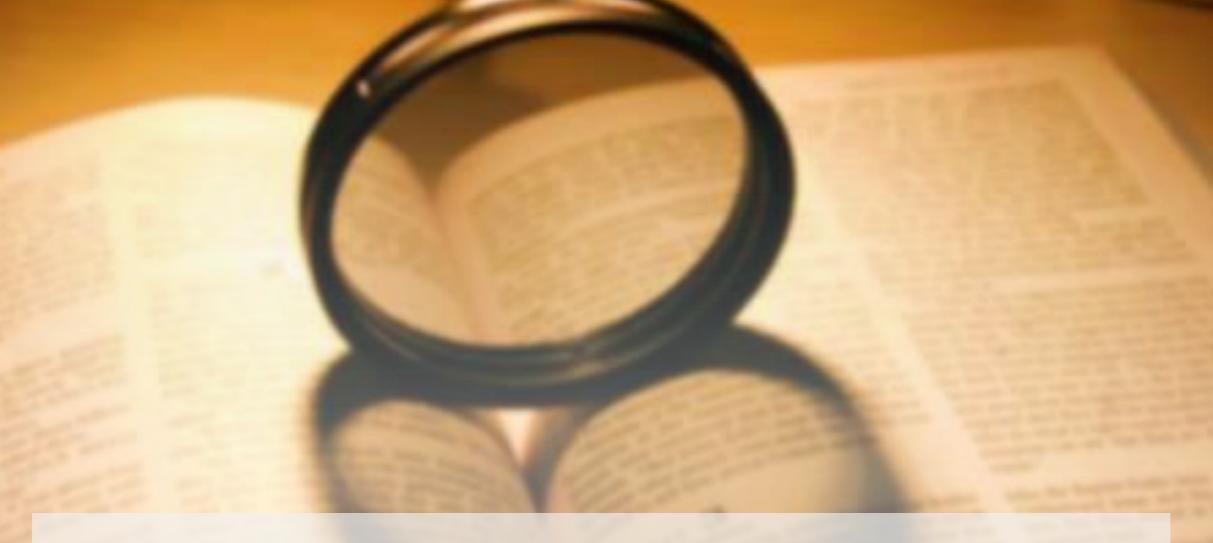
Data Structures Chapter 3

1. Stack

- Stack Concept
 - STL stack class
- Stack Implementations
 - Using Fixed Array
 - Using Dynamic Array
 - Using Vector
 - Using STL Template

2. Queue



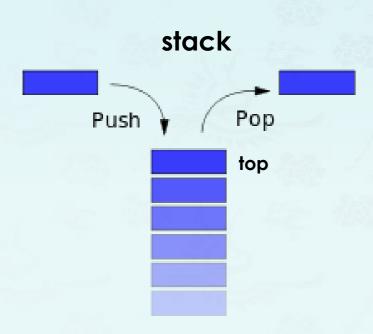
그러므로 예수께서 자기를 믿은 유대인들에게 이르시되 너희가 내 말에 거하면 참으로 내 제자가 되고 진리를 알지니 진리가 너희를 자유롭게 하리라 (요8:31-32)

Stack

• **Stack** is a linear data structure represented by a real physical stack or pile, a structure where insertion and deletion of items takes place at one end called top of the stack.

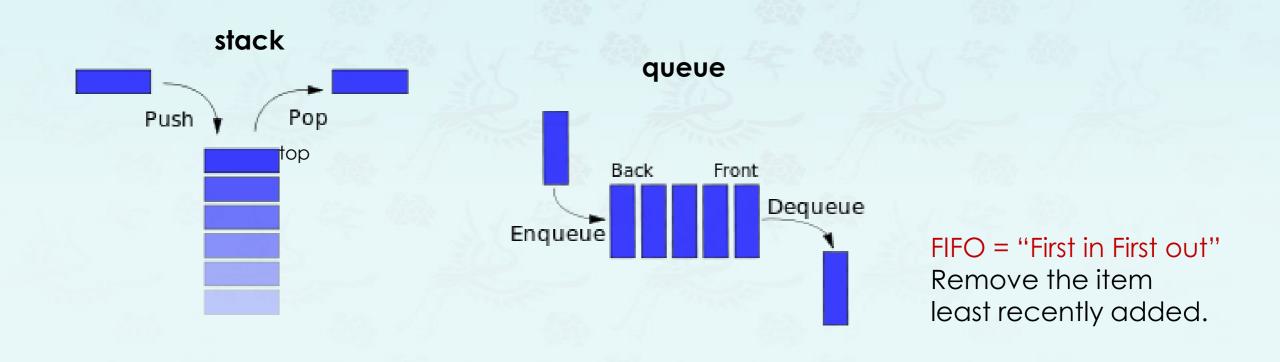
Stack

- **Stack** is a linear data structure represented by a real physical stack or pile, a structure where insertion and deletion of items takes place at one end called top of the stack.
- This particular order of the operation is called LIFO(Last In First Out).



Stack

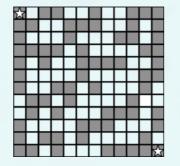
- **Stack** is a linear data structure represented by a real physical stack or pile, a structure where insertion and deletion of items takes place at one end called top of the stack.
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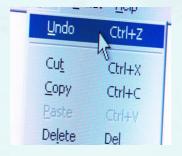
Stack Applications

- Parsing in a compiler.
- Undo in a word processor.
- Back button in a Web browser.
- PostScript language for printers.
- Backtracking as in a maze
- Implementing function calls in a compiler.

