Dynamic Memory

Memory Models and new/delete

Use `new` to create an object on the heap and get its address (`new` evaluates to the address of the newly-created object). Use `delete` on a heap object's address to deallocate it and free up memory.

ℹ Using `delete` on a `nullptr` does nothing.

Object Lifetimes/Creation Revisited:

- A dynamic object's lifetime begins when it's created via `new`, and its lifetime ends (and its dtor is called) only when you use `delete` on its address.
- Static objects (e.g. static variables in classes/functions, global variables) live until a program ends.
- Local objects are destroyed when their scope ends.

ℹ Array elements are constructed left-to-right and are destroyed in the reverse order. Class members are initialized in order of declaration in the class body.

```
struct X {⋯}; class Y {⋯};

new int; // does nothing (atomic type)

// Calling default ctor with new:
new Y; // calls default ctor
Y* ptr3 = new Y{}; // ditto
Y* ptr4 = new Y(); // Only works w/ new

// value initialization
int* ptr1 = new int(); // *ptr1 == 0
int* ptr2 = new int{}; // *ptr2 == 0

// direct initialization
int* ptr_d = new int(3);
X* ptr5 = new X{3}; // {} for struct
Y* ptr6 = new Y{3}; // {}, () for class
Y* ptr7 = new Y(3); // invokes Y ctor
```

ℹ In this example, every line where `new` is used causes a memory leak since we didn't `delete` any of the heap objects at the end.

Dynamic arrays are created with `new` (which yields a pointer to its first element) and deleted by using `delete[]` *on the address of its first element*. (Note that you can't delete individual elements.)

```
int N = 0;
cin >> N; // get num. elements from user
int* arr = new int[N]; // create size N array
arr[0] = 42; // sets arr's first element to 42
delete[] arr; // deletes entire dynamic array
```

ℹ While dynamic arrays are still fixed-size, they're allowed to have their sizes initialized at runtime, unlike non-dynamic arrays (which must have compile-time constant sizes).

❗ Deleting a dynamic array through a pointer with different static/dynamic types causes U.B.

Memory Management Errors

The following mistakes cause undefined behavior:

1. ***Use-after-free***: dereferencing a pointer after using `delete` on it (`delete` doesn't kill the pointer itself).
2. ***Bad delete***: Using `delete` on a dynamic array or non-dynamic object, or using `delete[]` on anything other than the address of a dynamic array's first element.
3. ***Double free***: Using `delete` on an address twice.

Forgetting to `delete` a heap object causes a **memory leak**, essentially "wasted" memory. Memory leaks are often caused by losing a dynamic object's address.

```
int* func(int x) {
  int *y = new int(x);
  y = new int[x]; // Orphaned mem.
  return y;
}  // This function leaks memory

int main() {
  int *a = func(5);
  int *b = a;
  delete b; // Wrong delete
  delete[] a; // double delete
  cout << a[2]; // use-after-free
} // We still have a memory leak...
```

RAII (Resource Aquisition Is Initialization)

RAII (or *scope-bound resource management*) is a strategy to prevent memory leaks by wrapping a dynamic object in a class. To create an RAII class:

1. Make the class's ctor allocate a dynamic object
2. Keep track of the object via a `private` pointer.
3. Make the class's dtor deallocate the object

This ties a dynamic object's lifetime to the scope of the non-dynamic class object that "holds" it.

```
template <typename T>
class UnsortedSet {
private:
  T *arr; // ptr to underlying array
  int cap; // array's size limit
  int N; // current size of array
public:
  UnsortedSet() // ctor allocates arr
    : arr(new T[10]), cap(50), N(0) { }
  ~UnsortedSet() { delete[] arr; }
}; // dtor deallocates arr
```

⚠ The destructor for an RAII container only cleans up resources allocated by the container, not the memory allocated by dynamic objects that were stored in the container.

