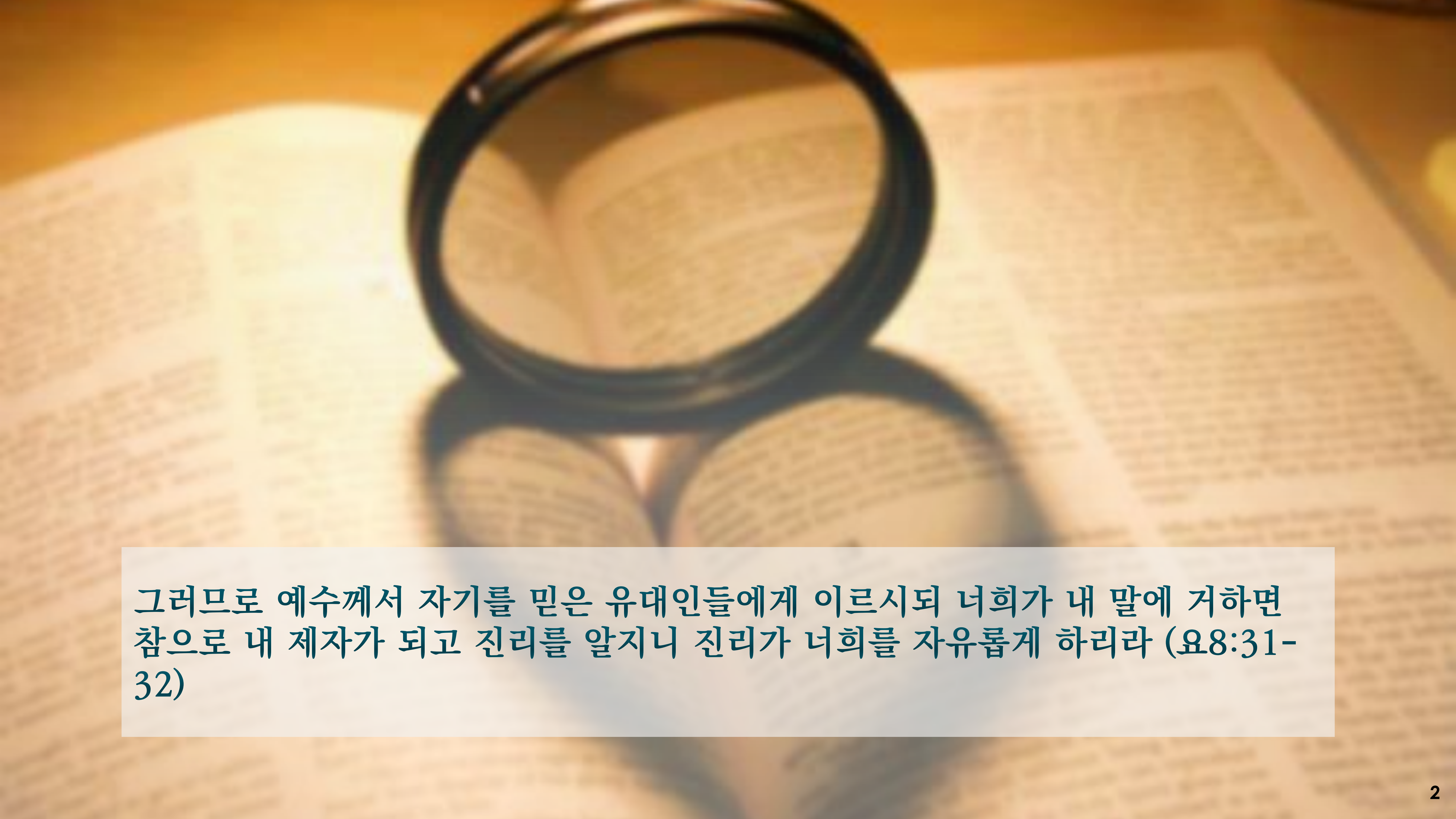
Data Structures
Chapter 3

1. **Stack**
   - Stack Concept
     - STL stack class
   - Stack Implementations
     - Using Fixed Array
     - Using Dynamic Array
     - Using Vector
     - Using STL Template
2. Queue

Prof. Youngsup Kim, idebtor@gmail.com, Data Structures, CSEE Dept., Handong Global University



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.

