

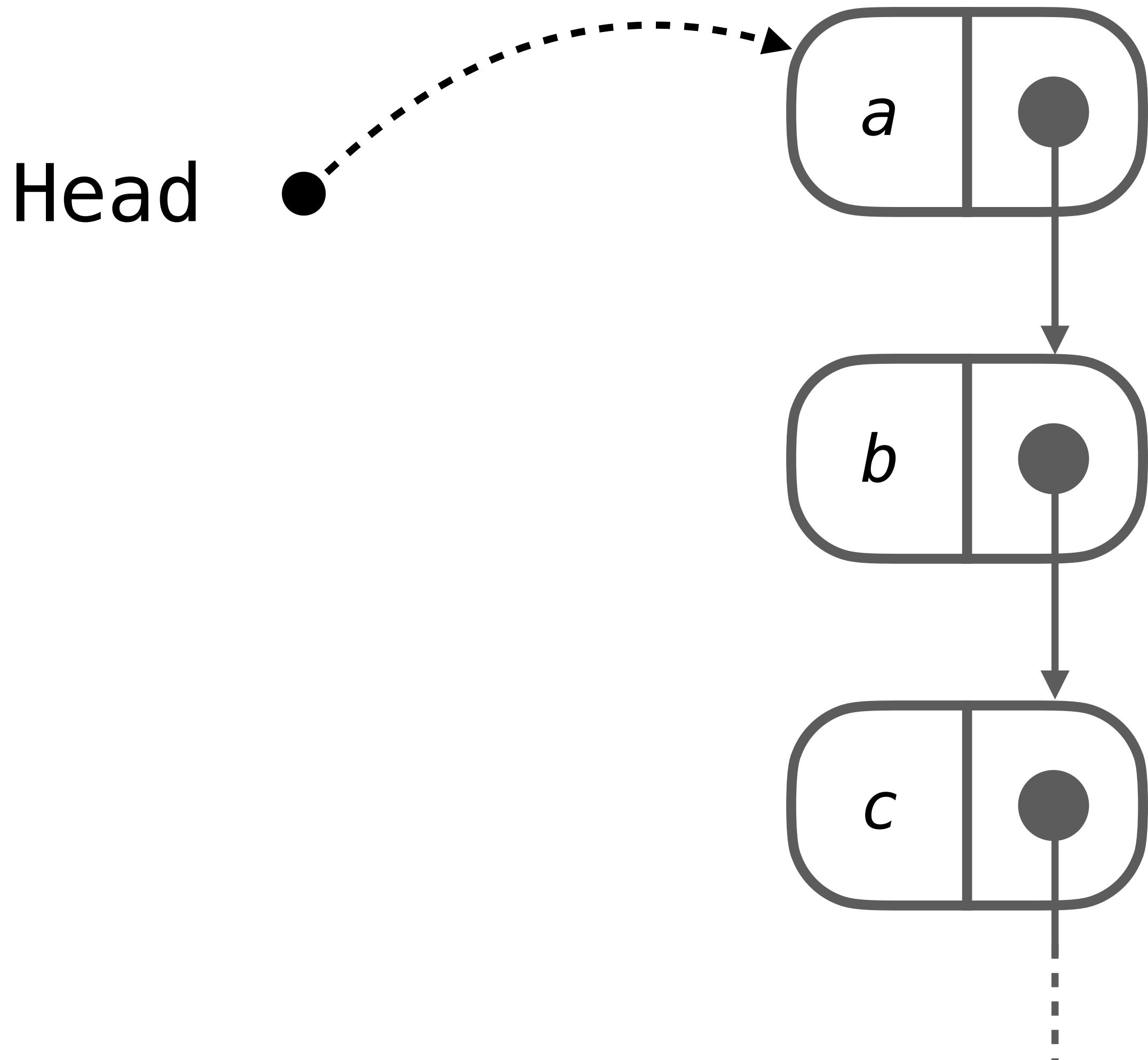
# **Verifying Non-blocking Data Structures with Manual Memory Management**

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Sebastian Wolff

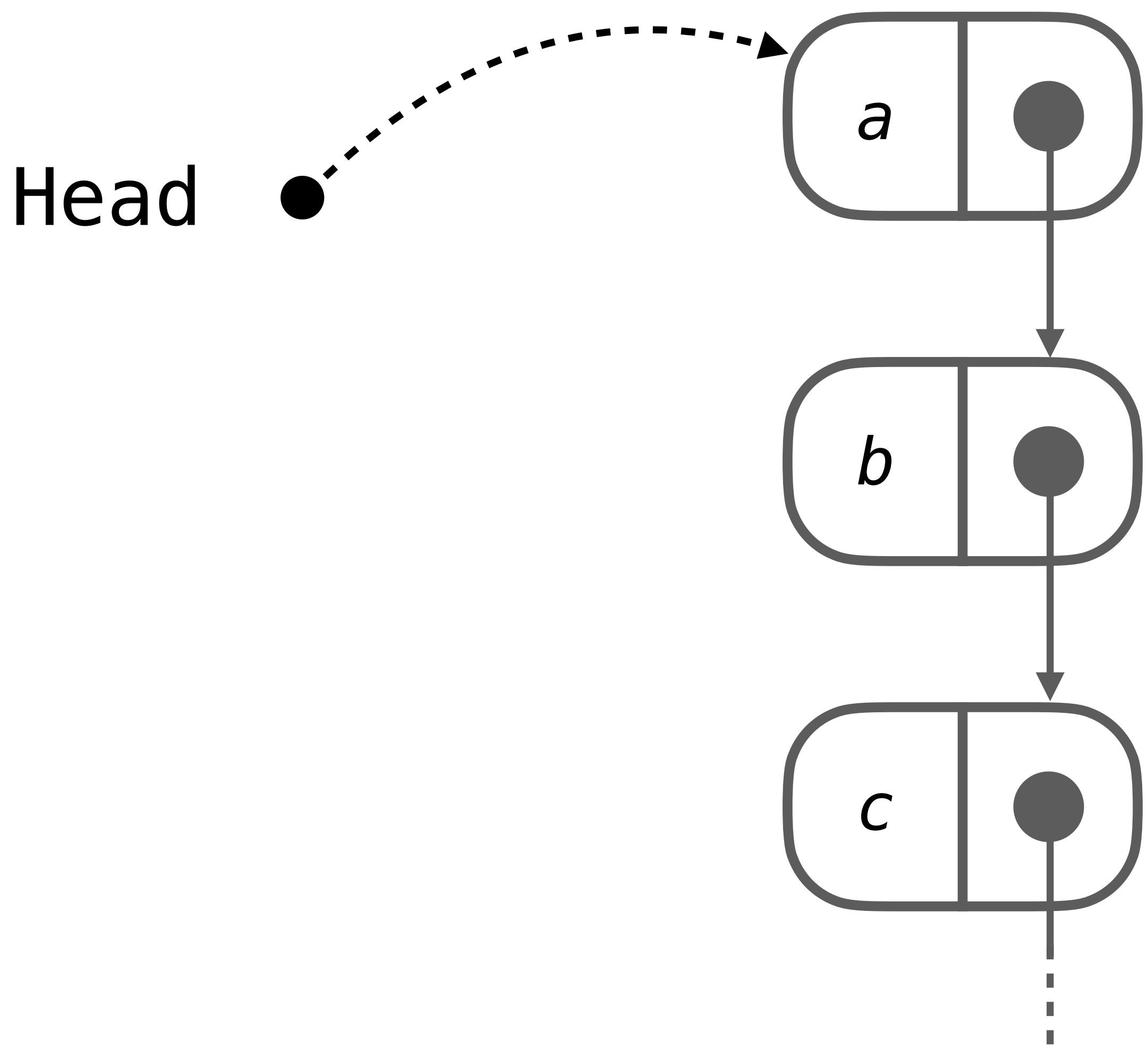
# Non-blocking Queue (Michael&Scott)

```
void dequeue() {  
    while (true) {  
        head = Head;  
        next = head->next;  
        // ...  
        if(CAS(Head, head, next)) {  
            // leak head?  
            return;  
        }  
    }  
}
```



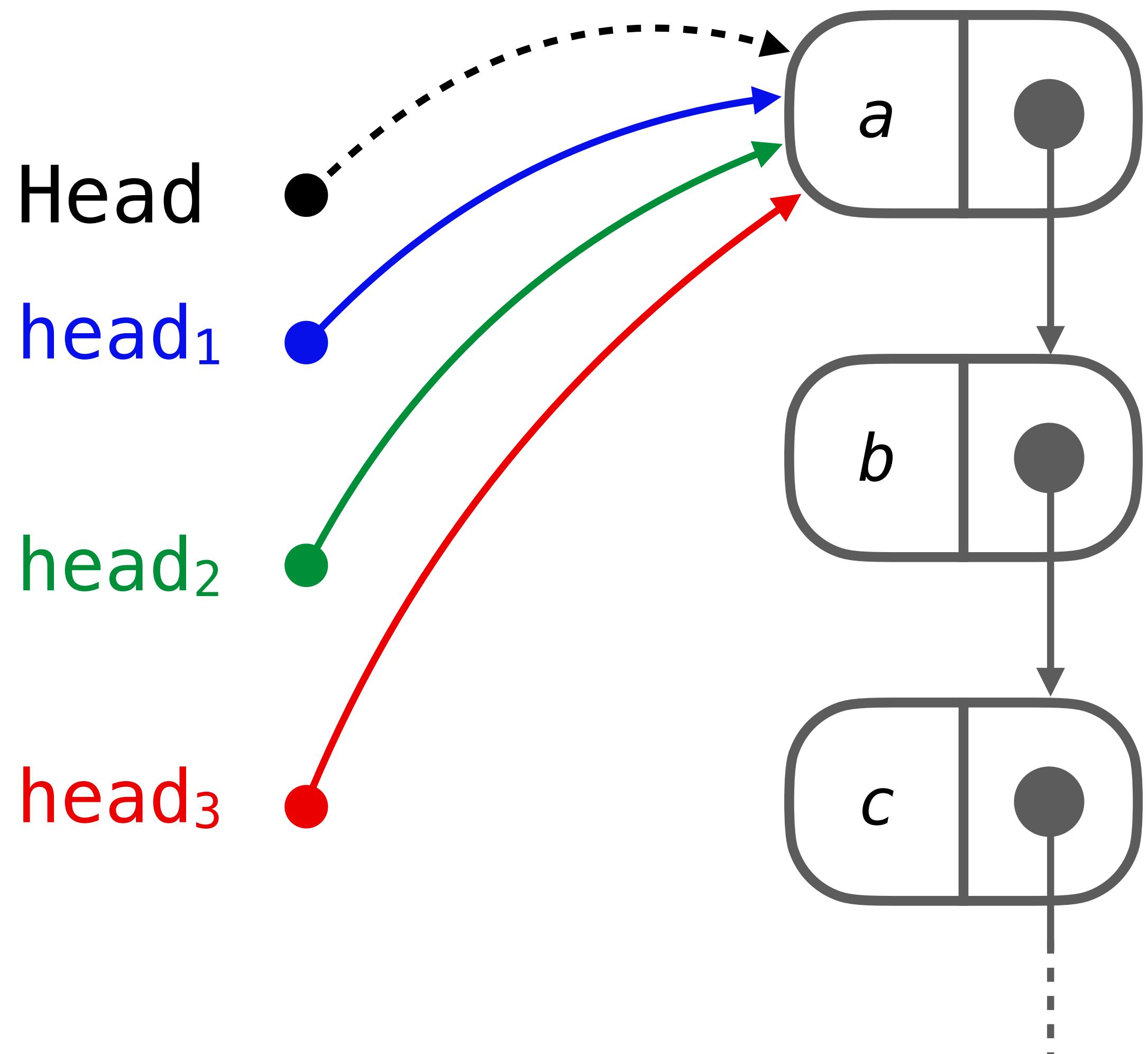
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        }  
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}
```



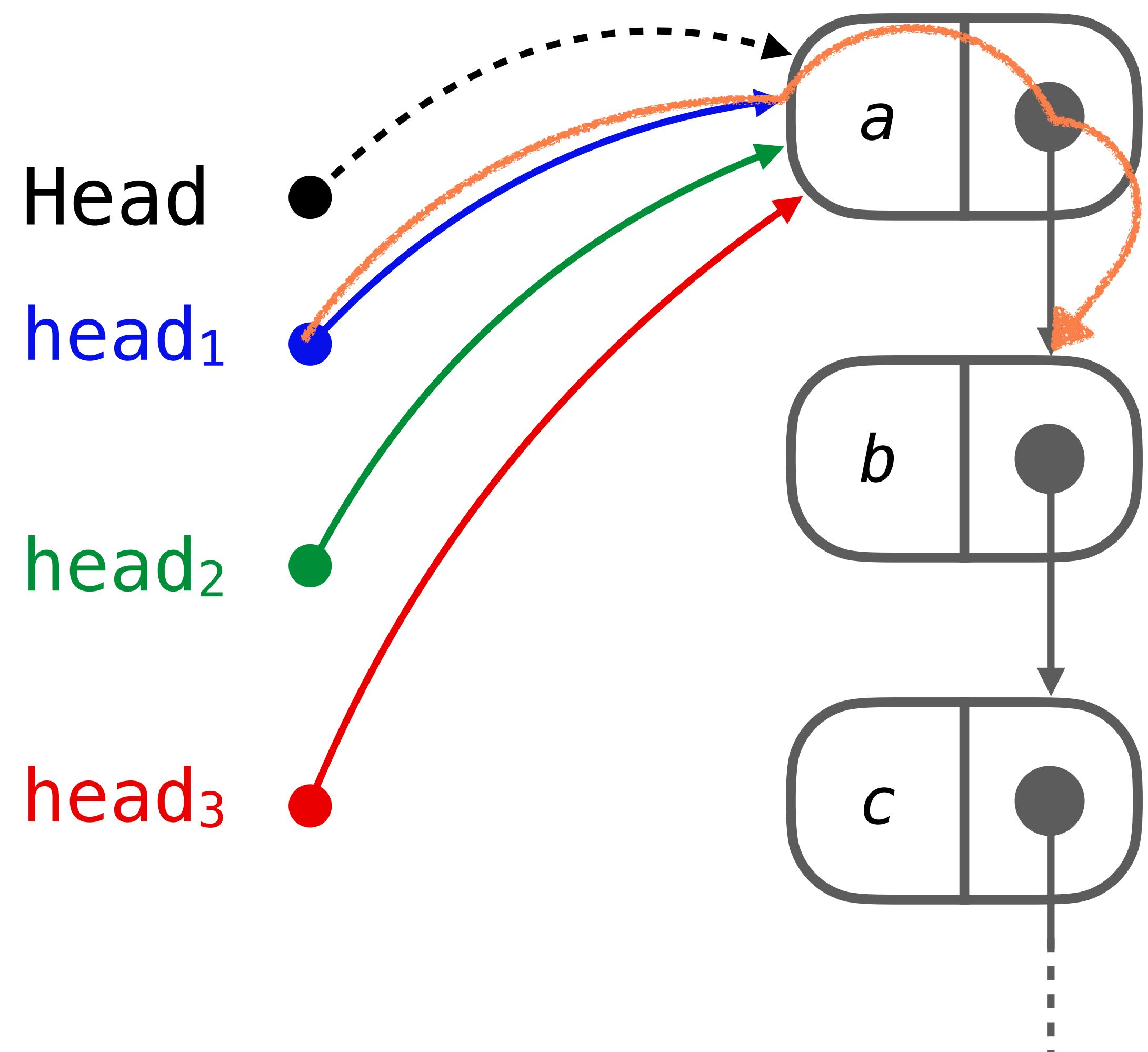
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        }  
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}
```



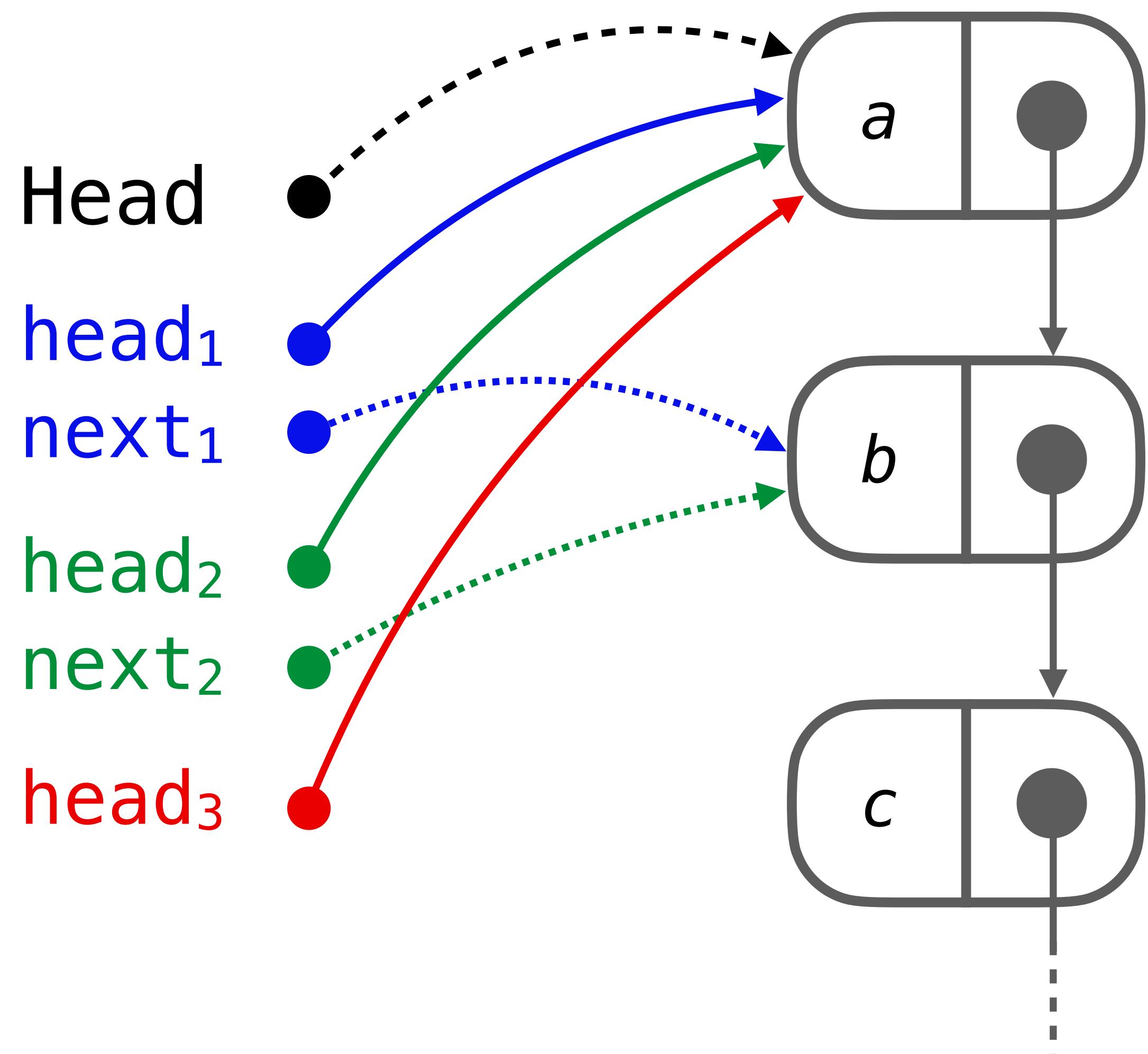
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            // leak head?  
            return;  
        }  
    }  
}
```



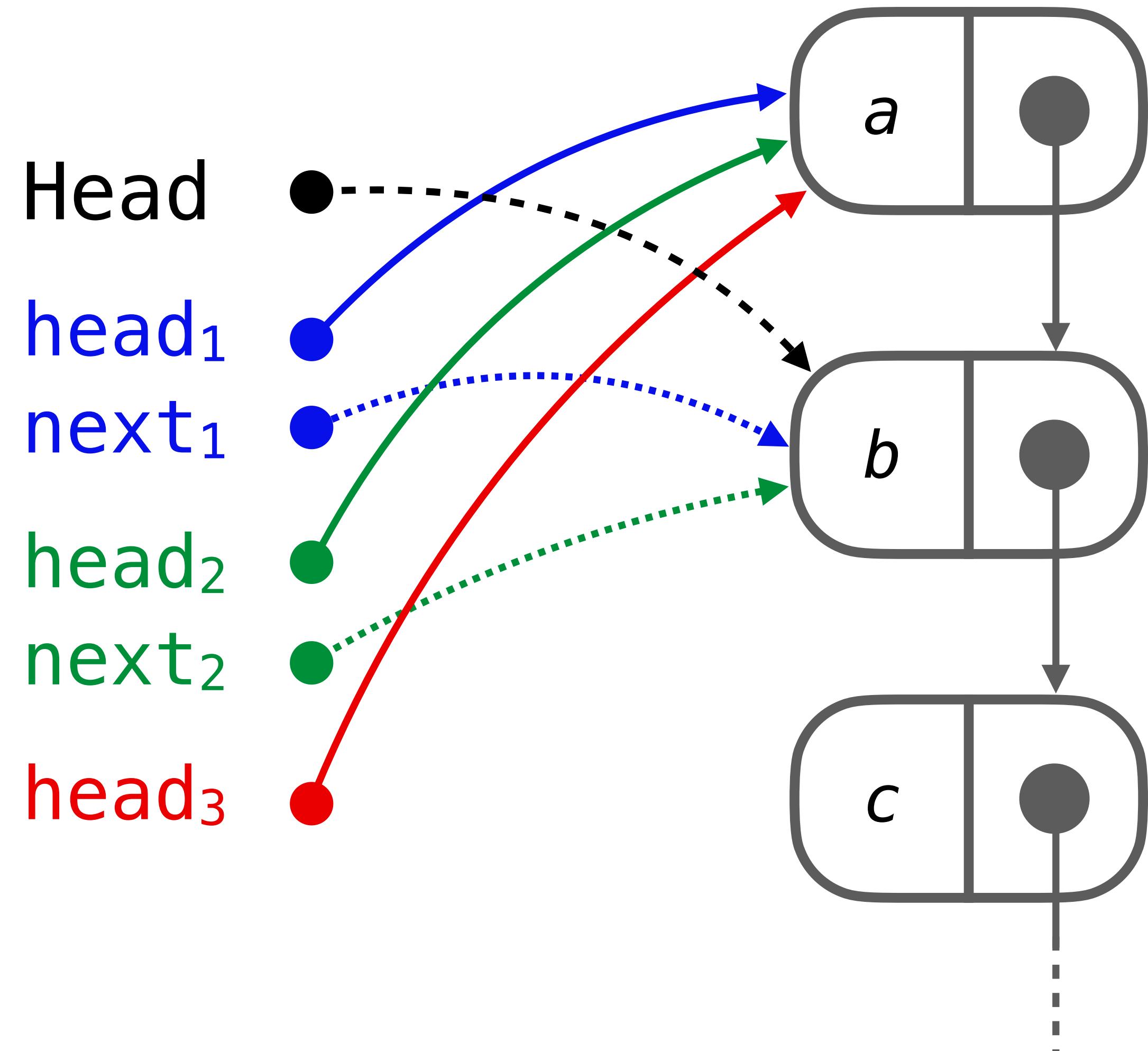
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        // ...  
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            // leak head?  
            return;  
    }}}
```



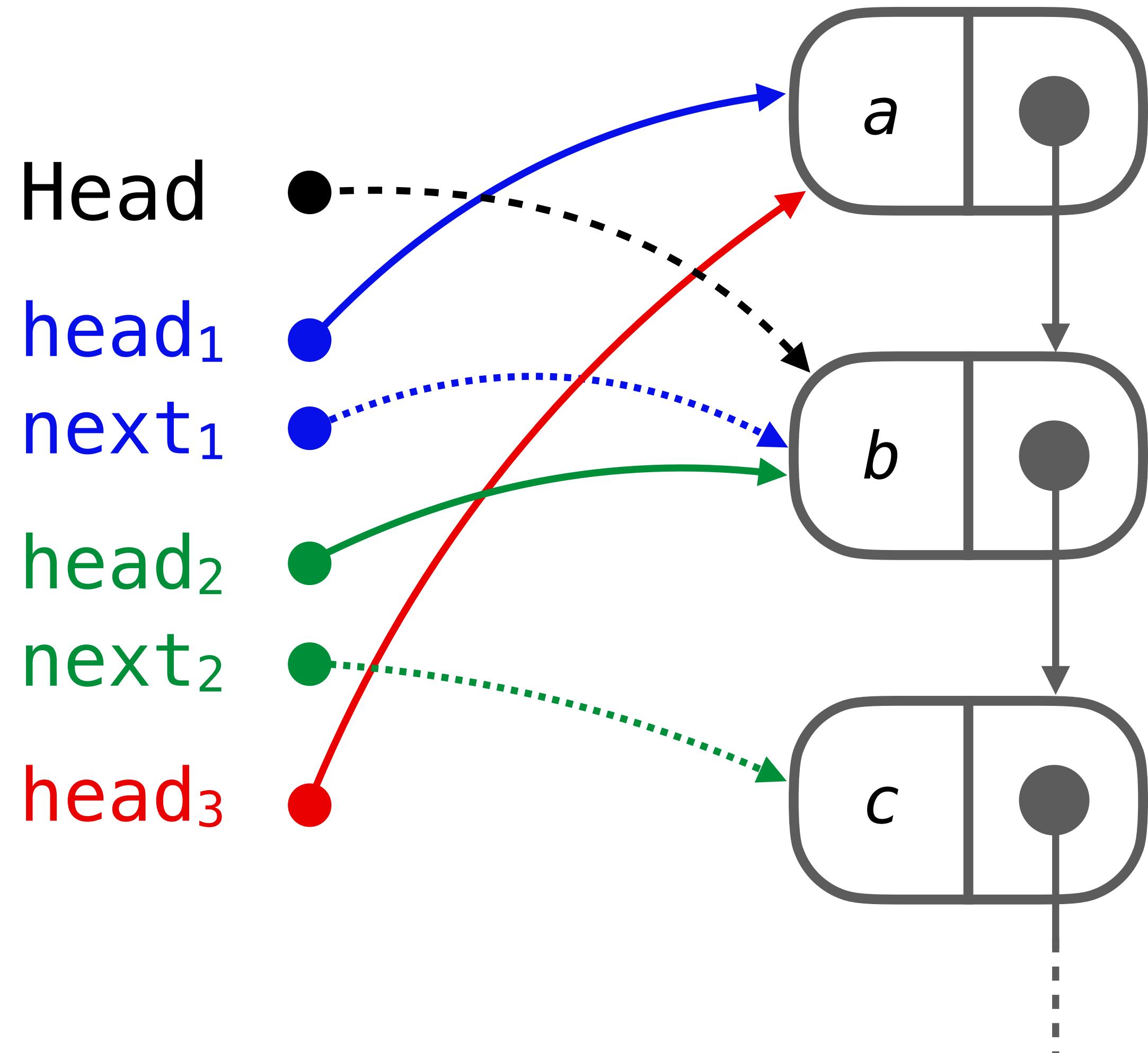
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            ① // leak head?  
            return;  
        }  
    }  
}
```



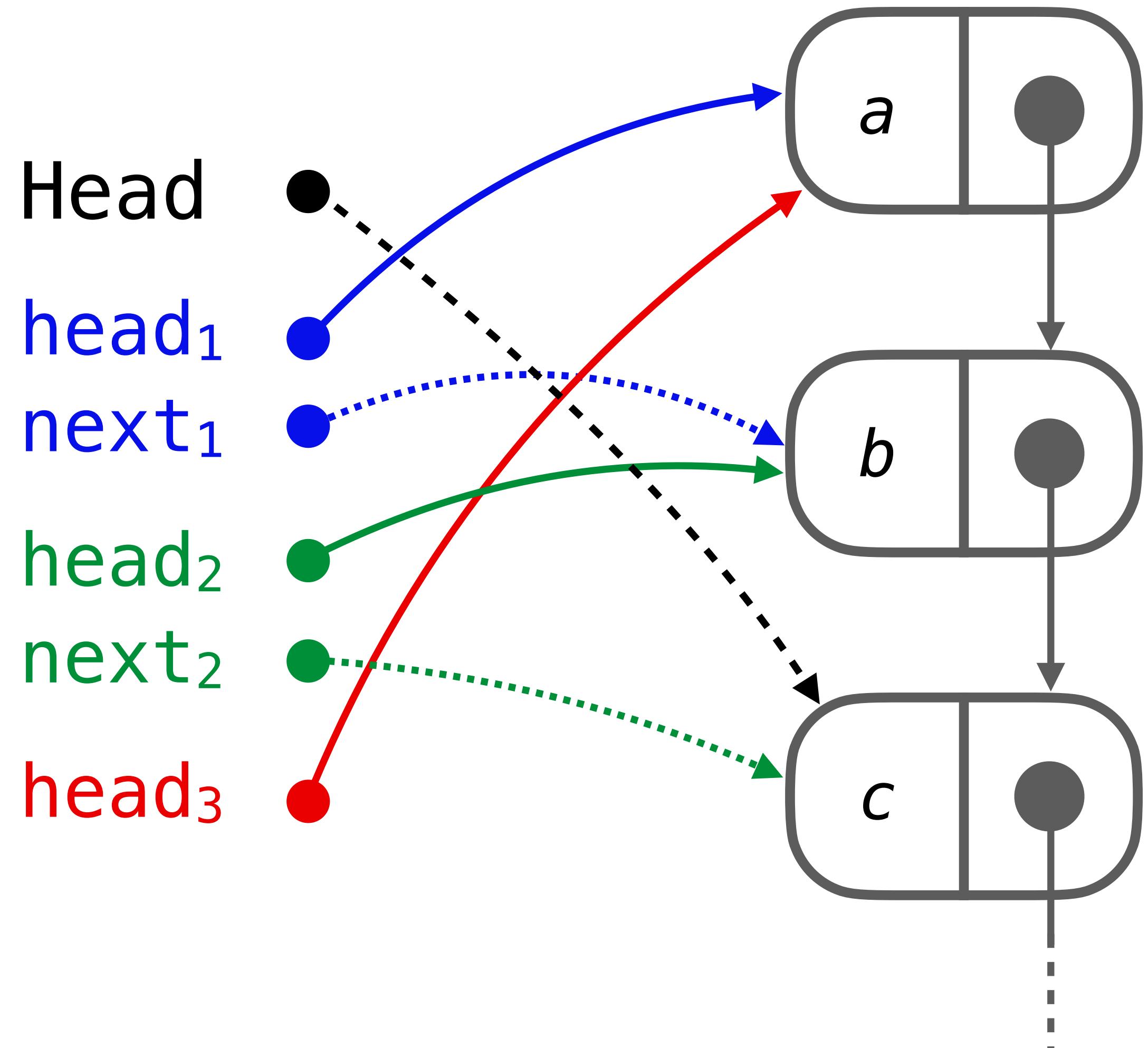
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            return;  
    }}}
```