Deep Copies and the Big Three

Shallow and Deep Copies

A ***deep copy*** of a class-type object is a copy whose pointer/reference data members are not shared with the original object's. A ***shallow copy***'s data members are "shared" with the original object's. E.g. if you create a shallow copy of an `UnsortedSet`, both objects will have pointers to the *same* dynamic array. The concept only applies to classes that have "owning" pointers/references.

Copy constructor: a constructor that takes a reference to an existing object (*not* a value) as an argument and uses it to initialize a new object of the same type. In general, they're called whenever an object is initialized (either via direct or copy initialization) from another object of the same type.

```
class Foo {⋯}; Foo f1;
Foo f2 = f1; // implicitly calls copy ctor
Foo f3(f1); // calls copy ctor
Foo f4 = { f1 }; // ditto
```

```
Foo* f5 = new Foo(f1); // ditto
try { throw f1; } // ditto (throw-by-value)
catch (Foo f6) { } // ditto (catch-by-value)
Foo arr[3] = {f1, f1, f1}; // 3 calls to copy ctor
```

ℹ A class can have multiple copy constructors, e.g. two copy ctors with different `const` qualification.

The default copy constructor and the default assignment `=` operator simply perform member-by-member copying of the original object, which creates a shallow copy. To avoid memory errors, you must implement custom versions of them for classes that have pointers to dynamic resources.

Ex: Copy Ctor Implementation

```
class IntSet { ⋯
// 1. Initialize copy's stack members
  IntSet(const IntSet& og)
    : cap(og.cap), N(og.size()) {
// 2. Create a new, separate dynamic array
    arr = new int[og.size()];
    for (int i = 0; i < og.size(); ++i) {
      arr[i] = og.arr[i];
    } // 3. Copy elements to new array
  }
};
```

Ex: Assignment Operator Overload

```
IntSet& operator=(const IntSet& og) {
  if (this == &og) { return *this; }
  delete[] this->elts;
  this->cap = og.cap;
  this->N = og.size();
  this->elts = new int[og.size()];
  for (int i = 0; i < og.size(); ++i) {
    this->elts[i] = og.elts[i];
  }
  return *this;
}
```

Destructors and Polymorphism (Virtual Destructors)

If you try to delete a derived-class object by calling `delete` on a base-class pointer to the object, the base class needs to have a `virtual` destructor defined or else undefined behavior will occur. Since the compiler-generated default destructor is not `virtual`, you must define a custom virtual destructor for polymorphic classes (i.e., classes that make use of inheritance).

⚠ If you call `delete` on an object whose static type and dynamic type are different, the static type must be a base class of the dynamic type (or U.B. will occur even with a `virtual` destructor).

ℹ You can prevent derived class objects from being deleted through base-class pointers by declaring the base class destructor `protected` and non-virtual.

The Rule of Three

The Big Three: a class's destructor, copy constructor, and assignment operator.

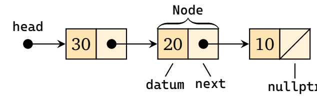
Rule of Three: a class that needs a custom version of one of the Big Three usually needs custom versions of the other two (generally, this describes classes that manage dynamic memory).

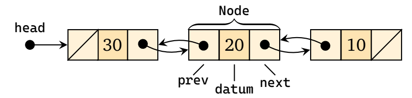
ℹ Not all classes with pointer data members need the Big Three. Ex: Linked List iterators store internal `Node*` pointers, but they don't need the Big Three because the List dtor is responsible for managing the nodes. Generally, classes that have "owning" pointers/references need the Big Three.

Linked Lists

The Linked List Interface (Single and Double)

A ***linked list*** is a container that stores its elements non-contiguously in memory; its elements are represented as distinct "nodes" that are linked together via pointers. If nodes are linked in one direction, the list is singly-linked, and if nodes are linked in both directions, the list is doubly-linked.





Iterators for a linked list store an internal pointer to a `Node`, so when you dereference a list iterator, it's the same as applying `->` to a Node pointer.