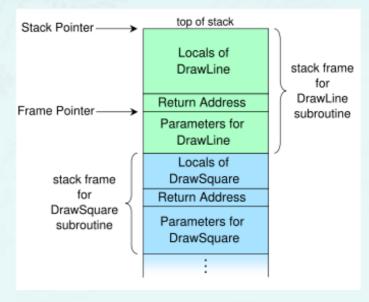
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Stack - ADT (Abstract Data Type)

ADT Stack is

- Objects: a finite ordered list with zero or more elements
- Operations (or Functions):

Stack - ADT (Abstract Data Type)

ADT Stack is

- Objects: a finite ordered list with zero or more elements
- Operations (or Functions):

```
Stack newStack(maxStackSize)
bool empty()
void push(item)
void pop()
int top()
int size;
```

Stack - Why ADT?

- Separate interface and implementation.
 - Ex: stack, queue, bag, priority queue, symbol table, union-find,
- Benefits.

Stack - Why ADT?

- Separate interface and implementation.
 - Ex: stack, queue, bag, priority queue, symbol table, union-find,

Benefits.

- Driver (or Client) can't know details of implementation
 - Client has many implementations from which to choose.
 - Program using operations defined in interface.
- Interface is description of data type, basic operations.
- Implementation is actual code implementing operations.
 - Design: creates modular, reusable libraries.
 - Performance: use optimized implementation where it matters.

Stack: Example in C++

STL	<pre>#include <stack></stack></pre>	Stack class in C++ STL
	stack <value_type></value_type>	creates an empty stack of <value_type></value_type>
void	<pre>push(value_type& item)</pre>	inserts a new item onto stack
void	pop()	removes top item from stack (which is most recently added)
value_type&	top()	returns a reference to the top item
bool	empty()	is the stack empty?
int	size()	returns the number of items in the stack

Warm-up client: Reverse sequence of strings using stack.

Stack: Driver/Client using stack class in C++ STL

- Read strings from a collection using a range-for loop.
 - If string equals "-", pop string from stack and print.
 - Otherwise, push string onto stack.

```
int main () { // stack initialization using range-based for
 string list[] = {"to", "be", "or", "not", "to", "-", "be", \
                    "-", "-", "that", "-", "-", "is"};
 stack<string> s;
 for (auto item : list) { // to be not that or be
    if (item != "-")
      s.push(item);
    else {
      cout << s.top() << ' ';
      s.pop();
 cout << "\nsize(): " << s.size();</pre>
 cout << "\ntop() : " << s.top();</pre>
```

Stack: Driver/Client using stack class in C++ STL

- Read strings from a collection using a range-for loop.
 - If string equals "-", pop string from stack and print.
 - Otherwise, push string onto stack.

```
int main () { // stack initialization using range-based for
 string list[] = {"to", "be", "or", "not", "to", "-", "be", \
                    "-", "-", "that", "-", "-", "is"};
 stack<string> s;
 for (auto item : list) { // to be not that or be
    if (item != "-")
      s.push(item);
                                                     void printStack(stack<string> s) {
    else {
                                                       while (!s.empty()) {
      cout << s.top() << ' ';
                                                         cout << s.top() << ' ';
      s.pop();
                                                         s.pop();
                                                       cout << endl; // now, s is empty</pre>
 cout << "\nsize(): " << s.size();</pre>
 cout << "\ntop() : " << s.top();</pre>
```

Stack: version.1 – using a stack class in C++ STL

```
int main () { // stack initialization using range-based for
 // int list[] = \{1, 2, 3, 4, 5, 0, 6, 0, 0, 7, 0, 0, 8\};
 string list[] = {"to", "be", "or", "not", "to", "-", "be", \
                   "-", "-", "that", "-", "-", "-", "is"};
 stack<string> s;
 for (auto item : list) { // to be not that or be (5 6 4 7 3 2)
   if (item != "-") // type specific
      s.push(item);
   else {
      cout << s.top() << ' ';
      s.pop();
 cout << "\nsize(): " << s.size(); // 2</pre>
 cout << "\ntop() : " << s.top(); // is
 printStack(s);
                  // is to (8 1)
 cout << "Happy Coding";</pre>
```

Stack: Implementation

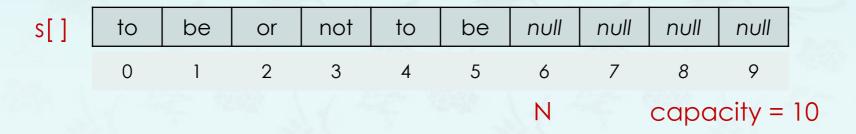
Let's implement our own stack in several different ways.

- Array implementation
 - fixed size array
 - dynamic array
- Vector implementation
- Using Template
 - Array implementation
 - Vector implementation

Stack: Array implementation

Let's implement our own stack in several different ways.

- Array implementation of a stack:
 - Use array s[] to store N items on stack.
 - push(): add new item at s[N].
 - top(): return item from s[N-1].
 - pop(): remove item from s[N-1], it just decrements N by one.



