Back to Basics: Lock-free

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C++ Russia
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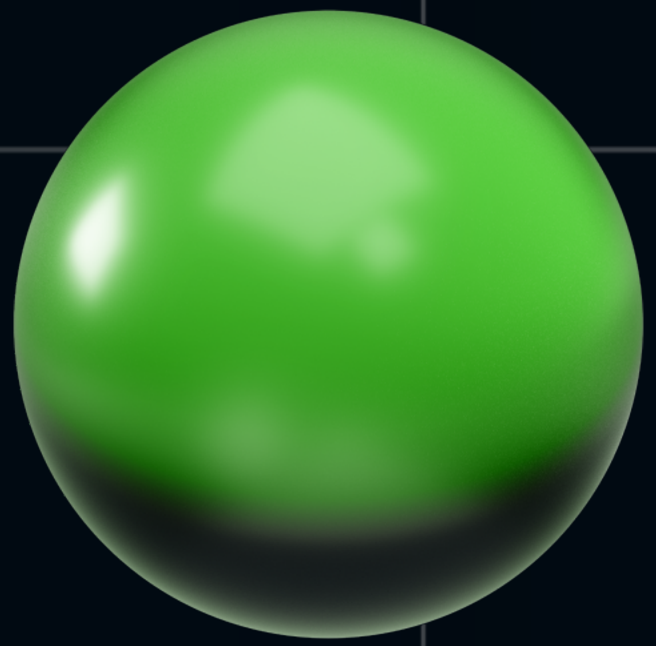
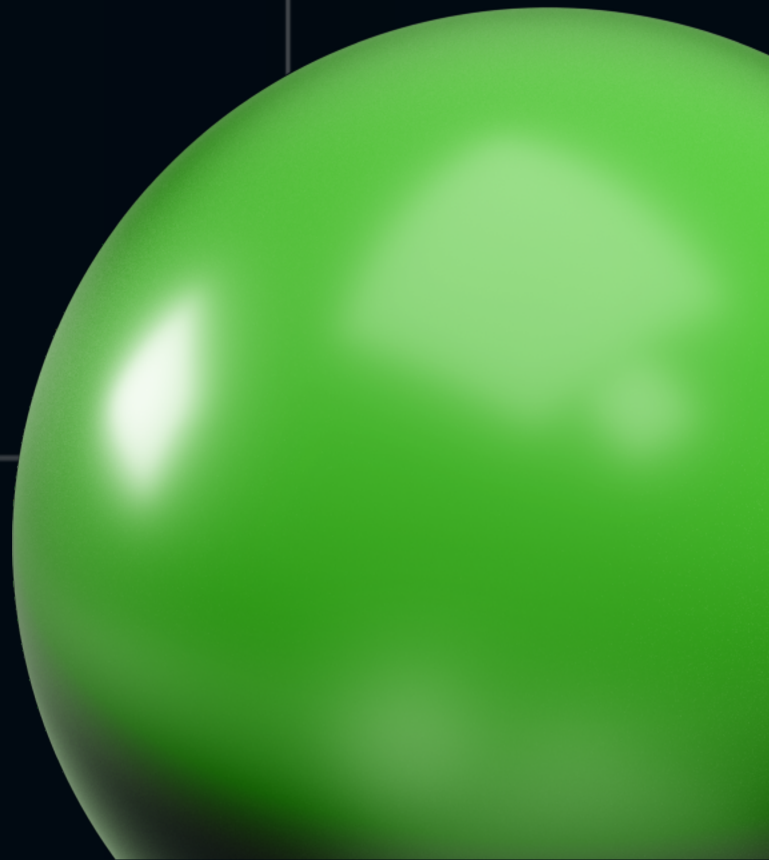
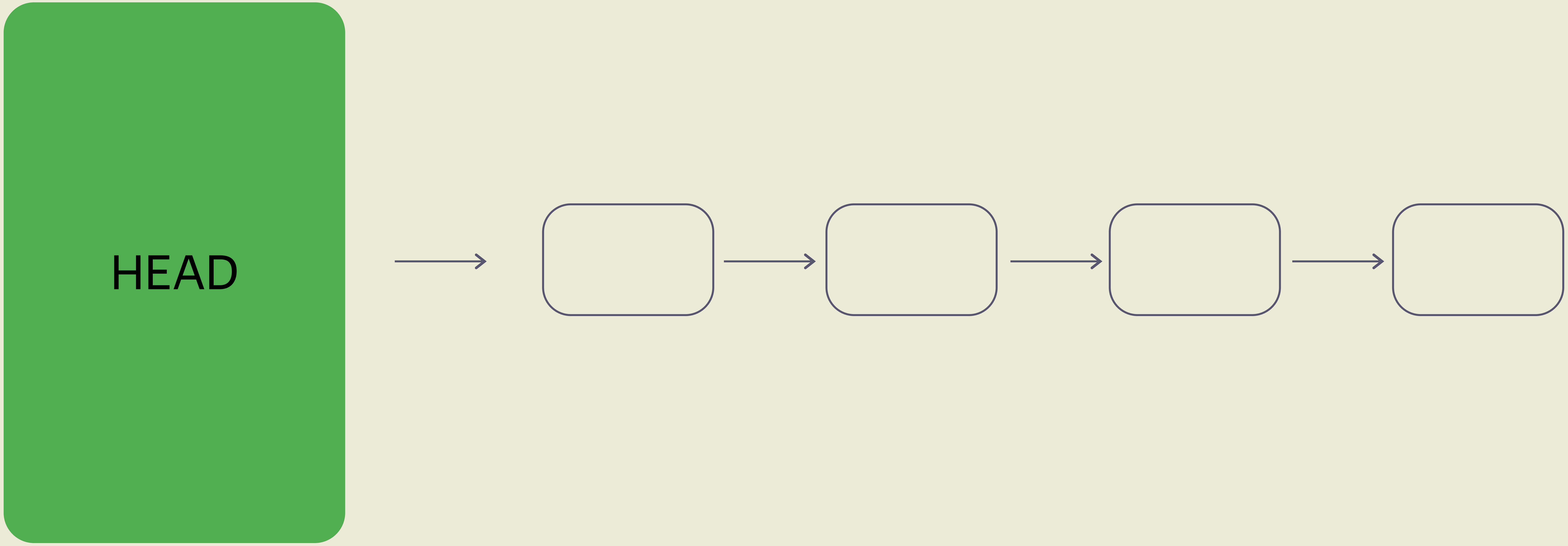


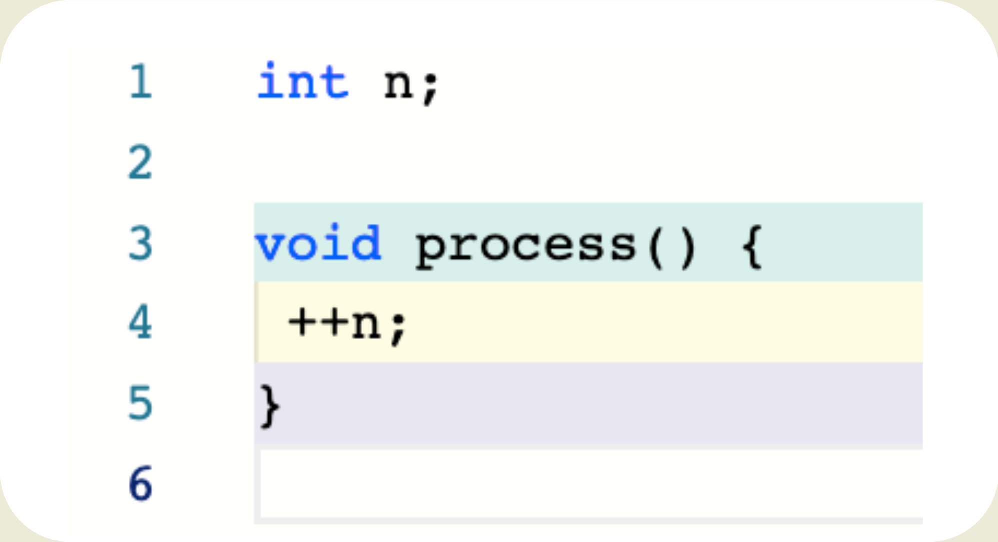


Список

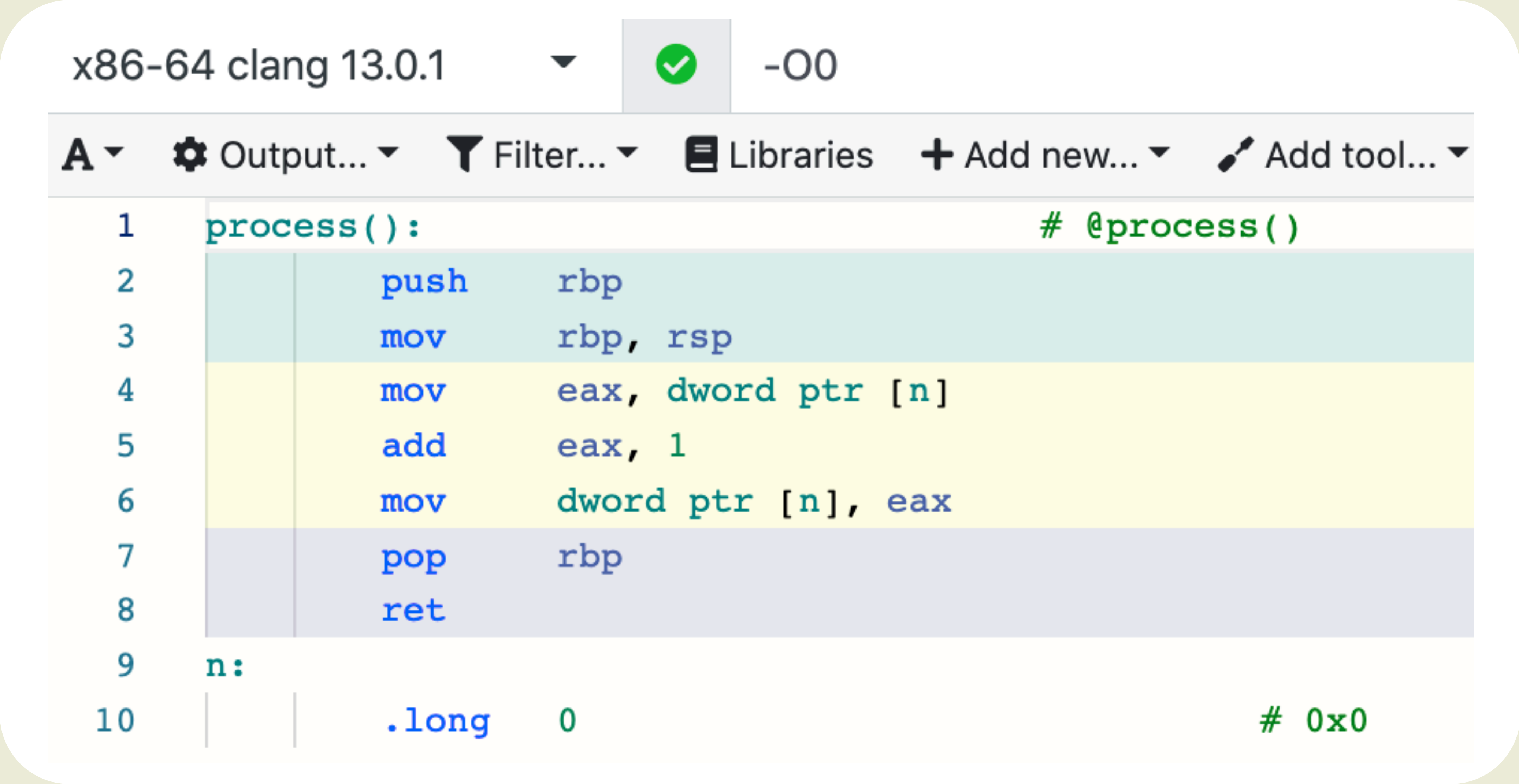


Гонка данных

Время	Thread 1	Thread 2
1	Read n (0)	
2		Read n (0)
3	++n (1)	++n (1)
4	Write n	Write n



```cpp
int n;

void process() {
 ++n;
}

```



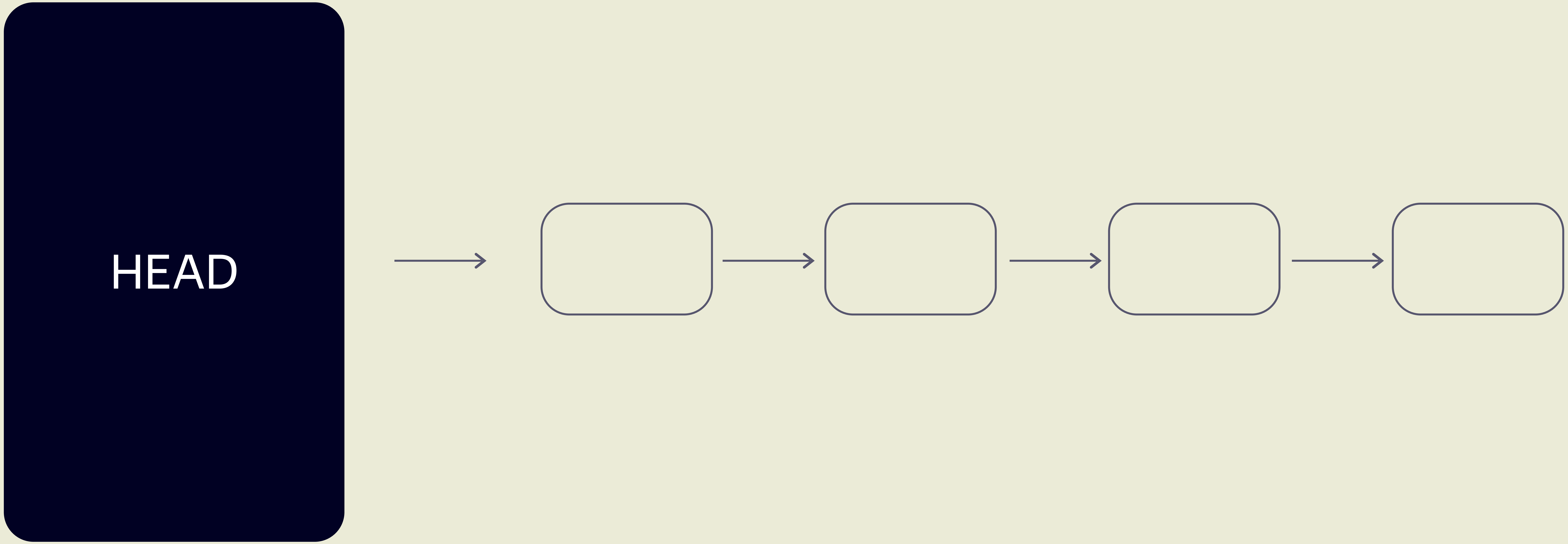
x86-64 clang 13.0.1 -O0

```asm
process():                              # @process()
        push    rbp
        mov     rbp, rsp
        mov     eax, dword ptr [n]
        add     eax, 1
        mov     dword ptr [n], eax
        pop     rbp
        ret
n:
        .long   0                               # 0x0
```

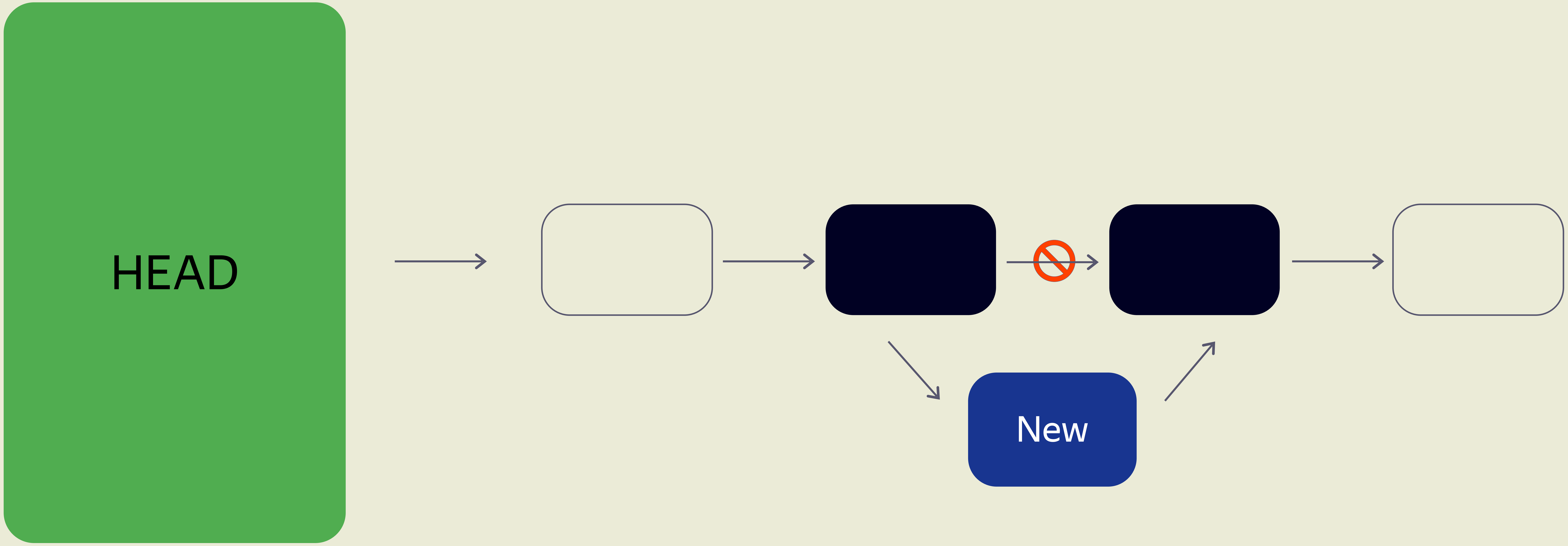
https://godbolt.org/z/5xz8hjj5E

Мьютексы

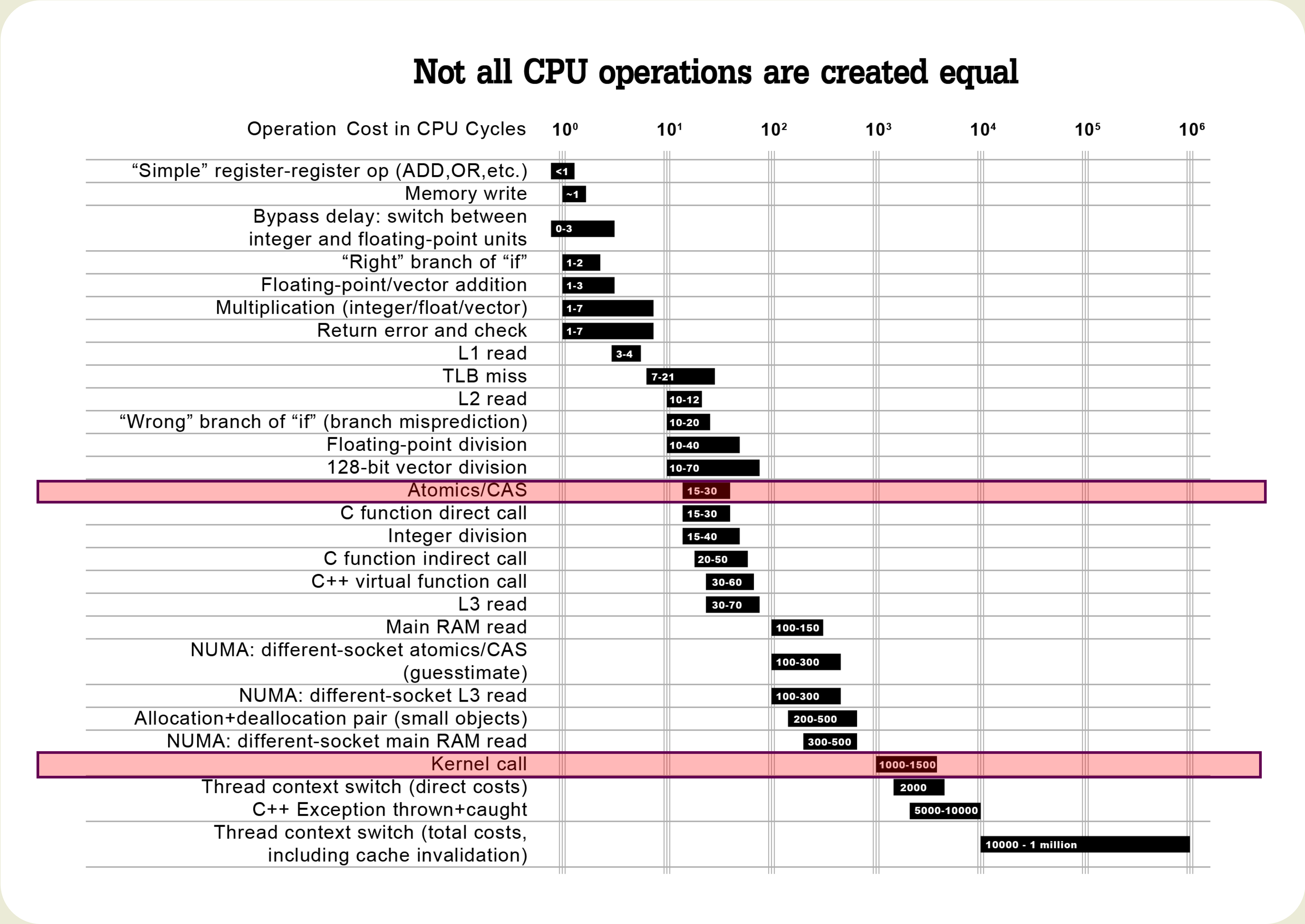
Общая блокировка



Гранулярная блокировка



CPU операции



Not all CPU operations are created equal

Operation	Cost in CPU Cycles
“Simple” register-register op (ADD,OR,etc.)	<1
Memory write	~1
Bypass delay: switch between integer and floating-point units	0-3
“Right” branch of “if”	1-2
Floating-point/vector addition	1-3
Multiplication (integer/float/vector)	1-7
Return error and check	1-7
L1 read	3-4
TLB miss	7-21
L2 read	10-12
“Wrong” branch of “if” (branch misprediction)	10-20
Floating-point division	10-40
128-bit vector division	10-70
Atomics/CAS	15-30
C function direct call	15-30
Integer division	15-40
C function indirect call	20-50
C++ virtual function call	30-60
L3 read	30-70
Main RAM read	100-150
NUMA: different-socket atomics/CAS (guesstimate)	100-300
NUMA: different-socket L3 read	100-300
Allocation+deallocation pair (small objects)	200-500
NUMA: different-socket main RAM read	300-500
Kernel call	1000-1500
Thread context switch (direct costs)	2000
C++ Exception thrown+caught	5000-10000
Thread context switch (total costs, including cache invalidation)	10000 - 1 million

http://ithare.com/infographics-operation-costs-in-cpu-clock-cycles/

CAS-операции

CAS

```
bool atomic_compare_exchange_weak(atomic<T>* obj, T* expected, T desired);
```