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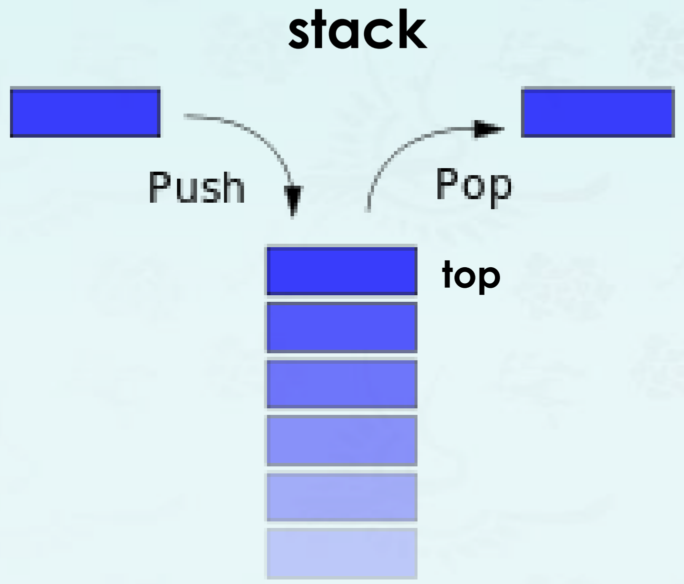
- This particular order of the operation is called **LIFO(Last In First Out).**



Stack

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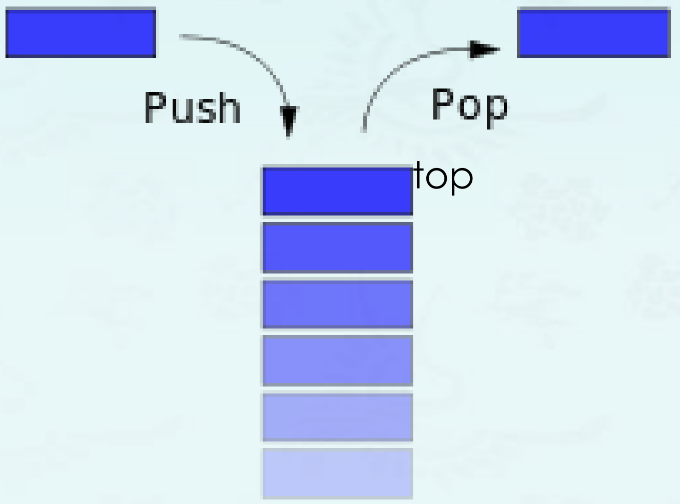
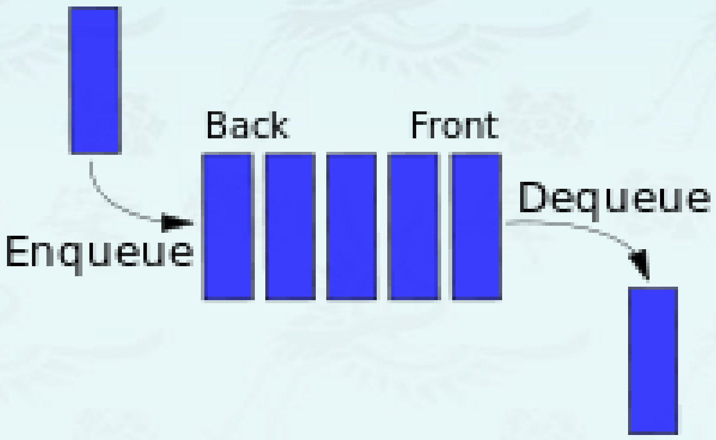
stack



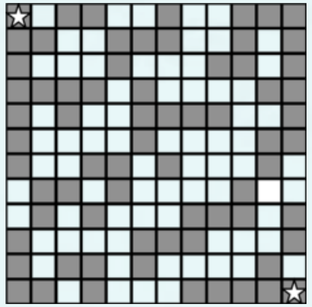
queue

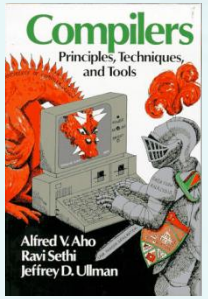


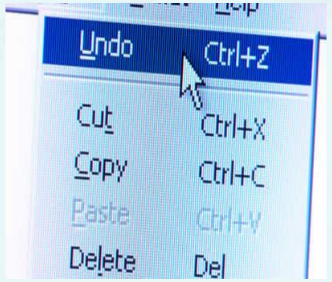
FIFO = "First in First out"
Remove the item
least recently added.