Defect. Stack overflows when N exceeds capacity. [stay tuned]

Stack: Things to consider

- Underflow:
 - Throw exception if pop from an empty stack or return null;

```
string top(stack s) {
  return s->item[s->N - 1];
}
```

```
string top(stack s) {
  if (empty())
    throw std::out_of_range("underflow");

return s->item[s->N - 1];
}
```

- Overflow:
 - Use resizing array for array implementation. [stay tuned]
 - Use successive doubling method
- Generic programming using Template in C++
 - It makes the stack data(item) type-independent
 - template<typename T>

Stack: version.2 – using a fixed size array

```
struct Stack {
  string *item;
  int N;
  int capacity;
                                  a shortcoming
using stack = Stack *;
                                  (stay tuned)
stack newStack(int capacity)
  stack s = new Stack;
  s->item = new string[capacity];
  s \rightarrow N = 0;
  s->capacity = capacity;
  return s;
void free(stack s) {
  delete[] s->item;
  delete s;
                  item[N] is next to be filled if any.
```

Stack: version.2 – using a fixed size array

```
struct Stack {
  string *item;
 int N;
 int capacity;
                                a shortcoming
using stack = Stack *;
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stack newStack(int capacity) {
  stack s = new Stack;
  s->item = new string[capacity];
 s->N=0;
  s->capacity = capacity;
  return s;
void free(stack s) {
  delete[] s->item;
 delete s;
                 item[N] is next to be filled if any.
```

```
int size(stack s) { return s->N; }
bool empty(stack s) { return s->N == 0; }
void pop(stack s) { s->N--; }
string top(stack s) {
 return s->item[s->N - 1]; N is not decremented
void push(stack s, string item) {
  s->item[s->N++] = item; use N and incremented
                            N points an empty slot
void printStack(stack s) {
  while (!empty(s)) {
    cout << top(s) << ' ';
    pop(s);
  cout << endl; // stack is empty now</pre>
```

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2. Queue

- Problem:
 - Requiring client to provide capacity (size of stack) is inappropriate.
 - Question: How to grow and shrink array?

Challenge: Ensure that array resizing happens infrequently.

- Problem:
 - Requiring client to provide capacity (size of stack) is inappropriate.
 - Question: How to grow and shrink array?
- First try.
 - push(): increase size of array s[] by 1.
 - pop(): decrease size of array s[] by 1.

Challenge: Ensure that array resizing happens infrequently.

- Problem:
 - Requiring client to provide capacity (size of stack) is inappropriate.
 - Question: How to grow and shrink array?
- First try.
 - push(): increase size of array s[] by 1.
 - pop(): decrease size of array s[] by 1.
- Too expensive.
 - Need to copy all items to a new array.
 - Inserting first N items takes time proportional to $1 + 2 + 3 + + N \approx N^2/2$.

infeasible for large N

Challenge: Ensure that array resizing happens infrequently.

Q. How to grow and shrink array?

"successive doubling"

```
stack newStack(int capacity = 1) {
  stack s = new Stack;
  s->item = new string[capacity];
 s->capacity = capacity;
 s \rightarrow N = 0;
  return s;
```

Q. How to grow and shrink array?

"successive doubling"

```
stack newStack(int capacity = 1) {
  stack s = new Stack;
 s->item = new string[capacity];
 s->capacity = capacity;
 s \rightarrow N = 0;
 return s;
void resize(stack s, int new_capacity) {
  string *copied = new string[new_capacity];
```

Q. How to grow and shrink array?

"successive doubling"

```
stack newStack(int capacity = 1) {
                                                    struct Stack {
 stack s = new Stack;
                                                      string *item;
 s->item = new string[capacity];
                                                     int N;
 s->capacity = capacity;
                                                     int capacity;
 s \rightarrow N = 0;
                                                    using stack = Stack *;
 return s;
void resize(stack s, int new_capacity) {
 string *copied = new string[new_capacity];
 for (int i = 0; i < s->N; i++)
                                        copy(s->item; s->item + s->N, copied);
    copied[i] = s->item[i];
 delete[] s->item;
```

Q. How to grow and shrink array?

"successive doubling"

