04 Monitors and Blocking Synchronisation

CS 6868: Concurrent Programming

KC Sivaramakrishnan

Spring 2026, IIT Madras

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)

```
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*

How to wait till there is an element?

Spin-wait

```ocaml
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 ();
  }
```

```ocaml
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)
```

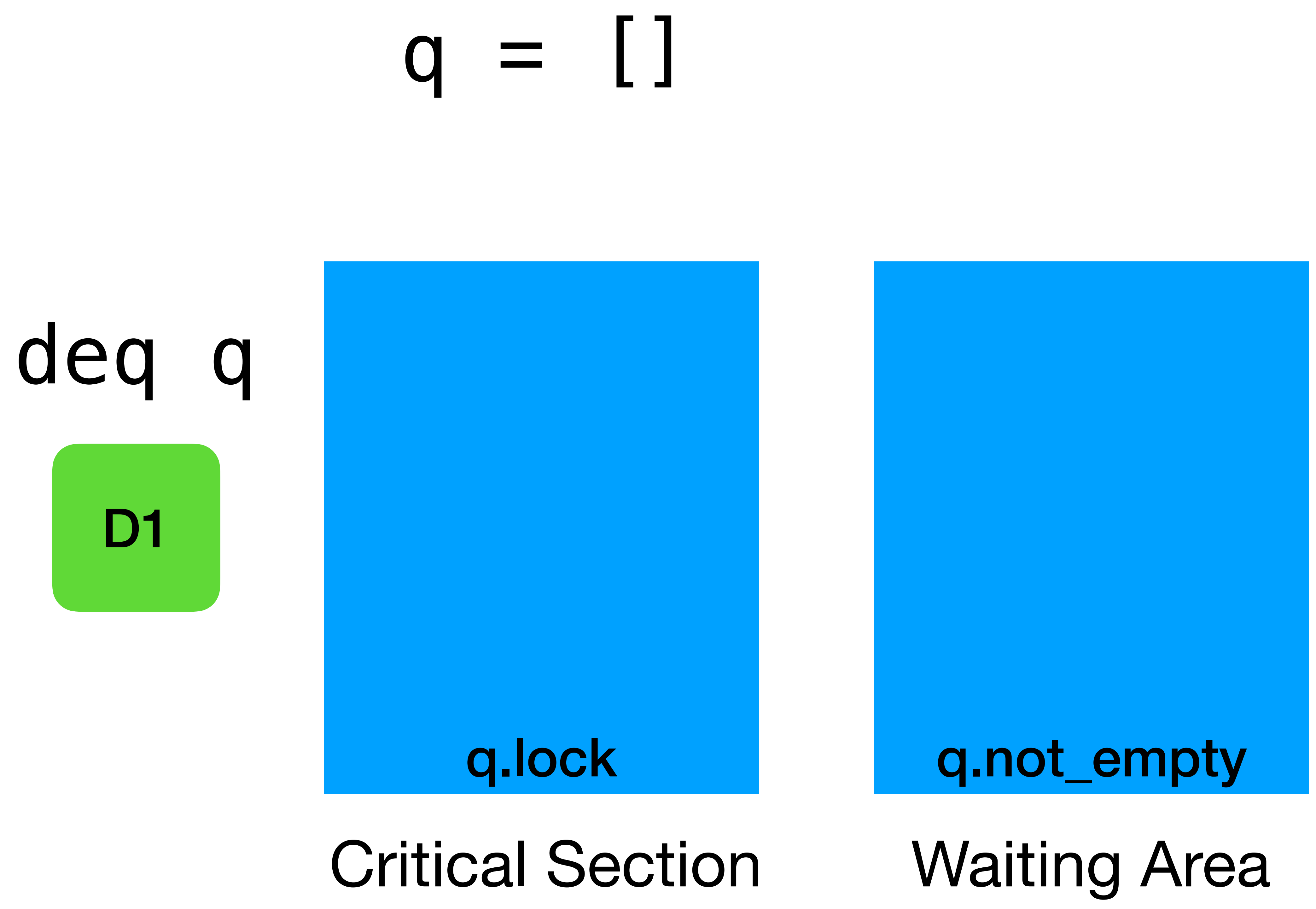
Blocking Queue

```
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)
```

q = []

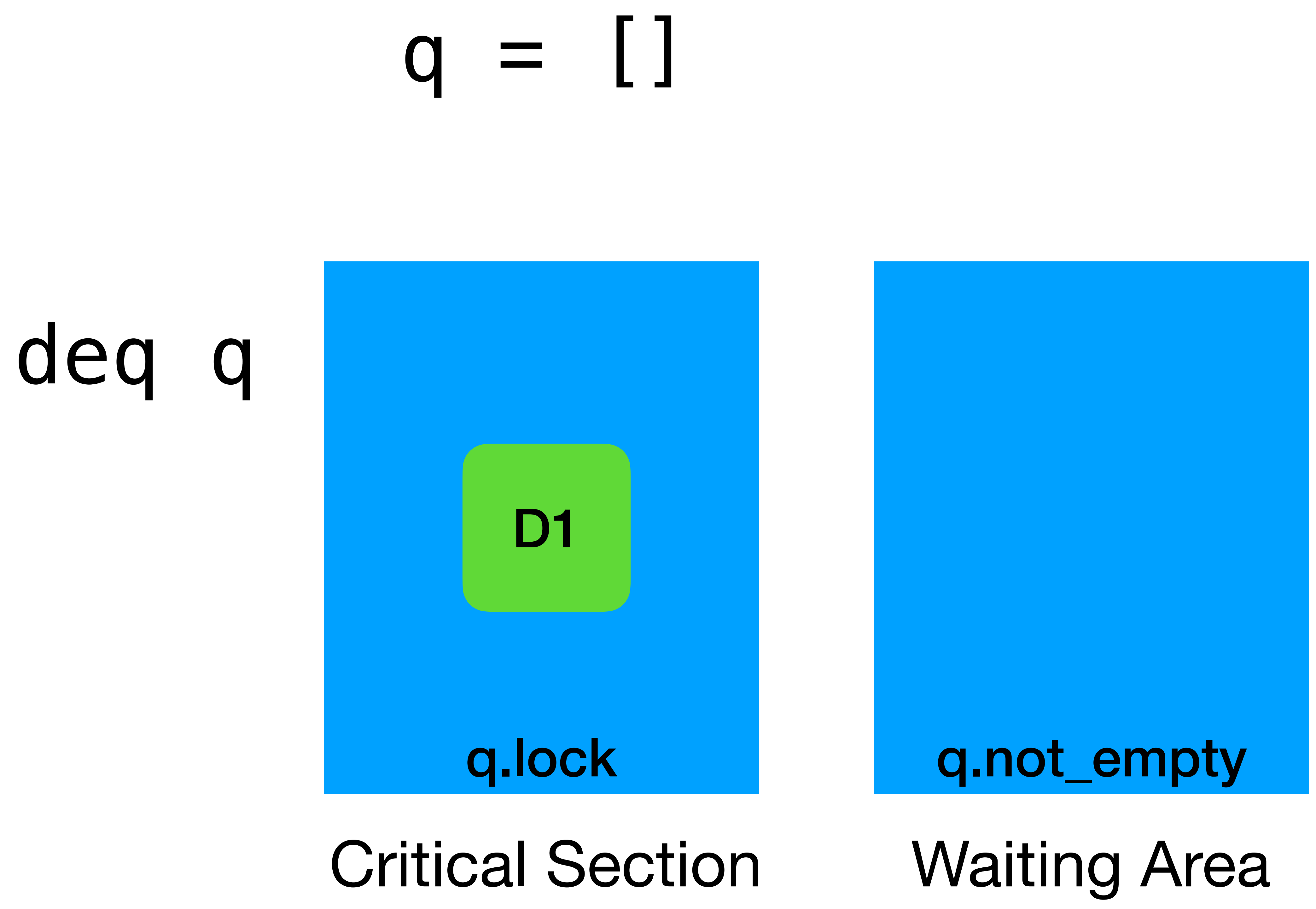
Blocking Queue

```
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)
```



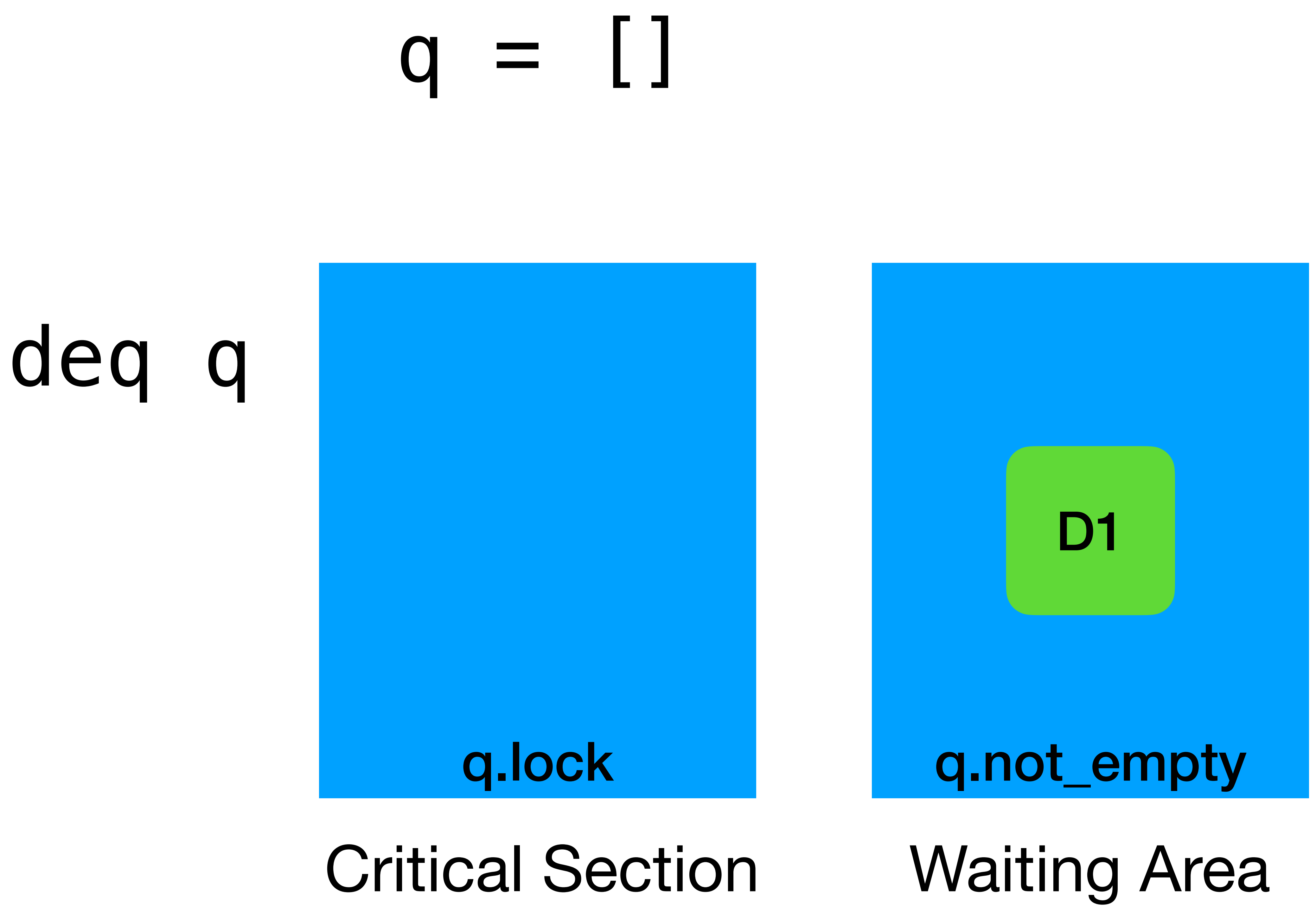
Blocking Queue

```
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)
```



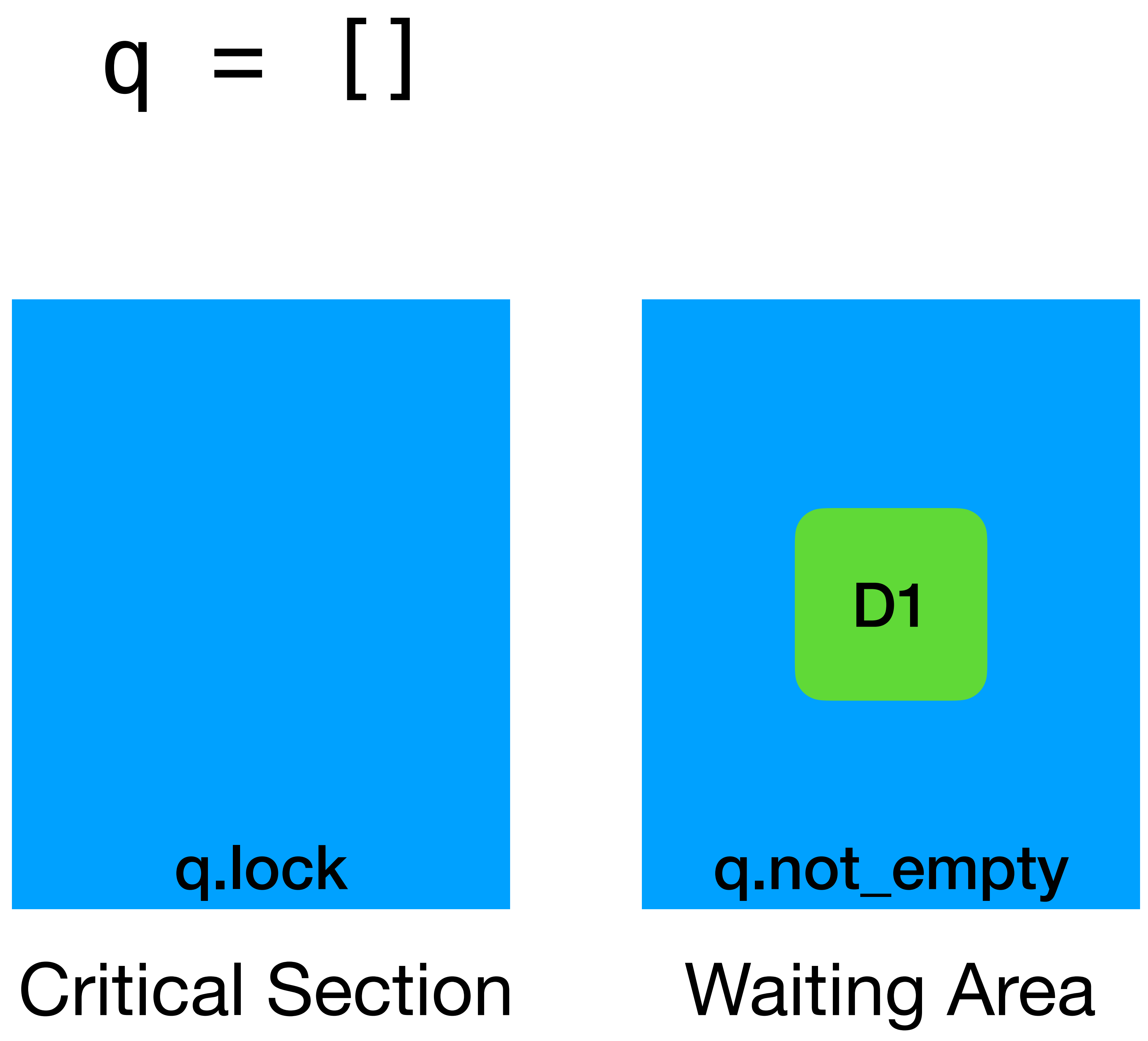
Blocking Queue