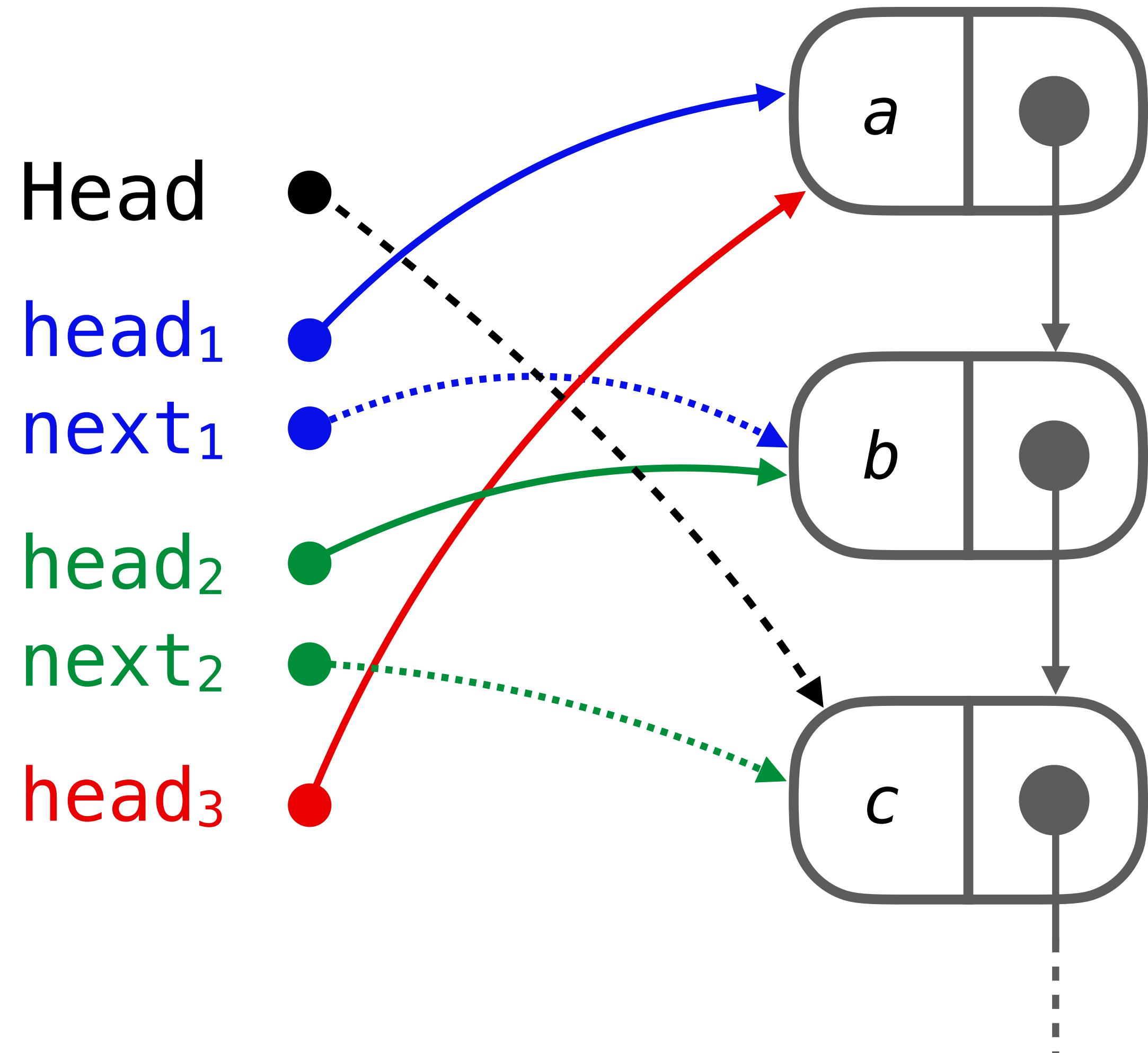
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        // ...  
        if(CAS(Head, head, next)) {  
            ①② // leak head?  
            return;  
        }  
    }  
}
```



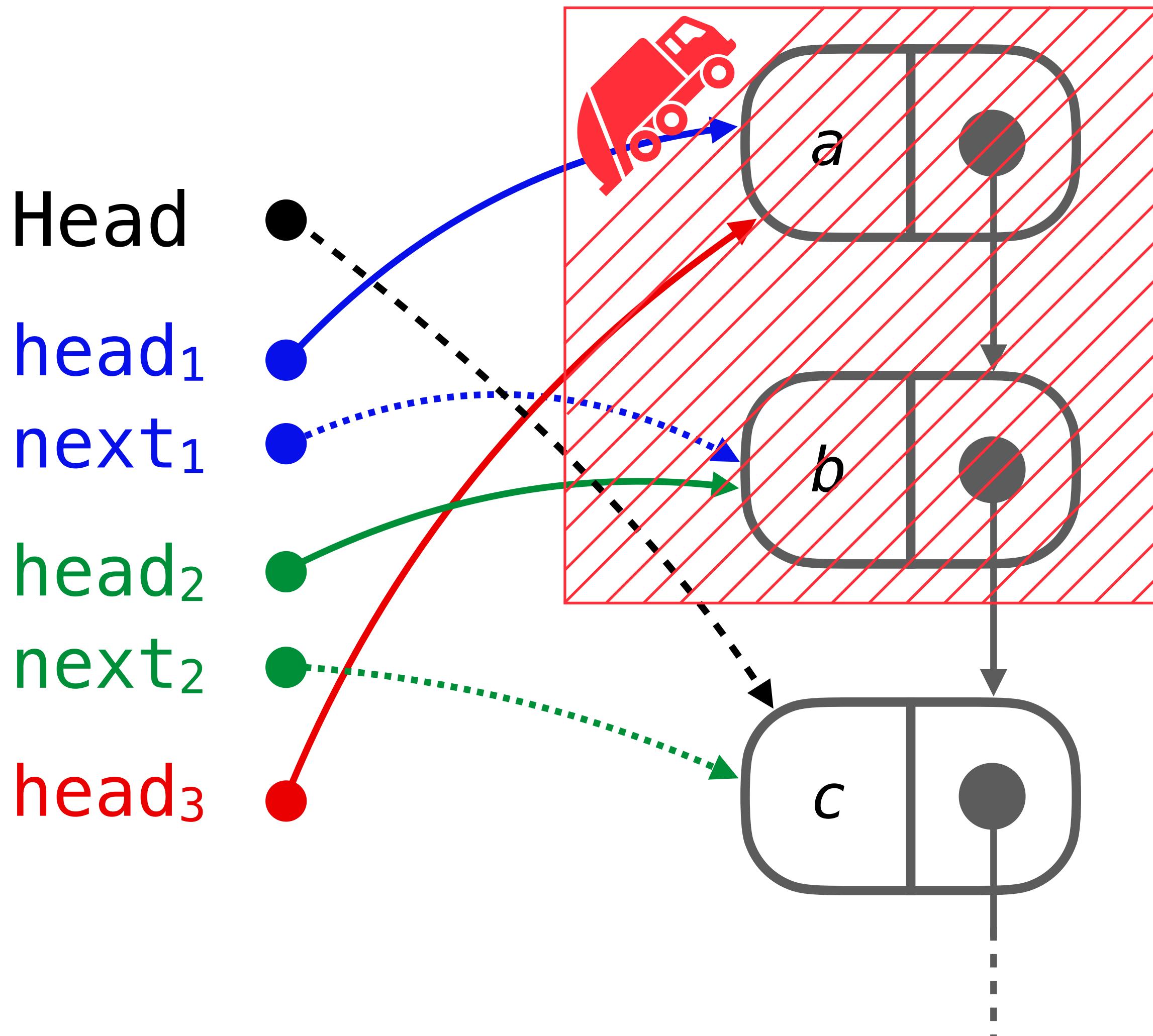
# Non-blocking Queue (Michael&Scott)

```
void dequeue() {  
    while (true) {  
        head = Head;  
        ③ next = head->next;  
        // ...  
        if(CAS(Head, head, next)) {  
            ①② delete head;  
            return;  
        }  
    }  
}
```



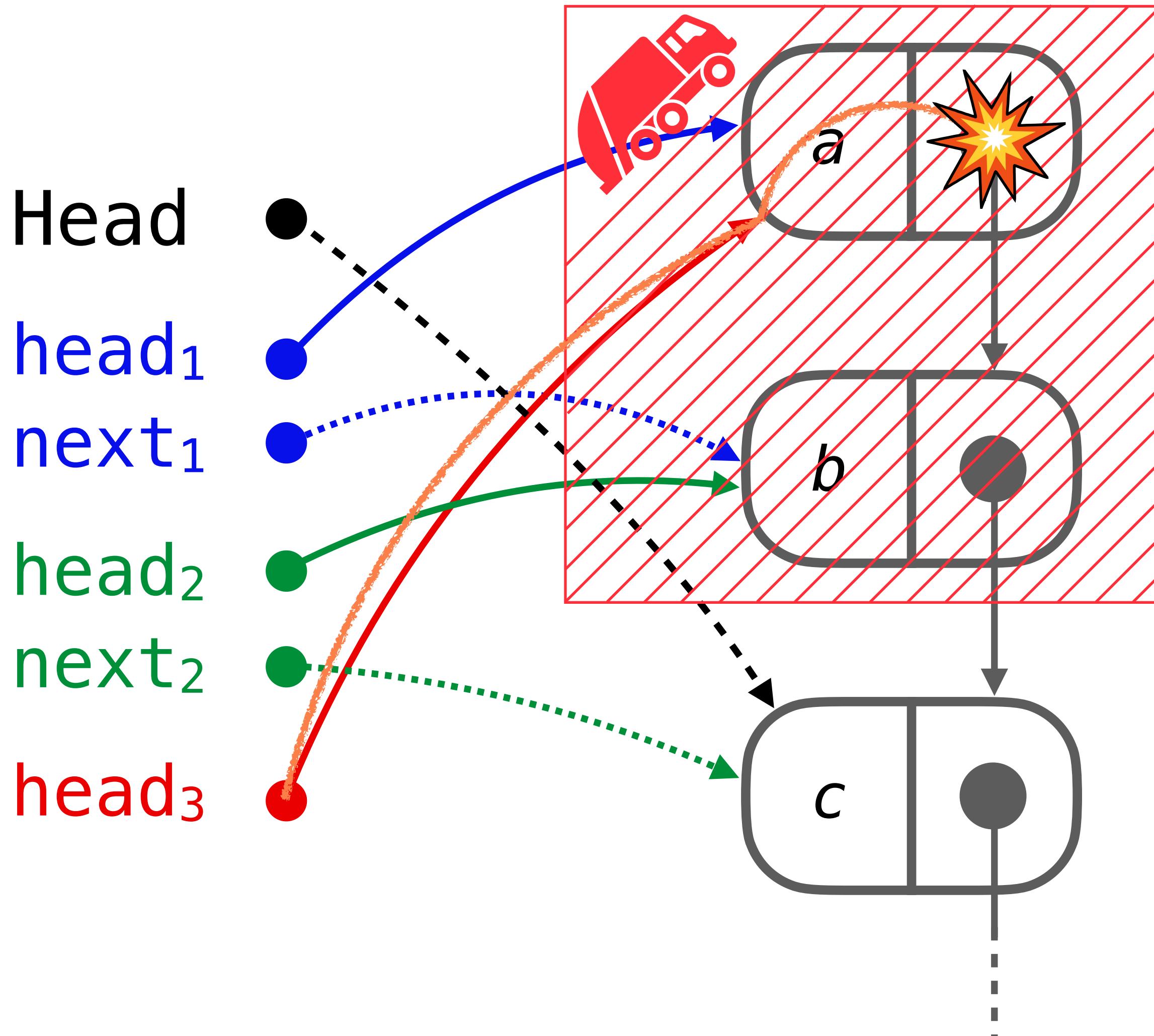
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            delete head;  
            return;  
        ①②  
    }}}
```



# Non-blocking Queue (Michael&Scott)

```
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    while (true) {  
        head = Head;  
        ③ next = head->next;  
        // ...  
        if(CAS(Head, head, next)) {  
            delete head;  
            return;  
        ①②  
    }}}
```



# Non-blocking Queue (Michael&Scott)

```
void dequeue() {  
    while (true) {  
        head = Head;  
        ③ next = head->r  
        // ...  
        if (CAS(Head, head,  
               delete head;  
        return;  
    }}}
```

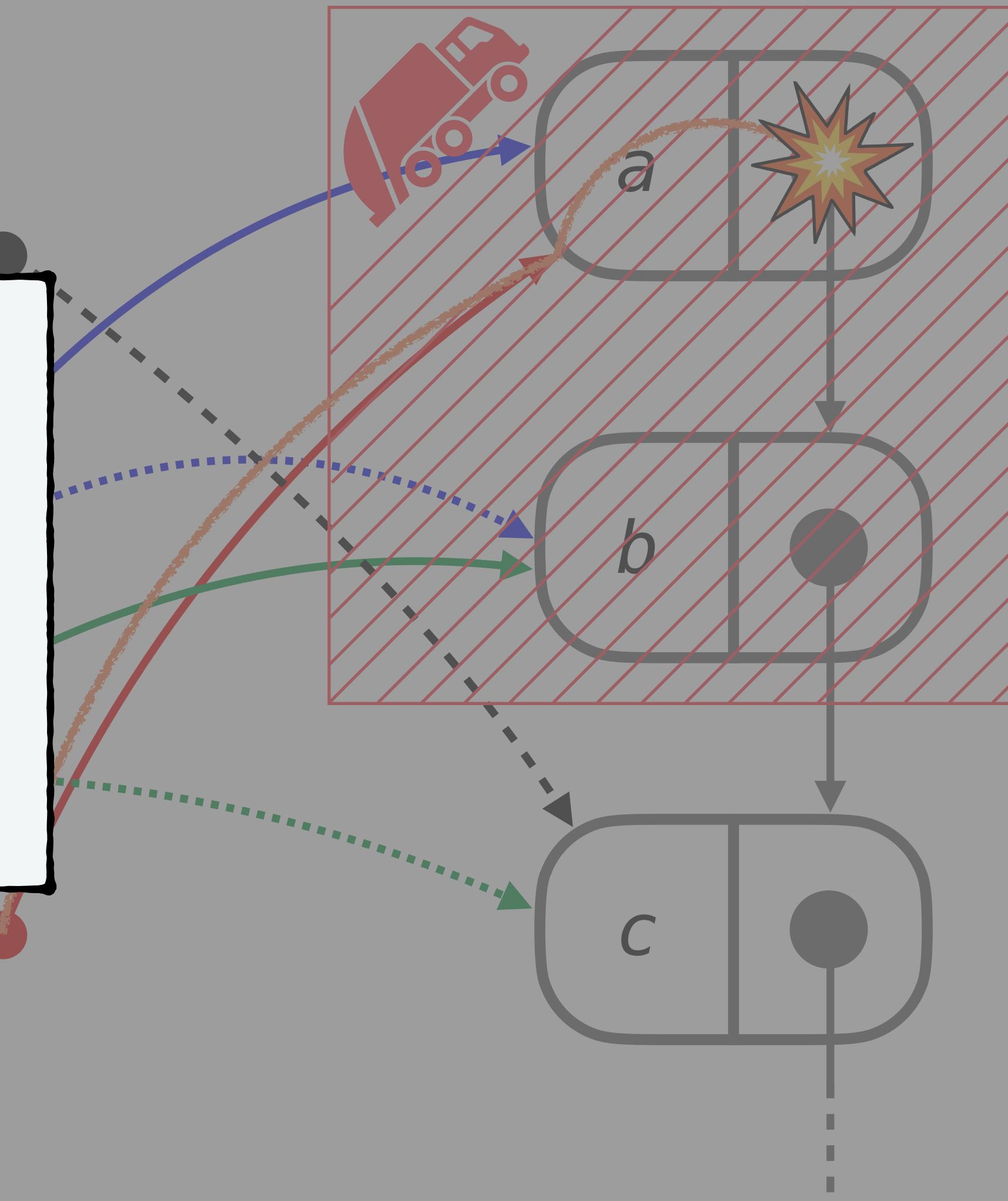
**Observation**

- unsynchronized traversal
- undetected dangling readers
- undetected deletion

⇒ naive deletion unsafe

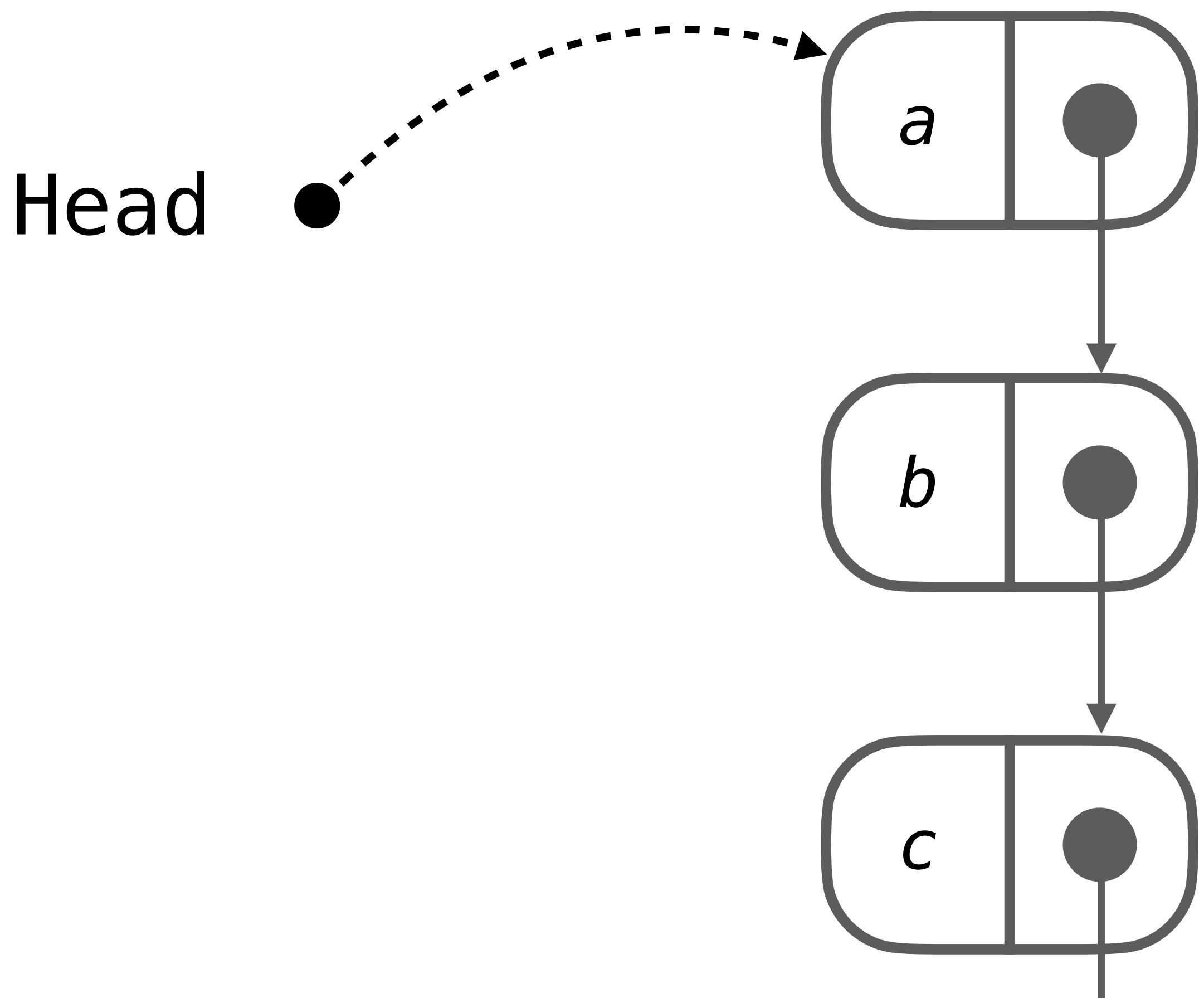
Head

head<sub>3</sub>



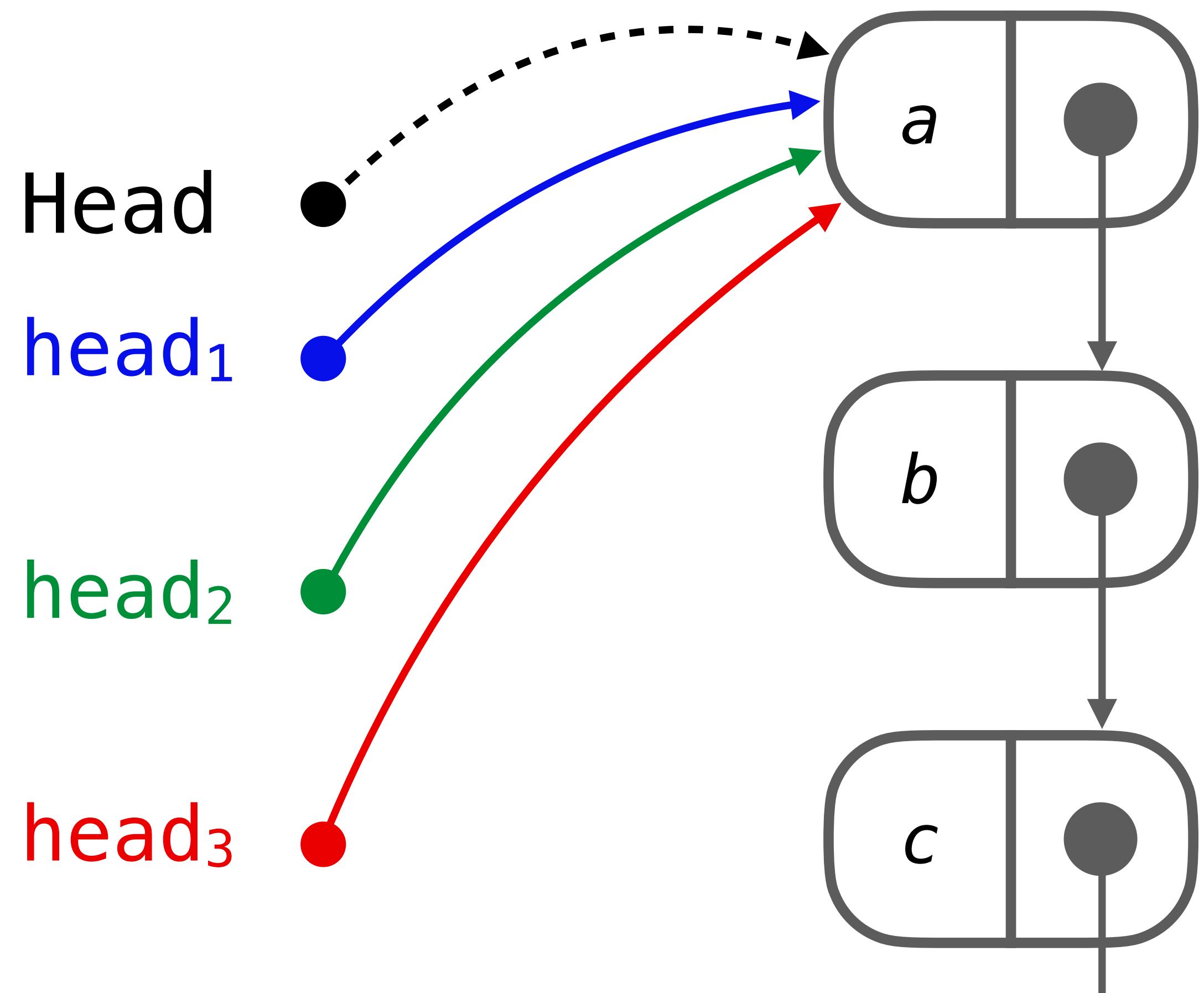
# Safe Memory Reclamation (SMR)

```
void dequeue() {  
    while (true) {  
        1 2 3 head = Head;  
        protect(head);  
        if(head != Head) continue;  
        next = head->next;  
        // ...  
        if(CAS(Head, head, next)) {  
            retire(head);  
            return;  
        }  
    }  
}
```



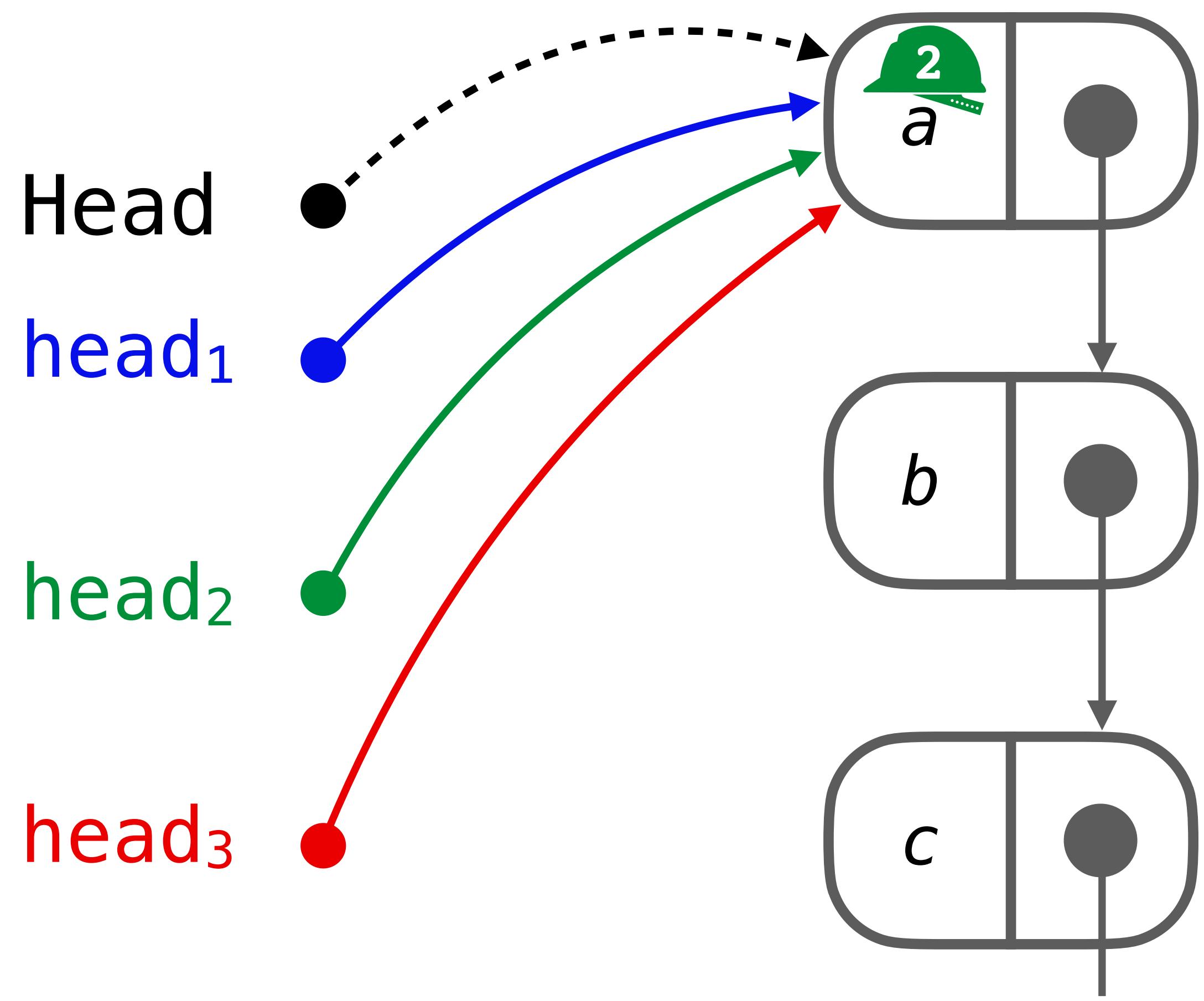
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        if(CAS(Head, head, next)) {  
            retire(head);  
            return;  
        }  
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}
```



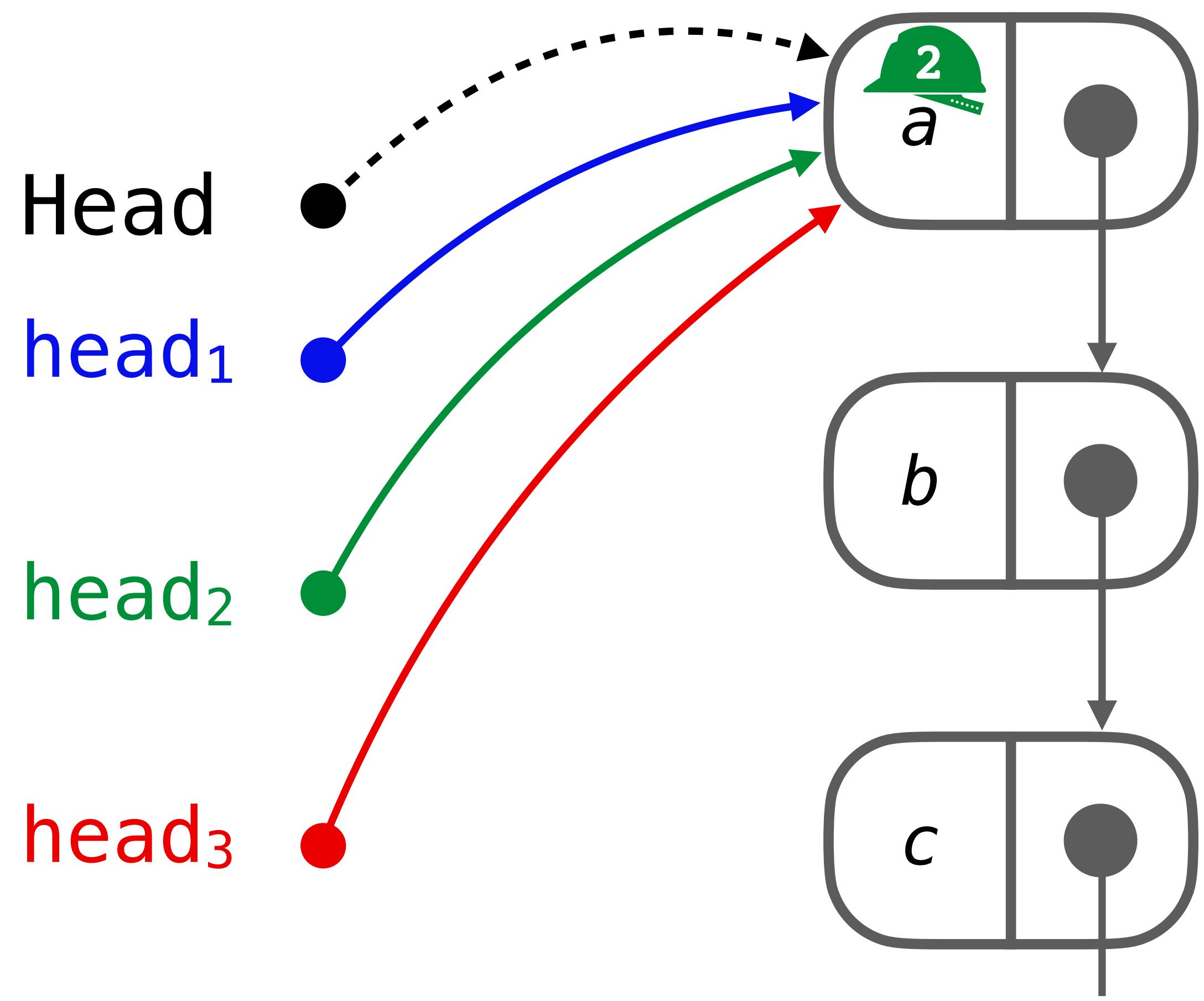
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        // ...  
        if(CAS(Head, head, next)) {  
            retire(head);  
            return;  
        }  
    }  
}
```