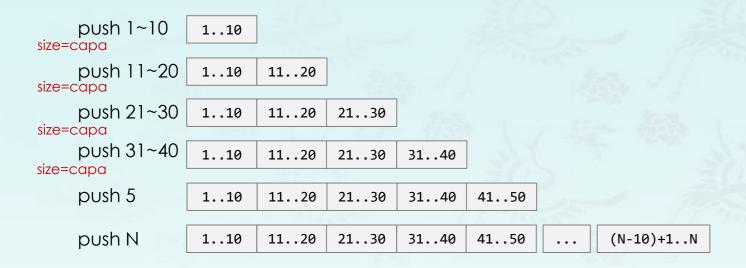
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 for (int i = 0; i < s->N; i++)
                                       copy(s->item; s->item + s->N, copied);
    copied[i] = s->item[i];
 delete[] s->item;
 s->item = copied;
  s->capacity = new_capacity;
```

- Q. Cost of inserting first N items by resize(s.length + 10)?
- A. T(N) = 10N + (10 + 20 + 30 + ... + N)

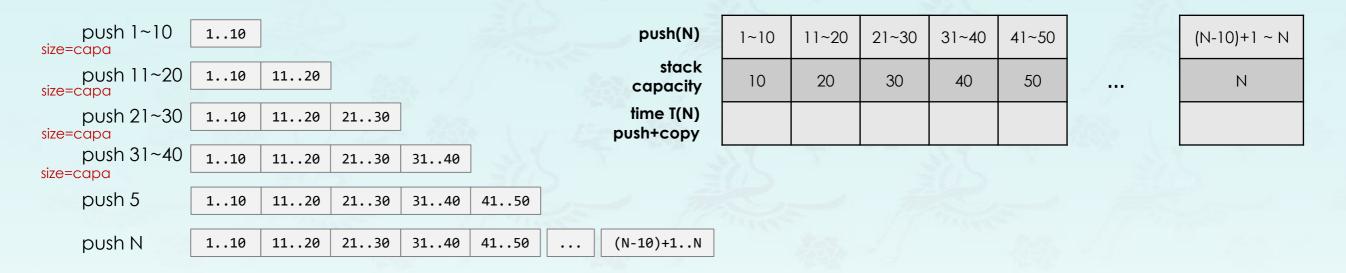
1 array access per push

k array accesses when memory is resized by increment of 10 (ignoring cost to create new array) (assuming new() costs copying each item one by one)

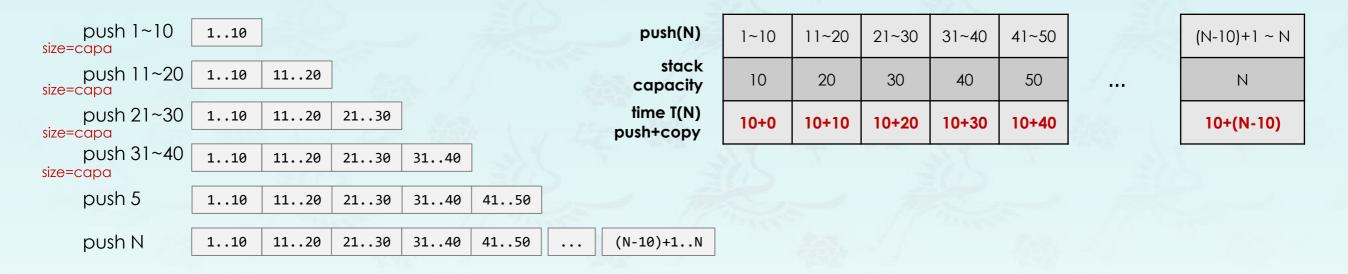
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- Let us consider an example of a simple array stack pushes.



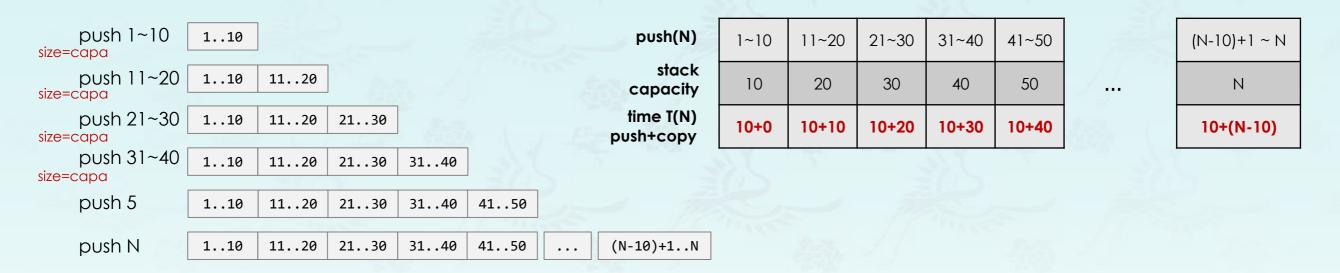
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- Q. Cost of inserting first N items by resize(s.length + 10)?
- Let us consider an example of a simple array stack pushes.