CAS

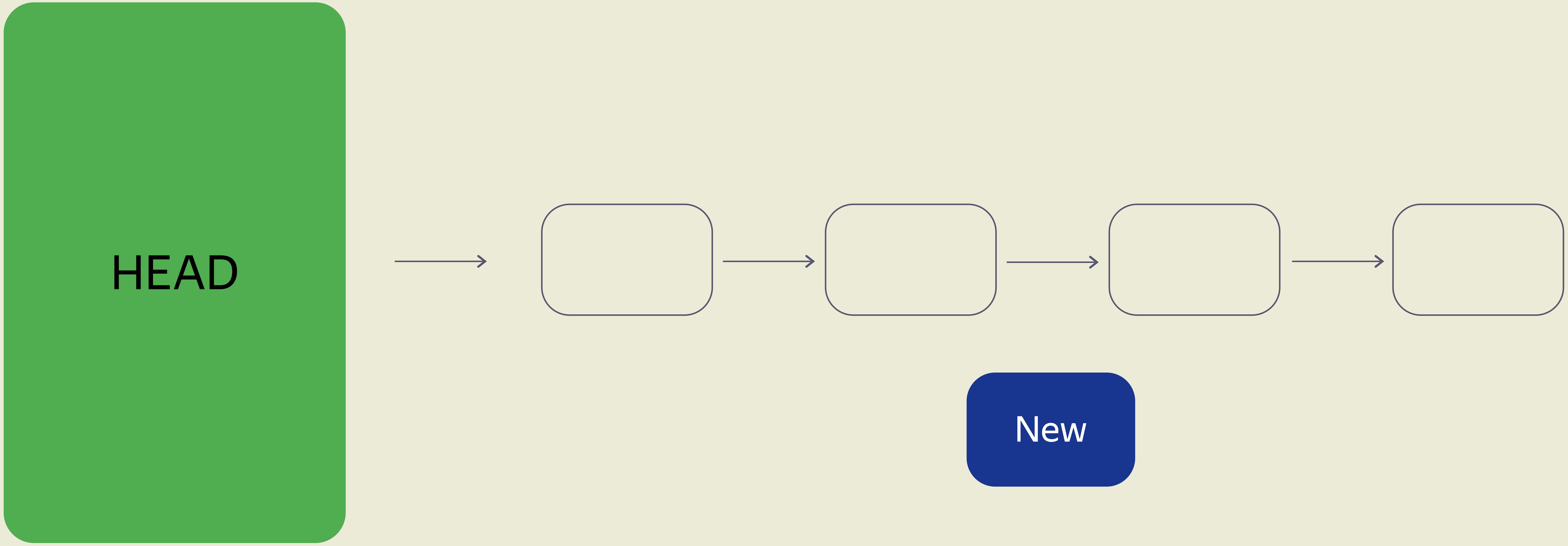
```
bool atomic_compare_exchange_weak(atomic<T>* obj, T* expected, T desired);

template <class T>
struct atomic {
    void store(T data);
    T load() const;
    T exchange(T data);
    bool compare_exchange_weak(T& expected, T desired);
};
```

CAS

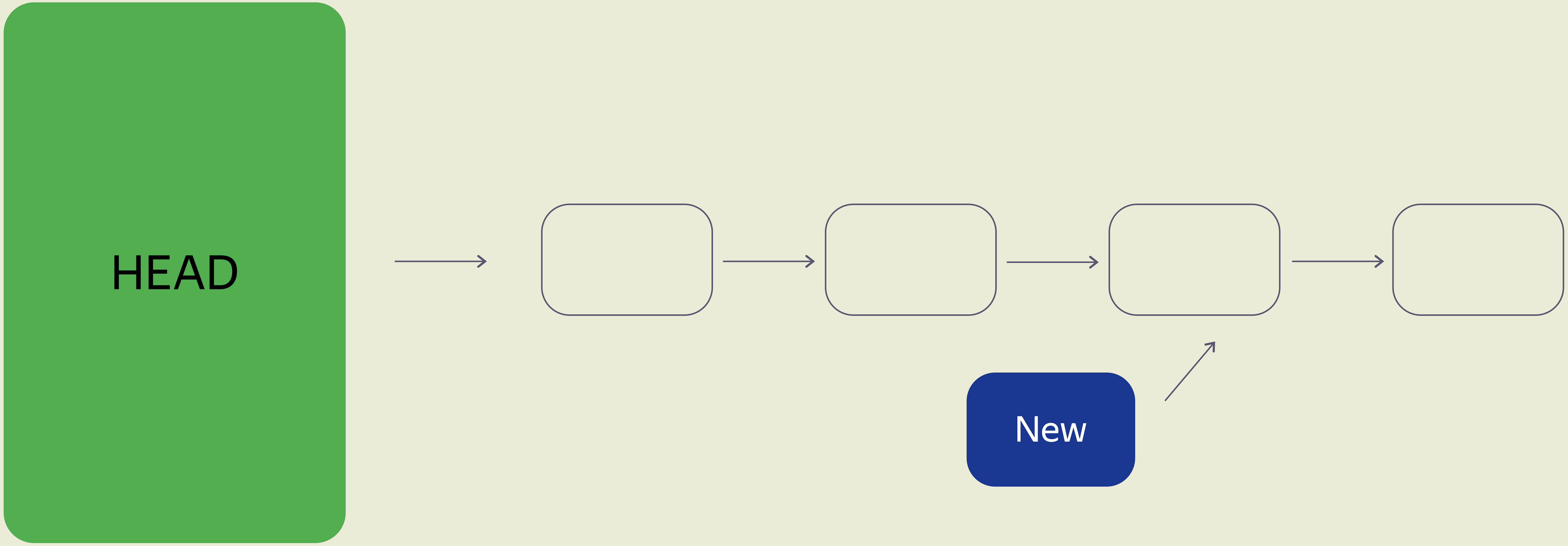
```
bool atomic_compare_exchange_weak(atomic<T>* obj, T* expected, T desired);
```

```
template<class T>
class stack{
   std::atomic<node<T>*> head;
  public:
   void push(const T& data){
     node<T>* new_node = new node<T>(data);
     new_node->next = head.load();
     while(!std::atomic_compare_exchange_weak(&head, &new_node->next, new_node));
   }
 };
```

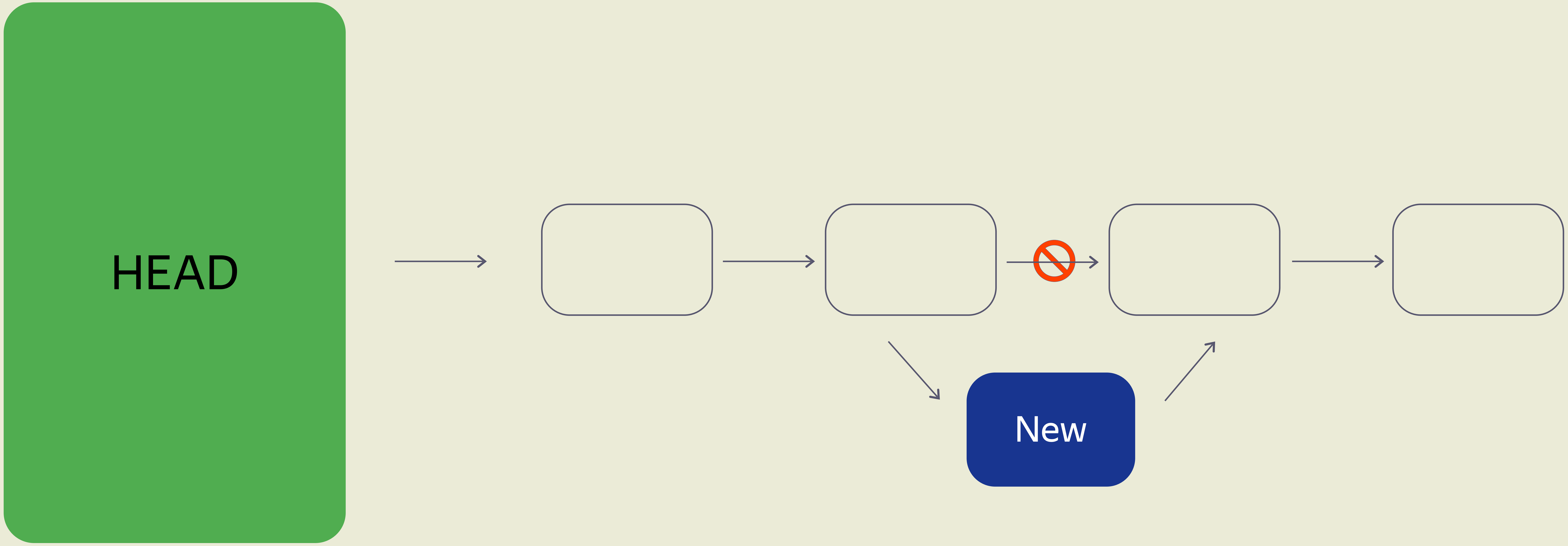
CAS



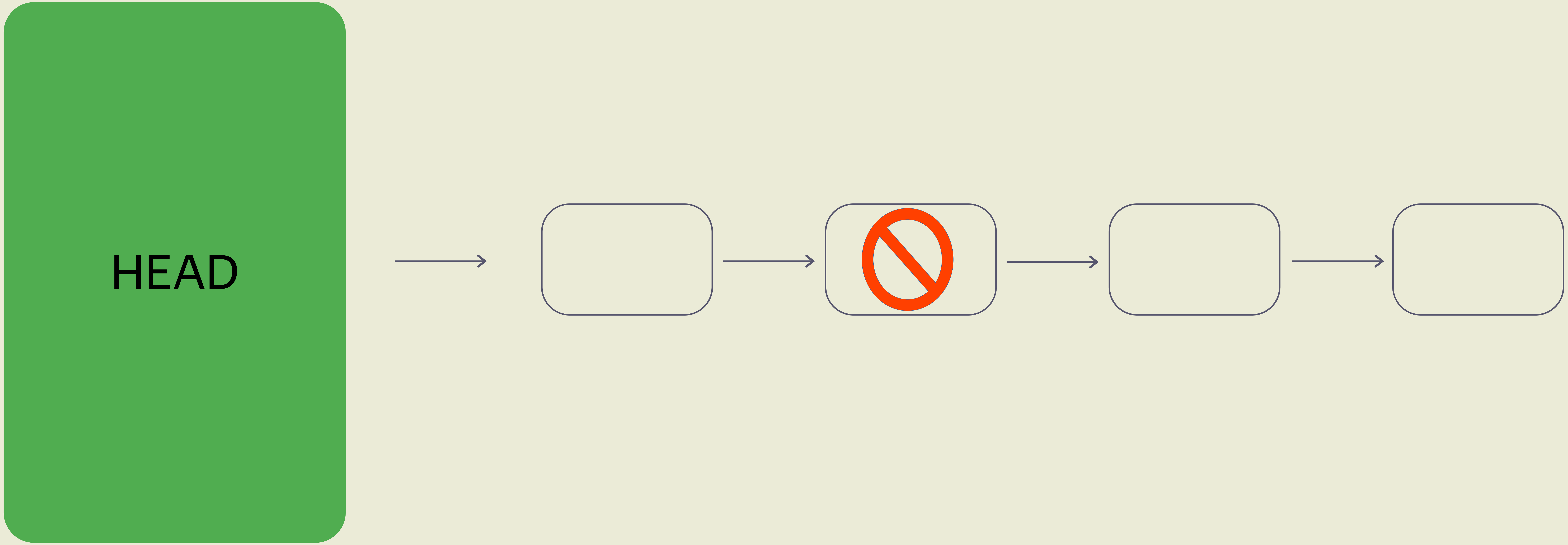
CAS



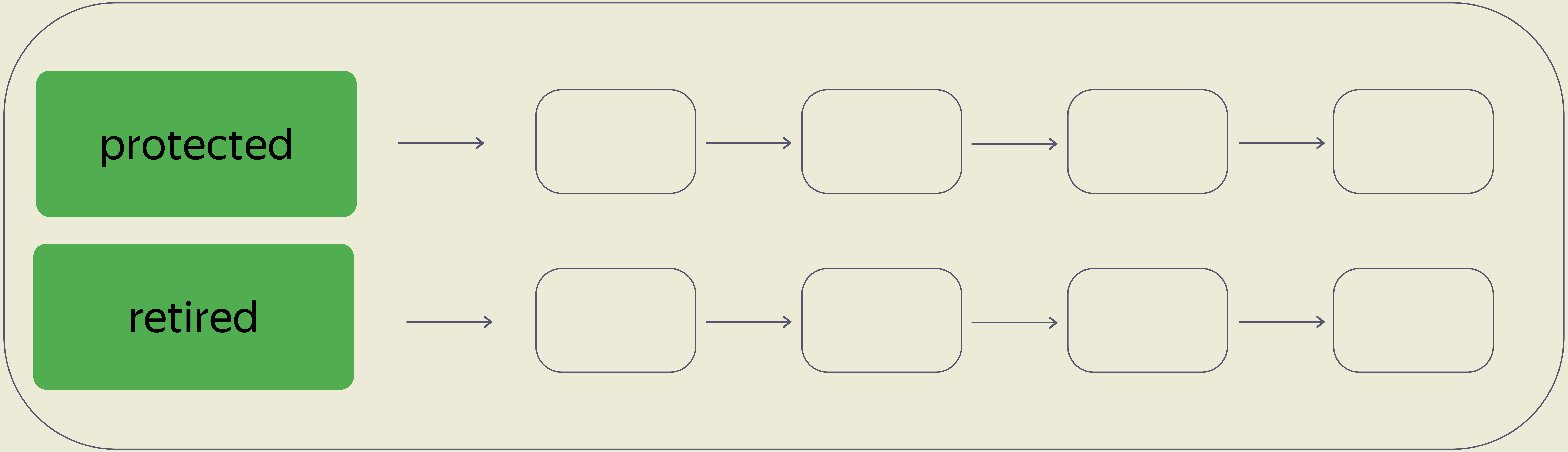
CAS

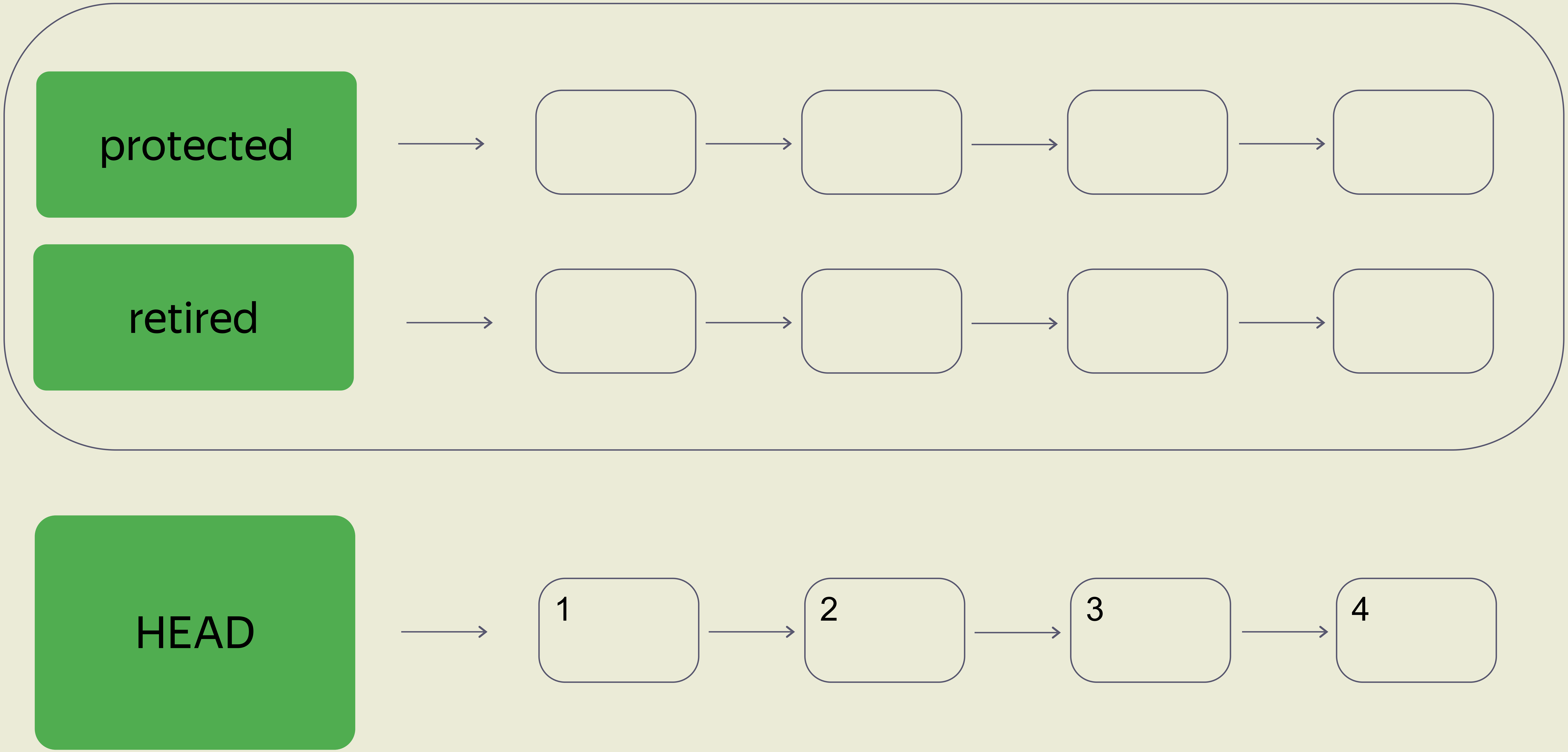


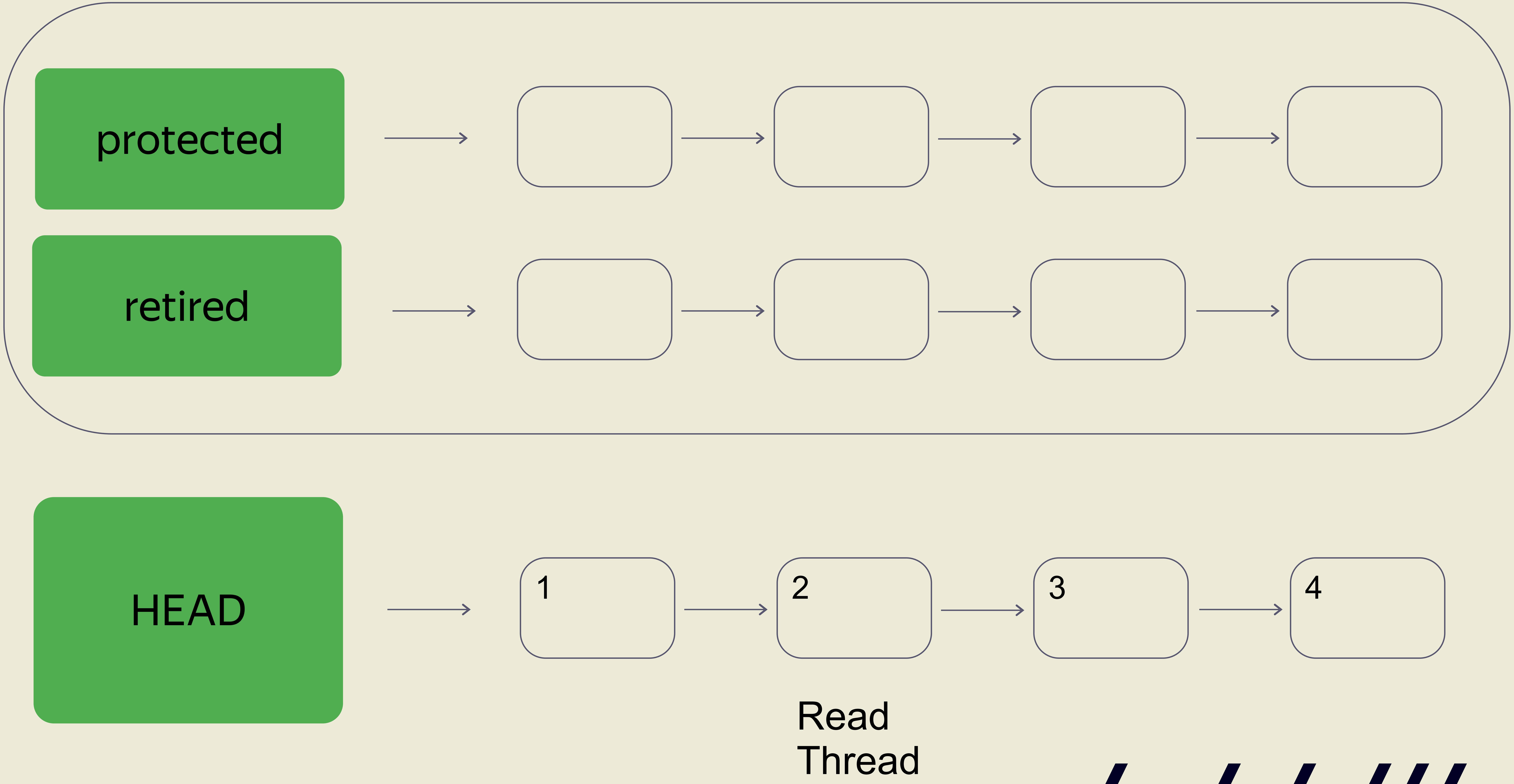
CAS как удалять?



