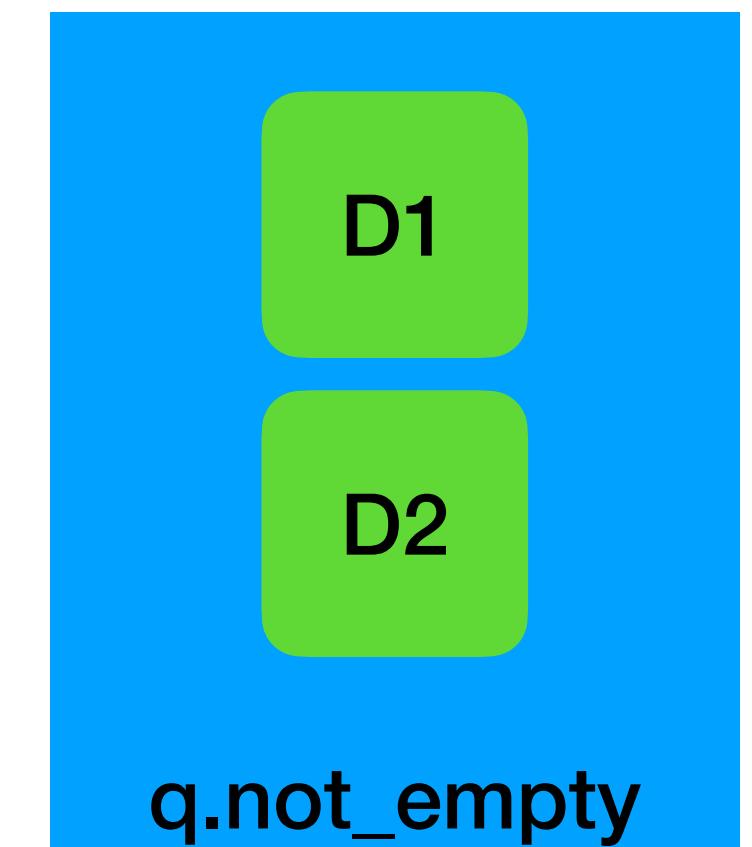
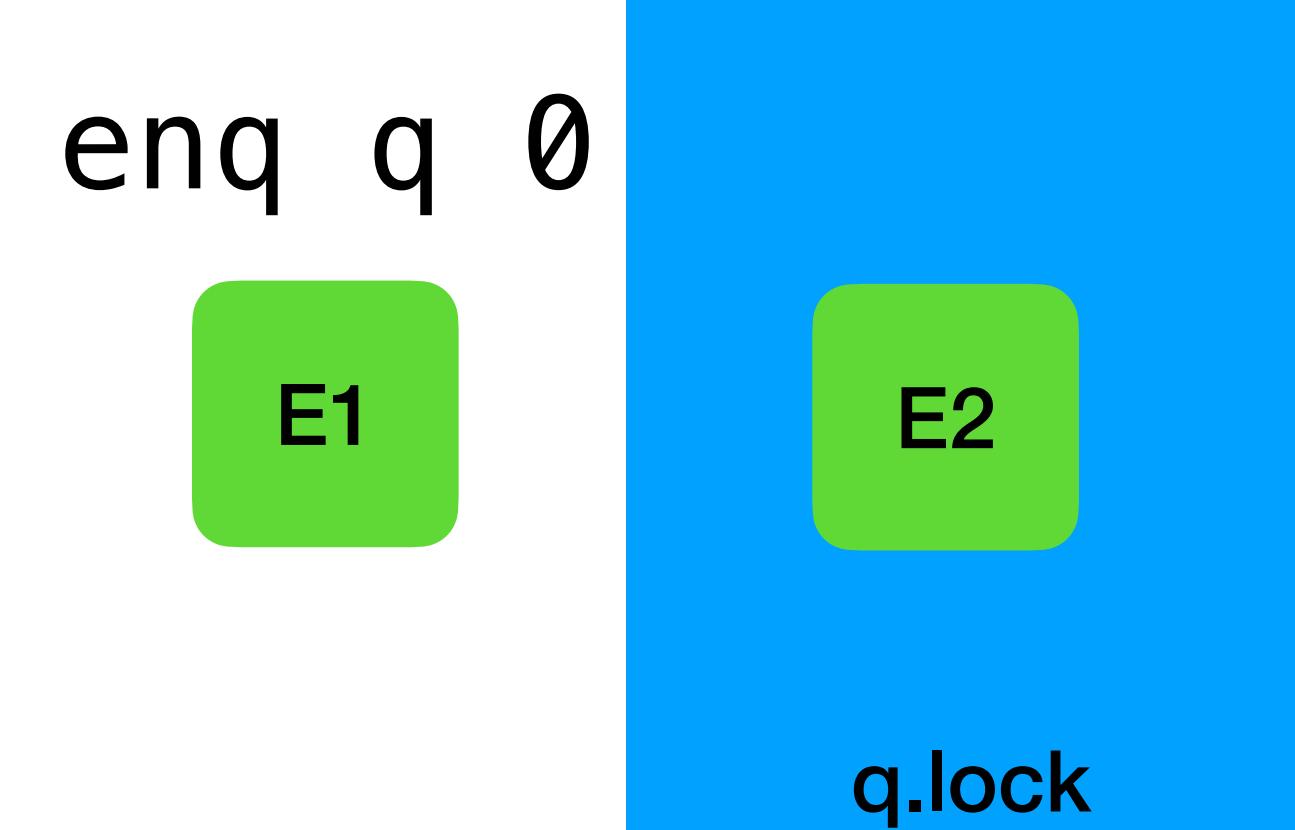