```
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)
```



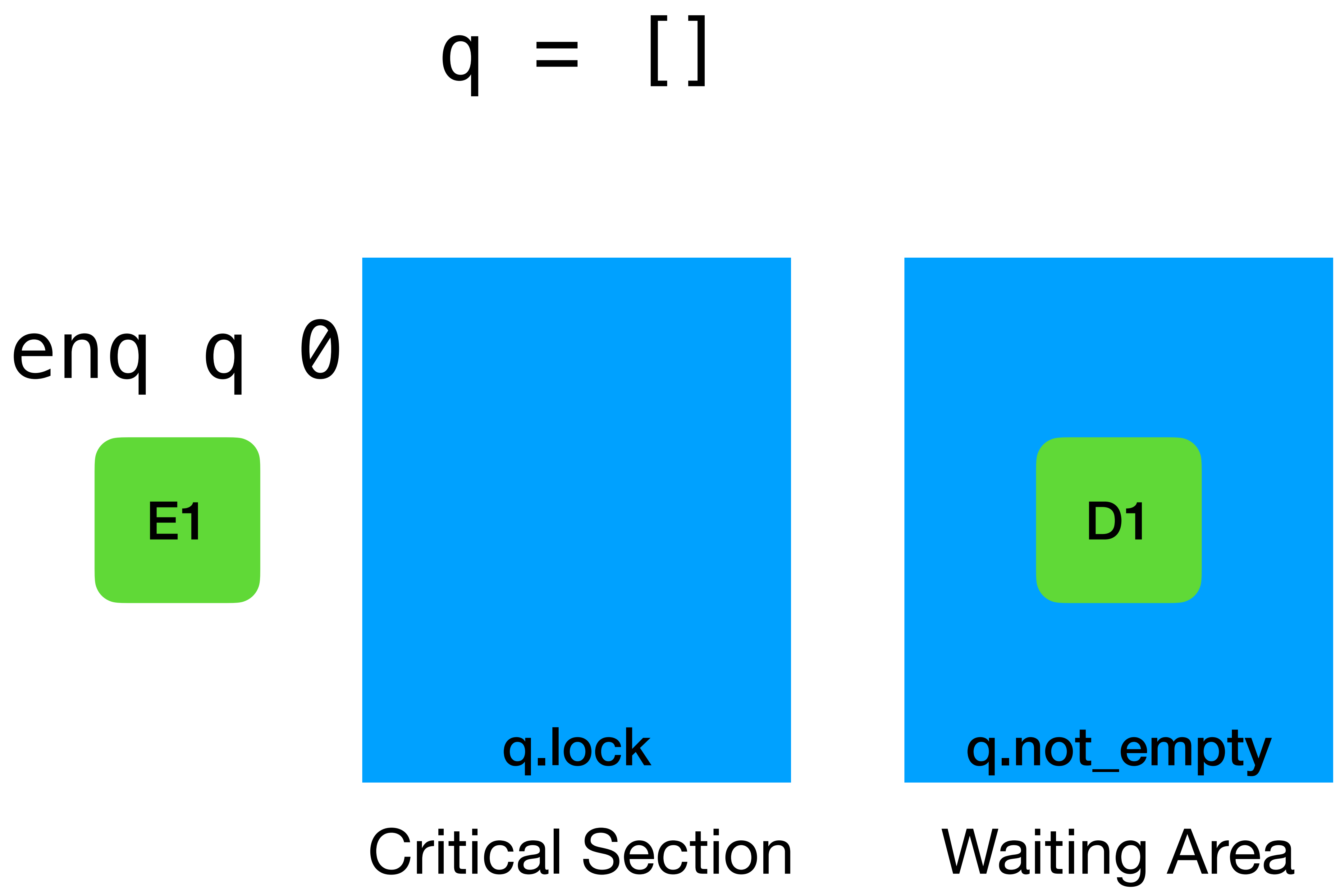
Blocking Queue

```
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)
```



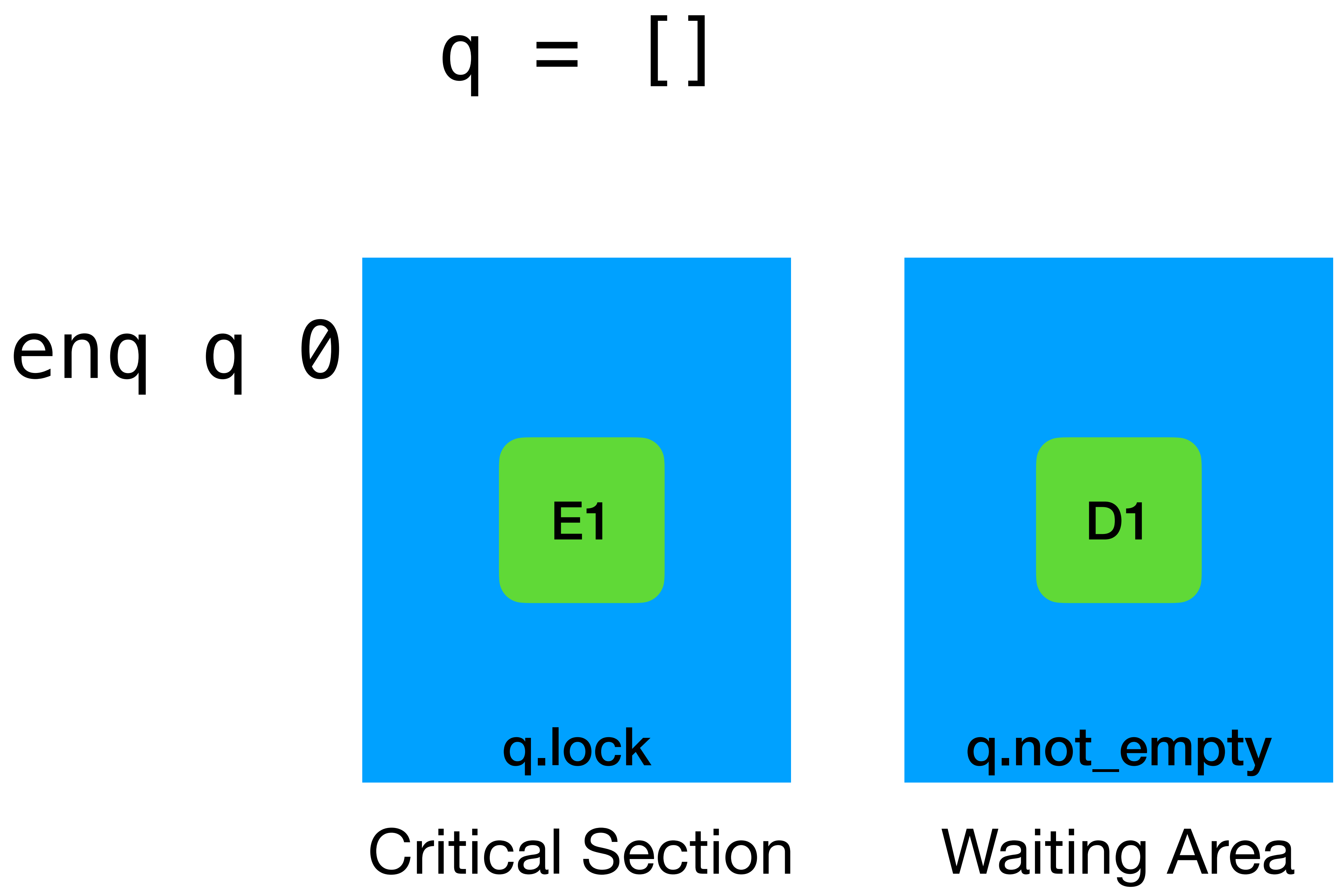
Blocking Queue

```
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)
```



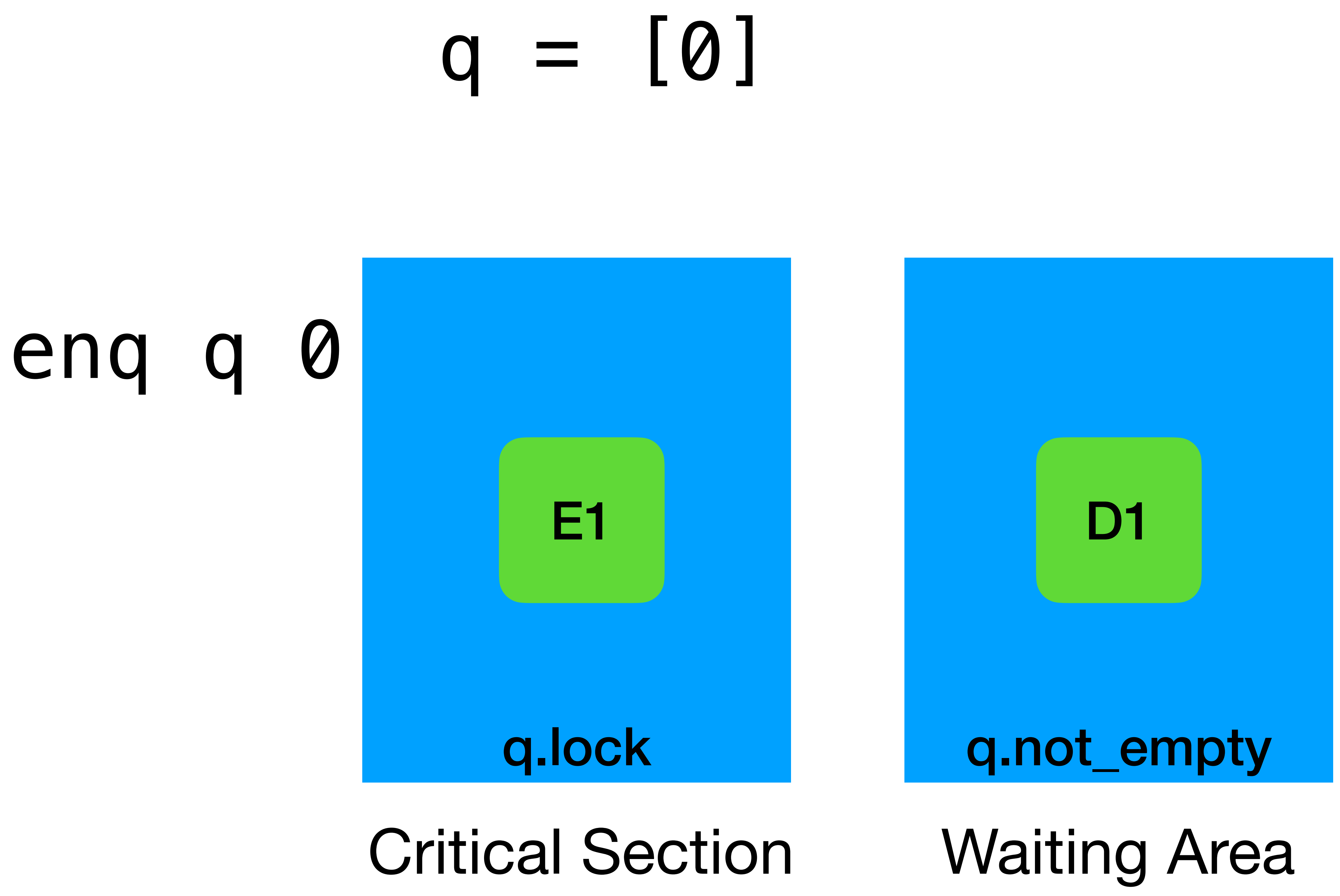
Blocking Queue

```
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)
```



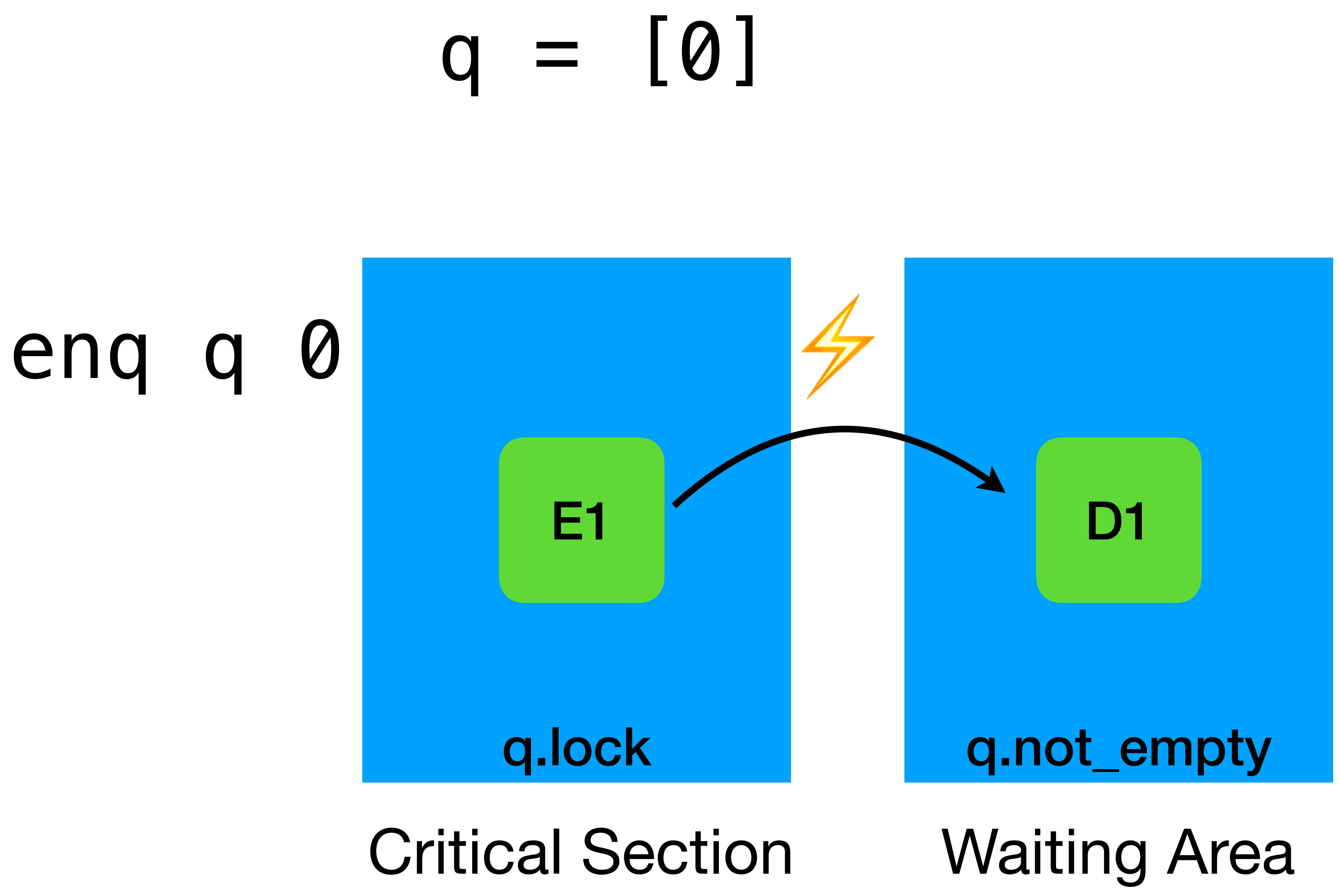
Blocking Queue

```
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)
```



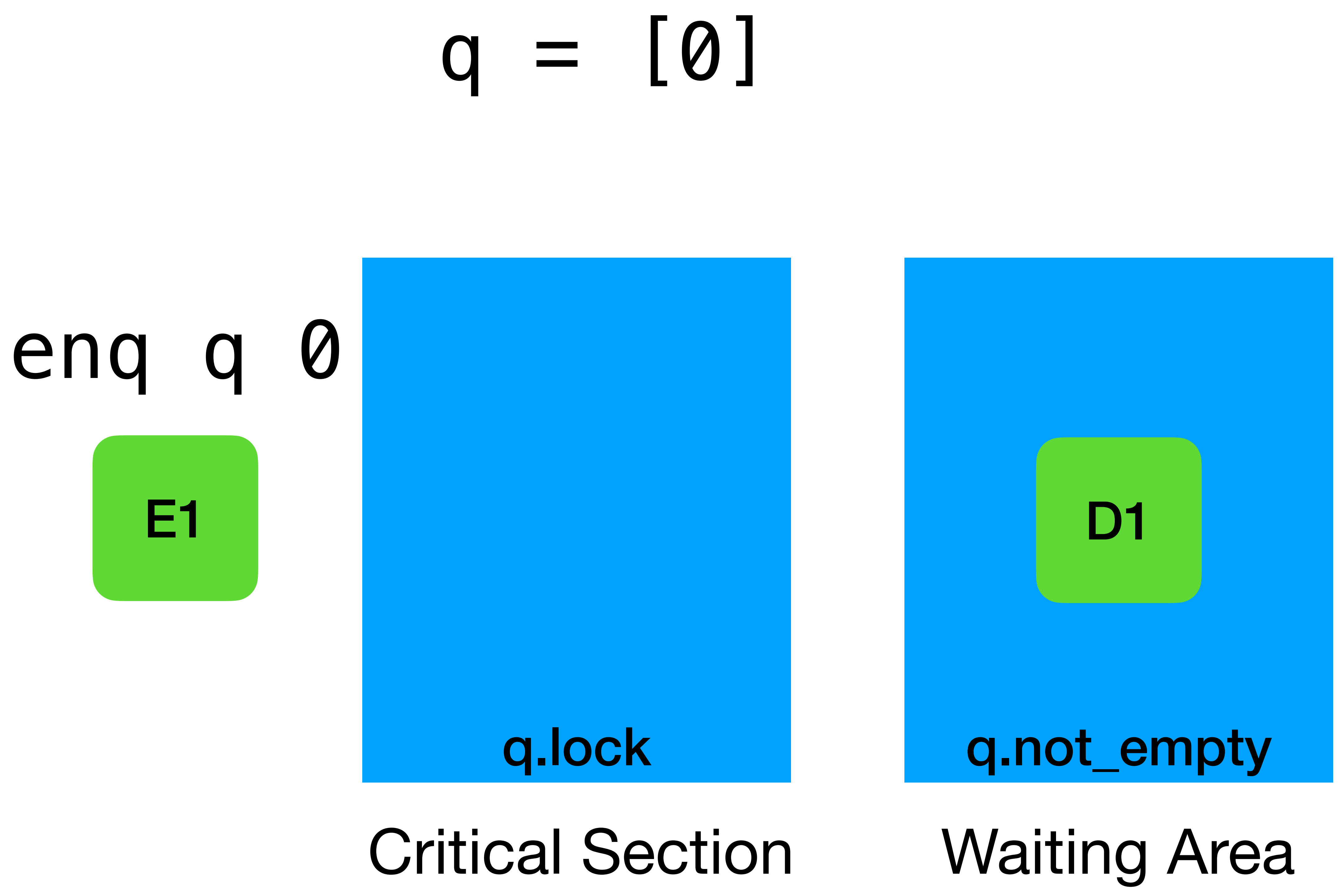
Blocking Queue

