19. Dynamic Data Structures II

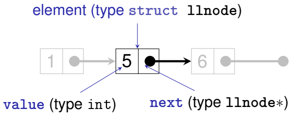
Linked Lists, Vectors as Linked Lists

Different Memory Layout: Linked List

- *No* contiguous area of memory and *no* random access
- Each element points to its successor
- Insertion and deletion of *arbitrary* elements is simple

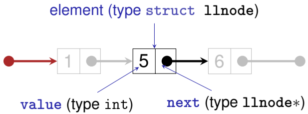
⇒ Our vector can be implemented as a linked list

Linked List: Zoom




```
struct llnode {
  int value;
  llnode* next;

  llnode(int v, llnode* n): value(v), next(n) {} // Constructor
};
```


Vector = Pointer to the First Element




```
class llvec {
  llnode* head;
public:
  // Public interface identical to avec's
  llvec(unsigned int size);
  unsigned int size() const;
  ...
};
```

Function llvec::print()

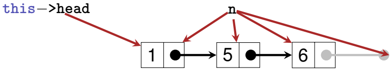
```
struct llnode {
  int value;
  llnode* next;
  ...
};
```

```
void llvec::print(std::ostream& sink) const {
  for (llnode* n = this->head;
       n != nullptr;
       n = n->next)
  {
    sink << n->value << ' ';
  }
}
```

- `for (llnode* n = this->head;` — Pointer to first element
- `n != nullptr;` — Abort if end reached
- `n = n->next)` — Advance pointer element-wise
- `sink << n->value << ' ';` — Output current element

Function llvec::print()

```
void llvec::print(std::ostream& sink) const {
  for (llnode* n = this->head;
       n != nullptr;
       n = n->next)
  {
    sink << n->value << ' ';  // 1 5 6
  }
}
```



Function llvec::operator[]

Accessing ith Element is implemented similarly to `print()`:

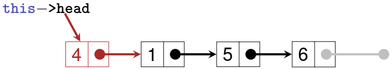
```
int& llvec::operator[](unsigned int i) {
  llnode* n = this->head;

  for (; 0 < i; --i)
    n = n->next;

  return n->value;
}
```

- `llnode* n = this->head;` — Pointer to first element
- `for (; 0 < i; --i) n = n->next;` — Step to ith element
- `return n->value;` — Return ith element

Function llvec::push_front()

Advantage `llvec`: Prepending elements is very easy:

```
void llvec::push_front(int e) {
  this->head =
    new llnode{e, this->head};
}
```



Attention: If the new `llnode` weren't allocated *dynamically*, then it would be deleted (= memory deallocated) as soon as `push_front` terminates

Function `llvec::llvec()`

Constructor can be implemented using `push_front()`:

```
llvec::llvec(unsigned int size) {
  this->head = nullptr;        // head initially points to nowhere

  for (; 0 < size; --size)     // Prepend 0 size times
    this->push_front(0);
}
```

Use case:

```
llvec v = llvec(3);
std::cout << v; // 0 0 0
```

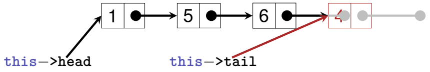

Function `llvec::push_back()`

Simple, but inefficient: traverse linked list to its end and append new element

```
void llvec::push_back(int e) {
  llnode* n = this->head;      // Start at first element ...

  for (; n->next != nullptr; n = n->next);   // ... and go to the last element

  n->next =
    new llnode{e, nullptr};    // Append new element to currently last
}
```


Function `llvec::push_back()`

- More efficient, but also slightly more complex:
  1. Second pointer, pointing to the last element: `this->tail`
  2. Using this pointer, it is possible to append to the end directly



- But: Several corner cases, e.g. vector still empty, must be accounted for

Function `llvec::size()`

Simple, but inefficient: *compute* size by counting

```
unsigned int llvec::size() const {
  unsigned int c = 0;          // Count initially 0

  for (llnode* n = this->head;     // Count linked-list length
       n != nullptr;
       n = n->next)
    ++c;

  return c;                    // Return count
}
```

Function `llvec::size()`

More efficient, but also slightly more complex: *maintain* size as member variable

1. Add member variable `unsigned int count` to class `llvec`
2. `this->count` must now be updated *each* time an operation (such as `push_front`) affects the vector's size