```
T(N) = (10) + (10+10) + (10+20) + (10+30) + \dots + (10+N-10)
= (10+10) + (10+20) + (10+30) + \dots + (10+N)
= (10 + 10 + 10 + \dots) + (10 + 20 + 30 + \dots + N)
= 10N + (10 + 20 + 30 + \dots + N)
```

- Q. Cost of inserting first N items by resize(s.length + 10)?
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1 array access per push

k array accesses when memory is resized by increment of 10 (ignoring cost to create new array) (assuming new() costs copying each item one by one)

- Q. Cost of inserting first N items by resize(s.length + 10)?
- A. T(N) = 10N + (10 + 20 + 30 + ... + N)

How many terms? k terms, then N = 10k

$$T(N) = 10N + (10 + 20 + 30 + \dots + N)$$
Let $N = 10k$, then it becomes
$$T(N) = 10N + (10 + 20 + 30 + \dots + 10k)$$

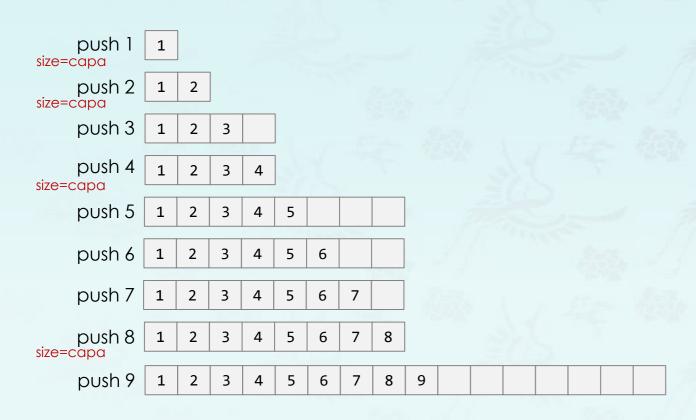
$$= 10N + 10(1 + 2 + 3 + \dots + k)$$

$$= 10N + 10 \frac{k(k+1)}{2}$$

$$= 10N + 10 \frac{\frac{N}{10}(\frac{N}{10} + 1)}{2}$$
Therefore, $T(N) = 10N + \frac{N}{2}(\frac{N}{10} + 1)$
The time complexity of the algorithm is $O(n^2)$.

- Q. Cost of inserting first N items by resize(capacity * 2)?
- A. T(N) = N + (1 + 2 + 4 + 8 + ... + N)

- Q. Cost of inserting first N items by resize(capacity * 2)?
- Let us consider an example of a simple array stack pushes.



- Q. Cost of inserting first N items by resize(capacity * 2)?
- Let us consider an example of a simple array stack pushes.



10

16

5

6

7

8

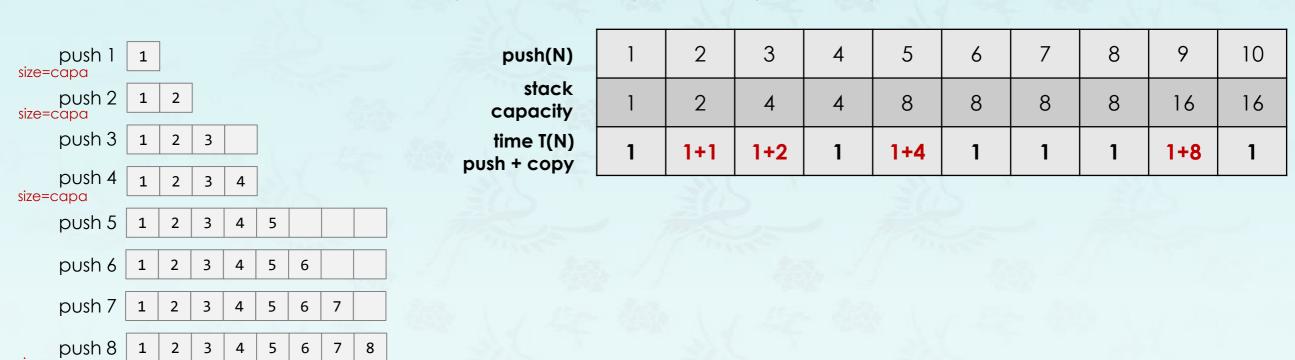
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size=capa

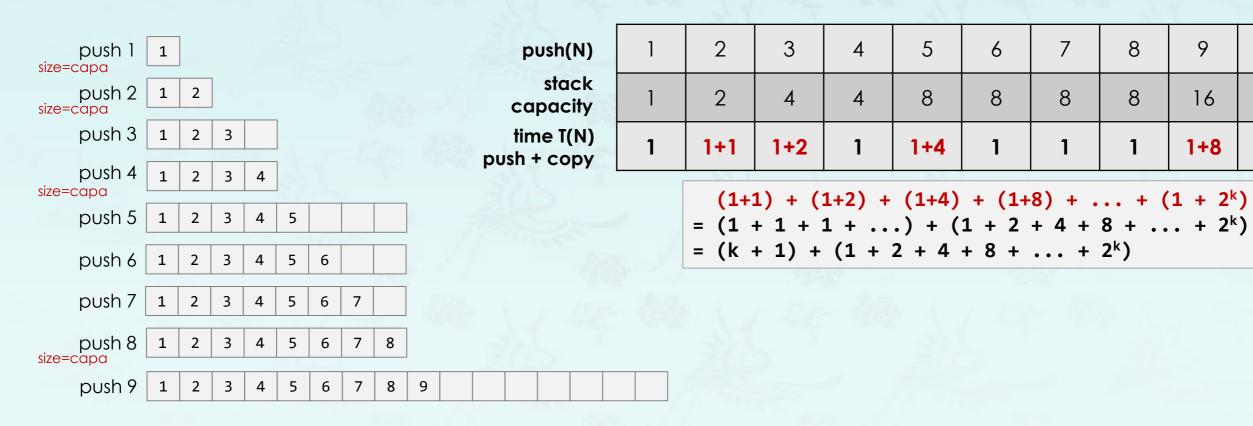
push 9

1

- Q. Cost of inserting first N items by resize(capacity * 2)?
- Let us consider an example of a simple array stack pushes.



- Q. Cost of inserting first N items by resize(capacity * 2)?
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9

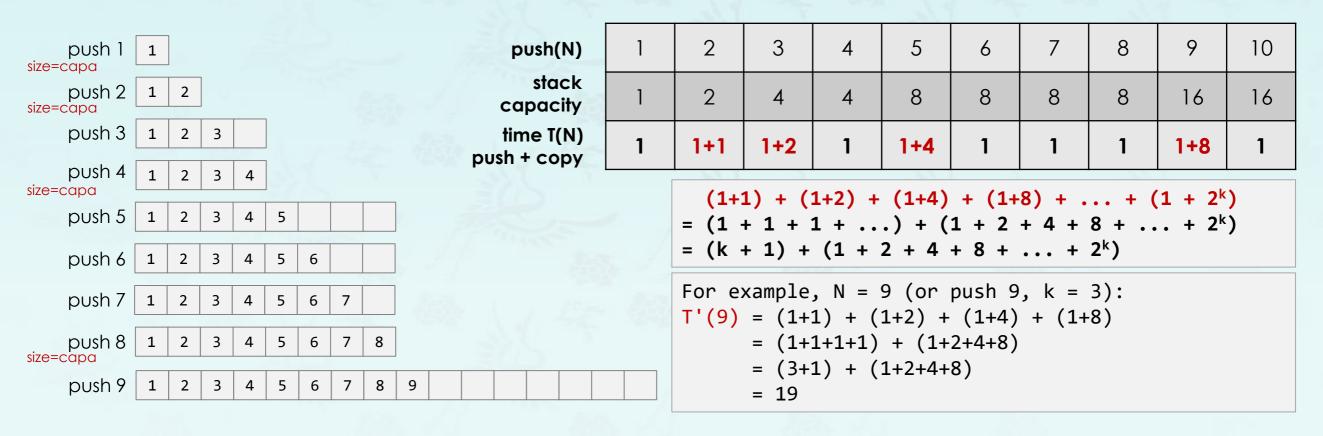
16

1+8

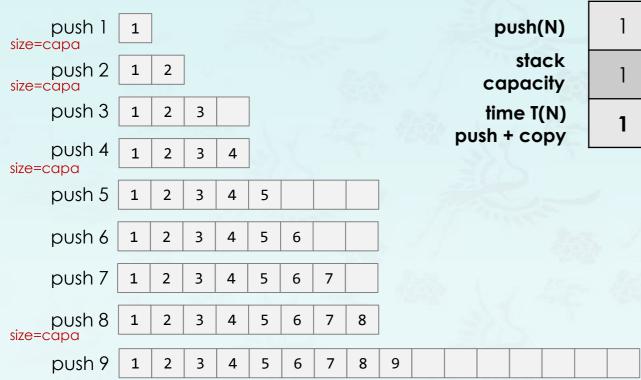
10

16

- Q. Cost of inserting first N items by resize(capacity * 2)?
- Let us consider an example of a simple array stack pushes.



- Q. Cost of inserting first N items by resize(capacity * 2)?
- Let us consider an example of a simple array stack pushes.



	1	1+1	1+2	1	1+4	1	1	1	1+8	1
8	1	2	4	4	8	8	8	8	16	16
	1	2	3	4	5	6	7	8	9	10