Hazard pointer


protected
retired


protected
retired
HEAD
1
2
3
4



protected

retired

HEAD

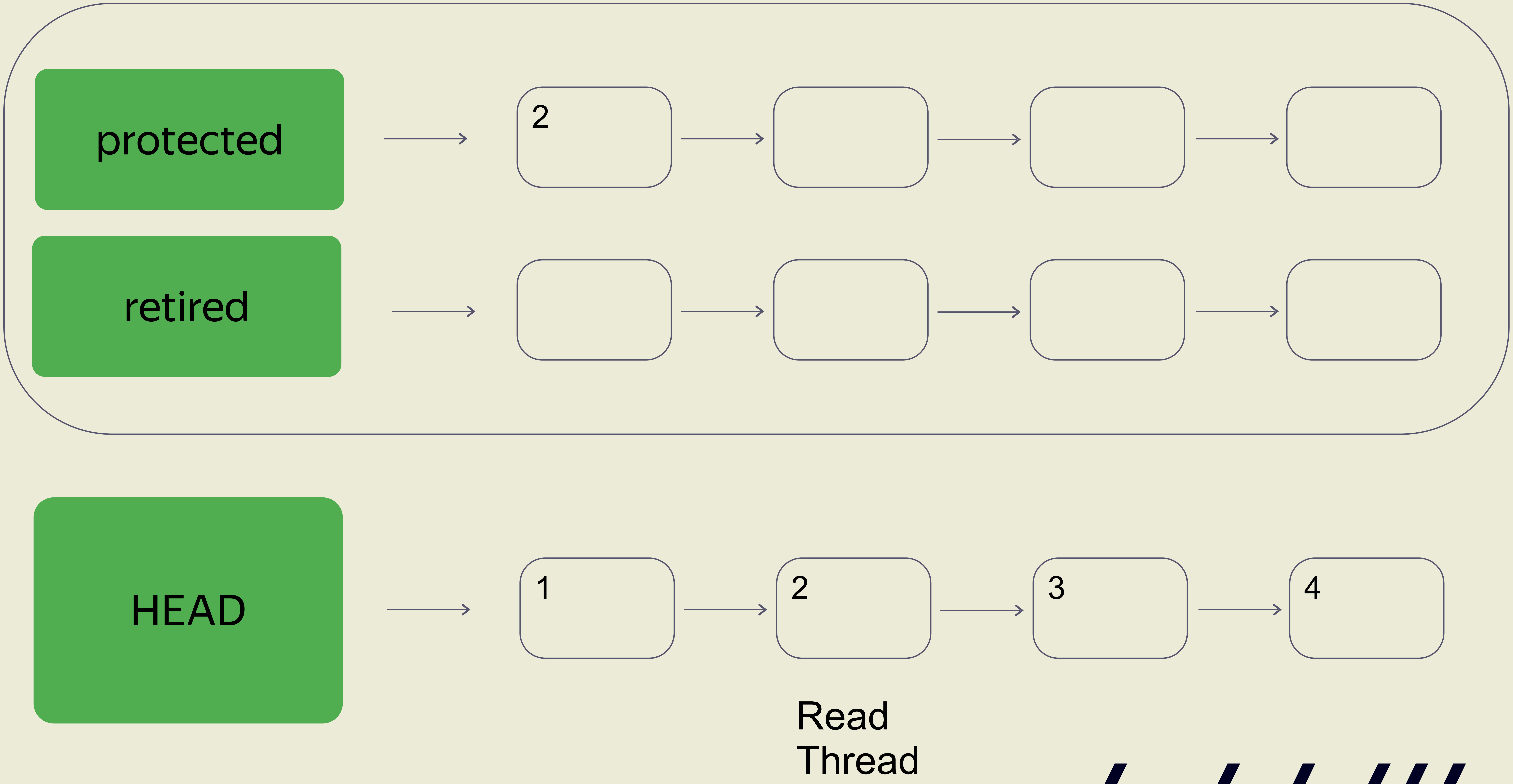
1

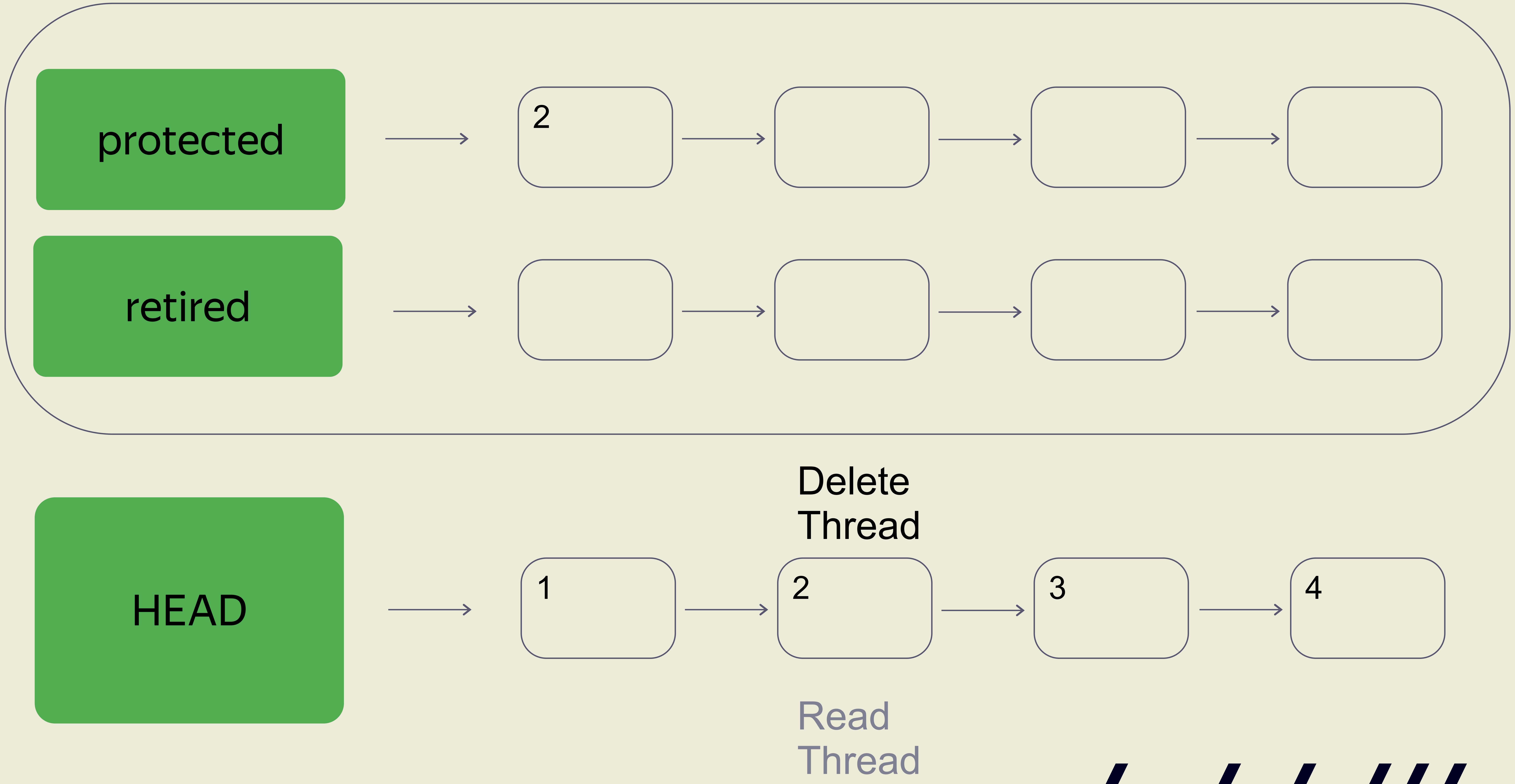
2

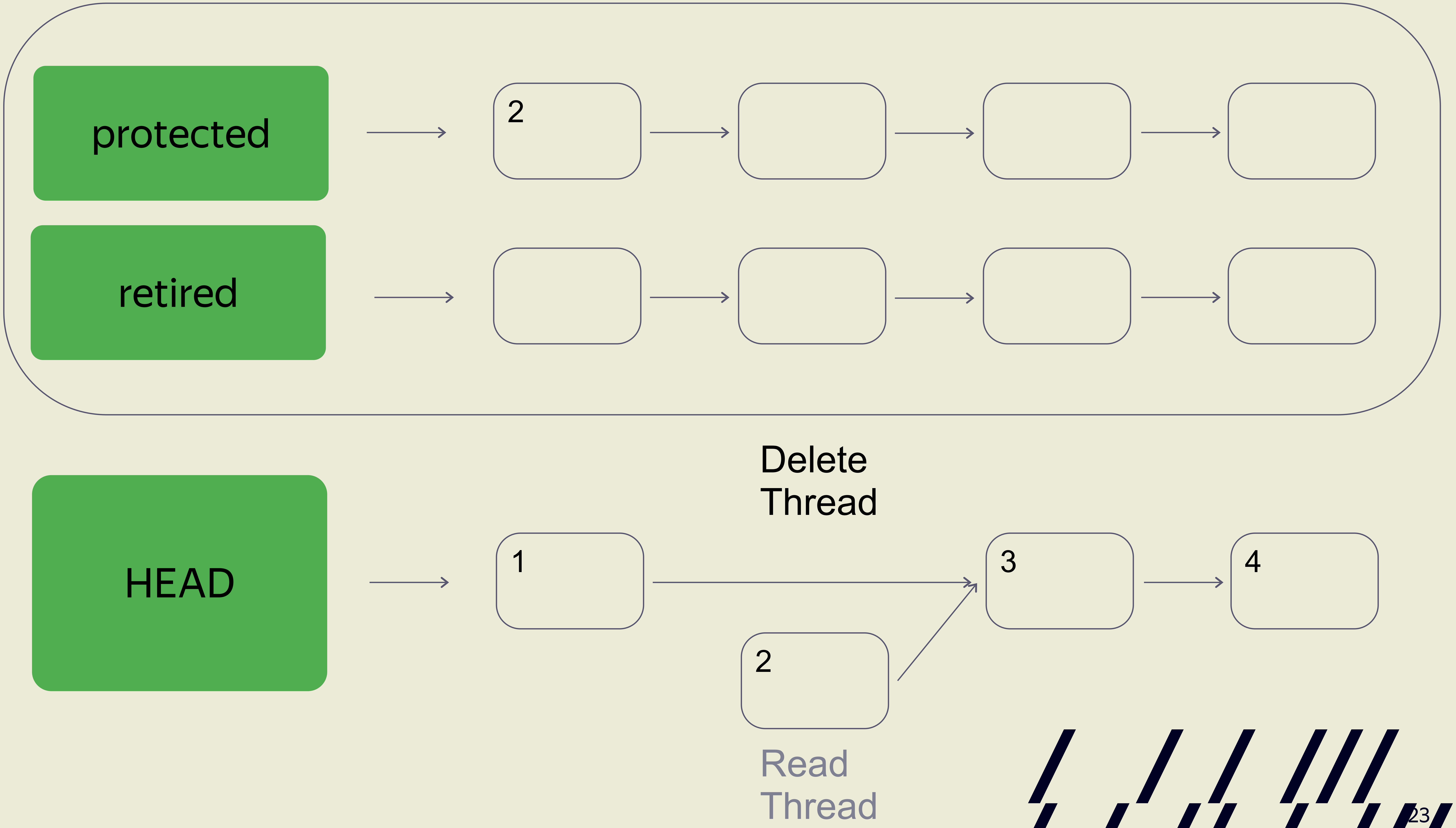
3

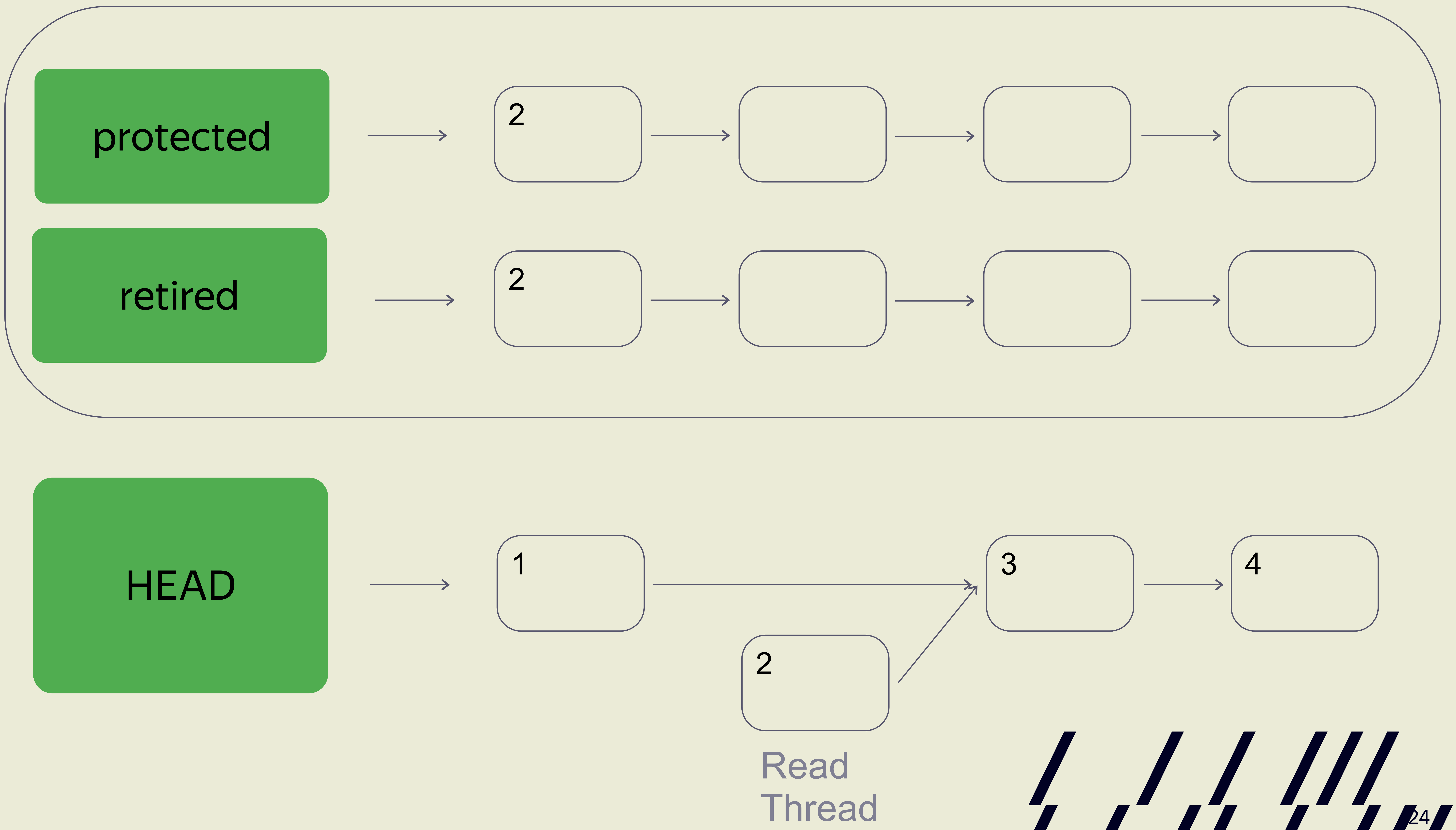
4

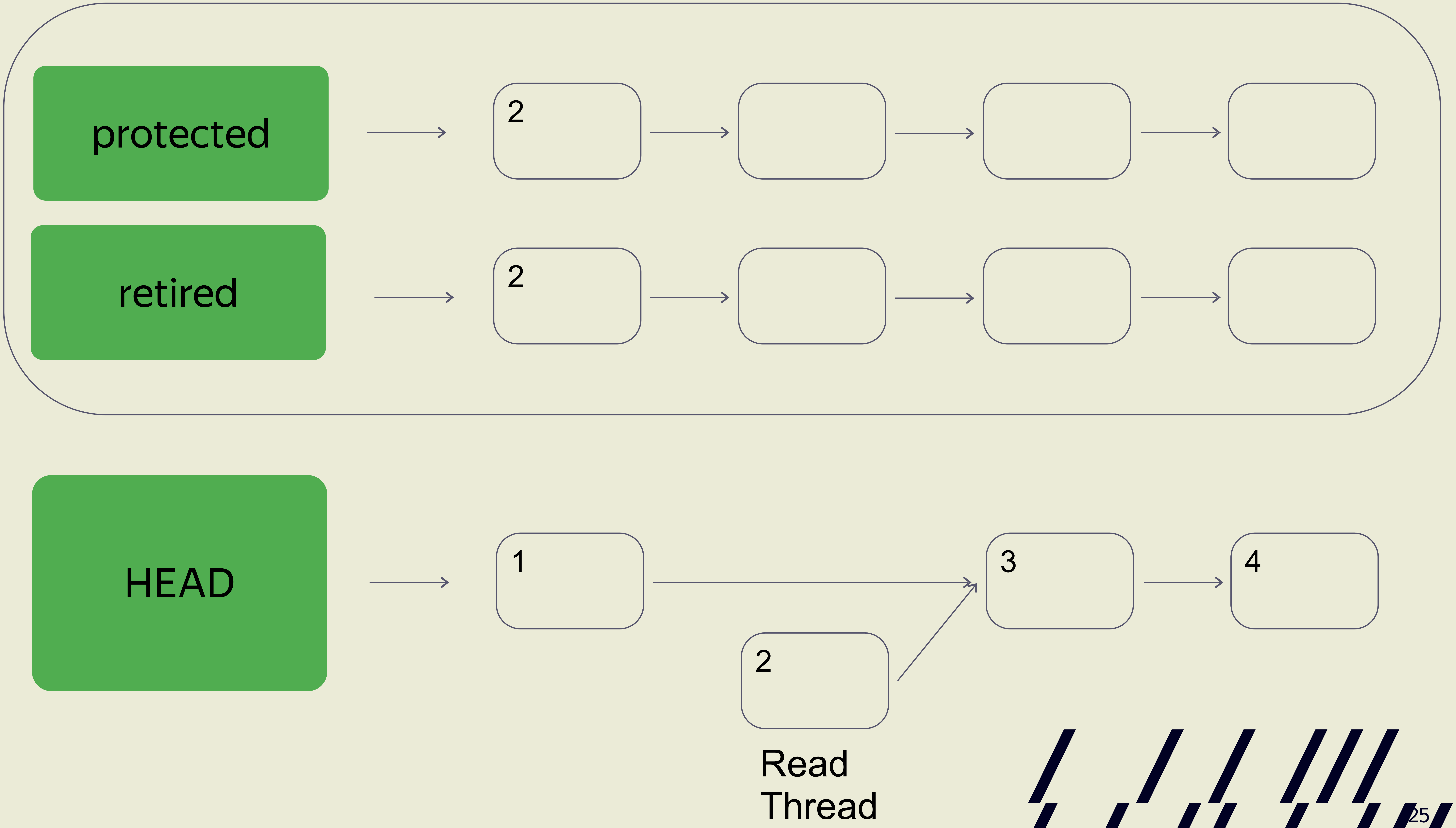
Read
Thread

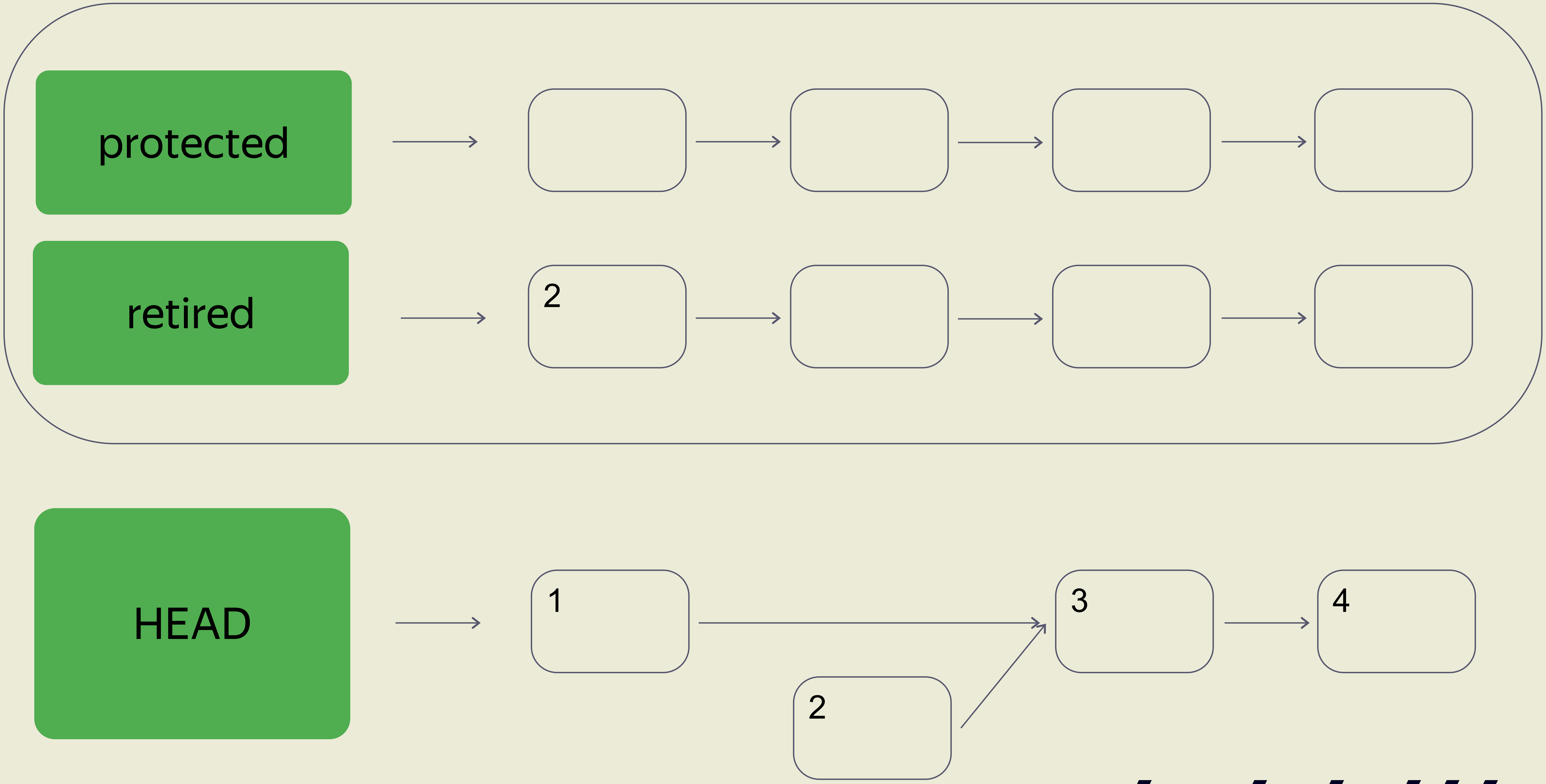

protected
2
retired
HEAD
1
2
3
4
Read Thread


protected
2
retired
Delete Thread
HEAD
1
2
3
4
Read Thread


protected
2
retired
Delete
Thread
HEAD
1
3
4
2
Read
Thread


protected
2
retired
2
HEAD
1
3
4
2
Read Thread


protected
2
retired
2
HEAD
1
3
4
2
Read Thread



protected

retired

2

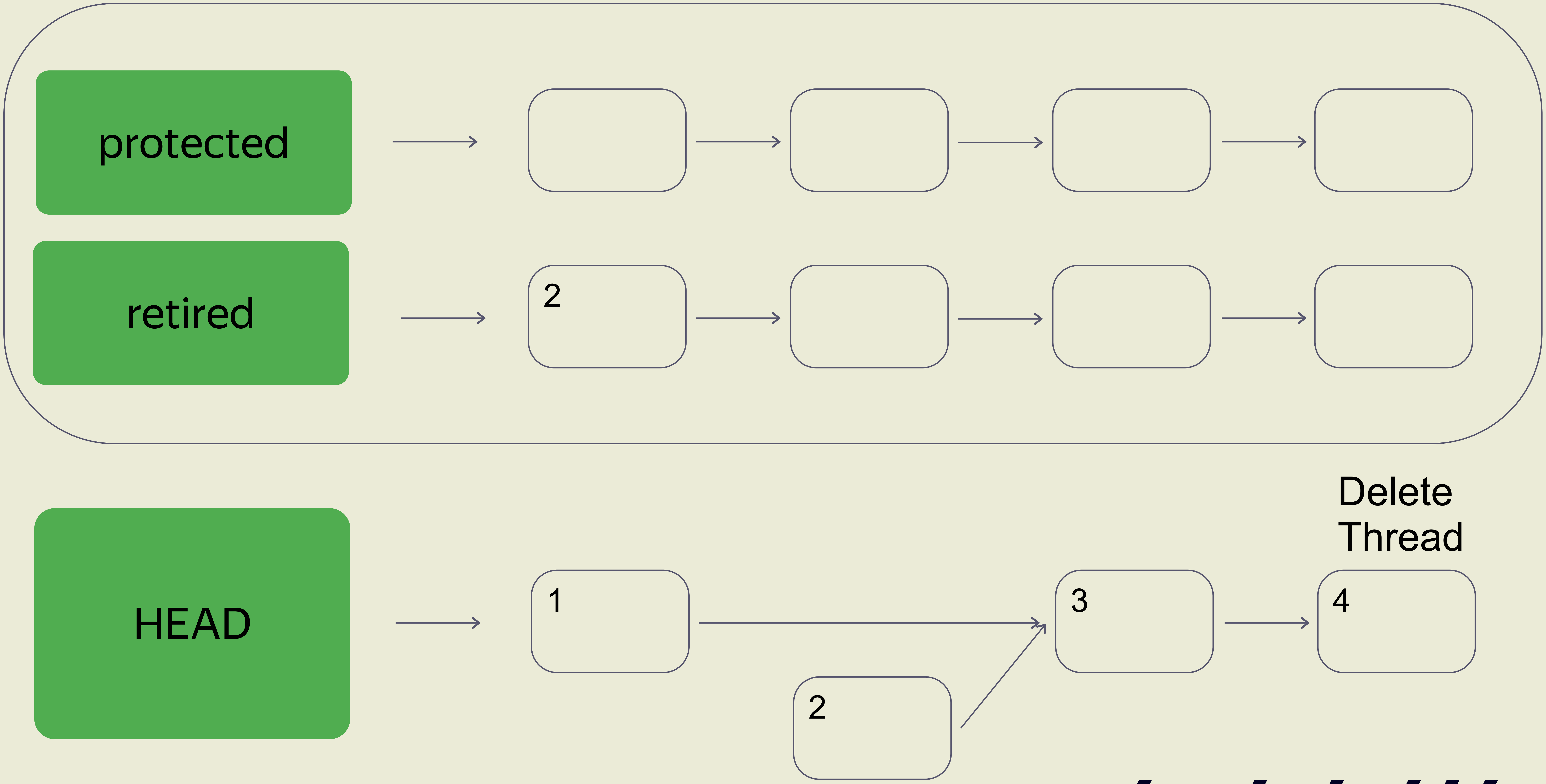
HEAD

1

3

4

2



protected

retired

2

HEAD

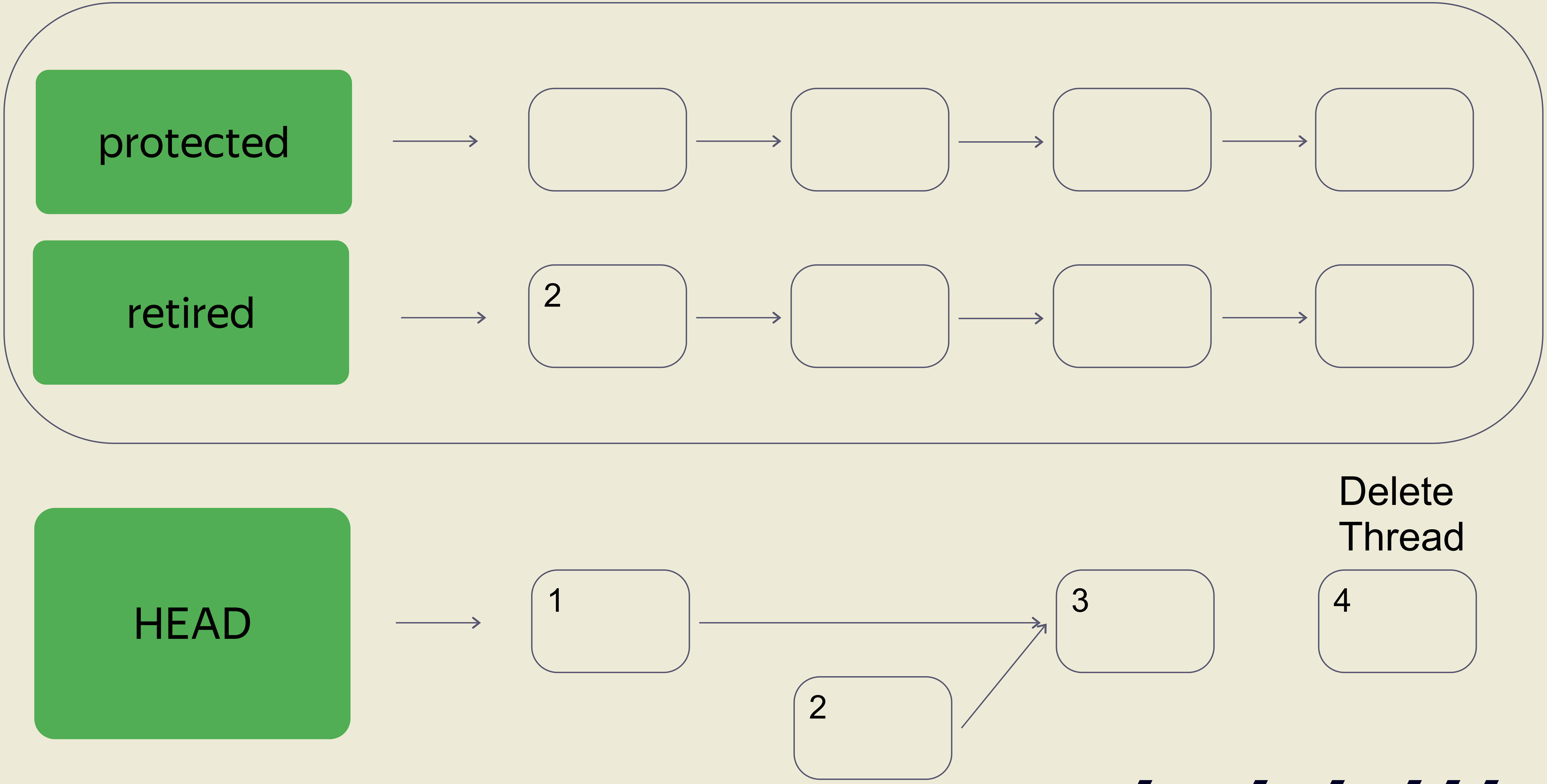
1

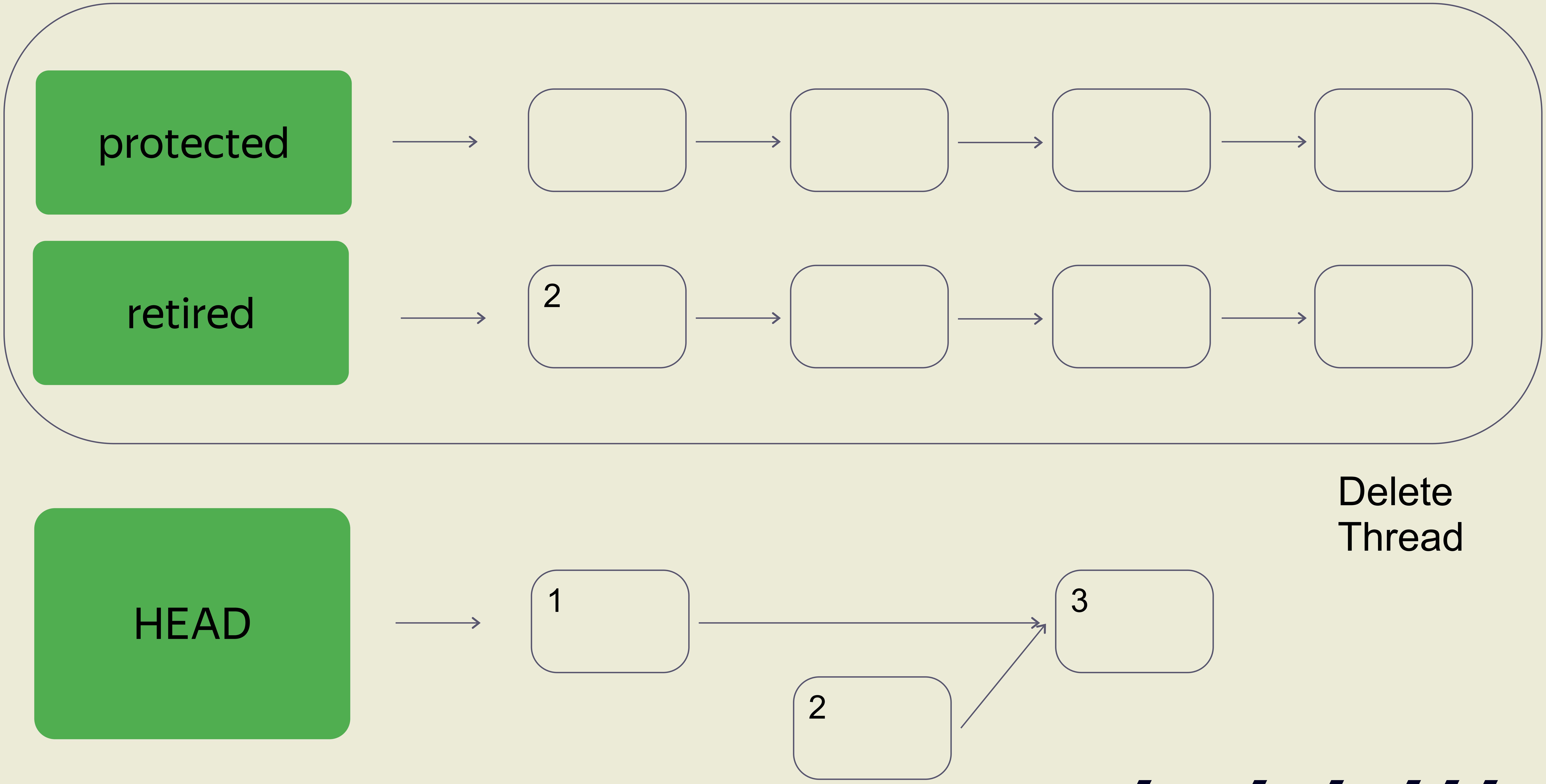
2

3

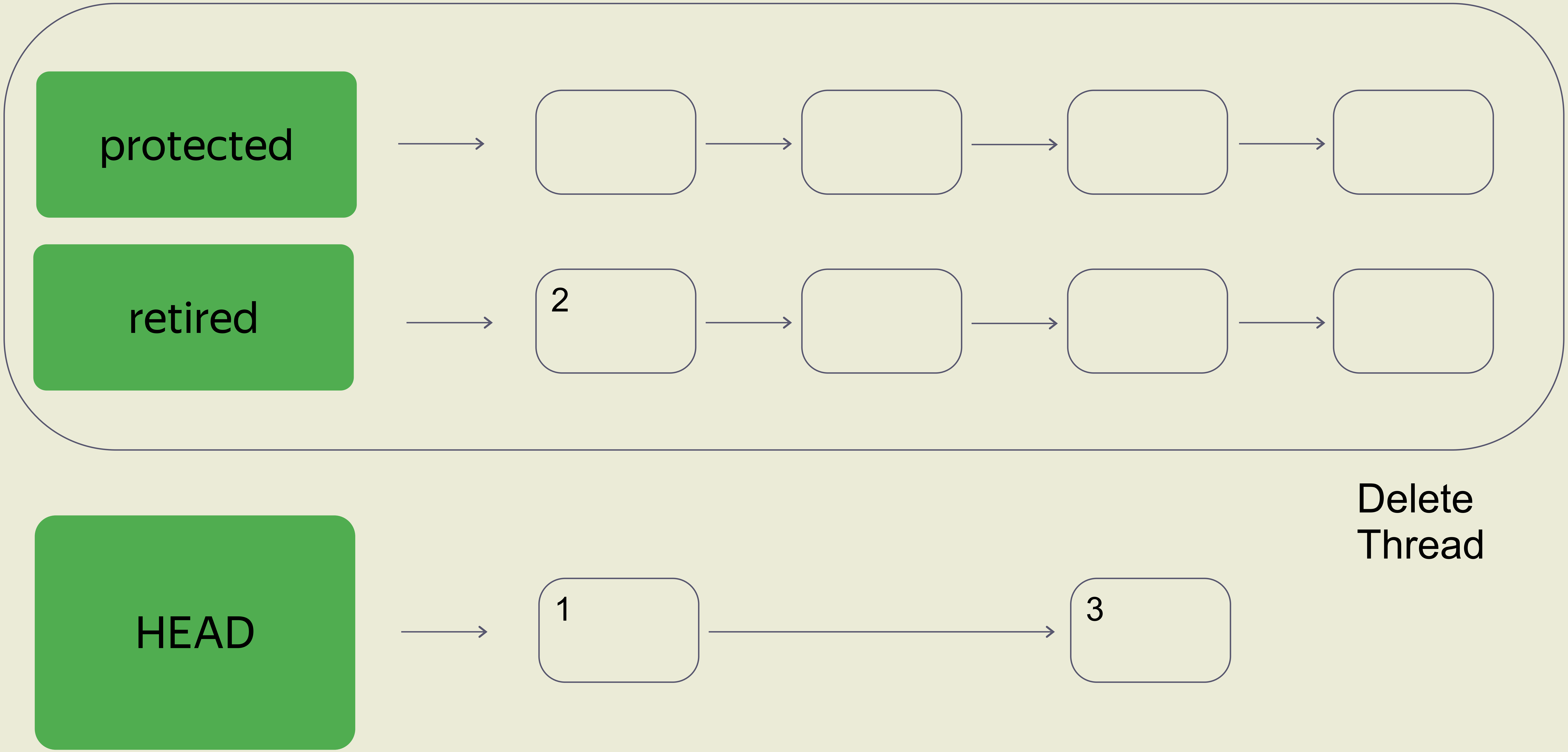
Delete Thread

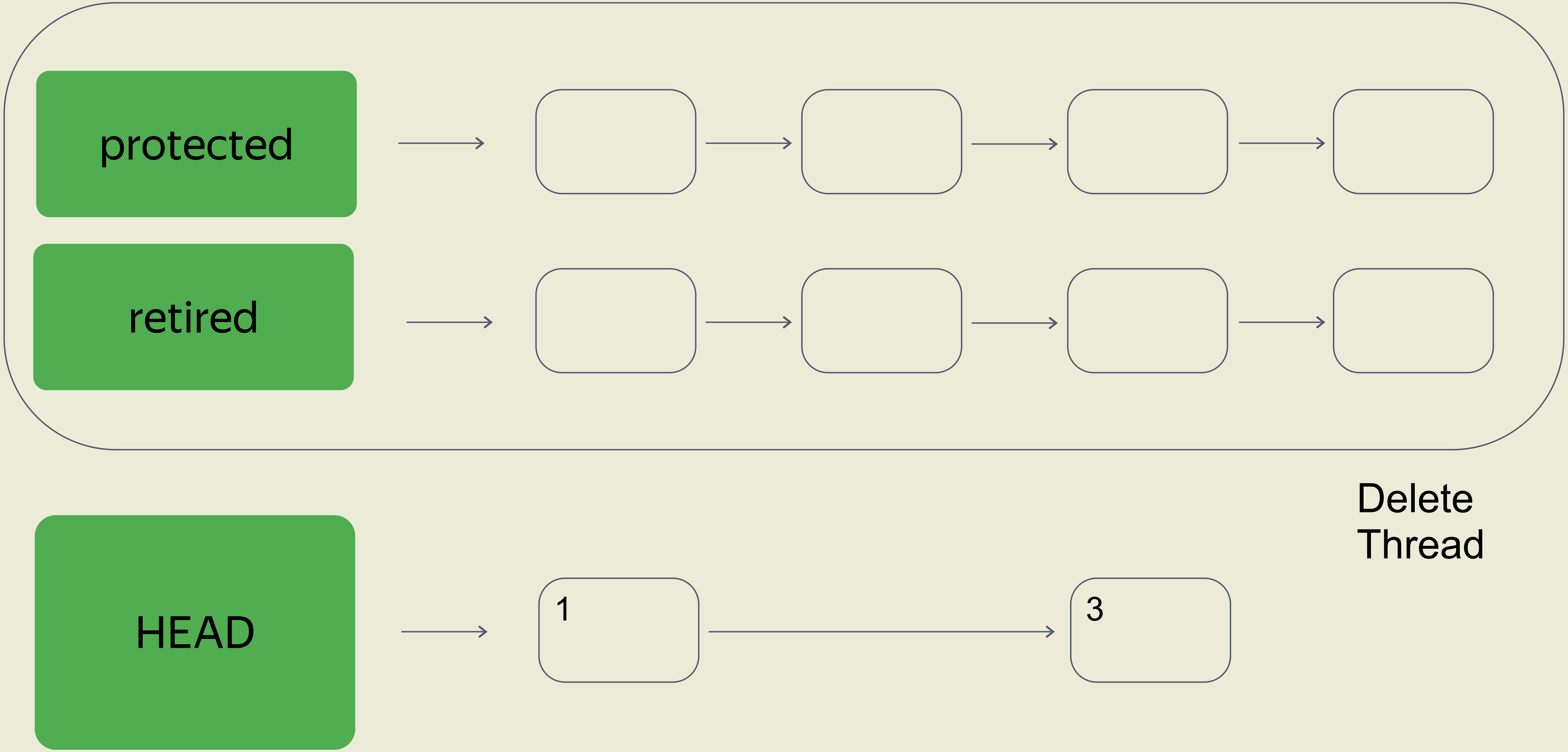
4


protected
retired
2
HEAD
1
3
Delete Thread
4
2



Delete Thread


protected
retired
2
Delete Thread
HEAD
1
3



protected

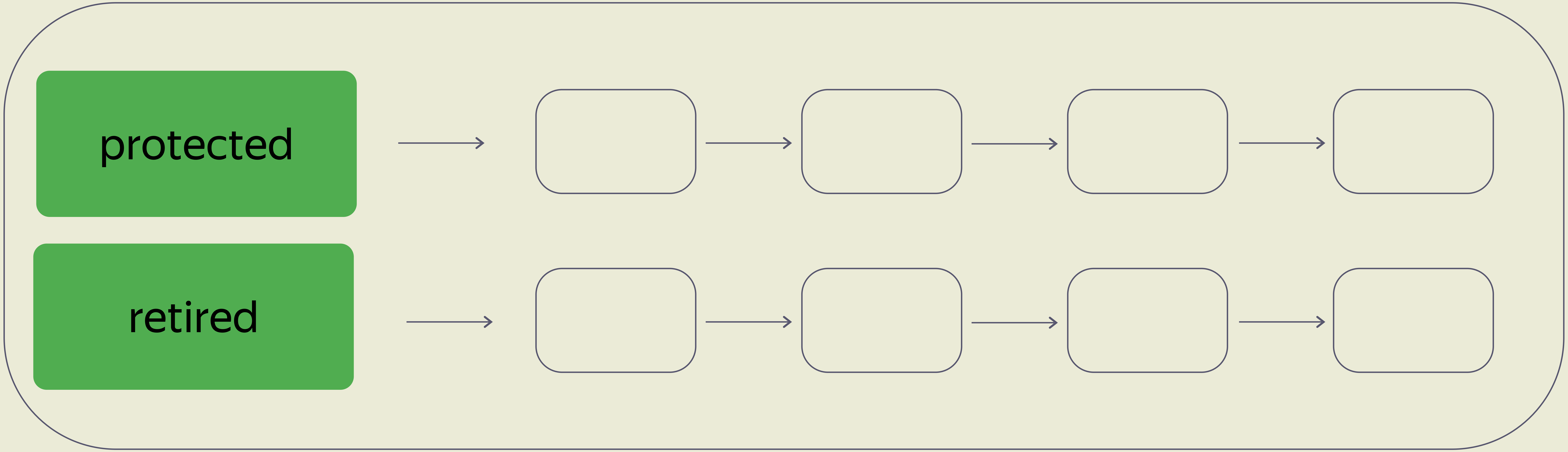
retired

HEAD

1

3

Delete
Thread



```
const unsigned max_hazard_pointers = 100;

struct hazard_pointer{
  std::atomic<std::thread::id> id;
  std::atomic<void*> pointer;
};

hazard_pointer hazard_pointers[max_hazard_pointers];
std::atomic<data_to_reclaim*> nodes_to_reclaim;
```

```
std::shared_ptr<T> pop(){
  std::atomic<void*>& hp = get_hazard_pointer_for_current_thread();
  node<T>* old_head = head.load();

  do {
    node<T>* temp;
    do{
      temp = old_head;
      hp.store(old_head);
      old_head = head.load();
    } while(old_head != temp)
  } while(old_head &&
          !head.compare_exchange_weak(old_head, old_head->next));

  hp.store(nullptr);

  std::shared_ptr<T> res;
  if (old_head){
    res.swap(old_head->data);
    if(outstanding_hazard_pointers_for(old_head)){
      reclaim_latter(old_head);
    } else {
      delete old_head;
    }
  }
  delete_nodes_with_no_hazards();
  return res;
}
```

```
std::shared_ptr<T> pop(){
  std::atomic<void*>& hp = get_hazard_pointer_for_current_thread();
  // ...
}
```

```
class hp_owner{
  hazard_pointer* hp_;
public:
  hp_owner(const hp_owner&) = delete;
  hp_owner operator=(const hp_owner&) = delete;

  hp_owner();
  ~hp_owner();

  std::atomic<void*>& get_pointer(){
    return hp_->pointer;
  }
};


std::atomic<void*>& get_hazard_pointer_for_current_thread(){
  thread_local static hp_owner hazard;
  return hazard.get_pointer();
}
```

```
const unsigned max_hazard_pointers = 100;

struct hazard_pointer{
  std::atomic<std::thread::id> id;
  std::atomic<void*> pointer;
};

hazard_pointer hazard_pointers[max_hazard_pointers];
```

```
hp_owner(): hp_(nullptr) {
  for(auto& hazard_pointer : hazard_pointers){
    std::thread::id old_id;
    if(hazard_pointer.id.compare_exchange_strong(old_id,
                                                 std::this_thread::get_id()))
    {
      hp_ = &hazard_pointer;
      break;
    }
  }
  if(!hp_) throw std::runtime_error(«No hp available»);
}
```

```
~hp_owner(){
  hp->pointer.store(nullptr);
  hp->id.store(std::thread::id());
}
```

```
class hp_owner{
  hazard_pointer* hp;
public:
  hp_owner(const hp_owner&) = delete;
  hp_owner operator=(const hp_owner&) = delete;

  hp_owner();
  ~hp_owner();

  std::atomic<void*>& get_pointer();
};


std::atomic<void*>& get_hazard_pointer_for_current_thread(){
  thread_local static hp_owner hazard;
  return hazard.get_pointer();
}
```

```
std::shared_ptr<T> pop(){
  std::atomic<void*>& hp = get_hazard_pointer_for_current_thread();
