

CSC 212: Data Structures and Abstractions

06: Dynamic Arrays

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C/C++ memory model

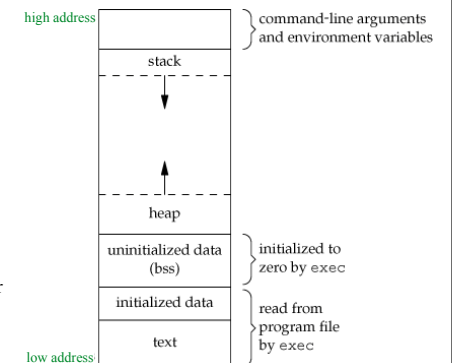
Memory model

- What is the C/C++ memory model?
 - ✓ a formal specification that defines how programs interact with memory at a high level, ensuring safe and predictable behavior
 - implementation details are delegated to the compiler and CPU architecture
 - ✓ the memory model establishes a "contract" between programmer and compiler
- Memory Layout
 - ✓ memory is divided into multiple segments
 - ✓ each segment serves a specific purpose and has different properties

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Memory layout

- Text Segment (code)
 - ✓ contains **instructions** generated by the compiler
 - ✓ marked as **read-only** to prevent accidental modification
- Data Segment (global/static variables)
 - ✓ contains multiple subsections (e.g. initialized data, uninitialized data, constant data)
 - ✓ size determined at compilation, addresses resolved during linking
- Heap
 - ✓ dedicated to **dynamic memory allocation**
 - ✓ requires explicit management by the programmer
- Stack (function calls, local variables)
 - ✓ implements last-in-first-out (LIFO) for function calls and local variables
 - ✓ no explicit deallocation required



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```
#include <iostream>
// global variable
float pi = 3.1416;
// constant global variable
const int min = 100;
// uninitialized global variable
int sum;
```

```
void foo(int arg) {
    // local variable
    int i = 1;
    std::cout << "address of arg\t" << &arg << std::endl;
    std::cout << "address of i\t" << &i << std::endl;
}

int main() {
    // heap variable
    int *A = new int[10];

    std::cout << "address of pi\t" << &pi << std::endl;
    std::cout << "address of min\t" << &min << std::endl;
    std::cout << "address of sum\t" << &sum << std::endl;
    std::cout << "value of A\t" << A << std::endl;
    std::cout << "address of A\t" << &A << std::endl;
    std::cout << "address of main\t" << (void*) &main << std::endl;
    std::cout << "address of foo\t" << (void*) &foo << std::endl;
    foo(5);

    delete [] A;

    return 0;
}
```

`./prog | sort -k 4`

```
address of foo 0x105499fc0
address of main 0x10549a0f0
address of min 0x10549af48
address of pi 0x10549c000
address of sum 0x10549c004
value of A 0x7fd29f705e90
address of i 0x7ff7baa66438
address of arg 0x7ff7baa6643c
address of A 0x7ff7baa66460
```

NOTE: leading zeros are ignored (64-bit addresses)

Can you tell what are the memory locations grouped by different colors?

What happens if you run the program multiple times?

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Dynamic arrays

C-style arrays

Contiguous sequence of elements of identical type

random access: $\text{base_address} + \text{index} * \text{sizeof}(\text{type})$

| 0 | 1 | 2 | 3 | | n-1 |
|------|------|------|------|-----|--------|
| A[0] | A[1] | A[2] | A[3] | ... | A[n-1] |

array name: A

array length: n

Statically allocated arrays

allocated in the stack (fixed-length), size known at compile time

Dynamic allocated arrays

allocated in the heap (fixed-length), size may be determined at runtime

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Dynamic arrays

Limitations of C-style arrays

- size must be known at compile time or use dynamic memory allocation — once created the array size does not change
- provide $\Theta(1)$ read/write cost, but inflexible

Dynamic arrays

- can **grow or shrink in size** during runtime
 - essential for many applications, for example, a server keeping track of a queue of requests
- combine the flexibility of dynamic memory allocation with the efficiency of fixed-length arrays
- e.g. `std::vector` in C++, `ArrayList` in Java, `List` in Python, `Array` in JavaScript, `List` in C#, `Vec` in Rust, etc.

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Dynamic array class in C++

```
class DynamicArray {
private:
    int *arr;           // pointer to the (internal) array
    int capacity;       // total number of elements that can be stored
    int size;           // number of elements currently stored

public:
    DynamicArray();      // constructor
    ~DynamicArray();     // destructor
    void push_back(int val); // add an element to the end
    void pop_back();     // remove the last element
    const int& operator[](int idx) const; // read-only access at a specific index
    int& operator[](int idx); // access at a specific index (can modify)
    void insert(int val, int idx); // insert an element at a specific index
    void erase(int idx); // remove an element at a specific index
    void resize(int len); // change the capacity of the array
    int size();          // return the number of elements
    int capacity();      // return the capacity
    bool empty();        // check if the array is empty
    void clear();        // remove all elements, maintaining the capacity