```
(1+1) + (1+2) + (1+4) + (1+8) + \dots + (1+2^k)
= (1+1+1+\dots) + (1+2+4+8+\dots+2^k)
= (k+1) + (1+2+4+8+\dots+2^k)
```

```
For example, N = 9 (or push 9, k = 3):

T'(9) = (1+1) + (1+2) + (1+4) + (1+8)

= (1+1+1+1) + (1+2+4+8)

= (3+1) + (1+2+4+8)

= 19
```

```
How many 1's in the time for N pushes?

Let it be x. Then T(N) can be expressed
T(N) = x + (k + 1) + (1 + 2 + 4 + 8 + ... + 2^k)
= N + (1 + 2 + 4 + 8 + ... + 2^k)
= N + (1 + 2 + 4 + 8 + ... + N)
```

- Q. Cost of inserting first N items by resize(capacity * 2)?
- Let us consider an example of a simple array stack pushes.

push(N)
stack
capacity
time T(N)
push + copy

1	2	3	4	5	6	7	8	9	10
1	2	4	4	8	8	8	8	16	16
1	1+1	1+2	1	1+4	1	1	1	1+8	1

$$(1+1) + (1+2) + (1+4) + (1+8) + \dots + (1 + 2^k)$$

= $(1 + 1 + 1 + \dots) + (1 + 2 + 4 + 8 + \dots + 2^k)$
= $(k + 1) + (1 + 2 + 4 + 8 + \dots + 2^k)$

```
For example, N = 9 (or push 9, k = 3):
T'(9) = (1+1) + (1+2) + (1+4) + (1+8)
= (1+1+1+1) + (1+2+4+8)
= (3+1) + (1+2+4+8)
= 19
```



```
How many 1's in the time for N pushes?