  node<T>* old_head = head.load();

  do {
    node<T>* temp;
    do{
      temp = old_head;
      hp.store(old_head);
      old_head = head.load();
    } while(old_head != temp)
  } while(old_head && !head.compare_exchange_weak(old_head, old_head->next));

  // ...
}
```

```
std::shared_ptr<T> pop(){
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   hp.store(old_head);
   old_head = head.load();
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 } while(old_head && !head.compare_exchange_weak(old_head, old_head->next));

 // ...
}
```

```
std::shared_ptr<T> pop(){
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  node<T>* old_head = head.load();

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    node<T>* temp;
    do{
      temp = old_head;
      hp.store(old_head);
      old_head = head.load();
    } while(old_head != temp)
  } while(old_head && !head.compare_exchange_weak(old_head, old_head->next));

  // ...
}
```
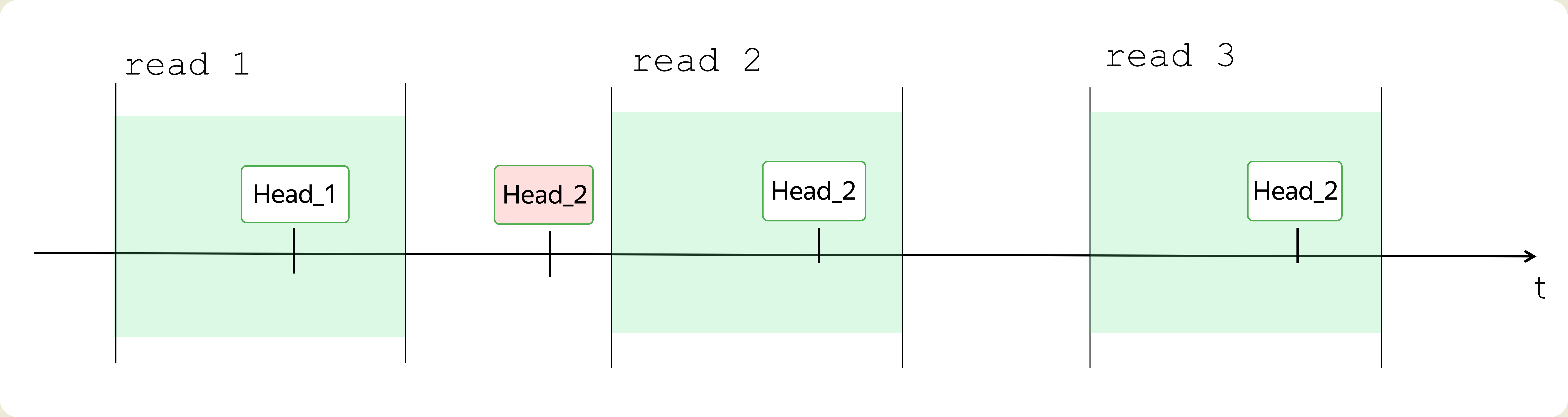



```
std::shared_ptr<T> pop(){
  std::atomic<void*>& hp = get_hazard_pointer_for_current_thread();
  node<T>* old_head = head.load();

  do {
      // ...
  } while(old_head &&
          !head.compare_exchange_weak(old_head, old_head->next));

  hp.store(nullptr);

  std::shared_ptr<T> res;
  if (old_head){
    res.swap(old_head->data);
    if(outstanding_hazard_pointers_for(old_head)){
      reclaim_latter(old_head);
    } else {
      delete old_head;
    }
  }
  delete_nodes_with_no_hazards();
  return res;
}
```

```
std::shared_ptr<T> pop(){
  // ..

  std::shared_ptr<T> res;
  if (old_head){
    res.swap(old_head->data);
    if(outstanding_hazard_pointers_for(old_head)){
      reclaim_latter(old_head);
    } else {
      delete old_head;
    }
  }
  delete_nodes_with_no_hazards();
  return res;
}
```

```cpp
const unsigned max_hazard_pointers = 100;

struct hazard_pointer{
  std::atomic<std::thread::id> id;
  std::atomic<void*> pointer;
};

hazard_pointer hazard_pointers[max_hazard_pointers];
```

```cpp
bool outstanding_hazard_pointers_for(void* p){
  for(auto & hazard_pointer : hazard_pointers){
    if(hazard_pointer.pointer.load() == p){
      return true;
    }
  }
  return false;
}
```

```
std::shared_ptr<T> pop(){
  // ..

  std::shared_ptr<T> res;
  if (old_head){
    res.swap(old_head->data);
    if(outstanding_hazard_pointers_for(old_head)){
      reclaim_latter(old_head);
    } else {
      delete old_head;
    }
  }
  delete_nodes_with_no_hazards();
  return res;
}
```

```
template<typename T>
void do_delete(void* p){
  delete static_cast<T*>(p);
}

struct data_to_reclaim
{
    void* data;
    std::function<void(void*)> deleter;
    data_to_reclaim* next;

    template<typename T>
    data_to_reclaim(T* p):
      data(p),
      deleter(&do_delete<T>),
      next(nullptr)
    {}

    ~data_to_reclaim(){
      deleter(data);
    }
};
```

```
std::atomic<data_to_reclaim*> nodes_to_reclaim;
```

```
void add_to_rlist(data_to_reclaim* node){
  node->next = nodes_to_reclaim.load();
  while(!nodes_to_reclaim.compare_exchange_weak(
                 node->next, node));
}

template<typename T>
void reclaim_later(T* data){
  add_to_reclaim_list(new data_to_reclaim(data));
}
```

```
template<typename T>
void do_delete(void* p){
  delete static_cast<T*>(p);
}

struct data_to_reclaim
{
    void* data;
    std::function<void(void*)> deleter;
    data_to_reclaim* next;

    template<typename T>
    data_to_reclaim(T* p):
      data(p),
      deleter(&do_delete<T>),
      next(nullptr)
    {}

    ~data_to_reclaim(){
      deleter(data);
    }
};
```

