CSCI 104
Linked Lists

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Updated for Fall 2022 by Andrew Goodney
Lists

• Ordered collection of items, which may contain duplicate values, usually accessed based on their position (index)
  – Ordered = Each item has an index and there is a front and back (start and end)
  – Duplicates allowed (i.e. in a list of integers, the value 0 could appear multiple times)
  – Accessed based on their position (list[0], list[1], etc.)

• What are the operations you perform on a list?
# List Operations

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
<th>Input(s)</th>
<th>Output(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>insert</strong></td>
<td>Add a new value at a particular location shifting others back</td>
<td>Index : int</td>
<td>Value</td>
</tr>
<tr>
<td><strong>remove</strong></td>
<td>Remove value at the given location</td>
<td>Index : int</td>
<td>Value at location</td>
</tr>
<tr>
<td><strong>get / at</strong></td>
<td>Get value at given location</td>
<td>Index : int</td>
<td>Value at location</td>
</tr>
<tr>
<td><strong>set</strong></td>
<td>Changes the value at a given location</td>
<td>Index : int</td>
<td>Value</td>
</tr>
<tr>
<td><strong>empty</strong></td>
<td>Returns true if there are no values in the list</td>
<td></td>
<td>bool</td>
</tr>
<tr>
<td><strong>size</strong></td>
<td>Returns the number of values in the list</td>
<td></td>
<td>int</td>
</tr>
<tr>
<td><strong>push_back / append</strong></td>
<td>Add a new value to the end of the list</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td><strong>find</strong></td>
<td>Return the location of a given value</td>
<td>Value</td>
<td>Int : Index</td>
</tr>
</tbody>
</table>
List Implementation Options

• Singly-Linked List
  – With or without tail pointer

• Doubly-Linked List
  – With or without tail pointer

• Array-based List
Implementation Options

Linked Implementations
• Allocate each item separately
• Random access (get the i-th element) is $O(\_\_\_)$
• Adding new items never requires others to move
• Memory overhead due to pointers

Array-based Implementations
• Allocate a block of memory to hold many items
• Random access (get the i-th element) is $O(\_\_\_)$
• Adding new items may require others to shift positions
• Memory overhead due to potentially larger block of memory with unused locations

```
head: 0x148

<table>
<thead>
<tr>
<th>val</th>
<th>next</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0x148</td>
</tr>
<tr>
<td>0x1c0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0x0</td>
</tr>
<tr>
<td>NULL</td>
<td></td>
</tr>
</tbody>
</table>

data:

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>51</td>
<td>52</td>
<td>53</td>
<td>54</td>
<td>10</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```
Note

• The basics of linked list implementations was taught in CS 103
  – We assume that you already have basic exposure and practice using a class to implement a linked list
  – We will highlight some of the more important concepts
Linked List

- Use structures/classes and pointers to make ‘linked’ data structures
- A linked list is...
  - Arbitrarily sized collection of values
  - Can add any number of new values via dynamic memory allocation
  - Supports typical List ADT operations:
    - Insert
    - Get
    - Remove
    - Size (Should we keep a size data member?)
    - Empty
- Can define a List class to encapsulate the head pointer and operations on the list

```cpp
#include<iostream>
using namespace std;

struct Item {
    int val;
    Item* next;
};

class List {
    public:
        List();
        ~List();
        void push_back(int v); ...
    private:
        Item* head_;
};
```

**Rule of thumb**: Still use ‘structs’ for objects that are purely collections of data and don’t really have operations associated with them. Use ‘classes’ when data does have associated functions/methods.
A Common Misconception

• Important Note:
  – 'head' is NOT an Item, it is a pointer to the first item
  – Sometimes folks get confused and think head is an item and so to get the location of the first item they write 'head->next'
  – In fact, head->next evaluates to the 2\textsuperscript{nd} items address

\[
\begin{array}{c}
\text{head} \\
0x148 \\
\end{array}
\quad
\begin{array}{c}
\text{head->next} \\
0x1c0 \\
\end{array}
\quad
\begin{array}{c}
3 \\
0x1c0 \\
\text{val} \\
\text{next} \\
9 \\
0x168 \\
\text{val} \\
\text{next} \\
2 \\
0x168 \\
\text{val} \\
\text{next (Null)}
\end{array}
\]

head->next yields a pointer to the 2\textsuperscript{nd} item!
head yields a pointer to the 1\textsuperscript{st} item!
Don't Need Classes

- Notice the class on the previous slide had **only 1 data member** (the head pointer)
- We don't have to use classes...
  - The class just acts as a wrapper around the head pointer and the operations
  - So while a class is probably the correct way to go in terms of organizing your code, for today we can show you a less modular, procedural approach
- Define functions for each operation and pass it the head pointer as an argument

