CSC 212: Data Structures and Abstractions

Dynamic Arrays

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THINK BIG WE DO℠

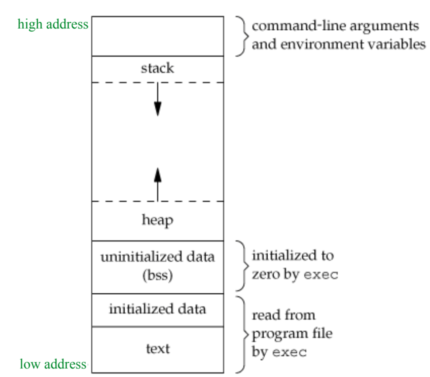
C/C++ memory model

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

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



```
#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?

Dynamic arrays

C-style arrays

- Contiguous sequence of elements of identical type
  - ✓ random access: `base_address + index * sizeof(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

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.

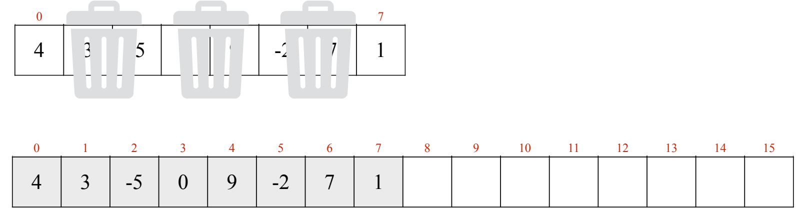
Dynamic array class in C++

```
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.

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



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		

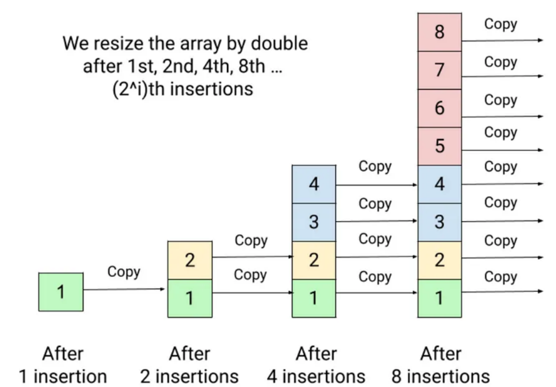
$$T(n) = n + \sum_{i=0}^{n-1} 2i$$

$$= n + 2\left(\frac{n(n-1)}{2}\right)$$

$$= \Theta(n^2)$$ cost of adding n elements

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.

Repeated doubling



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

Grow by factor

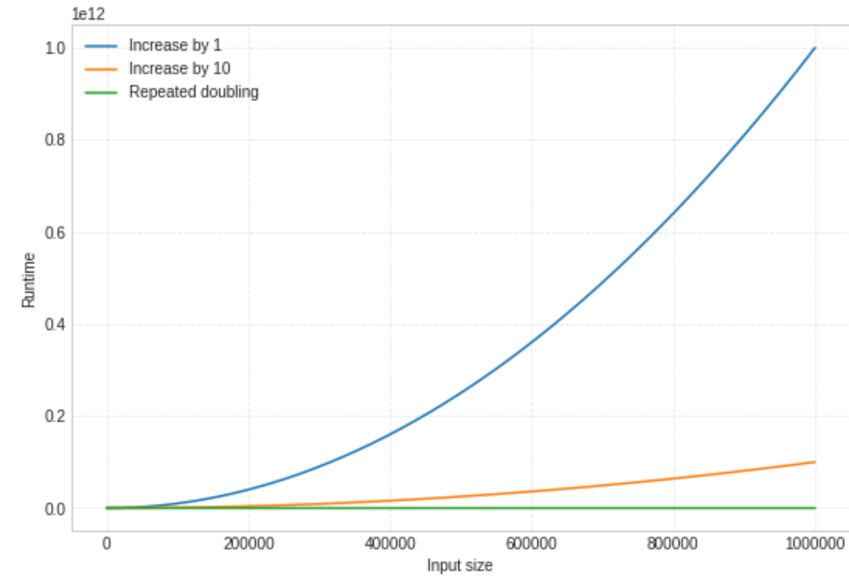
- When array is full, new capacity: `current * factor`
  - ✓ called **repeated doubling** when `factor == 2`
  - ✓ starting from an empty array, count number of array accesses (**reads and writes**) for adding *n* elements — assume n is a power of 2 (ignore cost of allocating/deallocating memory)

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		

$$T(n) = n + 2\sum_{i=0}^{\log n - 1} 2^i$$
$$= n + 2\left(2^{\log n} - 1\right)$$
$$= n + 2n - 2$$
$$= \Theta(n)$$

cost of adding n elements

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.



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

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			

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

std::vector

`std::vector is a sequence container that encapsulates dynamic arrays`

Quick Start

`#include <vector>`	
`std::vector<int> v {2, 4, 5};`	2 4 5
`v.push_back(6);`	2 4 5 6
`v.pop_back();`	2 4 5
`v[1] = 3;`	2 3 5
`v.resize(5, 0);`	2 3 5 0 0
`cout << v[2];`	prints 5
`for (int x : v)` `  cout << x << ' '`	prints 2 3 5 0 0

https://hackingcpp.com/cpp/std/vector.html

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

Live coding …

- Complete the implementation of the `DynamicArray` class:

```
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
};
```

Templates

- How to modify the code to support adding floats, or other data types?

```
#include <iostream>

int add_int(int a, int b) {
    return a + b;
}

double add_double(double a, double b) {
    return a + b;
}

int main() {
    std::cout << “Sum (int): " << add_int(5, 3) << “\n";
    std::cout << "Sum (double): " << add_double(2.5, 1.7) << “\n";

    return 0;
}
```


Templates

```
#include <iostream>

template <typename T>
T add(T a, T b) {
    return a + b;
}

int main() {
    std::cout << "Sum (int): " << add<int>(5, 3) << “\n";
    std::cout << "Sum (double): " << add<double>(2.5, 1.7) << “\n";

    return 0;
}
```

Template functions/classes allow writing **generic code** that can work with different data types <u>without the need to write separate code for each type</u>. The compiler generates the appropriate instantiation based on the data type specified to the function/class.

C++ topics to review

- Memory model and pointers
- Dynamic memory allocation
- Classes and objects
- References
- Templates
- STL containers