Waiting Area

Subtleties – Lost-wakeup Problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in
      (* Add element *)
      q.items.(q.tail mod q.capacity) <- Some x;
      q.tail <- q.tail + 1;
    (* Signal that queue is not empty *)
    if must_signal then
      Condition.signal q.not_empty)
```

q = [0]



Critical Section

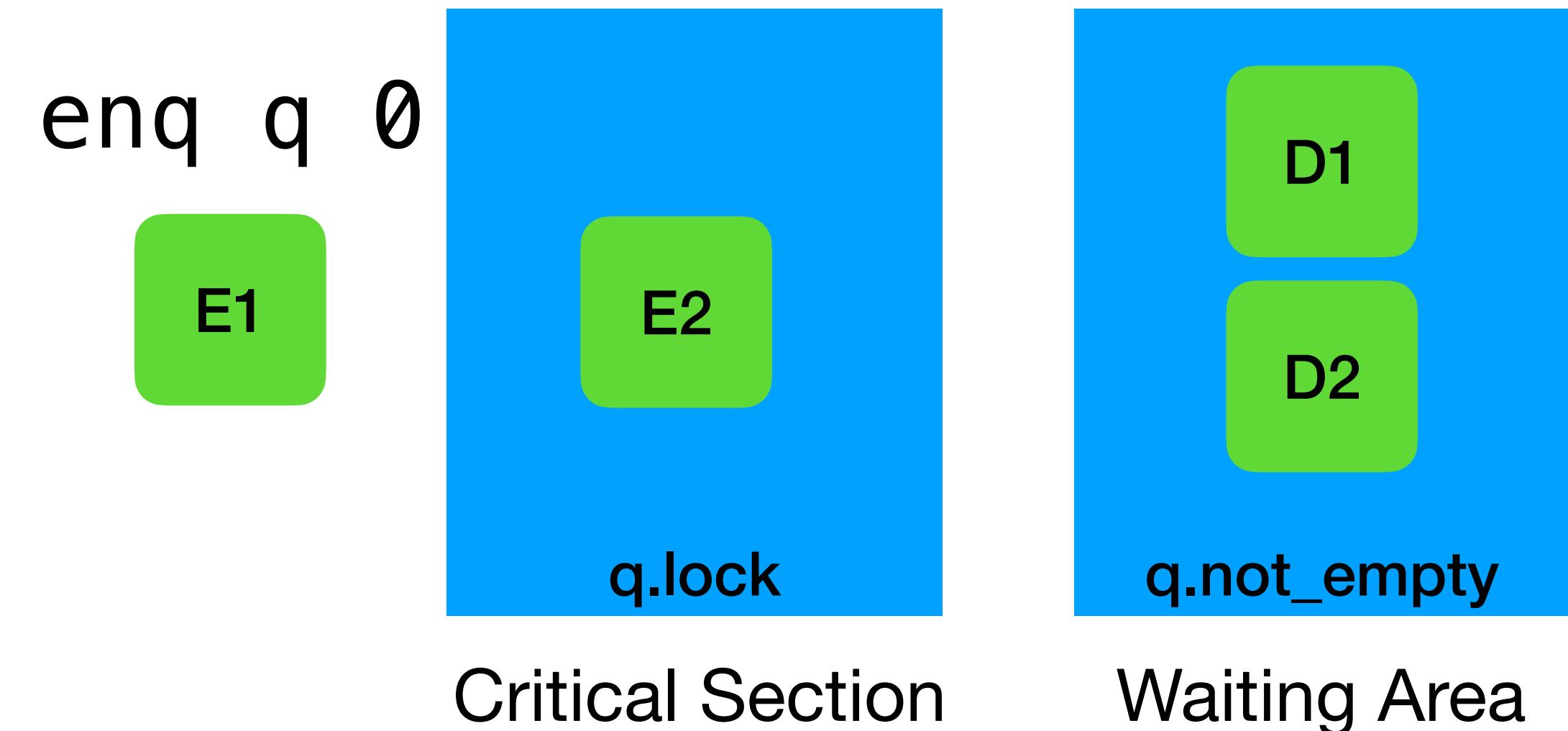
Waiting Area

enq q 1

Subtleties – Lost-wakeup Problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in
      (* Add element *)
      q.items.(q.tail mod q.capacity) <- Some x;
      q.tail <- q.tail + 1;
    (* Signal that queue is not empty *)
    if must_signal then
      Condition.signal q.not_empty)
```