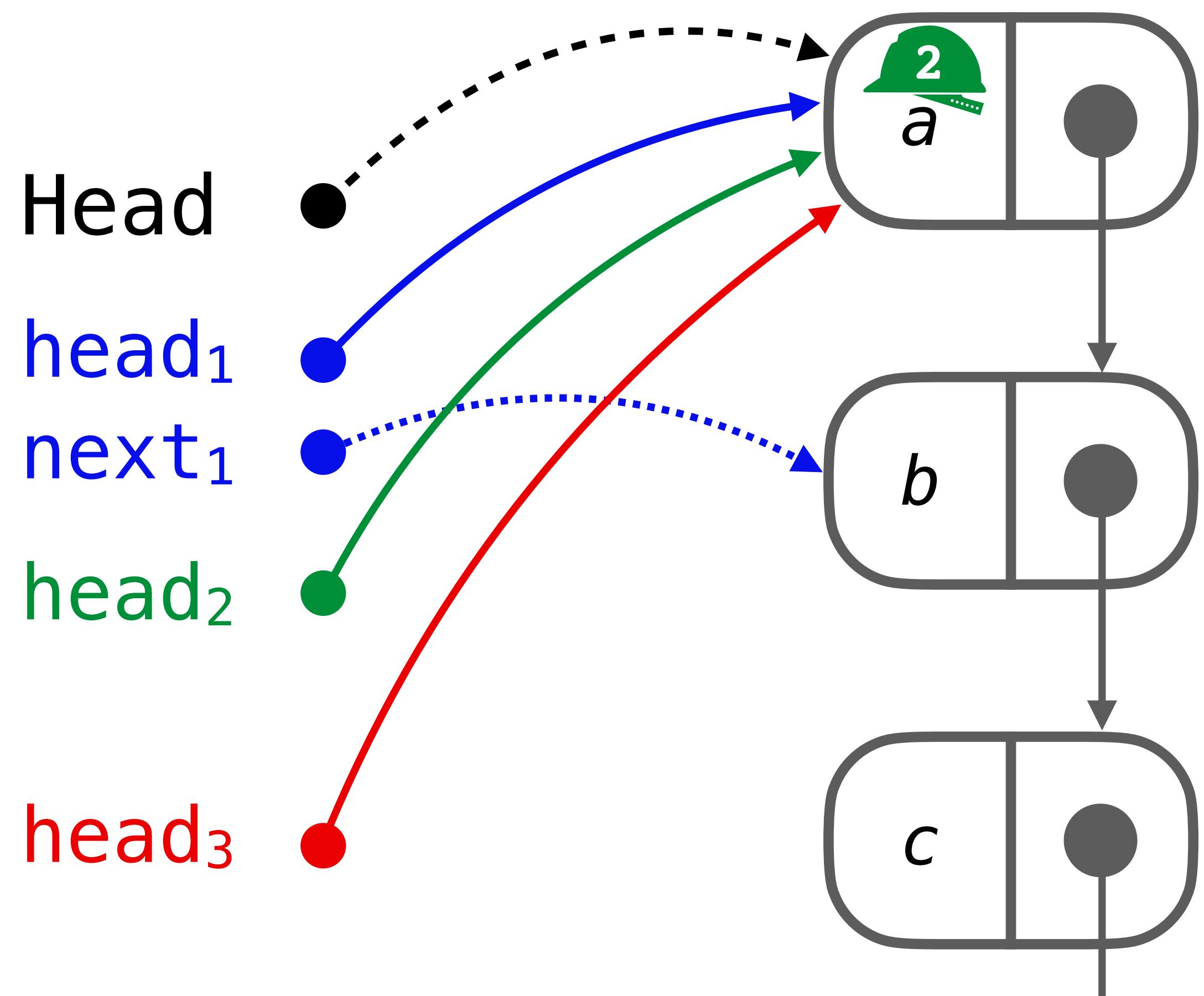
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        // ...  
        if(CAS(Head, head, next)) {  
            retire(head);  
            return;  
        }  
    }  
}
```



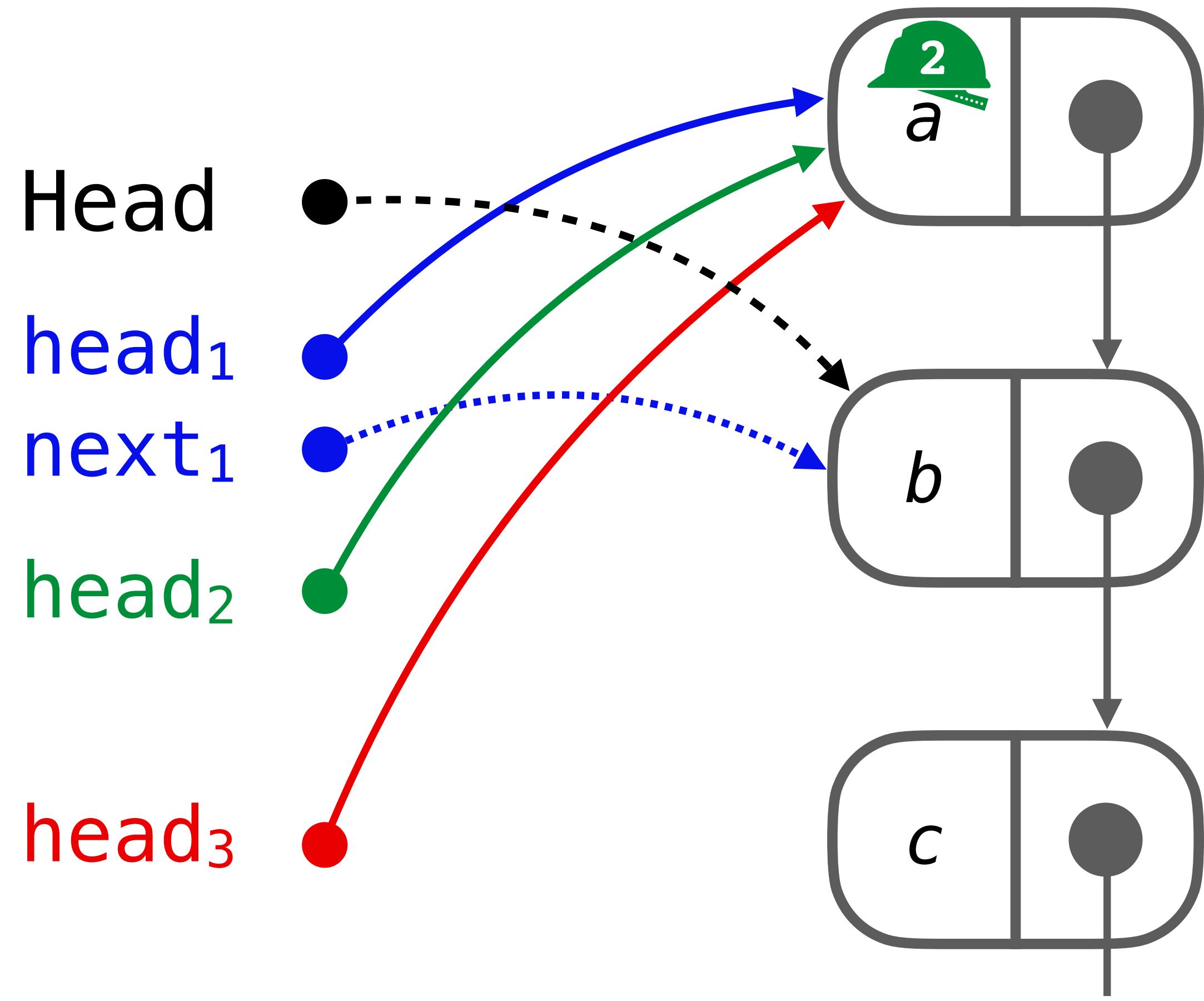
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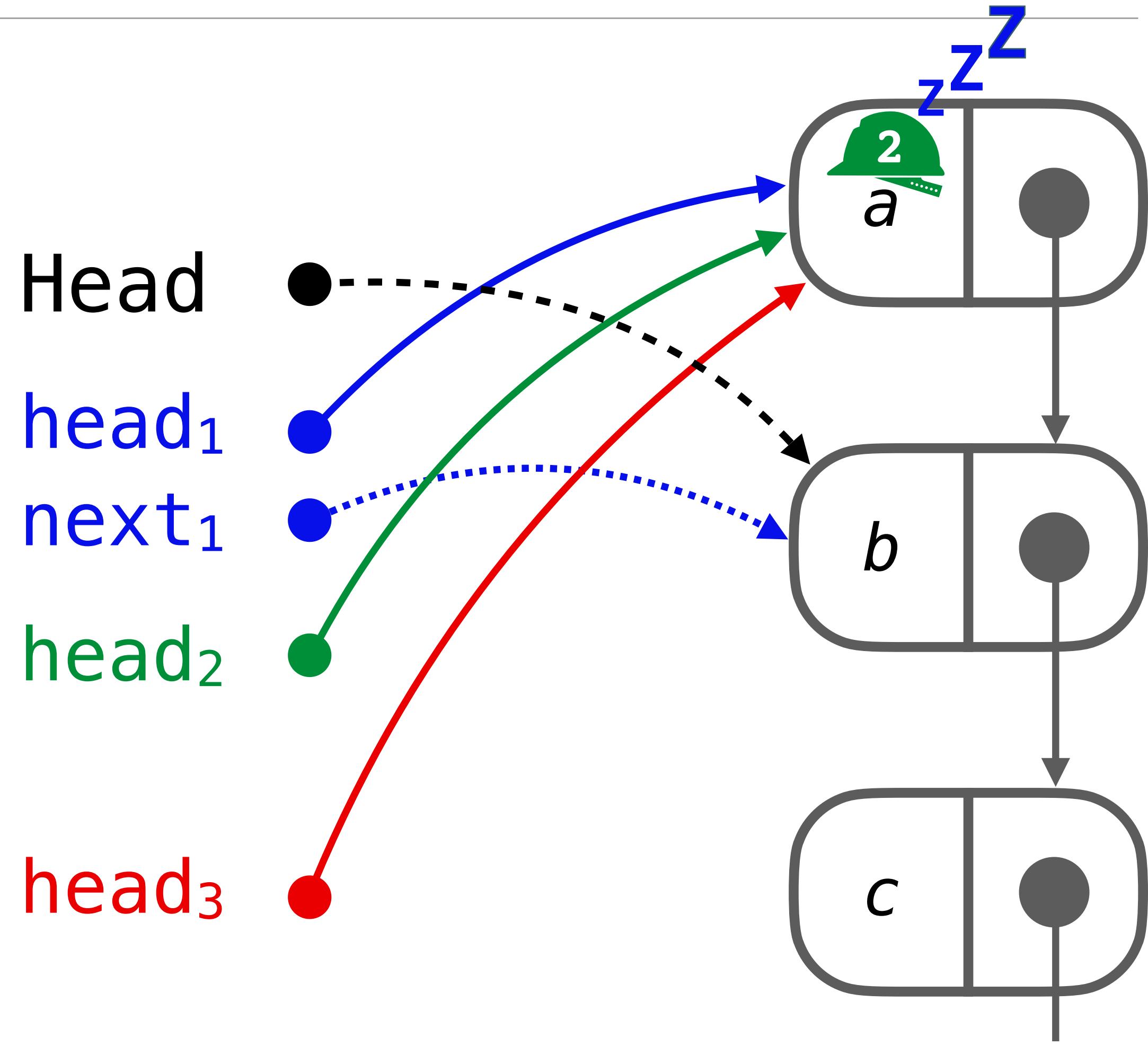
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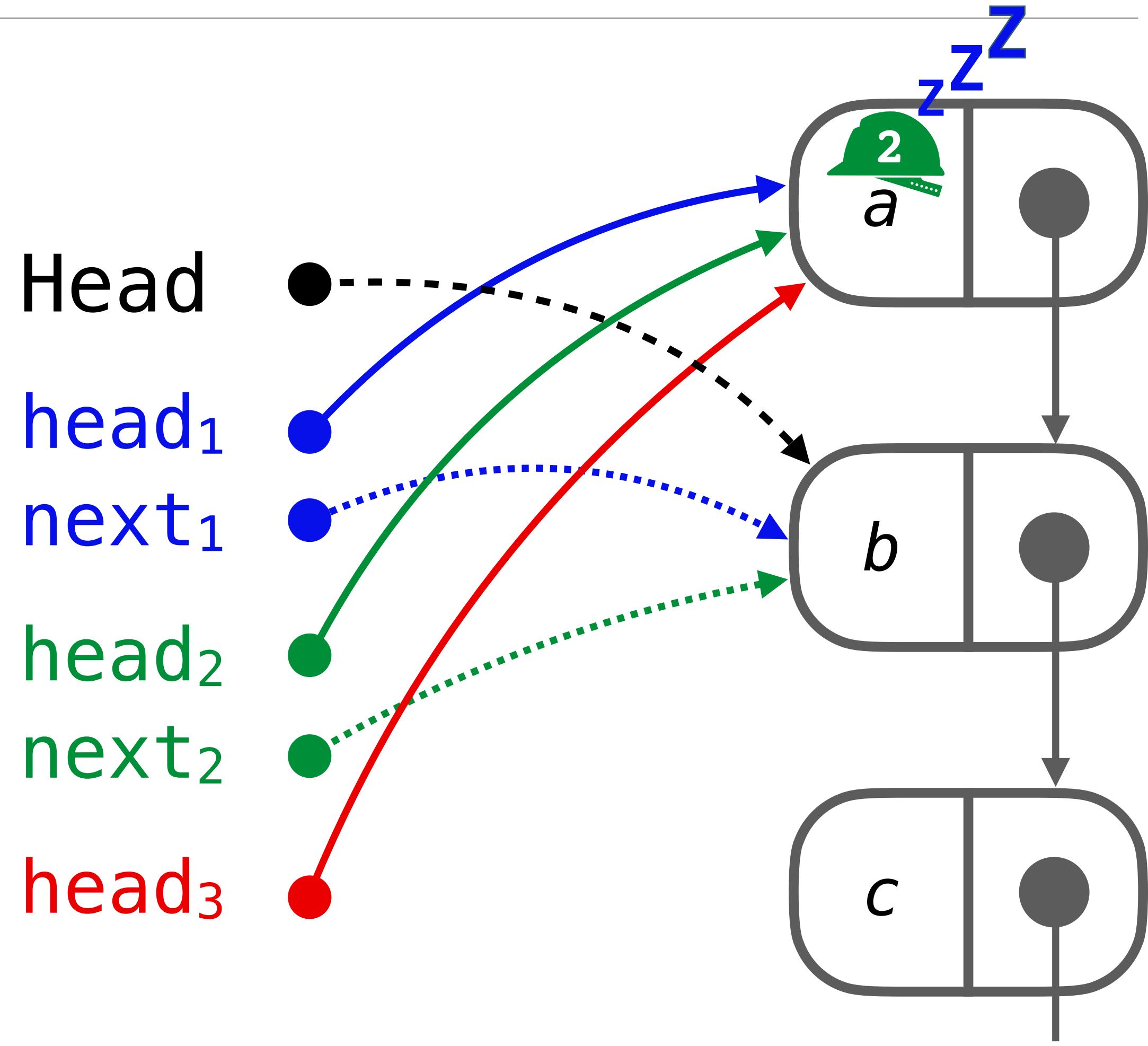
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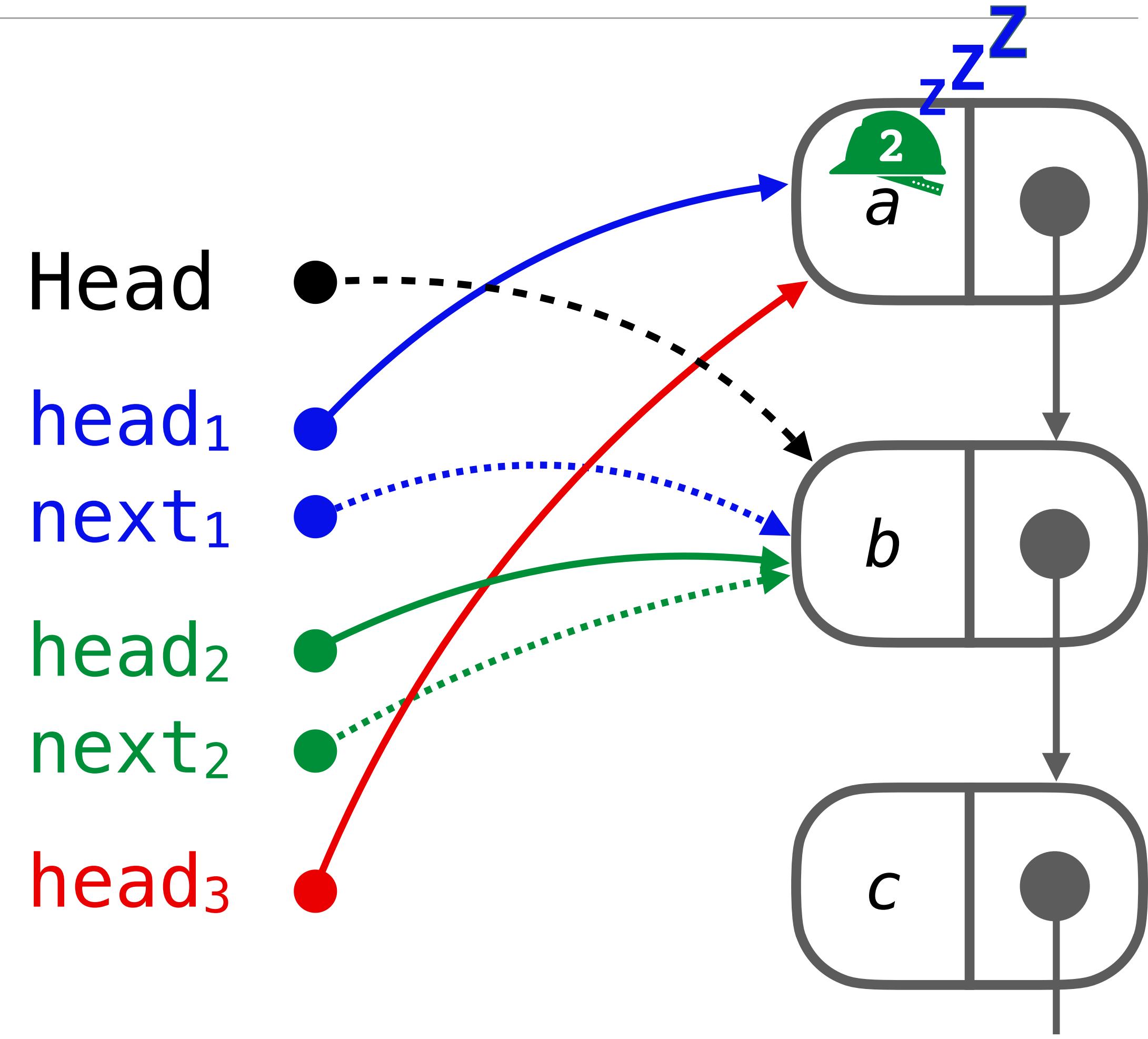
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            return;  
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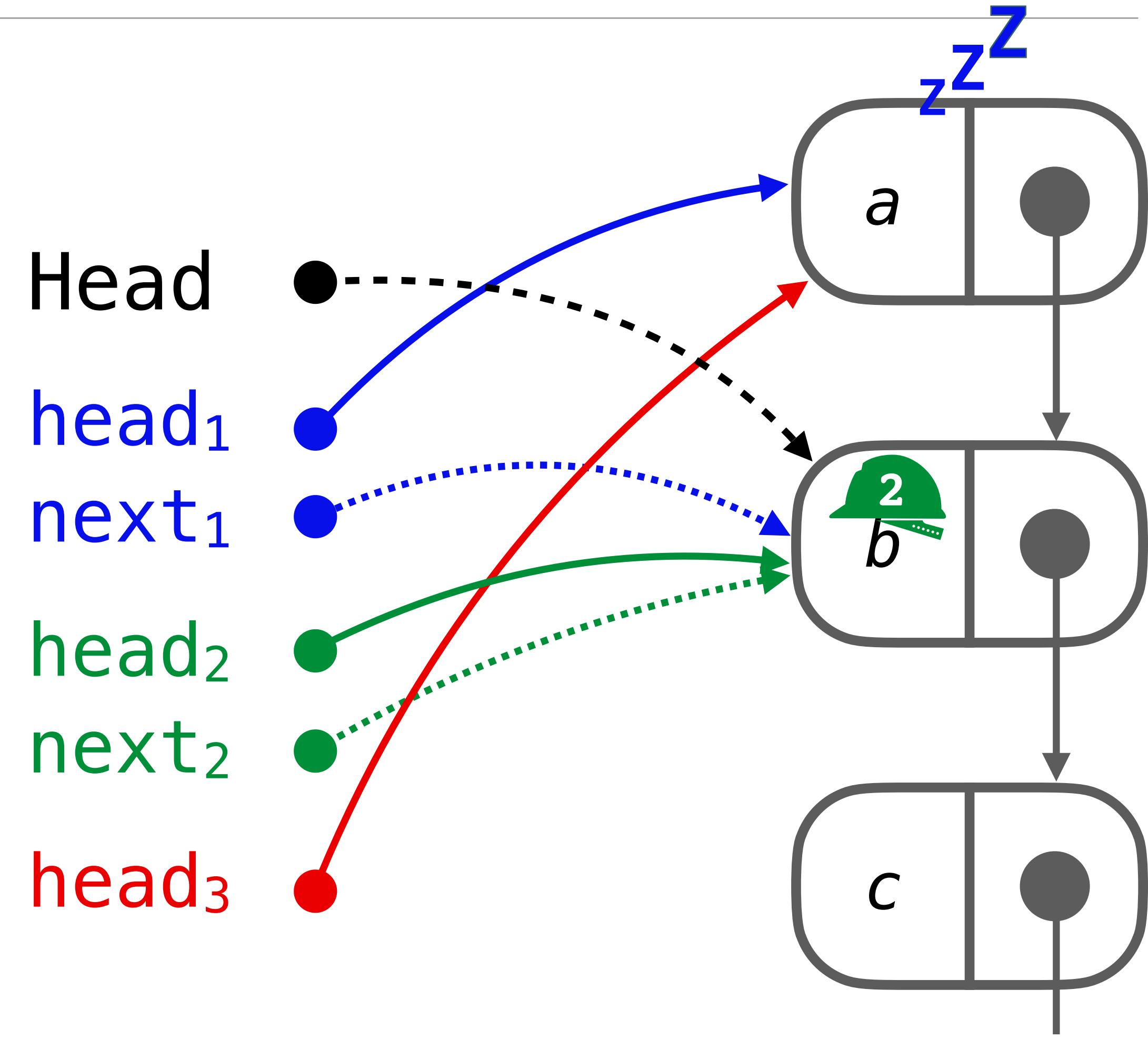
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            retire(head);  
            return;  
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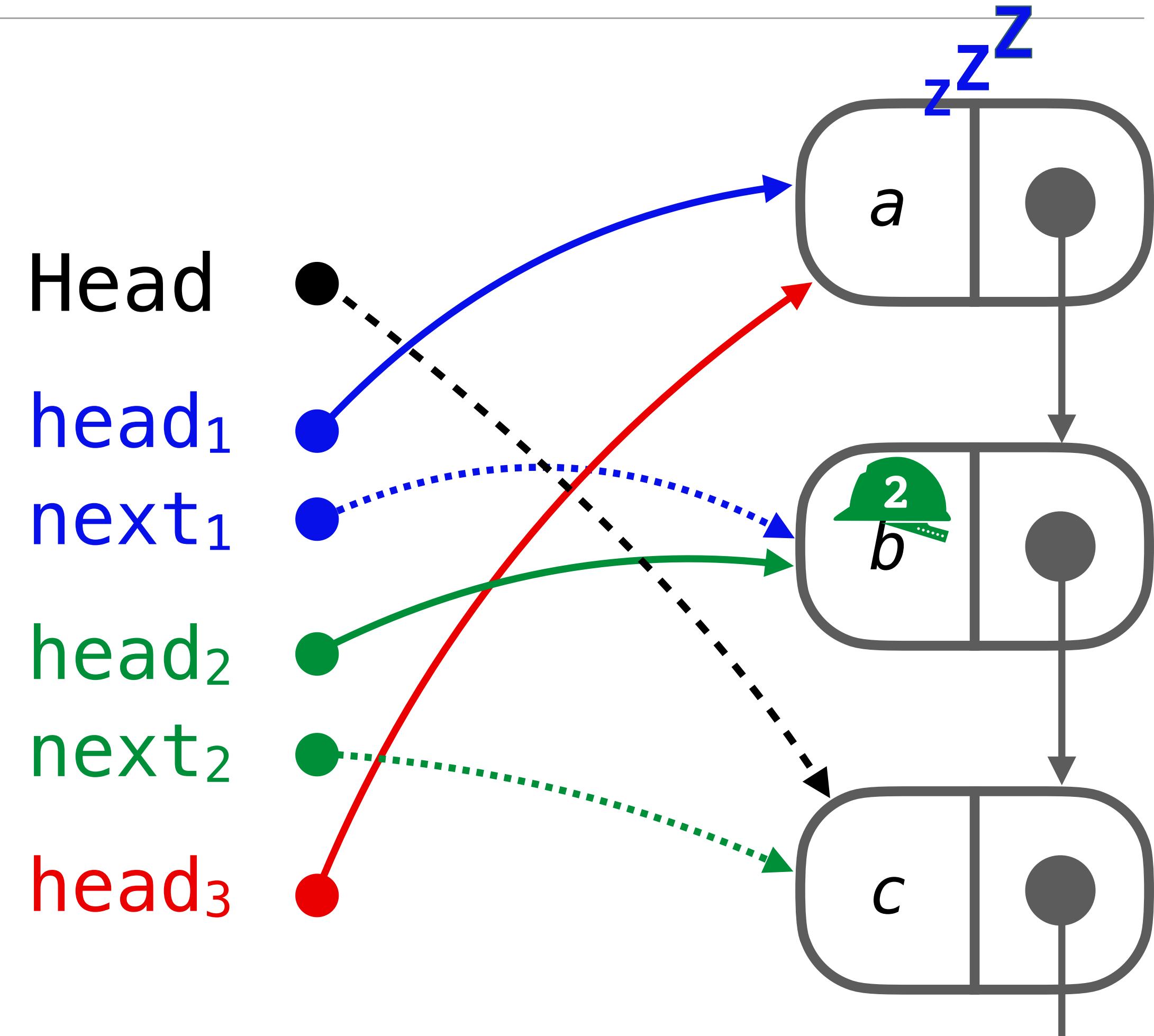
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            retire(head);  
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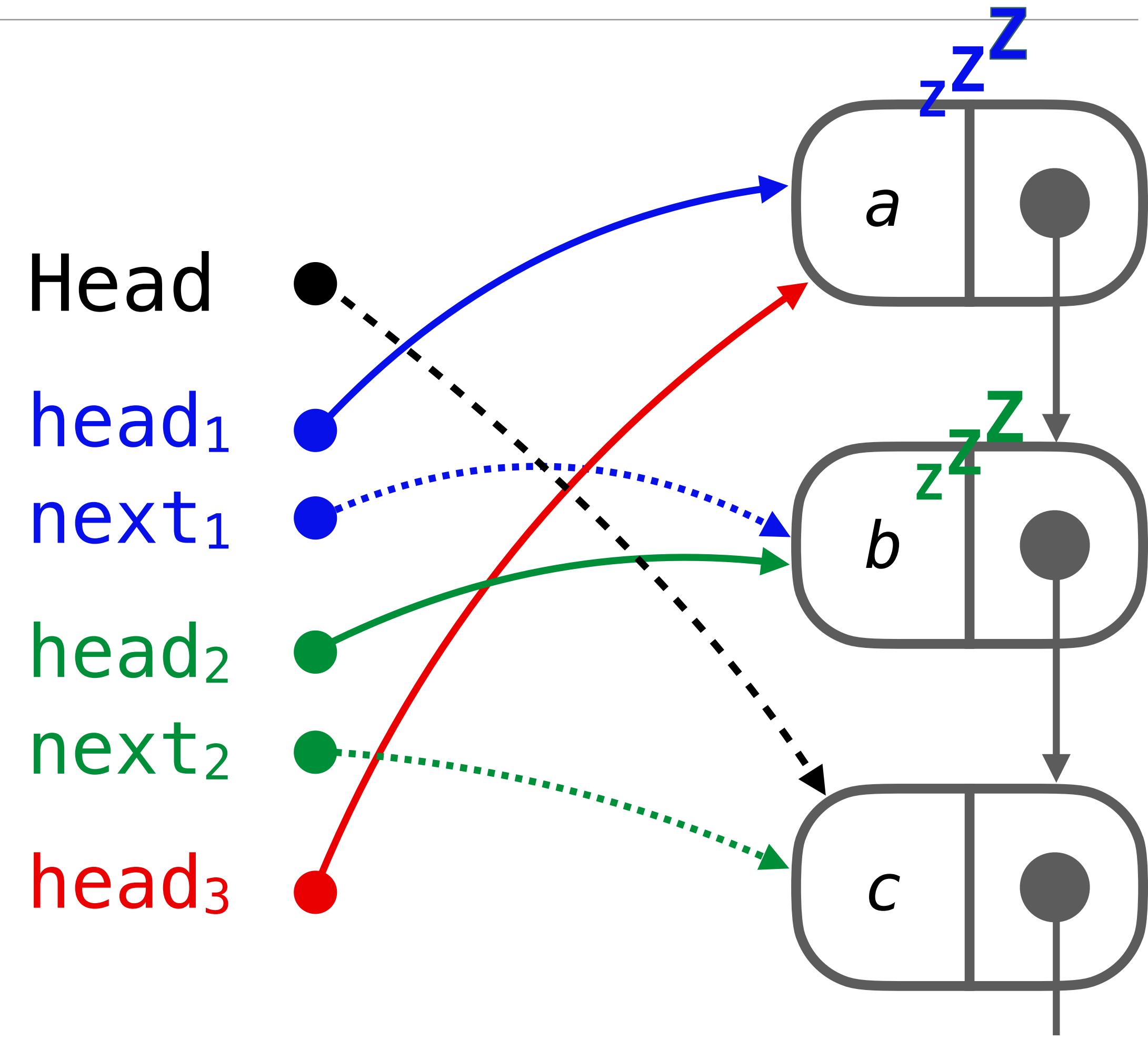
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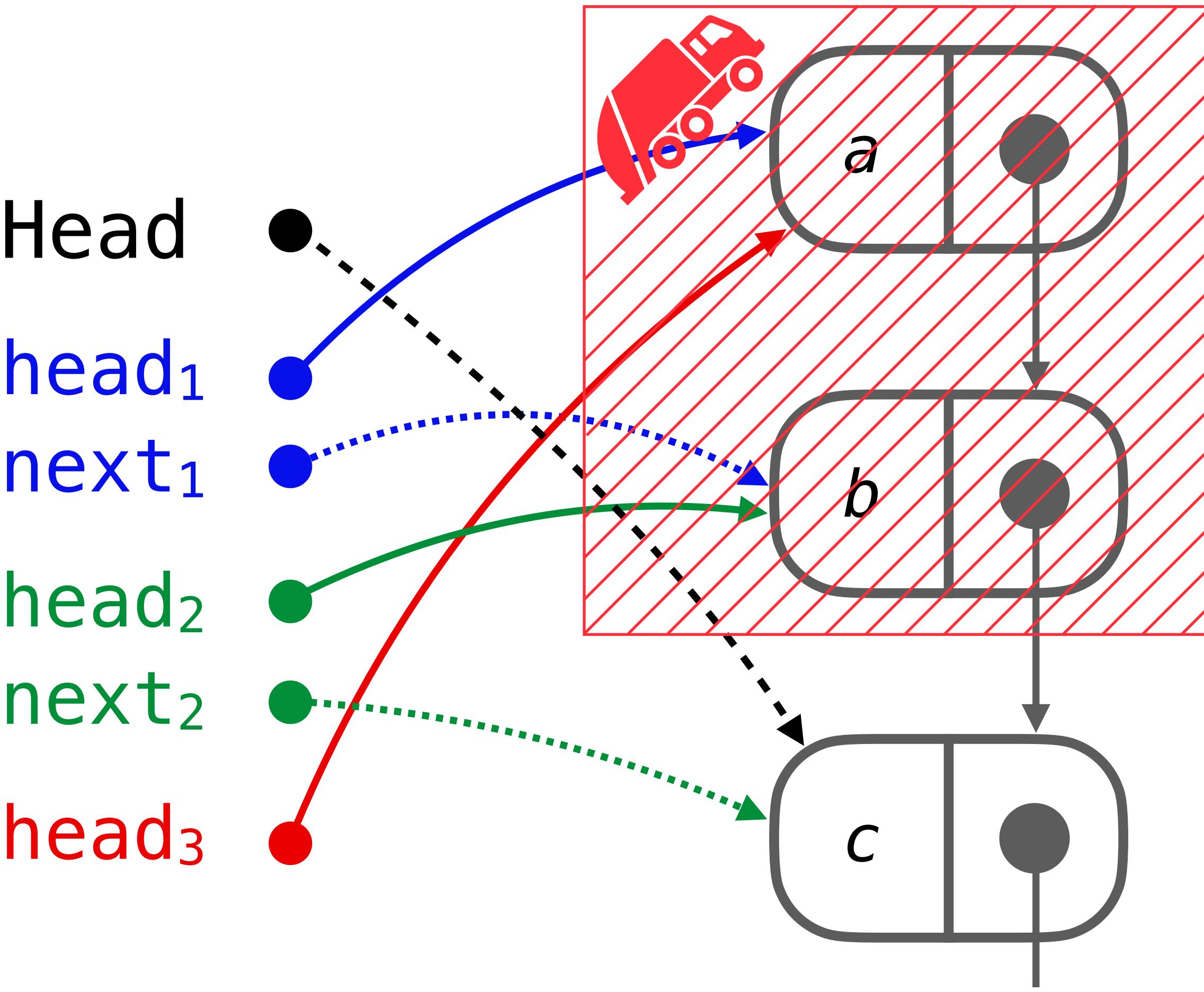
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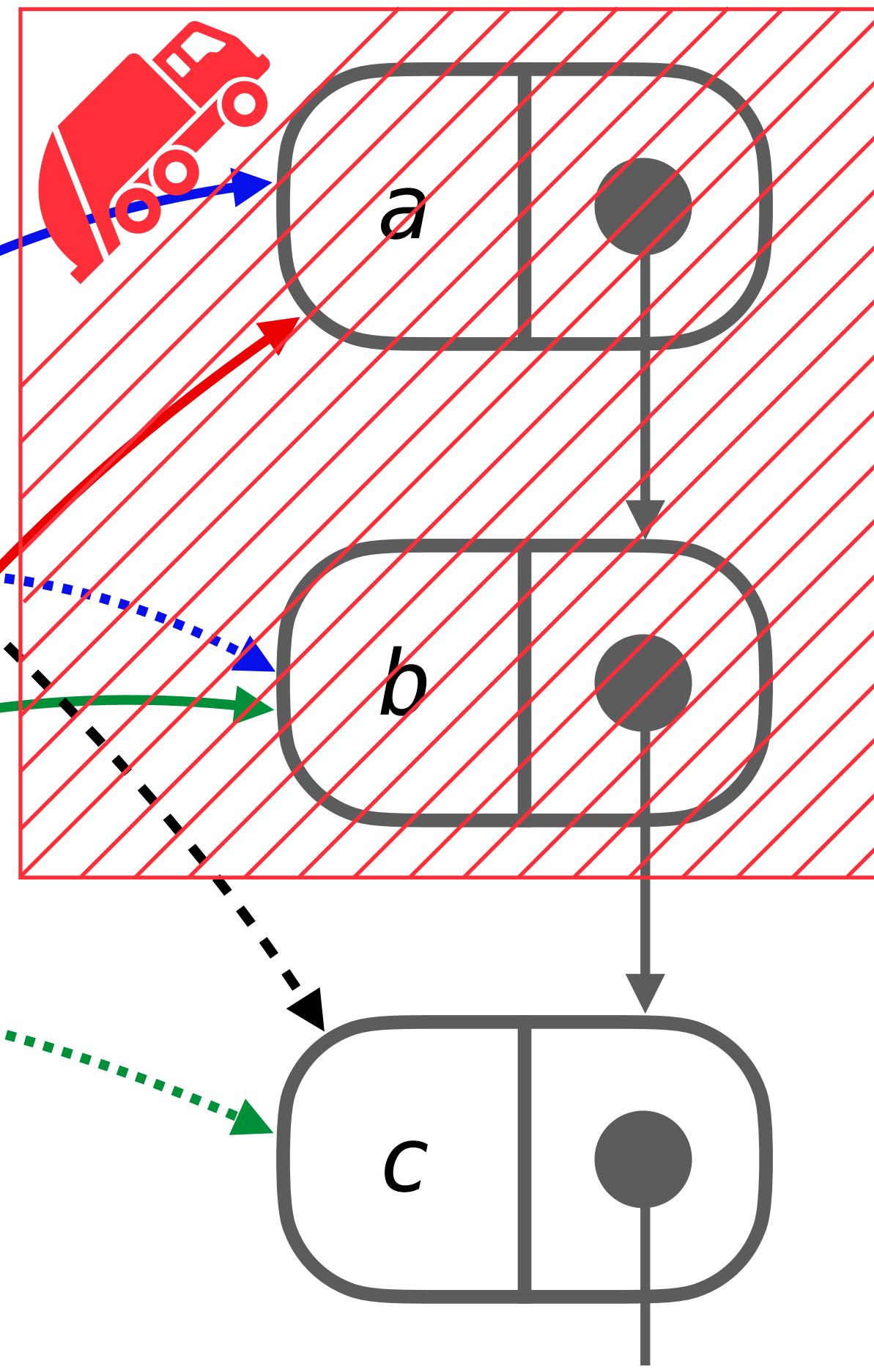
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            return;  
        } ②  
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            retire(head);  
            return;  
        }  
    }  
}
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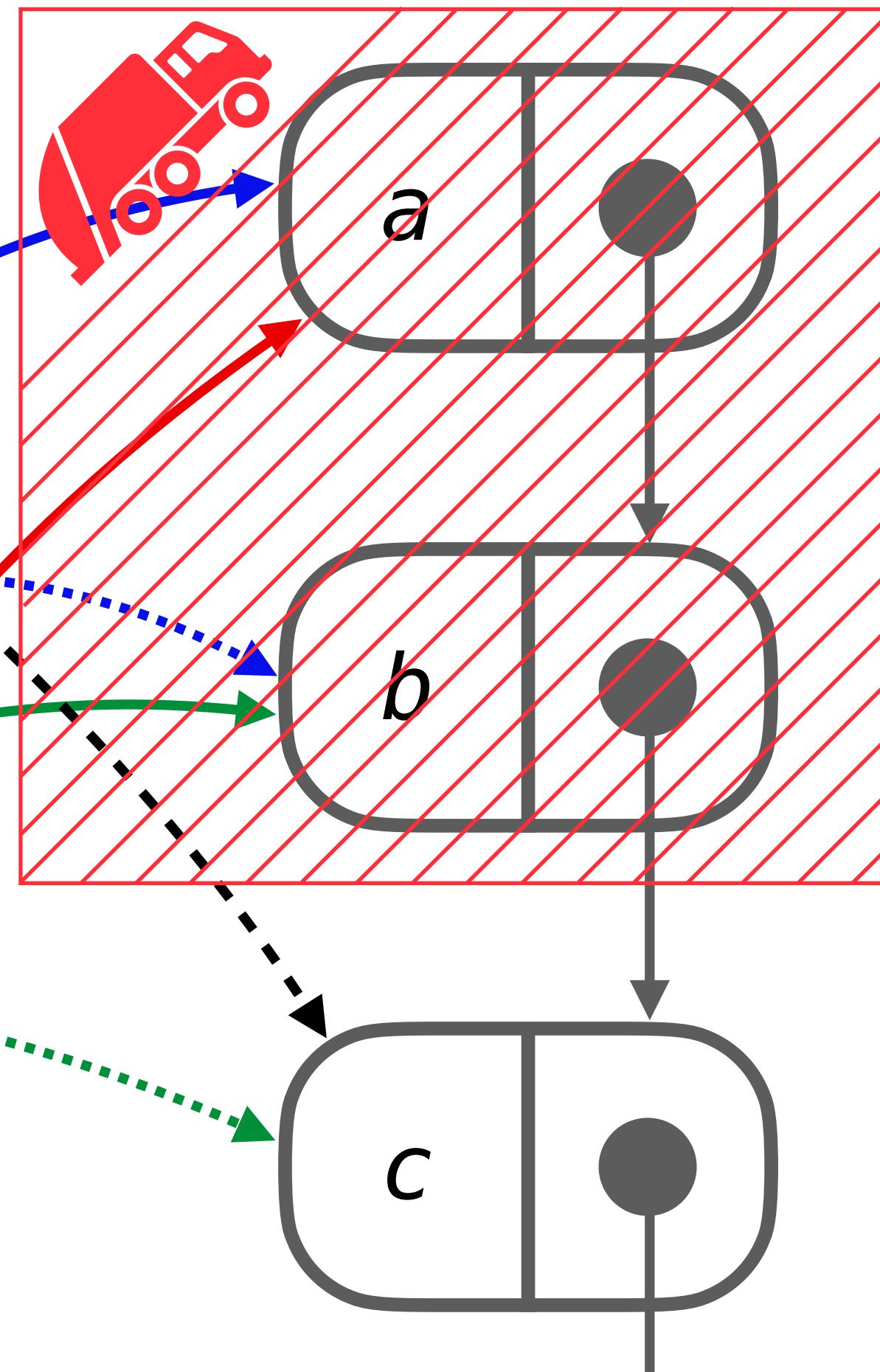
Head  
head<sub>1</sub>  
next<sub>1</sub>  
head<sub>2</sub>  
next<sub>2</sub>  
head<sub>3</sub>



# Safe Memory Reclamation (SMR)

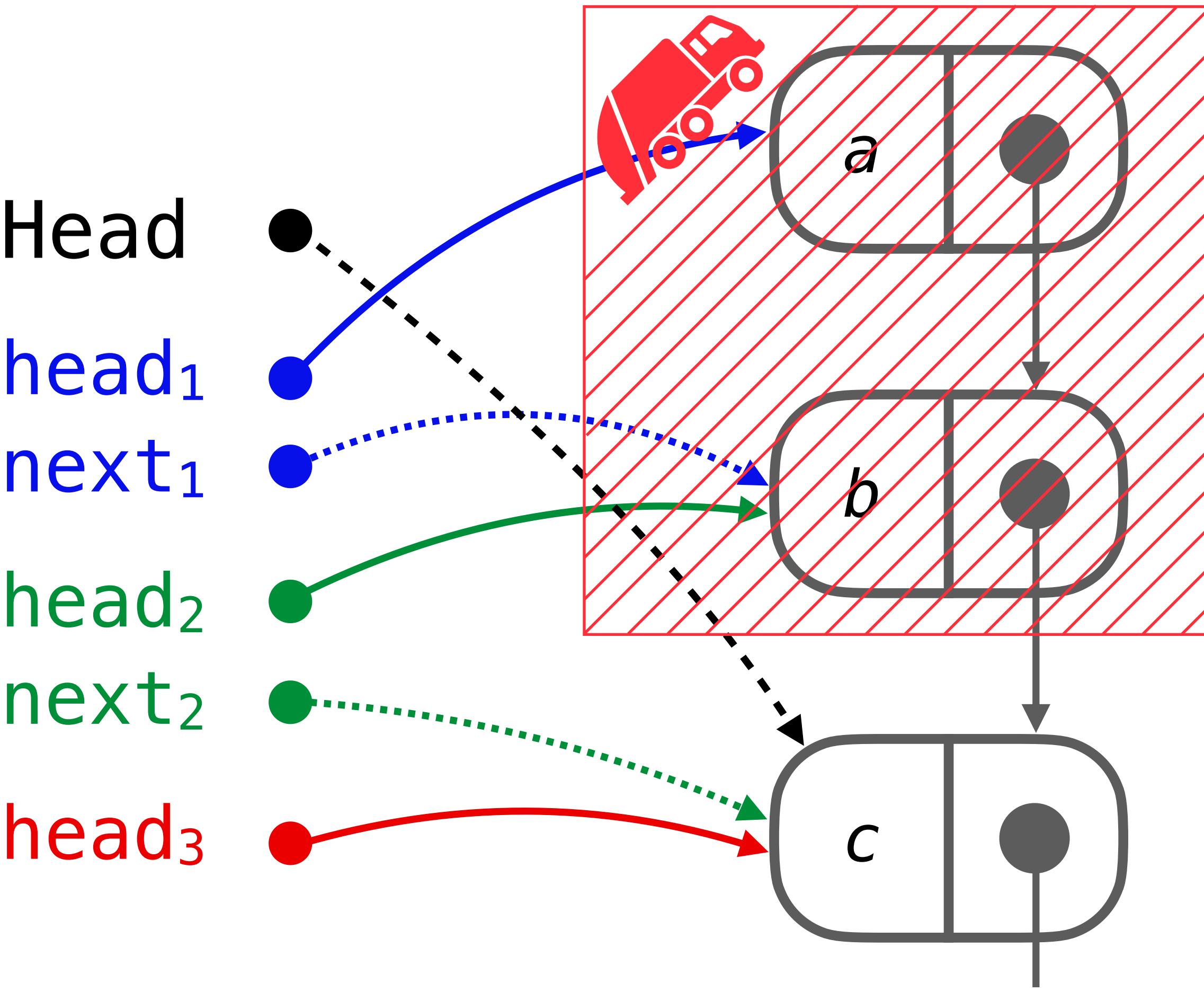
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        protect(head);  
        if(head != Head) continue;  
        next = head->next;  
        // ...  
        if(CAS(Head, head, next)) {  
            retire(head);  
            return;  
        }  
    }  
}
```