ℹ Since there's no need to maintain contiguity, inserting/removing nodes from a list is $\Theta(1)$ at any position, as the only adjustment you need to make is re-pointing the previous node's `next` pointer (and the following node's `prev` pointer in a doubly-linked list) instead of shifting every element. This does mean lists have $O(n)$ instead of $O(1)$ indexing, though.

Linked List Operations

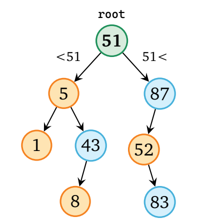
Binary Search Trees and Maps

Binary Search Trees

A *binary tree* is a tree data structure where each *node* points to at most 2 children. A ***binary search tree*** is a binary tree where, for any given node, each node in its left subtree has a lower value and each node in its right subtree has a greater value (an empty tree is also a BST).

A ***leaf*** of a BST is a childless node. A BST's ***size*** is the number of nodes it has, and its ***height*** is the maximum distance from the root to a leaf.

A BST is ***balanced*** if the heights of the left and right subtrees at any node differ by at most 1, so the height of a balanced BST is $O(\log n)$.



Binary Tree Traversal

There are multiple ways to traverse a binary tree:

1. ***In-order traversal***: recursively process the *left* subtree, then process the *head* (current) node, then recursively process the *right* subtree.
2. ***Pre-order traversal***: process the *head*, then recursively process the *left* subtree, then recursively process the *right* subtree.
3. ***Post-order traversal***: recursively process the *left* subtree, then recursively process the *right* subtree, then process the *head*.

ℹ In-order traversal of a BST visits nodes in order of ascending value.

In-order Traversal (LPR)

1	5	8	43	51	52	83	87

Pre-order Traversal (PLR)

51	5	1	43	8	87	52	83

Post-order Traversal (LRP)

1	8	43	5	83	52	87	51

```
void preOrder(Node* p) {
  if (!p) return;
  cout << (p->val) << '\n';
  preOrder(p->left);
  preOrder(p->right);
} // preorder traversal
```

```
void inOrder(Node* p) {
  if (!p) return;
  inOrder(p->left);
  cout << (p->val) << '\n';
  inOrder(p->right);
} // inorder traversal
```

```
void postOrder(Node* p) {
  if (!p) return;
  postOrder(p->left);
  postOrder(p->right);
  cout << (p->val) << '\n';
} // postorder traversal
```

Recursive Big Three

Operations on BSTs vs Sorted/Unsorted Sets

Search: due to the sorting invariant, searching a balanced BST for a value takes $O(\log n)$ $\Theta(\log n)$ time.

Binary Search with Recursion

```
template <typename Iter_T, typename T>
int binarySearch(Iter_T left, Iter_T right, const T& val) {
  int size = (right - left);
  if (size <= 0) return -1;
  Iter_T mid = left + (size / 2);
  if (*mid == val) return (mid - left);
  if (*mid > val) return binarySearch(left, mid, val);
  return binarySearch(mid + 1, right, val);
} // eliminates half the search space each loop
```

ℹ `std::map` and `std::set` are implemented using *self-balancing* binary search trees, which is how they maintain $O(\log n)$ insertion, removal, and searching. (This is why it's more efficient to search a map for a value with `.find()` or `operator[]` instead of iterating through elements).

Recursion

Properties and Types of Recursion

Recursive functions are functions defined in terms of themselves (i.e., that call themselves). They're defined in terms of **base cases**, problems small enough to solve without recursing, and **recursive cases**, which the function breaks down and passes to itself until they're reduced to base cases.

There are three types of recursive functions:

1. ***Linear recursive***: functions that make at most one call to themselves per invocation.
2. ***Tail recursive***: a linear recursive function where the recursive call (if made) is the last instruction.
3. ***Tree recursive***: a function that can call itself multiple times in the same stack frame.