$q = [0; 1]$

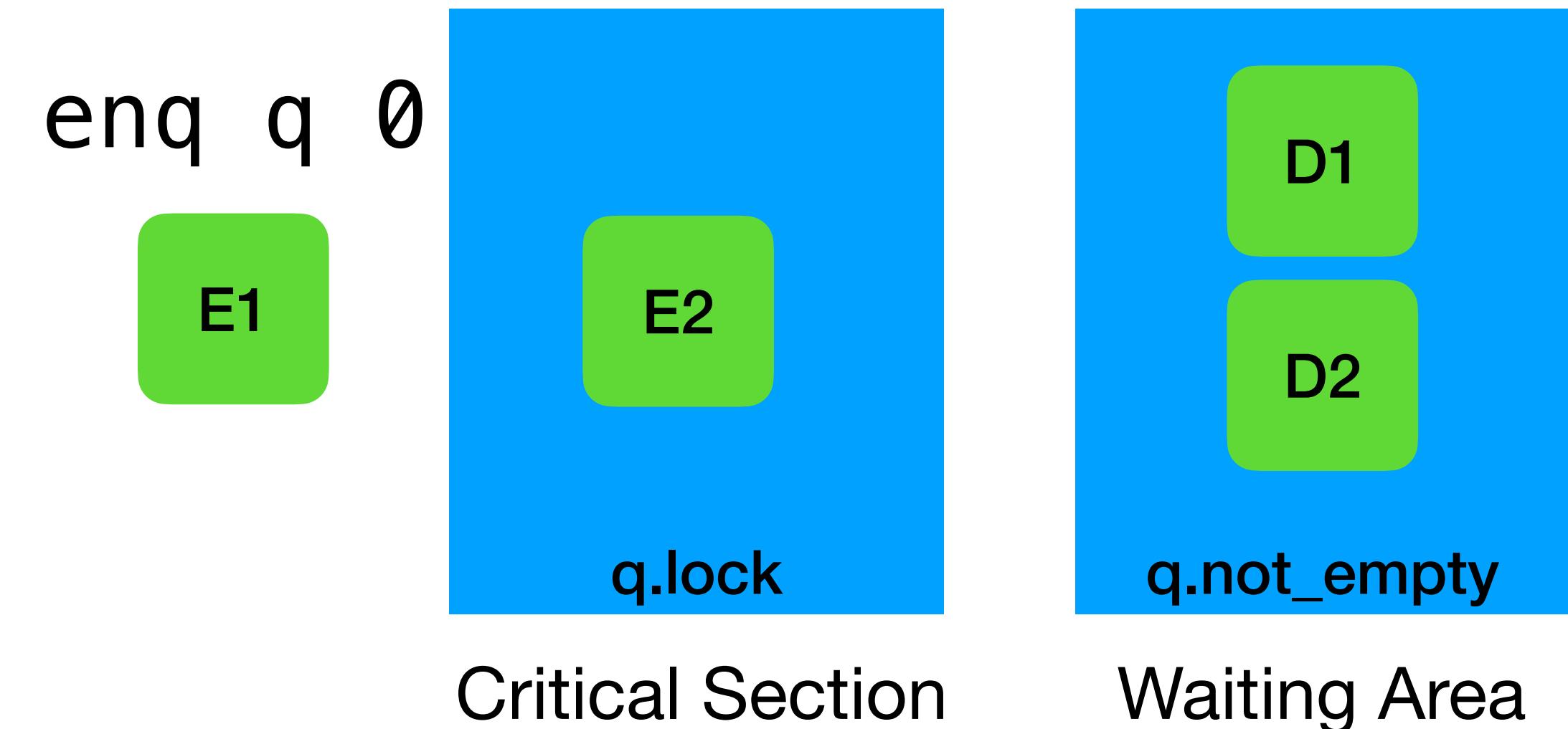


enq q 1

Subtleties – Lost-wakeup Problem

```
let enq q x =  
  Mutex.lock q.lock;  
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)  
  (fun () ->  
    (* Wait while queue is full *)  
    while q.tail - q.head = q.capacity do  
      Condition.wait q.not_full q.lock  
    done;  
    (* If queue is empty, we signal *)  
    let must_signal = q.tail = q.head in  
      (* Add element *)  
      q.items.(q.tail mod q.capacity) <- Some x;  
      q.tail <- q.tail + 1;  
  
    (* Signal that queue is not empty *)  
    if must_signal then  
      Condition.signal q.not_empty)
```

q = [0;1]