Stack Applications

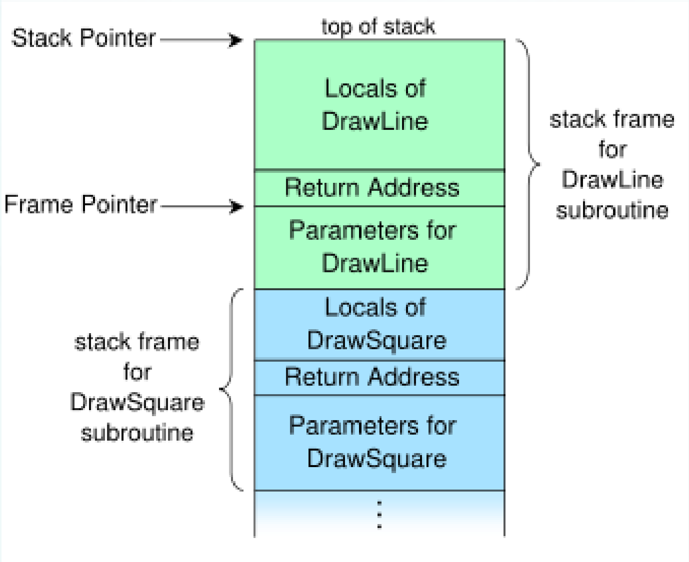
- Parsing in a compiler.
- Undo in a word processor.
- Back button in a Web browser.
- PostScript language for printers.
- Backtracking as in a maze
- Implementing function calls in a compiler.
- ...







Adobe® PostScript® 3™



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	`#include <stack>`	Stack class in C++ STL
	`stack<value_type>`	*creates an empty stack of <value_type>*
`void`	`push(value_type& item)`	*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();
  cout << "\ntop() : " << s.top();
}
```

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.
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```
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  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();
  cout << "\ntop() : " << s.top();
}
```

```
void printStack(stack<string> s) {
  while (!s.empty())  {
    cout << s.top() << ' ';
    s.pop();
  }
  cout << endl; // now, s is empty
}
```

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

stack1_stl.cpp

```
int main () { // stack initialization using range-based for
  // int list[] = {1, 2, 3, 4, 5, 0, 6, 0, 0, 7, 0, 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
  cout << "\ntop() : " << s.top();  // is
  printStack(s);                    // is to (8 1)
  cout << "Happy Coding";
}
```

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.

s[ ]	to	be	or	not	to	be	*null*	*null*	*null*	*null*
	0	1	2	3	4	5	6	7	8	9
							N		capacity = 10	

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

stack2_arr.cpp

```
struct Stack {
  string *item;
  int N;
  int capacity;
};
using stack = Stack *;

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;
}
```

a shortcoming (stay tuned)

item[N] is next to be filled if any.

Stack: version.2 – using a fixed size array

stack2_arr.cpp

```
struct Stack {
  string *item;
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  return s;
}
void free(stack s) {
  delete[] s->item;
  delete s;
}
```

a shortcoming
(stay tuned)

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];
}
void push(stack s, string item) {
  s->item[s->N++] = item;
}
void printStack(stack s) {
  while (!empty(s))  {
    cout << top(s) << ' ';
    pop(s);
  }
  cout << endl;  // stack is empty now
}
```

N is not decremented

use N and incremented
N points an empty slot

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Stack: Using dynamic arrays

- 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.

Stack: Using dynamic arrays

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  - 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.

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Stack: Using dynamic arrays

- 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.

Stack: Using dynamic arrays

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->N = 0;
  return s;
}
```

Stack: Using dynamic arrays

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  s->capacity = capacity;
  s->N = 0;
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}

void resize(stack s, int new_capacity) {
  string *copied = new string[new_capacity];
```


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}

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;
```

```
struct Stack {
  string *item;
  int N;
  int capacity;
};
using stack = Stack *;
```

```
copy(s->item; s->item + s->N, copied);
```