```
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)
```



Blocking Queue

```
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)
```



Subtleties — Recheck condition for spurious wakeups

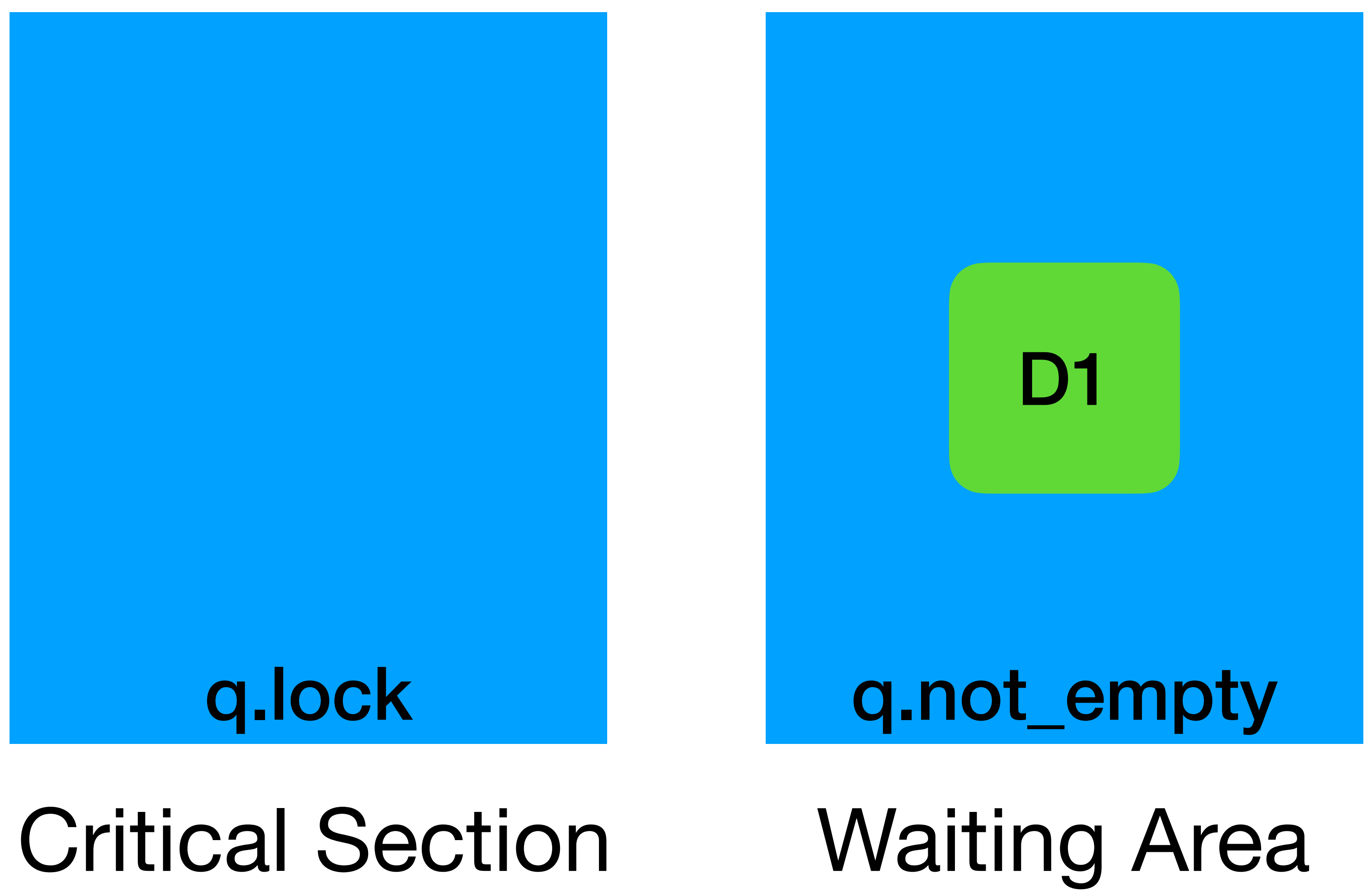
```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;

    (* 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 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)
```

Spurious wakeups possible

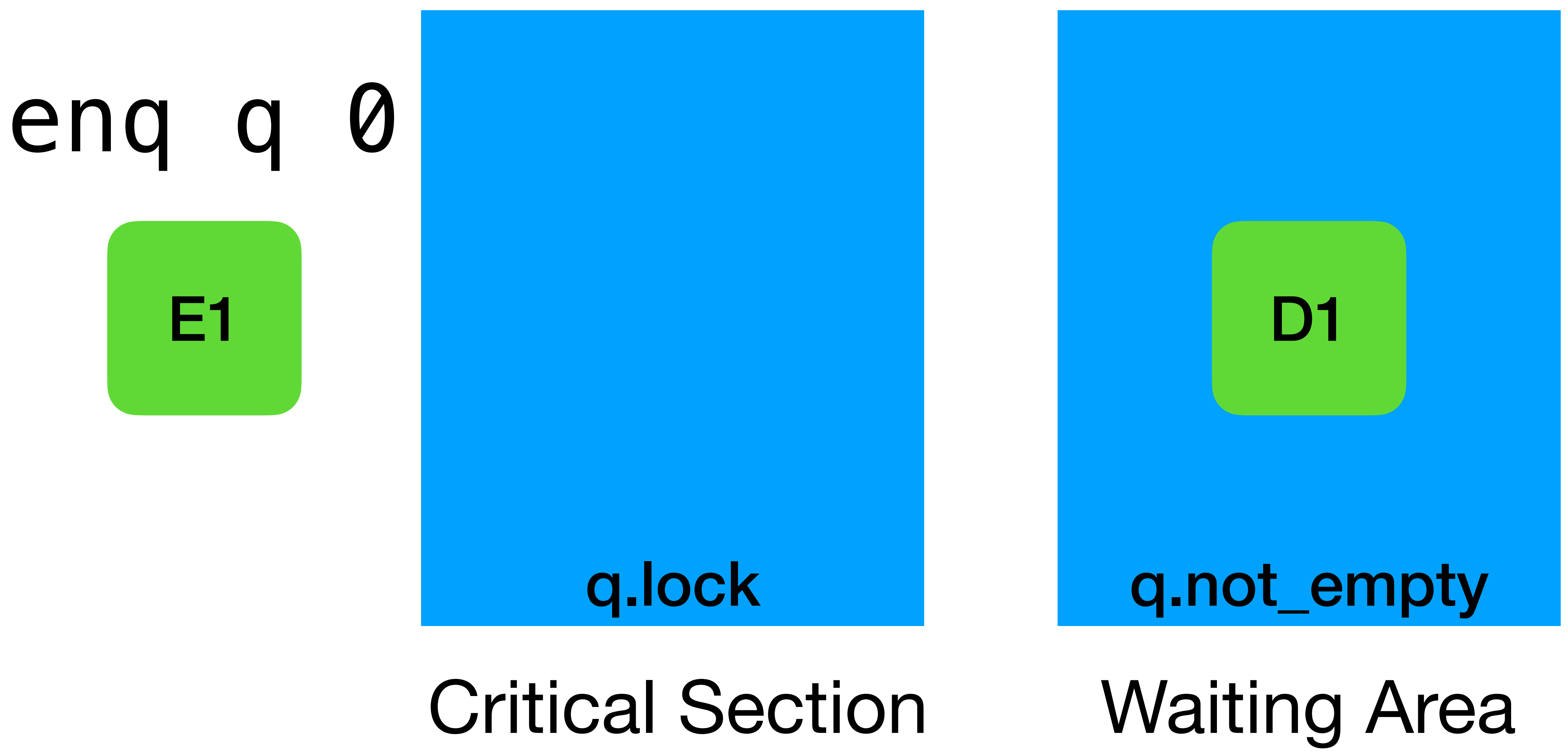
Subtleties — Recheck condition for concurrency

`q = []`



Subtleties — Recheck condition for concurrency

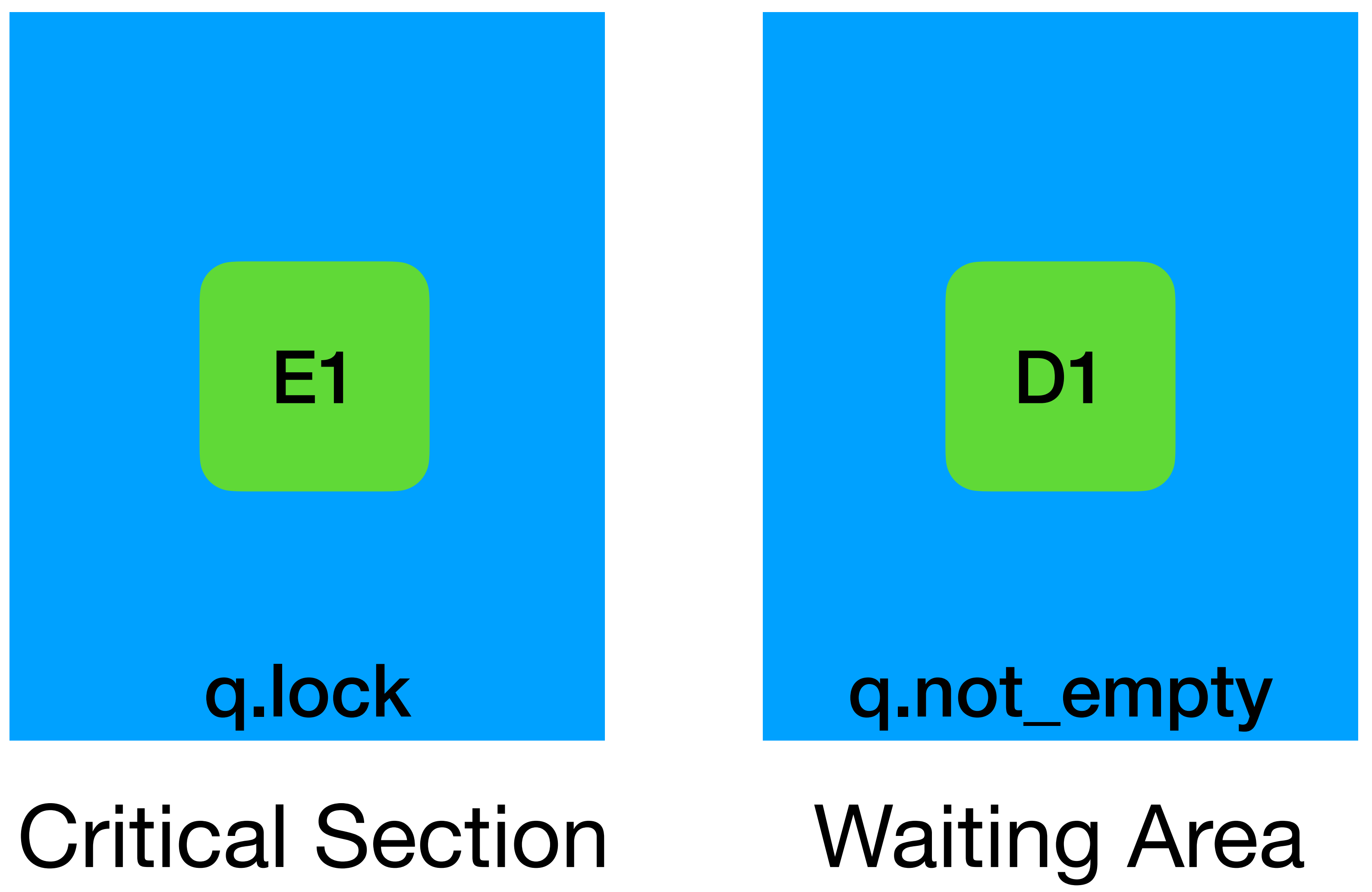
```
q = []
```



Subtleties — Recheck condition for concurrency

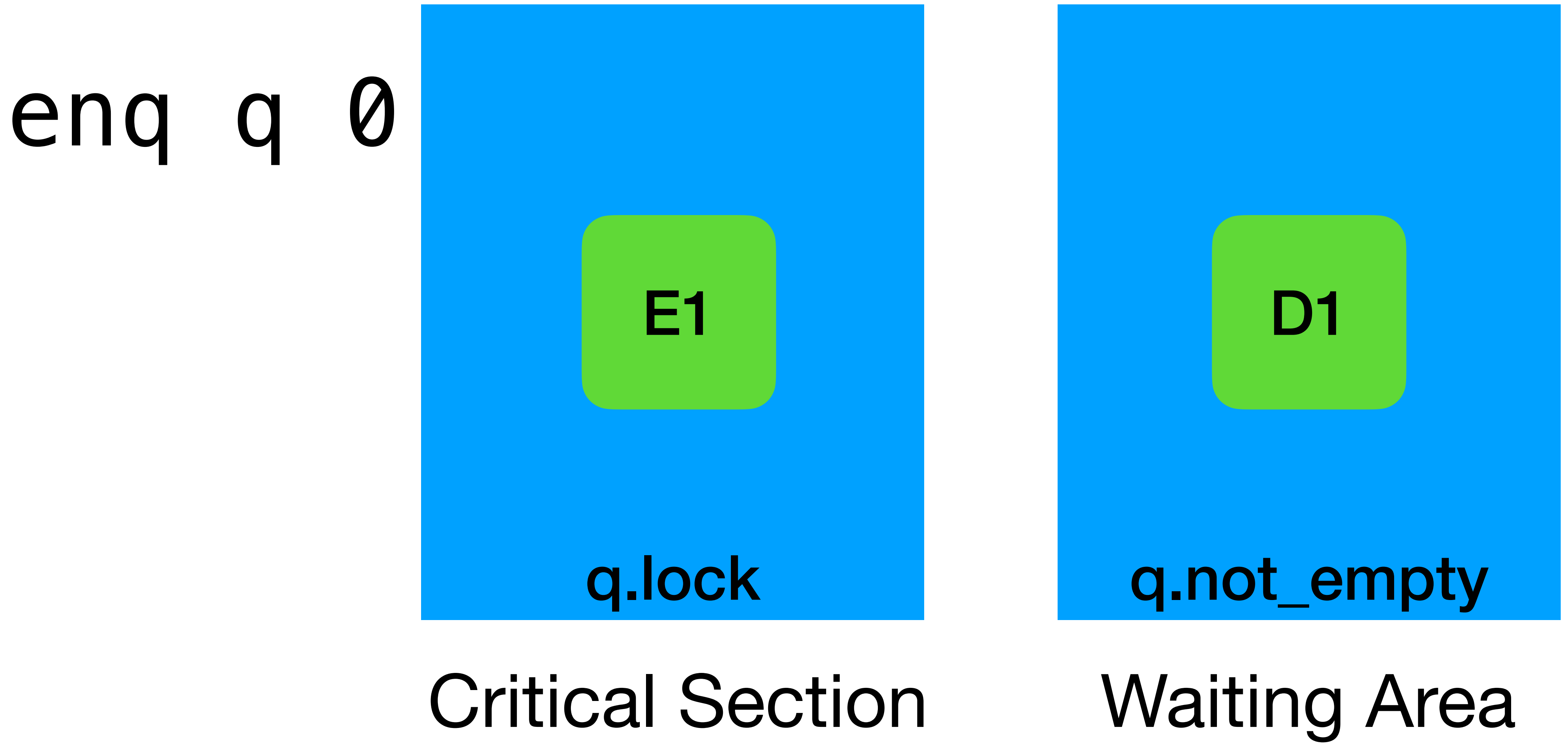
```
q = []
```