Head  
head<sub>1</sub>  
next<sub>1</sub>  
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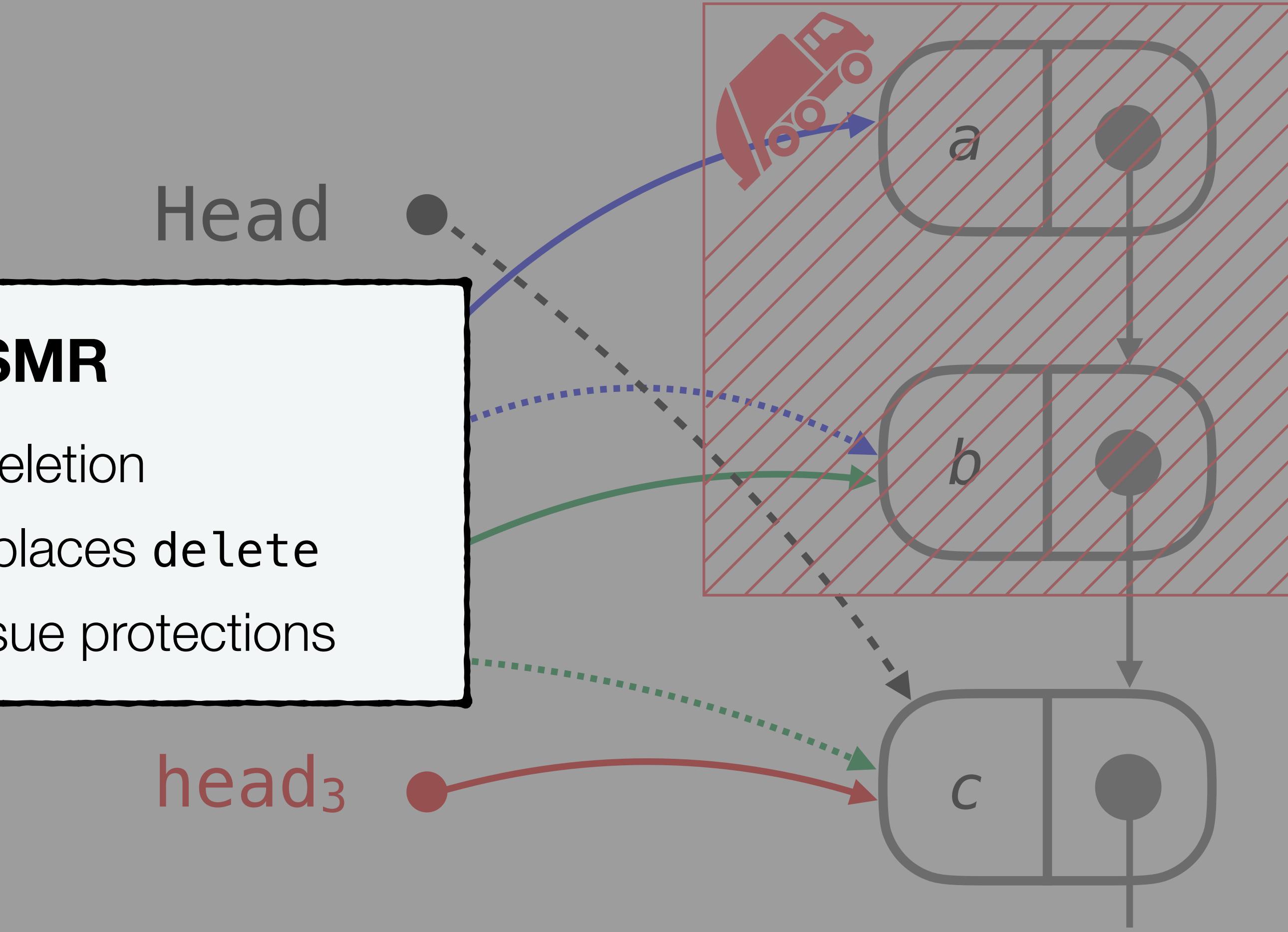
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        if(CAS(Head, head, next)) {  
            retire(head);  
            return;  
        } ②  
    } ①  
}
```



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```
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        ③ protect(head);  
        if(head != Head)  
            next = head->next;  
        // ...  
        if(CAS(Head, head, next)) {  
            retire(head);  
            return;  
        }  
    }  
}
```



head<sub>3</sub>

①②

# Non-blocking Queue (Michael&Scott)

```
struct Node {           shared:           void init() {
    data_t data;       Node* Head;        Head = new Node();
    Node* node;        Node* Tail;       Head->next = null;
}                         }                   Tail = Head;
                           }

void enqueue(data_t val) {           data_t dequeue() {
    Node* node = new Node();         while (true) {
    node->data = val;             Node* head = Head;
    node->next = null;            Node* tail = Tail;
    while (true) {                 Node* next = head->next;
        Node* tail = Tail;         if (Head != head) continue;
        Node* next = tail->next;   if (head == tail) {
        if (Tail != tail) continue;     if (next == null) return empty_t;
        if (next == null) return empty_t;
        if (next == null) return empty_t;
        if (CAS(tail->next, null, node)) {
            CAS(Tail, tail, node);
            }
        else {
            CAS(Tail, tail, next);
            }
        }
    }
}
}
```

queue

lock-free

GC

37 LOC

# Non-blocking Queue (Michael&Scott)

```
struct Node {           shared:           void init() {  
    data_t data;         Node* Head;        Head = new Node();  
    Node* node;          Node* Tail;       Head->next = null;  
}  
  
void enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        } else {  
            CAS(Tail, tail, next);  
        }  
    }  
}
```

queue

lock-free

GC

37

LOC

## Automated Verification for GC

- Vafeiadis, CAV'10 + VMCAI'10
- Abdulla et al., TACAS'13
- Zhu et al., CAV'15
- Abdulla et al., SAS'16 + ESOP'18

# Non-blocking Queue (Michael&Scott)

```

struct Node {
    data_t data;
    Node* node;
}

void enqueue(data_t val) {
    Node* node = new Node();
    node->data = val;
    node->next = null;
    while (true) {
        Node* tail = Tail;
        protect0(tail);
        if (Tail != tail) continue;
        Node* next = tail->next;
        if (Tail != tail) continue;
        if (next == null) {
            if (CAS(tail->next, null, node)) {
                CAS(Tail, tail, node);
            }
        } else {
            CAS(Tail, tail, next);
        }
    }
}

shared:
    Node* Head;
    Node* Tail;

void init() {
    Head = new Node();
    Head->next = null;
    Tail = Head;
}

data_t dequeue() {
    while (true) {
        Node* head = Head;
        protect0(head);
        if (Head != head) continue;
        Node* tail = Tail;
        Node* next = head->next;
        protect1(next);
        if (Head != head) continue;
        if (head == tail) {
            if (next == null) return empty_t;
            else CAS(Tail, tail, next);
        } else {
            data = head->data;
            if (CAS(Head, head, next)) {
                retire(head);
                return data;
            }
        }
    }
}

```

# queue

# lock-free

# SMR

# 37+6 LOC

# Non-blocking Queue (Michael&Scott)

```
struct Node {  
    data_t data;  
    Node* node;  
}  
  
void enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
        protect0(tail);  
        if (Tail != tail) continue;  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        } else {  
            CAS(Tail, tail, next);  
        }  
    }  
}
```

queue

lock-free

SMR

37+6 LOC

```
shared:  
    Node* Head;  
    Node* Tail;  
  
void init() {  
    Head = new Node();  
    Head->next = null;  
    Tail = Head;  
}  
  
data_t dequeue() {  
    while (true) {  
        Node* head = Head;  
        protect0(head);  
        if (Head != head) continue;  
        Node* tail = Tail;  
        Node* next = head->next;  
        protect1(next);  
        if (Head != head) continue;  
        if (head == tail) {  
            if (next == null) return empty_t;  
            else CAS(Tail, tail, next);  
        } else {  
            data = head->data;  
            if (CAS(Head, head, next)) {  
                retire(head);  
                return data;  
            }  
        }  
    }  
}
```

```
struct Rec {  
    Rec* next;  
    Node* hp0;  
    Node* hp1;  
}  
  
shared:  
    Rec* HPRecs;  
  
thread-local:  
    Rec* myRec;  
    List<Node*> retiredList;  
  
void join() {  
    myRec = new HPRec();  
    while (true) {  
        Rec* tmp = HPRecs;  
        myRec->next = tmp;  
        if (CAS(HPRecs, tmp, myRec)) {  
            break;  
        }  
    }  
}  
  
void part() {  
    unprotect(0);  
    unprotect(1);  
}
```

```
void protect0(Node* ptr) {  
    myRec->hp0 = ptr;  
}  
  
void protect1(Node* ptr) {  
    myRec->hp1 = ptr;  
}  
  
void retire(Node* ptr) {  
    retiredList.add(ptr);  
    if (*) reclaim();  
}  
  
void reclaim() {  
    List<Node*> protectedList;  
    Rec* tmp = HPRecs;  
    while (tmp != null) {  
        Node* hp0 = cur->hp0;  
        Node* hp1 = cur->hp1;  
        protectedList.add(hp0);  
        protectedList.add(hp1);  
        cur = cur->next;  
    }  
    for (Node* ptr : retiredList) {  
        if (!protectedList.contains(ptr)) {  
            retiredList.remove(ptr);  
            delete ptr;  
        }  
    }  
}
```

lock-free

HP

no reclamation

42 LOC

# Non-blocking Queue (Michael&Scott)

```
struct Node {  
    data_t data;  
    Node* node;  
}  
  
void enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
        protect0(tail);  
        if (Tail != tail) continue;  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            } else {  
                CAS(Tail, tail, next);  
            }  
        }  
    }  
}
```

```
shared:  
Node* Head;  
Node* Tail;  
  
void init() {  
    Head = new Node();  
    Head->next = null;  
    Tail = Head;  
}  
  
data_t dequeue() {  
    while (true) {  
        Node* head = Head;  
        protect0(head);  
        if (Head != head) continue;  
        Node* tail = Tail;  
        Node* next = head->next;  
        protect1(next);  
        if (Head != head) continue;  
        if (head == tail) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        }  
    }  
}
```

```
struct Rec {  
    Rec* next;  
    Node* hp0;  
    Node* hp1;  
}  
  
shared:  
Rec* HPRecs;  
  
thread-local:  
Rec* myRec;  
List<Node*> retiredList;  
  
void join() {  
    myRec = new HPRec();  
    while (true) {  
        Rec* tmp = HPRecs;  
        myRec->next = tmp;
```

```
void protect0(Node* ptr) {  
    myRec->hp0 = ptr;  
}  
  
void protect1(Node* ptr) {  
    myRec->hp1 = ptr;  
}  
  
void retire(Node* ptr) {  
    retiredList.add(ptr);  
    if (*) reclaim();  
}  
  
void reclaim() {  
    List<Node*> protectedList;  
    Rec* tmp = HPRecs;  
    while (tmp != null) {  
        Node* hp0 = cur->hp0;  
        Node* hp1 = cur->hp1;  
        protectedList.add(hp0);  
        protectedList.add(hp1);  
        cur = cur->next;  
    }  
    for (Node* ptr : retiredList) {  
        if (!protectedList.contains(ptr)) {  
            retiredList.remove(ptr);  
            delete ptr;  
        }  
    }  
}
```

**GC-techniques do not work (well)!**

In particular: ownership reasoning

queue  
lock-free

SMR

37+6 LOC

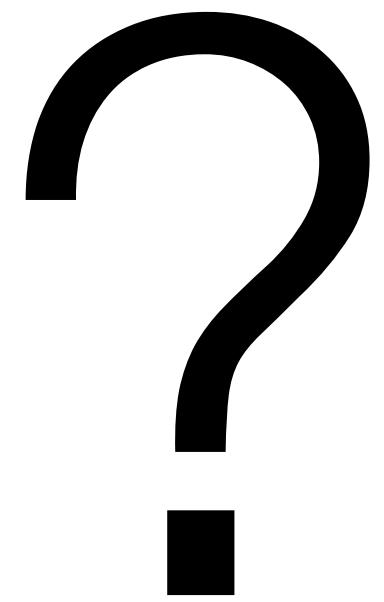
42 LOC

lock-free

HP  
no reclamation

# Our Approach

---



---

**Data structure + SMR impl  $\models$  Property**

# Contribution 1: Compositional Verification

# Compositionality in Practice

```
struct Node {  
    data_t data;  
    Node* node;  
}  
  
void enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
        protect0(tail);  
        if (Tail != tail) continue;  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        } else {  
            CAS(Tail, tail, next);  
        }  
    }  
}
```

queue

lock-free

SMR

37+6 LOC

```
void init() {  
    Head = new Node();  
    Head->next = null;  
    Tail = Head;  
}  
  
data_t dequeue() {  
    while (true) {  
        Node* head = Head;  
        protect0(head);  
        if (Head != head) continue;  
        Node* tail = Tail;  
        Node* next = head->next;  
        protect1(next);  
        if (Head != head) continue;  
        if (head == tail) {  
            if (next == null) return empty_t;  
            else CAS(Tail, tail, next);  
        } else {  
            data = head->data;  
            if (CAS(Head, head, next)) {  
                retire(head);  
                return data;  
            }  
        }  
    }  
}
```

```
struct Rec {  
    Rec* next;  
    Node* hp0;  
    Node* hp1;  
}  
  
shared:  
    Rec* HPRecs;  
  
thread-local:  
    Rec* myRec;  
    List<Node*> retiredList;  
  
void join() {  
    myRec = new HPRec();  
    while (true) {  
        Rec* tmp = HPRecs;  
        myRec->next = tmp;  
        if (CAS(HPRecs, tmp, myRec)) {  
            break;  
        }  
    }  
}  
  
void part() {  
    unprotect(0);  
    unprotect(1);  
}
```

```
void protect0(Node* ptr) {  
    myRec->hp0 = ptr;  
}  
  
void protect1(Node* ptr) {  
    myRec->hp1 = ptr;  
}  
  
void retire(Node* ptr) {  
    retiredList.add(ptr);  
    if (*) reclaim();  
}  
  
void reclaim() {  
    List<Node*> protectedList;  
    Rec* tmp = HPRecs;  
    while (tmp != null) {  
        Node* hp0 = cur->hp0;  
        Node* hp1 = cur->hp1;  
        protectedList.add(hp0);  
        protectedList.add(hp1);  
        cur = cur->next;  
    }  
    for (Node* ptr : retiredList) {  
        if (!protectedList.contains(ptr)) {  
            retiredList.remove(ptr);  
            delete ptr;  
        }  
    }  
}
```

lock-free

HP

no reclamation

42 LOC

# Compositionality in Practice

```
struct Node {  
    data_t data;  
    Node* node;  
}  
  
shared:  
Node* Head;  
Node* Tail;  
  
void init() {  
    Head = new Node();  
    Head->next = null;  
    Tail = Head;  
}  
  
void enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
        protect0(tail);  
        if (Tail != tail) continue;  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        } else {  
            CAS(Tail, tail, next);  
        }  
    }  
}  
  
data_t dequeue() {  
    while (true) {  
        Node* head = Head;  
        protect0(head);  
        if (Head != head) continue;  
        Node* tail = Tail;  
        protect1(next);  
        if (Head != head) continue;  
        if (head == tail) {  
            if (next == null) return empty_t;  
            else CAS(Tail, tail, next);  
        } else {  
            data = head->data;  
            if (CAS(Head, head, next)) {  
                retire(head);  
                return data;  
            }  
        }  
    }  
}
```

**NBDS**

queue

lock-free

SMR

37+6 LOC

```
struct Rec {  
    Rec* next;  
    Node* hp0;  
    Node* hp1;  
}  
  
shared:  
Rec* HPreCs;  
  
thread-local:  
Rec* myRec;  
List<Node*> retiredList;  
  
void join() {  
    myRec = new HPreC();  
    while (true) {  
        Rec* tmp = HPreCs;  
        myRec->next = tmp;  
        if (CAS(HPreCs, tmp, myRec)) {  
            break;  
        }  
    }  
}  
  
void part() {  
    unprotect(0);  
    unprotect(1);  
}  
  
void protect0(Node* ptr) {  
    myRec->hp0 = ptr;  
}  
  
void protect1(Node* ptr) {  
    myRec->hp1 = ptr;  
}  
  
void retire(Node* ptr) {  
    retiredList.add(ptr);  
    if (*) reclaim();  
}  
  
void reclaim() {  
    List<Node*> protectedList;  
    Rec* tmp = HPreCs;  
    while (tmp != null) {  
        Node* hp0 = cur->hp0;  
        Node* hp1 = cur->hp1;  
        protectedList.add(hp0);  
        protectedList.add(hp1);  
        cur = cur->next;  
    }  
    for (Node* ptr : retiredList) {  
        if (!protectedList.contains(ptr)) {  
            retiredList.remove(ptr);  
            delete ptr;  
        }  
    }  
}
```

42 LOC

lock-free

HP

no reclamation

# Compositionality in Practice

```
struct Node {  
    data_t data;  
    Node* node;  
}  
  
shared:  
    Node* Head;  
    Node* Tail;  
  
void init() {  
    Head = new Node();  
    Head->next = null;  
    Tail = Head;  
}  
  
data_t enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
        protect0(tail);  
        if (Tail != tail) continue;  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        } else {  
            CAS(Tail, tail, next);  
        }  
    }  
}
```

**NBDS**

queue

lock-free

SMR

37+6 LOC

```
data_t dequeue() {  
    while (true) {  
        Node* head = Head;  
        protect0(head);  
        if (Head != head) continue;  
        Node* tail = Tail;  
        Node* next = head->next;  
        protect1(next);  
        if (Head != head) continue;  
        if (head == tail) {  
            if (next == null) return empty_t;  
            else CAS(Tail, tail, next);  
        } else {  
            data = head->data;  
            if (CAS(Head, head, next)) {  
                retire(head);  
                return data;  
            }  
        }  
    }  
}
```

```
struct Rec {  
    Rec* next;  
    Node* hp0;  
    Node* hp1;  
}  
  
shared:  
    Rec* HPRecs;  
  
thread-local:  
    Rec* myRec;  
    List<Node*> retiredList;  
  
void join() {  
    myRec = new HPRec();  
    while (true) {  
        Rec* tmp = HPRecs;  
        myRec->next = tmp;  
        if (CAS(HPRecs, tmp, myRec)) {  
            break;  
        }  
    }  
}  
  
void part() {  
    unprotect(0);  
    unprotect(1);  
}
```

**SMR**

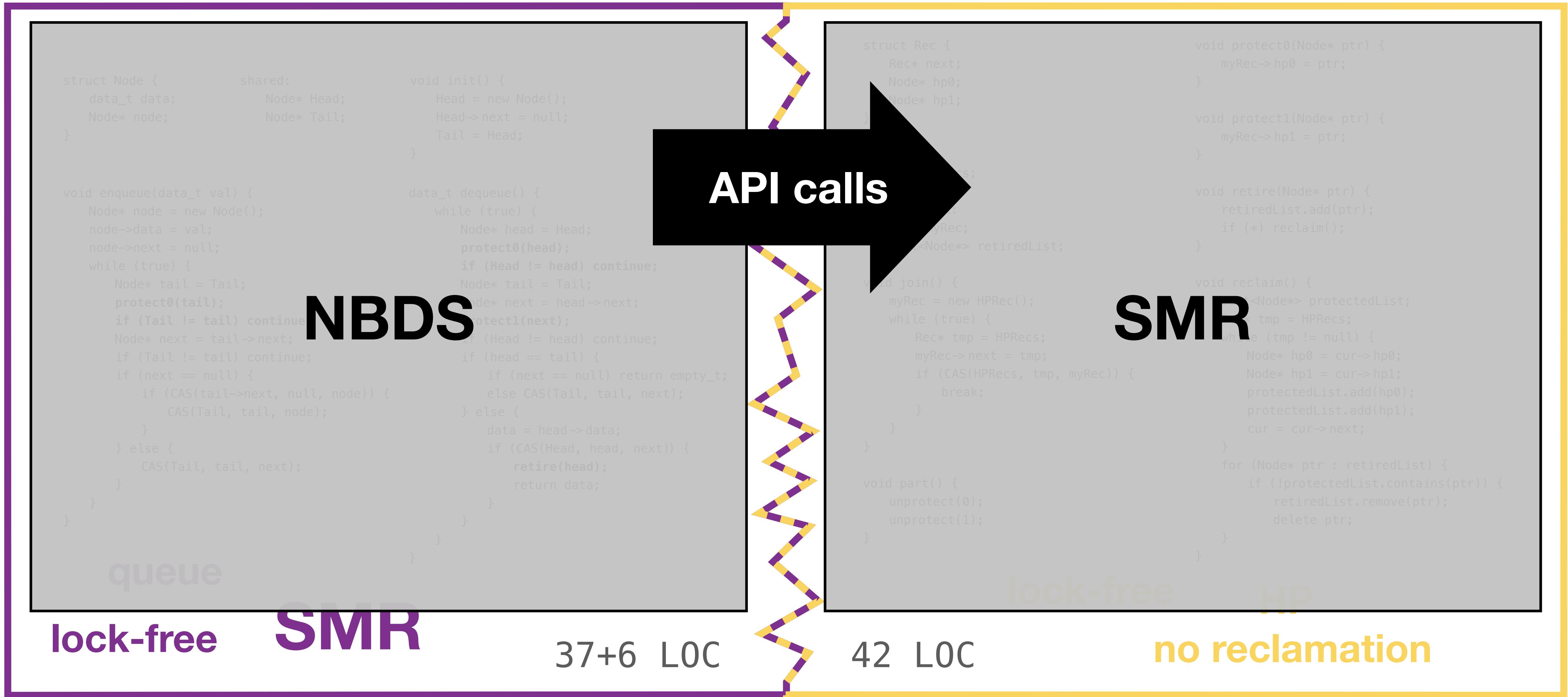
lock-free  
HP

42 LOC

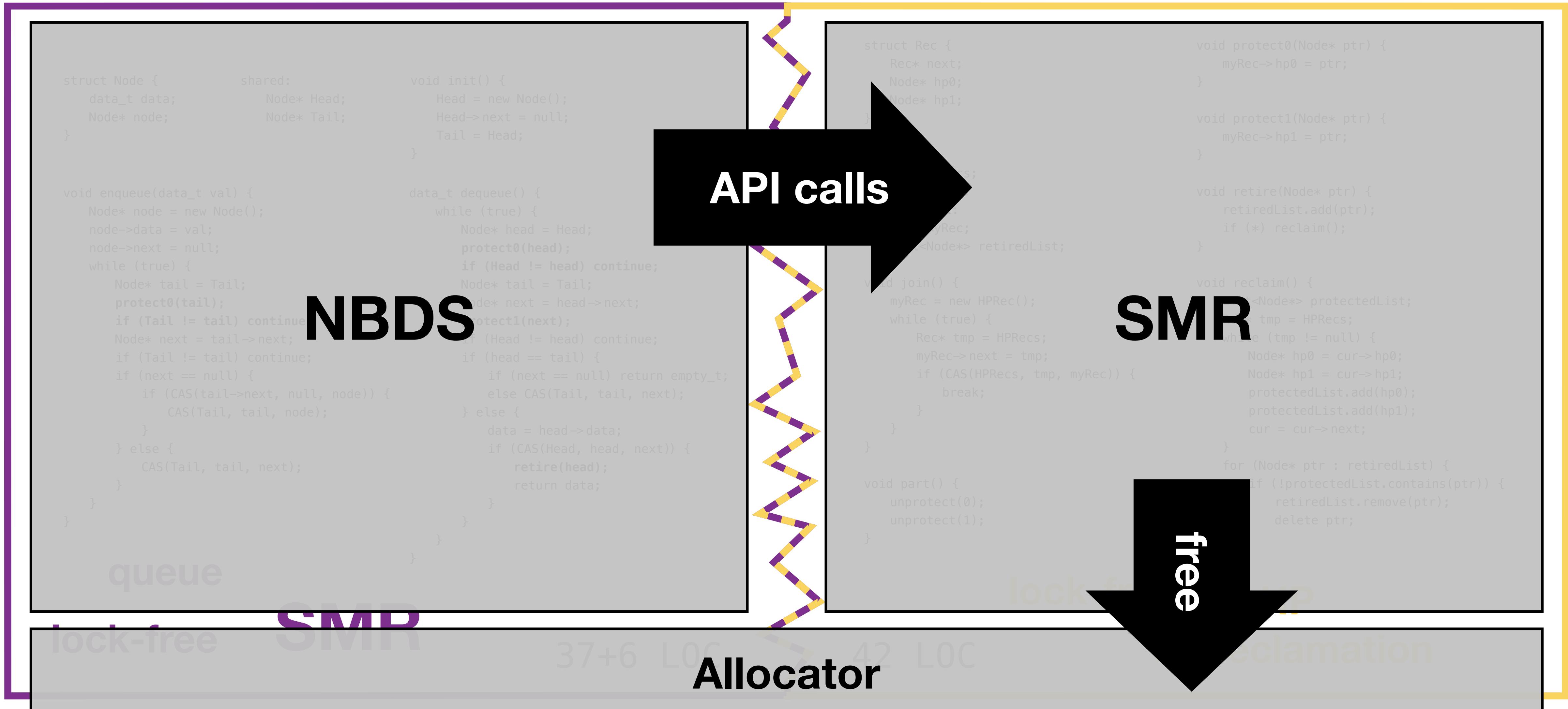
no reclamation

```
void protect0(Node* ptr) {  
    myRec->hp0 = ptr;  
}  
  
void protect1(Node* ptr) {  
    myRec->hp1 = ptr;  
}  
  
void retire(Node* ptr) {  
    retiredList.add(ptr);  
    if (*) reclaim();  
}  
  
void reclaim() {  
    <Node*> protectedList;  
    while (tmp != null) {  
        Node* hp0 = cur->hp0;  
        Node* hp1 = cur->hp1;  
        protectedList.add(hp0);  
        protectedList.add(hp1);  
        cur = cur->next;  
    }  
    for (Node* ptr : retiredList) {  
        if (!protectedList.contains(ptr)) {  
            retiredList.remove(ptr);  
            delete ptr;  
        }  
    }  
}
```