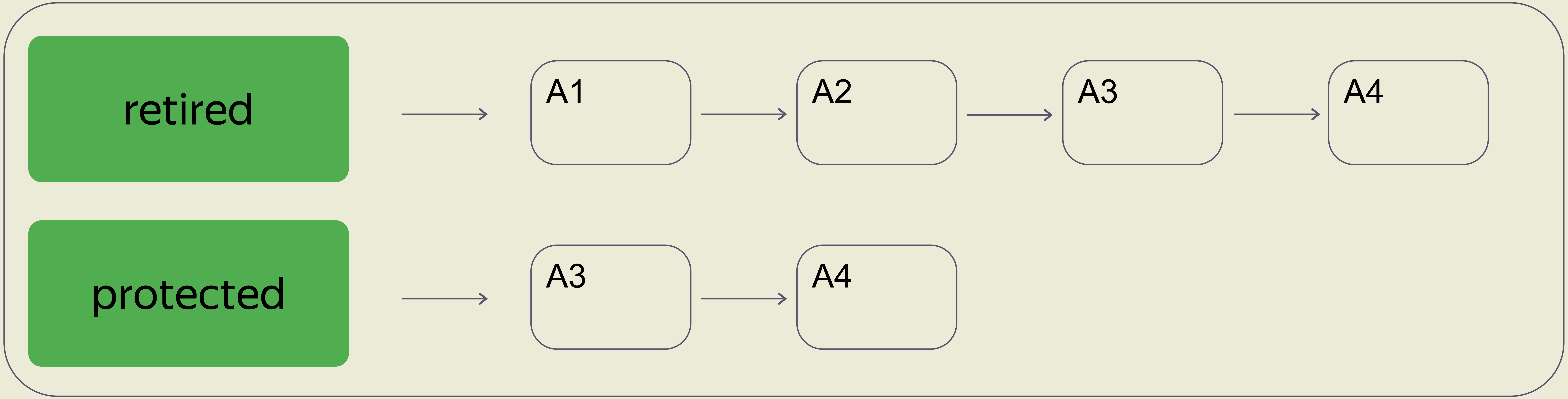
```
std::atomic<data_to_reclaim*> nodes_to_reclaim;
```

```
void add_to_rlist(data_to_reclaim* node){
  node->next = nodes_to_reclaim.load();
  while(!nodes_to_reclaim.compare_exchange_weak(
                 node->next, node));
}

template<typename T>
void reclaim_later(T* data){
  add_to_reclaim_list(new data_to_reclaim(data));
}
```

```
std::shared_ptr<T> pop(){
  // ...

  std::shared_ptr<T> res;
  // ...
  delete_nodes_with_no_hazards();
  return res;
}
```

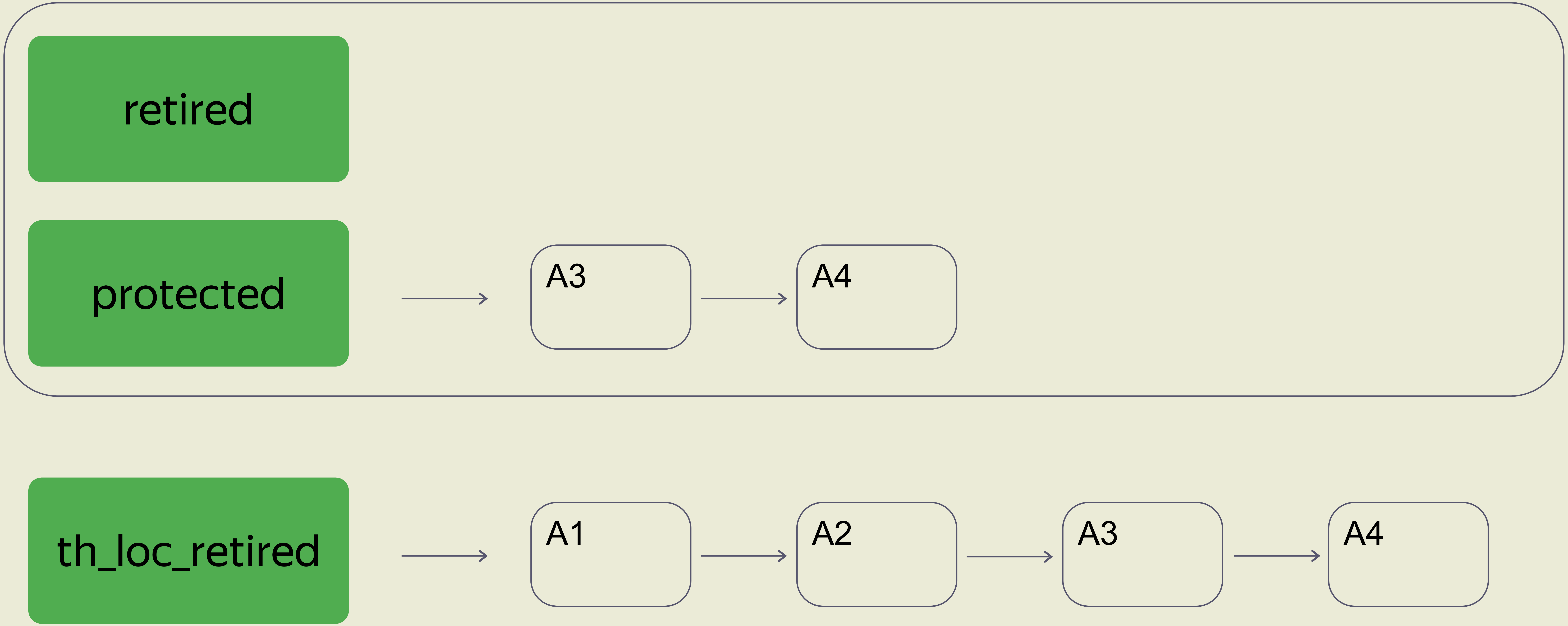
```
std::atomic<data_to_reclaim*> nodes_to_reclaim;
```

```
void delete_nodes_with_no_hazard(){
  data_to_reclaim* current = nodes_to_reclaim.exchange(nullptr);
  while (current)
  {
    data_to_reclaim* const next = current->next;
    if(!outstanding_hazard_pointers_for(current->data)){
      delete current;
    } else {
      add_to_reclaim_list(current);
    }
    current = next;
  }
}
```