    // additional methods can be added here
};
```

A class definition specifies the **data members** and **member functions** of the class. The data members are the attributes of the class, and the member functions are the operations that can be performed on the data members. The class definition is a blueprint for creating objects of the class.

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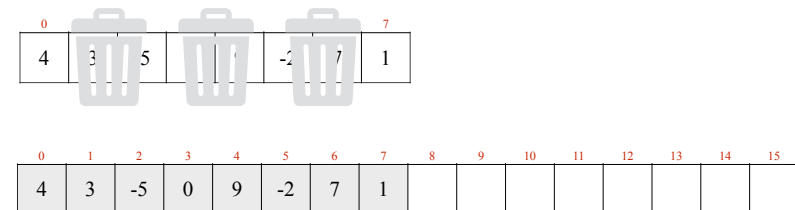
Resizing dynamic arrays

• Grow

- when the array is full (**size == capacity**), allocate a new array with increased capacity, copy elements from old to new array, deallocate old array

• Shrink

- optional optimization, used when the number of elements is "significantly" less than the capacity, allocate a new array with decreased capacity, copy the elements from old to new array, and deallocate the old array



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Grow by one

• When array is full, new capacity: **current + 1**

- starting from an empty array, **count number of array accesses (reads and writes)** for adding n elements (ignore cost of allocating/deallocating memory)

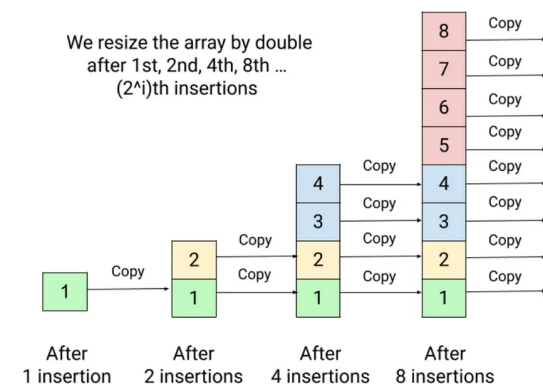
| n | copy | append |
|-----|-------|--------|
| 1 | 2 x 0 | 1 |
| 2 | 2 x 1 | 1 |
| 3 | 2 x 2 | 1 |
| 4 | | |
| 5 | | |
| 6 | | |
| | | |
| n-1 | | |
| n | | |

$$\begin{aligned}
 T(n) &= n + \sum_{i=0}^{n-1} 2i \\
 &= n + 2 \left(\frac{n(n-1)}{2} \right) \\
 &= \Theta(n^2) \quad \text{cost of adding } n \text{ elements}
 \end{aligned}$$

The amortized cost of inserting an element is $\Theta(n)$, meaning that any sequence of n insertions takes at most $\Theta(n^2)$ time in total.

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Repeated doubling



<https://itsfuad.medium.com/how-dynamic-arrays-actually-work-bff5bb5749bb>

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Grow by factor

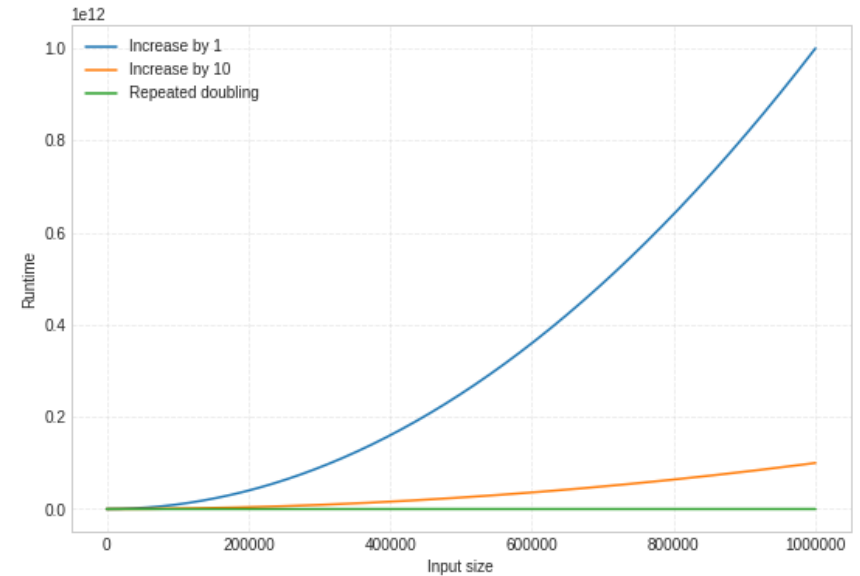
- When array is full, new capacity: $\text{current} * \text{factor}$
 - called **repeated doubling** when $\text{factor} == 2$
 - starting from an empty array, **count number of array accesses** (reads and writes) for adding n elements — assume n is a power of 2 (ignore cost of allocating/deallocating memory)

| n | copy | append |
|-----|-------|--------|
| 1 | 0 | 1 |
| 2 | 2 * 1 | 1 |
| 3 | 2 * 2 | 1 |
| 4 | 0 | 1 |
| 5 | 2 * 4 | 1 |
| 6 | 0 | 1 |
| 7 | 0 | 1 |
| 8 | 0 | 1 |
| 9 | 2 * 8 | 1 |
| 10 | 0 | 1 |
| | | |
| n-1 | | |
| n | | |

$$\begin{aligned}
 T(n) &= n + 2 \sum_{i=0}^{\log n - 1} 2^i \\
 &= n + 2(2^{\log n} - 1) \\
 &= n + 2n - 2 \\
 &= \Theta(n) \leftarrow \text{cost of adding } n \text{ elements}
 \end{aligned}$$

The amortized cost of inserting an element is $\Theta(1)$, meaning that any sequence of n insertions takes at most $\Theta(n)$ time in total.

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Shrinking the array

- May half the capacity when array is **one-half** full
 - worst-case** when the array is full and we alternate between adding and removing elements
 - each alternating operation would require resizing the array
- More efficient resizing
 - half the capacity when the array is **one-quarter** full
- In practice ...
 - most standard implementations do not automatically shrink capacity
 - avoids performance penalties from frequent resizing
 - instead, they provide explicit operations like `shrink_to_fit()` that allow the programmer to request size reduction when deemed necessary

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Live coding ...

- Complete the implementation of the `DynamicArray` class:

```

class DynamicArray {
private:
    int *arr;                // pointer to the (internal) array
    size_t capacity;         // total number of elements that can be stored
    size_t size;             // number of elements currently stored
    float growth_rate;       // growth rate

public:
    DynamicArray(float growth_rate); // constructor
    ~DynamicArray();                // destructor
    void push_back(int val);        // add an element to the end
    void pop_back();               // remove the last element
    const int& operator[](size_t idx) const; // read-only access at a specific index
    int& operator[](size_t idx);    // access at a specific index (can modify)
    void insert(int val, size_t idx); // insert an element at a specific index
    void erase(int uidx);           // remove an element at a specific index
    void resize(int ulen);         // change the capacity of the array
    size_t get_size();             // return the number of elements
    size_t get_capacity();         // return the capacity
    bool empty();                 // check if the array is empty
    void clear();                 // remove all elements, maintaining the capacity

    // additional methods can be added here
};
    
```

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References in C++

non-const References

```
int i = 2;
int& ri = i; // reference to i
```

ri and i refer to the same object / memory location:

```
cout << i << '\n'; // 2
cout << ri << '\n'; // 2
```

```
i = 5;
cout << i << '\n'; // 5
cout << ri << '\n'; // 5
```

```
ri = 88;
cout << i << '\n'; // 88
cout << ri << '\n'; // 88
```

- references cannot be "null", i.e., they must always refer to an object
- a reference must always refer to the same memory location
- reference type must agree with the type of the referenced object

```
int i = 2;
int k = 3;
int& ri = i; // reference to i
ri = k; // assigns value of k to i (target of ri)
int& r2; // * COMPILER ERROR: reference must be initialized
double& r3 = i; // * COMPILER ERROR: types must agree
```

<https://hackingcpp.com/cpp/lang/references.html>

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Growth factors by language

• C++ (`std::vector`)

- ✓ grow by 1.5 times the current capacity
- ✓ shrink when the array is one-quarter full

• Java (`ArrayList`)

- ✓ grow by 1.5 of the current capacity
- ✓ shrink when the array is one-half full

• Python (`list`)

- ✓ grow by 1.125 times the current capacity
- ✓ shrink when the array is one-quarter full

• Rust (`std::vec::Vec`)

- ✓ grow by 2 times the current capacity
- ✓ shrink when the array is one-half full

Information taken
from `claude.ai`
(to be confirmed)

bottom line: growth factors range from
~1.2 to ~2 depending on language used

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Practice

- Complete the following table with rates of growth using Θ notation
 - ✓ assume we implement a dynamic array with repeated doubling and no shrinking

| Operation | Best case | Average case | Worst case |
|-------------------------------------|-----------|--------------|------------|
| Append 1 element | | | |
| Remove 1 element from the end | | | |
| Insert 1 element at index idx | | | |
| Remove 1 element from index idx | | | |
| Read element from index idx | | | |
| Write (update) element at index idx | | | |

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Dynamic arrays in the STL (C++)

std::vector

Defined in header `<vector>`

