Data Structures (in C++)

- Deques -

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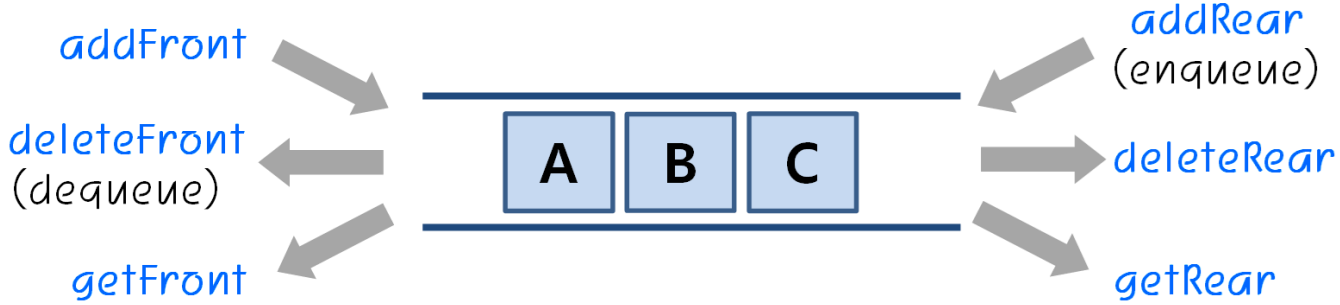
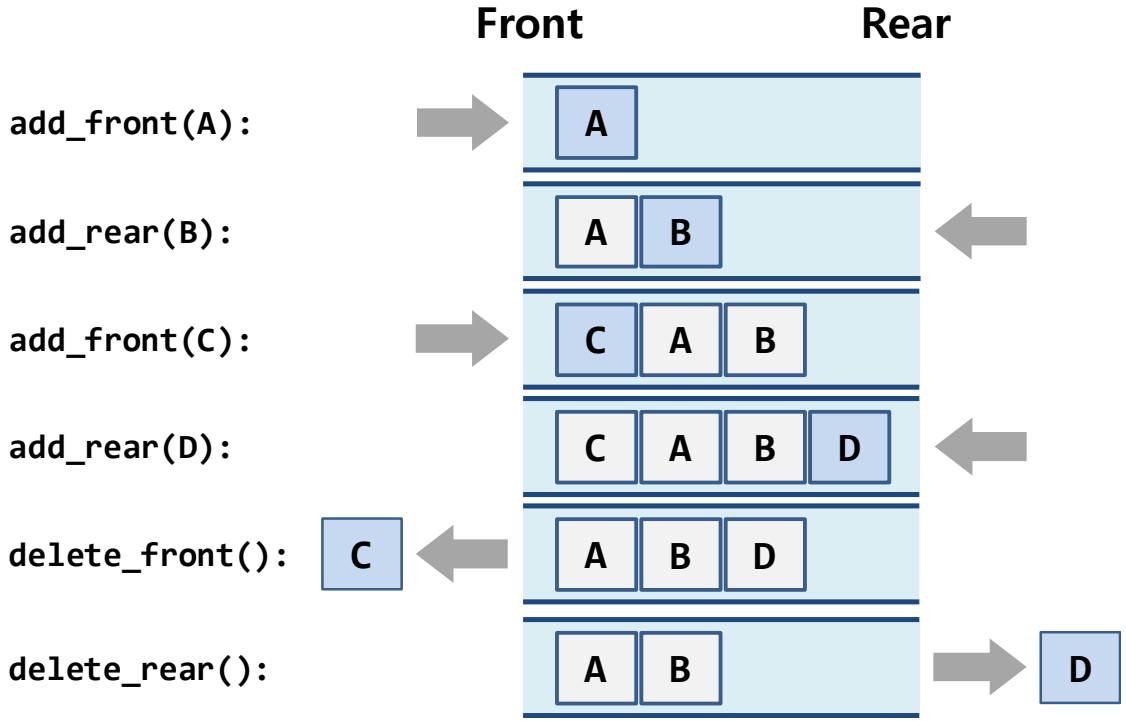
DEQUES

Deques

- **Deque (Double-Ended Queue)**
  - A queue-like data structure
  - Supports insertion and deletion at both ends (*i.e.*, the front and rear sides)
  - Pronounced "*deck*" (not "*D.Q.*")





Deque ADT

- The deque ADT supports the following operations:

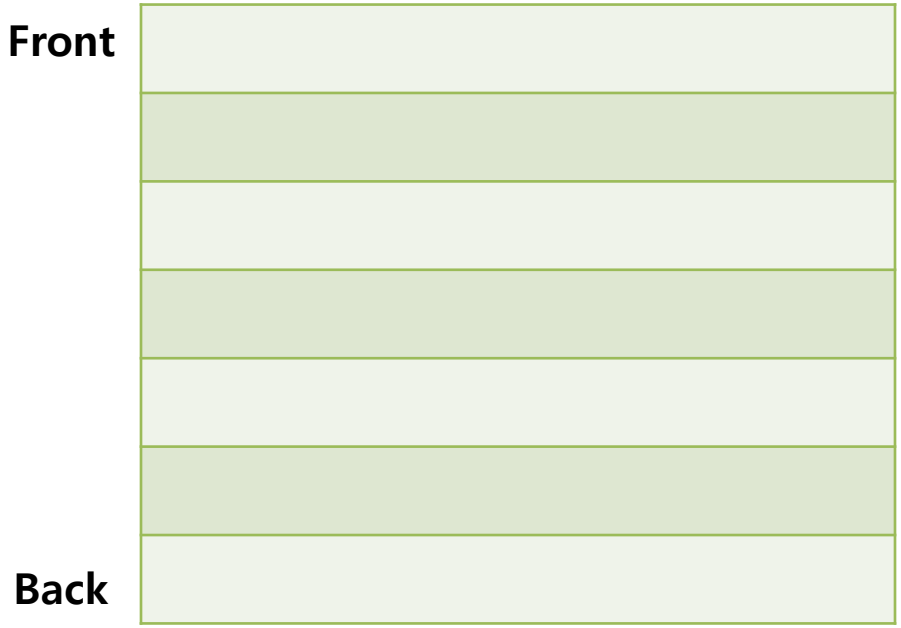
insertFront(e):	Insert a new element e at the beginning of the deque.
insertBack(e):	Insert a new element e at the end of the deque.
eraseFront():	Remove the first element of the deque; an error occurs if the deque is empty.
eraseBack():	Remove the last element of the deque; an error occurs if the deque is empty.

- Additional utility functions:

front():	Return the first element of the deque; an error occurs if the deque is empty.
back():	Return the last element of the deque; an error occurs if the deque is empty.
size():	Return the number of elements of the deque.
empty():	Return true if the deque is empty and false otherwise.

Deque Example

Operation	*Output*	*D*
insertFront(3)	–	(3)
insertFront(5)	–	(5,3)
front()	5	(5,3)
eraseFront()	–	(3)
insertBack(7)	–	(3,7)
back()	7	(3,7)
eraseFront()	–	(7)
eraseBack()	–	()



The STL Deque

- STL stack and queue are adapted from the STL deque.

```
#include <deque>
using std::deque;                    // make deque accessible
deque<string> myDeque;               // a deque of strings
```

size():	Return the number of elements in the deque.
empty():	Return true if the deque is empty and false otherwise.
push_front(*e*):	Insert *e* at the beginning the deque.
push_back(*e*):	Insert *e* at the end of the deque.
pop_front():	Remove the first element of the deque.
pop_back():	Remove the last element of the deque.
front():	Return a reference to the deque's first element.
back():	Return a reference to the deque's last element.

- Applying *front(), back(), pop_front(), or pop_back()* to an empty deque is undefined

The STL Deque

- **The STL Deque Reference Manual**

std::deque

Defined in header <deque>

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

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

`std::deque` (double-ended queue) is an indexed sequence container that allows fast insertion and deletion at both its beginning and its end. In addition, insertion and deletion at either end of a deque never invalidates pointers or references to the rest of the elements.

As opposed to `std::vector`, the elements of a deque are not stored contiguously: typical implementations use a sequence of individually allocated fixed-size arrays, with additional bookkeeping, which means indexed access to deque must perform two pointer dereferences, compared to vector's indexed access which performs only one.

The storage of a deque is automatically expanded and contracted as needed. Expansion of a deque is cheaper than the expansion of a `std::vector` because it does not involve copying of the existing elements to a new memory location. On the other hand, deques typically have large minimal memory cost; a deque holding just one element has to allocate its full internal array (e.g. 8 times the object size on 64-bit libstdc++; 16 times the object size or 4096 bytes, whichever is larger, on 64-bit libc++).

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

- Random access - constant $O(1)$
- Insertion or removal of elements at the end or beginning - constant $O(1)$
- Insertion or removal of elements - linear $O(n)$

`std::deque` meets the requirements of *Container*, *AllocatorAwareContainer*, *SequenceContainer* and *ReversibleContainer*.

Template parameters

T - The type of the elements.