Stack: Using dynamic arrays

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  stack s = new Stack;
  s->item = new string[capacity];
  s->capacity = capacity;
  s->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;
}
```

```
copy(s->item; s->item + s->N, copied);
```

Stack: Using dynamic arrays

- **Q.** Cost of inserting first N items by resize(s.length + 10)?
- **A.** $\mathrm{T(N)} = \mathbf{1} + (\mathbf{10} + \mathbf{20} + \mathbf{30} + \ \ldots + \mathbf{N})$

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)

Stack: Using dynamic arrays

- **Q.** Cost of inserting first N items by resize(s.length + 10)?
- **A.** $\mathrm{T}(\mathbf{N}) = \mathbf{N} + \underbrace{(\mathbf{10} + \mathbf{20} + \mathbf{30} + \ldots + \mathbf{N})}$

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

$$T(N) = 1 + (10 + 20 + 30 + \cdots + N)$$

$$Let\ N = 10k, then\ it\ becomes$$

$$\begin{aligned} T(N) &= N + (10 + 20 + 30 + \cdots + 10k) \\ &= N + 10(1 + 2 + 3 + \cdots + k) \\ &= N + 10\,\frac{k(k+1)}{2} \\ &= N + 10\,\frac{\frac{N}{10}(\frac{N}{10} + 1)}{2} \end{aligned}$$

$$Therefore, T(N) = N + \frac{N}{2}\left(\frac{N}{10} + 1\right)$$

The time complexity of the algorithm is $O(n^2)$.

Stack: Using dynamic arrays

- **Q.** Cost of inserting first N items by resize(capacity * 2)?
- **A.** $\mathrm{T(N)} = \mathbf{N} + (\mathbf{1} + \mathbf{2} + \mathbf{4} + \mathbf{8} + \ \ldots + \mathbf{N})$

↑ 1 array access per push

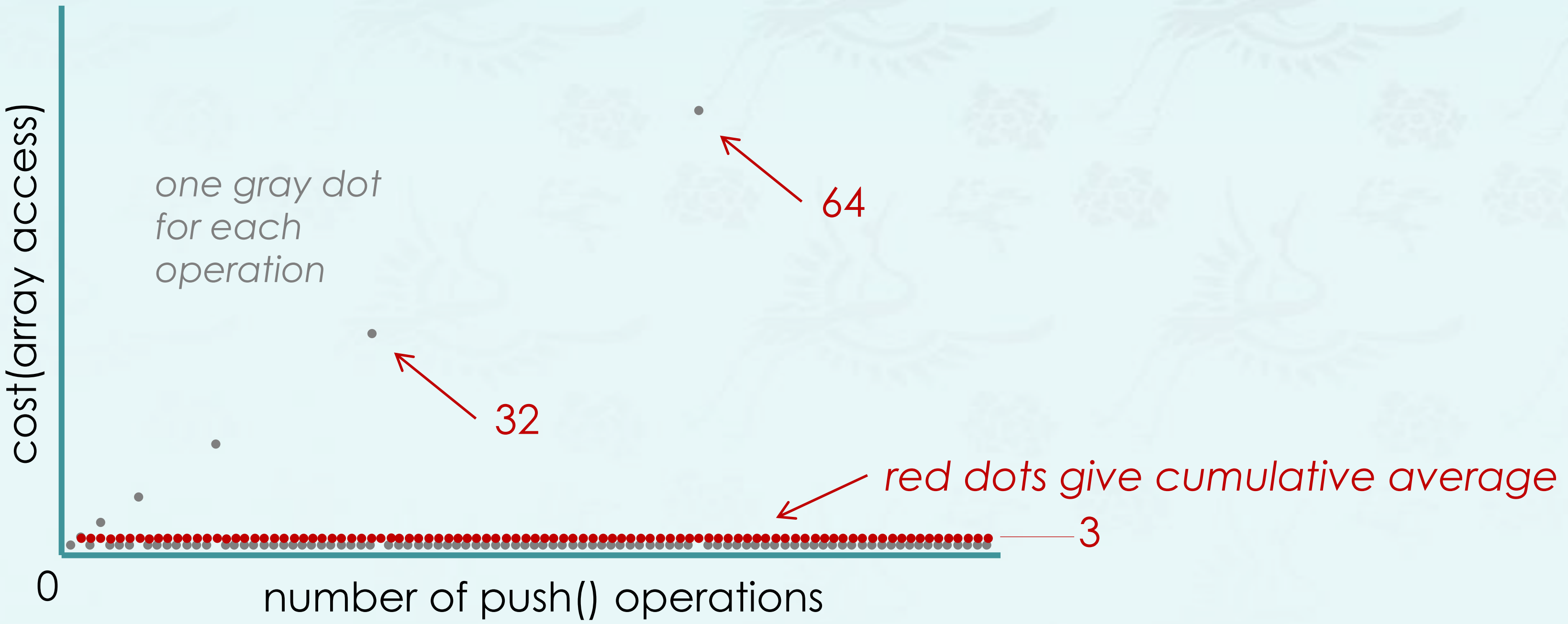
