Linked Lists

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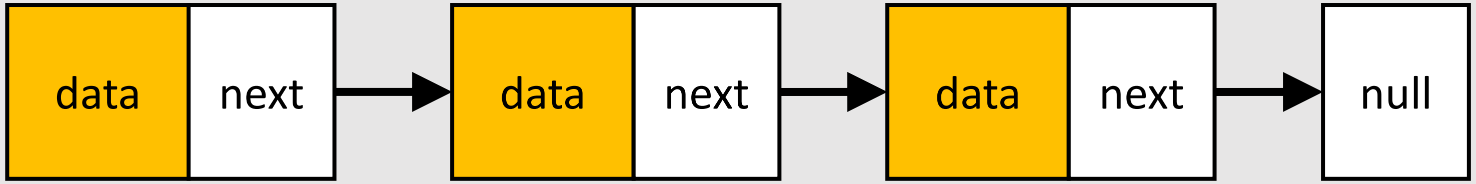
CSE 13S

Linked Lists

- The diagram below depicts a *singly linked list*.
- A *linked* data structure.
  - In a *singly* linked list, each node contains a data field and a pointer to the *next* node in the list.
  - In a *doubly* linked list, each node contains a data field and pointers to the *next and previous* nodes in the list.
- The last node in the list points to a terminator, usually a *null* pointer.



Linked Structures

- Linked lists are members of the class of *linked structures*.
  - Linked lists
  - Trees
  - Tries
  - Graphs
  - Sparse matrices
  - … and more.

Advantages

- No fixed memory allocation:
  - Grow and shrink at run-time without pre-allocating memory.
  - No need to know the initial size of the list.
- Insertion and Deletions:
  - No need to shift elements after insertion or deletion.
  - Only update the address to the next pointer of a node.
- Usage:
  - Easily implement linear data structures like stacks and queues.

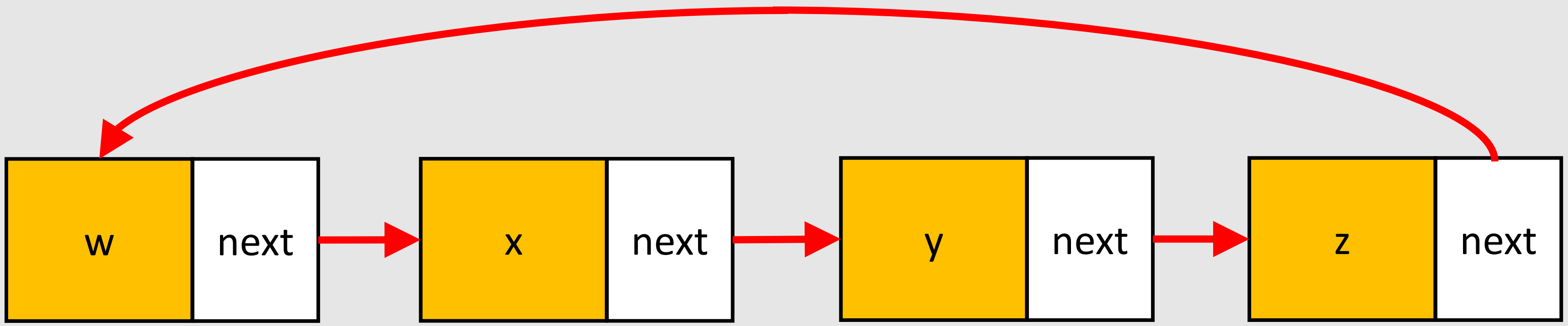
Disadvantages

- Memory usage:
  - Storing pointer to next node requires extra memory.
  - Arrays are friendlier to processor caches.
  - Slightly less memory efficient than arrays.

- Traversal:
  - Cannot randomly access elements, must traverse all elements up to the element we want to access.
  - Reverse traversing is difficult in singly linked lists.
    - Easy in doubly linked list but uses extra memory to store an additional pointer.

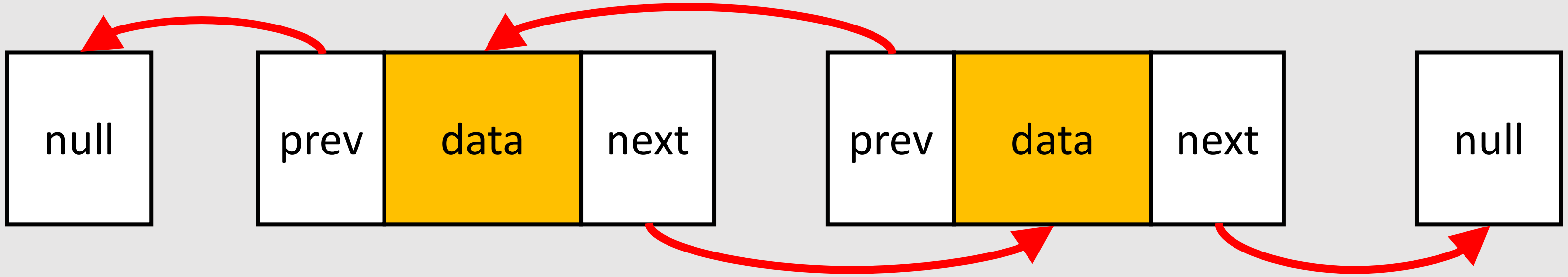
Circular Singly Linked List

- The last node of the linked list points back to the tail.



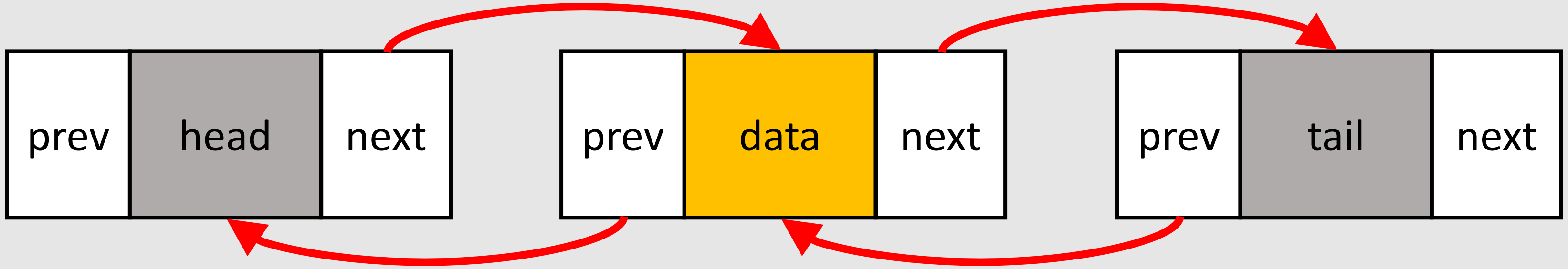
Doubly Linked Lists

- Each node has a pointer to both the previous and next nodes.
- Allows traversal in two directions.
- Less memory efficient than a normal linked list.
- Typically implemented with *sentinel nodes*.



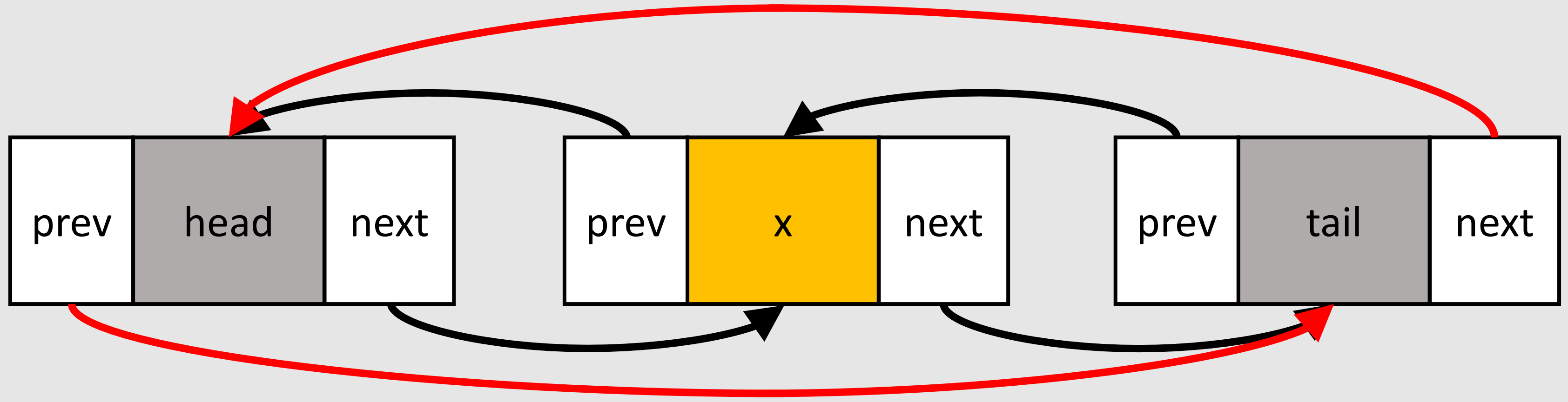
Sentinel Nodes

- Designated “dummy nodes” used to mark the ends of a linked list.
- In a doubly linked list, sentinel nodes are placed at the head and tail.
  - When performing an insertion, nodes will always go between two nodes.
  - The grayed boxes below indicate the sentinels.