```
enq q 0
```



Subtleties — Recheck condition for concurrency

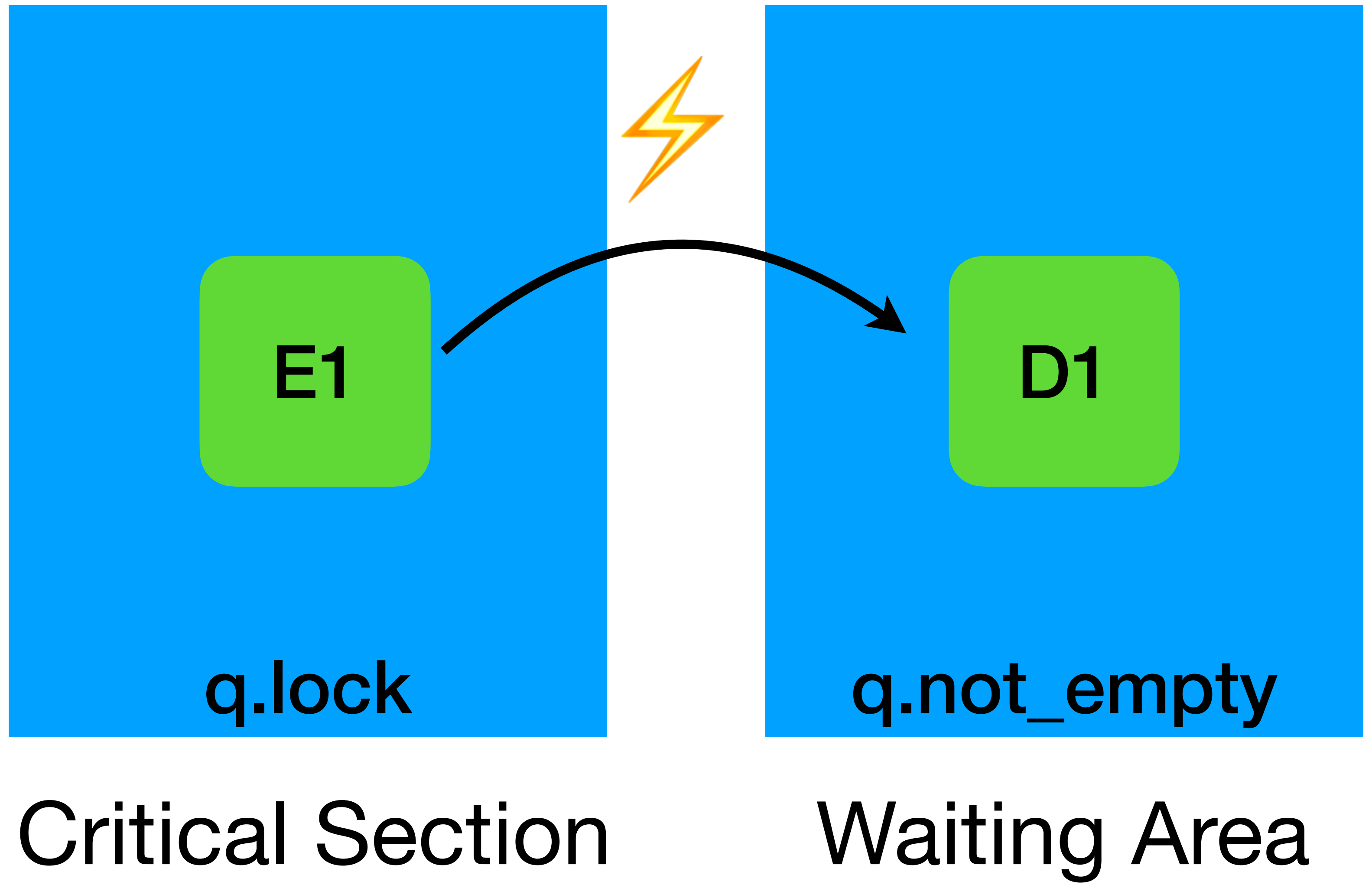
```
q = [0]
```



Subtleties — Recheck condition for concurrency

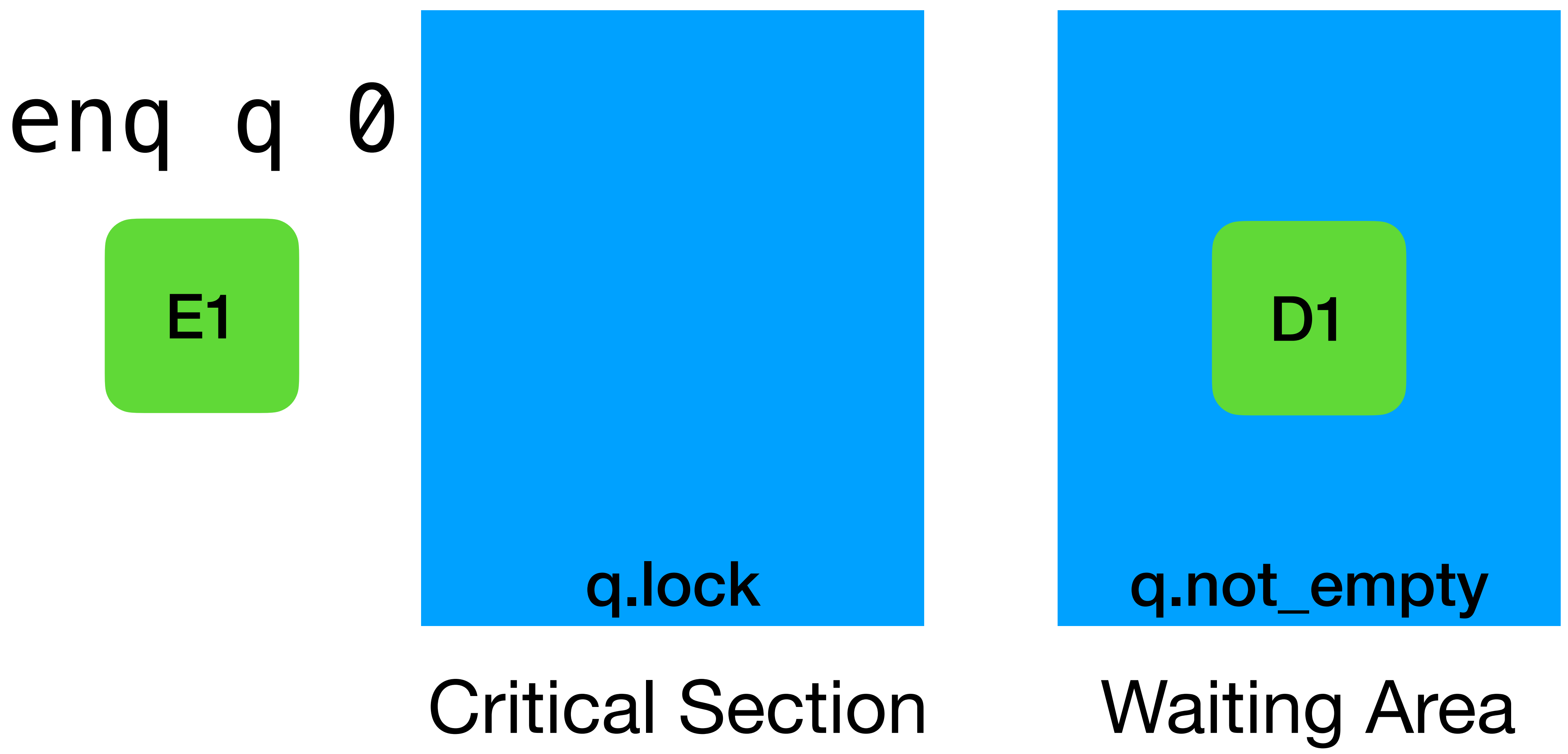
```
q = [0]
```

```
enq q 0
```

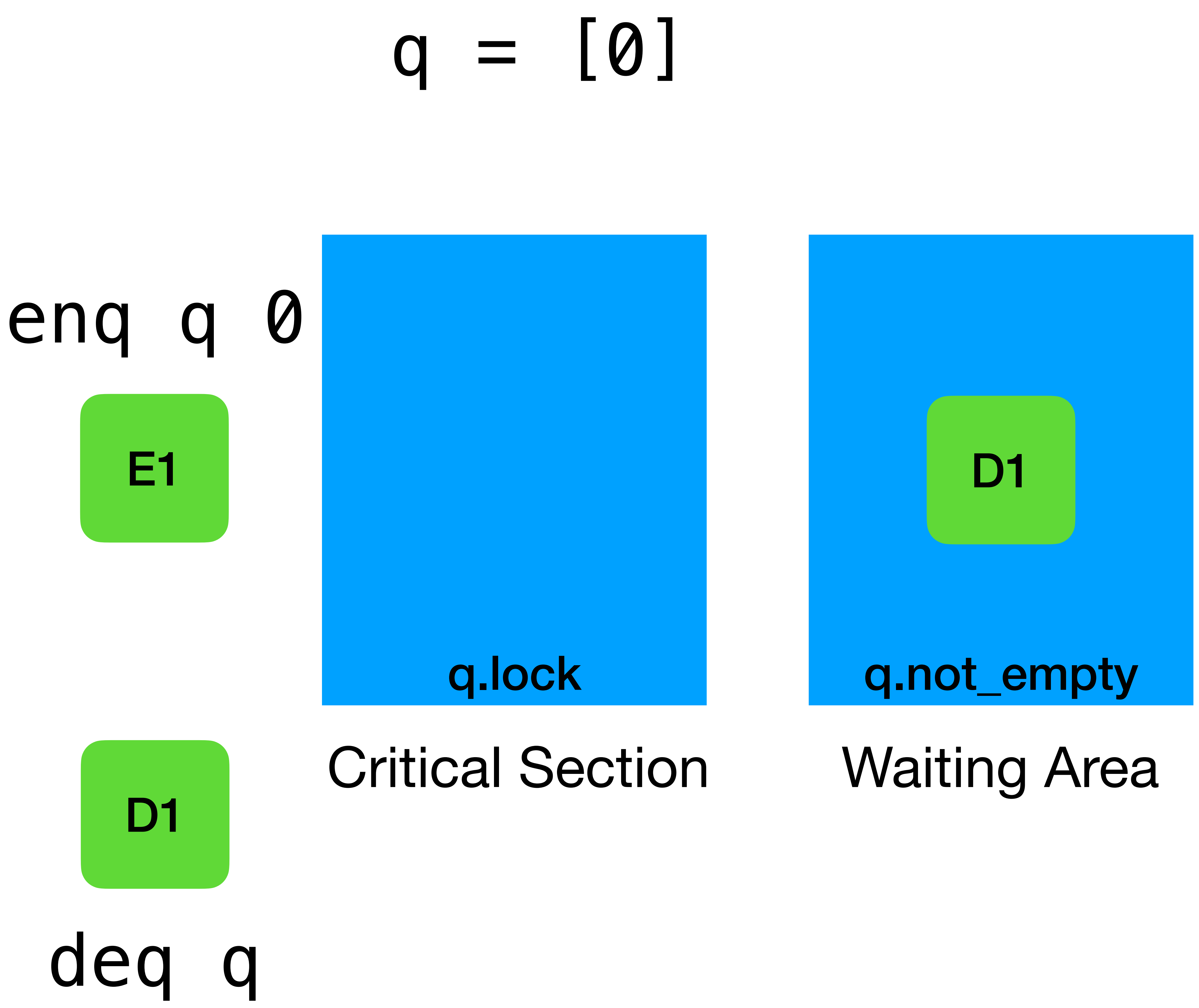


Subtleties — Recheck condition for concurrency

`q = [0]`



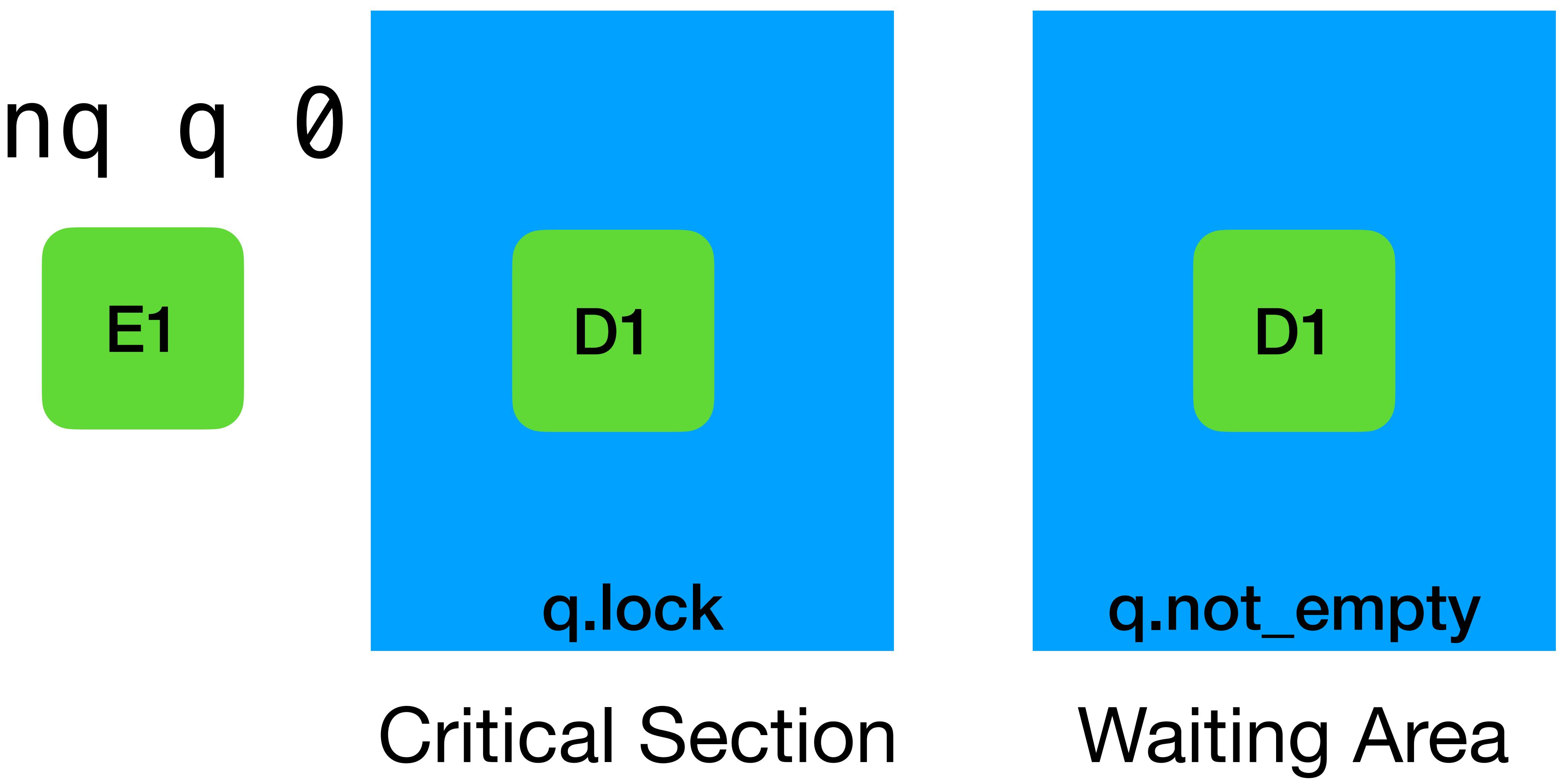
Subtleties — Recheck condition for concurrency



Subtleties — Recheck condition for concurrency

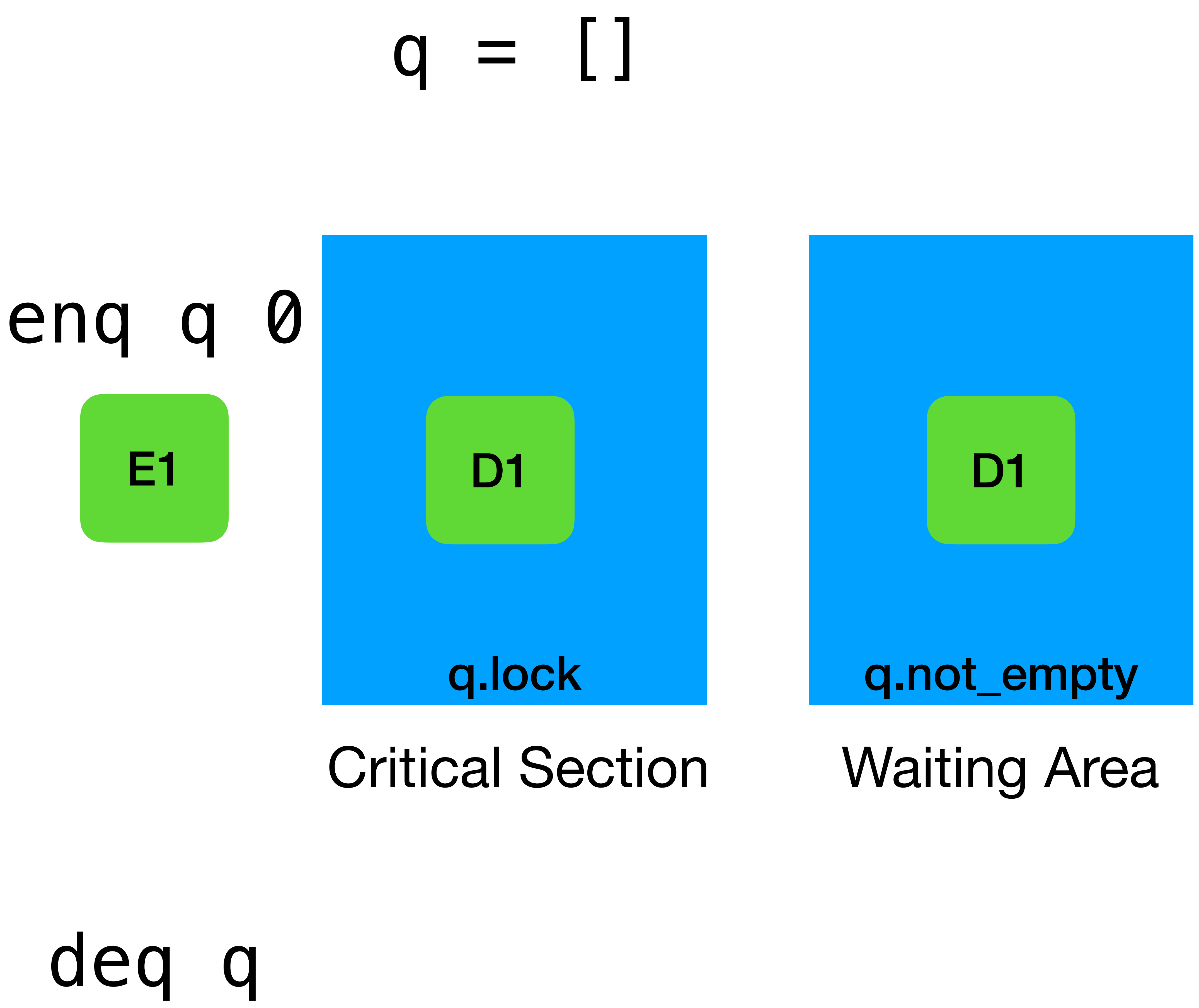
```
q = [0]
```