retired → A1 → A2 → A3 → A4

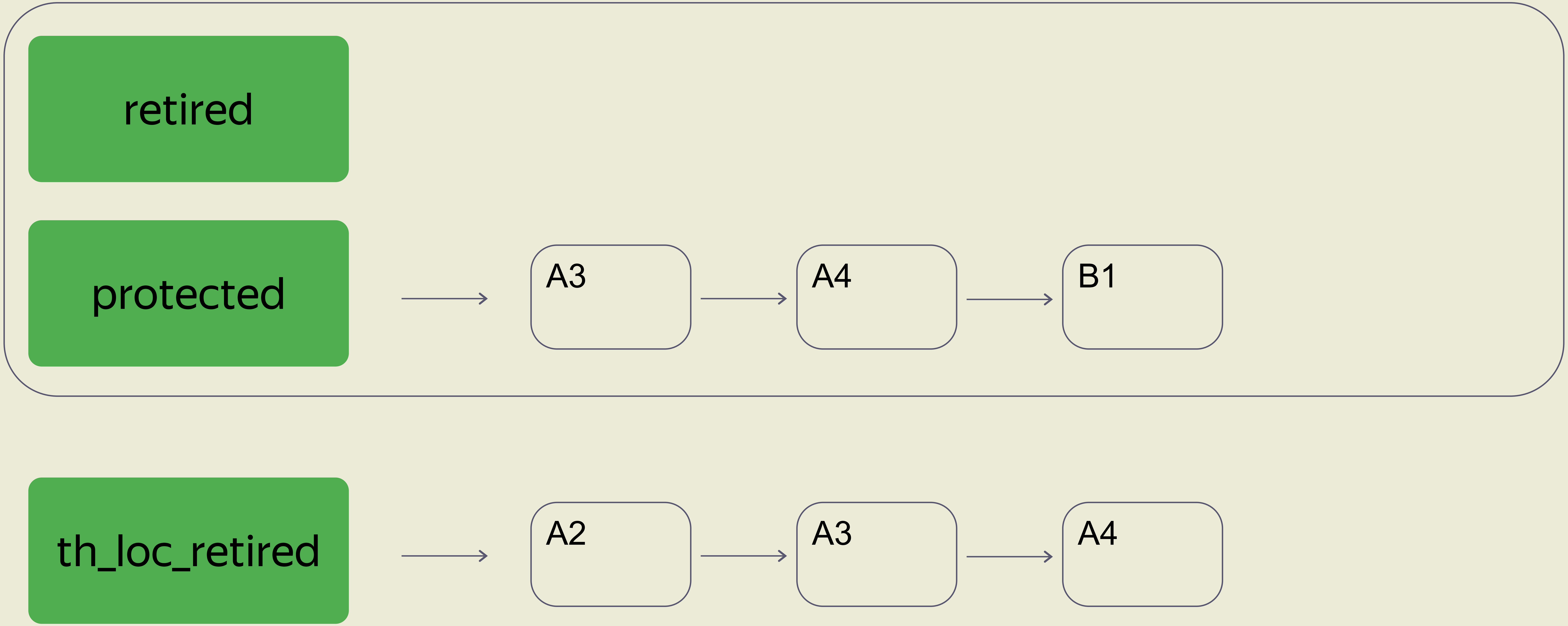
protected → A3 → A4



retired

protected → A3 → A4

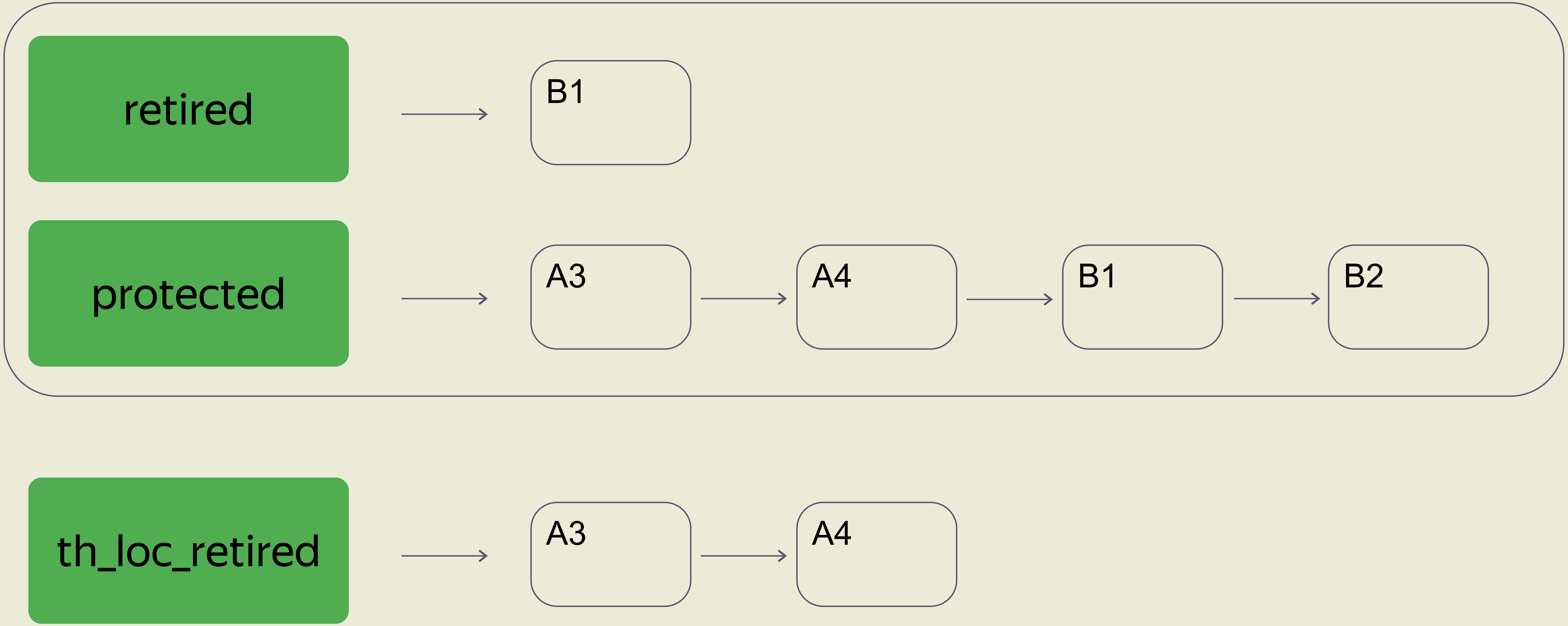
th_loc_retired → A1 → A2 → A3 → A4



retired

protected → A3 → A4 → B1

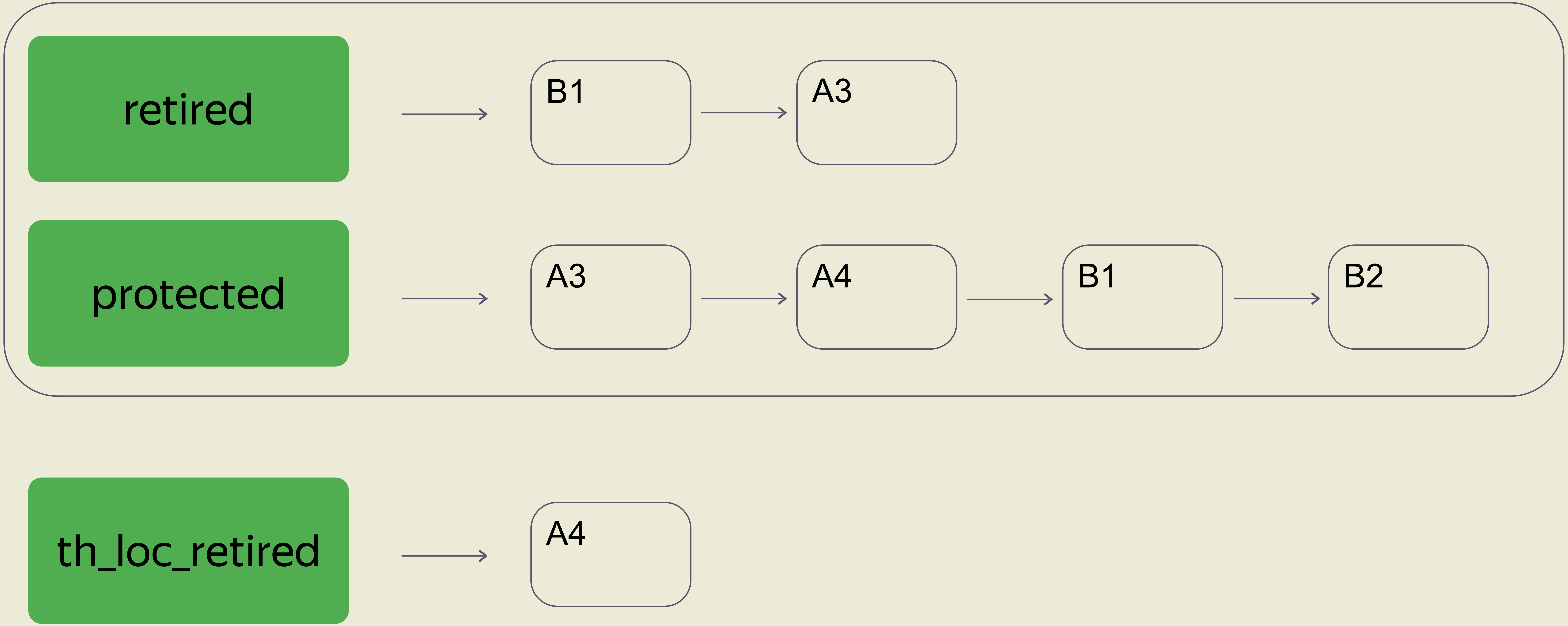
th_loc_retired → A2 → A3 → A4



retired → B1

protected → A3 → A4 → B1 → B2

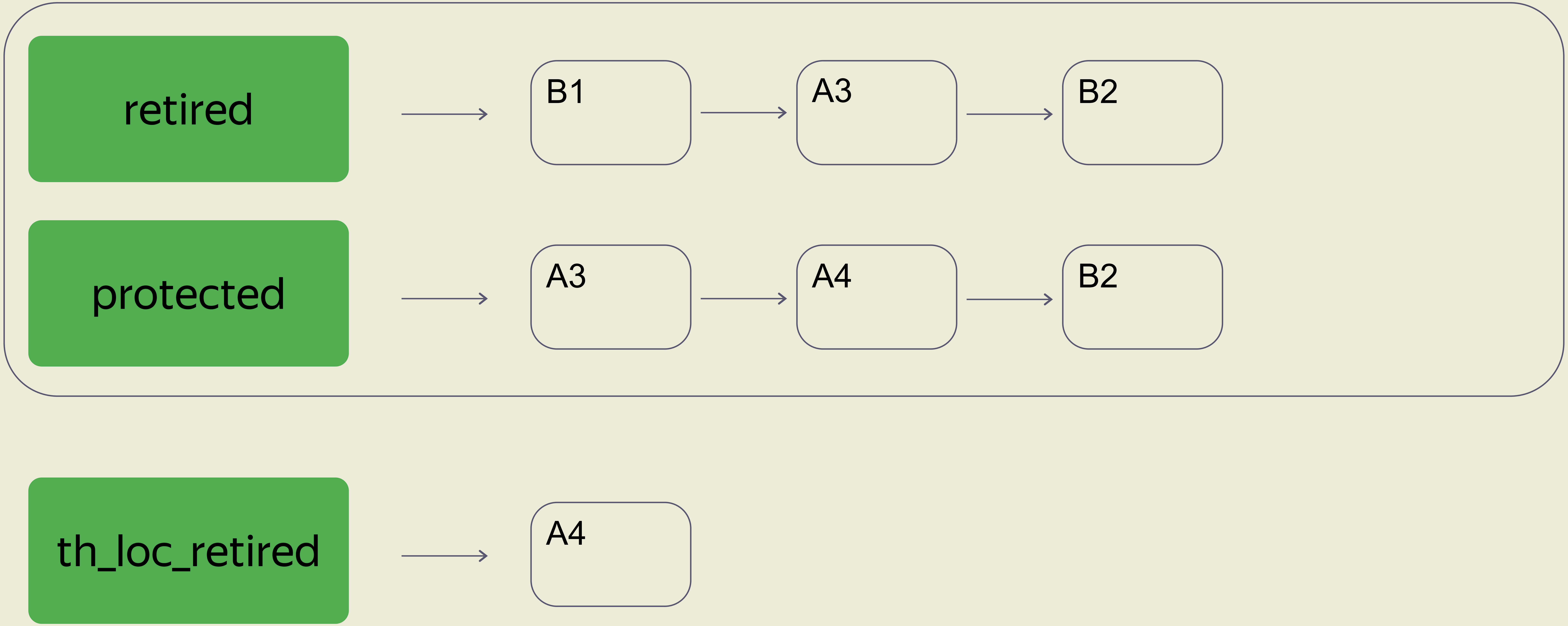
th_loc_retired → A3 → A4

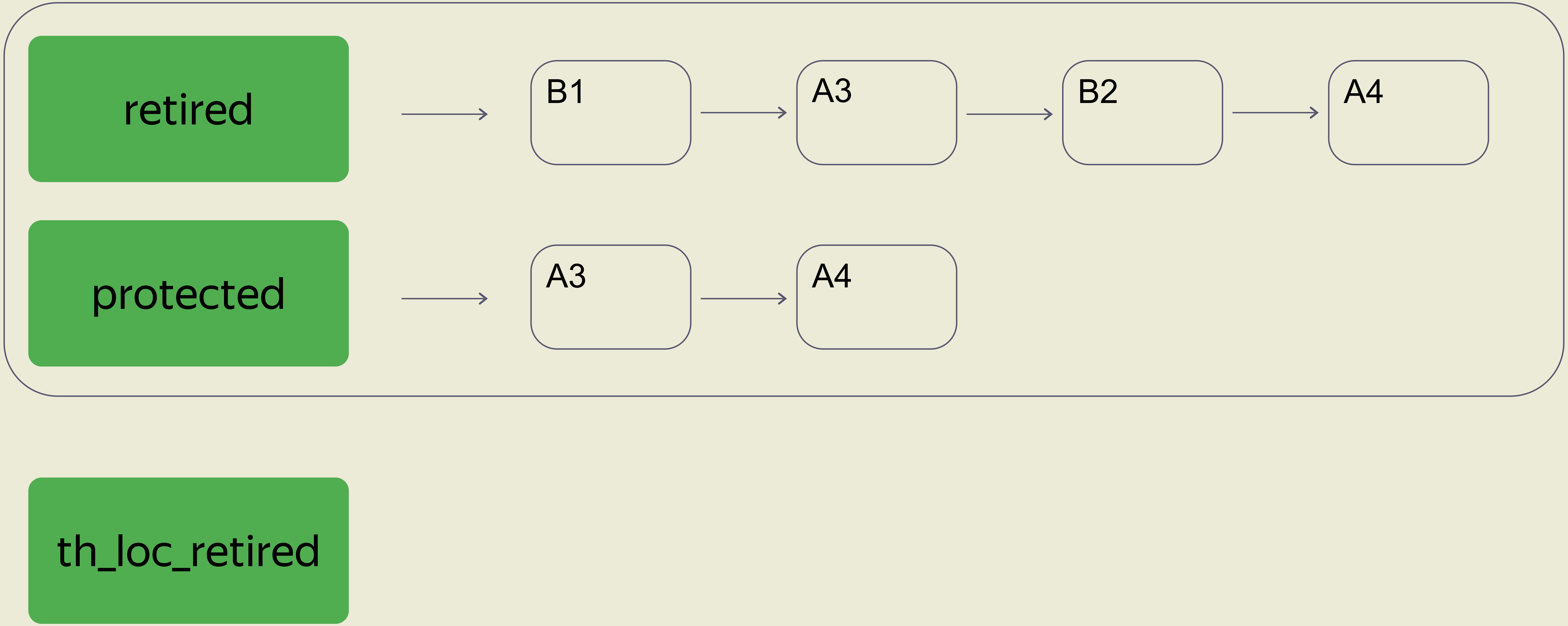


retired → B1 → A3

protected → A3 → A4 → B1 → B2

th_loc_retired → A4


retired
B1
A3
B2
protected
A3
A4
B2
th_loc_retired
A4



retired → B1 → A3 → B2 → A4

protected → A3 → A4

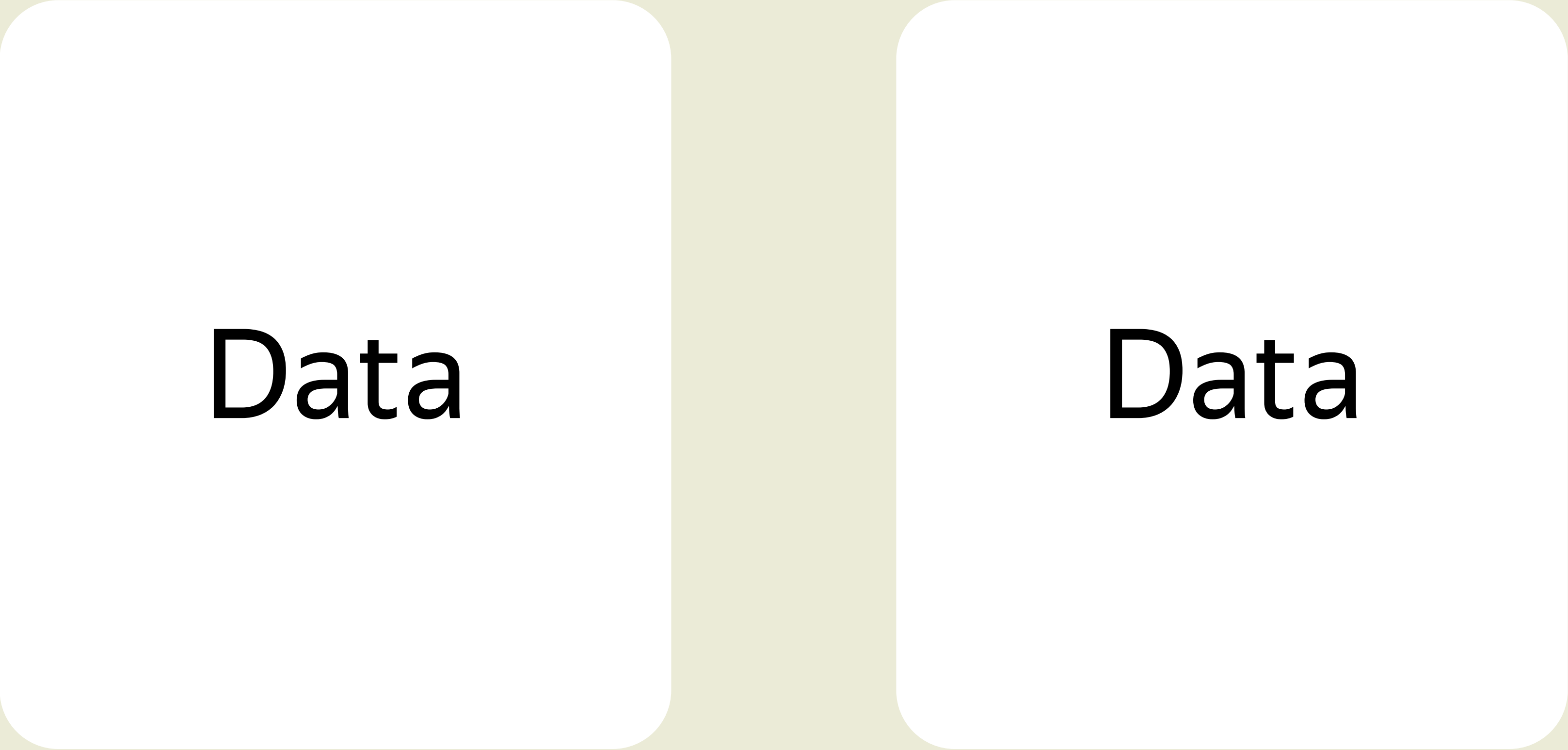
th_loc_retired

```
std::shared_ptr<T> pop(){
  std::atomic<void*>& hp = get_hazard_pointer_for_current_thread();
  node<T>* old_head = head.load();

  do {
    node<T>* temp;
    do{
      temp = old_head;
      hp.store(old_head);
      old_head = head.load();
    } while(old_head != temp)
  } while(old_head &&
          !head.compare_exchange_weak(old_head, old_head->next));

  hp.store(nullptr);

  std::shared_ptr<T> res;
  if (old_head){
    res.swap(old_head->data);
    if(outstanding_hazard_pointers_for(old_head)){
      reclaim_latter(old_head);
    } else {
      delete old_head;
    }
  }
  delete_nodes_with_no_hazards();
  return res;
}
```

```
// однопоточный stack
std::shared_ptr<T> pop(){
  if (head == nullptr)
    return nullptr;

  std::shared_ptr<T>
       res = head->data;

  head = head->next;
  return res;
}
```

Снимки атомарных регистров

Регистры LOCK-FREE

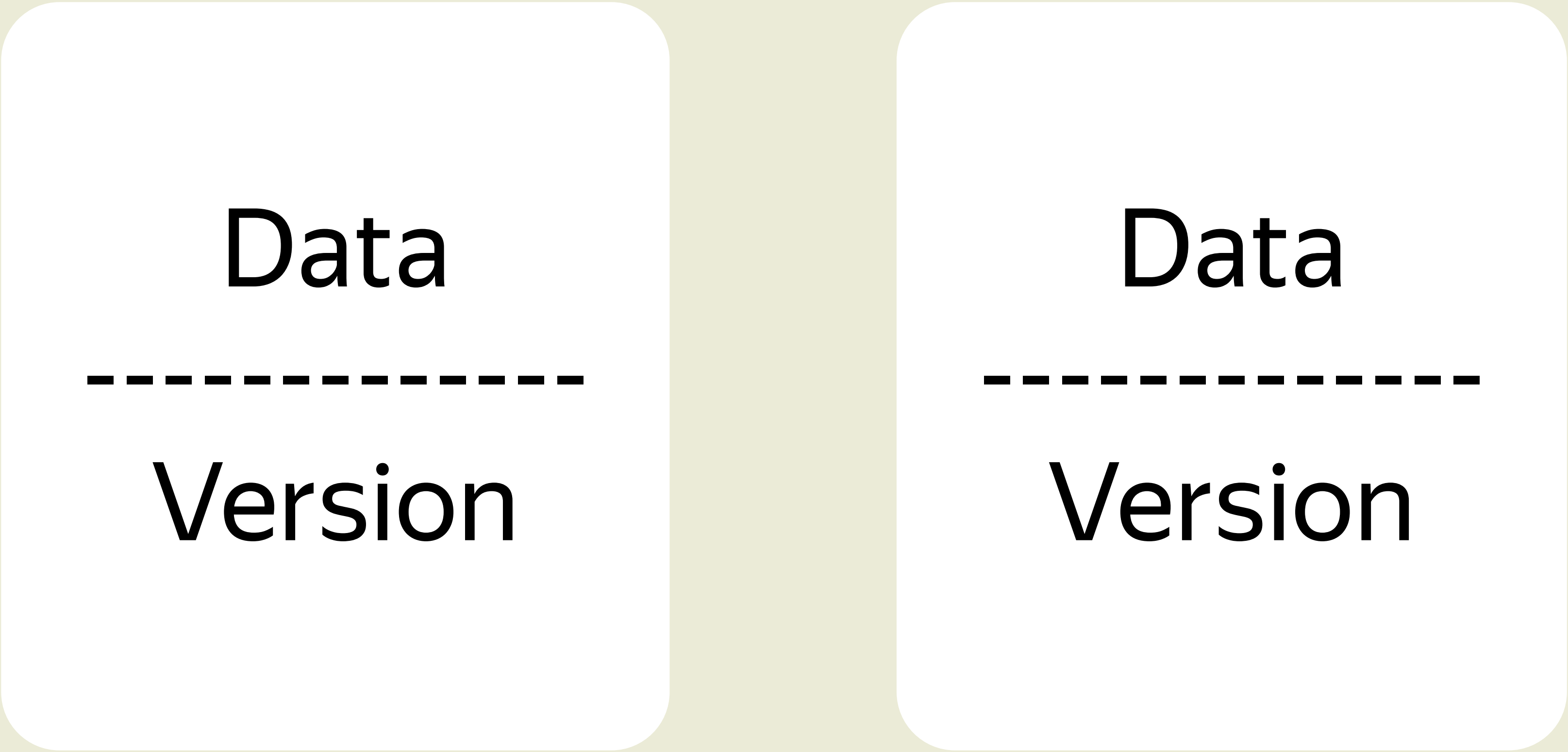


Data

Data

Время	(D)	(D)
1	(0)	(0)
2	(1)	(0)
3	(1)	(1)
4	(2)	(0)

Регистры LOCK-FREE



Data

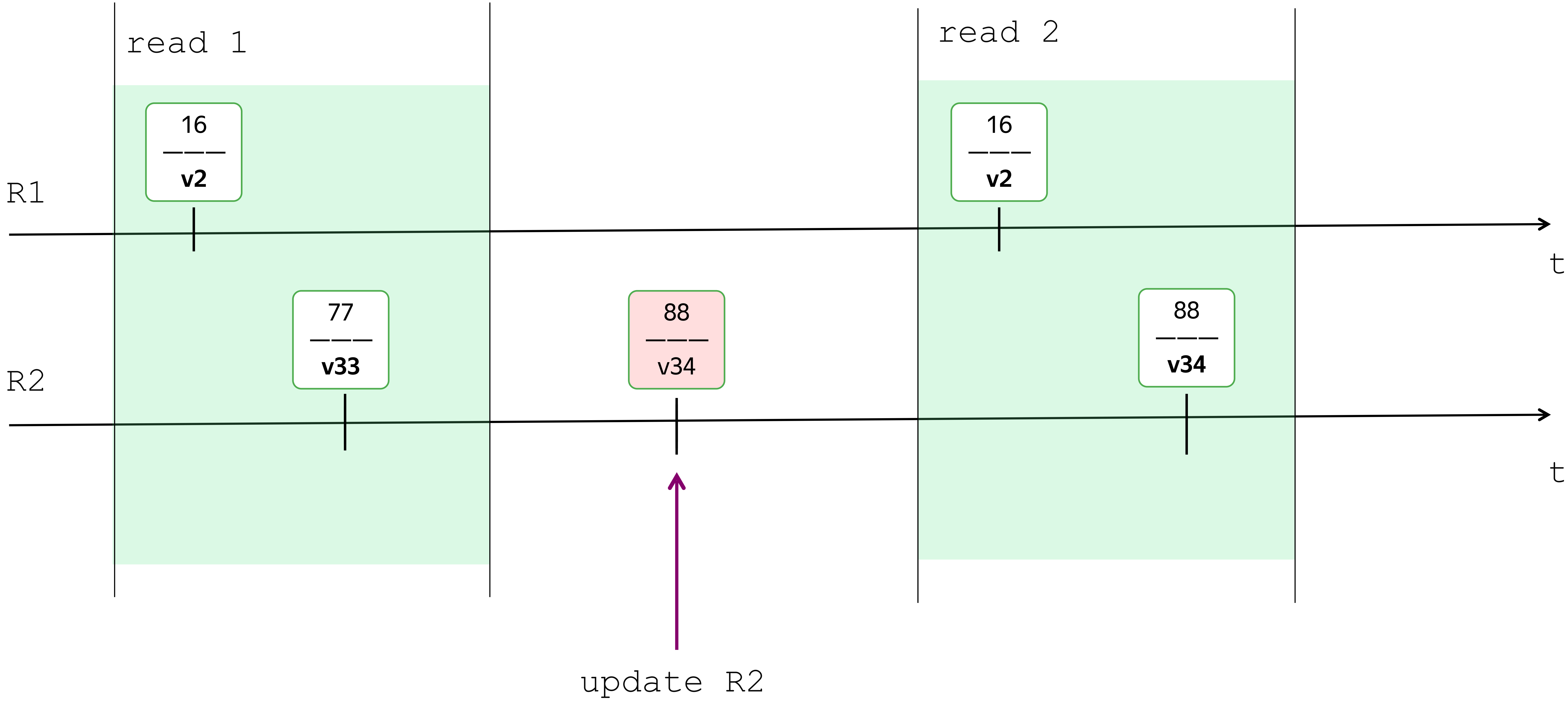
Version

Data

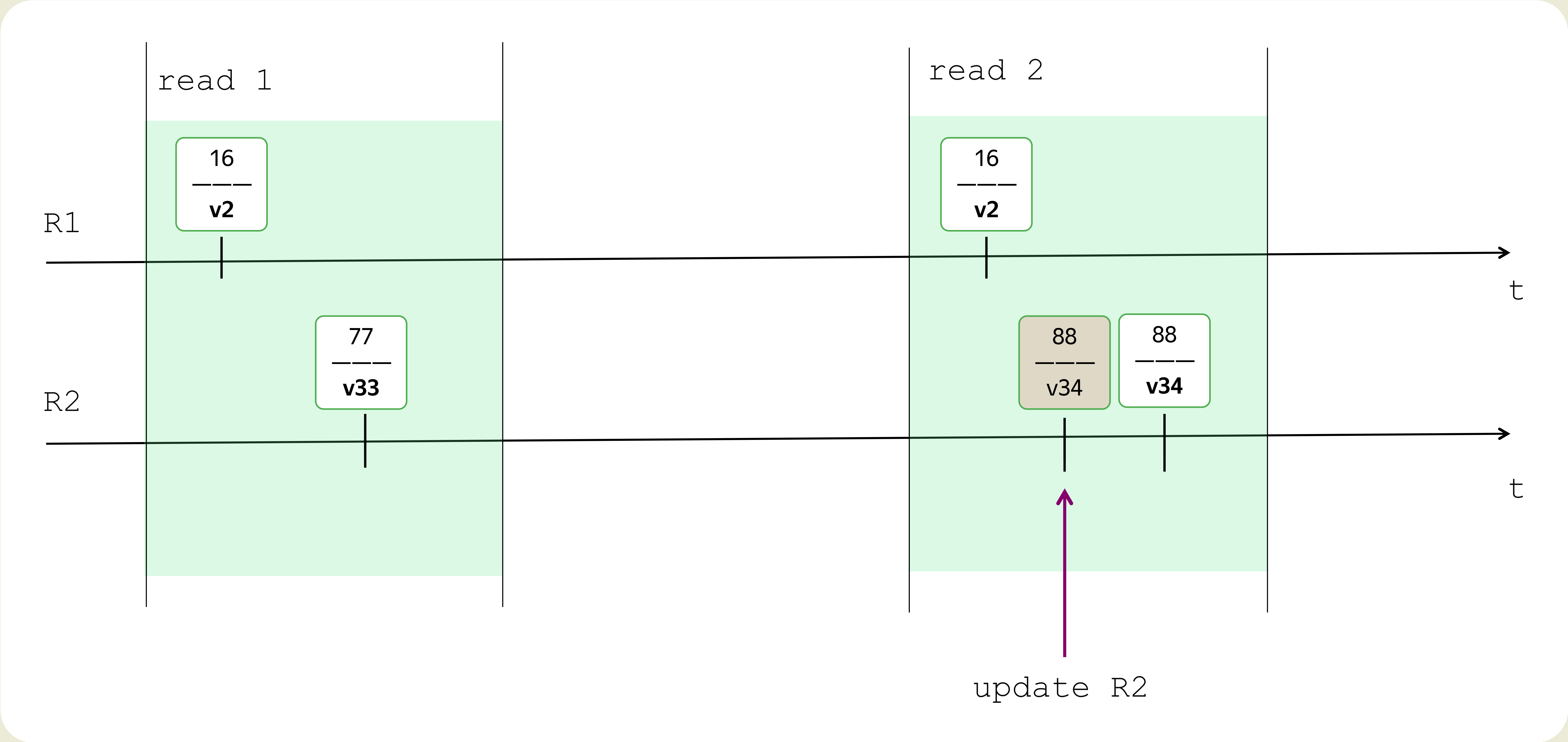
Version

Время	(D,V)	(D,V)
1	(0, v0)	(0, v0)
2	(1, v1)	(0, v0)
3	(1, v1)	(1, v1)
4	(2, v2)	(0, v2)

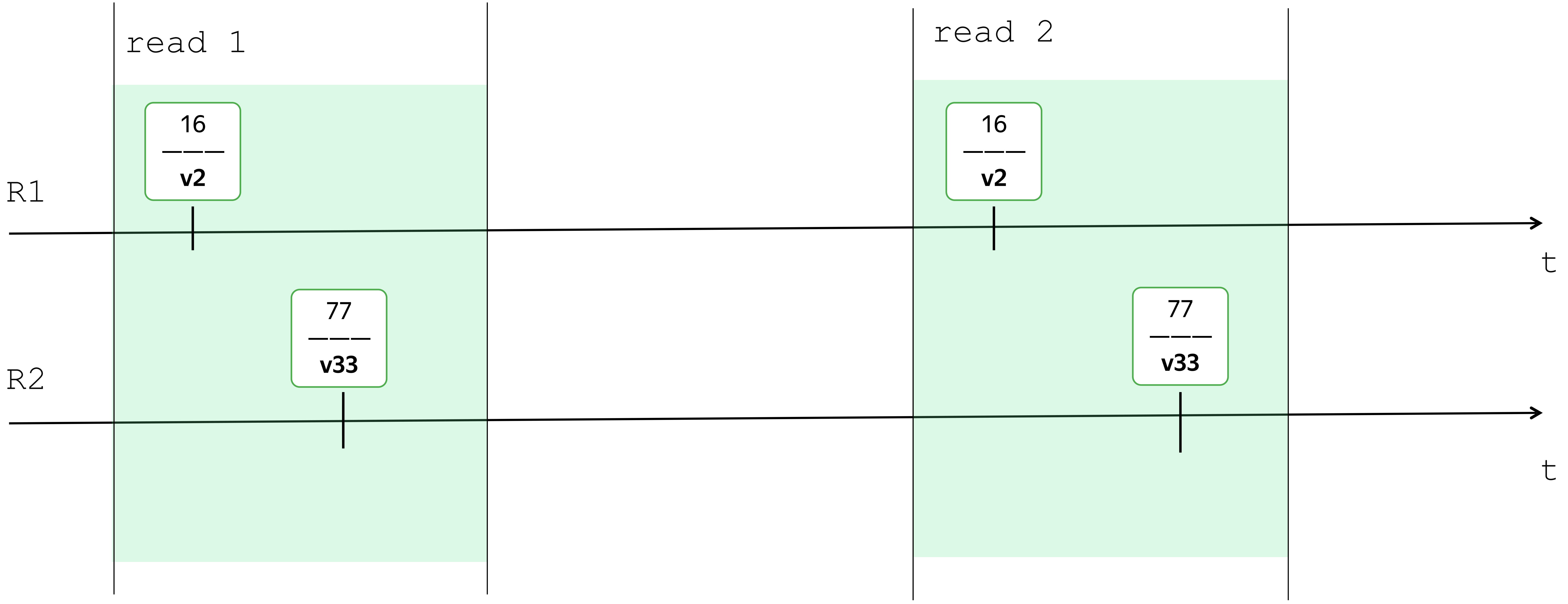
Регистры LOCK-FREE



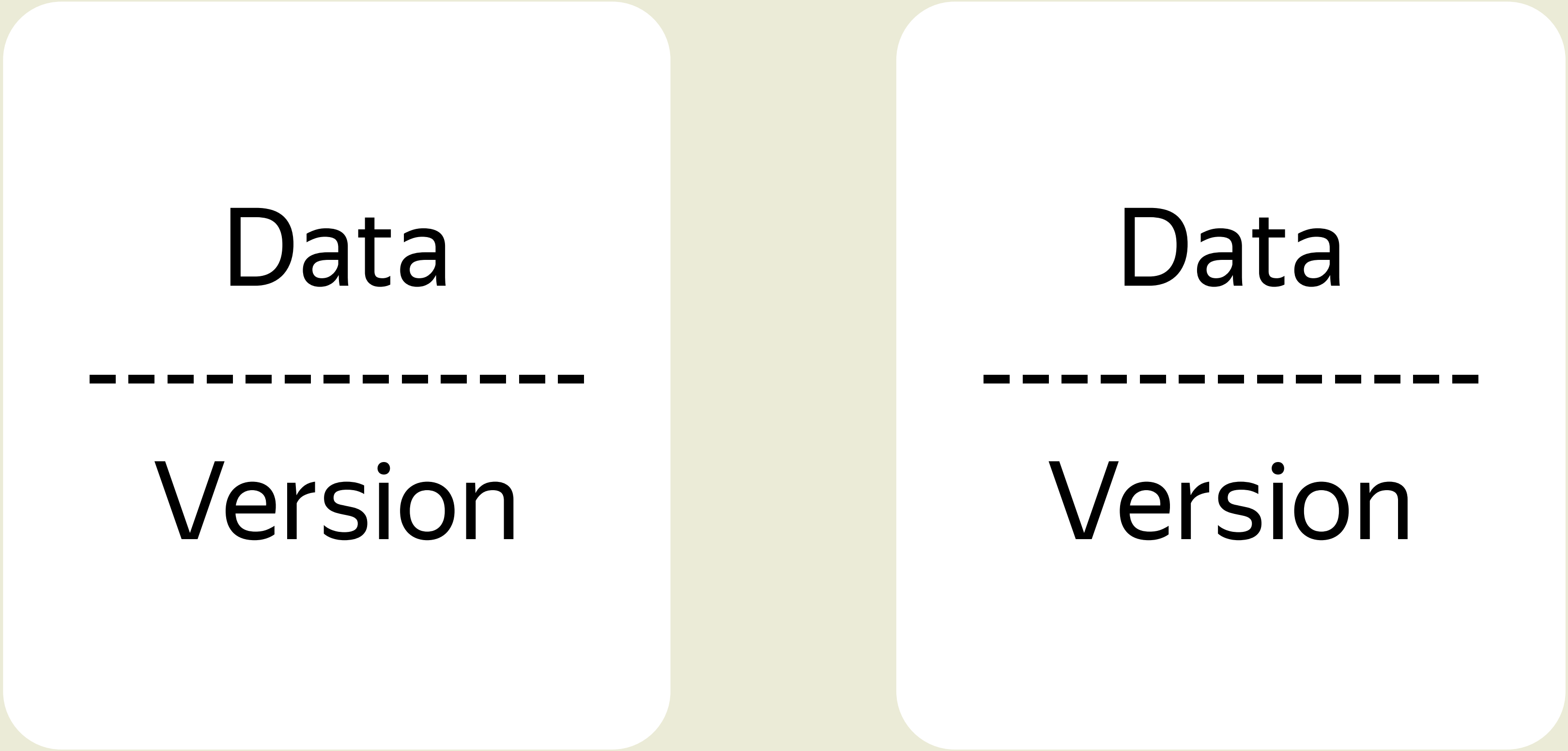
Регистры LOCK-FREE



Регистры LOCK-FREE



Регистры LOCK-FREE



Data

Version

Data

Version

SCAN() ->

(0, **v0**) (1, **v1**)

Время	(D,V)	(D,V)
1	(0, v0)	(0, v0)
2	(1, v1)	(0, v0)
3	(1, v1)	(1, v1)
4	(2, v2)	(0, v2)