T must meet the requirements of *CopyAssignable* and *CopyConstructible*.	(until C++11)
The requirements that are imposed on the elements depend on the actual operations performed on the container. Generally, it is required that element type is a complete type and meets the requirements of *Erasable*, but many member functions impose stricter requirements.	(since C++11)

Allocator - An allocator that is used to acquire/release memory and to construct/destroy the elements in that memory. The type must meet the requirements of *Allocator*. The behavior is undefined (until C++20) The program is ill-formed (since C++20) if `Allocator::value_type` is not the same as `T`.

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)

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)
`shrink_to_fit` (C++11)	reduces memory usage by freeing unused memory (public member function)

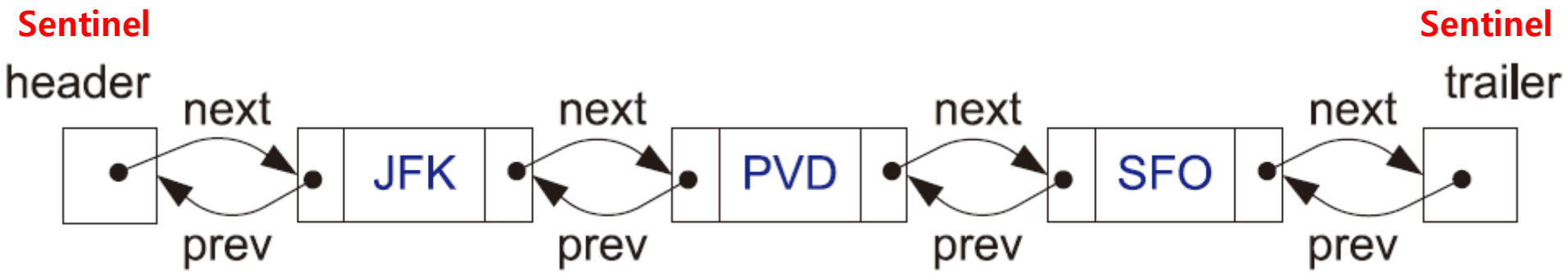
Modifiers

`clear`	clears the contents (public member function)
`insert`	inserts 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)
`pop_back`	removes the last element (public member function)
`push_front`	inserts an element to the beginning (public member function)
`emplace_front` (C++11)	constructs an element in-place at the beginning (public member function)
`pop_front`	removes the first 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/deque

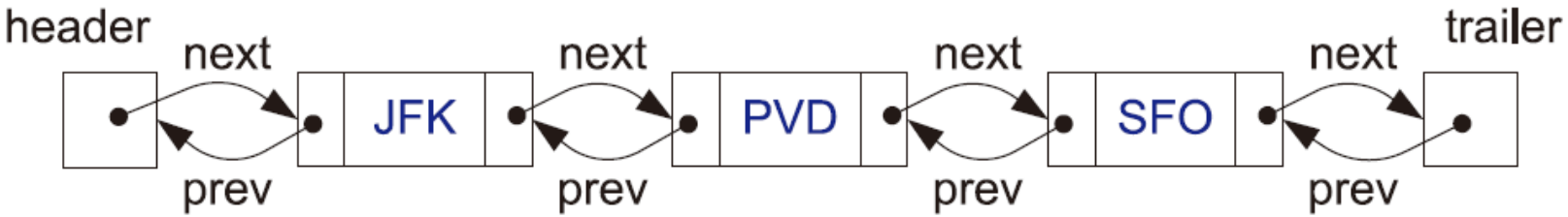
Deque Implementation: Doubly Linked List

- **Doubly Linked List**
  - A linked list that allows to traverse in both *forward and backward directions*
  - A node stores two links to the *previous* and *next* nodes
  - **Sentinel node** (*i.e.*, header or trailer)
    - A specifically designated node as a traversal path terminator for convenience
    - Does not hold any data



Deque Implementation: Doubly Linked List

- **Recap: Doubly Linked List**




```
                                        // insert new node before v
void DLinkedList::add(DNode* v, const Elem& e) {
  DNode* u = new DNode; u->elem = e; // create a new node for e
  u->next = v;                       // link u in between v
  u->prev = v->prev;                 // ...and v->prev
  u->prev->next = v->prev = u;
}

void DLinkedList::addFront(const Elem& e) // add to front of list
  { add(header->next, e); }

void DLinkedList::addBack(const Elem& e) // add to back of list
  { add(trailer, e); }
```

```
void DLinkedList::remove(DNode* v) {     // remove node v
  DNode* u = v->prev;                    // predecessor
  DNode* w = v->next;                    // successor
  u->next = w;                           // unlink v from list
  w->prev = u;
  delete v;
}

void DLinkedList::removeFront()          // remove from font
  { remove(header->next); }

void DLinkedList::removeBack()           // remove from back
  { remove(trailer->prev); }
```