```cpp
#include<iostream>
using namespace std;

struct Item {
    int val;
    Item* next;
};

// Function prototypes
void append(Item*& head, int v);
bool empty(Item* head);
int size(Item* head);

int main()
{
    Item* head1 = NULL;
    Item* head2 = NULL;
    int size1 = size(head1);
    bool empty2 = empty(head2);
    append(head1, 4);
}

class List:
    head_

0x0

**Rule of thumb**: Still use ‘structs’ for objects that are purely collections of data and don’t really have operations associated with them. Use ‘classes’ when data does have associated functions/methods.
Linked List Implementation

• To maintain a linked list you need only keep one data value: **head**
  – Like a train engine, we can attach any number of 'cars' to the engine
  – The engine looks different than all the others
    • In our linked list it's just a single pointer to an Item
    • All the cars are Item structs
    • Each car has a hitch for a following car (i.e. next pointer)

```
#include<iostream>

struct Item {
    int val;
    Item* next;
};

void append(Item*& head, int v);

int main()
{
    Item* head1 = NULL;
    Item* head2 = NULL;
}
```

Engine = "head"
Each car = "Item"
Append

- Adding an item (train car) to the back can be split into 2 cases:
  - Case 1: Attaching the car to the engine (i.e. the list is empty and we have to change the head pointer)
    - Changing the head pointer is a special case since we must ensure that change propagates to the caller
  - Case 2: Attaching the car to another car (i.e. the list has other Items already) and so we update the next pointer of an Item

```cpp
#include<iosstream>
using namespace std;
struct Item {
    int val;
    Item* next;
};

void append(Item*& head, int v) {
    if(head == NULL){
        head = new Item;
        head->val = v; head->next = NULL;
    } else {...}
}

int main() {
    Item* head1 = NULL;
    Item* head2 = NULL;
    append(head1, 3);
}
```
Linked List

• Adding an item (train car) to the back can be split into 2 cases:
  – Attaching the car to the engine (i.e. the list is empty and we have to change the head pointer)
  – Attaching the car to another car (i.e. the list has other Items already) and so we update the next pointer of an Item

```cpp
#include <iostream>
using namespace std;

struct Item {
    int val;
    Item* next;
};

void append(Item*& head, int v) {
    if(head == NULL){
        head = new Item;
        head->val = v; head->next = NULL;
    } else {...}
}

int main() {
    Item* head1 = NULL;
    Item* head2 = NULL;
    append(head1,3); append(head1,9);
}
```
Passing Pointers "by-Value"

- Look at how the head parameter is passed...Can you explain it?
  - Append() may need to change the value of head and we want that change to be visible back in the caller.
  - **Even pointers are passed by value**...wait, huh?
  - When one function calls another and passes a pointer, it is the data being pointed to that can be changed by the function and seen by the caller, but the pointer itself is passed by value.
  - You email your friend a URL to a Google doc. The URL is copied when the email is sent but the document being referenced is shared.
  - If we want the pointer to be changed and visible we need to pass the pointer by reference
  - We choose Item*& but we could also pass an Item**

```cpp
void append(Item*& head, int v)
{
    Item* newptr = new Item;
    newptr->val = v; newptr->next = NULL;
    if(head == NULL){
        head = newptr;
    } else {
        Item* temp = head;
        // iterate to the end
        ...
    }
}
```

```cpp
void append(Item** head, int v)
{
    Item* newptr = new Item;
    newptr->val = v; newptr->next = NULL;
    if(*head == NULL){
        *head = newptr;
    } else {
        Item* temp = *head;
        // iterate to the end
        ...
    }
}
```
void append(Item* head, int v)
{
    Item* newptr = new Item;
    newptr->val = v;
    newptr->next = NULL;
    if(head == 0){
        head = newptr;
    }
    else {
        Item* temp = head;
        ...
    }
}

void append(Item* &head, int v)
{
    Item* newptr = new Item;
    newptr->val = v;
    newptr->next = NULL;
    if(head == 0){
        head = newptr;
    }
    else {
        Item* temp = head;
        ...
    }
}

void append(Item** head, int v)
{
    Item* newptr = new Item;
    newptr->val = v;
    newptr->next = NULL;
    if(*head == 0){
        *head = newptr;
    }
    else {
        Item* temp = *head;
        ...
    }
}

int main()
{
    Item* head1 = 0;
    append(head1, 3);
}
Iterating Through a Linked List