Efficiency: Arrays vs. Linked Lists

- Memory: our **avec** requires roughly n `int`s (vector size n), our **llvec** roughly $3n$ `int`s (a pointer typically requires 8 byte)
- Runtime (with **avec** = **std::vector**, **llvec** = **std::list**):

20. Containers, Iterators and Algorithms

Containers, Sets, Iterators, const-Iterators, Algorithms, Templates

Vectors are Containers

- Viewed abstractly, a vector is
  1. A collection of elements
  2. Plus operations on this collection
- In C++, **vector**<T> and similar data structures are called *container*
- Called *collections* in some other languages, e.g. Java

Container properties

- Each container has certain *characteristic properties*
- For an array-based vector, these include:
  - Efficient index-based access (`v[i]`)
  - Efficient use of memory: Only the elements themselves require space (plus element count)
  - Inserting at/removing from arbitrary index is potentially inefficient
  - Looking for a specific element is potentially inefficient
  - Can contain the same element more than once
  - Elements are in insertion order (ordered but not sorted)

Containers in C++

- Nearly every application requires maintaining and manipulating arbitrarily many data records
- But with different requirements (e.g. only append elements, hardly ever remove, often search elements, ...)
- That's why C++'s standard library includes several containers with different properties, see `https://en.cppreference.com/w/cpp/container`
- Many more are available from 3rd-party libraries, e.g. `https://www.boost.org/doc/libs/1_68_0/doc/html/container.html`, `https://github.com/abseil/abseil-cpp`

Example Container: `std::unordered_set<T>`

- A *mathematical set* is an unordered, duplicate-free collection of elements:

$$\{1,2,1\} = \{1,2\} = \{2,1\}$$

- In C++: `std::unordered_set<T>`
- Properties:
  - Cannot contain the same element twice
  - Elements are not in any particular order
  - Does not provide index-based access (`s[i]` undefined)
  - Efficient "element contained?" check
  - Efficient insertion and removal of elements
- Side remark: implemented as a hash table

Use Case `std::unordered_set<T>`

Problem:

- given a sequence of pairs *(name, percentage)* of Code Expert submissions ...

```
// Input: file submissions.txt
Friedrich 90
Schwerhoff 10
Lehner 20
Schwerhoff 11
```

- ... determine the submitters that achieved at least 50%

```
// Output
Friedrich
```

Use Case std::unordered_set<T>

```
std::ifstream in("submissions.txt");           // Open submissions.txt
std::unordered_set<std::string> names;         // Set of names, initially empty

std::string name;                              // Pair (name, score)
unsigned int score;

while (in >> name >> score) {                  // Input next pair
  if (50 <= score)                             // Record name if score suffices
    names.insert(name);
}

std::cout << "Unique submitters: "             // Output recorded names
          << names << '\n';
```


Example Container: std::set<T>

- Nearly equivalent to `std::unordered_set<T>`, but the elements are *ordered*

$$\{1, 2, 1\} = \{1, 2\} \neq \{2, 1\}$$

- Element look-up, insertion and removal are still efficient (better than for `std::vector<T>`), but less efficient than for `std::unordered_set<T>`
- That's because maintaining the order does not come for free
- Side remark: implemented as a red-black tree

Use Case std::set<T>

```
std::ifstream in("submissions.txt");
std::set<std::string> names;                   // set instead of unsorted_set ...

std::string name;
unsigned int score;

while (in >> name >> score) {
  if (50 <= score)
    names.insert(name);
}

std::cout << "Unique submitters: "             // ... and the output is in alphabetical order
          << names << '\n';
```


Printing Containers

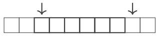
- Recall: `avec::print()` and `llvec::print()`
- What about printing `set`, `unordered_set`, ...?
- Commonality: iterate over container elements and print them

Similar Functions

- Lots of other useful operations can be implemented by iterating over a container:
- `contains(c, e)`: true iff container `c` contains element `e`
- `min/max(c)`: Returns the smallest/largest element
- `sort(c)`: Sorts `c`'s elements
- `replace(c, e1, e2)`: Replaces each `e1` in `c` with `e2`
- `sample(c, n)`: Randomly chooses `n` elements from `c`
- ...