```
enq q 0
```

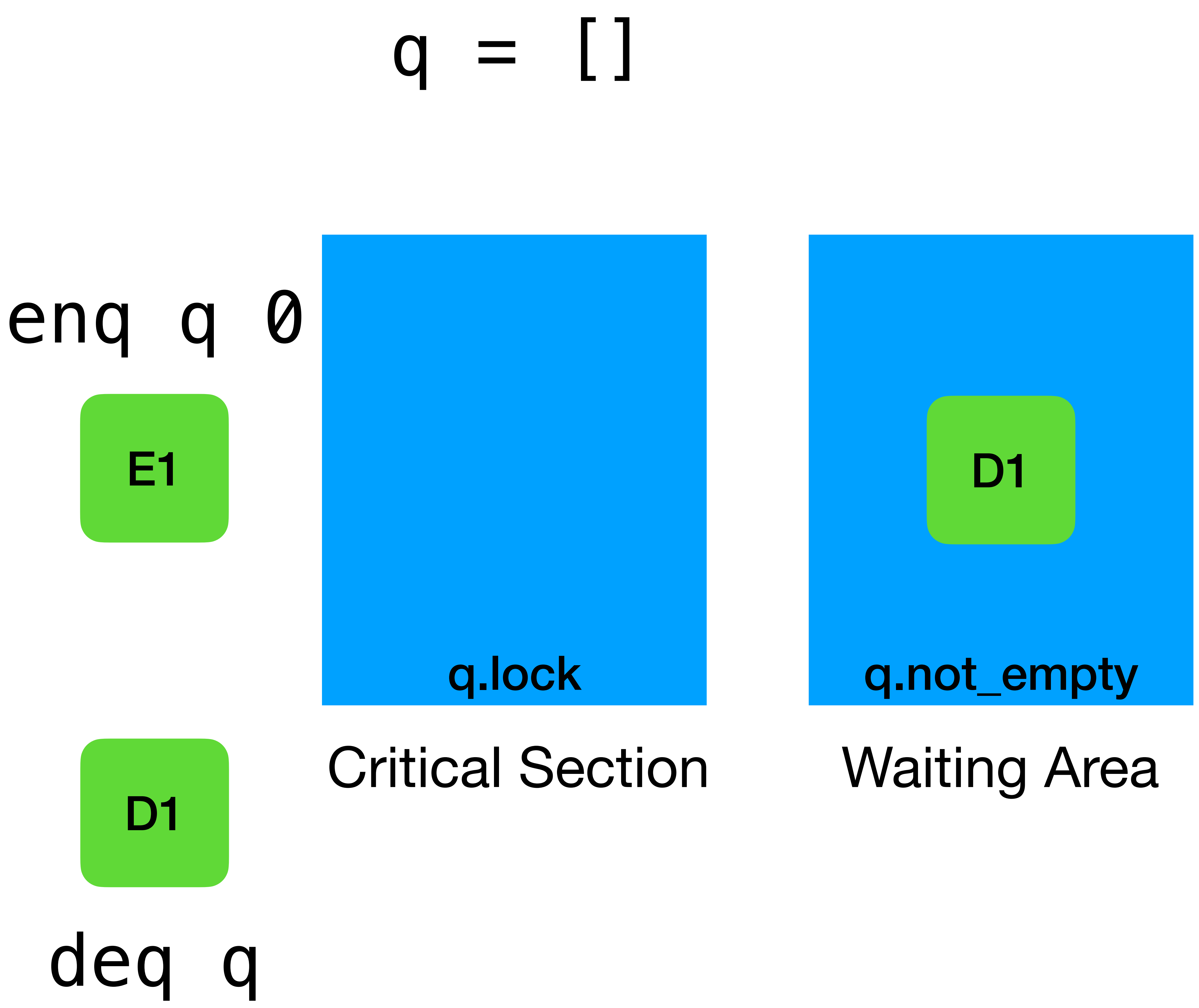



```
deq q
```

Subtleties — Recheck condition for concurrency



Subtleties — Recheck condition for concurrency



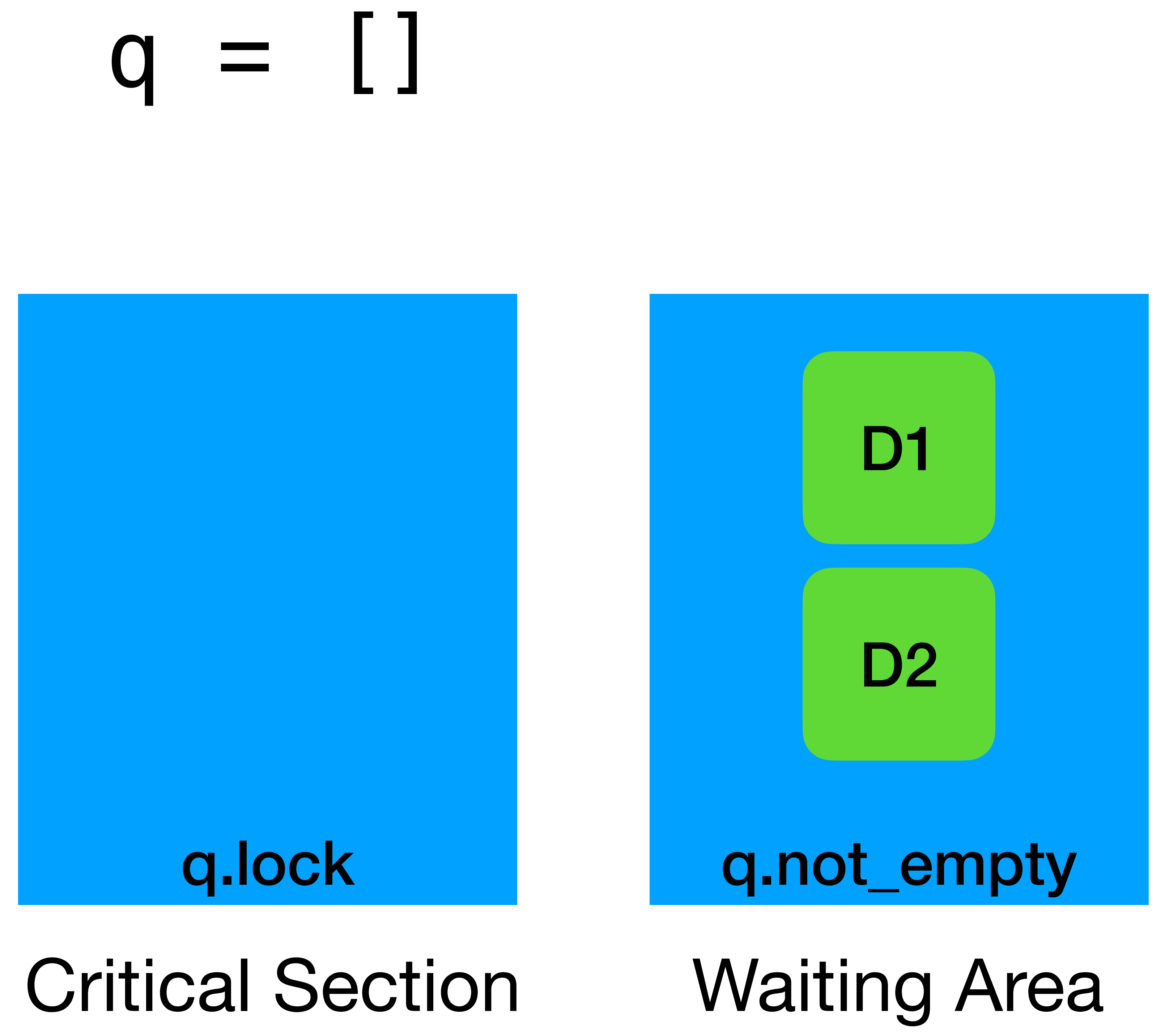
Subtleties — Lost-wakeup Problem

```
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

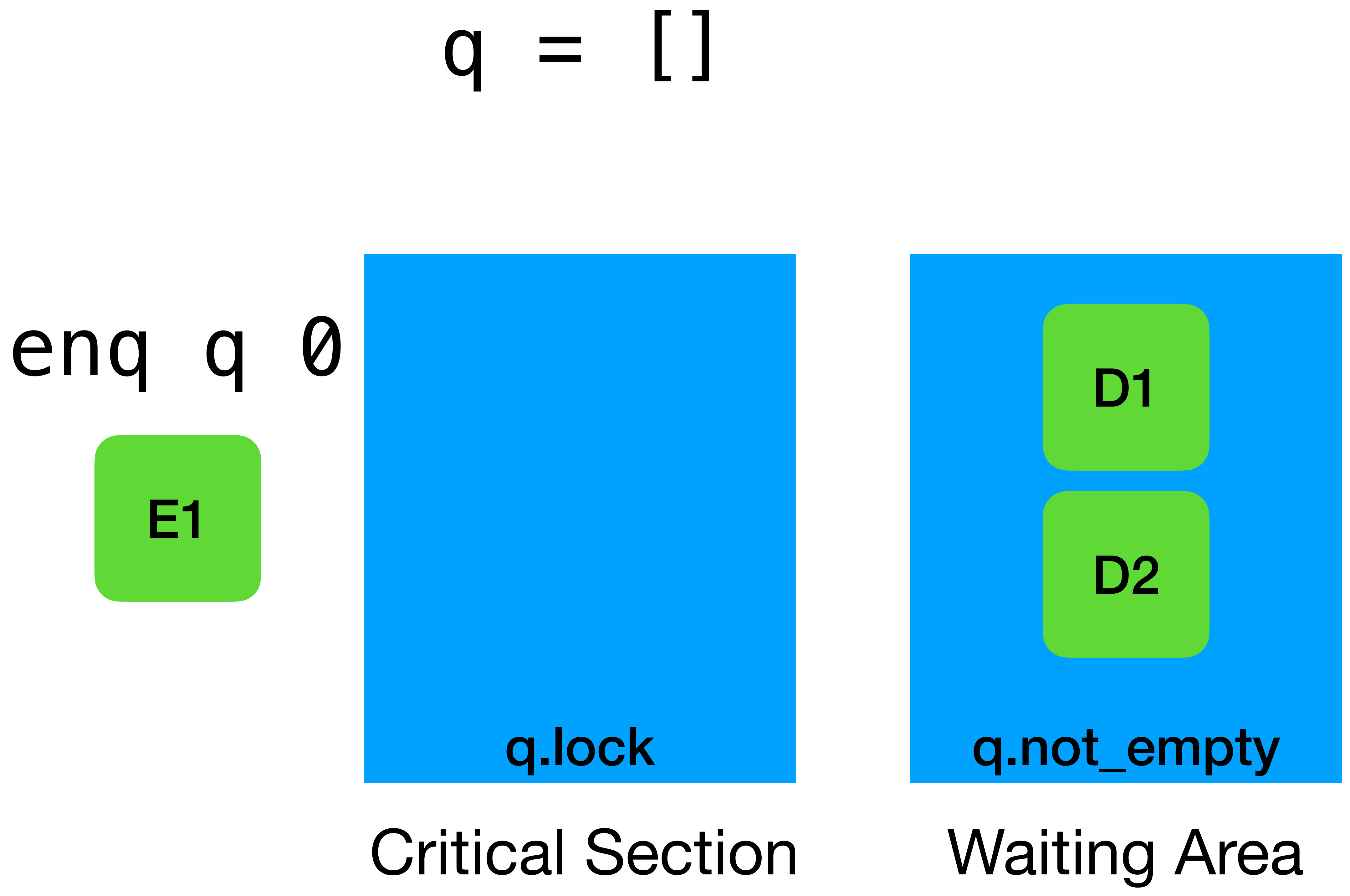
Subtleties — Lost-wakeup Problem

```
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)
```



