4. C++ advanced (I)

Repetition: Vectors, Pointers and Iterators,
Range for, Keyword auto, a Class for Vectors, Subscript-operator,
Move-construction, Iterators

Learning objectives

- Keyword **`auto`**
- Ranged **`for`**
- Short recap of the Rule of Three
- Subscript operator
- Move Semantics, X-Values and the Rule of Five
- Custom Iterators

We look back...

```
#include <iostream>
#include <vector>
using iterator = std::vector<int>::iterator;

int main(){
  // Vector of length 10
  std::vector<int> v(10);
  // Input
  for (int i = 0; i < v.size(); ++i)
    std::cin >> v[i];
  // Output
  for (iterator it = v.begin(); it != v.end(); ++it)
    std::cout << *it << " ";
}
```

We want to understand this in depth!

Not as good as it could be!

4.1 Useful Tools

On our way to elegant, less complicated code.

auto

The keyword **auto** (from C++11):
The type of a variable is inferred from the initializer.

```
int x = 10;
auto y = x; // int
auto z = 3; // int
std::vector<double> v(5);
auto i = v[3]; // double
```

Slightly better...

```
#include <iostream>
#include <vector>

int main(){
  std::vector<int> v(10); // Vector of length 10

  for (int i = 0; i < v.size(); ++i)
    std::cin >> v[i];

  for (auto it = v.begin(); it != v.end(); ++it) {
    std::cout << *it << " ";
  }
}
```

Range `for` (C++11)

```
for (range-declaration : range-expression)
    statement;
```

- **range-declaration:** named variable of element type specified via the sequence in range-expression
- **range-expression:** Expression that represents a sequence of elements via iterator pair `begin()`, `end()`, or in the form of an intializer list.

```
std::vector<double> v(5);
for (double x: v) std::cout << x; // 00000
for (int x: {1,2,5}) std::cout << x; // 125
for (double& x: v) x=5;
```

Cool!

```
#include <iostream>
#include <vector>

int main(){
  std::vector<int> v(10); // Vector of length 10

  for (auto& x: v)
    std::cin >> x;

  for (const auto x: v)
    std::cout << x << " ";
}
```

4.2 Memory Allocation

Construction of a vector class

For our detailed understanding

We build a vector class with the same capabilities ourselves!

On the way we learn about

- **RAII (Resource Acquisition is Initialization) and move construction**
- **Subscript operators and other utilities**
- Templates
- Exception Handling
- Functors and lambda expressions

A class for (double) vectors

```
class Vector{
public:
    // constructors
    Vector(): sz{0}, elem{nullptr} {};
    Vector(std::size_t s): sz{s}, elem{new double[s]} {}
    // destructor
    ~Vector(){
        delete[] elem;
    }
    // (something is missing here)
private:
  std::size_t sz;
  double* elem;
}
```

Element access

```
class Vector{
    ...
    // getter. pre: 0 <= i < sz;
    double get(std::size_t i) const{
        return elem[i];
    }
    // setter. pre: 0 <= i < sz;
    void set(std::size_t i, double d){
        elem[i] = d;
    }
    // size property
    std::size_t size() const {
        return sz;
    }
}
```

```
class Vector{
public:
  Vector();
  Vector(std::size_t s);
  ~Vector();
  double get(std::size_t i) const;
  void set(std::size_t i, double d);
  std::size_t size() const;
}
```

(Vector Interface)

What's the problem here?

```
int main(){
  Vector v(32);
  for (std::size_t i = 0; i!=v.size(); ++i)
    v.set(i, i);
  Vector w = v;
  for (std::size_t i = 0; i!=w.size(); ++i)
    w.set(i, i*i);
  return 0;
}
```

```
class Vector{
public:
  Vector();
  Vector(std::size_t s);
  ~Vector();
  double get(std::size_t i) const;
  void set(std::size_t i, double d);
  std::size_t size() const;
}
```

(Vector Interface)

```
*** Error in `vector1': double free or corruption
(!prev): 0x0000000000d23c20 ***
======= Backtrace: =========
/lib/x86_64-linux-gnu/libc.so.6(+0x777e5)[0x7fe5a5ac97e5]
...
```