Регистры LOCK-FREE

Data

Version

Data

Version

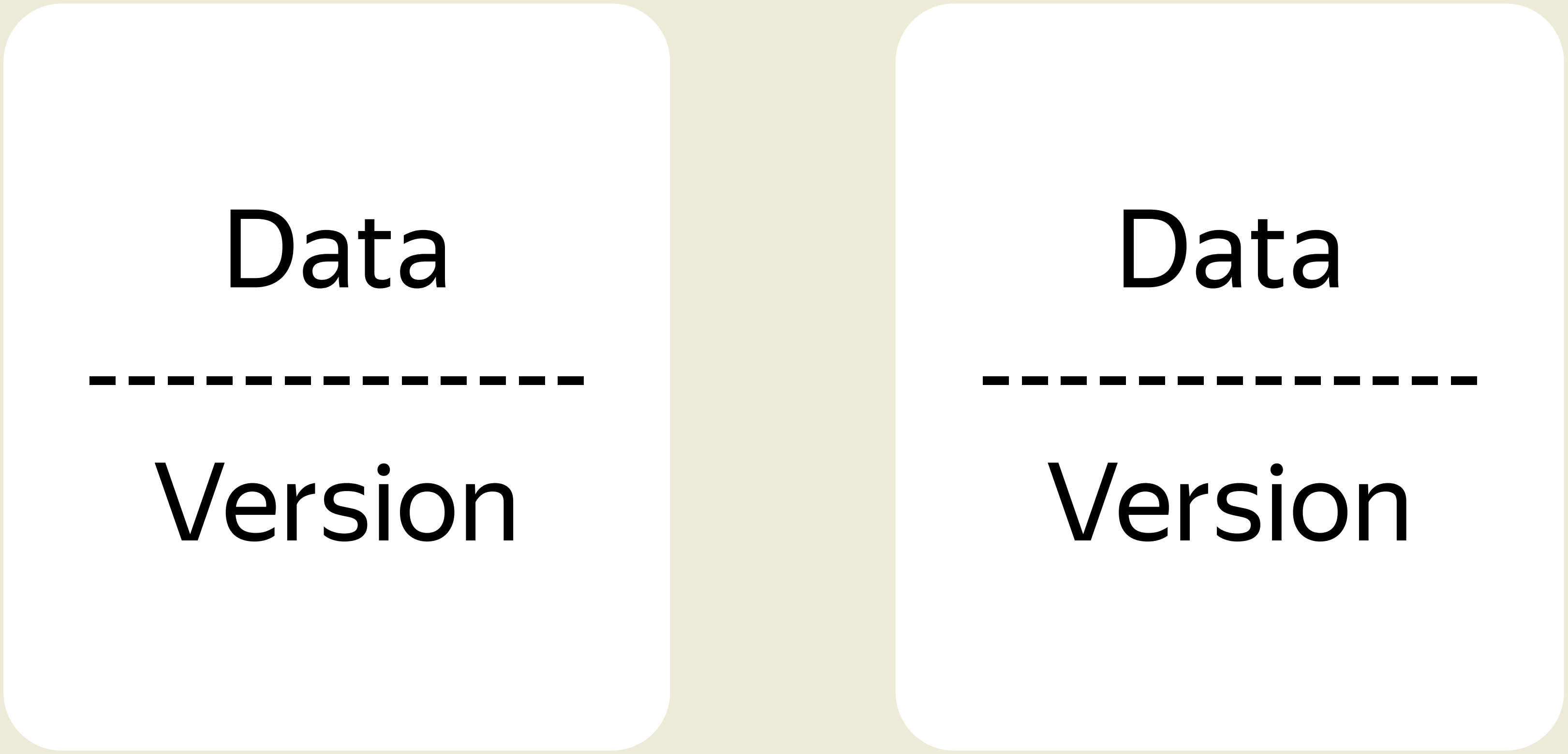
SCAN() ->

(0, **v0**) (1, **v1**)

(1, **v1**) (1, **v1**)

Время	(D,V)	(D,V)
1	(0, v0)	(0, v0)
2	(1, v1)	(0, v0)
3	(1, v1)	(1, v1)
4	(2, v2)	(0, v2)

Регистры LOCK-FREE

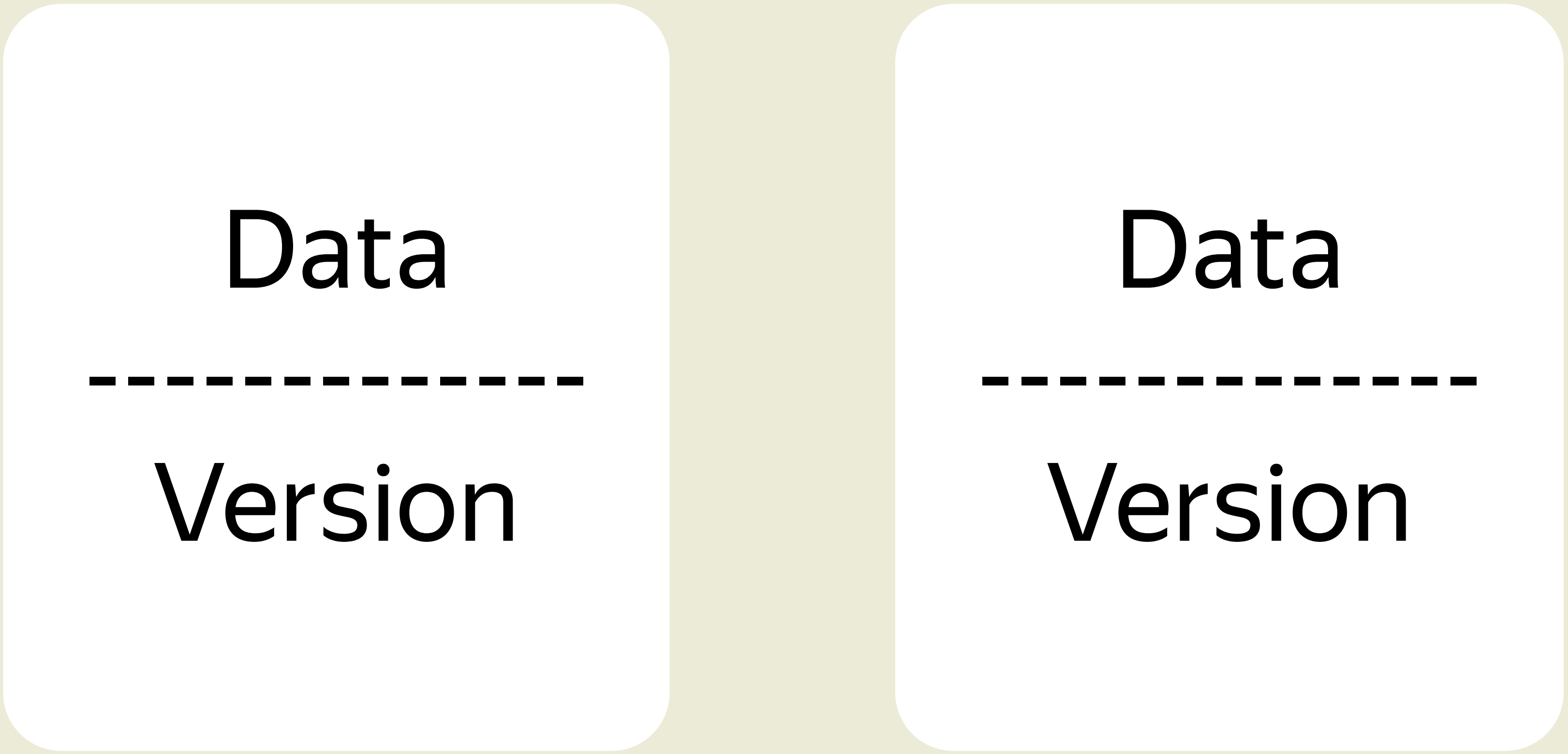


SCAN() ->

(0, **v0**) (1, **v1**)

(1, **v1**) (1, **v1**)

Регистры LOCK-FREE



SCAN() ->

(0, **v0**) (1, **v1**)

(1, **v1**) (1, **v1**)

(1, **v1**) (0, **v2**)

Время	(D,V)	(D,V)
1	(0, v0)	(0, v0)
2	(1, v1)	(0, v0)
3	(1, v1)	(1, v1)
4	(2, v2)	(0, v2)

Регистры LOCK-FREE

Data

Version

Data

Version

SCAN() ->

(0, **v0**) (1, **v1**)

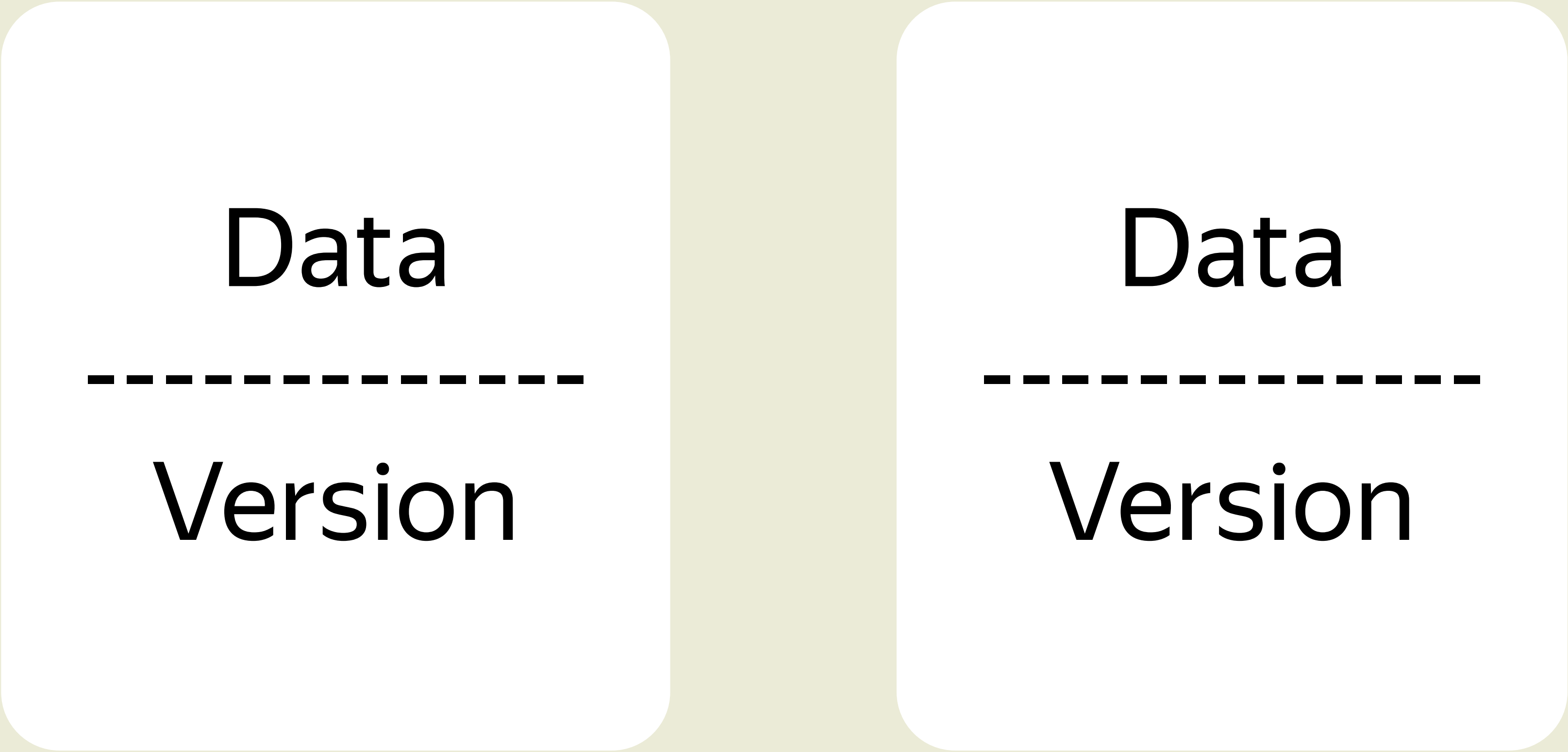
(1, **v1**) (1, **v1**)

(1, **v1**) (0, **v2**)

(2, **v2**) (0, **v2**)

Время	(D,V)	(D,V)
1	(0, v0)	(0, v0)
2	(1, v1)	(0, v0)
3	(1, v1)	(1, v1)
4	(2, v2)	(0, v2)

Регистры LOCK-FREE



Data

Version

Data

Version

SCAN() ->

(0, **v0**) (1, **v1**)

(1, **v1**) (1, **v1**)

(1, **v1**) (0, **v2**)

(2, **v2**) (0, **v2**)

(2, **v2**) (0, **v2**)

Время	(D,V)	(D,V)
1	(0, v0)	(0, v0)
2	(1, v1)	(0, v0)
3	(1, v1)	(1, v1)
4	(2, v2)	(0, v2)

Регистры SWMR WAIT-FREE

Data

Version

Data

Version

Время	(D,V)	(D,V)
1	(0, v0)	(0, v0)
2	(1, v1)	(0, v0)
3	(1, v1)	(1, v1)
4	(2, v2)	(0, v2)

Регистры SWMR WAIT-FREE

Data

Version

Snapshot

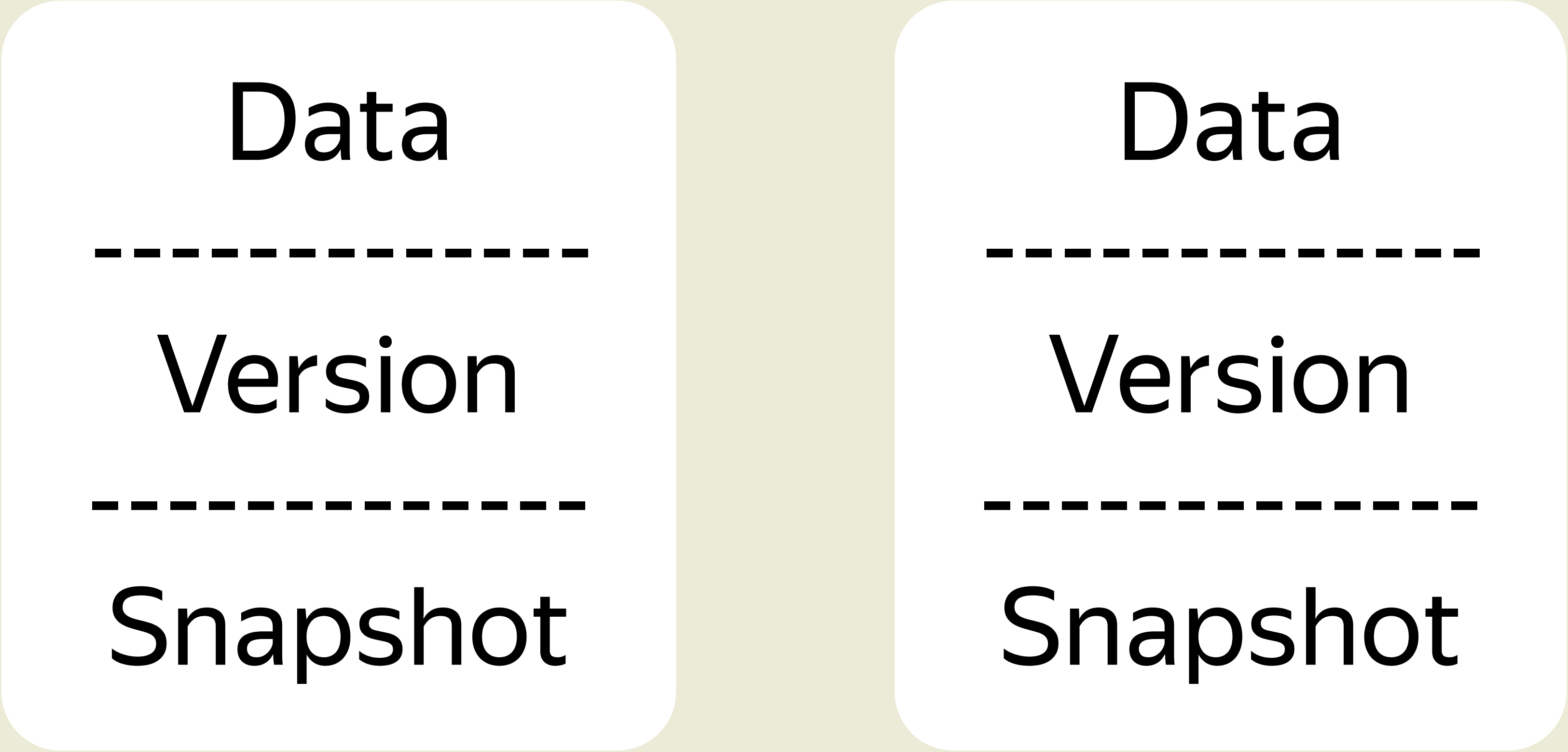
Data

Version

Snapshot

Время	(D,V,Snapshot)	(D,V,Snapshot)
1	(0, v0,[0;0])	(0, v0,[0;0])
2	(1, v1,**[0;0]**)	(0, v0,[0;0])
3	(1, v1,[0;0])	(1, v1,**[1;0]**)
4	(2, v2,**[1;1]**)	(0, v2,**[1;1]**)

Регистры SWMR WAIT-FREE



Data

Version

Snapshot

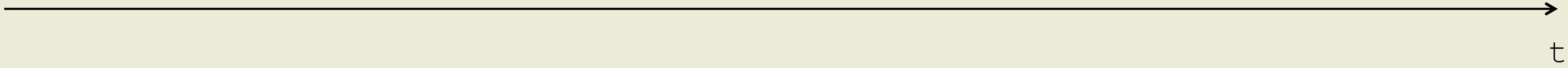
Data

Version

Snapshot

```
update(Data d) {
  Snapshot s = get_snapshot();
  write(d, v + 1, s);
}
```

```
get_snapshot():
```



Регистры SWMR WAIT-FREE

Data

Version

Snapshot

Data

Version

Snapshot

```
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}
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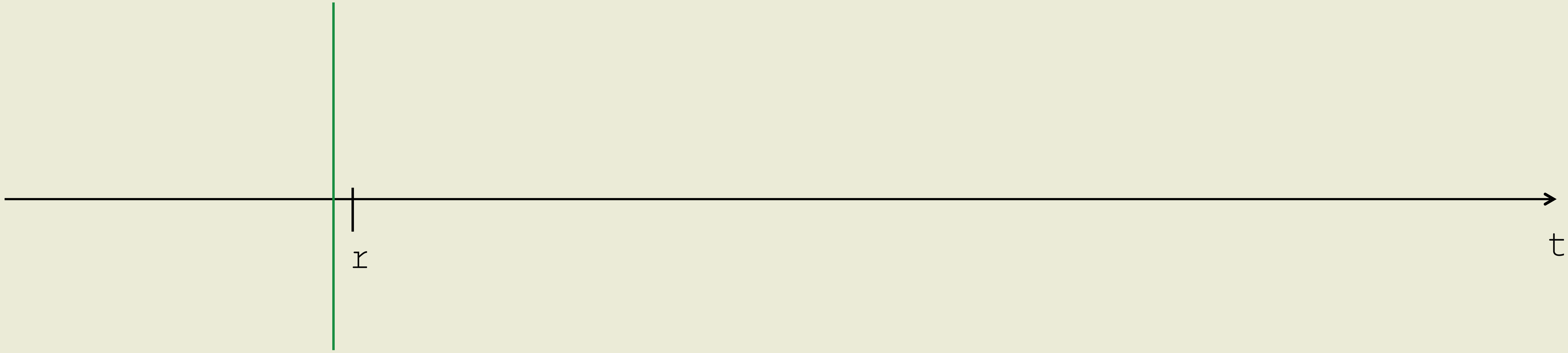
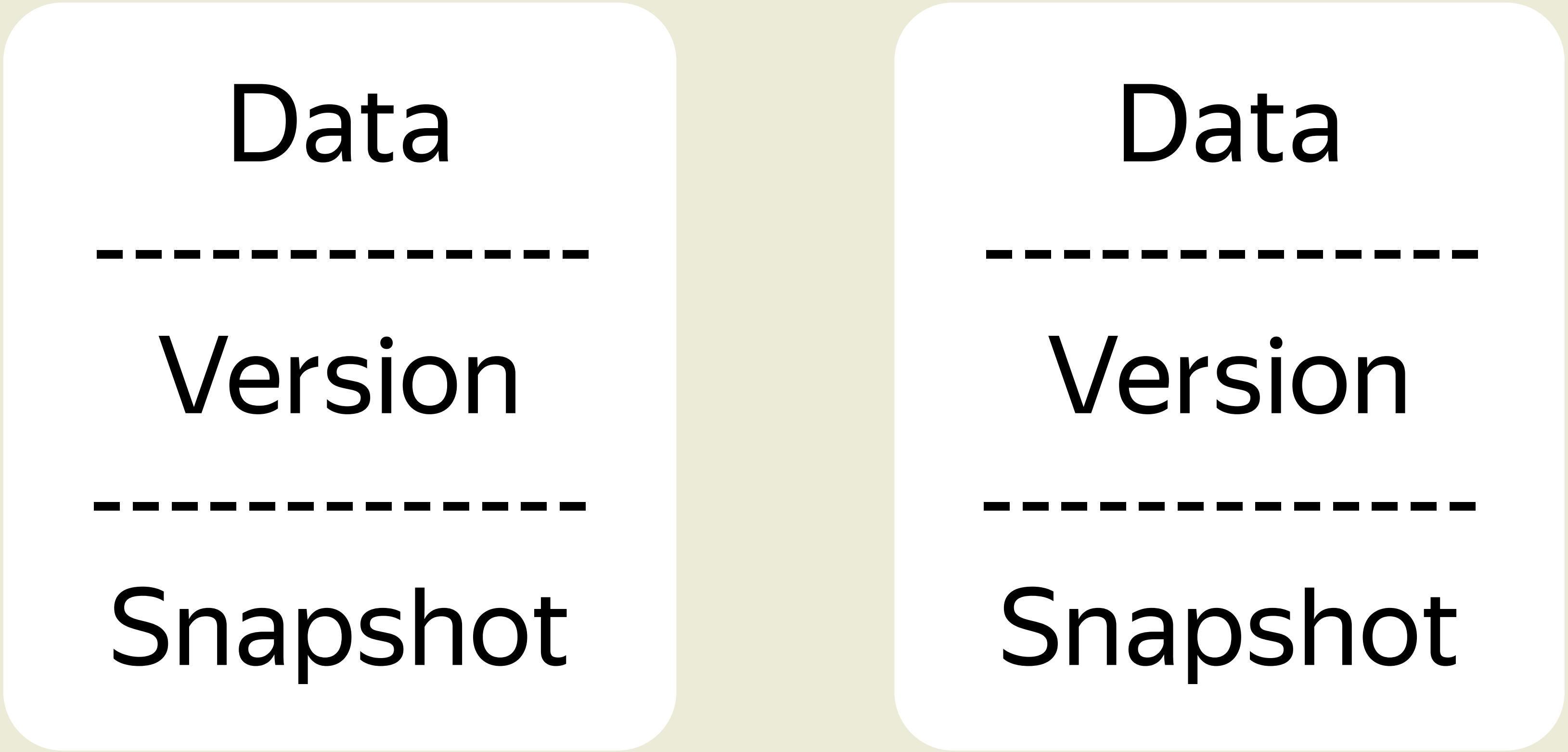
```
get_snapshot():
```



Регистры SWMR WAIT-FREE



```
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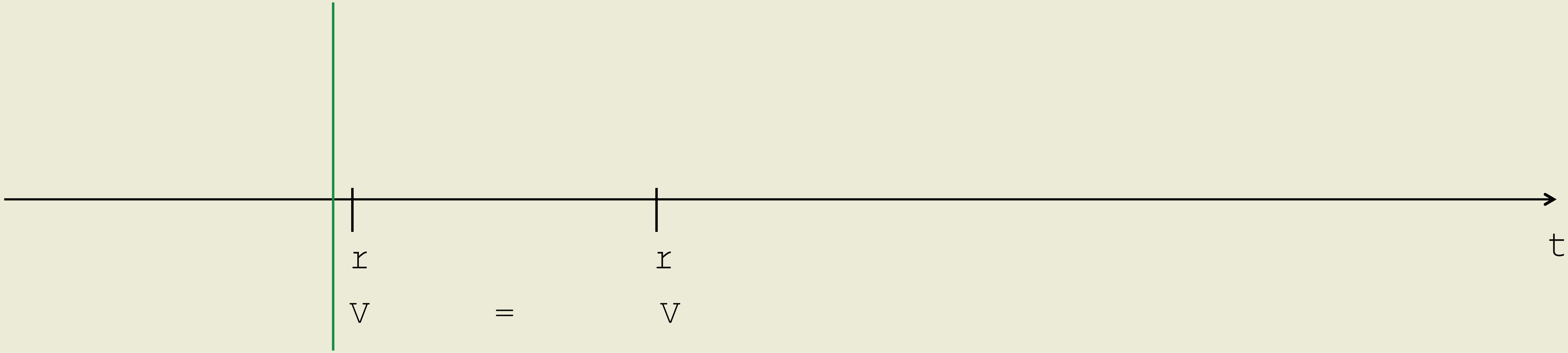
}
```

get_snapshot():



Регистры SWMR WAIT-FREE

Data
Version
Snapshot

Data
Version
Snapshot