Recall: Iterating With Pointers

- Iteration over an *array*:
  - Point to start element: `p = this->arr`
  - Access current element: `*p`
  - Check if end reached: `p == p + size`
  - Advance pointer: `p = p + 1`



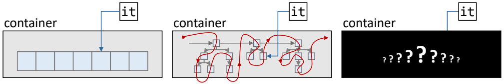
- Iteration over a *linked list*:
  - Point to start element: `p = this->head`
  - Access current element: `p->value`
  - Check if end reached: `p == nullptr`
  - Advance pointer: `p = p->next`

Iterators

- Iteration requires only the previously shown four operations
- But their implementation depends on the container
- ⇒ Each C++container implements their own *Iterator*
- Given a container `c`:
  - `it = c.begin()`: Iterator pointing to the first element
  - `it = c.end()`: Iterator pointing *behind* the last element
  - `*it`: Access current element
  - `++it`: Advance iterator by one element
- Iterators are essentially pimped pointers

Iterators

- Iterators allow accessing different containers in a *uniform* way: `*it`, `++it`, etc.
- Users remain independent of the container implementation
- Iterator knows how to iterate over the elements of “its” container
- Users don’t need to and also shouldn’t know internal details
- ⇒



Example: Iterate over `std::vector`

```
std::vector<int> v = {1, 2, 3};

for (std::vector<int>::iterator it = v.begin();
     it != v.end();
     ++it) {

  *it = -*it;
}

std::cout << v; // -1 -2 -3
```

> `it` is an iterator specific to `std::vector<int>`
>
> `it` initially points to the first element
>
> Abort if `it` reached the end
>
> Advance `it` element-wise
>
> Negate current element ($e \to -e$)

Example: Iterate over `std::vector`

Recall: type aliases can be used to shorten often-used type names

```
using ivit = std::vector<int>::iterator; // int-vector iterator

for (ivit it = v.begin();
     ...
```


Negate as a Function

```
void neg(std::vector<int>& v) {
  for (std::vector<int>::iterator it = v.begin();
       it != v.end();
       ++it) {

    *it = -*it;
  }
}

// in main():
std::vector<int> v = {1, 2, 3};
neg(v); // v = {-1, -2, -3}
```

Disadvantage: Always negates the complete vector

Negate as a Function

Better: negate inside a specific *range (interval)*

```
void neg(std::vector<int>::iterator begin;
         std::vector<int>::iterator end) {

  for (std::vector<int>::iterator it = begin;
       it != end;
       ++it) {

    *it = -*it;
  }
}
```

> Negate elements in interval [`begin`, `end`)

Negate as a Function

Better: negate inside a specific *range (interval)*

```
void neg(std::vector<int>::iterator start;
         std::vector<int>::iterator end);

// in main():
std::vector<int> v = {1, 2, 3};
neg(v.begin(), v.begin() + (v.size() / 2)); ← Negate first half
```


Algorithms Library in C++

- The C++standard library includes lots of useful algorithms (functions) that work on iterator-defined intervals [*begin, end*)
- For example `find`, `fill` and `sort`
- See also `https://en.cppreference.com/w/cpp/algorithm`

An iterator for `llvec`

We need:

1. An `llvec`-specific iterator with at least the following functionality:
   - Access current element: `operator*`
   - Advance iterator: `operator++`
   - End-reached check: `operator!=` (or `operator==`)
2. Member functions `begin()` and `end()` for `llvec` to get an iterator to the beginning and past the end, respectively

Iterator `avec::iterator` (Step 1/2)

```
class llvec {
  ...
public:
  class iterator {
    ...
  };

  ...
}
```

- The iterator belongs to our vector, that's why `iterator` is a public *inner class* of `llvec`
- Instances of our iterator are of type `llvec::iterator`

Iterator `llvec::iterator` (Step 1/2)

```
class iterator {
  llnode* node;                                      // Pointer to current vector element

public:
  iterator(llnode* n);                               // Create iterator to specific element
  iterator& operator++();                            // Advance iterator by one element
  int& operator*() const;                            // Access current element
  bool operator!=(const iterator& other) const;      // Compare with other iterator
};
```