Rule of Three!

```
class Vector{
...
  public:
  // copy constructor
  Vector(const Vector &v)
    : sz{v.sz}, elem{new double[v.sz]} {
    std::copy(v.elem, v.elem + v.sz, elem);
  }
}
```

```
class Vector{
public:
  Vector();
  Vector(std::size_t s);
  ~Vector();
  Vector(const Vector &v);
  double get(std::size_t i) const;
  void set(std::size_t i, double d);
  std::size_t size() const;
}
```

(Vector Interface)

Rule of Three!

```
class Vector{
...
  // assignment operator
  Vector& operator=(const Vector& v){
    if (v.elem == elem) return *this;
    if (elem != nullptr) delete[] elem;
    sz = v.sz;
    elem = new double[sz];
    std::copy(v.elem, v.elem+v.sz, elem);
    return *this;
  }
}
```

```
class Vector{
public:
  Vector();
  Vector(std::size_t s);
  ~Vector();
  Vector(const Vector &v);
  Vector operator=(const Vector&v);
  double get(std::size_t i) const;
  void set(std::size_t i, double d);
  std::size_t size() const;
}
```

(Vector Interface)

Now it is correct, but cumbersome.

Constructor Delegation

```
public:
// copy constructor
// (with constructor delegation)
Vector(const Vector &v): Vector(v.sz)
{
  std::copy(v.elem, v.elem + v.sz, elem);
}
```

Copy-&-Swap Idiom

```
class Vector{
...
  // Assignment operator
  Vector& operator= (const Vector&v){
    Vector cpy(v);
    swap(cpy);
    return *this;
  }
private:
  // helper function
  void swap(Vector& v){
    std::swap(sz, v.sz);
    std::swap(elem, v.elem);
  }
}
```

copy-and-swap idiom: all members of `*this` are exchanged with members of `cpy`. When leaving `operator=`, `cpy` is cleaned up (deconstructed), while the copy of the data of `v` stay in `*this`.

Clarification of Terms: Idioms and Patterns

Idiom and **(Design) Pattern** are notions coming from **software engineering**

- Design patterns are general, reusable solutions to commonly occurring design problems. They capture best practices and usually describe relationships and interactions among classes and objects, e.g. the visitor pattern.
- Idioms are language-specific ways of implementing certain tasks/steps, e.g. the RAII idiom, or the Copy-&-Swap Idiom in C++. Idioms usually require less code than patterns.

Syntactic sugar.

Getters and setters are poor. We want a subscript (index) operator.

Overloading! So?

```
class Vector{
...
  double operator[] (std::size_t pos) const{
    return elem[pos];
  }

  void operator[] (std::size_t pos, double value){
    elem[pos] = value;
  }
}
```

No!

Reference types!

```
class Vector{
...
  // for non-const objects
  double& operator[] (std::size_t pos){
    return elem[pos]; // return by reference!
  }
  // for const objects
  const double& operator[] (std::size_t pos) const{
    return elem[pos];
  }
}
```

So far so good.

```
int main(){
  Vector v(32); // constructor
  for (int i = 0; i<v.size(); ++i)
    v[i] = i; // subscript operator

  Vector w = v; // copy constructor
  for (int i = 0; i<w.size(); ++i)
    w[i] = i*i;

  const auto u = w;
  for (int i = 0; i<u.size(); ++i)
    std::cout << v[i] << ":" << u[i] << " "; // 0:0 1:1 2:4 ...
  return 0;
}
```

4.3 Iterators

How to support the range **`for`**

Range `for`

We wanted this:

```
Vector v = ...;
for (auto x: v)
  std::cout << x << " ";
```

In order to support this, an iterator must be provided via **`begin`** and **`end`** .

Iterator for the vector

```
class Vector{
...
    // Iterator
    double* begin(){
        return elem;
    }
    double* end(){
        return elem+sz;
    }
}
```

(Pointers support iteration)

Const Iterator for the vector

```
class Vector{
...
  // Const-Iterator
    const double* begin() const{
        return elem;
    }
    const double* end() const{
        return elem+sz;
    }

}
```

Intermediate result

```
Vector Natural(int from, int to){
  Vector v(to-from+1);
  for (auto& x: v) x = from++;
  return v;
}

int main(){
  auto v = Natural(5,12);
  for (auto x: v)
    std::cout << x << " "; // 5 6 7 8 9 10 11 12
  std::cout << std::endl;
            << "sum = "
            << std::accumulate(v.begin(), v.end(),0); // sum = 68
  return 0;
}
```