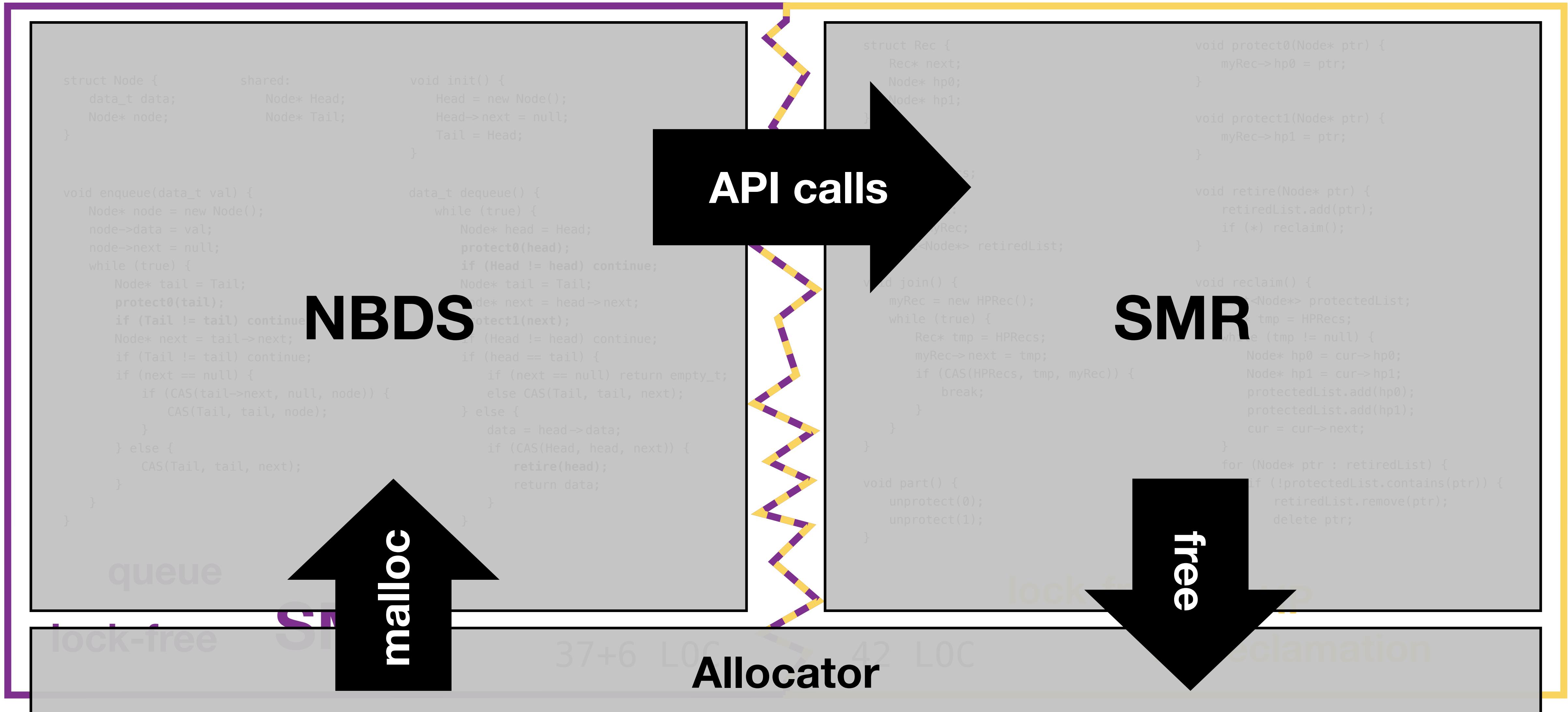
# Compositionality in Practice



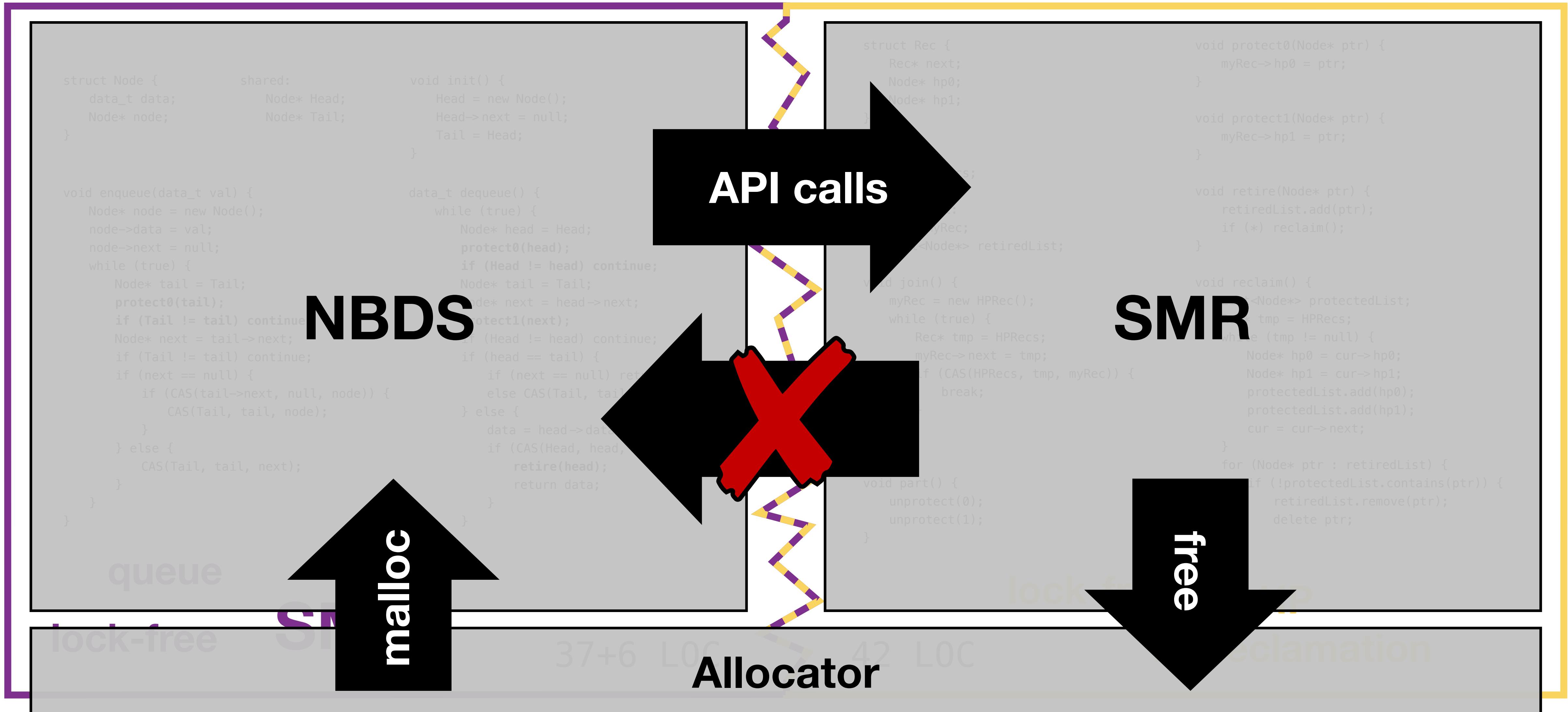
# Compositionality in Practice



# Compositionality in Practice



# Compositionality in Practice



# Compositionality in Verification

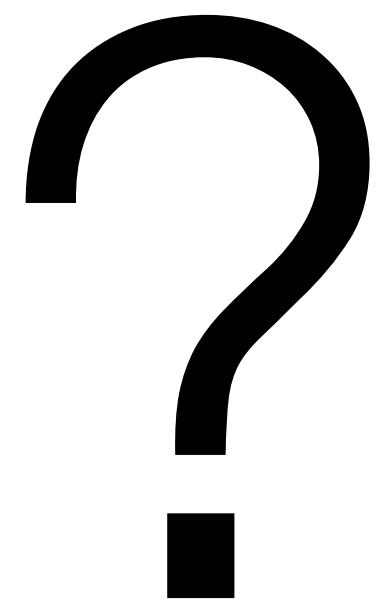
---

API between **data structure** and **SMR impl**

- give a formal specification **SMR spec**
- **SMR spec** states *which&when* addresses are freed
- use new class of automata as **SMR spec**

# Our Approach

---



---

**Data structure + SMR impl  $\models$  Property**

# Our Approach

---

**SMR impl**  $\models$  **SMR spec**

**Data structure** + **SMR spec**  $\models$  **Property**

---

**Data structure** + **SMR impl**  $\models$  **Property**

# Our Approach

**SMR impl**  $\models$  **SMR spec**

**Data structure + SMR spec**  $\models$  **Property**

**Data structure + SMR impl**  $\models$  **Property**

**[POPL'19]**

with Roland Meyer



Decoupling Lock-Free Data Structures from  
Memory Reclamation for Static Analysis

ROLAND MEYER, TU Braunschweig, Germany  
SEBASTIAN WOLFF, TU Braunschweig, Germany

Verification of concurrent data structures is one of the most challenging tasks in software verification. The topic has received considerable attention over the course of the last decade. Nevertheless, human-driven techniques remain cumbersome and notoriously difficult while automated approaches suffer from limited applicability. The main obstacle for automation is the complexity of concurrent data structures. This is particularly true in the absence of garbage collection. The intricacy of lock-free memory management paired with the complexity of concurrent data structures makes automated verification prohibitive.

In this work we present a method for verifying concurrent data structures and their memory management separately. We suggest two simpler verification tasks that imply the correctness of the data structure. The first task establishes an over-approximation of the reclamation behavior of the memory management. The second task exploits this over-approximation to verify the data structure without the need to consider the implementation of the memory management itself. To make the resulting verification tasks tractable for automated techniques, we establish a second result. We show that a verification tool needs to consider only executions where a single memory location is reused. We implemented our approach and were able to verify linearizability of Michael&Scott's queue and the DGLM queue for both hazard pointers and epoch-based reclamation. To the best of our knowledge, we are the first to verify such implementations fully automatically.

CCS Concepts: • Theory of computation → Data structures design and analysis; Program verification; Shared memory algorithms; Program specifications; Program analysis;

Additional Key Words and Phrases: static analysis, lock-free data structures, verification, linearizability, safe memory reclamation, memory management

ACM Reference Format:

Roland Meyer and Sebastian Wolff. 2019. Decoupling Lock-Free Data Structures from Memory Reclamation for Static Analysis. *Proc. ACM Program. Lang.* 3, POPL, Article 58 (January 2019), 31 pages. <https://doi.org/10.1145/3290371>

## 1 INTRODUCTION

Data structures are a basic building block of virtually any program. Efficient implementations are typically a part of a programming language's standard library. With the advent of highly concurrent computing being available even on commodity hardware, concurrent data structure implementations are needed. The class of lock-free data structures has been shown to be particularly efficient. Using fine-grained synchronization and avoiding such synchronization whenever possible results in unrivaled performance and scalability.

Unfortunately, this use of fine-grained synchronization is what makes lock-free data structures also unrivaled in terms of complexity. Indeed, bugs have been discovered in published lock-free

Authors' addresses: Roland Meyer, TU Braunschweig, Germany, roland.meyer@tu-bs.de; Sebastian Wolff, TU Braunschweig, Germany, sebastian.wolff@tu-bs.de.



# Compositionality on an Example

```
struct Node {  
    data_t data;  
    Node* node;  
}  
  
void enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
        protect0(tail);  
        if (Tail != tail) continue;  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        } else {  
            CAS(Tail, tail, next);  
        }  
    }  
}
```

queue  
lock-free  
SMR

```
shared:  
Node* Head;  
Node* Tail;  
  
void init() {  
    Head = new Node();  
    Head->next = null;  
    Tail = Head;  
}  
  
data_t dequeue() {  
    while (true) {  
        Node* head = Head;  
        protect0(head);  
        if (Head != head) continue;  
        Node* tail = Tail;  
        Node* next = head->next;  
        protect1(next);  
        if (Head != head) continue;  
        if (head == tail) {  
            if (next == null) return empty_t;  
            else CAS(Tail, tail, next);  
        } else {  
            data = head->data;  
            if (CAS(Head, head, next)) {  
                retire(head);  
                return data;  
            }  
        }  
    }  
}
```

37+6 LOC

```
struct Rec {  
    Rec* next;  
    Node* hp0;  
    Node* hp1;  
}  
  
shared:  
Rec* HPRecs;  
  
thread-local:  
Rec* myRec;  
List<Node*> retiredList;  
  
void join() {  
    myRec = new HPRec();  
    while (true) {  
        Rec* tmp = HPRecs;  
        myRec->next = tmp;  
        if (CAS(HPRecs, tmp, myRec)) {  
            break;  
        }  
    }  
}  
  
void part() {  
    unprotect(0);  
    unprotect(1);  
}
```

42 LOC

```
void protect0(Node* ptr) {  
    myRec->hp0 = ptr;  
}  
  
void protect1(Node* ptr) {  
    myRec->hp1 = ptr;  
}  
  
void retire(Node* ptr) {  
    retiredList.add(ptr);  
    if (*) reclaim();  
}  
  
void reclaim() {  
    List<Node*> protectedList;  
    Rec* tmp = HPRecs;  
    while (tmp != null) {  
        Node* hp0 = cur->hp0;  
        Node* hp1 = cur->hp1;  
        protectedList.add(hp0);  
        protectedList.add(hp1);  
        cur = cur->next;  
    }  
    for (Node* ptr : retiredList) {  
        if (!protectedList.contains(ptr)) {  
            retiredList.remove(ptr);  
            delete ptr;  
        }  
    }  
}
```

lock-free  
HP  
no reclamation

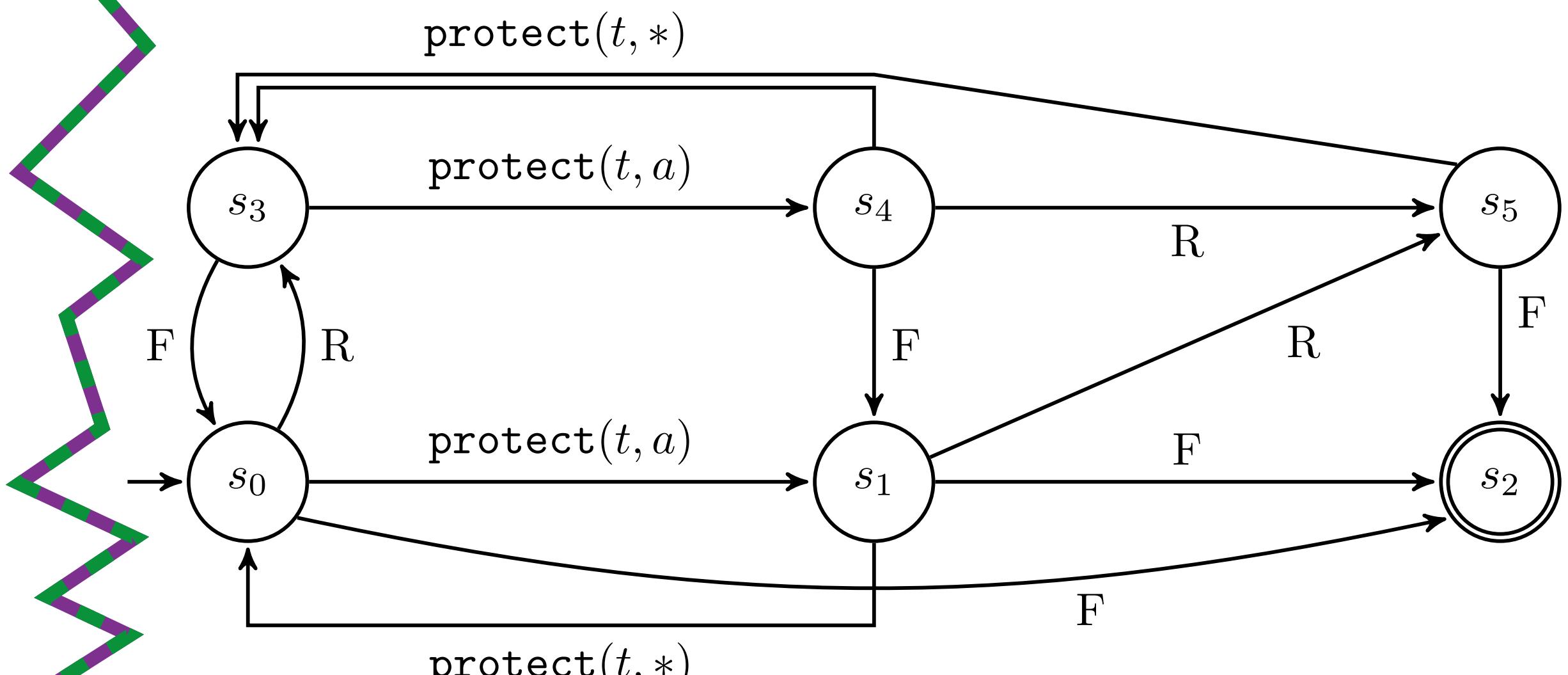
# Compositionality on an Example

```
struct Node {           shared:  
    data_t data;      Node* Head;  
    Node* node;       Node* Tail;  
}  
  
void enqueue(data_t val) {  
    Node* node = new Node();  
    node->data = val;  
    node->next = null;  
    while (true) {  
        Node* tail = Tail;  
        protect0(tail);  
        if (Tail != tail) continue;  
        Node* next = tail->next;  
        if (Tail != tail) continue;  
        if (next == null) {  
            if (CAS(tail->next, null, node)) {  
                CAS(Tail, tail, node);  
            }  
        } else {  
            CAS(Tail, tail, next);  
        }  
    }  
}
```

queue  
lock-free  
SMR

```
void init() {  
    Head = new Node();  
    Head->next = null;  
    Tail = Head;  
}  
  
data_t dequeue() {  
    while (true) {  
        Node* head = Head;  
        protect0(head);  
        if (Head != head) continue;  
        Node* tail = Tail;  
        Node* next = head->next;  
        protect1(next);  
        if (Head != head) continue;  
        if (head == tail) {  
            if (next == null) return empty_t;  
            else CAS(Tail, tail, next);  
        } else {  
            data = head->data;  
            if (CAS(Head, head, next)) {  
                retire(head);  
                return data;  
            }  
        }  
    }  
}
```

37+6 LOC



automaton

$$F := \text{free}(t, a) \vee \text{free}(*, a)$$

$$R := \text{retire}(t, a) \vee \text{retire}(*, a)$$

# Experiments



- **SMR impl**  $\models$  **SMR spec**:

<b>SMR implementation</b>	<b>SMR spec size</b>	<b>Correctness</b>
Hazard Pointers (HP)	3x5x5	1.5s ✓
Epoch-based Reclamation (EBR)	3x5	11.2s ✓

# Experiments



- **SMR impl**  $\models$  **SMR spec**:

SMR implementation	SMR spec size	Correctness
Hazard Pointers (HP)	3x5x5	1.5s ✓
Epoch-based Reclamation (EBR)	3x5	11.2s ✓

- **Data structure + SMR spec**  $\models$  **Linearizability**

Infeasible: state space explosion!

Contribution 2: ABA Freedom

# ABAs

---

- Problem
  - impracticality due to state space explosion
  - state space explosion due to reallocations
- Observation
  - verification under GC instead of SMR is unsound
  - discrepancy manifests as ABA

# State Space Reduction

---

- Theorem 1:

**Verifying a data structure under garbage collection is sound,  
if data structure + SMR spec is free from ABAs.**

# State Space Reduction

---

- Theorem 1:

**Verifying a **data structure** under **garbage collection** is sound,  
if **data structure + SMR spec** is free from ABAs.**
- Theorem 2:

**For an ABA check of **data structure + SMR spec**,  
it is sound to restrict re-allocations to a single address.**

(Side condition: **SMR spec** is invariant to re-allocations.)

# Our Approach

---

**SMR impl**  $\models$  **SMR spec**

**Data structure** + **SMR spec**  $\models$  **Property**

---

**Data structure** + **SMR impl**  $\models$  **Property**

# Our Approach

---

**SMR impl**  $\models$  **SMR spec**

~~**Data structure** + **SMR spec**  $\vdash$  **Property**~~

**Data structure** + **Garbage Collection**  $\models$  **Property**

**Data structure** + **SMR spec**  $\models$  **ABA Freedom**

---

**Data structure** + **SMR impl**  $\models$  **Property**

# Our Approach

**SMR impl**  $\models$  **SMR spec**

**Data structure + SMR spec**  $\vdash$  **Property**

**Data structure + Garbage Collection**  $\models$  **Property**

**Data structure + SMR spec**  $\models$  **ABA Freedom**

**Data structure + SMR impl**  $\models$  **Property**

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SEBASTIAN WOLFF, TU Braunschweig, Germany

Verification of concurrent data structures is one of the most challenging tasks in software verification. The topic has received considerable attention over the course of the last decade. Nevertheless, human-driven techniques remain cumbersome and notoriously difficult while automated approaches suffer from limited applicability. The main obstacle for automation is the complexity of concurrent data structures. This is particularly true in the absence of garbage collection. The intricacy of lock-free memory management paired with the complexity of concurrent data structures makes automated verification prohibitive.

In this work we present a method for verifying concurrent data structures and their memory management separately. We suggest two simpler verification tasks that imply the correctness of the data structure. The first task establishes an over-approximation of the reclamation behavior of the memory management. The second task exploits this over-approximation to verify the data structure without the need to consider the implementation of the memory management itself. To make the resulting verification tasks tractable for automated techniques, we establish a second result. We show that a verification tool needs to consider only executions where a single memory location is reused. We implemented our approach and were able to verify linearizability of Michael&Scott's queue and the DGLM queue for both hazard pointers and epoch-based reclamation. To the best of our knowledge, we are the first to verify such implementations fully automatically.

CCS Concepts: • Theory of computation → Data structures design and analysis; Program verification; Shared memory algorithms; Program specifications; Program analysis;

Additional Key Words and Phrases: static analysis, lock-free data structures, verification, linearizability, safe memory reclamation, memory management

ACM Reference Format:

Roland Meyer and Sebastian Wolff. 2019. Decoupling Lock-Free Data Structures from Memory Reclamation for Static Analysis. *Proc. ACM Program. Lang.* 3, POPL, Article 58 (January 2019), 31 pages. <https://doi.org/10.1145/3290371>

## 1 INTRODUCTION

Data structures are a basic building block of virtually any program. Efficient implementations are typically a part of a programming language's standard library. With the advent of highly concurrent computing being available even on commodity hardware, concurrent data structure implementations are needed. The class of lock-free data structures has been shown to be particularly efficient. Using fine-grained synchronization and avoiding such synchronization whenever possible results in unrivaled performance and scalability.

Unfortunately, this use of fine-grained synchronization is what makes lock-free data structures also unrivaled in terms of complexity. Indeed, bugs have been discovered in published lock-free

Authors' addresses: Roland Meyer, TU Braunschweig, Germany, roland.meyer@tu-bs.de; Sebastian Wolff, TU Braunschweig, Germany, sebastian.wolff@tu-bs.de.



# Experiments



Data Structures	SMR	ABA Freedom	Linearizability
Treiber's stack	EBR	16s ✓	— ✓
	HP	19s ✓	— ✓
Michael&Scott's queue	EBR	44m ✓	— ✓
	HP	120m ✓	— ✓
DGLM queue	EBR	63m ✓	— ✓
	HP	117m ✓	— ✓

# Experiments



Data Structures	SMR	ABA Freedom	Linearizability
Treiber's stack	EBR	16s ✓	— ✓
	HP	19s ✓	— ✓
Michael&Scott's queue	EBR	44m ✓	— ✓
	HP	120m ✓	— ✓
DGLM queue	EBR	63m ✓	— ✓
	HP	117m ✓	— ✓

Reallocations remain the bottleneck!

## Contribution 3: Pointer Race Freedom

# Pointer Races

---

- Observation:

**In every ABA participates at least one dangling pointer.**

# Pointer Races

---

- Observation:

**In every ABA participates at least one dangling pointer.**

- Pointer races
  - operations involving dangling pointers
  - operations that observe reclamation
- Pointer race freedom  $\Rightarrow$  no ABAs + memory safety

# Pointer Race Check

---

## Type system:

- to establish:  
**Data structure + SMR spec ⊢ Pointer Race Freedom**
- that is parametrized by the **SMR spec**
- externalizes shape analysis to a **GC** tool

# External Shape Analysis

---

- Problem
  - danglingness may depend on shape invariant
  - type checks bad at finding shape invariants
- Solution
  - “*don’t try*”
  - annotate **data structure** with light-weight **annotations**
  - discharge **annotations** under **garbage collection**
  - guess&check finds annotations automatically

# Our Approach

---

**SMR impl**  $\models$  **SMR spec**

**Data structure + Garbage Collection**  $\models$  **Property**

**Data structure + SMR spec**  $\models$  **ABA Freedom**

---

**Data structure + SMR impl**  $\models$  **Property**

# Our Approach

---

**SMR impl**  $\models$  **SMR spec**

**Data structure + Garbage Collection**  $\models$  **Property**

~~**Data structure + SMR spec + ABA Freedom**~~

**Annot.** **Data structure + SMR spec**  $\vdash$  **Pointer Race Freedom**

**Data structure + Garbage Collection**  $\models$  **Annotations**

---

**Data structure + SMR impl**  $\models$  **Property**

# Our Approach

**SMR impl**  $\models$  **SMR spec**

**Data structure + Garbage Collection**  $\models$  **Property**

~~**Data structure + SMR spec**  $\models$  **ABA Freedom**~~

**Annot.** **Data structure + SMR spec**  $\vdash$  **Pointer Race Freedom**

**Data structure + Garbage Collection**  $\models$  **Annotations**

**Data structure + SMR impl**  $\models$  **Property**

**[POPL'20]**

with Roland Meyer



**Pointer Life Cycle Types for Lock-Free Data Structures with Memory Reclamation**

ROLAND MEYER, TU Braunschweig, Germany  
SEBASTIAN WOLFF, TU Braunschweig, Germany

We consider the verification of lock-free data structures that manually manage their memory with the help of a safe memory reclamation (SMR) algorithm. Our first contribution is a type system that checks whether a program properly manages its memory. If the type check succeeds, it is safe to ignore the SMR algorithm and consider the program under garbage collection. Intuitively, our types track the protection of pointers as guaranteed by the SMR algorithm. There are two design decisions. The type system does not track any shape information, which makes it extremely lightweight. Instead, we rely on invariant annotations that postulate a protection by the SMR. To this end, we introduce angels, ghost variables with angelic semantics. Moreover, the SMR algorithm is not hard-coded but a parameter of the type system definition. To achieve this, we rely on a recent specification language for SMR algorithms. Our second contribution is to automate the type inference and the invariant check. For the type inference, we show a quadratic-time algorithm. For the invariant check, we give a source-to-source translation that links our programs to off-the-shelf verification tools. It compiles away the angelic semantics. This allows us to infer appropriate annotations automatically in a guess-and-check manner. To demonstrate the effectiveness of our type-based verification approach, we check linearizability for various list and set implementations from the literature with both hazard pointers and epoch-based memory reclamation. For many of the examples, this is the first time they are verified automatically. For the ones where there is a competitor, we obtain a speed-up of up to two orders of magnitude.

CCS Concepts: • Theory of computation → Program verification; Type theory; Shared memory algorithms; Concurrent algorithms; Program analysis; Invariants; • Software and its engineering → Memory management; Model checking; Automated static analysis.

Additional Key Words and Phrases: lock-free data structures, safe memory reclamation, garbage collection, linearizability, verification, type systems, type inference

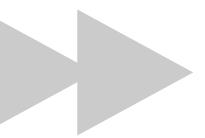
**ACM Reference Format:**  
Roland Meyer and Sebastian Wolff. 2020. Pointer Life Cycle Types for Lock-Free Data Structures with Memory Reclamation. *Proc. ACM Program. Lang.* 4, POPL, Article 68 (January 2020), 36 pages. <https://doi.org/10.1145/3371136>

## 1 INTRODUCTION

In the last decade we have experienced an upsurge in massive parallelization being available even in commodity hardware. To keep up with this trend, popular programming languages include in their standard libraries features to make parallelization available to everyone. At the heart of this effort are concurrent (thread-safe) data structures. Consequently, efficient implementations are in high demand. In practice, lock-free data structures are particularly efficient.

Authors' addresses: Roland Meyer, TU Braunschweig, Germany, roland.meyer@tu-bs.de; Sebastian Wolff, TU Braunschweig, Germany, sebastian.wolff@tu-bs.de.