Linear Recursion (Non-Tail)

```
Node* reverseList(Node* head) {
  if (!head || !head->next) return head;
  Node* new_head = reverseList(head->next);
  head->next->next = head;
  head->next = nullptr;
  return new_head;
}
```

Tail Recursion

```
int func( int x, int y ) {
  if (x <= 0 || y < 0 ) return 1;
  else if (x > y) return func(x - y, y);
  else return func(x, y - x);
}
```

Tree Recursion

```
bool SameTree(TreeNode* p,TreeNode* q) {
  if (!p || !q) {return (!p == !q);}
  if (p->val != q->val) {return false;}
  return SameTree(p->L, q->L)
         && SameTree(p->R, q->R);
} // check if two trees are identical
```

```
void func(int n) { // makes (2^n) - 1 calls
  for (int i = 0; i < n; ++i) func(i);
} // Yes, this is actually tree-recursive
```

⚠ A recursive call being on the last line or in the return statement does NOT itself guarantee that the function is tail recursive—the recursive call must be the last *instruction* executed by the function.

⚠ If you see multiple recursive calls separated by `if-else` branches, treat them as one recursive call when classifying the recursion type (because only one branch can execute per invocation).

```
int factorial(int n) {
  return (n <= 1) ? 1 : n * factorial(n - 1);
} /* This is NOT tail-recursive because the last instruction the function executes is
     multiplying the recursive result by n, not the recursive call itself. */
```

Memory Usage of Recursive Functions

Non-tail linear recursive functions allocate an additional stack frame with each recursive call. However, the compiler can optimize a tail recursive function to reuse the same stack frame, which means that tail-recursive functions can be optimized to use a constant number of stack frames.

⚠ The total number of recursive calls a function makes to itself does not indicate its space complexity, since not all stack frames have to exist at the same time. Instead, look at the number of return statements until the base case. For example, a recursive algorithm to traverse a balanced BST of height h uses a maximum of $O(h)$ space—not $O(2^h)$ space—at any given time.

Structural Recursion

Structural recursion is when an abstract data type is defined in terms of itself. The `Node` structs of a linked list are one example: each `Node` contains a pointer to another `Node`. Recursive structures have base cases and recursive cases just like recursive functions do: for a linked list, the "base case" is an empty list, and the recursive cases are non-empty lists.

Recursion vs Iteration (and Converting Between Them)

Iterators and Functors

Iterators are a type of object that are designed to emulate the interface of a pointer. They provide a unified way to access the elements of containers with different underlying implementations. Since iterators are specific to their container, they're usually defined as nested classes of their container.

Iterators don't need the Big Three because their role isn't to manage memory (the container should do that). They need to at least have the dereference `*`, prefix `++`, and `!=`/`==` operators overloaded.

Functors (function objects): *first-class* entities that provide the same interface as a function. They can be created from classes that overload the function-call operator, i.e., `operator()`.

ℹ First-class entities can *store state* (store and access information), be created at runtime, and be passed as an argument to/returned by a function.

ℹ `operator()` can only be overloaded from within a class body. It and `operator[]` are also the only operators that can be overloaded as `static` member functions.

Function Pointers

	`std::sort(it1,it2)`	`it2 - it1`	`it[n]`	`it += n`	`it1 < it2`	`--it`	`++it`	`it1 == it2`	`*it`
Random Access	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes
Bidirectional	✖ No	✖ No	✖ No	✖ No	✖ No	✔ Yes	✔ Yes	✔ Yes	✔ Yes
Forward	✖ No	✖ No	✖ No	✖ No	✖ No	✖ No	✔ Yes	✔ Yes	✔ Yes

Iterator	`array<T,N>::iterator`	`vector<T>::iterator`	`list<T>::iterator`	`map<Key,T>::iterator`	`set<Key>::iterator`
Iterator Class	Random Access	Random Access	Bidirectional	Bidirectional	Bidirectional
Container Resizing	N/A	All iterators invalidated	Dynamic	Empty container	Linked
Insertion	Sequential	Iterators at/above point of insertion are invalididated	Unaffected	Unaffected	Unaffected
Erasure	Sequential	Iterators at/above point of erasure are invalididated	Dynamic	Empty container	Linked

Friend Classes/Functions

If a class `A` declares class `B` as a `friend`, that will make `A`'s private/protected data members accessible to `B` (but `B`'s private members won't become accessible to `A` that). You can also declare a non-member function as a `friend` to give it access to a class's private/protected member variables.