Iterator `llvec::iterator` (Step 1/2)

```
// Constructor
llvec::iterator::iterator(llnode* n): node(n) {}     // Let iterator point to n initially

// Pre-increment
llvec::iterator& llvec::iterator::operator++() {
  assert(this->node != nullptr);

  this->node = this->node->next;                     // Advance iterator by one element

  return *this;                                      // Return reference to advanced iterator
}
```


Iterator `llvec::iterator` (Step 1/2)

```
// Element access
int& llvec::iterator::operator*() const {
  return this->node->value;                          // Access current element
}


// Comparison
bool llvec::iterator::operator!=(const llvec::iterator& other)
   const {
  return this->node != other.node;                   // this iterator different from other if they
}                                                    // point to different element
```


An iterator for `llvec` (Repetition)

We need:

1. An `llvec`-specific iterator with at least the following functionality:
   - Access current element: `operator*`
   - Advance iterator: `operator++`
   - End-reached check: `operator!=` (or `operator==`)
2. Member functions `begin()` and `end()` for `llvec` to get an iterator to the beginning and past the end, respectively

Iterator `avec::iterator` (Step 2/2)

```
class llvec {
  ...
public:
  class iterator {...};

  iterator begin();
  iterator end();

  ...
}
```

`llvec` needs member functions to issue iterators pointing *to the beginning* and *past the end*, respectively, of the vector

Iterator `llvec::iterator` (Step 2/2)

```
llvec::iterator llvec::begin() {
  return llvec::iterator(this->head);
}

llvec::iterator llvec::end() {
  return llvec::iterator(nullptr);
}
```

Iterator to first vector element

Iterator past last vector element

Const-Iterators

- In addition to `iterator`, every container should also provide a *const-iterator* `const_iterator`
- Const-iterators grant only read access to the underlying Container
- For example for `llvec`:

```
llvec::const_iterator llvec::cbegin() const;
llvec::const_iterator llvec::cend() const;

const int& llvec::const_iterator::operator*() const;
...
```

- Therefore not possible (compiler error): `*(v.cbegin()) = 0`

Const-Iterators

Const-Iterator *can* be used to allow only reading:

```
llvec v = ...;
for (llvec::const_iterator it = v.cbegin(); ...)
  std::cout << *it;
```

It would also possible to use the non-const `iterator` here

Const-Iterators

Const-Iterator *must* be used if the vector is const:

```
const llvec v = ...;
for (llvec::const_iterator it = v.cbegin(); ...)
  std::cout << *it;
```

It is not possible to use `iterator` here (compiler error)

Excursion: Templates

- Goal: A *generic* output operator << for *iterable Containers*: `llvec`, `avec`, `std::vector`, `std::set`, ...
- I.e. `std::cout << c << 'n'` should work for any such container `c`

Excursion: Templates

Templates enable *type-generic* functions and classes:

- Templates enable the use of *types as arguments*

```
template <typename S, typename C>
S& operator<<(S& sink, const C& container);
```

We already know the pointy brackets from vectors. Vectors are also implemented as templates.

Intuition: operator works for every output stream `sink` of type `S` and every container `container` of type `C`

Excursion: Templates

Templates enable *type-generic* functions and classes:

- Templates enable the use of *types as arguments*

```
template <typename S, typename C>
S& operator<<(S& sink, const C& container);
```

- The compiler *infers* suitable types from the call arguments

```
std::set<int> s = ...;
std::cout << s << '\n';   ← S = std::ostream, C = std::set<int>
```

Excursion: Templates

Implementation of << *constrains* `S` and `C` (Compiler errors if not satisfied):

```
template <typename S, typename C>
S& operator<<(S& sink, const C& container) {
  for (typename C::const_iterator it = container.begin();
       it != container.end();
       ++it) {

    sink << *it << ' ';
  }

  return sink;
}
```

`C` must appropriate iterators
– with appropriate functions

Excursion: Templates

Implementation of << *constrains* `S` and `C` (Compiler errors if not satisfied):

```
template <typename S, typename C>
S& operator<<(S& sink, const C& container) {
  for (typename C::const_iterator it = container.begin();
       it != container.end();
       ++it) {

    sink << *it << ' ';
  }

  return sink;
}
```

`S` must support outputting elements (`*it`) and characters (`' '`)