Deque Implementation: Doubly Linked List

- **C++ Implementation**

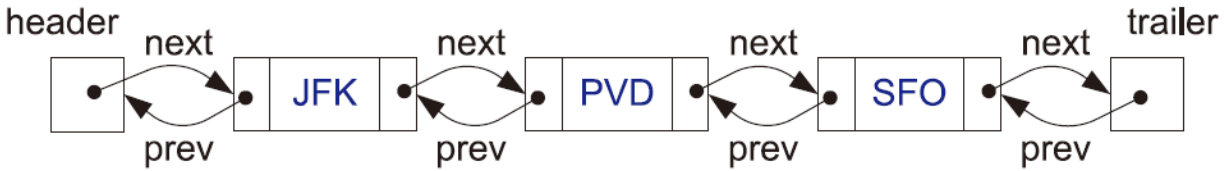
```
typedef string Elem;                          // deque element type
class LinkedDeque {                           // deque as doubly linked list
public:
  LinkedDeque();                              // constructor
  int size() const;                           // number of items in the deque
  bool empty() const;                         // is the deque empty?
  const Elem& front() const throw(DequeEmpty); // the first element
  const Elem& back() const throw(DequeEmpty); // the last element
  void insertFront(const Elem& e);            // insert new first element
  void insertBack(const Elem& e);             // insert new last element
  void removeFront() throw(DequeEmpty);       // remove first element
  void removeBack() throw(DequeEmpty);        // remove last element
private:                                      // member data
  DLinkedList D;                              // linked list of elements
  int n;                                      // number of elements
};
```

size() is not supported by the DLinkedList

Deque Implementation: Doubly Linked List

- **C++ Implementation**

```
                                        // insert new first element
void LinkedDeque::insertFront(const Elem& e) {
  D.addFront(e);
  n++;
}
                                        // insert new last element
void LinkedDeque::insertBack(const Elem& e) {
  D.addBack(e);
  n++;
}
                                        // remove first element
void LinkedDeque::removeFront() throw(DequeEmpty) {
  if (empty())
    throw DequeEmpty("removeFront of empty deque");
  D.removeFront();
  n--;
}
                                        // remove last element
void LinkedDeque::removeBack() throw(DequeEmpty) {
  if (empty())
    throw DequeEmpty("removeBack of empty deque");
  D.removeBack();
  n--;
}
```



Operation	*Time*
size	$O(1)$
empty	$O(1)$
front, back	$O(1)$
insertFront, insertBack	$O(1)$
eraseFront, eraseBack	$O(1)$

Adapters

- **Adapters (or Wrappers)**
  - A data structure that translates one interface to another

- **Examples**

Stack Method	*Deque Implementation*
size()	size()
empty()	empty()
top()	front()
push(o)	insertFront(o)
pop()	eraseFront()

Table 5.3: Implementing a stack with a deque.

Queue Method	*Deque Implementation*
size()	size()
empty()	empty()
front()	front()
enqueue(e)	insertBack(e)
dequeue()	eraseFront()

Table 5.4: Implementing a queue with a deque.

std::stack

Defined in header <stack>

```
template<
    class T,
    class Container = std::deque<T>
> class stack;
```

std::queue

Defined in header <queue>

```
template<
    class T,
    class Container = std::deque<T>
> class queue;
```

Adapters

- **Stack Implementation using Deque**

```
typedef string Elem;                          // element type
class DequeStack {                            // stack as a deque
public:
  DequeStack();                               // constructor
  int size() const;                           // number of elements
  bool empty() const;                         // is the stack empty?
  const Elem& top() const throw(StackEmpty); // the top element
  void push(const Elem& e);                   // push element onto stack
  void pop() throw(StackEmpty);               // pop the stack
private:
  LinkedDeque D;                              // deque of elements
};
```

```
DequeStack::DequeStack()                      // constructor
  : D() { }

                                              // number of elements
int DequeStack::size() const
  { return D.size(); }

                                              // is the stack empty?
bool DequeStack::empty() const
  { return D.empty(); }

                                              // the top element
const Elem& DequeStack::top() const throw(StackEmpty) {
  if (empty())
    throw StackEmpty("top of empty stack");
  return D.front();
}

                                              // push element onto stack
void DequeStack::push(const Elem& e)
  { D.insertFront(e); }

                                              // pop the stack
void DequeStack::pop() throw(StackEmpty)
{
  if (empty())
    throw StackEmpty("pop of empty stack");
  D.removeFront();
}
```