```
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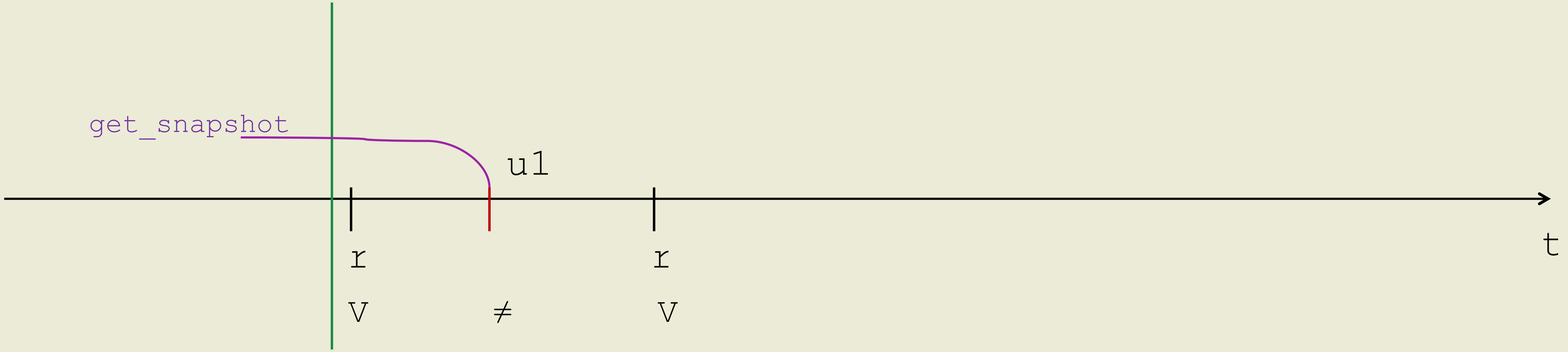
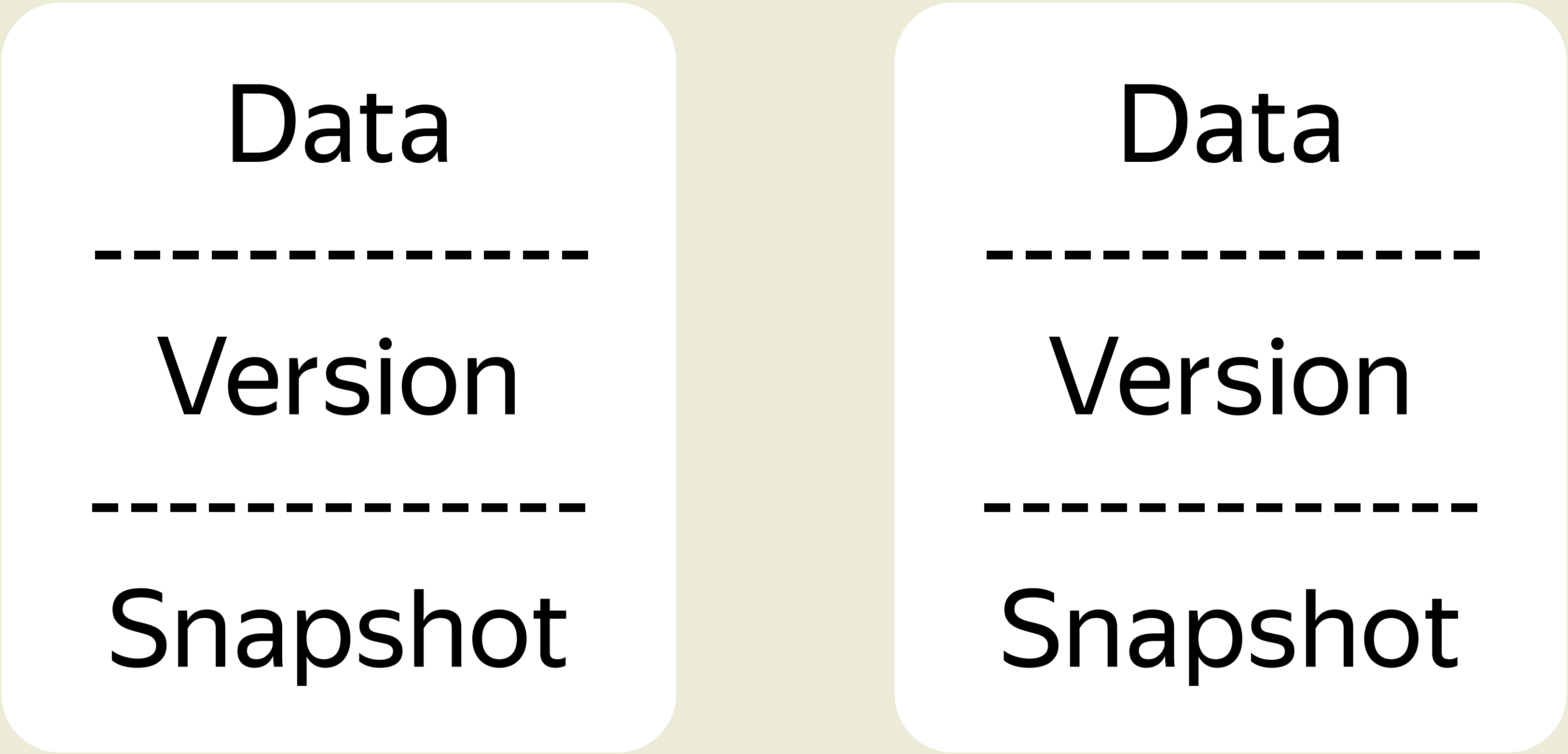
}
```

get_snapshot():



Регистры SWMR WAIT-FREE



Data

Version

Snapshot

Data

Version

Snapshot

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  Snapshot s = get_snapshot();
  write(d, v + 1, s);
}
```
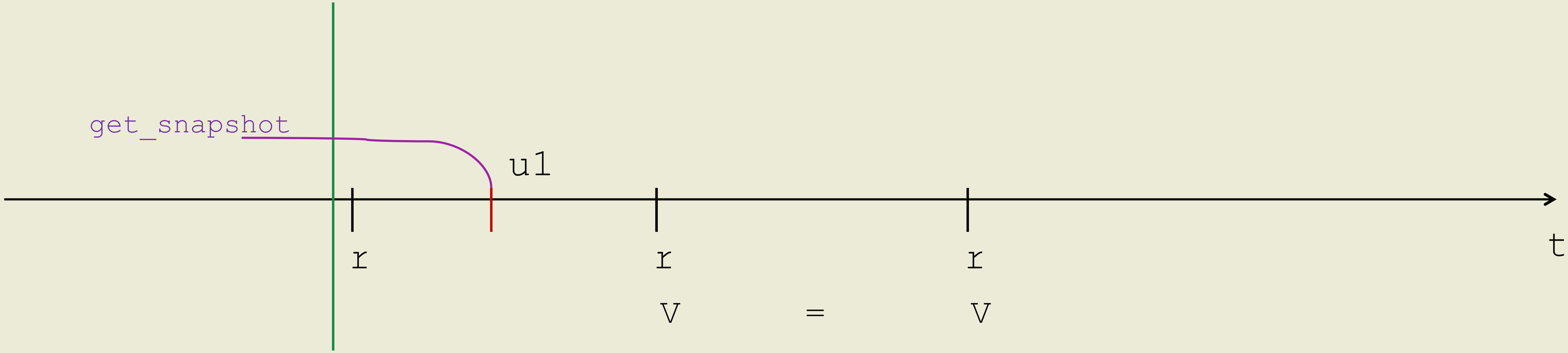

get_snapshot():



Регистры SWMR WAIT-FREE

Data

Version

Snapshot

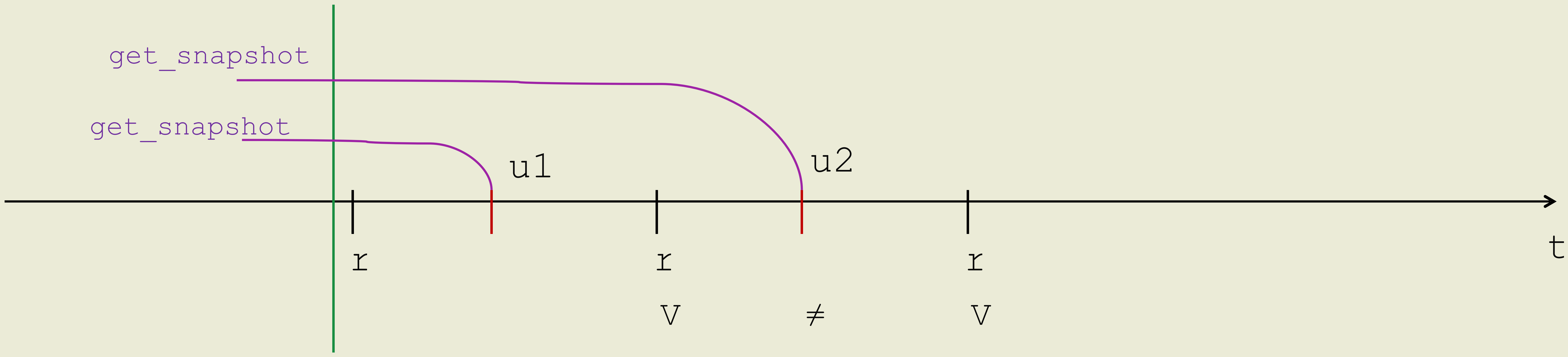
Data

Version

Snapshot

```
update(Data d) {
  Snapshot s = get_snapshot();
  write(d, v + 1, s);
}
```

get_snapshot():



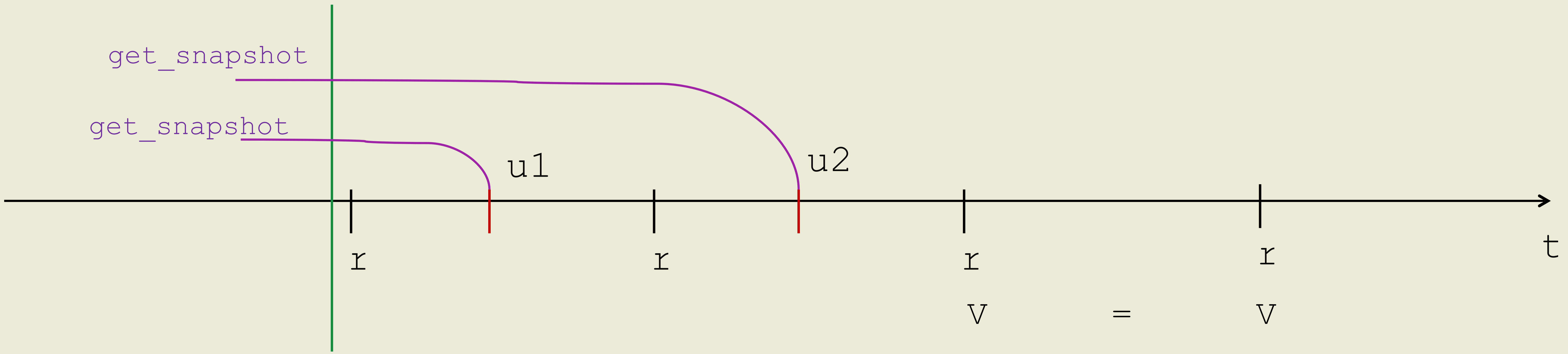
Регистры SWMR WAIT-FREE

Data
Version
Snapshot

Data
Version
Snapshot

```
update(Data d) {
  Snapshot s = get_snapshot();
  write(d, v + 1, s);
}
```

get_snapshot():



Регистры SWMR WAIT-FREE

Data

Version

Snapshot

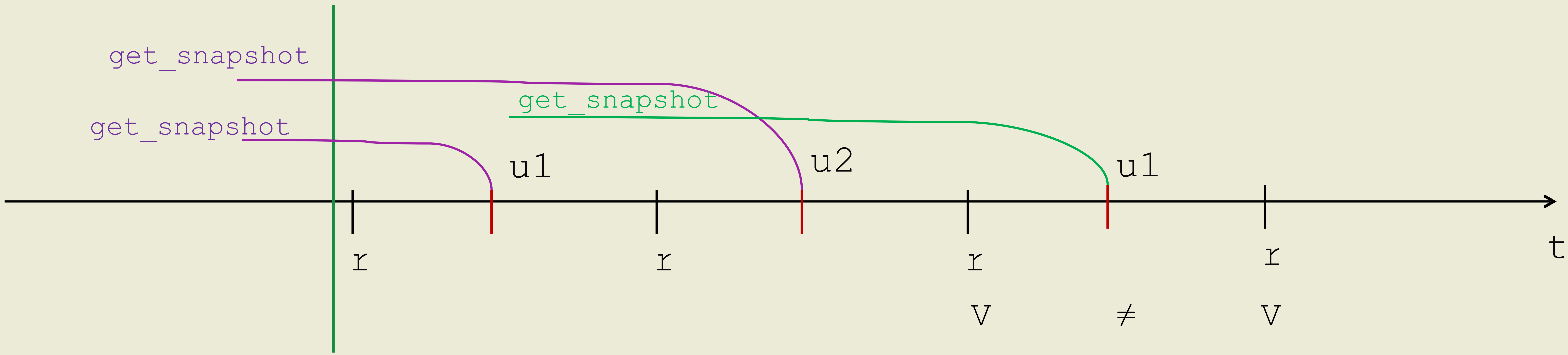
Data

Version

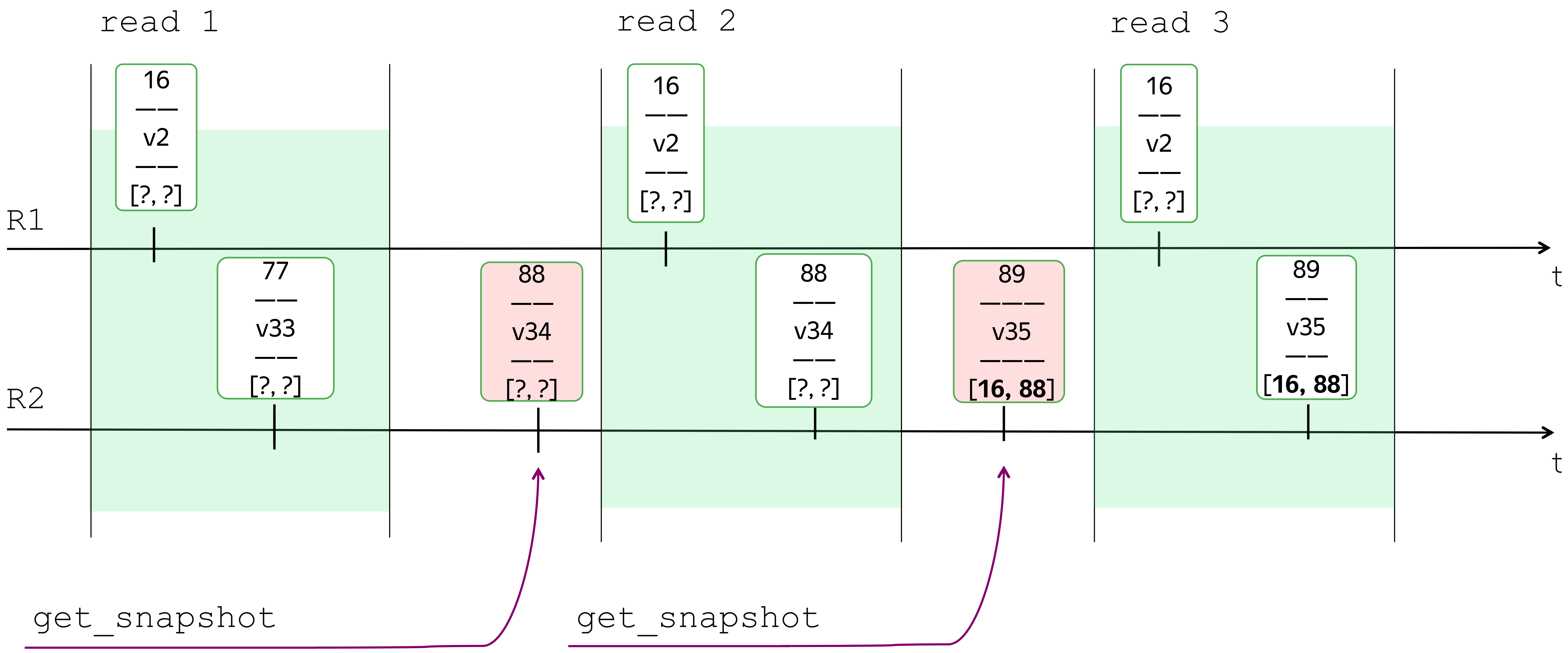
Snapshot

```
update(Data d) {
  Snapshot s = get_snapshot();
  write(d, v + 1, s);
}
```

get_snapshot():



Регистры SWMR WAIT-FREE



Конец

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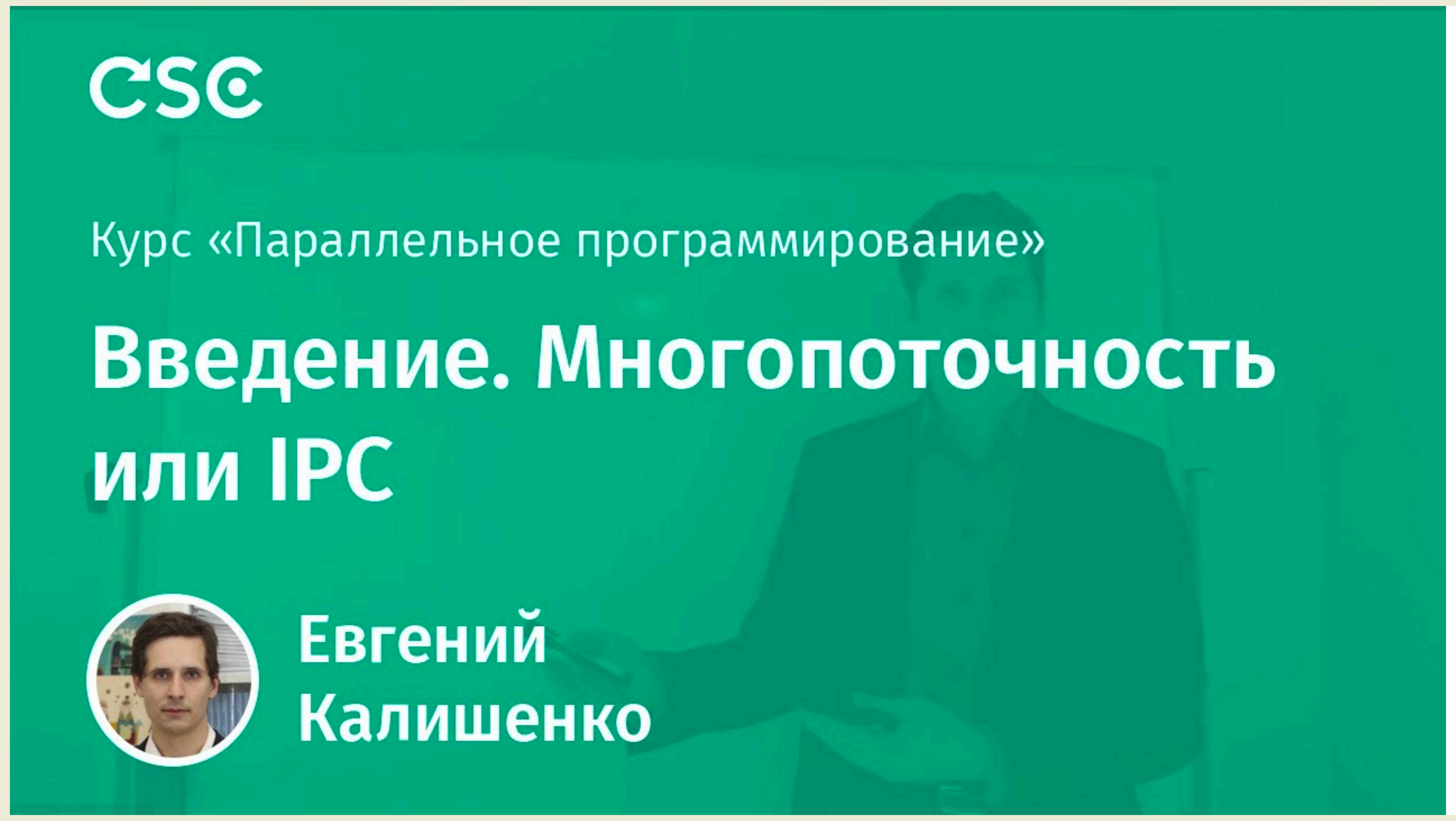
Энтони Уильямс

Практика разработки многопоточных программ

ДМК MANNING



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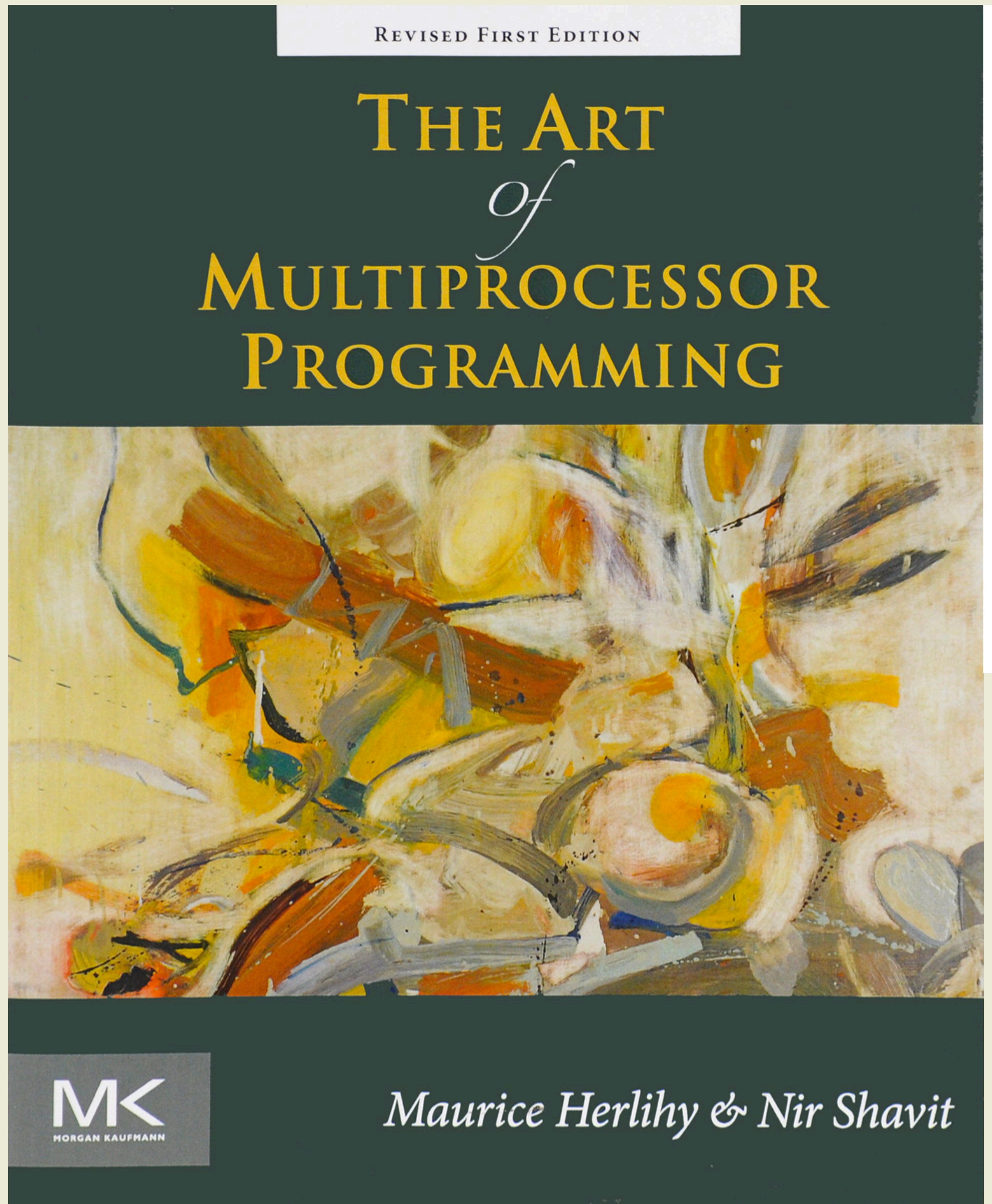

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