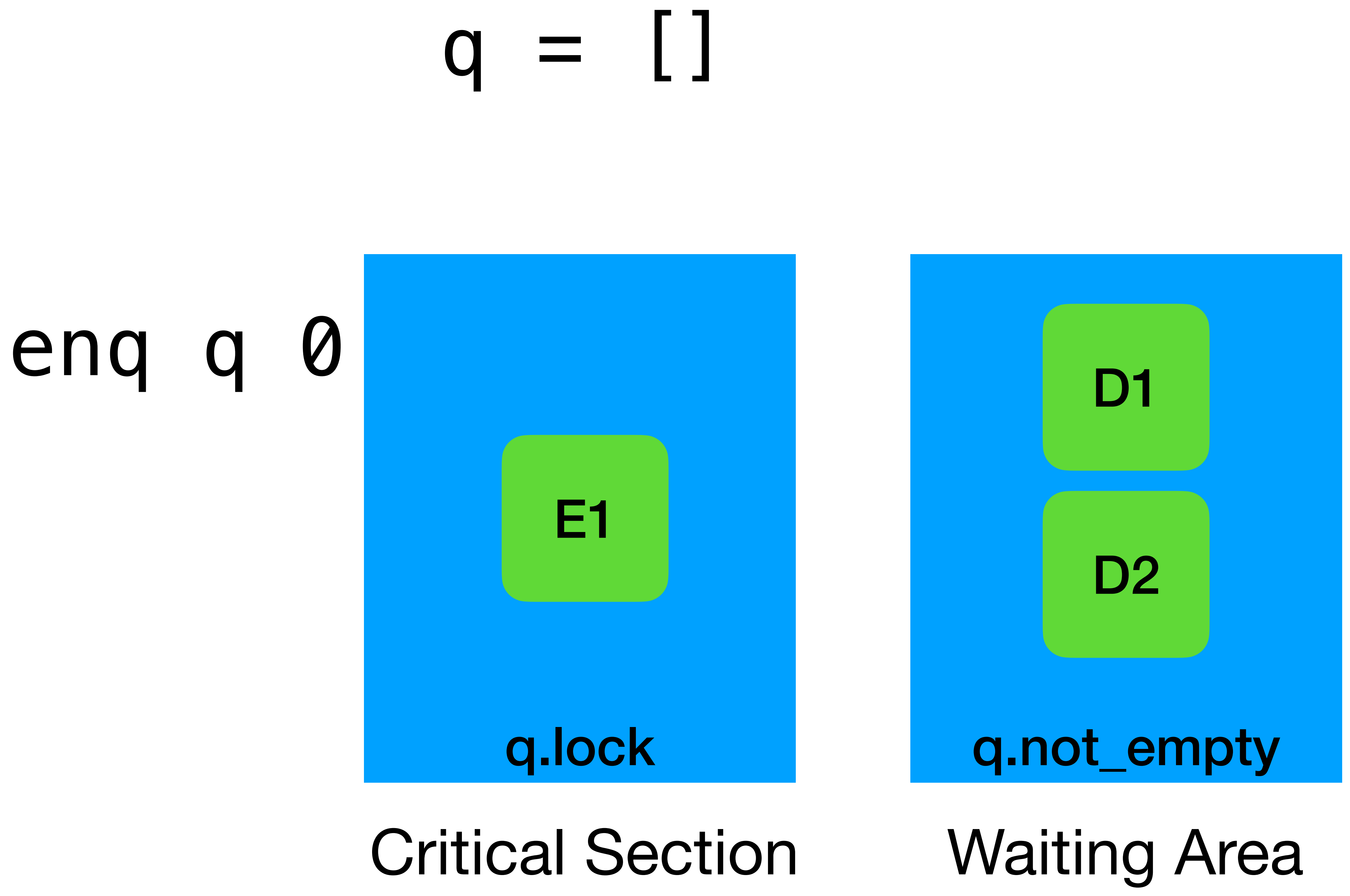
Subtleties — Lost-wakeup Problem

```
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)
```



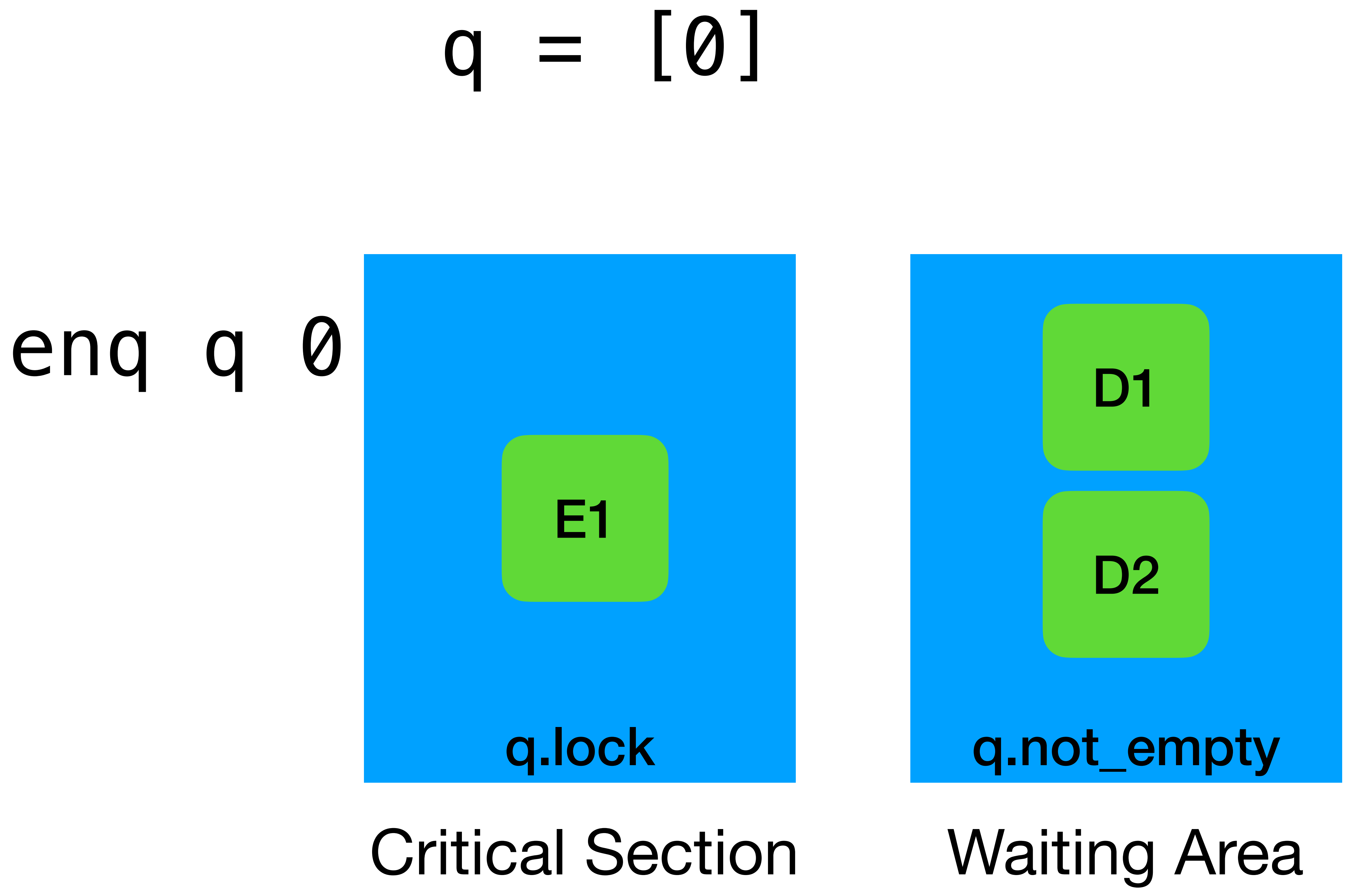
Subtleties — Lost-wakeup Problem

```
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)
```



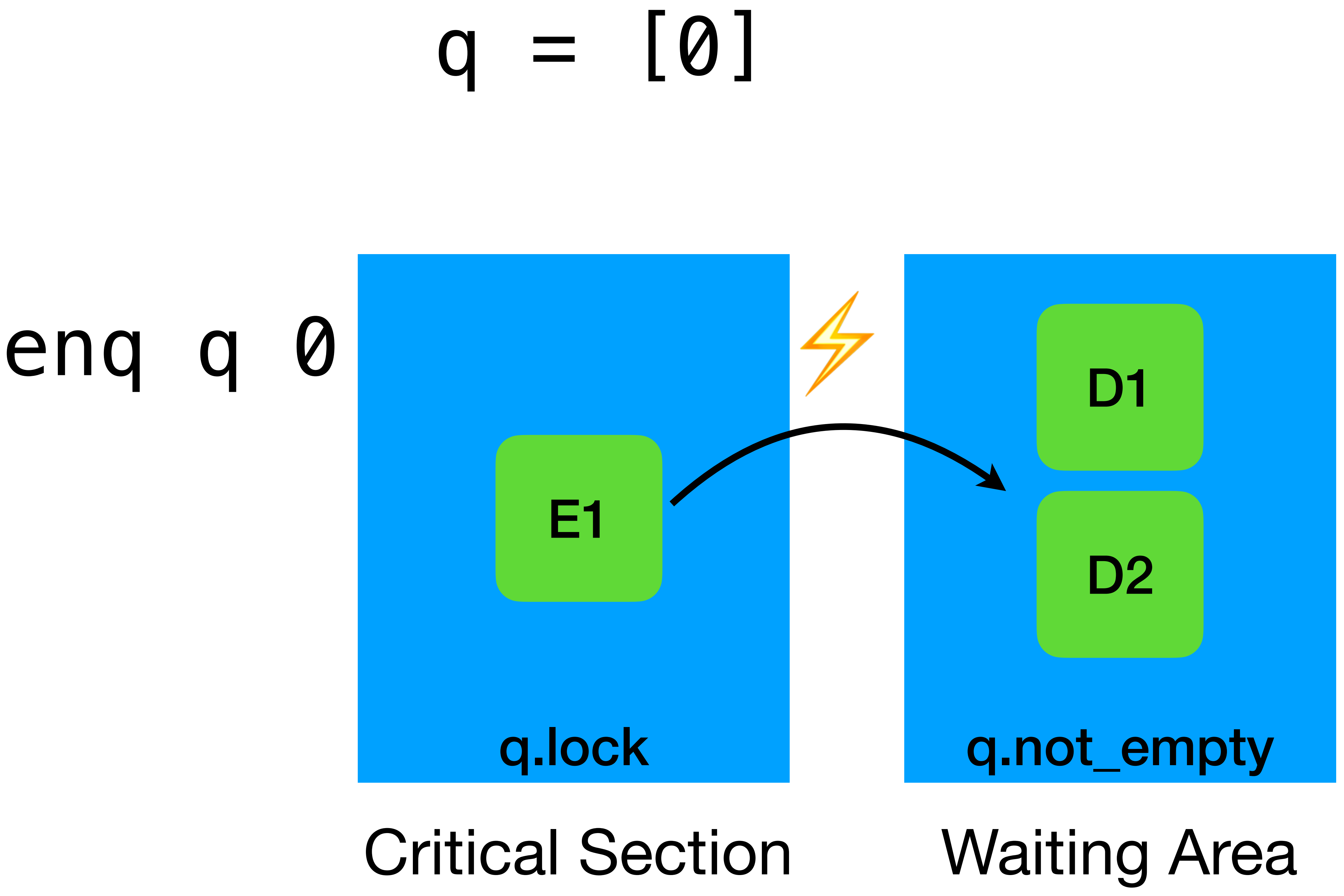
Subtleties — Lost-wakeup Problem

```
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)
```



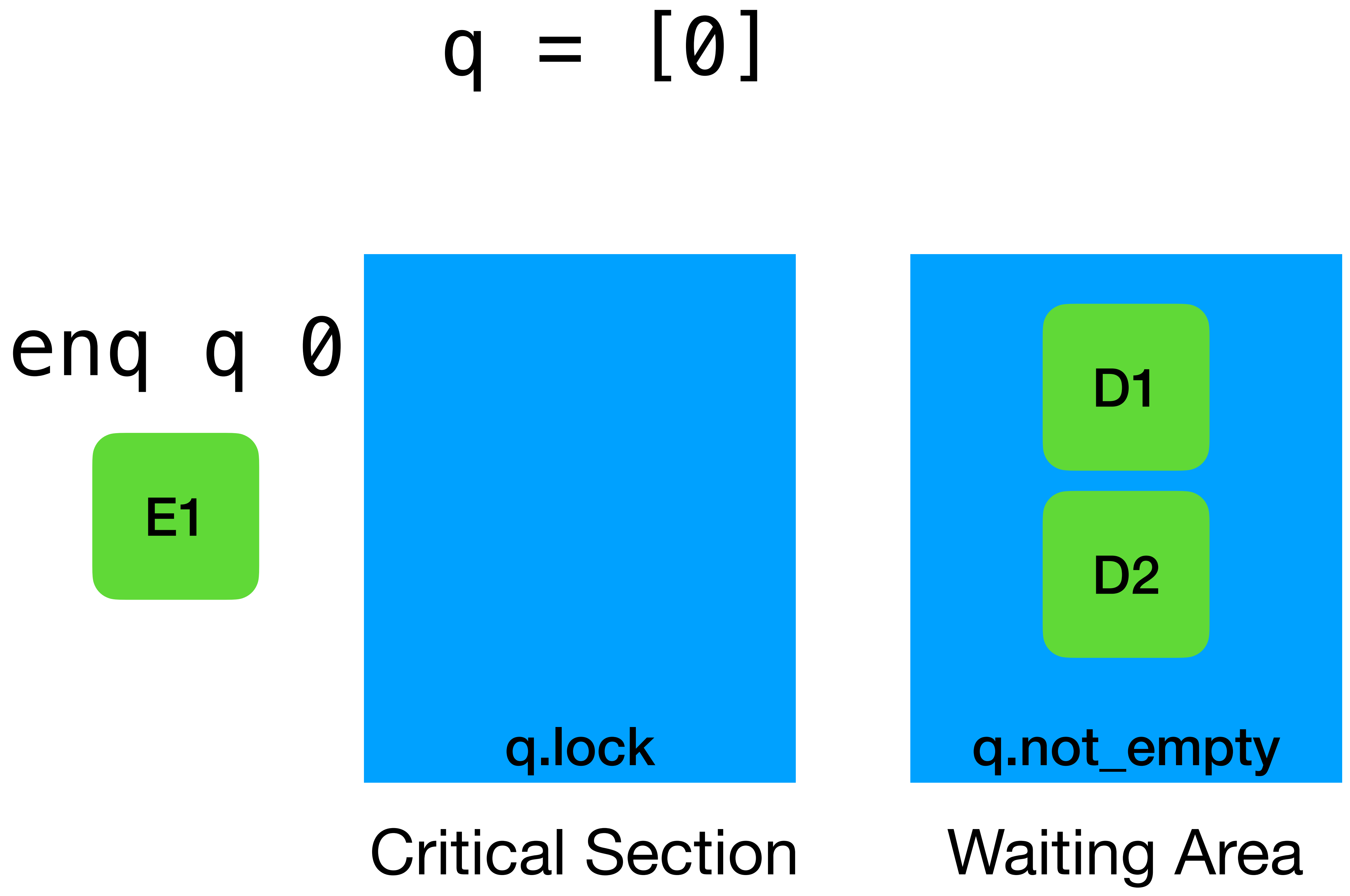
Subtleties — Lost-wakeup Problem

```
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)
```



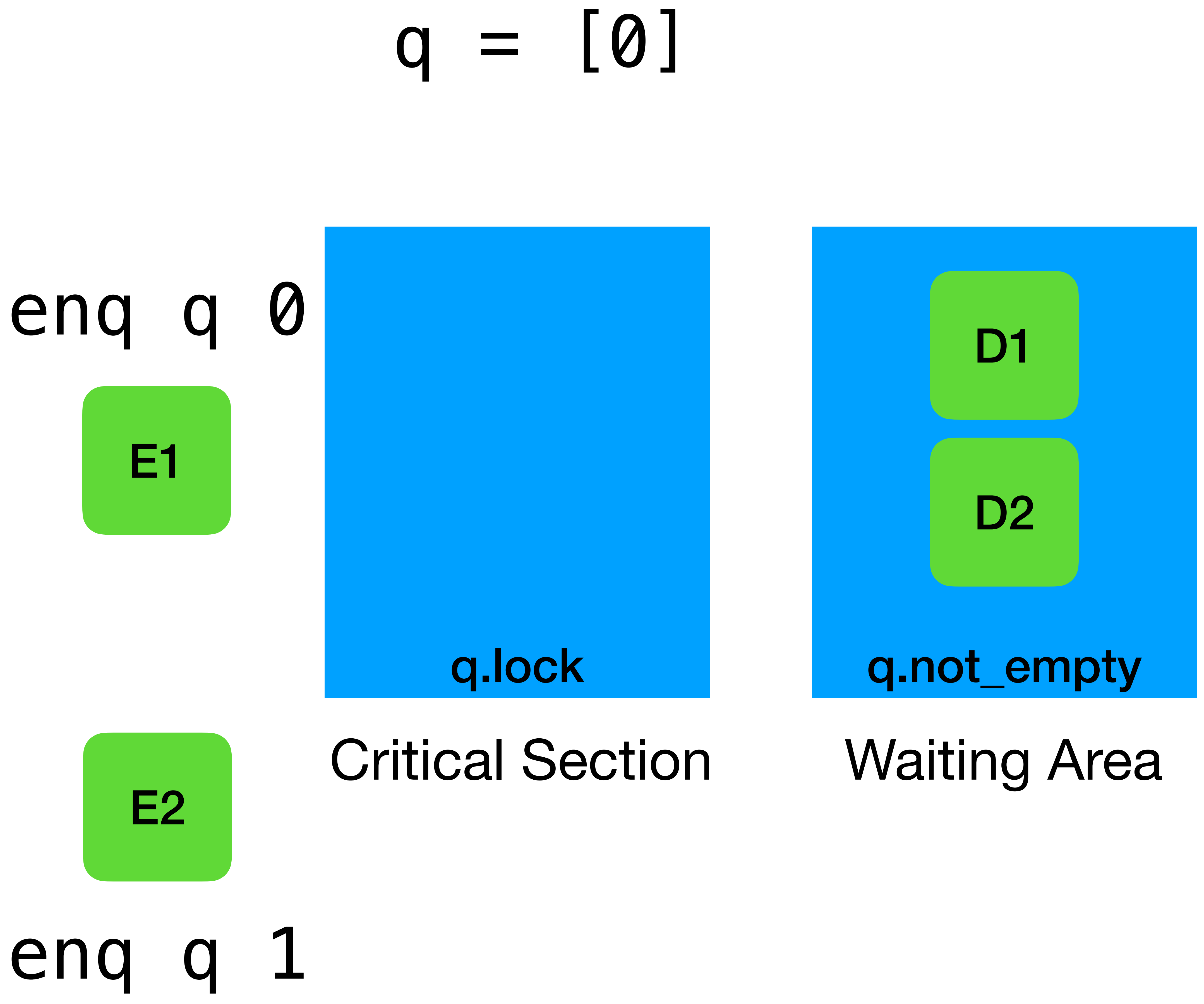
Subtleties — Lost-wakeup Problem

```
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)
```