```
template<
    class T,
    class Allocator = std::allocator<T>
> class vector;                                     (1)

namespace pmr {
    template< class T >
        using vector = std::vector<T, std::pmr::polymorphic_allocator<T>>;    (2) (since C++17)
}
```

- 1) std::vector is a sequence container that encapsulates dynamic size arrays.
- 2) std::pmr::vector is an alias template that uses a [polymorphic allocator](#).

The elements are stored contiguously, which means that elements can be accessed not only through iterators, but also using offsets to regular pointers to elements. This means that a pointer to an element of a vector may be passed to any function that expects a pointer to an element of an array.

The storage of the vector is handled automatically, being expanded as needed. Vectors usually occupy more space than static arrays, because more memory is allocated to handle future growth. This way a vector does not need to reallocate each time an element is inserted, but only when the additional memory is exhausted. The total amount of allocated memory can be queried using [capacity\(\)](#) function. Extra memory can be returned to the system via a call to [shrink_to_fit\(\)](#)^[1].

Reallocations are usually costly operations in terms of performance. The [reserve\(\)](#) function can be used to eliminate reallocations if the number of elements is known beforehand.

The complexity (efficiency) of common operations on vectors is as follows:

- Random access - constant $O(1)$.
- Insertion or removal of elements at the end - amortized constant $O(1)$.
- Insertion or removal of elements - linear in the distance to the end of the vector $O(n)$.

std::vector (for T other than `bool`) meets the requirements of [Container](#), [AllocatorAwareContainer](#) (since C++11), [SequenceContainer](#), [ContiguousContainer](#) (since C++17) and [ReversibleContainer](#).

<https://en.cppreference.com/w/cpp/container/vector>

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Member functions

| | |
|----------------------|--|
| (constructor) | constructs the vector (public member function) |
| (destructor) | destructs the vector (public member function) |
| operator= | assigns values to the container (public member function) |
| assign | assigns values to the container (public member function) |
| assign_range (C++23) | assigns a range of values to the container (public member function) |
| get_allocator | returns the associated allocator (public member function) |
| Element access | |
| at | access specified element with bounds checking (public member function) |
| operator[] | access specified element (public member function) |
| front | access the first element (public member function) |
| back | access the last element (public member function) |
| data | direct access to the underlying contiguous storage (public member function) |
| Iterators | |
| begin | returns an iterator to the beginning (public member function) |
| cbegin (C++11) | returns an iterator to the beginning (public member function) |
| end | returns an iterator to the end (public member function) |
| cend (C++11) | returns an iterator to the end (public member function) |
| rbegin | returns a reverse iterator to the beginning (public member function) |
| crbegin (C++11) | returns a reverse iterator to the beginning (public member function) |
| rend | returns a reverse iterator to the end (public member function) |
| crend (C++11) | returns a reverse iterator to the end (public member function) |

| | |
|----------------------|--|
| Capacity | |
| empty | checks whether the container is empty (public member function) |
| size | returns the number of elements (public member function) |
| max_size | returns the maximum possible number of elements (public member function) |
| reserve | reserves storage (public member function) |
| capacity | returns the number of elements that can be held in currently allocated storage (public member function) |
| shrink_to_fit (DR7) | reduces memory usage by freeing unused memory (public member function) |
| Modifiers | |
| clear | clears the contents (public member function) |
| insert | inserts elements (public member function) |
| insert_range (C++23) | inserts a range of elements (public member function) |
| emplace (C++11) | constructs element in-place (public member function) |
| erase | erases elements (public member function) |
| push_back | adds an element to the end (public member function) |
| emplace_back (C++11) | constructs an element in-place at the end (public member function) |
| append_range (C++23) | adds a range of elements to the end (public member function) |
| pop_back | removes the last element (public member function) |
| resize | changes the number of elements stored (public member function) |
| swap | swaps the contents (public member function) |

<https://en.cppreference.com/w/cpp/container/vector>

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std::vector

```
#include <iostream>
#include <vector>

int main()
{
    // create a vector containing integers
    std::vector<int> v = {8, 4, 5, 9};

    // add two more integers to vector
    v.push_back(6);
    v.push_back(9);

    // overwrite element at position 2
    v[2] = -1;

    // print out the vector
    for (int n : v)
        std::cout << n << ' ';
    std::cout << '\n';
}
```

<https://en.cppreference.com/w/cpp/container/vector>

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