# Example

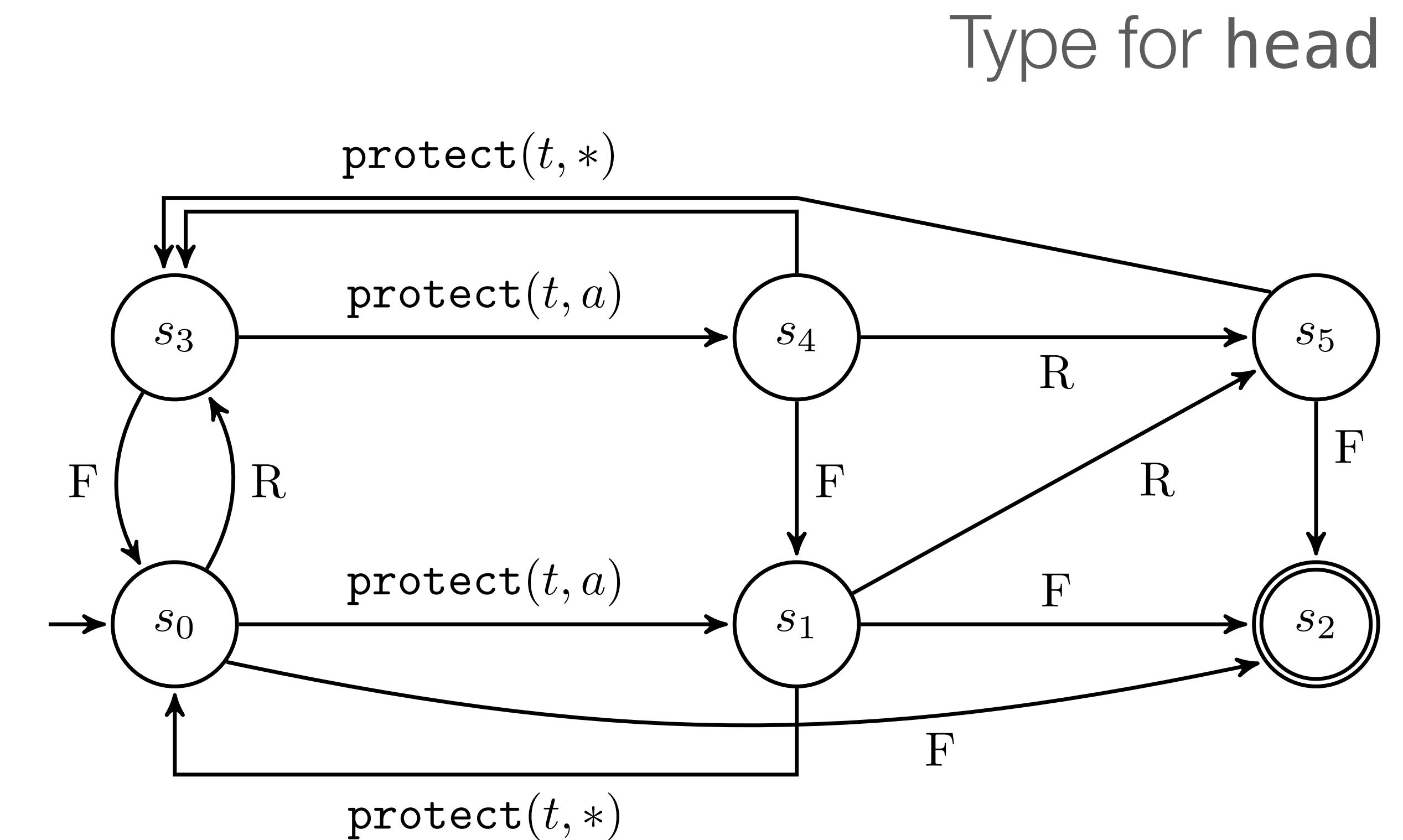
```
Node* head = Head;
```

```
protect(head);
```

```
atomic {
```

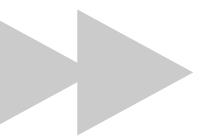
```
    @active Head
```

```
    assume(head == Head);
```



$$F := \text{free}(t, a) \vee \text{free}(*, a)$$

$$R := \text{retire}(t, a) \vee \text{retire}(*, a)$$



# Example

{ Head: $\emptyset$  }

Node\* head = Head;

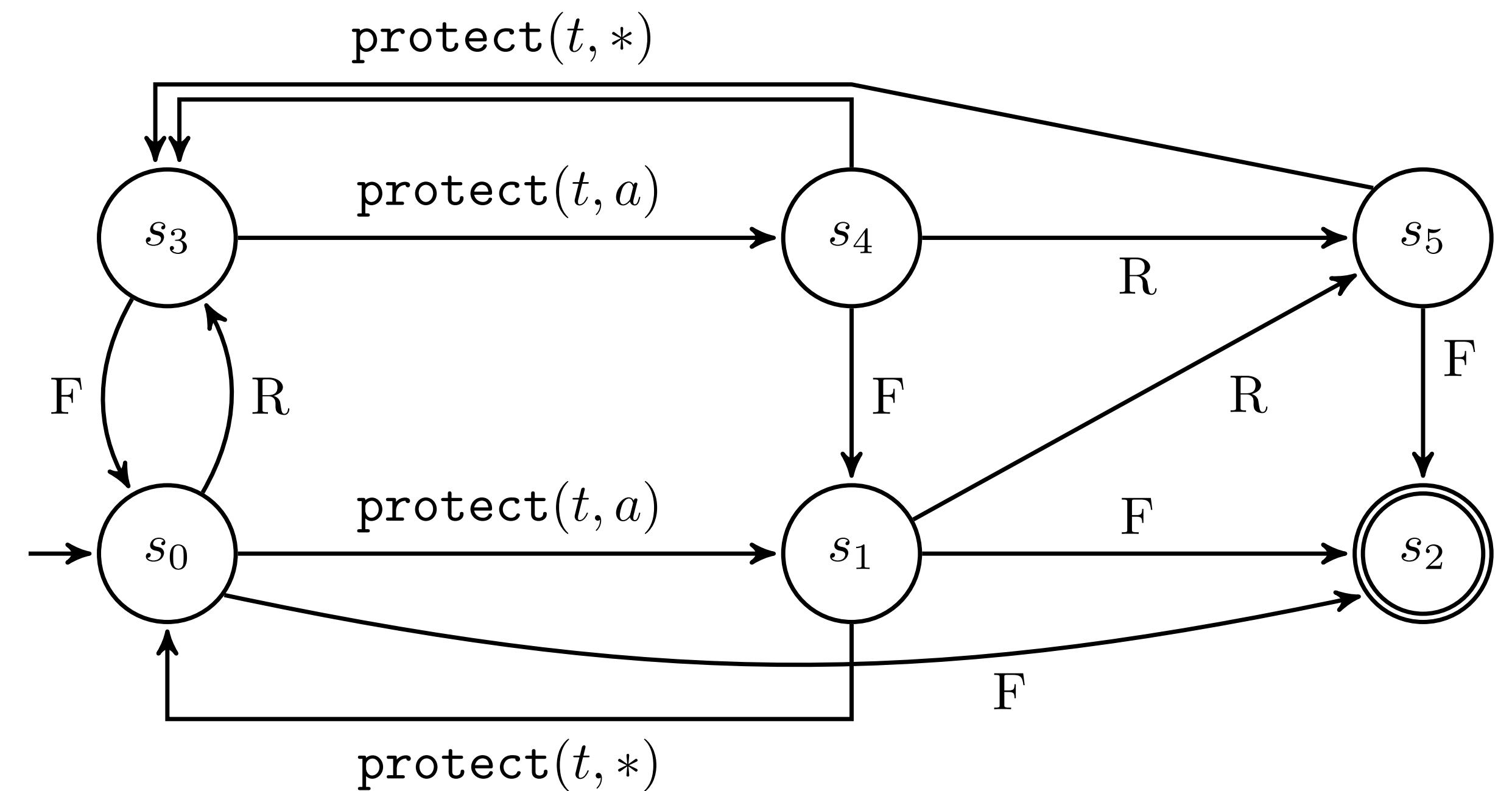
protect(head);

atomic {

@active Head

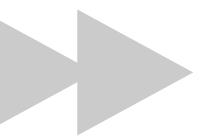
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Type for head



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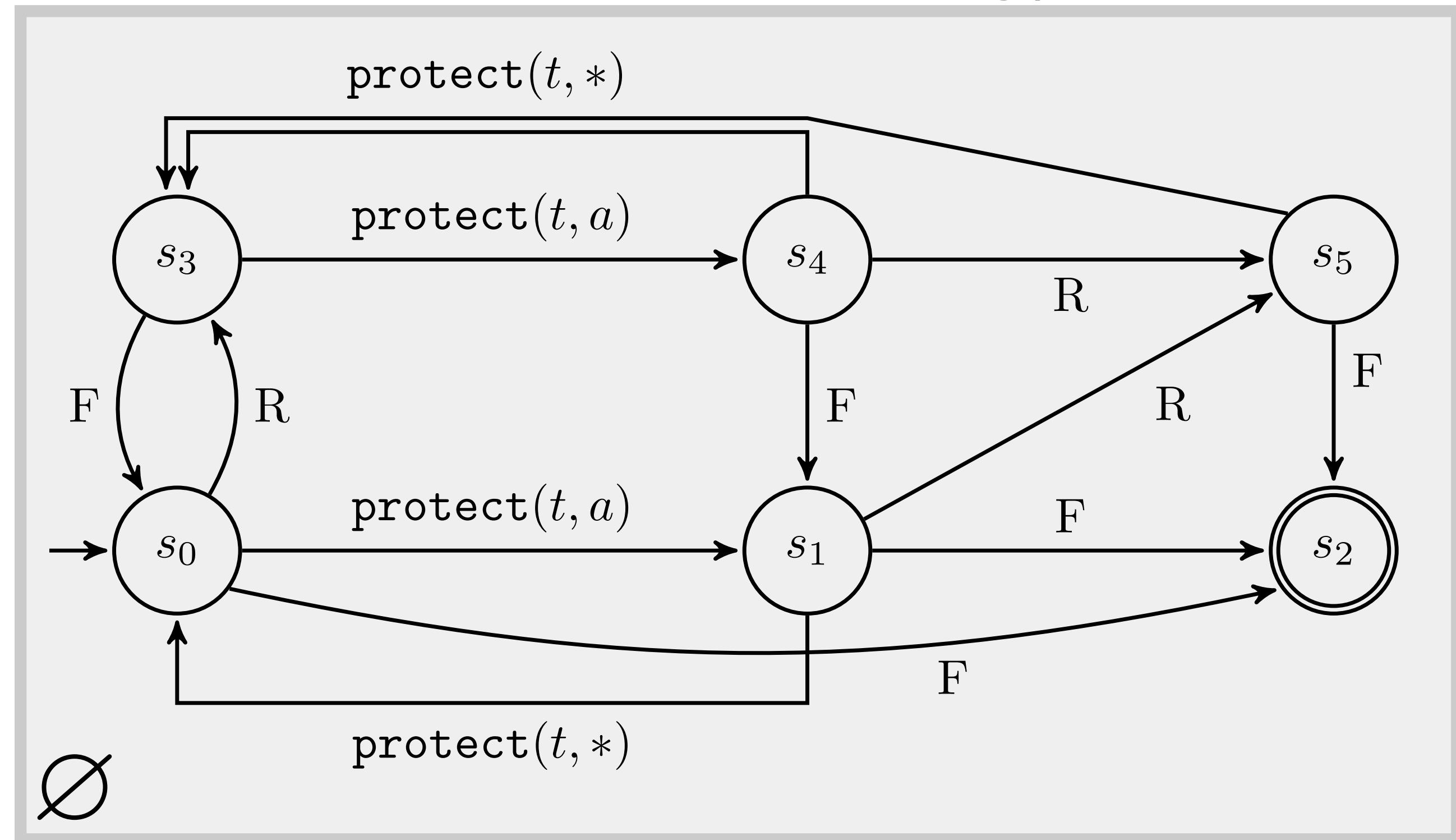
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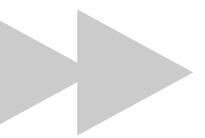
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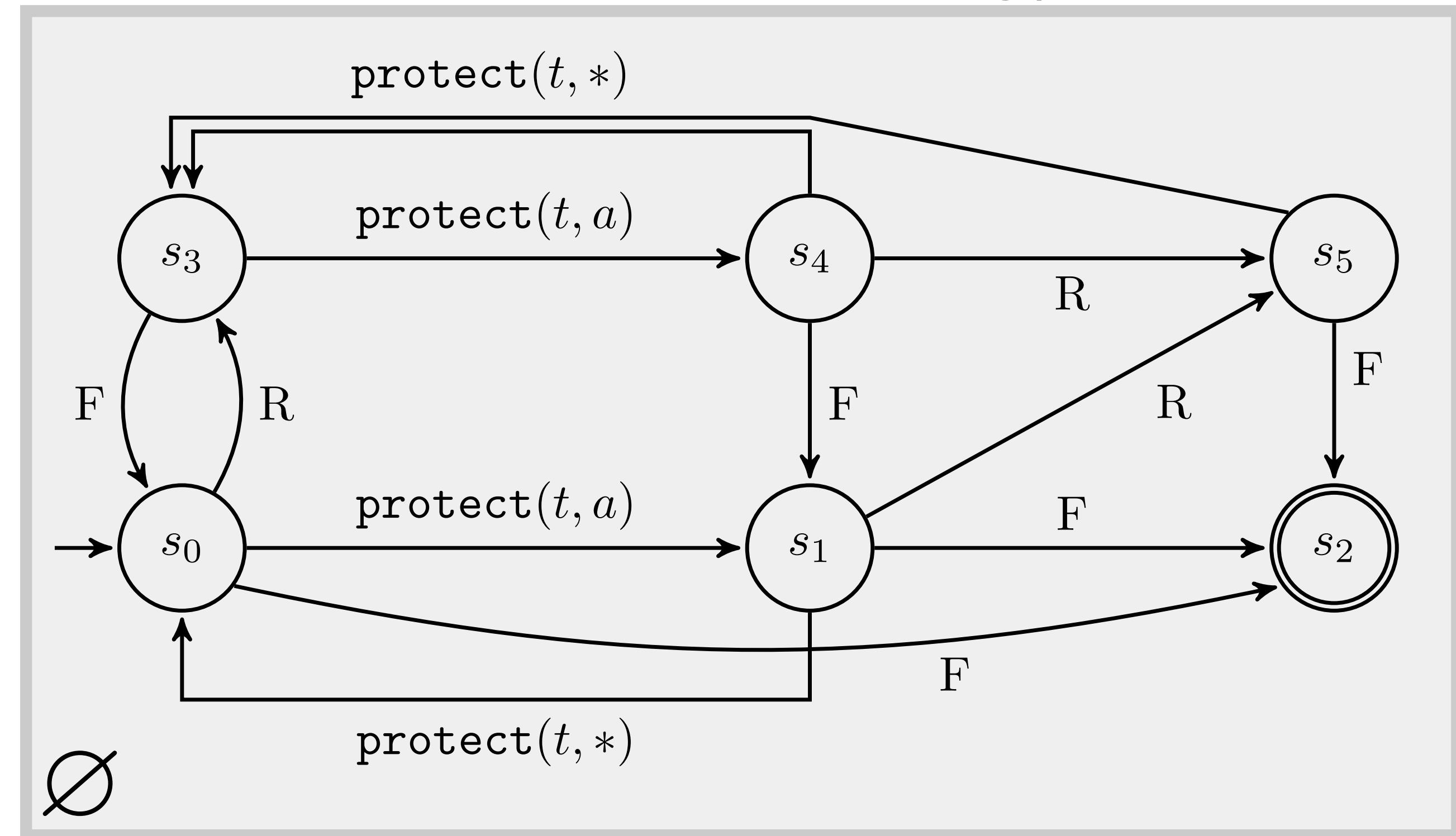
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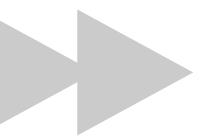
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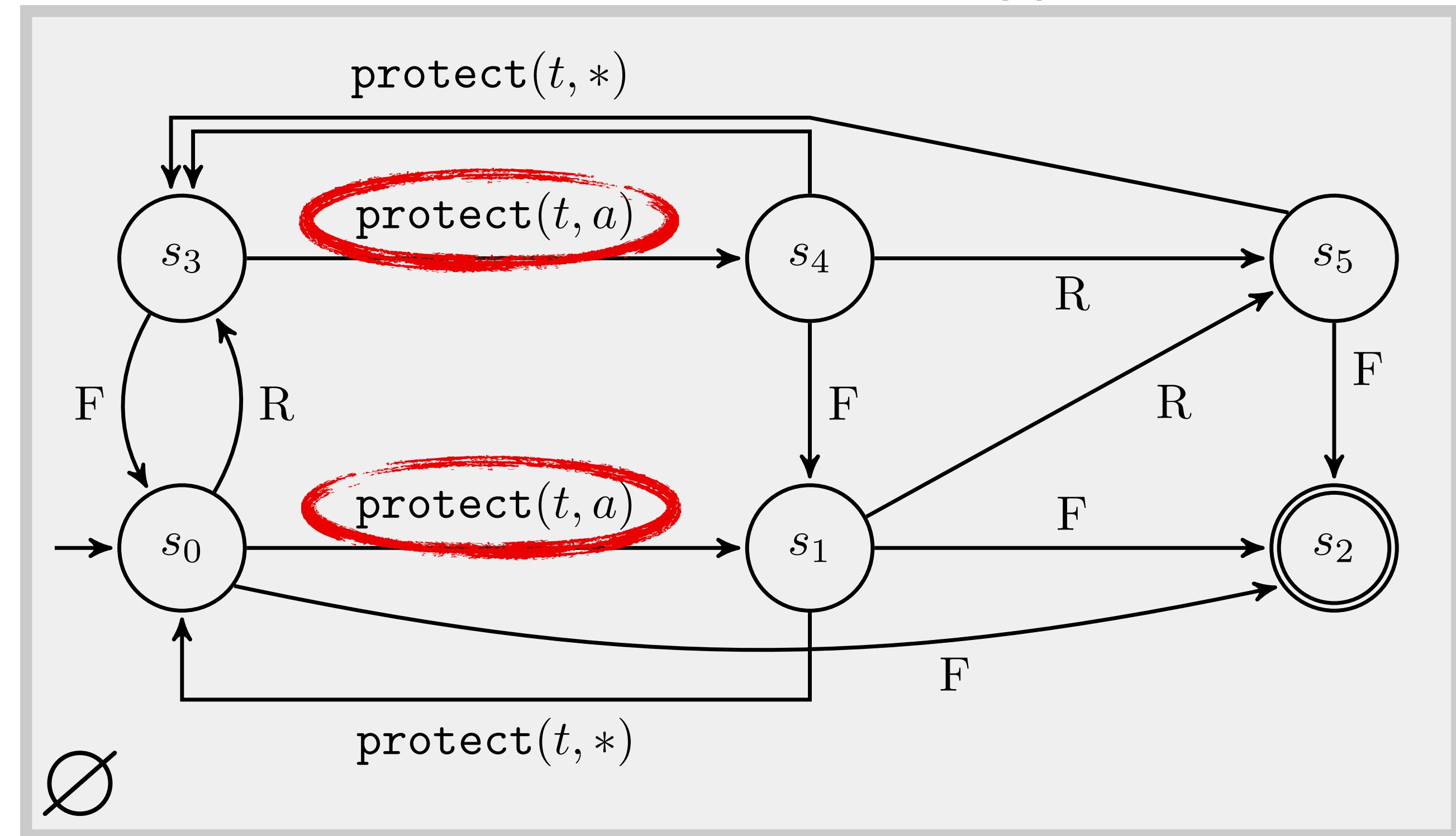
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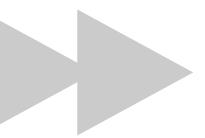
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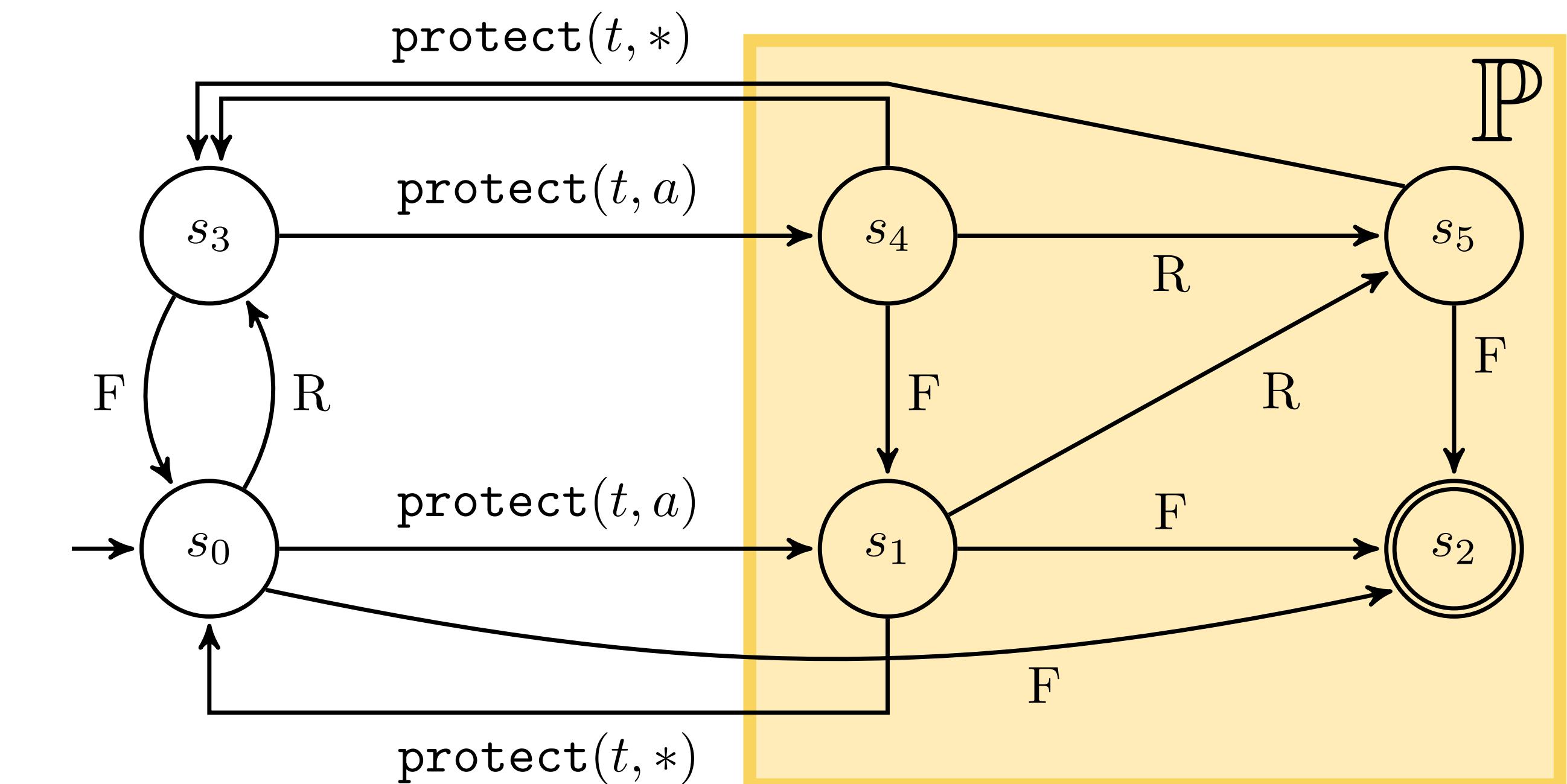
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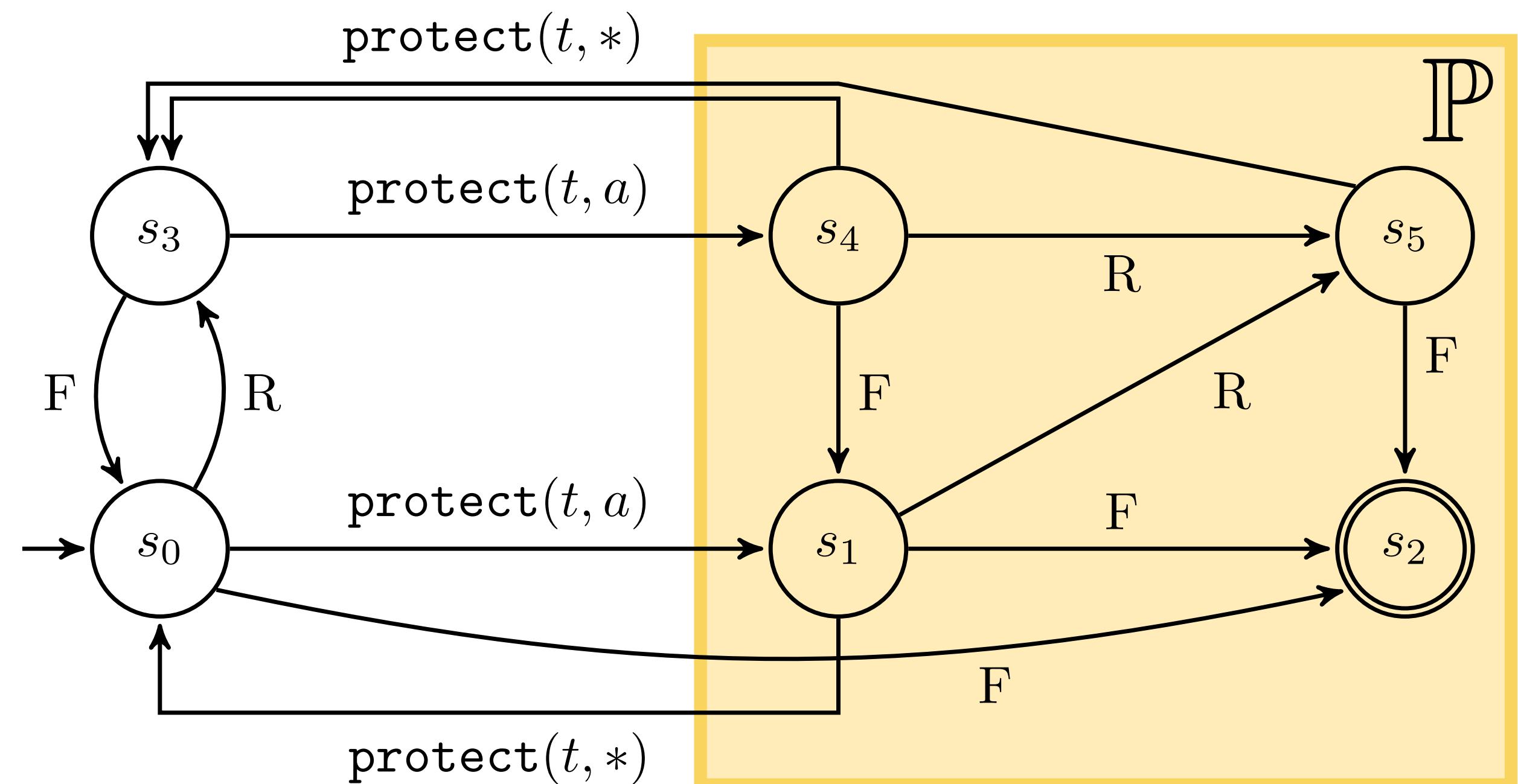
{ Head: $\emptyset$ , head: $\mathbb{P}$  }

```
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```

*@active* Head

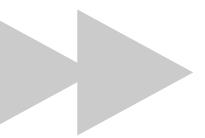
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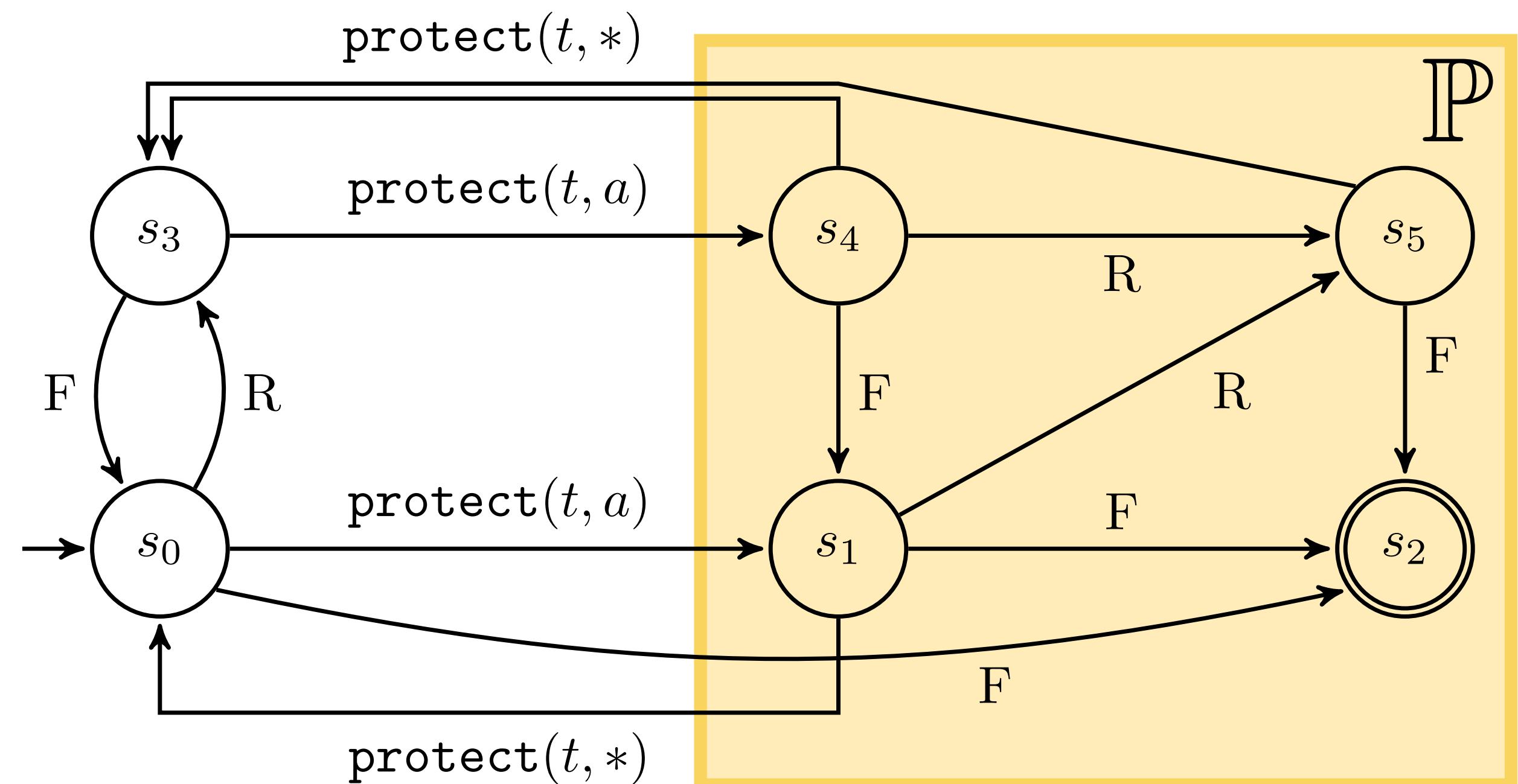
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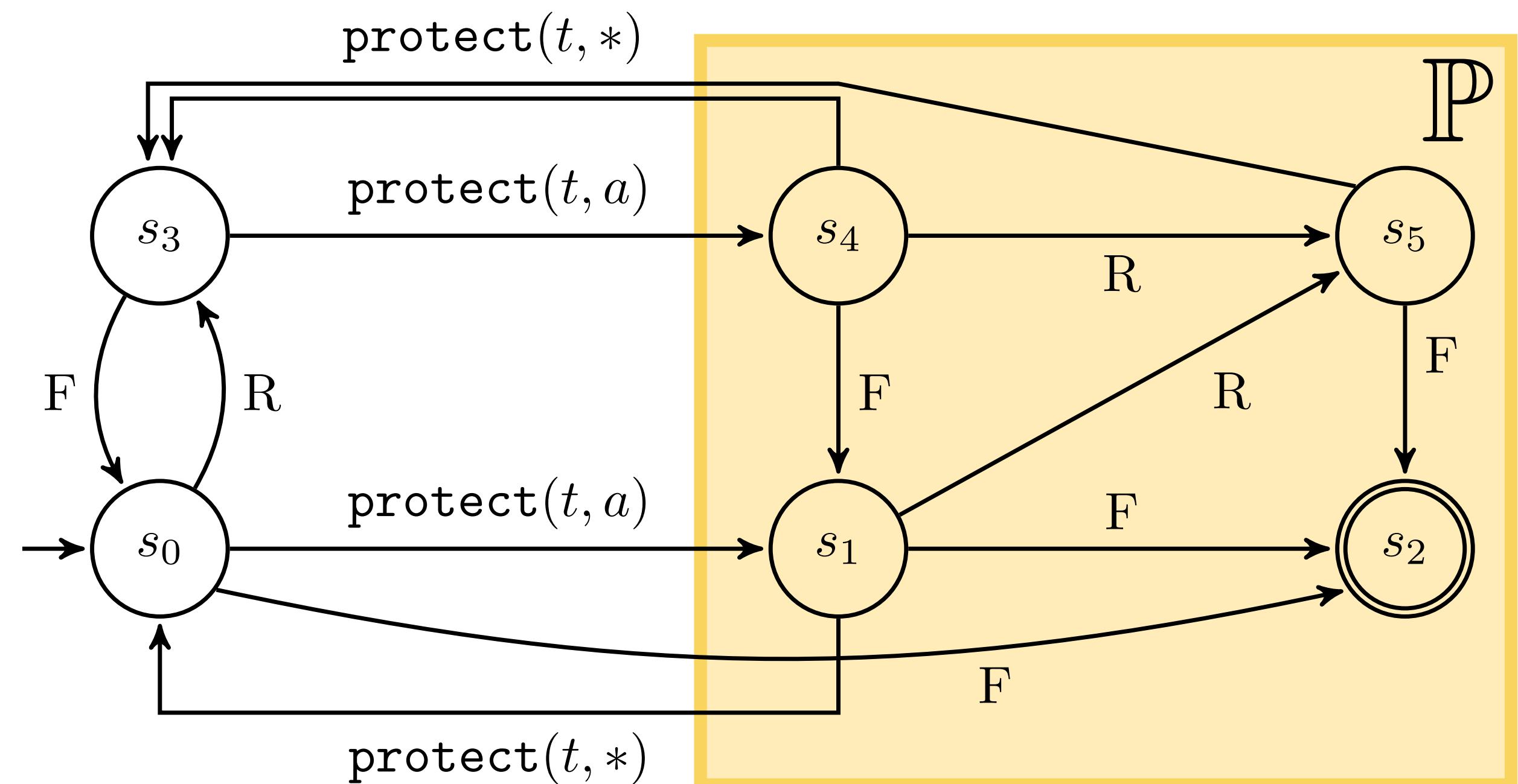
{ Head: $\emptyset$ , head: $\mathbb{P}$  }

*@active* Head

{ Head: $\mathbb{A}$ , head: $\mathbb{P}$  }

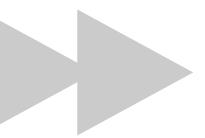
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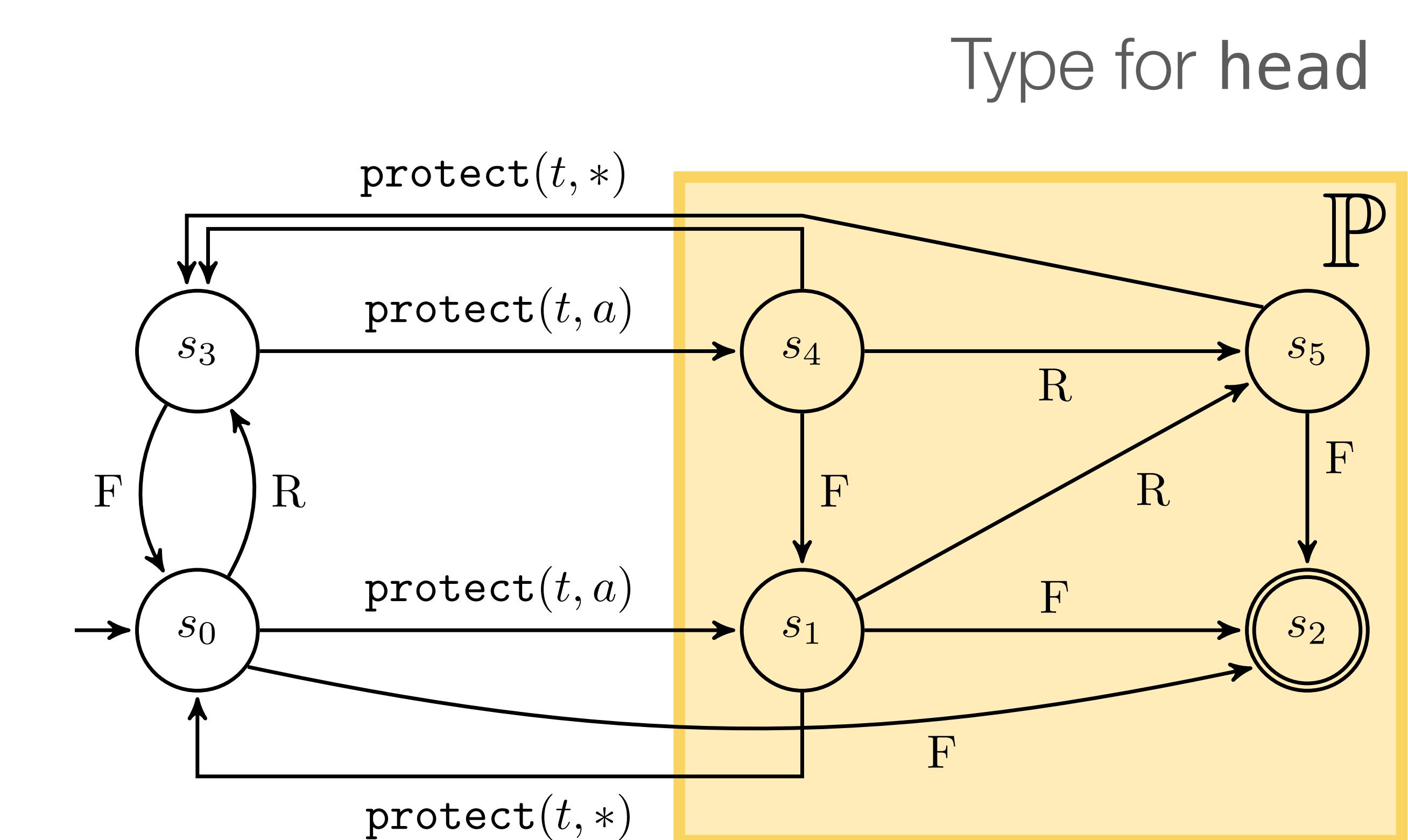
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```
// ...
```

```
Node* next = head->next;
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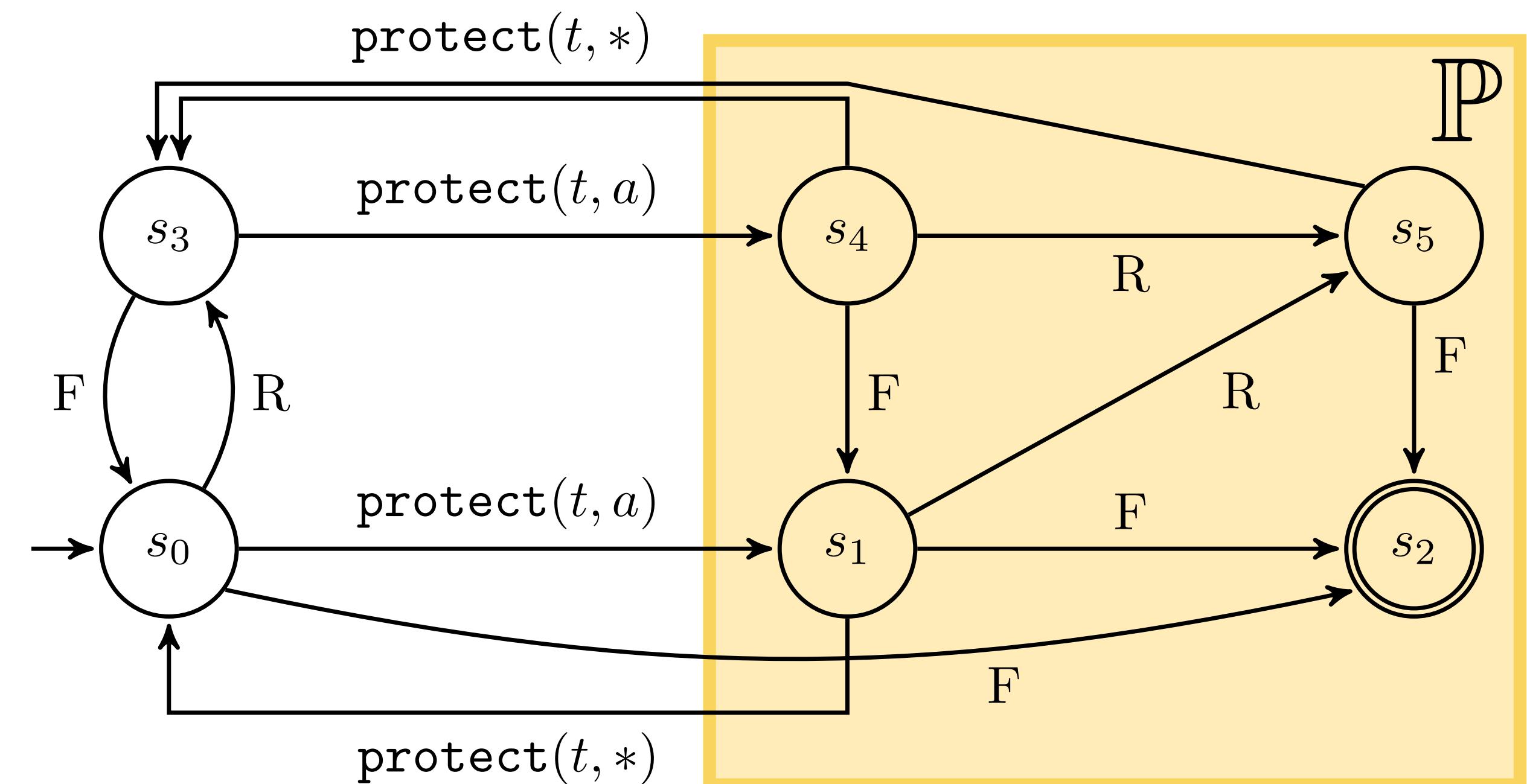
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{ Head:P ∧ A, head:P ∧ A }
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} // end atomic
```

```
// ...
```