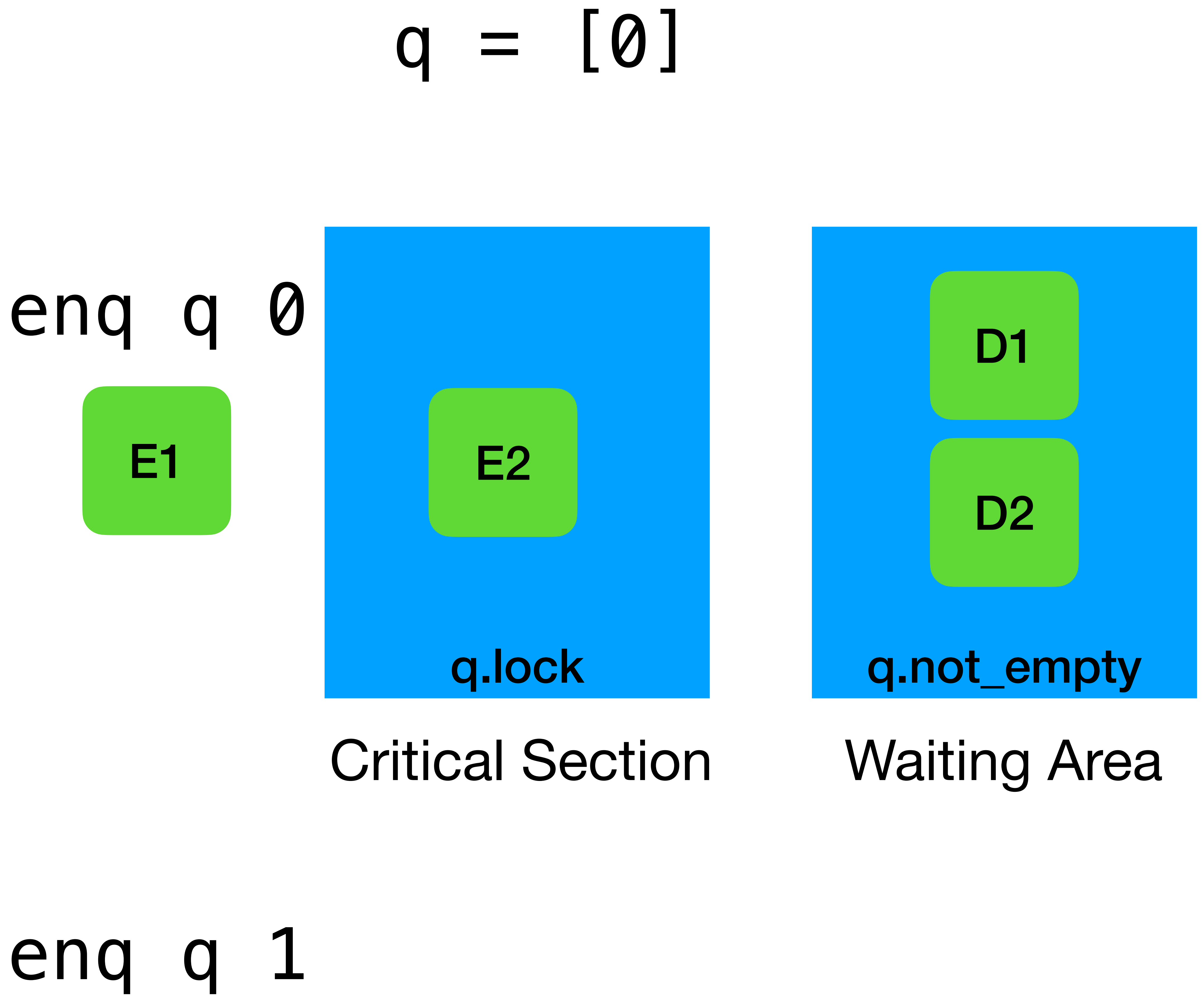
Subtleties — Lost-wakeup Problem

```
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)
```



Subtleties — Lost-wakeup Problem

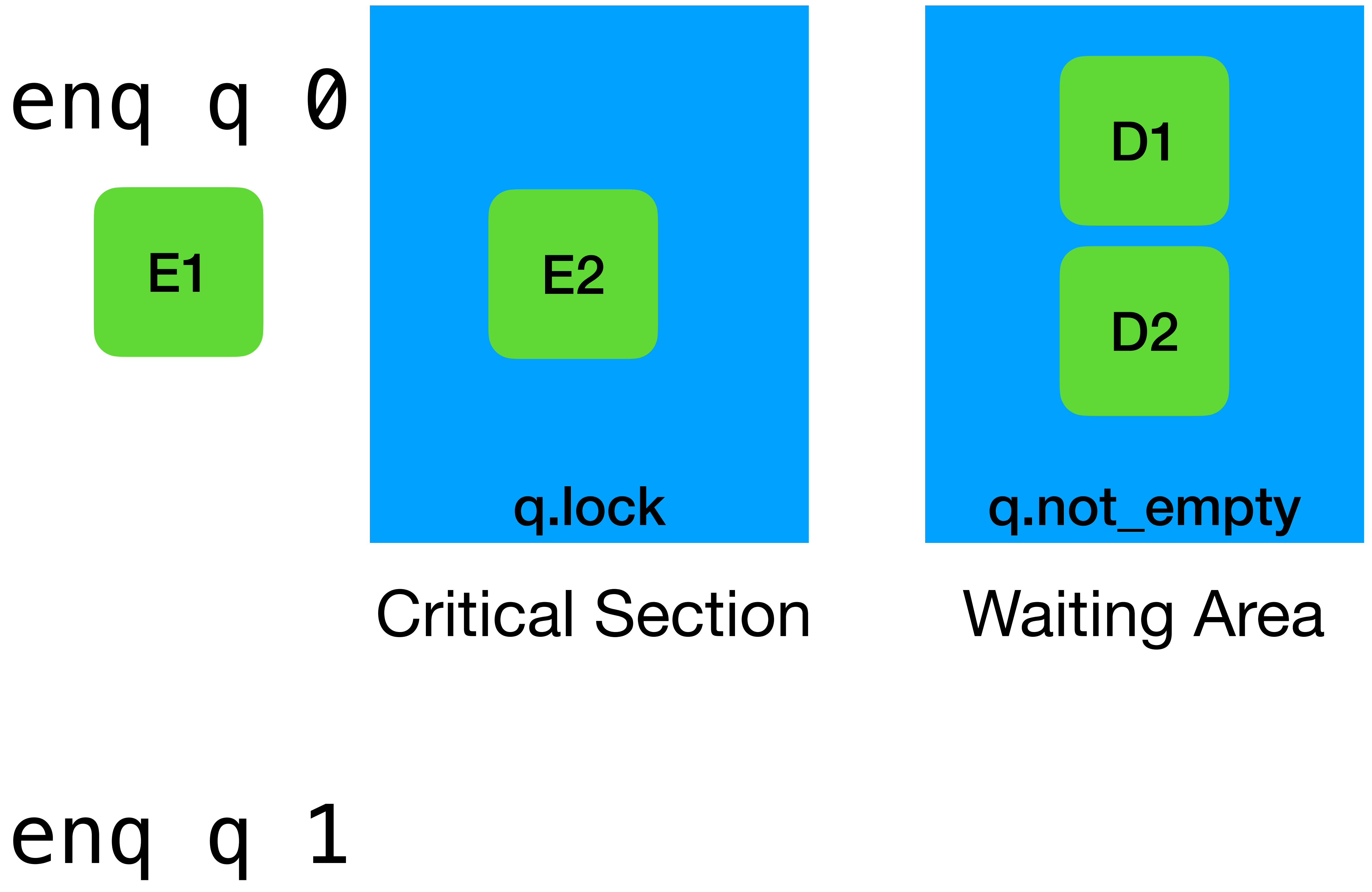
```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail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



Subtleties — Lost-wakeup Problem

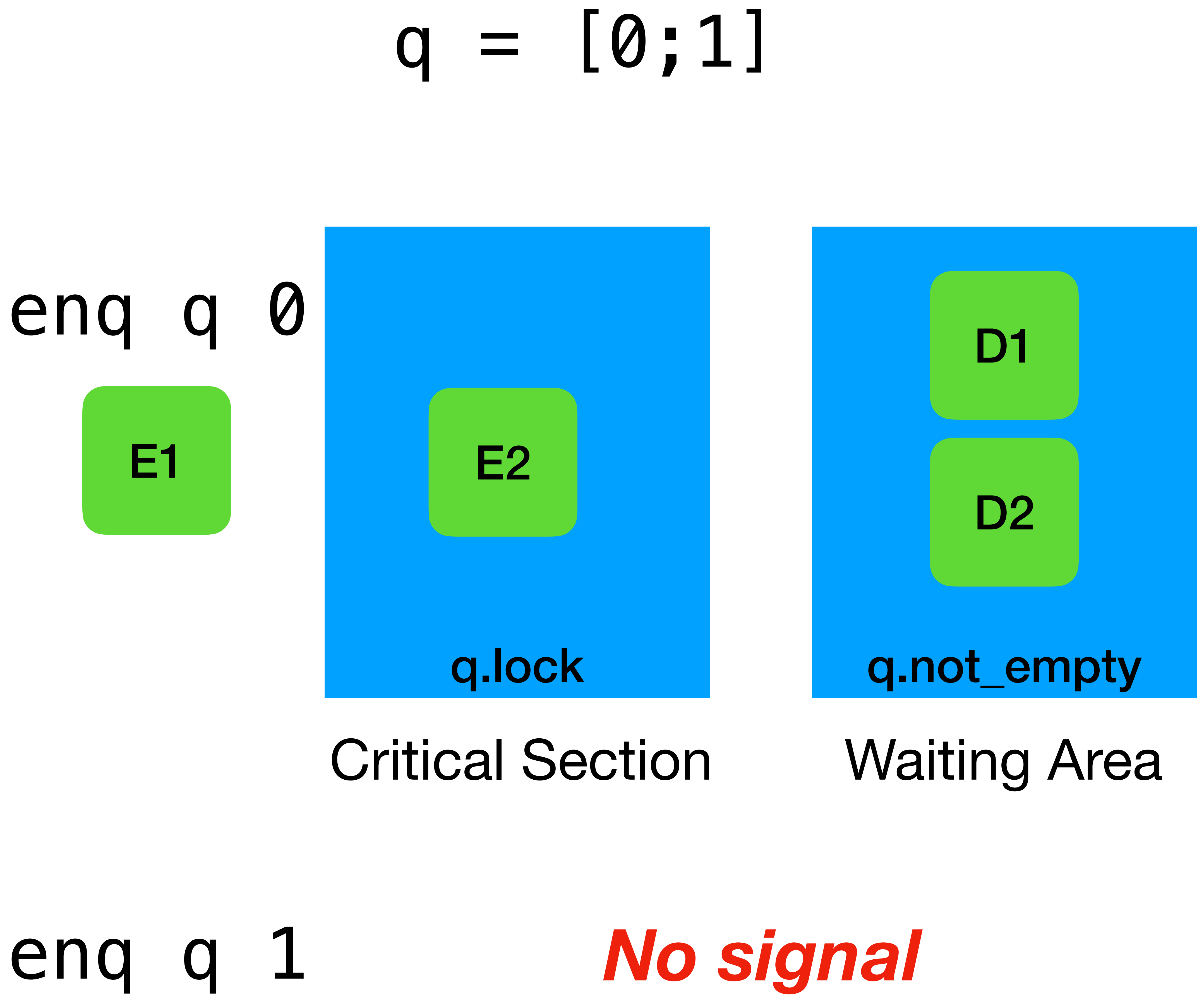
```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail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



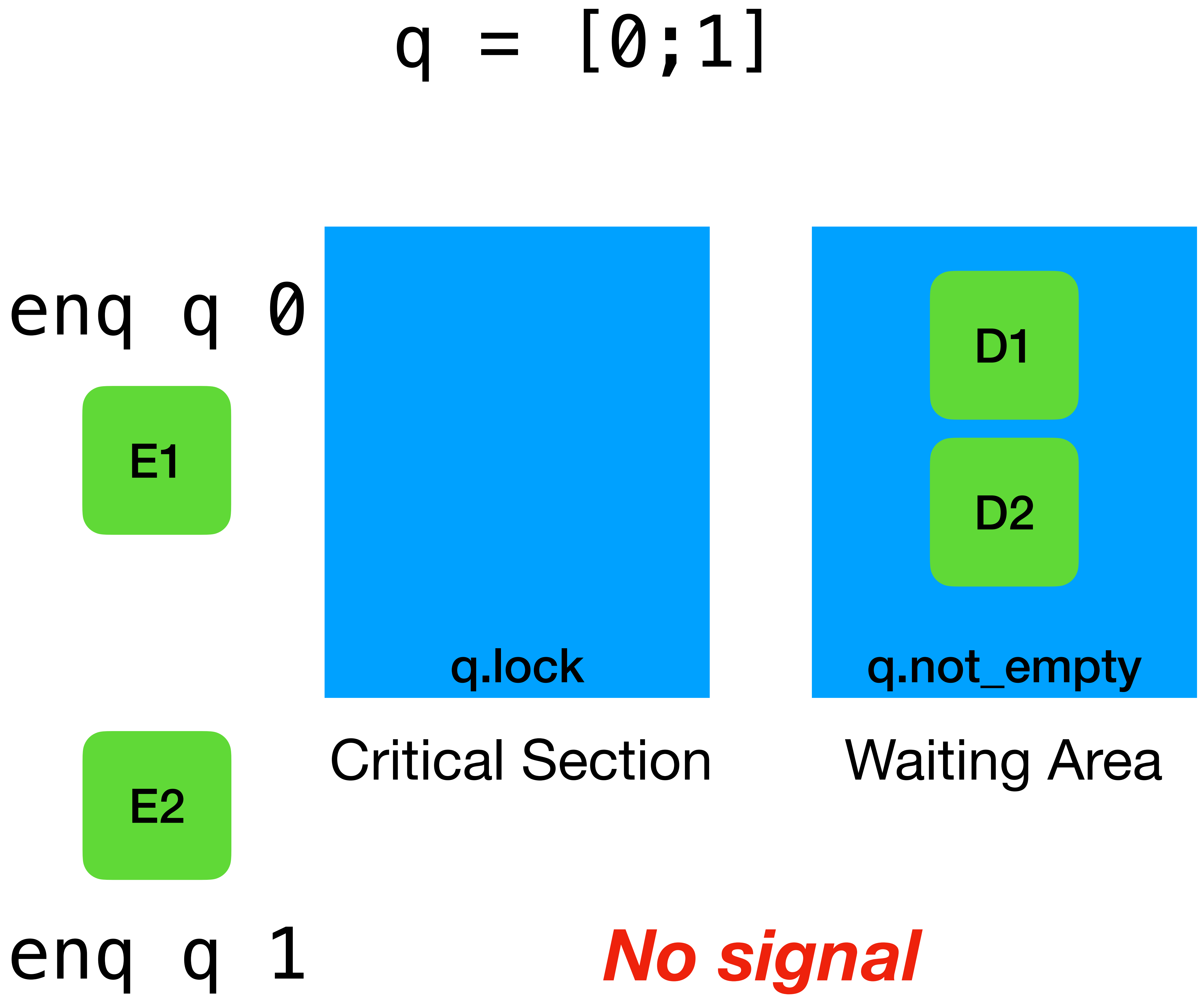
Subtleties — Lost-wakeup Problem

```
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)
```