A `friend` function (or operator) needs to be declared as a `friend` inside of the class it's befriending, and it has to be declared before the friend declaration.

```
friend class F;
friend F; // access specifiers don't affect friend declarations
{
```

ℹ Friendships are neither inheritable nor transitive (a friend of a friend is not a friend).

ℹ If you declare an unqualified function or class as a `friend` inside of a local class, name lookup doesn't go beyond the innermost scope outside of the class you're declaring the friendship in.

ℹ A friend class can access virtual (and only virtual) functions of its friend's derived classes.

Error Handling and Exceptions

C++ exceptions separate error detection from error handling and provide a separate control flow for automatic error handling. They do this by transferring control of the program to **handler** functions.

To catch an exception, enclose a portion of potentially buggy code in a `try`-`catch` **block**. If the code inside of a `try` block `throw`s an ***exception*** (an object that signifies an error) when it's run, execution of the program will pause and all code will be skipped until the error is handled by a `catch` block (an *object* is "thrown" and is "caught" by a `catch` block.

ℹ An unhandled exception causes a program crash (i.e., termination of the program) at runtime.

ℹ A `try` block can have multiple `catch` blocks (e.g. with different parameters) associated with it.

Don't throw exception objects by reference.

C++ Stuff and Impostor Syndrome

Impostor syndrome is characterized by doubt in one's abilities that aren't backed up by evidence and an inability to recognize/take credit for one's achievements. These feelings are common and can affect anyone, although people from underrepresented groups may be more susceptible to it.

A ***static member function*** does *not* have access to the `this` pointer and also can't access non-`static` data members (reminder: `static` members are "shared" between all instances of a class).

Templates and function overloading are forms of ***compile-time polymorphism***, while subtype polymorphism is a form of ***runtime polymorphism***.

Container ADTs

`static` keyword: used to make one copy of a class data member "shared" between all instances of that class. A `static` data member has static storage duration but exists only within the scope of a class.

stack: a container that's designed to operate in a LIFO order.

queue: a container designed to operate in a first-in/first-out (FIFO) order.

Container	Interface Operations - Optimal Implementations are All O(1)					
Stack	`empty`	`size`	`top (next to pop)`		`push_back`	`pop_back`
Queue	`empty`	`size`	`front (next)`	`back (last)`	`push_back`	`pop_front`

ℹ An efficient way to implement a queue is to create a vector with free space at both ends (a **ring/circular buffer**). This requires keeping track of the data's "head" (inclusive) and "tail" (exclusive).

Useful `std::vector` Functions and Constructors				
`.size()`	`v[i]/.at(i)`	`.push_back(val)`	`.pop_back()`	`.resize(n)`
`.front()`	`.back()`	`.erase(iterator)`	`.empty()`	`.clear()`
`vector<T> v2(v1.begin(), v1.end())`			`vector<T> v2(v1)`	

* These refer to the array-based sets we saw in class, *not* STL sets.

C++ Standard Library Containers

`std::array`: Containers with *compile-time constant* sizes that store elements in contiguous memory.

`std::vector`: resizable containers that store elements at the front and free space at the back.

⚠ Element insertions/deletions will invalidate `std::vector` iterators *at and after* the modified index. Also, any operation that changes the maximum capacity of a vector invalidates all existing iterators.

`std::list`: a container whose elements are linked via pointers (i.e., in non-contiguous memory).

`std::map`: an associative array that maps unique keys to values. Keys act like indexes for a map.

`std::set`: an associative sorted container that only stores unique keys.