- Start from head and iterate to end of list
  - Copy head to a temp pointer (because if we modify head we can never recover where the list started)
  - Use temp pointer to iterate through the list until we find the tail (element with next field = NULL)
  - To take a step we use the line: `temp = temp->next;`
  - Optional: Update old tail item to point at new tail item)

```cpp
void append(Item*& head, int v)
{
    Item* newptr = new Item;
    newptr->val = v; newptr->next = NULL;

    if(head == NULL){
        head = newptr;
    }
    else {
        Item* temp = head;
        // iterate to the end
        ...
    }
}
```

Given only head, we don’t know where the list ends so we have to traverse to find it.
Adding a Tail Pointer

• If in addition to maintaining a head pointer we can also maintain a tail pointer
• A tail pointer saves us from iterating to the end to add a new item
• Need to update the tail pointer when...
  – We add an item to the end
    • Easy, fast!
  – We remove an item from the end
    • ________________
Removal

• To remove the last item, we need to update the 2\textsuperscript{nd} to last item (set it's next pointer to NULL)
• We also need to update the tail pointer
• But this would require us to traverse the full list requiring O(n) time
• ONE SOLUTION: doubly-linked list
Doubly-Linked Lists

- Includes a previous pointer in each item so that we can traverse/iterate backwards or forward
- First item's previous field should be NULL
- Last item's next field should be NULL
- The key to performing operations is updating all the appropriate pointers correctly!
  - Let's practice identifying this.
  - We recommend drawing a picture of a sample data structure before coding each operation

```cpp
#include<iostream>
using namespace std;

struct DLItem {
  int val;
  DLItem* prev;
  DLItem* next;
};

int main() {
  DLItem* head, *tail;
}
```
## Summary of Linked List Implementations

<table>
<thead>
<tr>
<th>Operation vs Implementation for Edges</th>
<th>Push_front</th>
<th>Pop_front</th>
<th>Push_back</th>
<th>Pop_back</th>
<th>Memory Overhead Per Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singly linked-list w/ head ptr ONLY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 pointer (next)</td>
</tr>
<tr>
<td>Singly linked-list w/ head and tail ptr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 pointer (next)</td>
</tr>
<tr>
<td>Doubly linked-list w/ head and tail ptr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 pointers (prev + next)</td>
</tr>
</tbody>
</table>

- What is worst-case runtime of get(i)?
- What is worst-case runtime of insert(i, value)?
- What is worst-case runtime of remove(i)?
Key Ideas for Linked Lists

- A head pointer is all that is needed to maintain a linked list.
- When iterating...
  - Don't lose the head.
  - Given a pointer to an item, taking a step to the next node is accomplished with `ptr = ptr->next`.
  - Carefully consider when to stop: at the end, one before the end, on the desired item, one before the desired item based on what needs to be updated.
- For a singly linked list, use of a tail pointer allows for fast insertion at the end but not removal.
- When writing functions that take (head) pointers to linked lists:
  - Always ensure you check and handle if the pointer is NULL.
  - If the head/pointer will change, consider how to return that new value (or use pass-by-reference).
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</tr>
</thead>
<tbody>
<tr>
<td>Singly linked-list w/ head ptr ONLY</td>
<td>Θ(1)</td>
<td>Θ(1)</td>
<td>Θ(n)</td>
<td>Θ(n)</td>
<td>1 pointer (next)</td>
</tr>
<tr>
<td>Singly linked-list w/ head and tail ptr</td>
<td>Θ(1)</td>
<td>Θ(1)</td>
<td>Θ(1)</td>
<td>Θ(n)</td>
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</tr>
</tbody>
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- What is worst-case runtime of get(i)? Θ(i)
- What is worst-case runtime of insert(i, value)? Θ(i)
- What is worst-case runtime of remove(i)? Θ(i)