Circular Doubly Linked List

- The head of the linked list points back to the tail.
- The tail of the linked list points to the head.

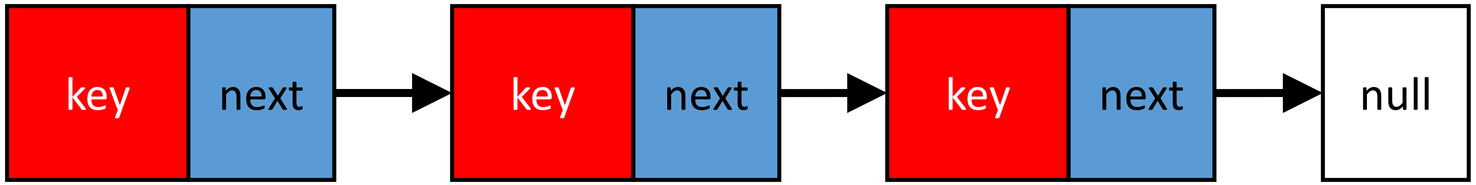


A singly linked list ADT

17 May 2023

```c
typedef struct ListNode ListNode;

struct Listnode {
    char *key;
    ListNode *next;
};
```



Wrong way to declare a singly linked list ADT

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Why we declare it in two parts:

- If we used **one** typedef, then ListNode would need to be used before it was declared.

```
typedef struct {
        char *key;
        ListNode *next;
} ListNode;
```

Use is before Declaration

A singly linked list ADT

17 May 2023

Why we declare it in two parts:

- If we used **one** typedef, then ListNode would need to be used before it was declared.

```
typedef struct ListNode ListNode;

struct Listnode {
    char *key;
    ListNode *next;
};
```

Alternate way to declare a singly linked list ADT

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This approach does work
for a **single** node type.

```
typedef struct ListNode {
      char *key;
      struct ListNode *next;
} ListNode;
```

Multiple node types?
Use separate typedefs
and structs, as shown earlier

```c
ListNode *node_create(const char *key) {
    ListNode *t = (ListNode *) malloc(sizeof(ListNode));
    if (t) {
        t->key = strdup(key);
        t->next = NULL;
    }
    return t;
}
```


Constructor

- Allocate memory needed for a single node.
- A node's key is the duplicated key.
- A node initially points to `NULL`.

```c
void node_delete(ListNode **n) {
    if (*n) {
        free((*n)->key);
        free(*n);
        *n = NULL;
    }
    return;
}
```


Node destructor

- Free memory allocated for a node.
- A double pointer is passed so we can `NULL` the original pointer.

```c
void ll_delete(ListNode **head) {
    while (*head != NULL) {
        ListNode *next = NULL; // Save pointer to next node.
        next = (*head)->next;
        node_delete(head);
        *head = next;
    }
    return;
}
```


Linked list destructor

- Walks the linked list and deletes each node.

```c
ListNode *ll_lookup(ListNode *head, const char *key) {
    for (ListNode *curr = head; curr != NULL; curr = curr->next) {
        if (strcmp(curr->key, key) == 0) {
            return curr;
        }
    }
    return NULL;
}
```


Lookup

- Walks the linked list to look for a specified key.
  - If the key matches, then return the node, move on otherwise.
- Linear search complexity for singly and doubly linked lists is *O(n)*.
  - For keys that are strings with a maximum of *m* characters, the search complexity is *O(mn)*.
- Worst case: the key is *absent*.

```c
ListNode *ll_insert(ListNode **head, const char *key) {
    if (ll_lookup(*head, key) != NULL) {
        return *head;
    }
    ListNode *n = node_create(key);
    n->next = *head;
    *head = n;
    return *head;
}
```


Insertion

- Check if the key is already in the list.
    - We don't want duplicates.
- Create a node with the key.
- Point the created node at the head.
- The new head is the created node.

```c
void ll_print(ListNode *head) {
    for (ListNode *curr = head; curr != NULL; curr = curr->next) {
        printf("%s\n", curr->key);
    }
    return;
}
```


Printing

- Walk through the linked list and print out each node’s key.

```c
ListNode *ll_remove(ListNode **head, const char *key) {
    if (*head) {
        ListNode *curr = *head;
        ListNode *prev = NULL;
        while (curr != NULL) {
            if (strcmp(curr->key, key) == 0) {
                if (prev != NULL) {
                    prev->next = curr->next;
                } else {
                    // If prev is NULL, we're on the head.
                    *head = curr->next;
                }
                node_delete(&curr);
                return *head;
            }
            prev = curr;
            curr = curr->next;
        }
    }
    return *head;
}
```

Removing

- Track the current and previous nodes.
    - Initially, the previous node is `NULL`.
- Walk the linked list.
    - If the current node contains a matching key:
        - If there was a previous node, point it at the node after the current node.
        - Else, we were on the head, so make the head point to the node the current node is point at.
        - Delete the found node, then we're done.
    - The previous node is now the current node.
    - The current node is its next node.

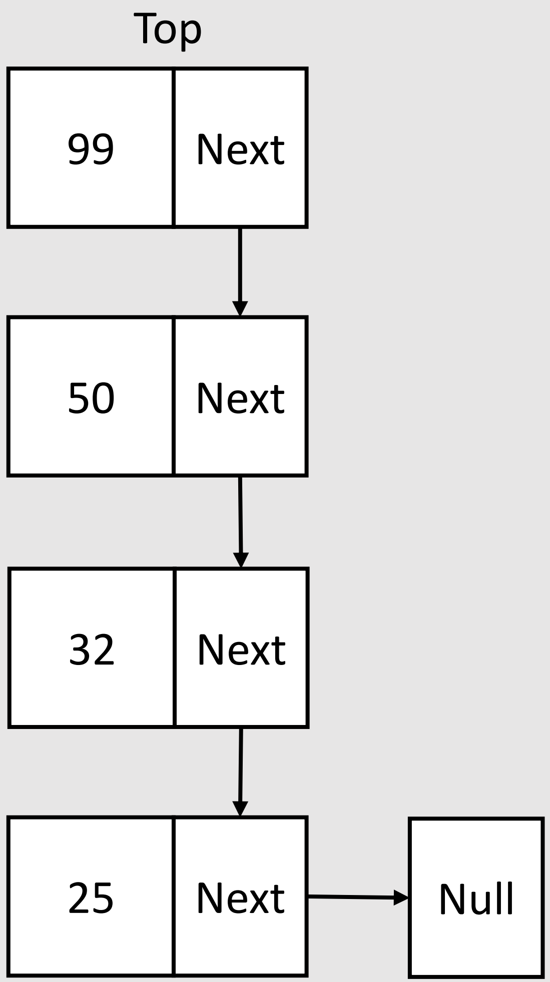
```c
ListNode *ll_mtf(ListNode **head, const char *key) {
    if (*head) {
        ListNode *curr = *head;
        ListNode *prev = NULL;
        while (curr != NULL) {
            if (strcmp(curr->key, key) == 0) {
                if (prev != NULL) {
                    prev->next = curr->next;
                    curr->next = *head;
                    *head = curr;
                    return *head;
                }
            }
            prev = curr;
            curr = curr->next;
        }
    }
    return *head;
}
```

Move-to-front

- Track the current and previous nodes.
  - Initially, the previous node is `NULL`.
- Walk the linked list.
  - If the current node contains a matching key:
    - If there was a previous node, point it at the node after the current node.
      - The current node should node should now point at the head.
      - The new head is the current node, so we're done.
    - Else, we were on the head, so no need to move to the front.
  - The previous node is now the current node.
  - The current node is its next node.