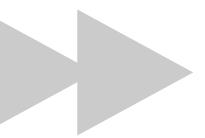
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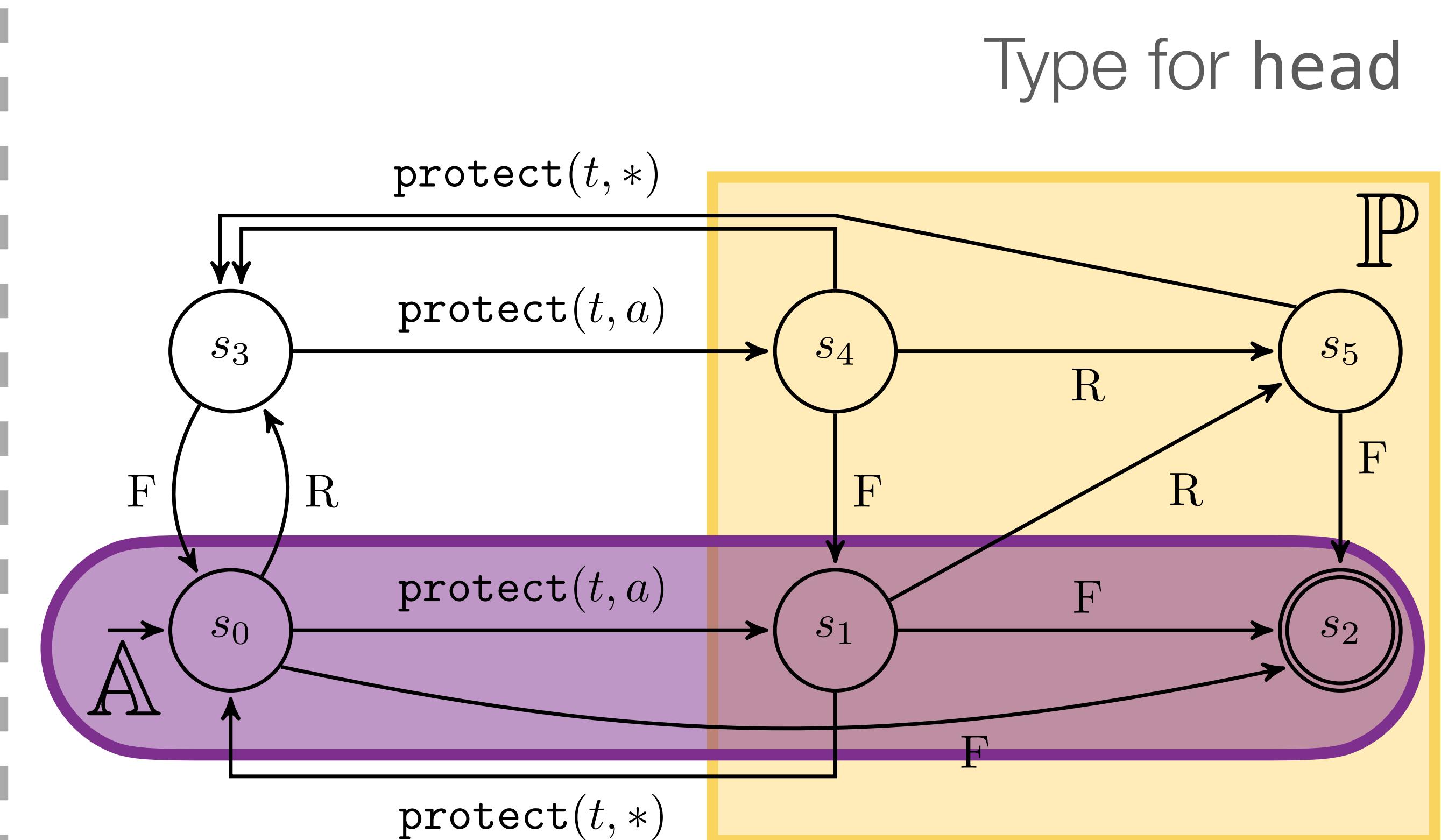
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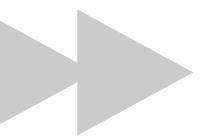
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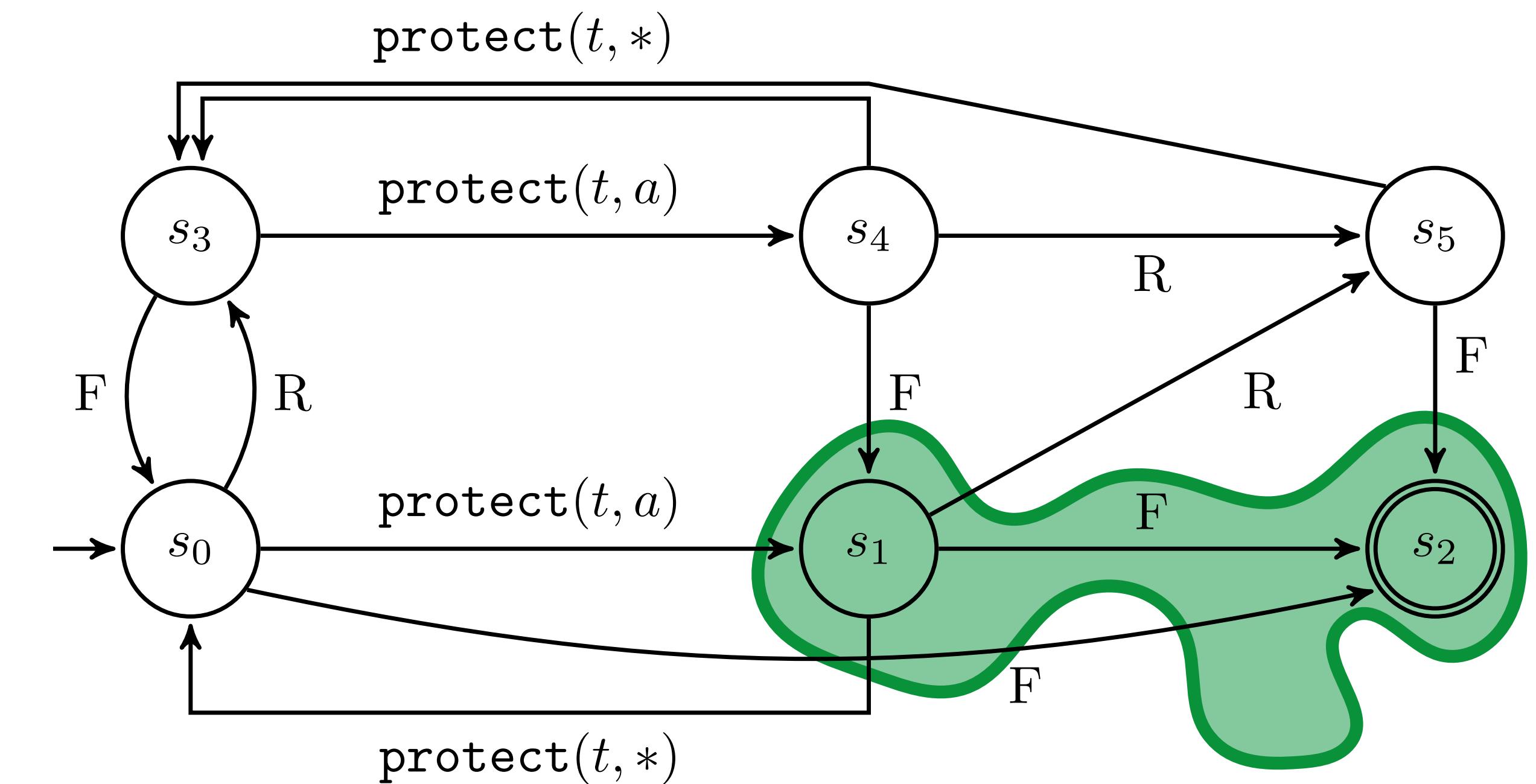
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// ...

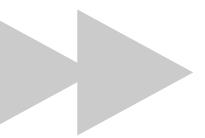
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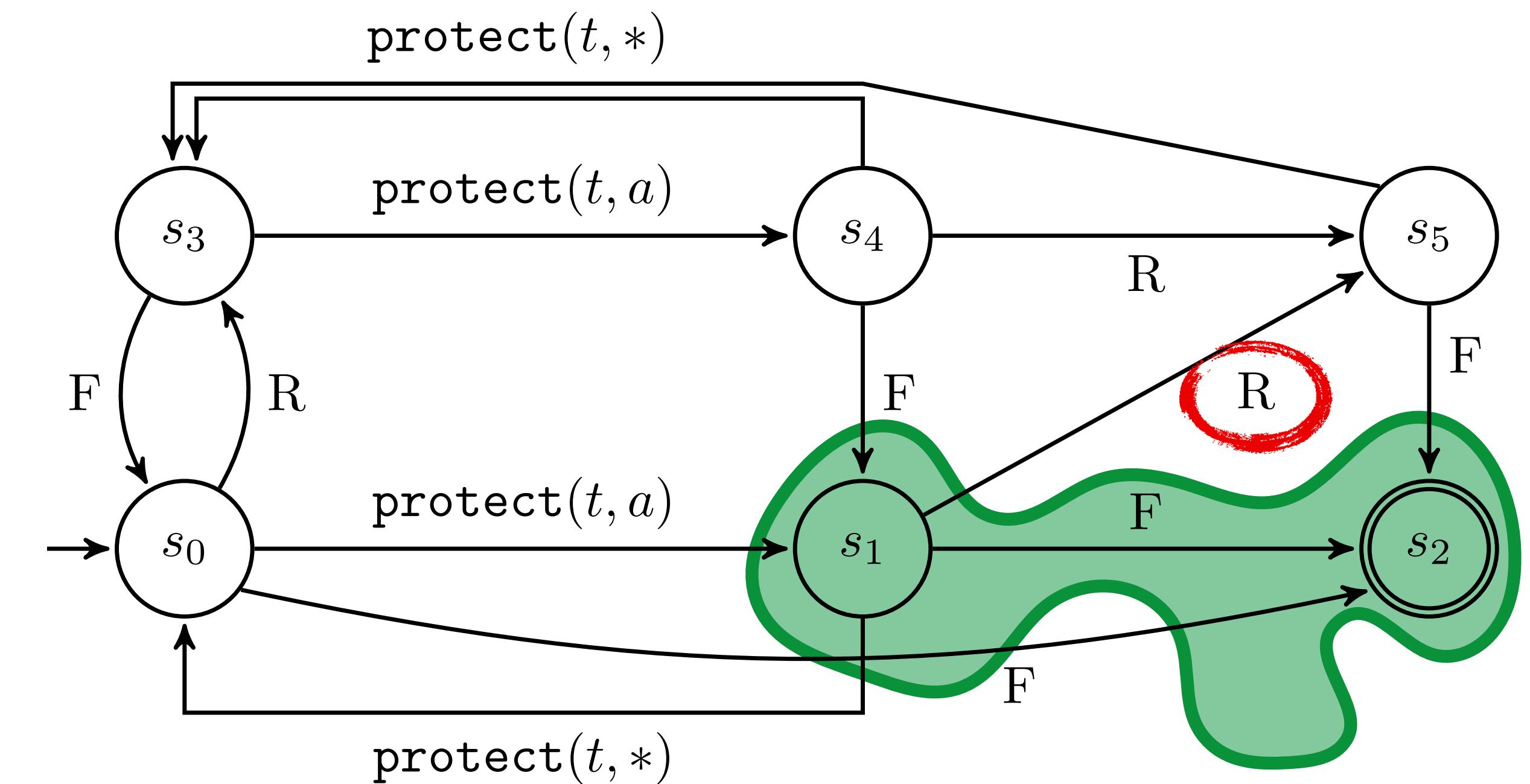
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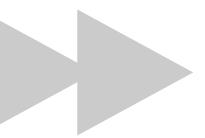
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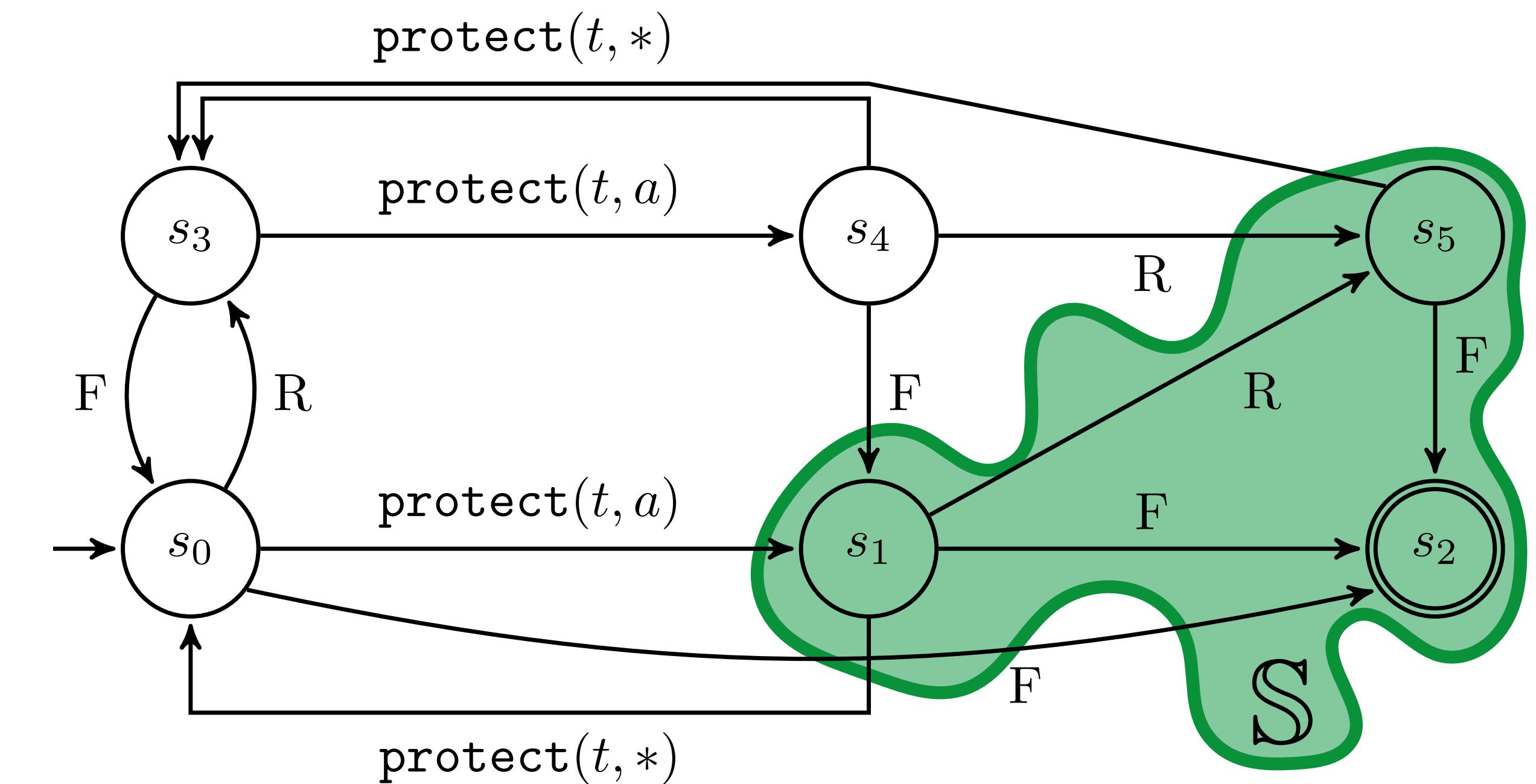
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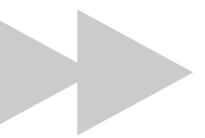
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$$F := \text{free}(t, a) \vee \text{free}(*, a)$$

$$R := \text{retire}(t, a) \vee \text{retire}(*, a)$$



# Example

{ Head:A, head:P }

assume(head == Head);

{ Head:P  $\wedge$  A, head:P  $\wedge$  A }

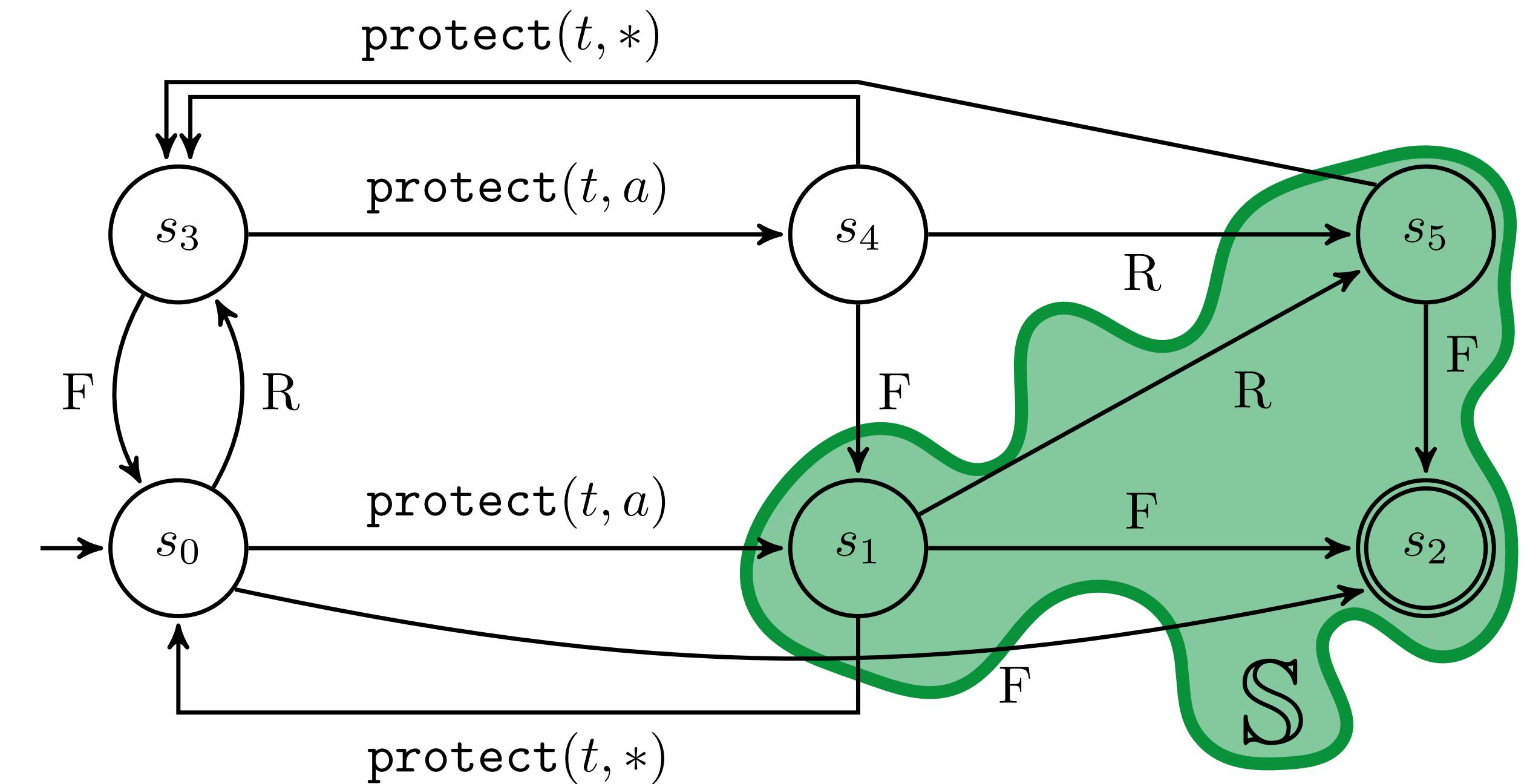
{ Head:S, head:S }

} // end atomic

// ...

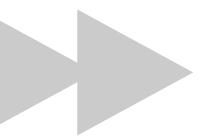
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# Example

```

{ Head:A, head:P }

    assume(head == Head);

{ Head:P ∧ A, head:P ∧ A }

{ Head:S, head:S }

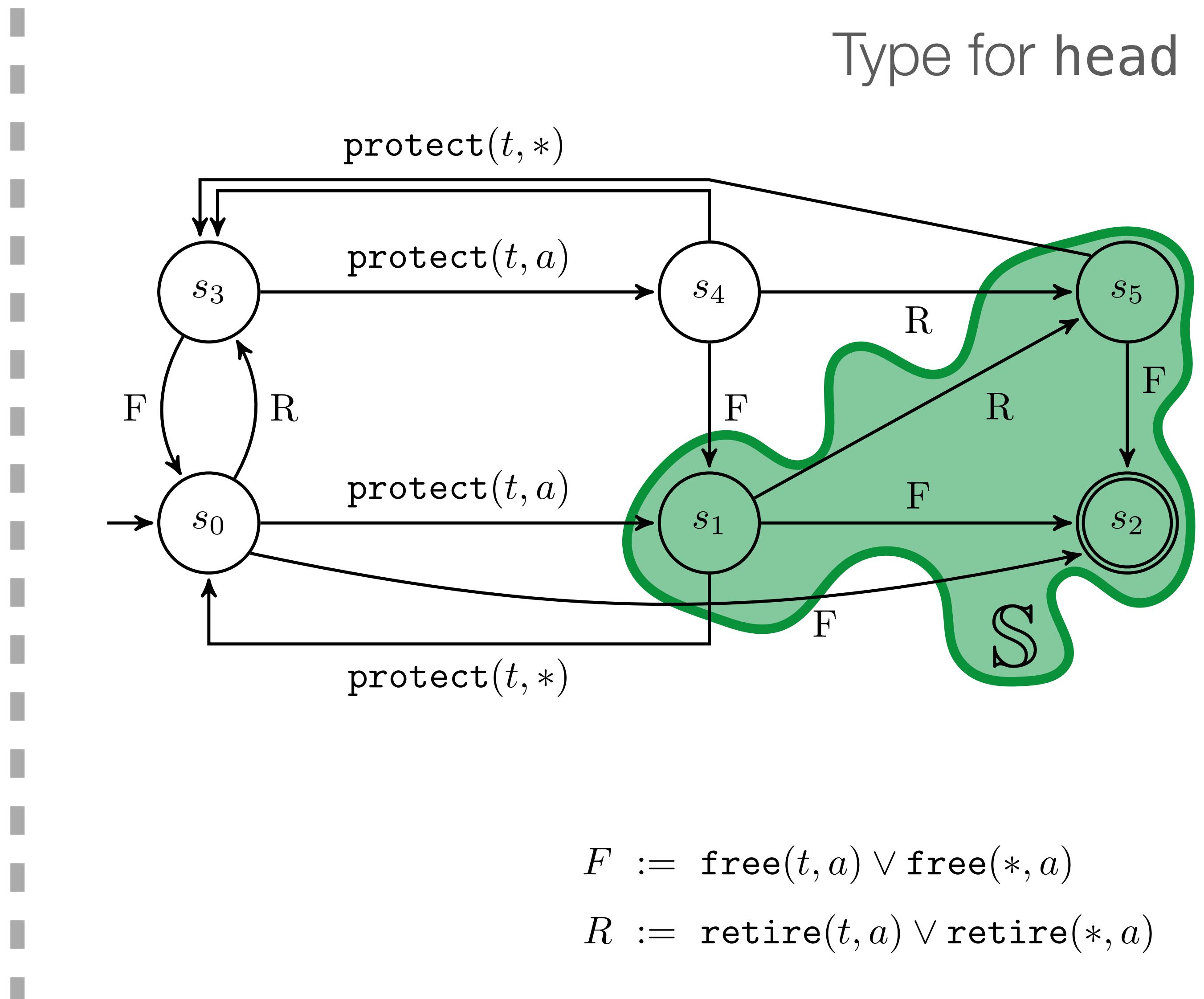
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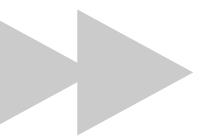
{ Head:∅, head:S }

// ...

Node* next = head->next;

```





# Example

{ Head:A, head:P }

assume(head == Head);

{ Head:P  $\wedge$  A, head:P  $\wedge$  A }

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} // end atomic

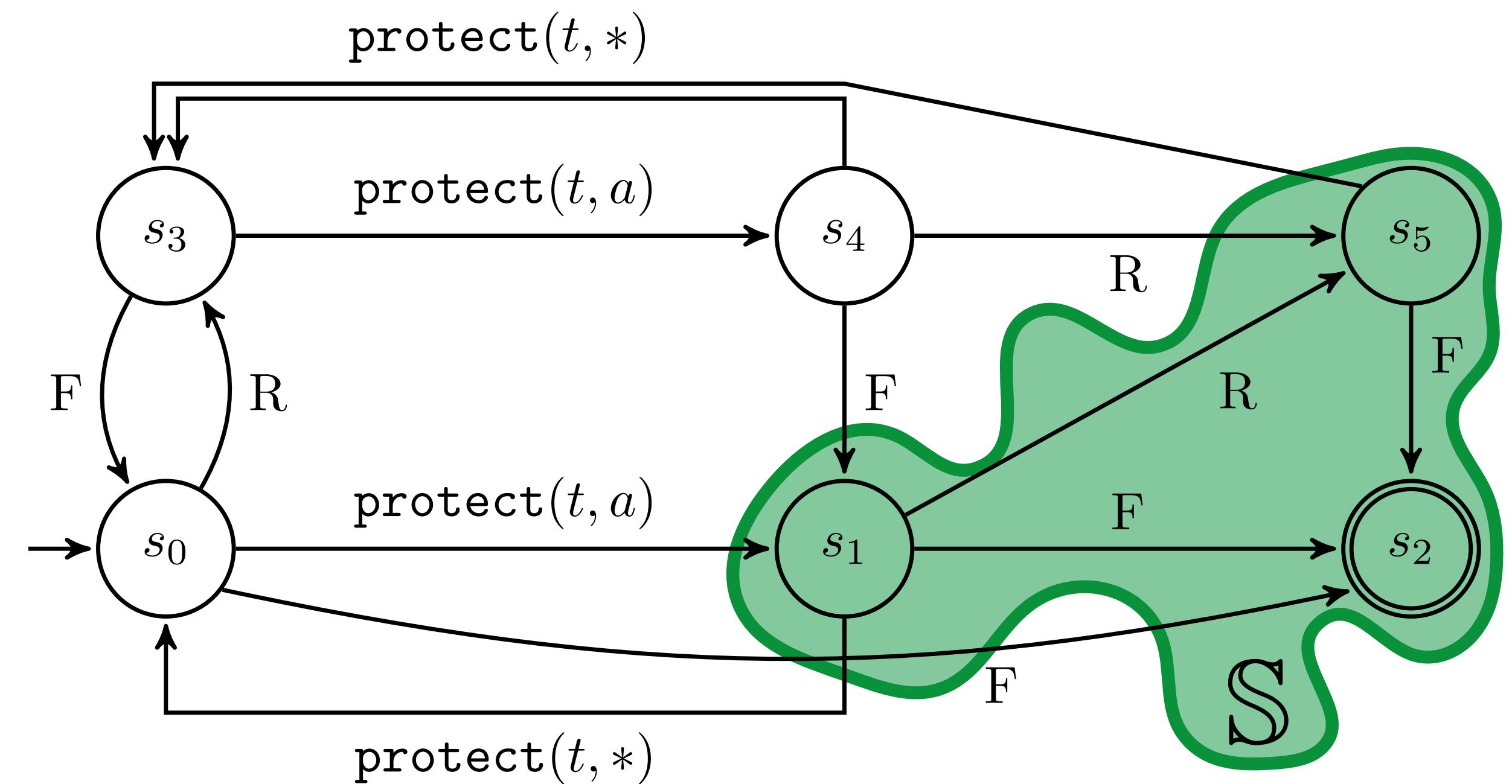
{ Head: $\emptyset$ , head:S }

// ...