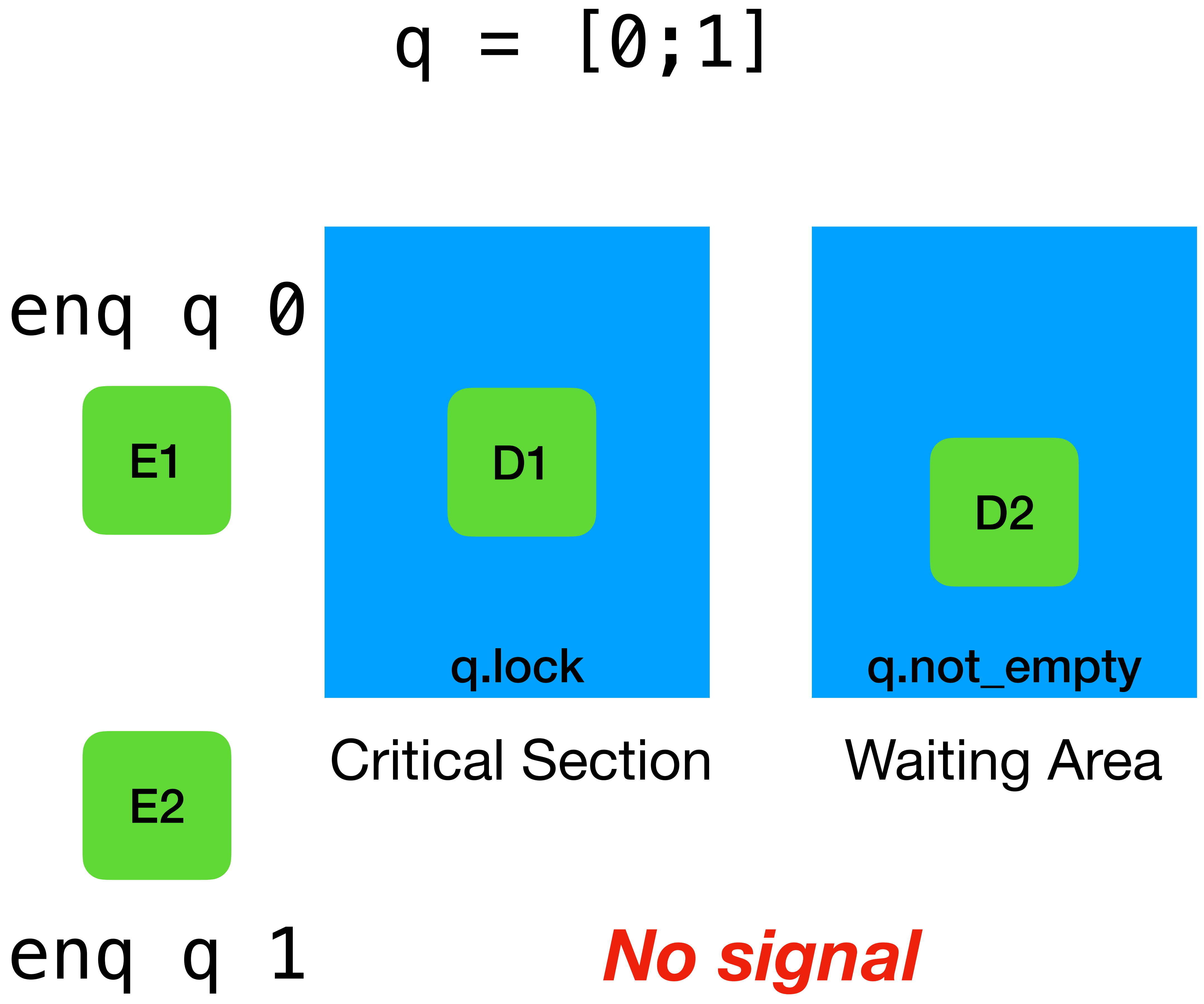
Subtleties — Lost-wakeup Problem

```
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)
```



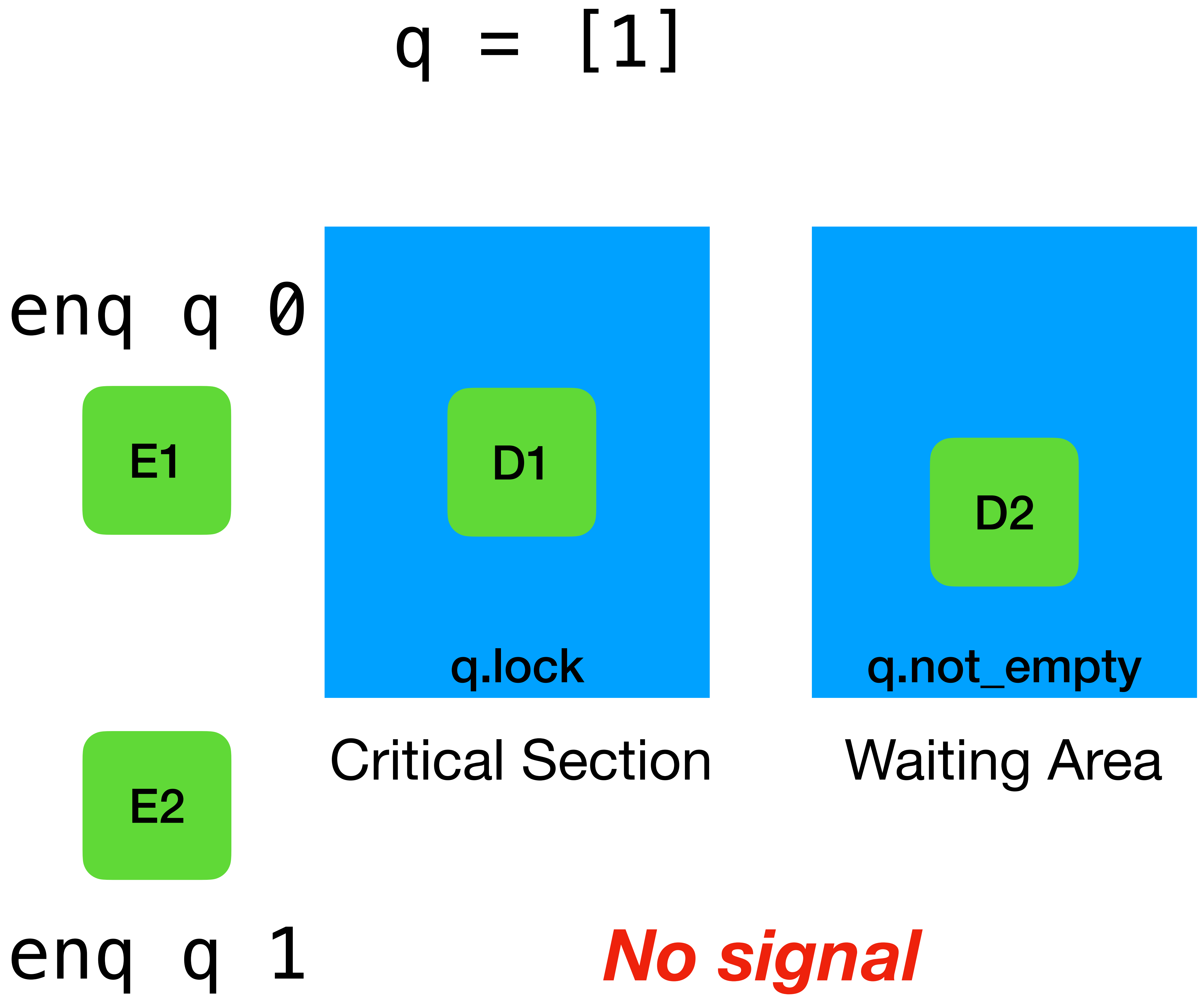
Subtleties — Lost-wakeup Problem

```
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)
```



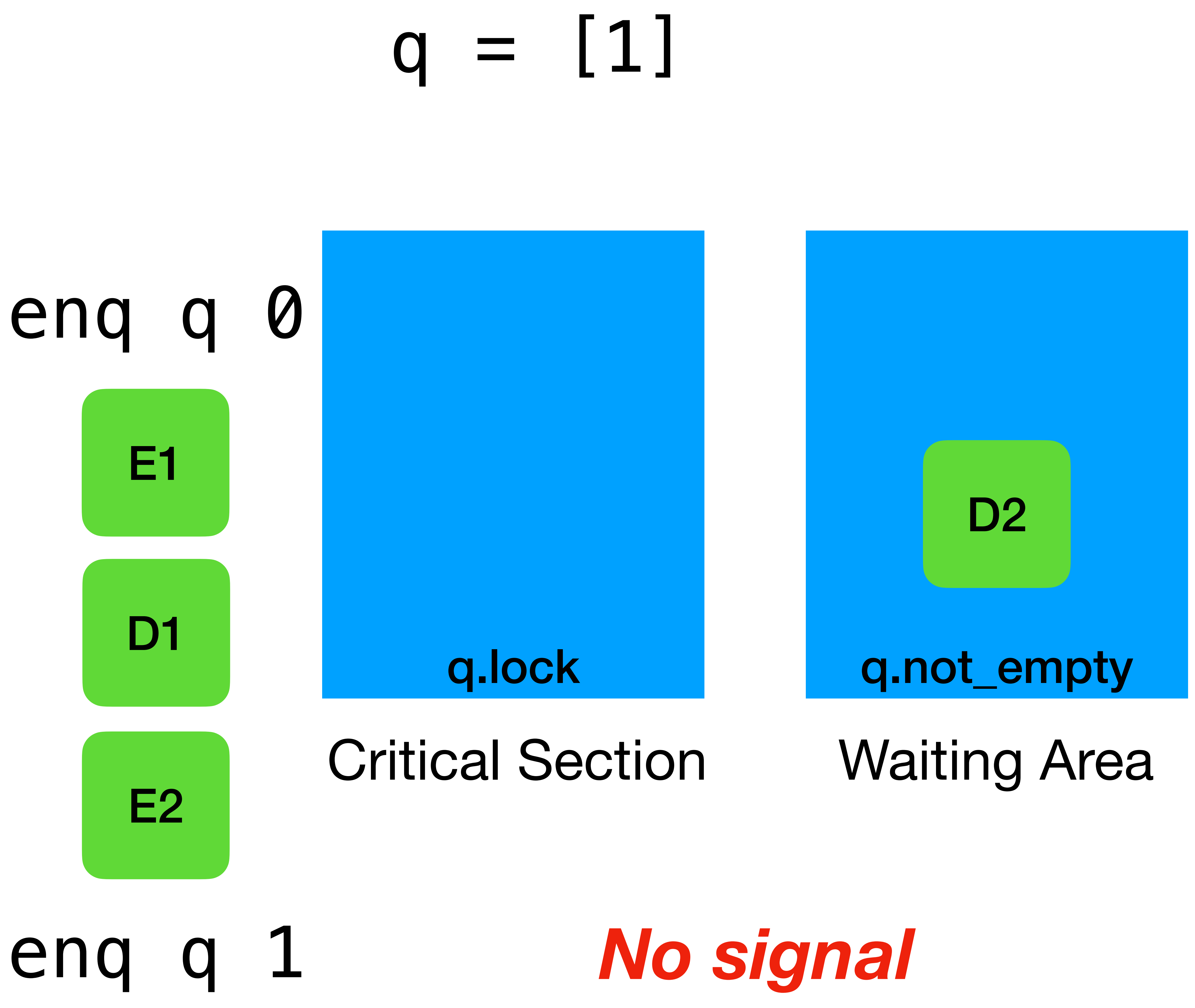
Subtleties — Lost-wakeup Problem

```
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)
```



Subtleties — Lost-wakeup Problem

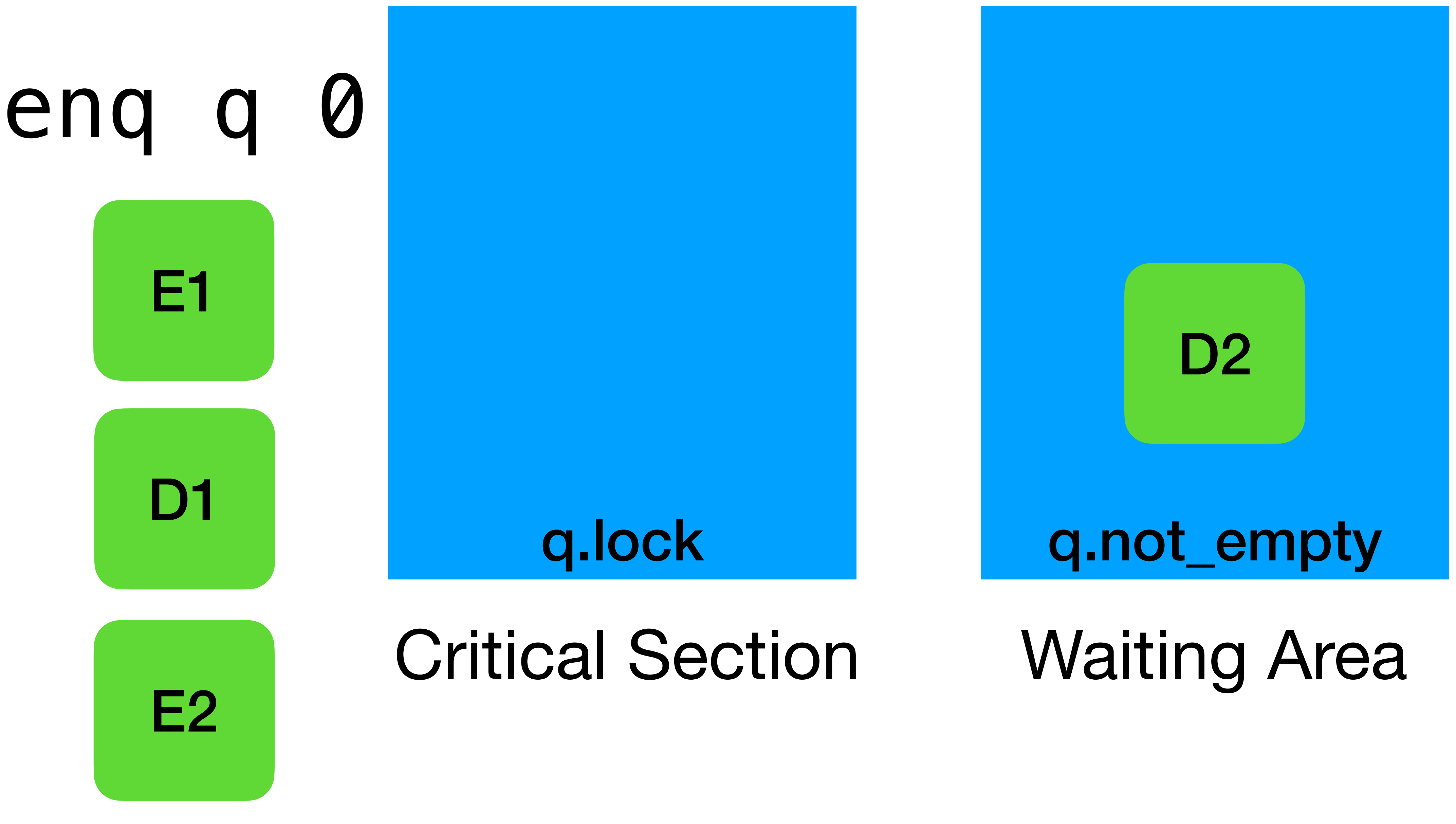
```
let enq q x =
  Mutex.lock q.lock;
  Fun.protect ~finally:(fun () -> Mutex.unlock q.lock)
  (fun () ->
    (* Wait while queue is full *)
    while q.tail - q.head = q.capacity do
      Condition.wait q.not_full q.lock
    done;
    (* If queue is empty, we signal *)
    let must_signal = q.tail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



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)
```

Signal all the time

```
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 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 head
- *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