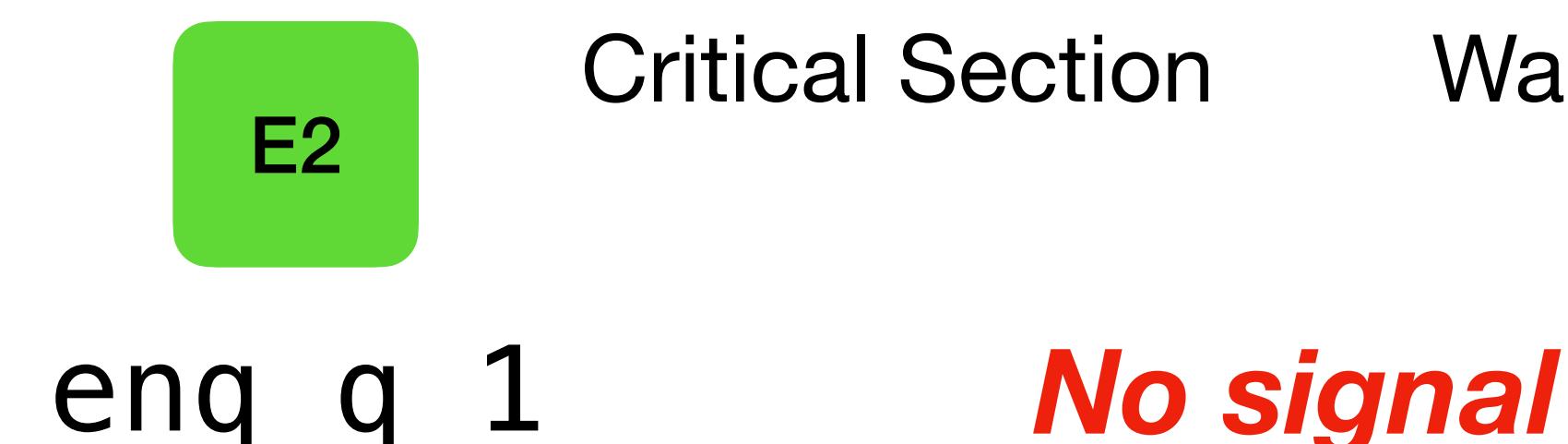
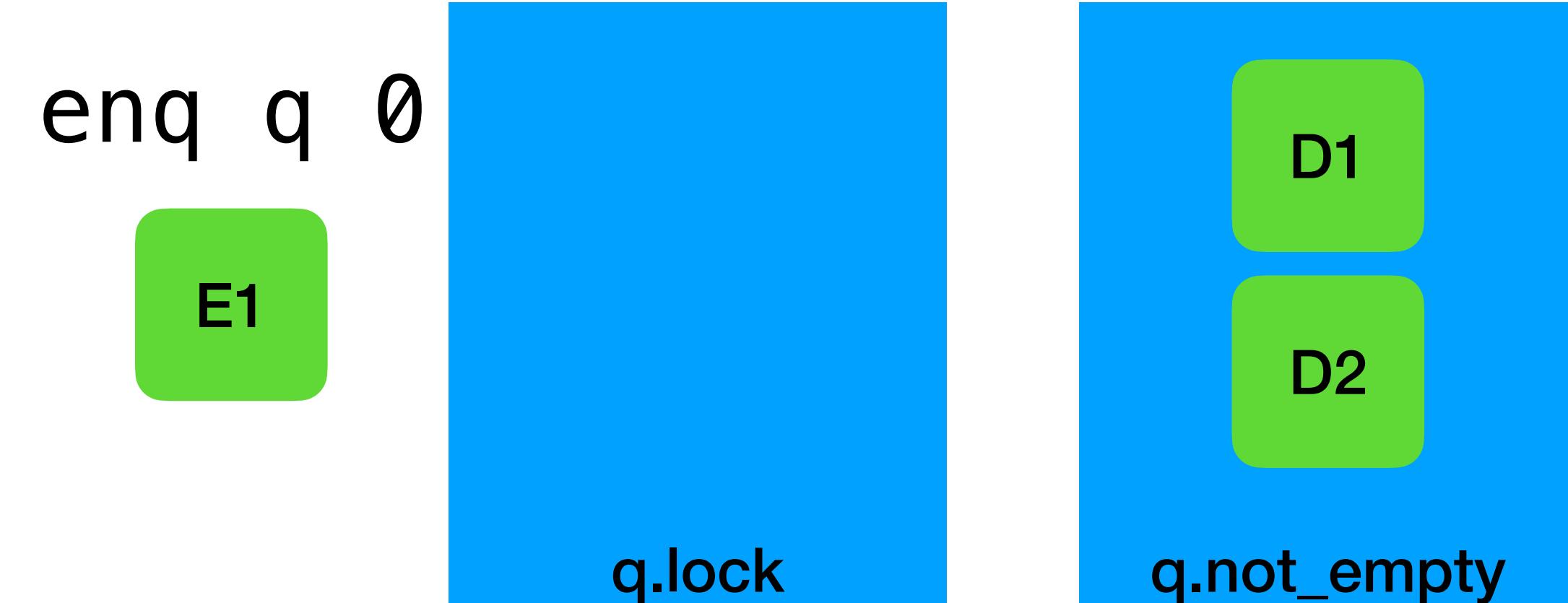


enq q 1 **No signal**

Subtleties – Lost-wakeup Problem

```
let enq q x =  
  Mutex.lock q.lock;  
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)  
  (fun () ->  
    (* Wait while queue is full *)  
    while q.tail - q.head = q.capacity do  
      Condition.wait q.not_full q.lock  
    done;  
    (* If queue is empty, we signal *)  
    let must_signal = q.tail = q.head in  
      (* Add element *)  
      q.items.(q.tail mod q.capacity) <- Some x;  
      q.tail <- q.tail + 1;  
  
    (* Signal that queue is not empty *)  
    if must_signal then  
      Condition.signal q.not_empty)
```