ℹ Removing an element from a `std::list`, `std::set`, or `std::map` only invalidates iterators to the removed element. Also, inserting an element doesn't ever invalidate iterators for those containers.

C++ Standard Library Containers

```
std::array<int, 4> arr = {-4,0,3,6};
std::array arr2{1, 2}; // Only way to omit
    size
std::list<int> doubly_linked = {1,2,3};
std::forward_list<int> singly_linked = {4,5,6
    };
std::set<int> nums = {3,2,2,1}; // {1,2,3}
std::map<string, int> EECS = { {"Bill", 183}
    };
cout << EECS["Bill"] << endl; // prints 183
// Two ways to insert into a map:
EECS["Emily"] = 203;
EECS.insert(pair<string, int>("James", 280));
```

Useful `std::map` functions

```
// Returns iterator to the pair with Key == k
// Returns .end() iterator if no such pair
    exists
iterator find(const Key_type& k) const;
// Inserts a <key, value> std::pair into a map
// Returns <iterator, false> if Key already in
    use
pair<iterator,bool> insert(const Pair_type&
    pair);
/* Finds or enters a value for a given key,
    then
returns a reference to the associated value */
Value_type& operator[](const Key_type& key);
```

Templates (Parametric Polymorphism)

Templates: special functions that take a data type as a parameter at compile time and instantiate an object or function compatible with that type. They help reduce code duplication in container interfaces.

Class Template Syntax

```
template <typename T>
class UnsortedSet {
public:
  void insert(T my_val);
  bool contains(T my_val) const;
  int size() const;
private:
  T elts[ELTS_CAPACITY];
  int elts_size;
  ...
}; // Syntax: UnsortedSet<type> s;
```

Function Template Syntax

```
// Note: "class" also works in place of "typename"
template <typename T> // "T" is also an arbitrary name
T maxValue(const T &valA, const T &valB) {
  return (valB > valA) ? valB : valA;
} // This function returns the greater of valA and valB
// Syntax to call it: maxValue<int/double/etc>(...);
```

Templated Class Member Function Syntax

```
template <typename T> // Necessary if outside class body
void UnsortedSet<T>::insert(T my_val) {···}
```

Iterators, Traversal by Iterator and Range-Based Loops

Iterators: objects that have the same interface as pointers; they provide a general interface for traversing and accessing the elements of different types of containers. Note that each container's iterator has its own invalidation conditions (and that using an invalidated iterator causes undefined behavior).

ℹ `std::begin()` returns an iterator to the start of an STL container. `std::end()` returns an iterator that's *1 past* the end of an STL container (the iterator returned by `std::end()` should not be dereferenced).

	`std::sort(it1,it2)`	`it2 - it1`	`it[n]`	`it += n`	`<,<=`	`--`	`++`	`==, !=`	`*it`
Random Access Iterators	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes	✔ Yes
Bidirectional Iterators	✖ No	✖ No	✖ No	✖ No	✖ No	✔ Yes	✔ Yes	✔ Yes	✔ Yes
Forward Iterators	✖ No	✖ No	✖ No	✖ No	✖ No	✖ No	✔ Yes	✔ Yes	✔ Yes

Traversal by iterator: a more general form of traversing a container data type by pointer.

```
vector<int> v(3, -1); // this syntax initializes v to
    {-1,-1,-1}
for (vector<int>::iterator it = v.begin(); it != v.end(); ++it)
  { cout << *it << endl; } // ::const_iterator if const vector
```

Range-Based For Loop (Works on Any Sequence Traversible by Iterator)

```
vector<int> v = { 1, 2, 3, 4 };
// for (<type> <variable> : <sequence>) {...}
for (int item : v) { // works with arrays too
  cout << item << endl;
} // could also declare item as const or a ref
```

```
// Compiler translation of range-based for
    loop
for (auto it = v.begin(); it != v.end(); ++it)
    {
  int item = *it;
  cout << item << endl;
} // auto keyword makes compiler deduce type
```