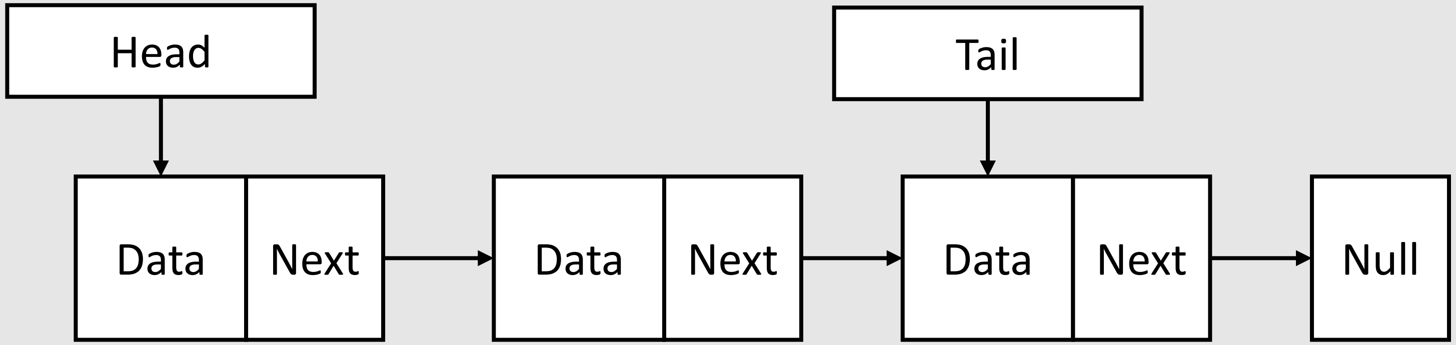
Linked List Stacks

- Stack size is limited only by available memory.
- Pushing an element is inserting it at the head.
- Popping an element is removing it from the head.



Linked List Queues

- Add at the tail.
- Remove at the head.



A doubly linked list ADT

17 May 2023

```c
typedef struct listNode listNode;

struct listNode {
  char *key;
  listNode *fwd, *rev;
};

typedef struct {
  listNode *head, *tail;
} listHead;
```

```c
listNode *newNode(char *key) {
    listNode *n = (listNode *) malloc(sizeof(listNode));
    if (n) {
        n->key = strdup(key);
        n->fwd = n->rev = NIL;
    }
    return n;
}

listHead *newList(void) {
    listHead *h = (listHead *) malloc(sizeof(listHead));
    if (h) {
        h->head = h->tail = NIL;
    }
    return h;
}
```

Constructors

- To create a node:
  - Allocate memory for the node.
  - Duplicate the key for the node.
  - The forward and reverse pointers are `NIL` (`NULL`) to start with.
- To create a list:
  - Allocate memory for the list.
  - The head and tail of the list are `NIL` to start with.

```c
bool prependList(listHead *h, listNode *n) {
    if (h && n) {
        if (h->head == NIL && h->tail == NIL) {
            h->head = h->tail = n;
        } else {
            n->fwd = h->head;
            h->head->rev = n;
            h->head = n;
            n->rev = NIL;
        }
        return true;
    } else {
        return false;
    }
}
```

Prepending

- Prepends a node *n* to the list (inserts at the head).
- If both the head and tail are `NIL`:
  - The only node in the list is the node to prepend.
- Else:
  - The node after *n* is the head.
  - The node before the head is now *n*.
  - The new head is *n.*
  - There is no node behind *n*.

```c
bool appendList(listHead *h, listNode *n) {
    if (h && n) {
        if (h->head == NIL && h->tail == NIL) {
            h->head = h->tail = n;
        } else {
            n->rev = h->tail;
            h->tail->fwd = n;
            h->tail = n;
            n->fwd = NIL;
        }
        return true;
    } else {
        return false;
    }
}
```

Appending

- Appends a node *n* to the list (inserts at the tail).
- If both the head and tail are `NIL`:
  - The only node in the list is the node to append.
- Else:
  - The node before *n* is the tail.
  - The node after the tail is now *n*.
  - The new tail is *n.*
  - There is no node after *n*.

```c
bool insertList(listHead *h, listNode *n) {
    if (h && n) {
        if (h->head == NIL && h->tail == NIL) {
            h->head = h->tail = n;
        } else {
            listNode *p = h->head;
            while (p != NIL && strcmp(n->key, p->key) > 0) {
                p = p->fwd;
            }
            if (p == NIL || p == h->tail) {
                appendList(h, n);
            } else if (p == h->head) {
                prependList(h, n);
            } else {
                n->fwd = p->fwd;
                n->rev = p;
                p->fwd->rev = n;
                p->fwd = n;
            }
        }
        return true;
    } else {
        return false;
    }
}
```

Inserting

- Inserts a node *n* lexicographically.
  - Specifically, in reverse alphabetic order.
- If both the head and tail are `NIL`:
  - The only node in the list is the node to insert.
- Else:
  - Traverse to where the node should go.
  - If we're at the end of the of the linked list, we append the node.
  - If we're at the head of the linked list, we prepend the node.
  - If we're in the middle:
    - The current node is *p*.
    - The node after *n* is the node *p* is point to.
    - The node before *n* is now *p.*
    - The node after *p* should point back to *n*.
    - The node after *p* is now *n*.

```c
listNode *popList(listHead *h) {
    if (h && h->head) {
        listNode *p = h->head;
        h->head = p->fwd;
        p->fwd = p->rev = NIL;
        return p;
    }
    return NIL;
}
```

Popping

- Disconnects and returns the head of the linked list.
- If the head exists:
  - Save a pointer *p* to the head.
  - The new head is the node after *p*.
  - Make sure *p* doesn’t point anywhere and return it.
- Else:
  - Return `NIL`.

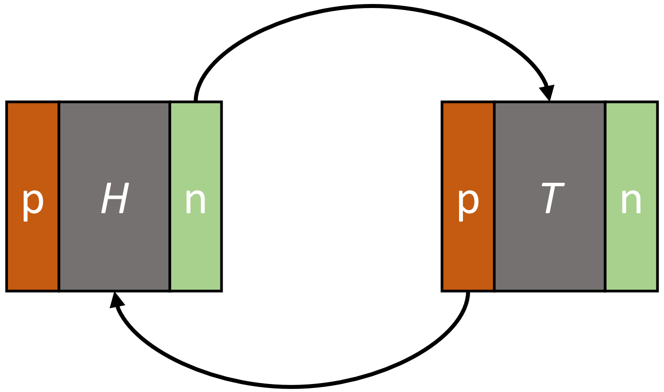
```c
listNode *dropList(listHead *h) {
    if (h && h->tail) {
        listNode *p = h->tail;
        h->tail = p->rev;
        p->fwd = p->rev = NIL;
        return p;
    }
    return NIL;
}
```

Dropping

- Disconnects and returns the tail of the linked list.
- If the tail exists:
  - Save a pointer *p* to the tail.
  - The new tail is the node before *p*.
  - Make sure *p* doesn't point anywhere and return it.
- Else:
  - Return `NIL`.