$q = [0; 1]$

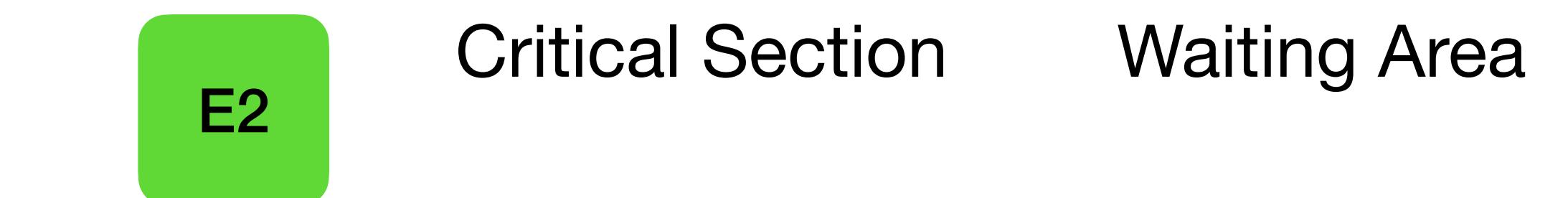
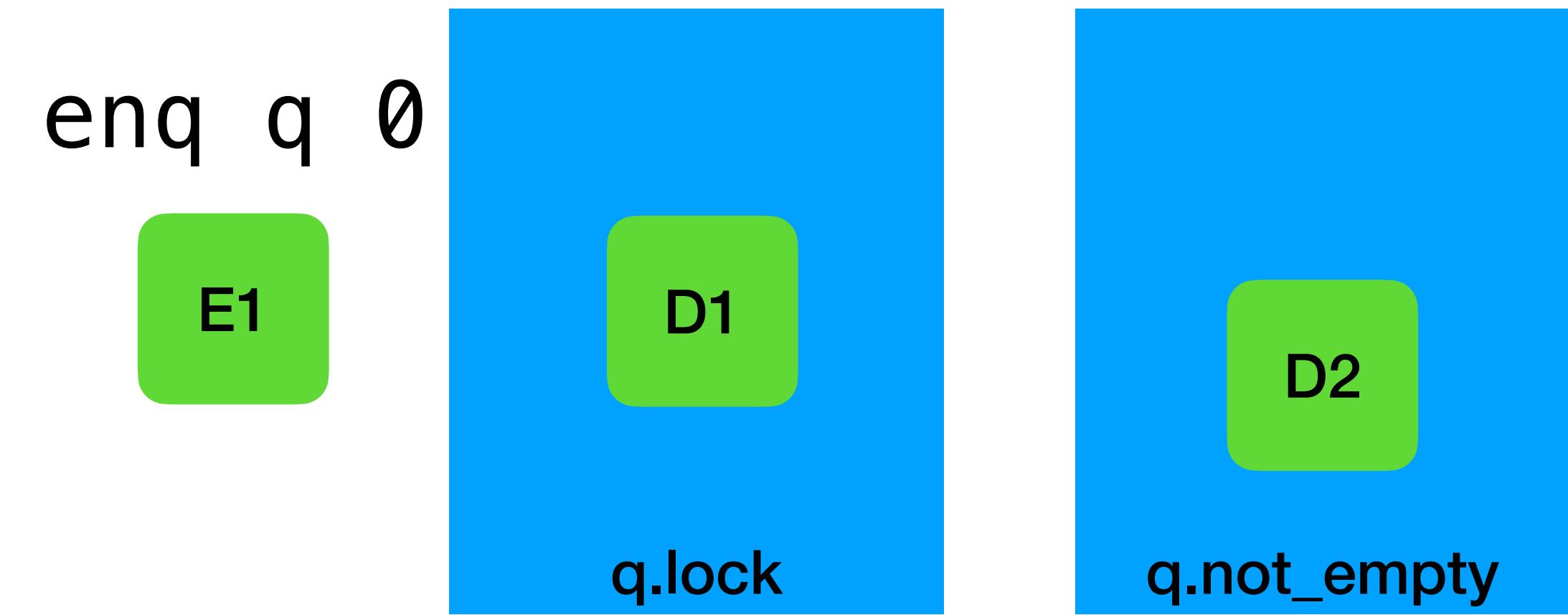


No signal

Subtleties – Lost-wakeup Problem

```
let enq q x =  
  Mutex.lock q.lock;  
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)  
  (fun () ->  
    (* Wait while queue is full *)  
    while q.tail - q.head = q.capacity do  
      Condition.wait q.not_full q.lock  
    done;  
    (* If queue is empty, we signal *)  
    let must_signal = q.tail = q.head in  
      (* Add element *)  
      q.items.(q.tail mod q.capacity) <- Some x;  
      q.tail <- q.tail + 1;  
  
    (* Signal that queue is not empty *)  
    if must_signal then  
      Condition.signal q.not_empty)
```

q = [0;1]