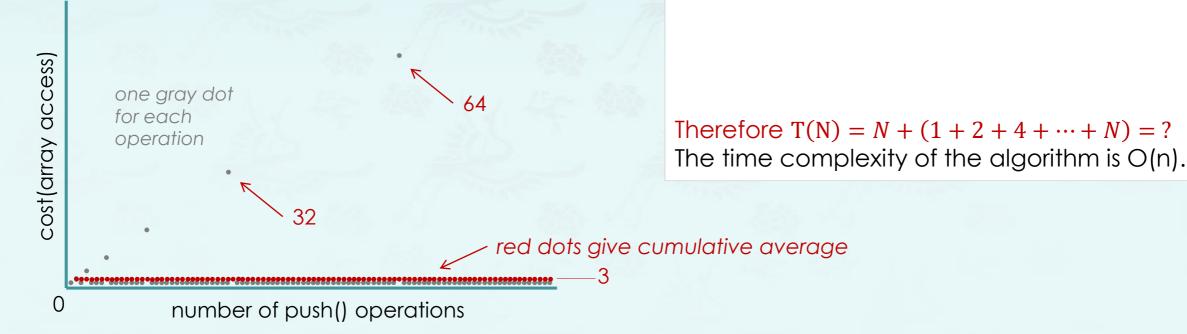
Let it be x. Then T(N) can be expressed

T(N) = x + (k + 1) + (1 + 2 + 4 + 8 + ... + 2^k)
= N + (1 + 2 + 4 + 8 + ... + N)
```

- Q. Cost of inserting first N items by resize (capacity * 2)?
- A. T(N) = N + (1 + 2 + 4 + 8 + ... + N)

$$1 + a + a^2 + a^3 + \dots + a^n = \frac{a^{n+1} - 1}{a - 1}$$

$$1 + 2 + 4 + \dots + 2^n = \frac{2^{n+1} - 1}{2 - 1} = 2^{n+1} - 1$$



Q. How to grow and shrink array?

"successive doubling"

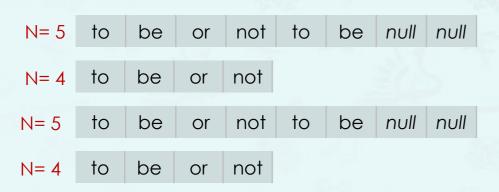
A. If array is full, create a new array of twice the size, and copy items.

```
stack newStack(int capacity = 1) {
  stack s = new Stack;
 s->item = new string[capacity];
 s->capacity = capacity;
 s \rightarrow N = 0;
 return s;
void resize(stack s, int new_capacity) {
  string *copied = new string[new_capacity];
  for (int i = 0; i < s->N; i++)
    copied[i] = s->item[i];
 delete[] s->item;
 s->item = copied;
  s->capacity = new_capacity;
```

```
void push(stack s, string item) {
   // your code here
   s->item[s->N++] = item;
}
```

- Q: How to shrink array?
- First try.
 - push(): double size of array s[] when array is full
 - pop(): halve size of array s[] when array is one-half full.

- Q: How to shrink array?
- First try.
 - push(): double size of array s[] when array is full
 - pop(): halve size of array s[] when array is one-half full.
- Too expensive in worst case.
 - Consider push-pop-push-pop- ... sequence when array is full
 - Each operation takes time proportional to N.



- Q: How to shrink array?
- Efficient solution
 - push(): double size of array s[] when array is full
 - pop(): halve size of array s[] when array is one-quarter full.

```
void pop(stack s) {
  s->N--;
  // your code here
}
```

❖ Invariant. Array is between 25% and 100% full.

Amortized analysis:

Average running time per operation over a worst-case sequence of operations.

Proposition:

 Starting from an empty stack, any sequence of N push and pop operations takes time proportional to N.

	best	worst	amortized	
construct	O(1)	O(1)	O(1)	
push	O(1)	O(n) ←	O(1)	
рор	O(1)	O(n) ←	O(1)	doubling and halving operations
size	O(1)	O(1)	O(1)	

order of growth of running time for resizing stack with N items

Q. How to grow and shrink array?

"successive doubling"

A. If array is full, create a new array of twice the size, and copy items.

```
stack newStack(int capacity = 1) {
  stack s = new Stack;
 s->item = new string[capacity];
 s->capacity = capacity;
 s \rightarrow N = 0;
 return s;
void resize(stack s, int new_capacity) {
  string *copied = new string[new_capacity];
  for (int i = 0; i < s->N; i++)
    copied[i] = s->item[i];
 delete[] s->item;
 s->item = copied;
  s->capacity = new capacity;
```

```
bool empty(stack s) { return s->N == 0; }
string top(stack s) {
  return s->item[s->N - 1];
void push(stack s, string item) {
  // your code here
  s \rightarrow item[s \rightarrow N++] = item;
void pop(stack s) {
  s->N--;
  // your code here
```

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Stack: Vector implementation

Let's implement our own stack in several different ways.

- Array implementation
 - fixed size array
 - dynamic array
- Vector implementation
 - A good tutorial in Korean at https://codechacha.com/ko/cpp-stl-vector/
- Using Template
 - Array implementation
 - Vector implementation

Vector Container

- An alternative to the built-in array.
- A vector is self-grown.
 - No allocation/free is necessary!
- Template implementation advantage!!
- For example:
 vector<int> vector of integers.
 vector<string> vector of strings.
 vector<int *> vector of pointers to integers.
 vector<Shape> vector of Shape objects. Shape is a user defined class.