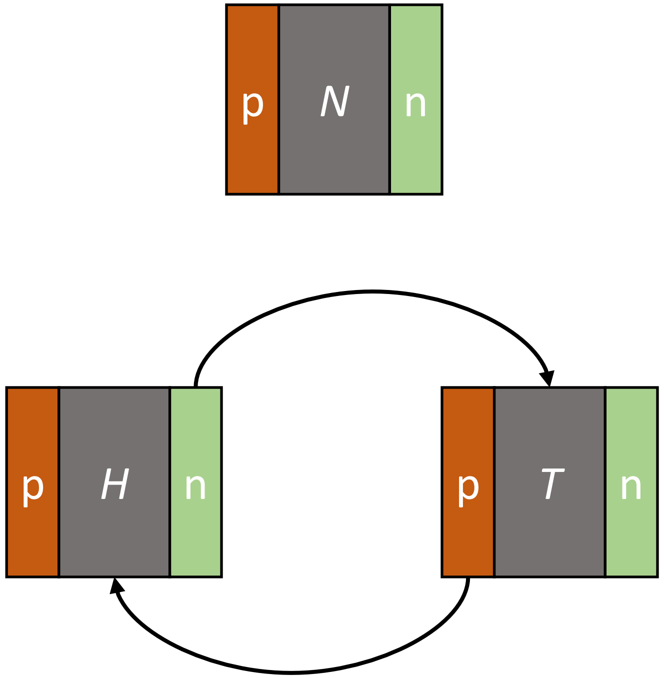
Inserting Into a Doubly Linked List

- Assume there are two dummy nodes to serve as the head and tail.
  - These are referred to as *sentinel nodes*.
  - We'll label them as *H* and *T, respectively.*
- The presence of the sentinel nodes means there are always two nodes to insert between.
  - Con: Overhead of needing two extra nodes.
  - Pro: Cleans up the logic needed to insert a node.
- Each node has its own *p* and *n*.
  - These are the pointers to the previous and next nodes.



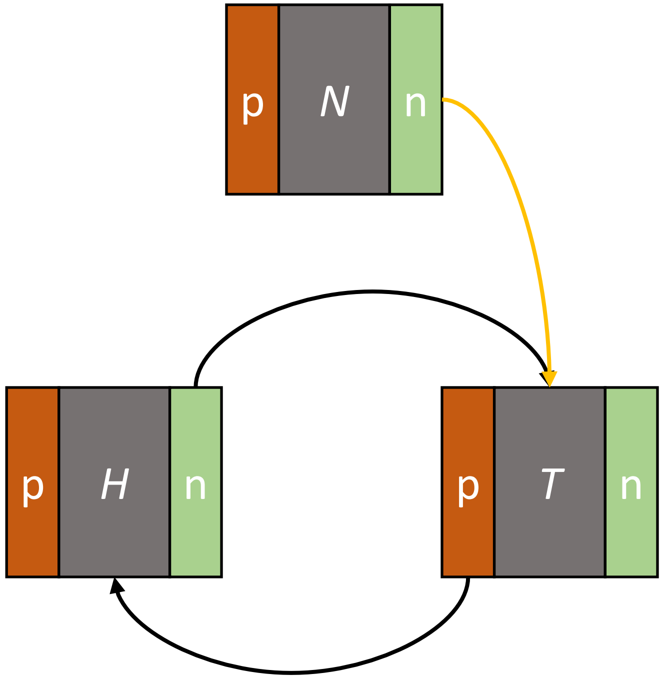
Inserting Into a Doubly Linked List

- We have a new node *N* that we will insert.



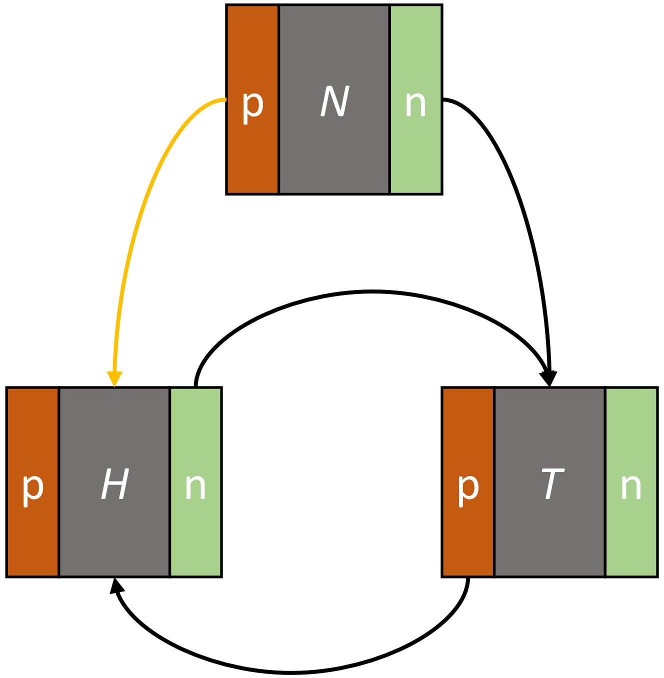
Inserting Into a Doubly Linked List

- We have a new node *N* that we will insert into the doubly linked list.
    1. The node after *N* should be the node that *H* was pointing to.



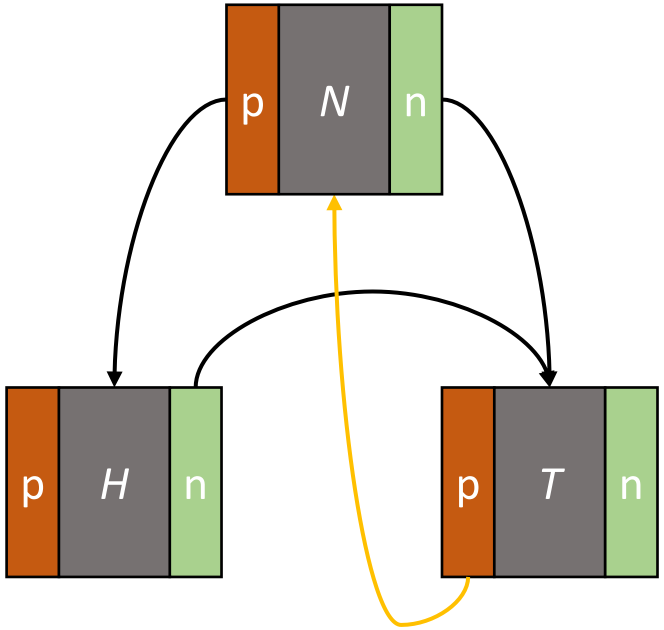
Inserting Into a Doubly Linked List

- We have a new node *N* that we will insert.
    1. The node after *N* should be the node that *H* was pointing to.
    2. The node before *N* should be the head sentinel node, *H*.



Inserting Into a Doubly Linked List

- We have a new node *N* that we will insert.
    1. The node after *N* should be the node that *H* was pointing to.
    2. The node before *N* should be the head sentinel node, *H*.
    3. The node *H* is pointing to should now point back to *N*.



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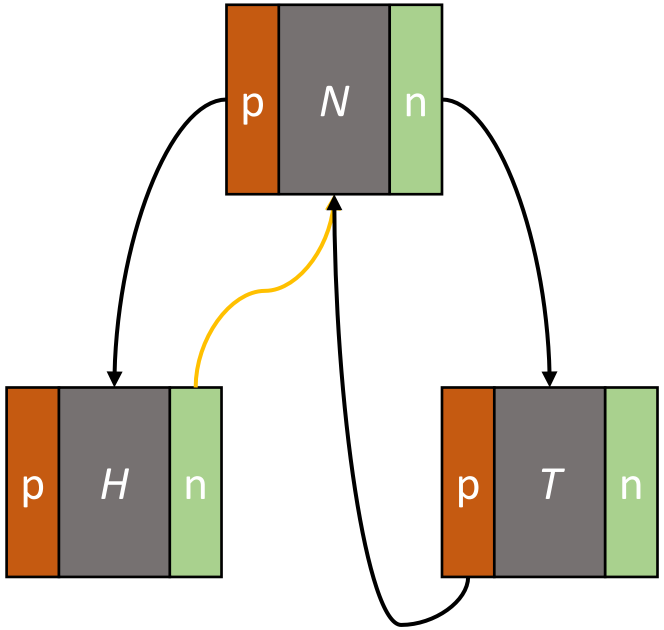
    4. The node after *H* should now be *N*.