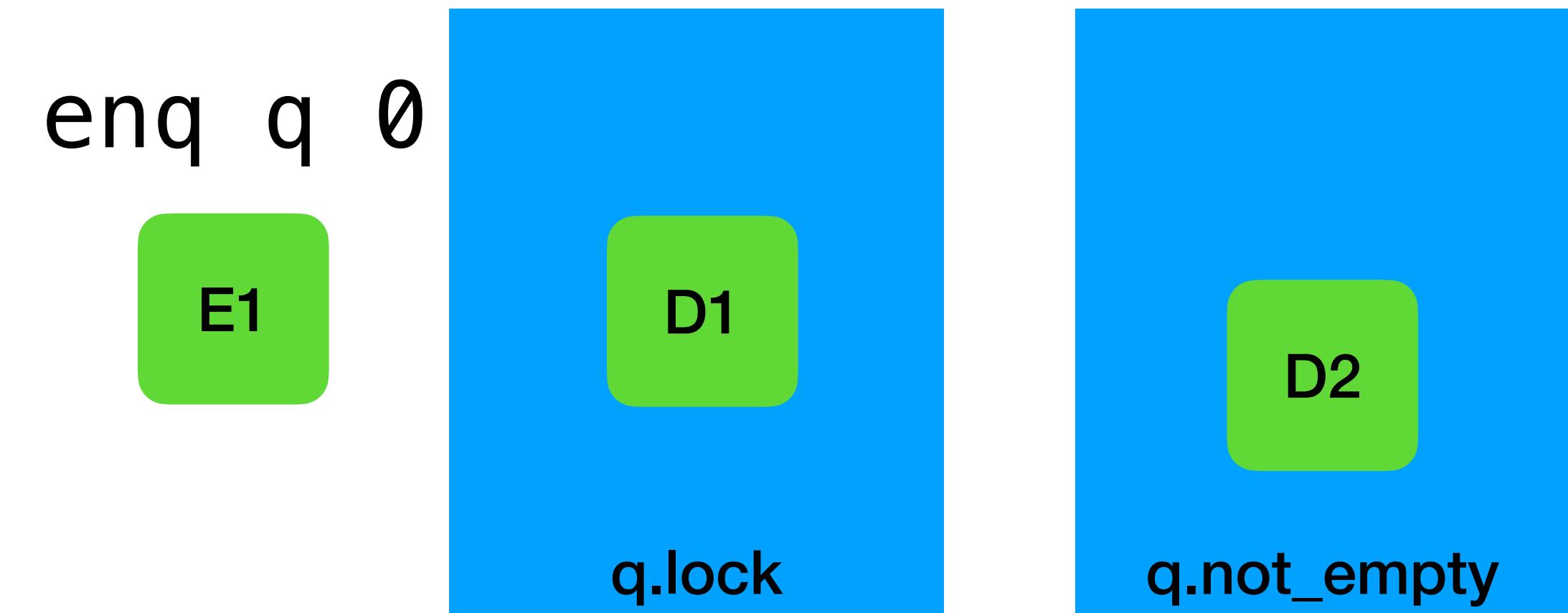
enq q 1

No signal

Subtleties – Lost-wakeup Problem

```
let enq q x =  
  Mutex.lock q.lock;  
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)  
  (fun () ->  
    (* Wait while queue is full *)  
    while q.tail - q.head = q.capacity do  
      Condition.wait q.not_full q.lock  
    done;  
    (* If queue is empty, we signal *)  
    let must_signal = q.tail = q.head in  
      (* Add element *)  
      q.items.(q.tail mod q.capacity) <- Some x;  
      q.tail <- q.tail + 1;  
  
    (* Signal that queue is not empty *)  
    if must_signal then  
      Condition.signal q.not_empty)
```

q = [1]