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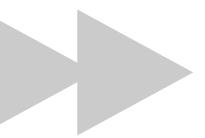


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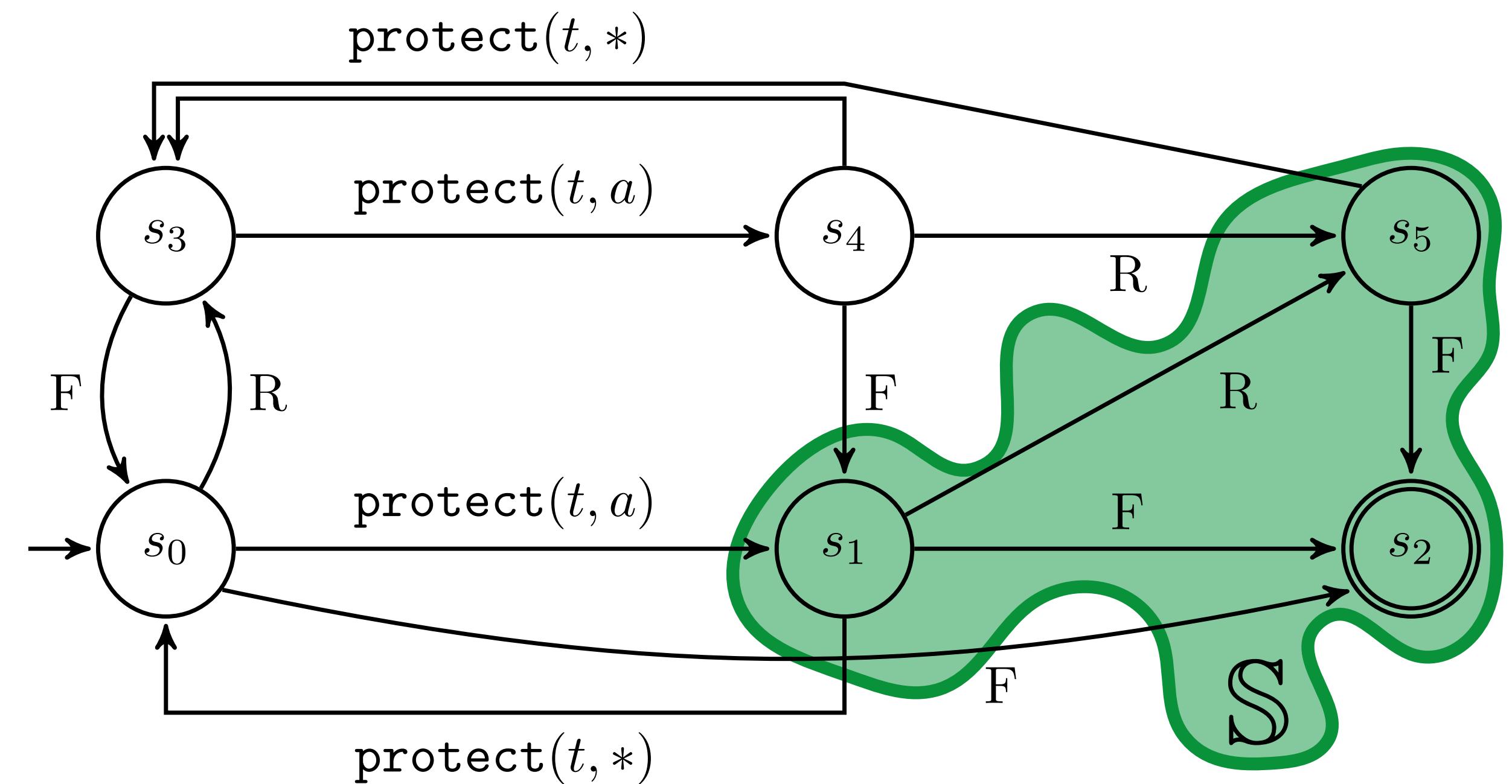
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Type for head



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# Experiments



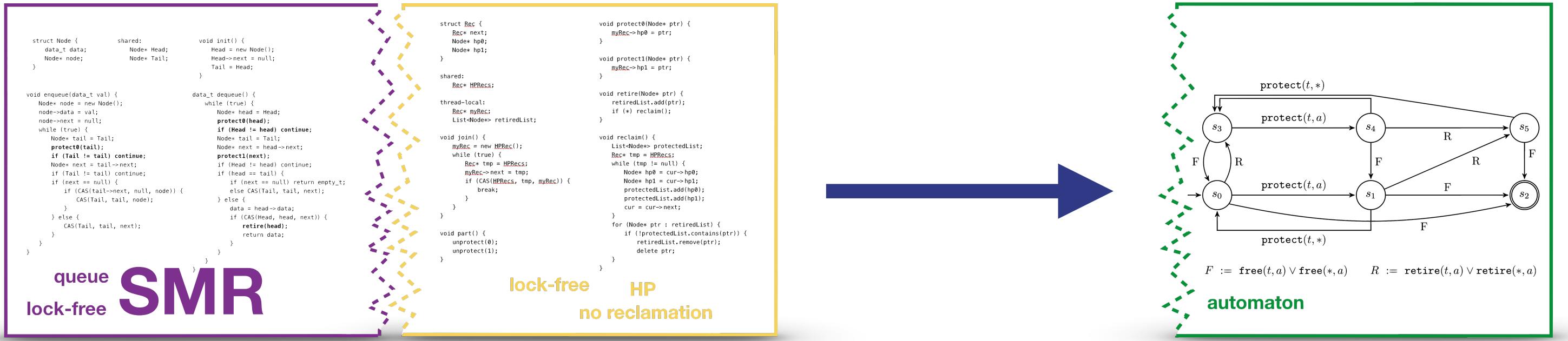
Data Structure with HP	Types	Annot.	Lin.
Treiber's stack	0.7s ✓	12s ✓	1s ✓
Michael&Scott's queue	0.6s ✓	11s ✓	4s ✓
DGLM queue	0.6s ✓	1s ✗*	5s ✓
Vechev&Yahav's 2CAS set	1.2s ✓	13s ✓	98s ✓
Vechev&Yahav's CAS set	1.2s ✓	3.5h ✓	42m ✓
ORVYY set	1.2s ✓	3.2h ✓	47m ✓
Michael's set	1.2s ✓	90s ✗*	t/o ⏳

\* imprecision in the back-end verifier

# Final Approach



# Final Approach



# Final Approach

```

struct Node {
    data_t data;
    Node* node;
} shared;
void init() {
    Head = new Node();
    Head->next = NULL;
    Tail = Head;
}

void enqueue(data_t val) {
    Node* node = new Node();
    node->data = val;
    node->next = NULL;
    while (true) {
        Node* tail = Tail;
        protect(tail);
        if (tail == tail) continue;
        Node* next = tail->next;
        if (Tail == tail) continue;
        if (next == NULL) {
            if (CAS(tail->next, NULL, node)) {
                CAS(tail, tail, node);
            } else {
                CAS(tail, tail, next);
            }
        } else {
            CAS(tail, tail, next);
        }
    }
}

data_t dequeue() {
    while (true) {
        Node* head = Head;
        protect(head);
        if (head == head) continue;
        Node* next = head->next;
        if (head == tail) {
            if (next == NULL) return empty_t;
            else CAS(tail, tail, next);
        } else {
            data = head->data;
            if (!CAS(head, head, next)) {
                retire(data);
            }
        }
    }
}

```

**queue** **SMR**

**lock-free** **HP**  
**no reclamation**

```

struct Rec {
    Rec* next;
    Node* hp;
    Node* hpl;
}
shared: Rec* HPRecs;
thread-local: Rec* myRec;
List<Node*> retiredList;

void protect0(Node* ptr) {
    myRec->hp0 = ptr;
}
void protect1(Node* ptr) {
    myRec->hp1 = ptr;
}

void retire(Node* ptr) {
    retiredList.addptr(ptr);
    if (*ptr) reclaim();
}

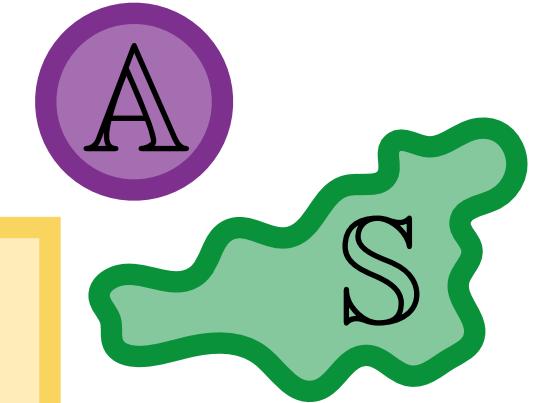
void protect(t,a) {
    R
}
void reclaim() {
    List<Node*> protectedList;
    Rec* tmp = HPRecs;
    while (tmp != NULL) {
        Node* hp0 = tmp->hp;
        Node* hp1 = cur->hp1;
        protectedList.add(hp0);
        protectedList.add(hp1);
        cur = cur->next;
    }
}

F := free(t,a) ∨ free(*,a)
R := retire(t,a) ∨ retire(*,a)

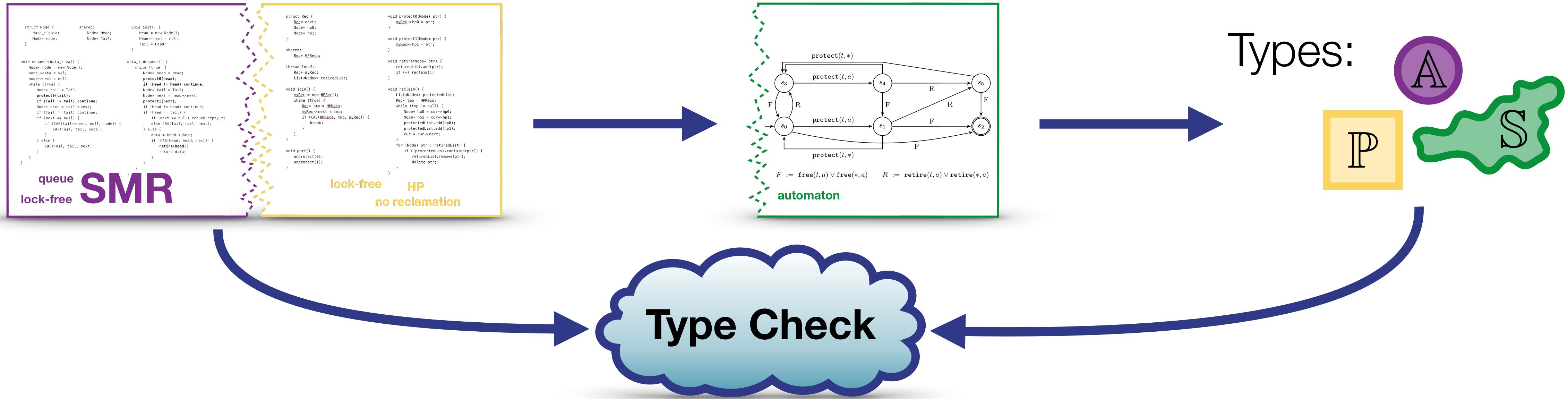
```

**automaton**

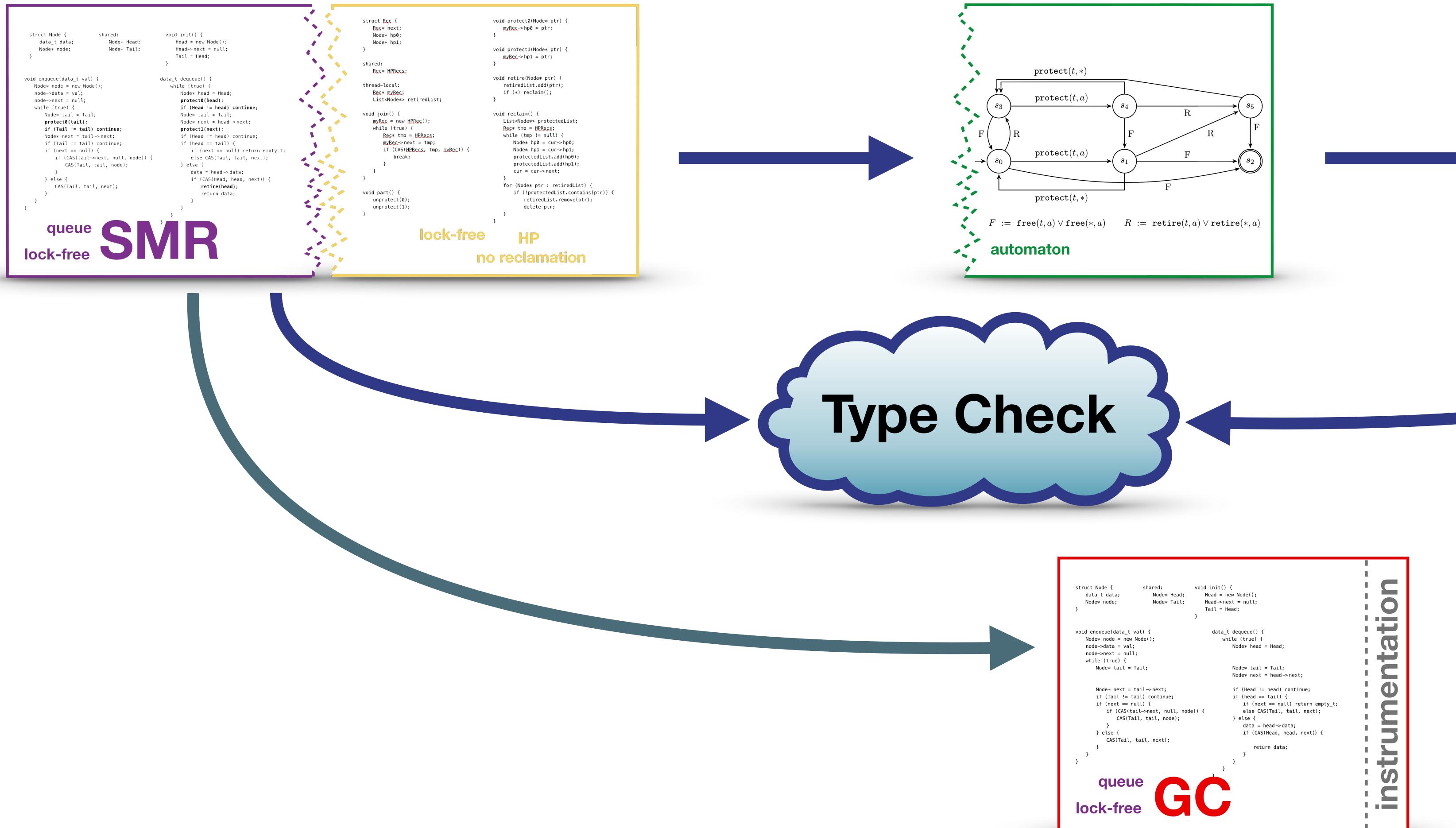
Types:



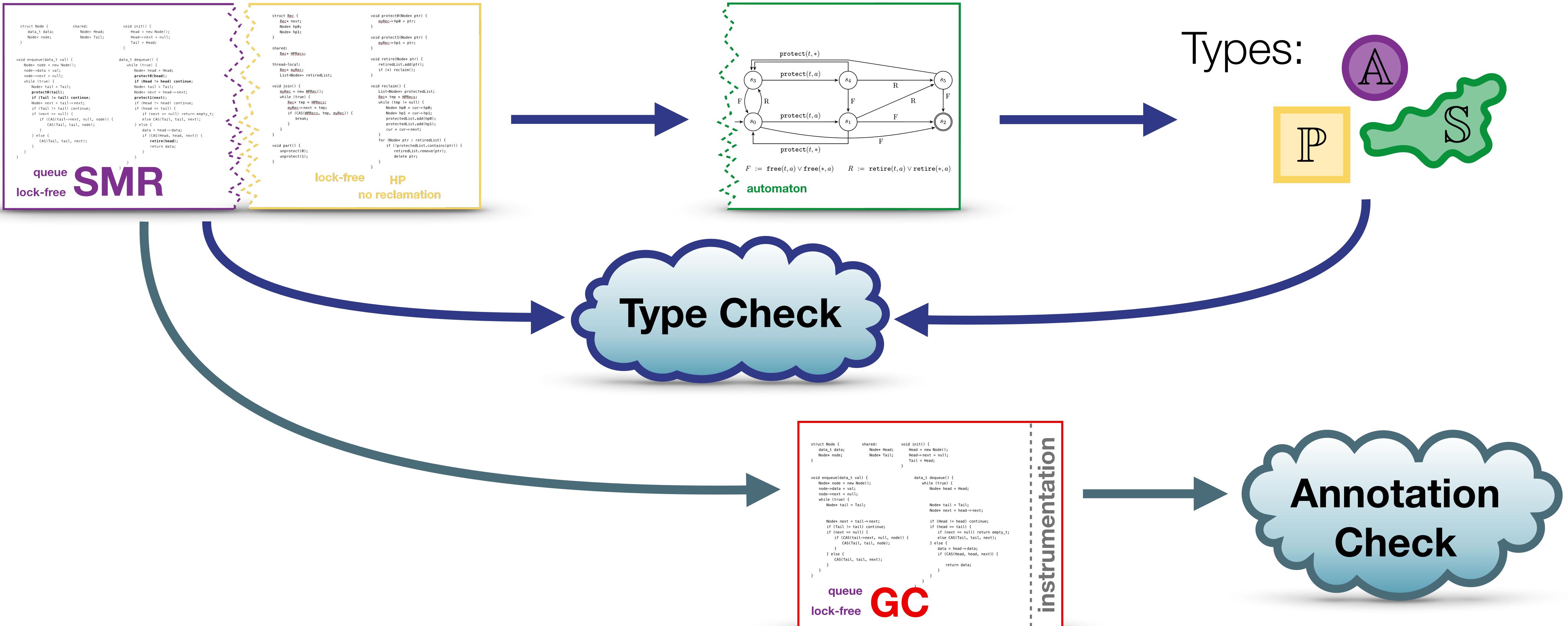
# Final Approach



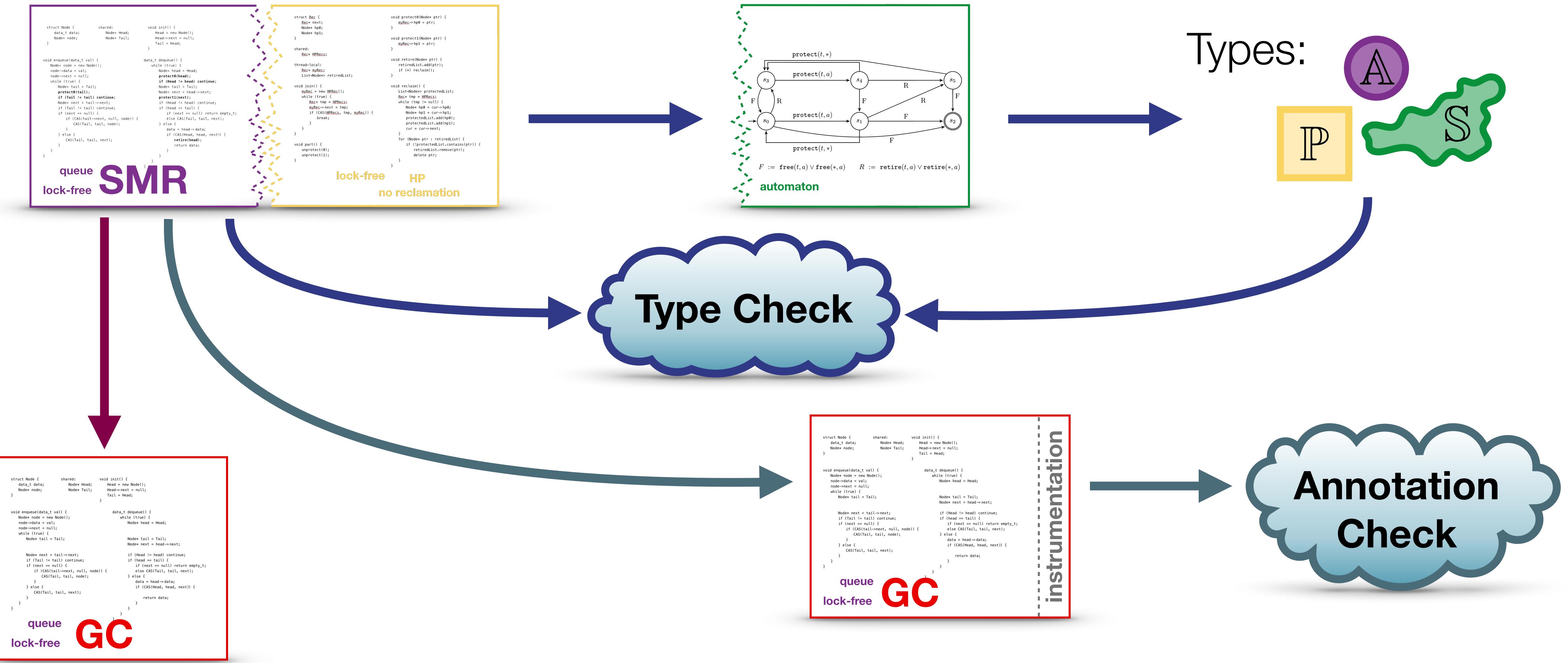
# Final Approach



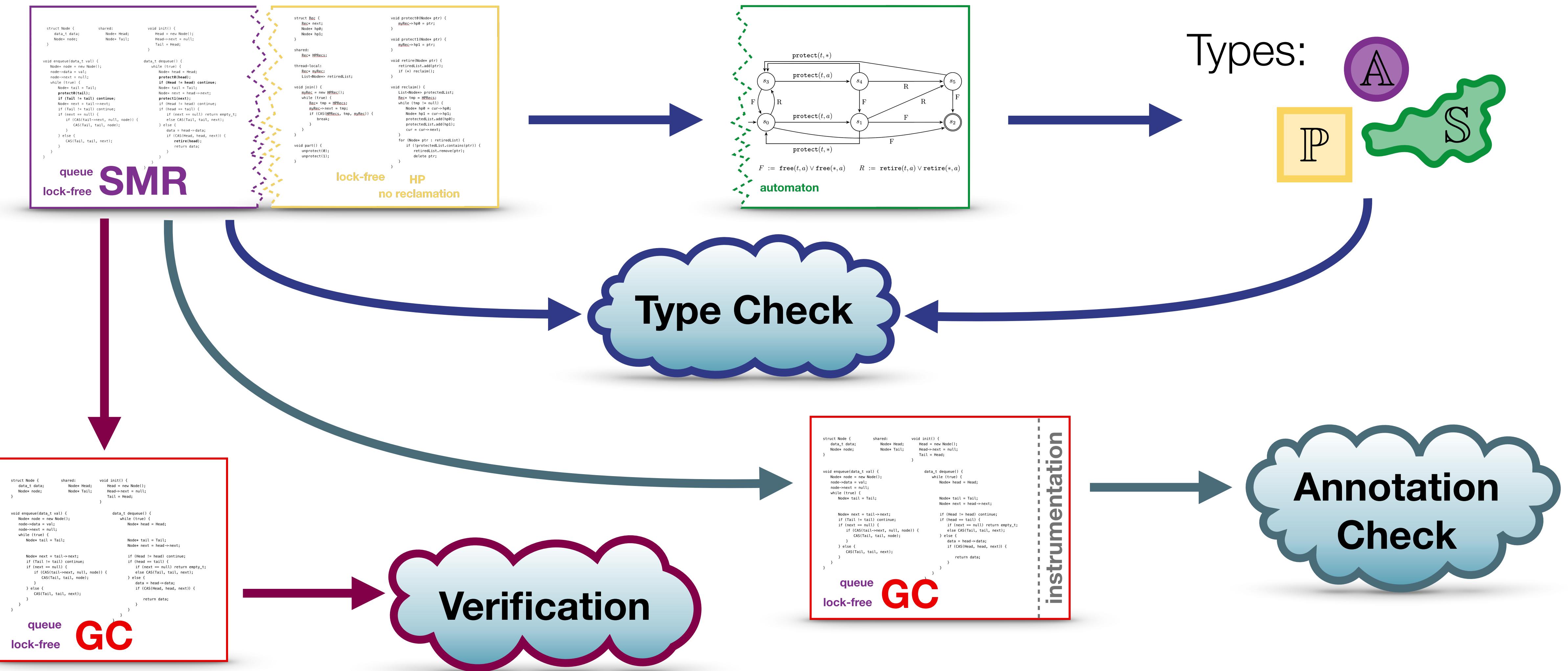
# Final Approach



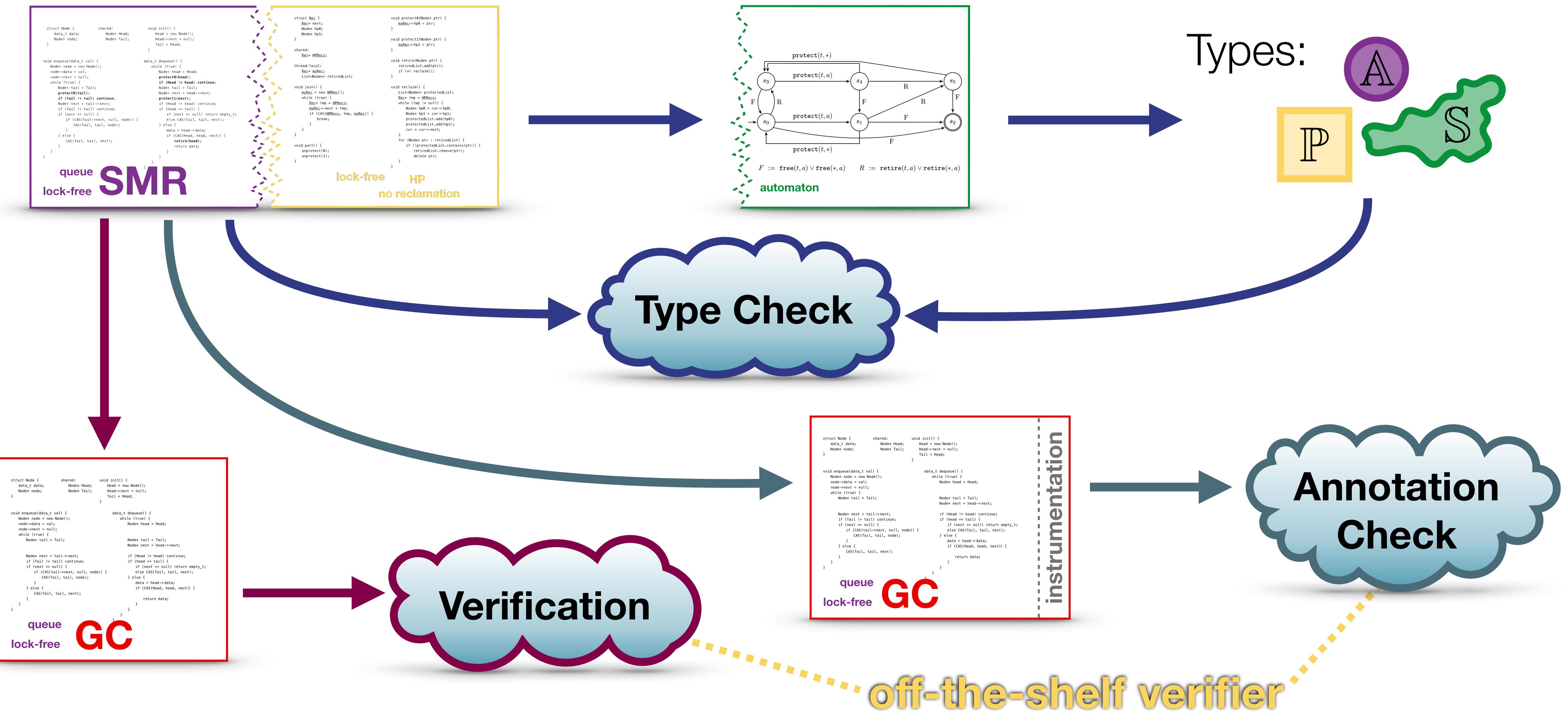
# Final Approach



# Final Approach

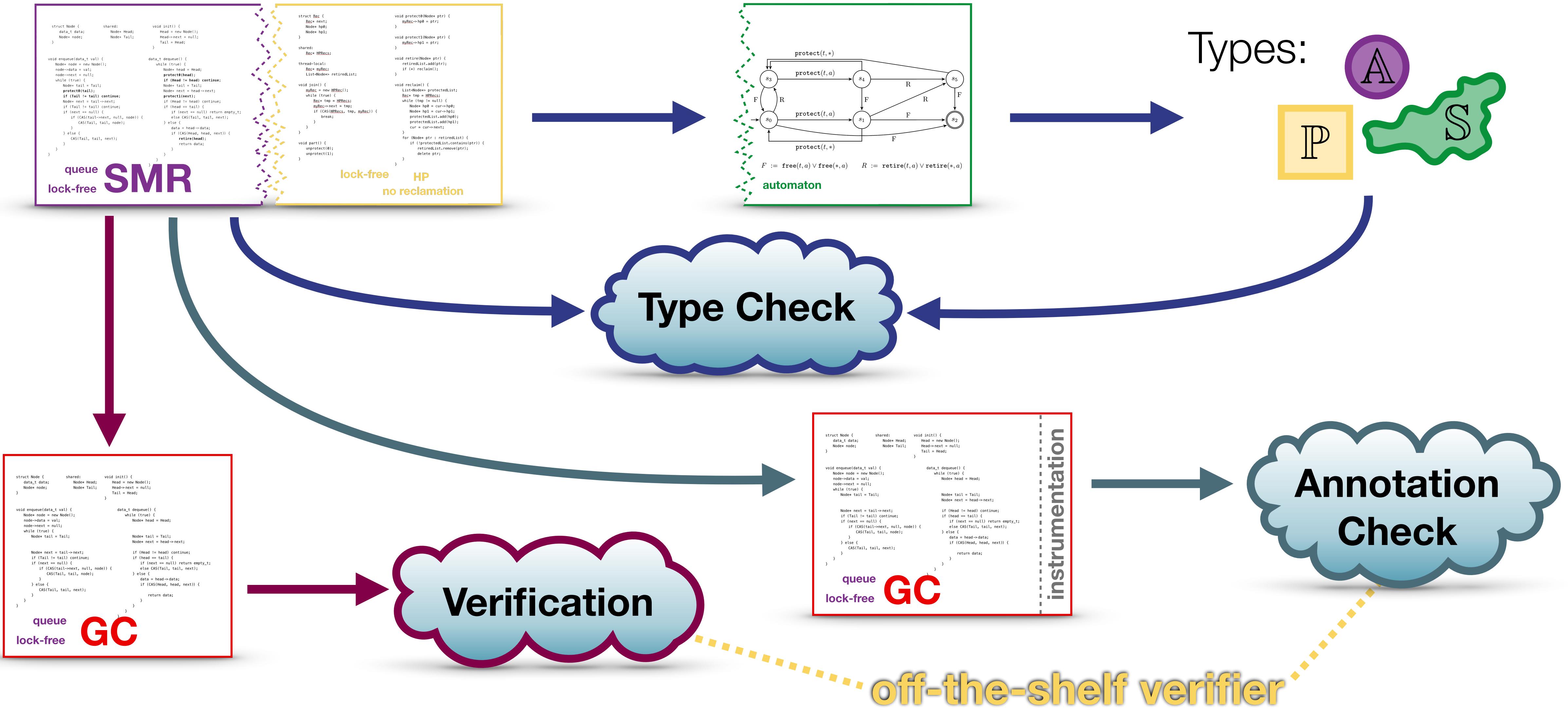


# Final Approach



# Final Approach

# Thanks



Fin.