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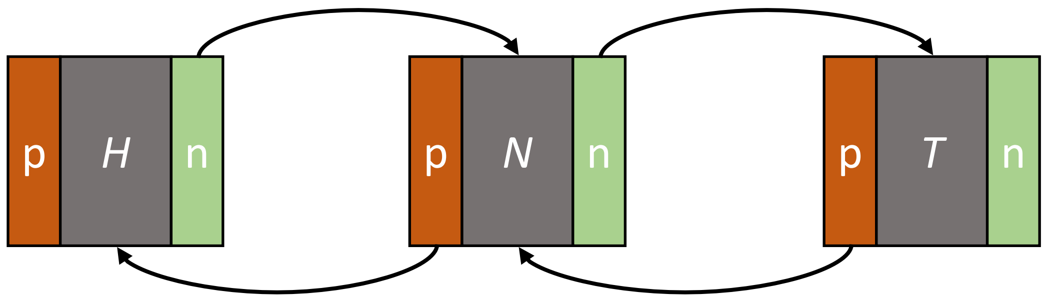
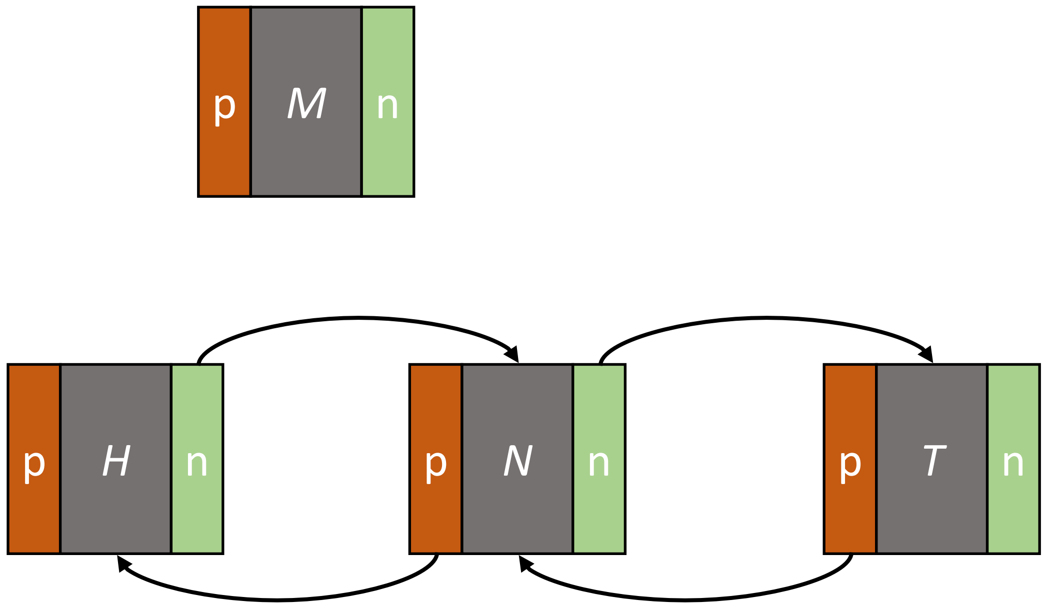
  2. The node before *N* should be the head sentinel node, *H*.
  3. The node *H* is pointing to should now point back to *N*.
  4. The node after *H* should now be *N*.
- *N* is now at the front of the doubly linked list.



Inserting Into a Doubly Linked List

- Let's try inserting another node *M* following the same steps as done with *N*.
    1. The node after *M* should be the node that *H* was pointing to.
    2. The node before *M* should be the head sentinel node, *H*.
    3. The node *H* is pointing to should now point back to *M*.
    4. The node after *H* should now be *M*.



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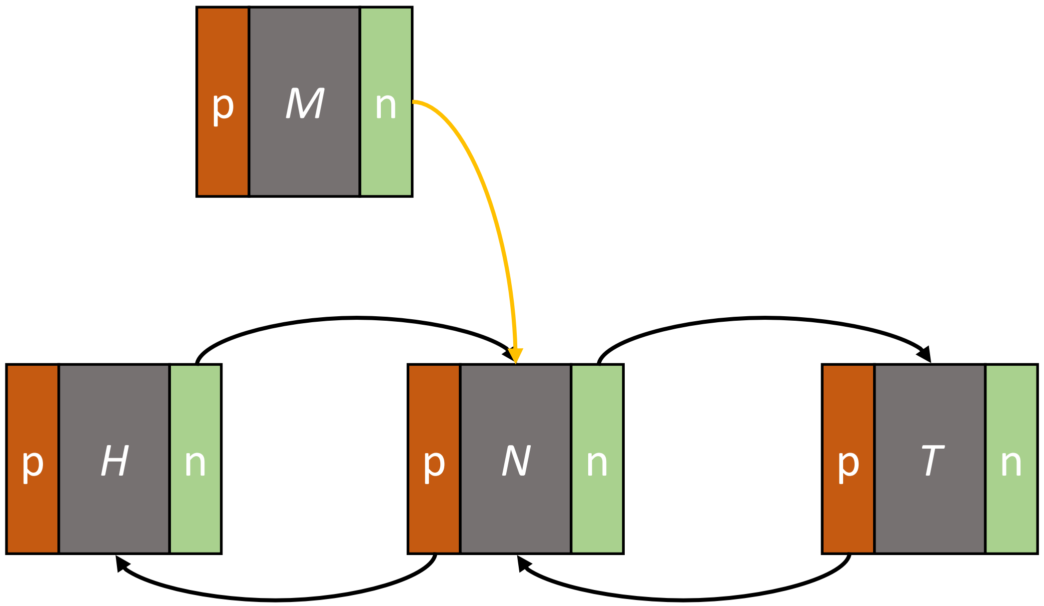

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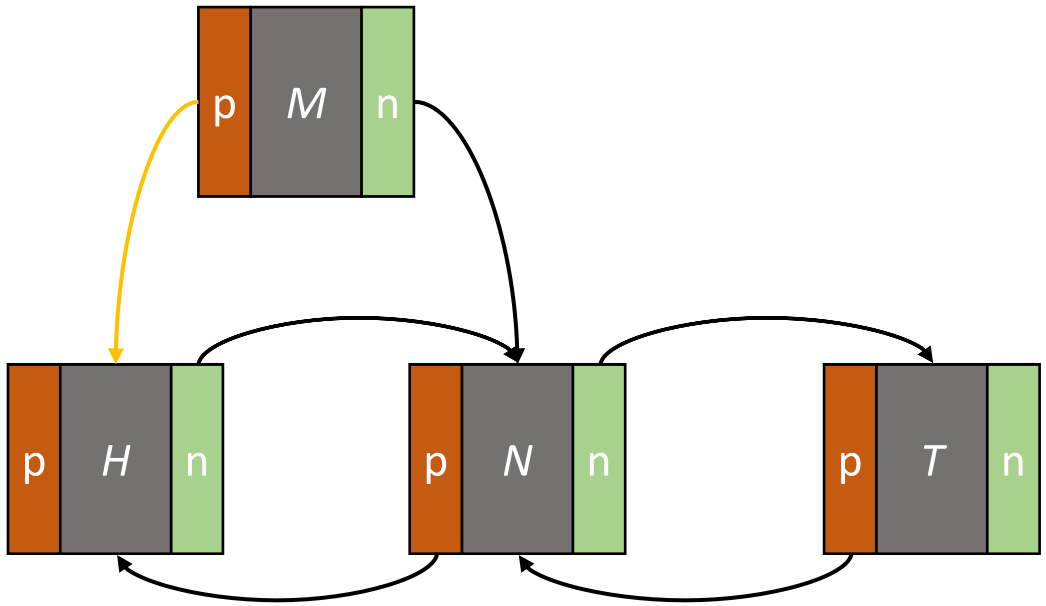