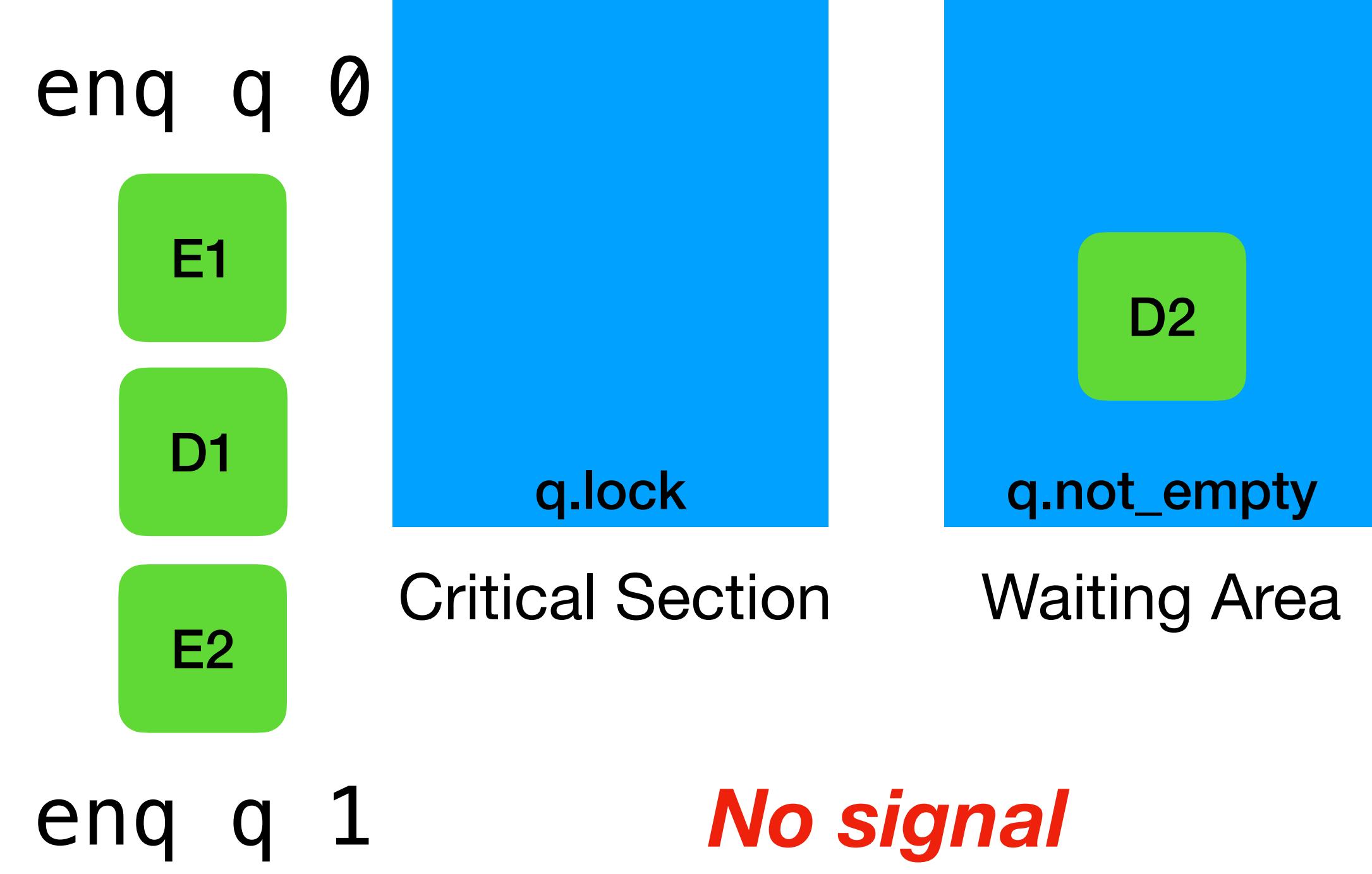
enq q 1

No signal

Subtleties – Lost-wakeup Problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in
    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;
    (* Signal that queue is not empty *)
    if must_signal then
      Condition.signal q.not_empty)
```

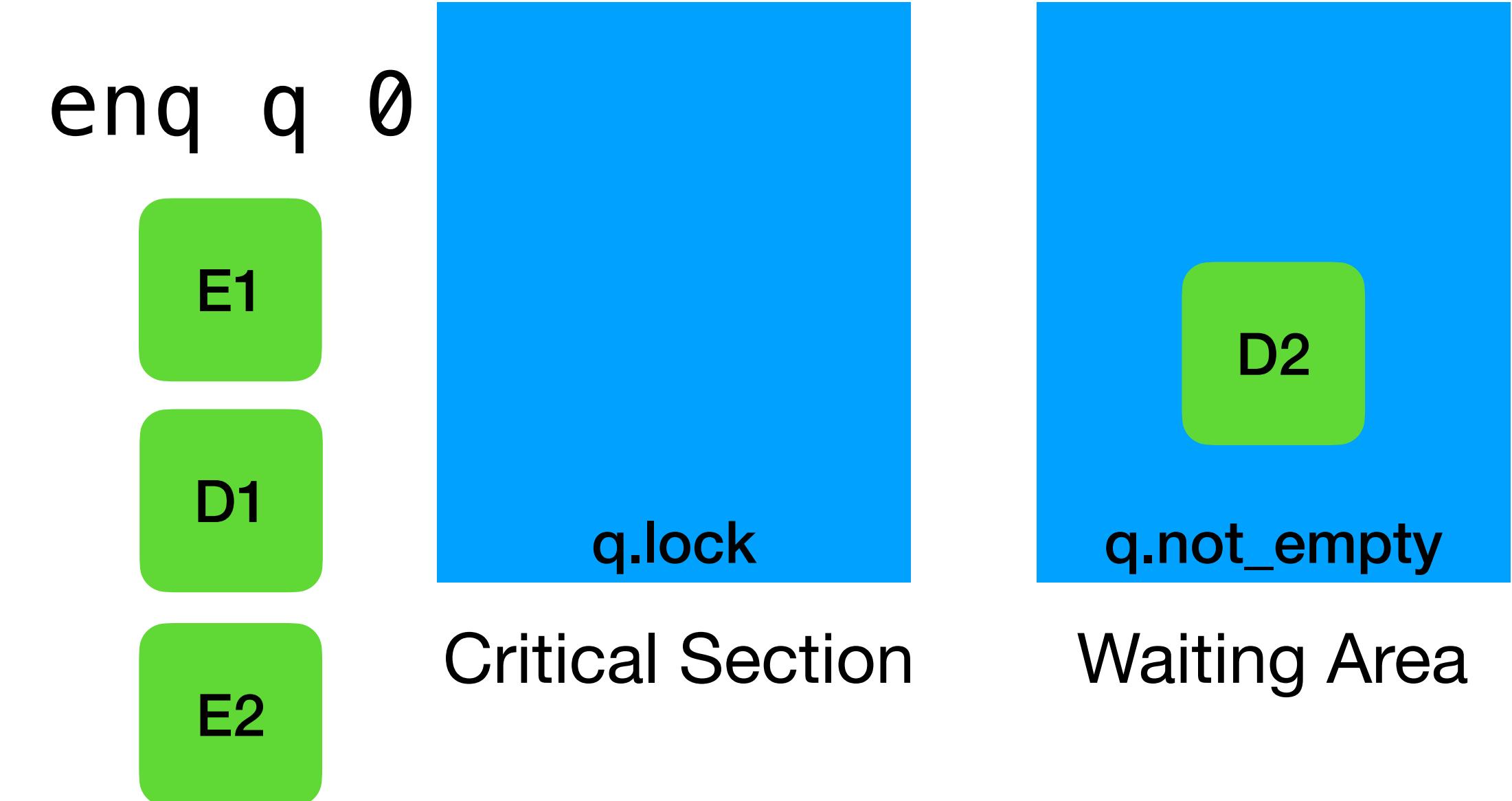
q = [1]



Subtleties – Lost-wakeup Problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in
    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;
    (* Signal that queue is not empty *)
    if must_signal then
      Condition.signal q.not_empty)
```

q = [1]



enq q 1

No signal

**D2 still waiting even though
the queue is non empty**

Avoiding Lost wakeup problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;