↑ k array accesses to double to size k
(ignoring cost to create new array)
(assuming new() costs copying each item one by one)

When N = 1, Capacity = 1
  Cost: 1 // no items to copy
When N = 2, Capacity = 1
  Cost: 1 + **(1)** // (1) items to copy
When N = 3, Capacity = 2
  Cost: 1 + **(2)** // (2) items to copy into the new array
When N = 4, Capacity = 4
  Cost: 1 + (0) // (0) since no copy is needed
When N = 5, Capacity = 4
  Cost: 1 + **(4)** // (4) items to copy into the new array
When N = 6, Capacity = 8
  Cost: 1 + (0)
When N = 7, Capacity = 8
  Cost: 1 + (0)
When N = 8, Capacity = 8
  Cost: 1 + (0)
When N = 9, Capacity = 8
  Cost: 1 + **(8)** // (8) items to copy into the new array

cost 1 per push

Stack: Using dynamic arrays

- **Q.** Cost of inserting first N items by resize(capacity * 2)?
- **A.** $\mathrm{T}(\mathbf{N}) = \mathbf{N} + (\mathbf{1} + \mathbf{2} + \mathbf{4} + \mathbf{8} + \ \ldots + \mathbf{N})$



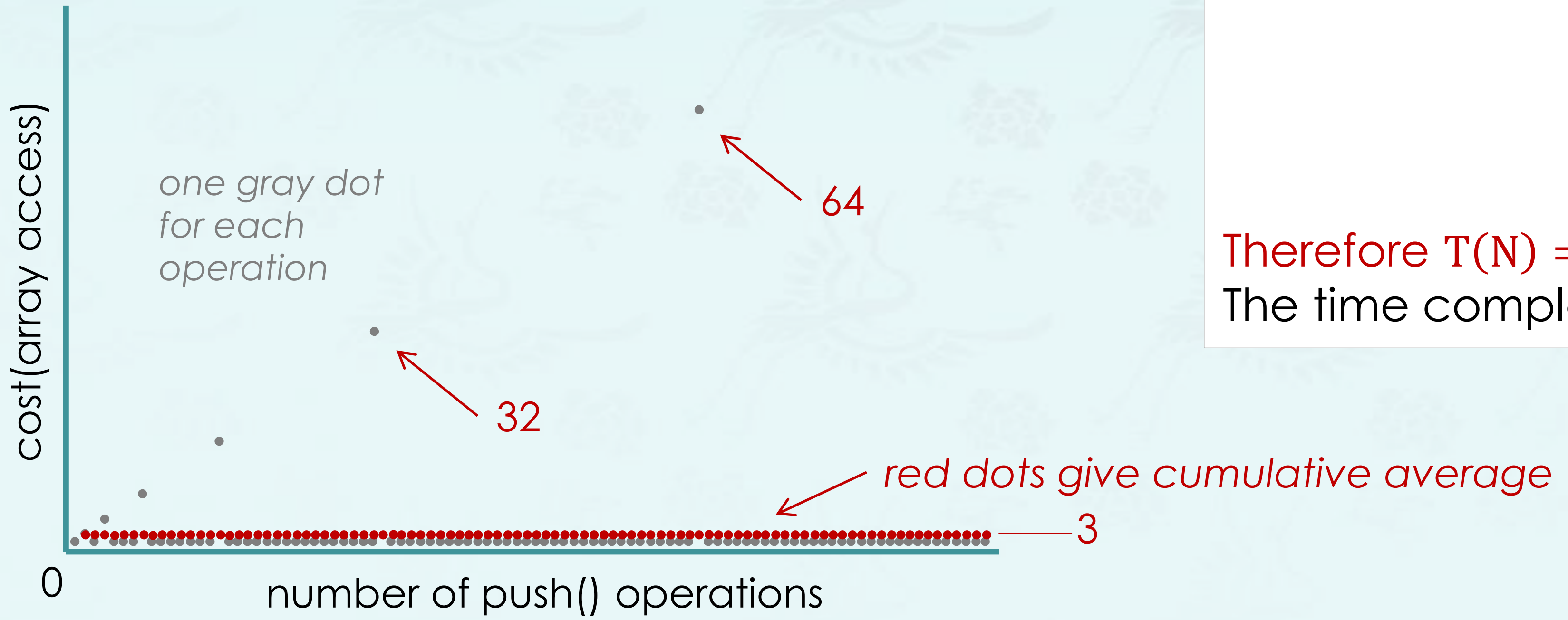
Stack: Using dynamic arrays

- **Q.** Cost of inserting first N items by resize(capacity * 2)?
- **A.** $\mathrm{T(N)} = \mathbf{N + (1 + 2 + 4 + 8 + \ldots + N)}$

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

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

Therefore $\mathrm{T(N)} = N + (1 + 2 + 4 + \cdots + N) = ?$
The time complexity of the algorithm is O(n).



Stack: Using dynamic arrays

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->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;
}
```