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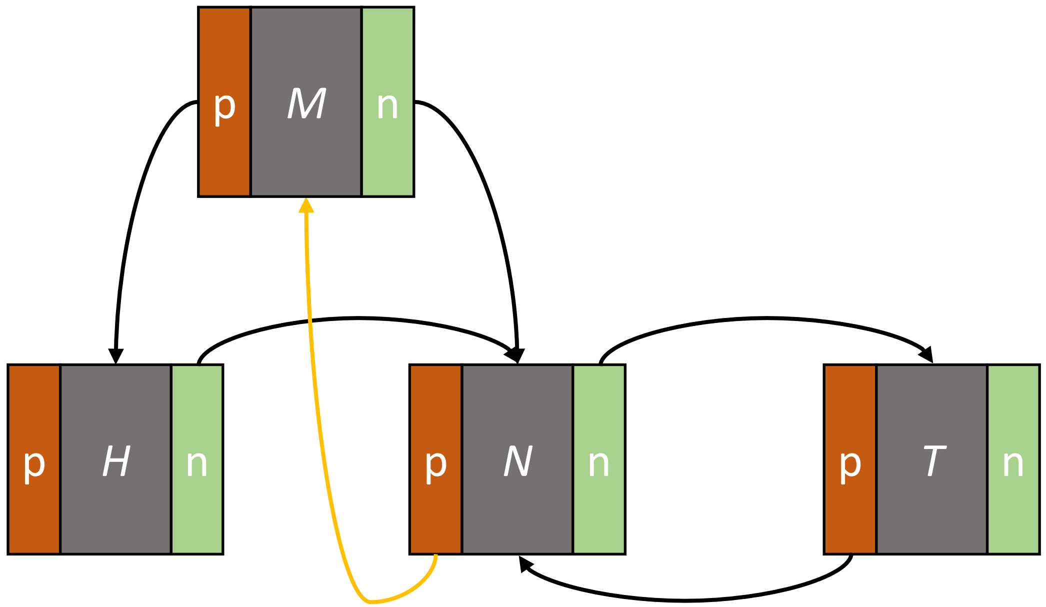

Inserting Into a Doubly Linked List

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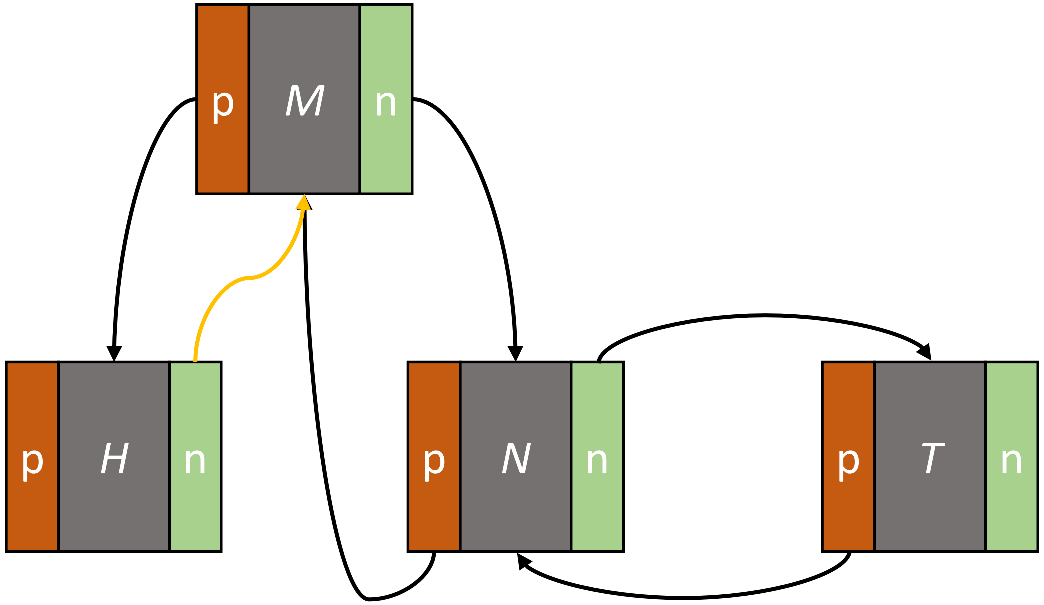
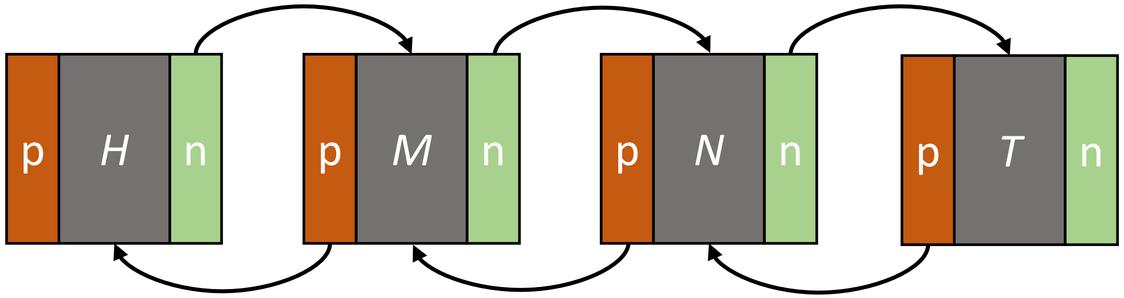


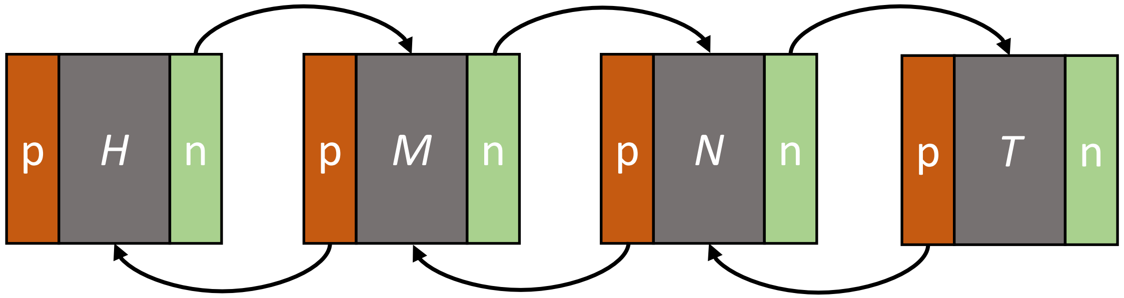
Inserting Into a Doubly Linked List

- Let's try inserting another node *M* following the same steps as done with *N*.
    1. The node after *M* should be the node that *H* was pointing to.
    2. The node before *M* should be the head sentinel node, *H*.
    3. The node *H* is pointing to should now point back to *M*.
    4. The node after *H* should now be *M*.
- *M* is now at the front of the doubly linked list.



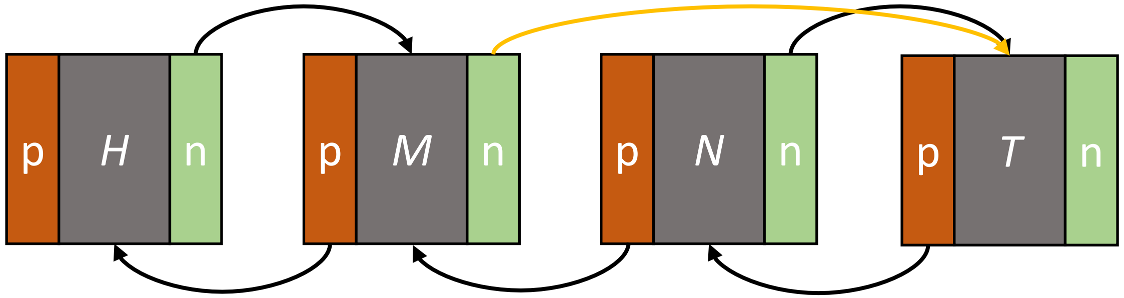
Move-to-front

- Now that we've inserted *M*, we decide we don't like the current order of the linked list.
  - We want *N* to be at the front.