    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;

    (* Signal that queue is not empty *)
    Condition.signal q.not_empty)
```

Signal all the time

Avoiding Lost wakeup problem

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;

    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;

    (* Signal that queue is not empty *)
    Condition.signal q.not_empty)
```

```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;

    (* If queue is empty, we signal *)
    let must_signal = q.tail = q.head in

    (* Add element *)
    q.items.(q.tail mod q.capacity) <- Some x;
    q.tail <- q.tail + 1;

    (* Signal that queue is not empty *)
    if must_signal then
      Condition.broadcast q.not_empty)
```

Signal all the time

Signal all the waiters when transitioning

Readers–Writers Locks

- Common pattern – *Read* shared resource frequently, but *modify* rarely
- Read-write Lock Invariant
 - Can't get write lock when read or write lock is held
 - Can't get read lock when write lock is held
- *Multiple readers can concurrently hold the lock!*
- **Note:** 1st edition of the AMP book has the wrong algorithm for read-write locks
 - 2nd edition has the right algorithm

Simple Read-write Lock

```
type t

val create : unit -> t

val read_lock : t -> unit
val read_unlock : t -> unit

val write_lock : t -> unit
val write_unlock : t -> unit
```

Simple Read-write Lock

```
type t  
  
val create : unit -> t  
  
val read_lock : t -> unit  
val read_unlock : t -> unit  
  
val write_lock : t -> unit  
val write_unlock : t -> unit
```

```
type t = {  
    mutable readers : int; (* Current number of active readers *)  
    mutable writer : bool; (* Is a writer active? *)  
    lock : Mutex.t;  
    condition : Condition.t;  
}  
  
let create () = {  
    readers = 0;  
    writer = false;  
    lock = Mutex.create ();  
    condition = Condition.create ();  
}
```

Simple Read-write Lock

Simple Read-write Lock

```
let read_lock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Wait while a writer is active *)
    while rwlock.writer do
      Condition.wait rwlock.condition rwlock.lock
    done;
    (* Increment reader count *)
    rwlock.readers <- rwlock.readers + 1

let read_unlock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Decrement reader count *)
    rwlock.readers <- rwlock.readers - 1;
    (* If no more readers, wake up all waiting threads *)
    if rwlock.readers = 0 then
      Condition.broadcast rwlock.condition
```

Simple Read-write Lock

Simple Read-write Lock

```
let write_lock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Wait while readers are active OR another writer is active *)
    while rwlock.readers > 0 || rwlock.writer do
      Condition.wait rwlock.condition rwlock.lock
    done;
    (* Mark writer as active *)
    rwlock.writer <- true

let write_unlock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Clear writer flag *)
    rwlock.writer <- false;
    (* Wake up all waiting threads (readers and writers) *)
    Condition.broadcast rwlock.condition
```

Simple Read-write Lock

- Is unfair to writers
 - Can lead to starvation of writers if readers keep coming in

Fair Read-write Locks

```
type t = {
    mutable read_acquires : int; (* Total read locks acquired *)
    mutable read_releases : int; (* Total read locks released *)
    mutable writer : bool;       (* Is a writer active? *)
    lock : Mutex.t;
    condition : Condition.t;
}

let create () = {
    read_acquires = 0;
    read_releases = 0;
    writer = false;
    lock = Mutex.create ();
    condition = Condition.create ();
}
```

Fair Read-write Locks

```
let read_lock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Wait while a writer is active BEFORE incrementing counter *)
    while rwlock.writer do
      Condition.wait rwlock.condition rwlock.lock
    done;
    (* Only now increment acquisition counter *)
    rwlock.read_acquires <- rwlock.read_acquires + 1

let read_unlock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Increment release counter *)
    rwlock.read_releases <- rwlock.read_releases + 1;
    (* If all acquired reads have been released, wake up waiting writers *)
    if rwlock.read_acquires = rwlock.read_releases then
      Condition.broadcast rwlock.condition
```

Fair Read-write Locks

```
let write_lock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Phase 1: Wait for no active writer *)
    while rwlock.writer do
      Condition.wait rwlock.condition rwlock.lock
    done;
    (* Claim writer status to block new readers *)
    rwlock.writer <- true;
    (* Phase 2: Wait for existing readers to drain *)
    while rwlock.read_acquires <> rwlock.read_releases do
      Condition.wait rwlock.condition rwlock.lock
    done

let write_unlock rwlock =
  Mutex.lock rwlock.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock rwlock.lock) @@ fun () ->
    (* Clear writer flag *)
    rwlock.writer <- false;
    (* Wake up all waiting threads *)
    Condition.broadcast rwlock.condition
```

When should we use monitors?

- Monitors are complementary to spin-locks
- Spin-locks are good when the ***expected wait time is small***
- Monitors are good when the ***expected wait time is large***
 - Expensive to context-switch
- OS mutexes already spin for a little while before going to block

Other Synchronisation mechanisms

- **Monitors** are generally the most popular synchronisation mechanism used widely
- A **semaphore** allows at most $n \geq 1$ threads to concurrently be in the critical section
 - Edsger Dijkstra (the same as in Dijkstra's algorithm) in 1963
 - A **Mutex** is a semaphore with $n = 1$

Fin