Stack: Using dynamic arrays

- **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.

Stack: Using dynamic arrays

- **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.

N= 5	to	be	or	not	to	be	*null*	*null*
N= 4	to	be	or	not				
N= 5	to	be	or	not	to	be	*null*	*null*
N= 4	to	be	or	not				

Stack: Using dynamic arrays

- **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.

Stack: Using dynamic arrays

- **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)
pop	O(1)	O(n)	O(1)
size	O(1)	O(1)	O(1)

doubling and
halving operations

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

Stack: Using dynamic arrays

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  s->capacity = capacity;
  s->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->item[s->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.**

Operations on vector

- **`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();`

Vector Container Example

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

  for(int i=0; i < v.size(); i++)
    cout << v[i] << ' ';
  cout << endl;
}
```

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    cout << v[i] << ' ';
  cout << endl;
}
```

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

Vector Container Example

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    cin >> v[i];

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    cout << v[i] << ' ';
  cout << endl;
}
```

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

for(auto x: v)
  cout << x << ' ';
cout << endl;
```

Vector Container Example

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

  for(int i=0; i < v.size(); i++)
    cout << v[i] << ' ';
  cout << endl;
}
```

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

for(auto x: v)
  cout << x << ' ';
cout << endl;

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

Operations on vector

- `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;
  return 0;
}
```

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```
int main () {
  vector<int> vec;
  vec.push_back(10);
  while (vec.back() != 0) {
    vec.push_back ( vec.back() - 1 );
  }

  cout << "vec contains: ";
  for (unsigned i=0; i<vec.size() ; i++)
    cout << vec[i] << ' ';
  cout << endl;
  return 0;
}
```

Operations on vector

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  }

  cout << "vec contains: ";
  for (unsigned i=0; i<vec.size() ; i++)
    cout << vec[i] << ' ';
  cout << endl;
  return 0;
}
```

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

Operations on vector

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```
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;
}
```

```
size: 100
capa: 128
```

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

stack4_vec.cpp

```
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
}
```

Stack: Using template

- 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++.

Stack: Using template

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- Use **templates** when we need functions/classes that apply the same algorithm to a several types. So we can use the same function/class regardless of the types of the argument or result.

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  or
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Stack: Using template

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**:

Stack: Using template

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  - 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

stack4_vecT.cpp

stack4_vec.cpp

```
struct Stack {
  vector<string> item;
};

using stack = Stack *;

void free(stack s) {
  delete s;
}

string top(stack s) {
  return s->item.back();
}
```

```
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();
}
```

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

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