Move-to-front

1. The node before *N* should point to the node after *N*.



Move-to-front

1. The node before *N* should point to the node after *N*.
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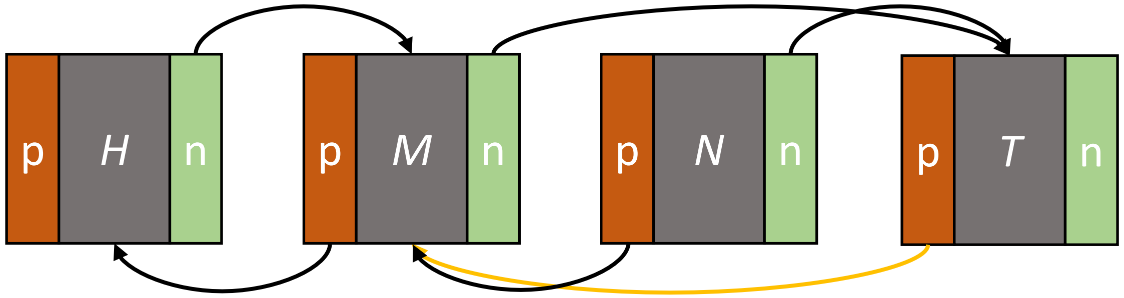
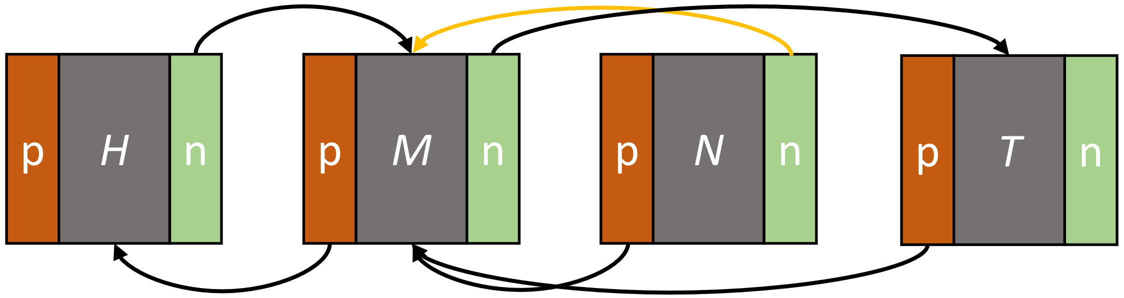


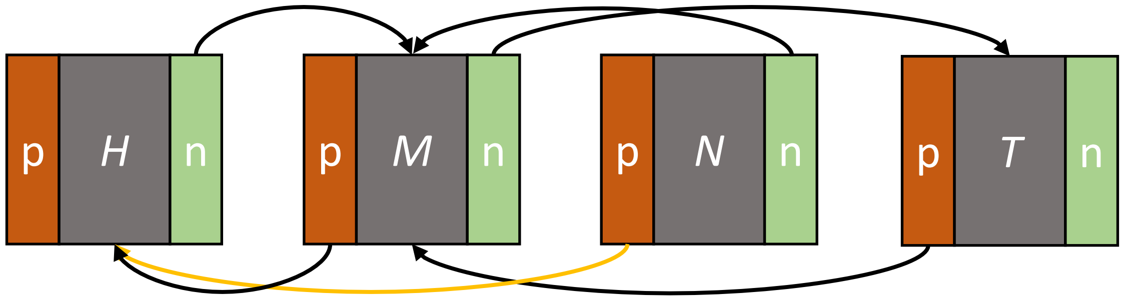
Move-to-front

1. The node before *N* should point to the node after *N*.
2. The node after *N* should point to the node before *N*.
3. The node after *N* should be the node that the head sentinel node *H* was pointing to (this will look a bit messy).

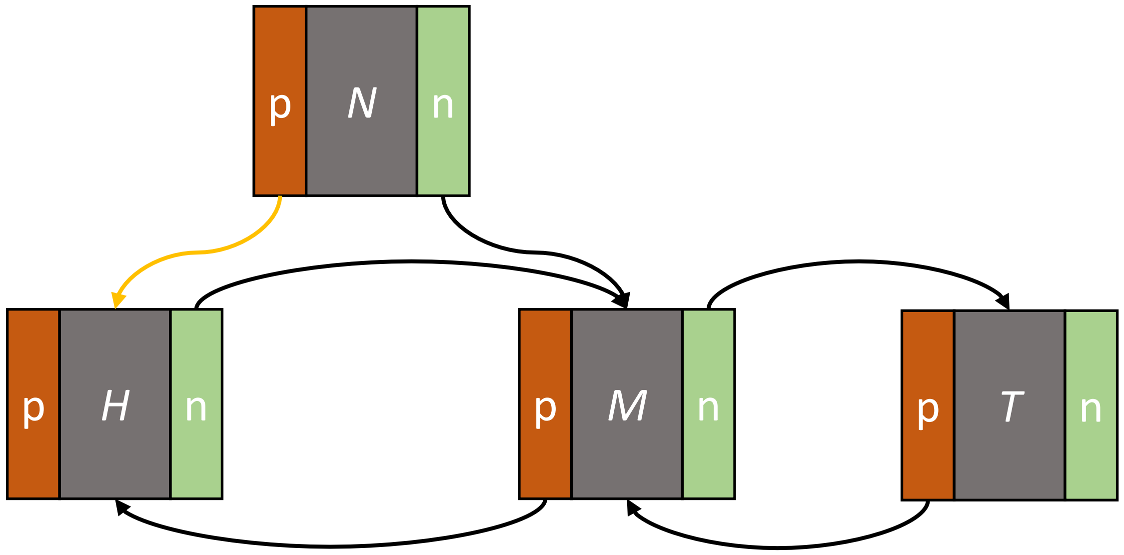


Move-to-front

1. The node before *N* should point to the node after *N*.
2. The node after *N* should point to the node before *N*.
3. The node after *N* should be the node that the head sentinel node *H* was pointing to.
4. The node before *N* should now be *H*.

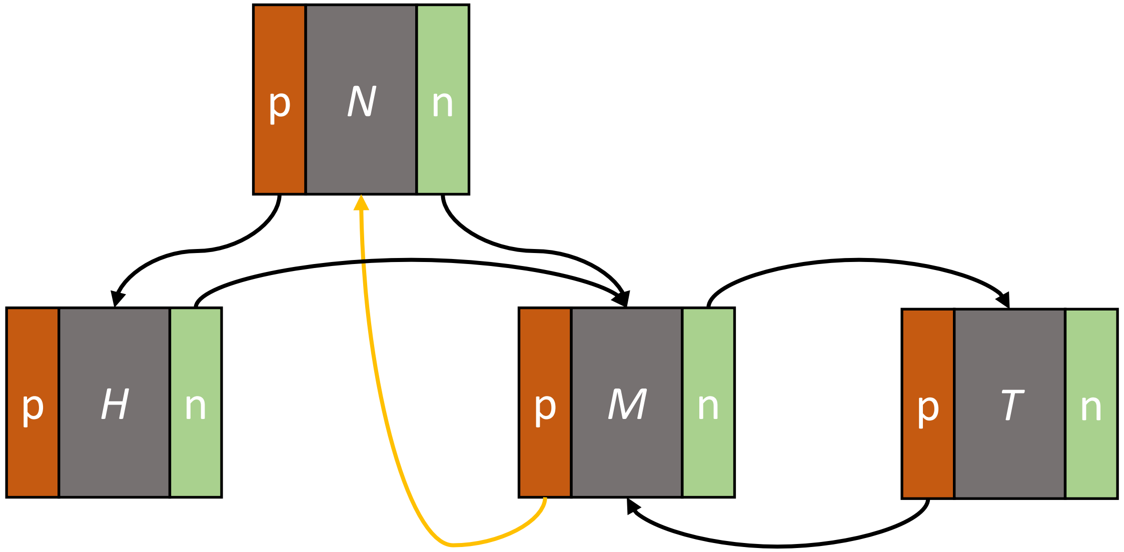


Just to clean things up a bit.



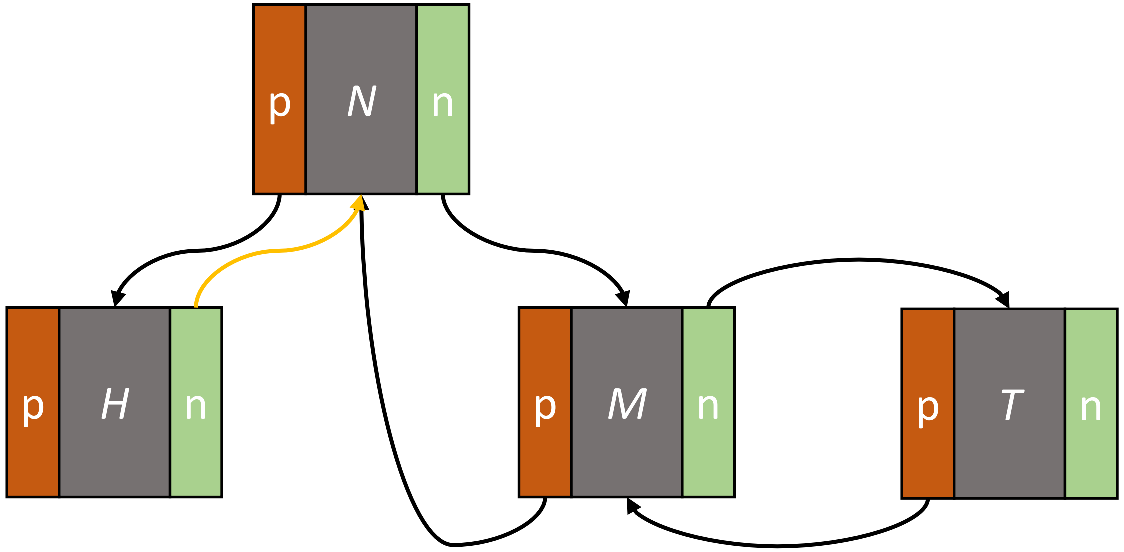
Move-to-front

1. The node before *N* should point to the node after *N*.
2. The node after *N* should point to the node before *N*.
3. The node after *N* should be the node that the head sentinel node *H* was pointing to.
4. The node before *N* should now be *H.*
5. The node after *H* should point back to *N*.