```
iterator begin();
 iterator end();
bool empty();
void push_back(const T& x);
void pop_back();
void back();
void clear();
size_type size();
size_type capacity();
```

```
#include<iostream>
#include<vector>
using namespace std;
int main(){
  vector<int> v(5);
  for(int i=0; i < v.size(); i++)</pre>
    cin >> v[i];
  for(int i=0; i < v.size(); i++)</pre>
    cout << v[i] << ' ';
  cout << endl;</pre>
```

```
#include<iostream>
#include<vector>
using namespace std;
int main(){
  vector<int> v(5);
  for(int i=0; i < v.size(); i++)</pre>
    cin >> v[i];
  for(int i=0; i < v.size(); i++)</pre>
    cout << v[i] << ' ';
  cout << endl;</pre>
```

```
for(int x: v)
  cout << x << ' ';
cout << endl;</pre>
```

```
#include<iostream>
#include<vector>
using namespace std;
int main(){
  vector<int> v(5);
  for(int i=0; i < v.size(); i++)</pre>
    cin >> v[i];
  for(int i=0; i < v.size(); i++)</pre>
    cout << v[i] << ' ';
  cout << endl;</pre>
```

```
for(int x: v)
  cout << x << ' ';
cout << endl;</pre>
for(auto x: v)
  cout << x << ' ';
cout << endl;</pre>
```

```
#include<iostream>
#include<vector>
using namespace std;
int main(){
  vector<int> v(5);
  for(int i=0; i < v.size(); i++)</pre>
    cin >> v[i];
  for(int i=0; i < v.size(); i++)</pre>
    cout << v[i] << ' ';
  cout << endl;</pre>
```

```
for(int x: v)
  cout << x << ' ';
cout << endl;</pre>
for (auto x: v)
  cout << x << ' ';
cout << endl;</pre>
vector<int>::iterator it;
for(it = v.begin(); it!=v.end(); it++)
    cout << *it << ' ';
cout << endl;</pre>
```

```
iterator begin();
 iterator end();
bool empty();
void push_back(const T& x);
void pop_back();
const_reference back();
void clear();
size_type size();
size_type capacity();
```

```
int main() {
  int count = 0;
  vector<int> vec;
  vec.push_back(1);
  vec.push_back(2);
  vec.push_back(3);
  while (!vec.empty()) {
    count++;
    vec.pop back();
  cout << count;</pre>
  return 0;
```

```
iterator begin();
 iterator end();
bool empty();
void push back(const T& x);
void pop back();
const_reference back();
void clear();
size_type size();
size_type capacity();
```

```
int main () {
  vector<int> vec;
  vec.push_back(10);
  while (vec.back() != 0) {
    vec.push_back ( vec.back() - 1 );
  cout << "vec contains: ";</pre>
  for (unsigned i=0; i<vec.size(); i++)</pre>
    cout << vec[i] << ' ';
  cout << endl;</pre>
  return 0;
```

```
iterator begin();
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void push back(const T& x);
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int main () {
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  cout << "vec contains: ";</pre>
  for (unsigned i=0; i<vec.size(); i++)</pre>
    cout << vec[i] << ' ';
  cout << endl;</pre>
  return 0;
```

vec contains: 10 9 8 7 6 5 4 3 2 1 0

```
iterator begin();
 iterator end();
bool empty();
void push back(const T& x);
void pop_back();
const reference back();
void clear();
size_type size();
size_type capacity();
```

```
int main () {
  vector<int> vec;
  for (int i=0; i<100; i++) vec.push_back(i);
  cout << "size: " << vec.size() << endl;
  cout << "capa: " << vec.capacity() << endl;
  return 0;
}</pre>
```

size: 100 capa: 128

Stack: version.4 – using a vector in C++ STL

```
struct Stack {
 vector<string> item;
using stack = Stack *;
void free(stack s) {
 delete s;
int size(stack s) {
 return s->item.size();
bool empty(stack s) {
 return s->item.empty();
```

```
void pop(stack s) {
  // your code here
string top(stack s) {
 // your code here
void push(stack s, string item) {
  // your code here
void printStack(stack s) {
  while (!empty(s)) {
    cout << top(s) << ' ';
    pop(s);
  cout << endl; // stack is empty now</pre>
```

- A template is a mechanism that allows a programmer to use types as
 parameters for a class or a function. The compiler then generates a specific
 class or function when we later provide specific types as arguments.
- A function/class defined using template is called a generic function/class.
 This is one of the key features of C++.

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Pros and Cons of Templates

Pros:

- It provides us type-safe, efficient generic containers and generic algorithms
- The main reason for using C++ and templates is the trade-offs in performance and maintainability outweigh the bigger size of the resulting code and longer compile times.
- The drawbacks of not using them are likely to be much greater.

Cons:

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- It provides us type-safe, efficient generic containers and generic algorithms
- The main reason for using C++ and templates is the trade-offs in performance and maintainability outweigh the bigger size of the resulting code and longer compile times.
- The drawbacks of not using them are likely to be much greater.

Cons:

- Templates can lead to slower compile-times and possibly larger executable.
- Compilers often produce incomprehensible poor error diagnostics and poor error messages.

Stack: version.4T – using a vector<> in C++ STL

```
struct Stack {
                       stack4_vec.cpp
 vector<string> item;
};
using stack = Stack *;
void free(stack s) {
 delete s;
string top(stack s) {
 return s->item.back();
```

Compare these two program segments and see how to use **Templates** in C++ for generic programming.

```
template<typename T>
struct Stack {
 vector<T> item;
template<typename T>
using stack = Stack<T> *;
template<typename T>
void free(stack<T> s) {
  delete s;
template<typename T>
T top(stack<T> s) {
  return s->item.back();
```

Data Structures Chapter 3

1. Stack

- Stack Concept
 - STL stack class
- Stack Implementations
 - Using Fixed Array
 - Using Dynamic Array
 - Using Vector
 - Using STL Template

2. Queue