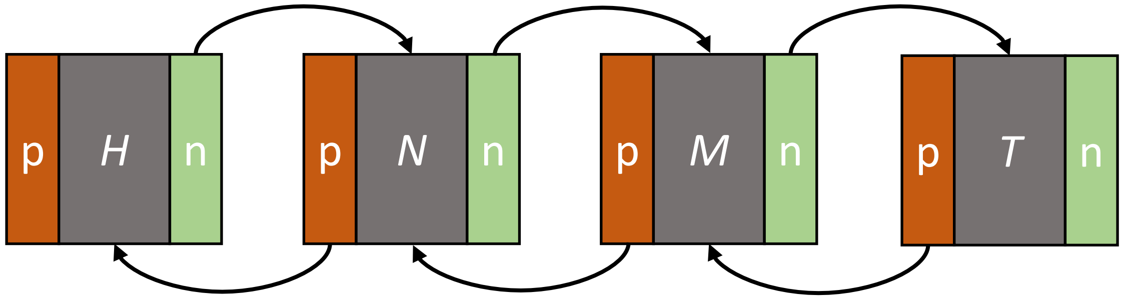
Move-to-front

1. The node before *N* should point to the node after *N*.
2. The node after *N* should point to the node before *N*.
3. The node after *N* should be the node that the head sentinel node *H* was pointing to.
4. The node before *N* should now be *H.*
5. The node after *H* should point back to *N*.
6. The node after *H* should now be *N*.



Move-to-front

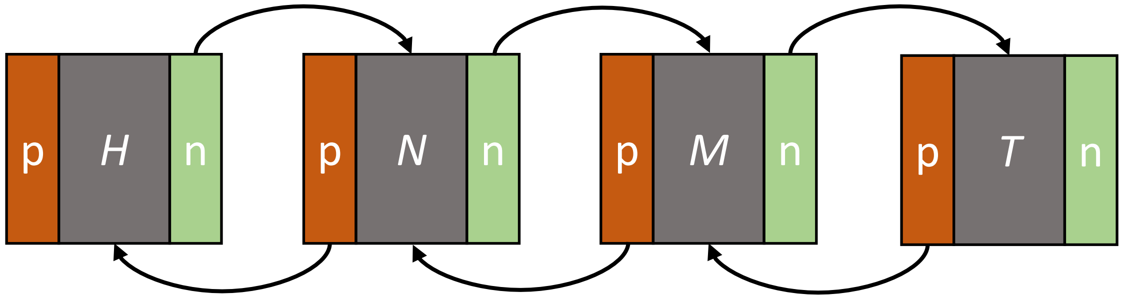
1. The node before *N* should point to the node after *N*.
2. The node after *N* should point to the node before *N*.
3. The node after *N* should be the node that the head sentinel node *H* was pointing to.
4. The node before *N* should now be *H.*
5. The node after *H* should point back to *N*.
6. The node after *H* should now be *N*.



N is now at the front.

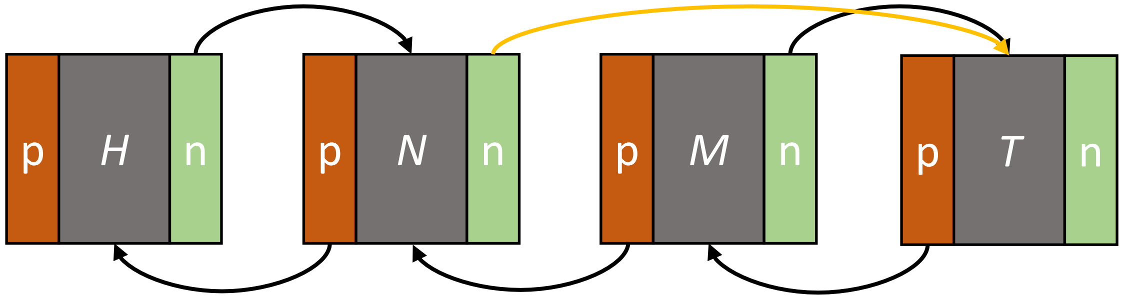
Removing a node

- We decide that we don't like node *M* very much and want to remove it.



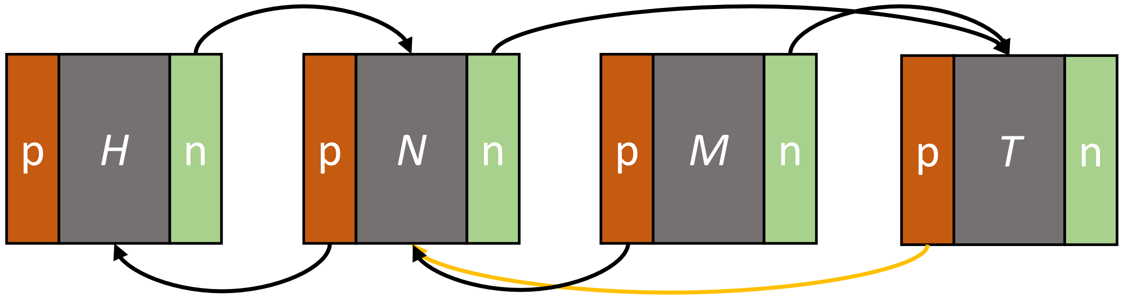
Removing a node

- We decide that we don’t like node *M* very much and want to remove it.
    1. The node before *M* should point to the node after *M*.



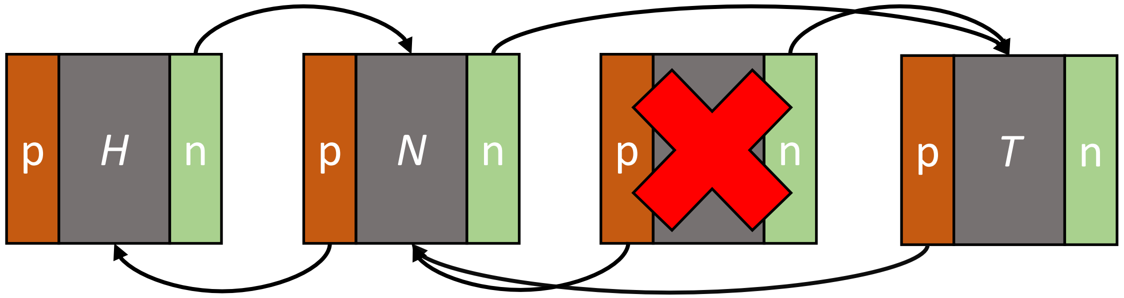
Removing a node

- We decide that we don't like node *M* very much and want to remove it.
  1. The node before *M* should point to the node after *M*.
  2. The node after *M* should point to the node before *M*.



Removing a node

- We decide that we don't like node *M* very much and want to remove it.
  1. The node before *M* should point to the node after *M*.
  2. The node after *M* should point to the node before *M*.
  3. Goodbye *M*.



Removing a node

- We decide that we don't like node *M* very much and want to remove it.
    1. The node before *M* should point to the node after *M*.
    2. The node after *M* should point to the node before *M*.
    3. Goodbye *M*.
- *M* is removed now.