Vector Interface

```
class Vector{
public:
  Vector(); // Default Constructor
  Vector(std::size_t s); // Constructor
  ~Vector(); // Destructor
  Vector(const Vector &v); // Copy Constructor
  Vector& operator=(const Vector&v); // Assignment Operator
  double& operator[] (std::size_t pos); // Subscript operator (read/write)
  const double& operator[] (std::size_t pos) const; // Subscript operator
  std::size_t size() const;
  double* begin(); // iterator begin
  double* end(); // iterator end
  const double* begin() const; // const iterator begin
  const double* end() const; // const iterator end
}
```

4.4 Efficient Memory-Management*

How to avoid copies

Number copies

How often is `v` being copied?

```
Vector operator+ (const Vector& l, double r){
    Vector result (l);  // copy of l to result
    for (std::size_t i = 0; i < l.size(); ++i)
      result[i] = l[i] + r;
    return result; // deconstruction of result after assignment
}
int main(){
    Vector v(16); // allocation of elems[16]
    v = v + 1;   // copy when assigned!
    return 0;    // deconstruction of v
}
```

`v` is copied (at least) twice

Move construction and move assignment

```
class Vector{
...
    // move constructor
    Vector (Vector&& v): Vector() {
        swap(v);
    };
    // move assignment
    Vector& operator=(Vector&& v){
        swap(v);
        return *this;
    };
}
```

Vector Interface

```
class Vector{
public:
  Vector();
  Vector(std::size_t s);
  ~Vector();
  Vector(const Vector &v);
  Vector& operator=(const Vector&v);
  Vector (Vector&& v);
  Vector& operator=(Vector&& v);
  const double& operator[] (std::size_t pos) const;
  double& operator[] (std::size_t pos);
  std::size_t size() const;
}
```

Explanation

When the source object of an assignment will not continue existing after an assignment the compiler can use the move assignment instead of the assignment operator.[5] Expensive copy operations are then avoided.

Number of copies in the previous example goes down to 1.

[5] Analogously so for the copy-constructor and the move constructor

Illustration of the Move-Semantics

```
// nonsense implementation of a "vector" for demonstration purposes
class Vec{
public:
  Vec () {
    std::cout << "default constructor\n";}
  Vec (const Vec&) {
    std::cout << "copy constructor\n";}
  Vec& operator = (const Vec&) {
    std::cout << "copy assignment\n"; return *this;}
  ~Vec() {}
};
```

How many Copy Operations?

```
Vec operator + (const Vec& a, const Vec& b){
    Vec tmp = a;
    // add b to tmp
    return tmp;
}

int main (){
    Vec f;
    f = f + f + f + f;
}
```

Output
default constructor
copy constructor
copy constructor
copy constructor
copy assignment

4 copies of the vector

Illustration of the Move-Semantics

```
// nonsense implementation of a "vector" for demonstration purposes
class Vec{
public:
  Vec () { std::cout << "default constructor\n";}
  Vec (const Vec&) { std::cout << "copy constructor\n";}
  Vec& operator = (const Vec&) {
    std::cout << "copy assignment\n"; return *this;}
  ~Vec() {}
  // new: move constructor and assignment
  Vec (Vec&&) {
    std::cout << "move constructor\n";}
  Vec& operator = (Vec&&) {
    std::cout << "move assignment\n"; return *this;}
};
```

How many Copy Operations?

```
Vec operator + (const Vec& a, const Vec& b){
    Vec tmp = a;
    // add b to tmp
    return tmp;
}

int main (){
    Vec f;
    f = f + f + f + f;
}
```

Output
default constructor
copy constructor
copy constructor
copy constructor
move assignment

3 copies of the vector

How many Copy Operations?

```
Vec operator + (Vec a, const Vec& b){
    // add b to a
    return a;
}

int main (){
    Vec f;
    f = f + f + f + f;
}
```

Output
default constructor
copy constructor
move constructor
move constructor
move constructor
move assignment

1 copy of the vector

Explanation: move semantics are applied when an x-value (expired value) is assigned. R-value return values of a function are examples of x-values.

`http://en.cppreference.com/w/cpp/language/value_category`

How many Copy Operations?

```
void swap(Vec& a, Vec& b){
    Vec tmp = a;
    a=b;
    b=tmp;
}

int main (){
    Vec f;
    Vec g;
    swap(f,g);
}
```

Output
default constructor
default constructor
copy constructor
copy assignment
copy assignment

3 copies of the vector

Forcing x-values

```
void swap(Vec& a, Vec& b){
    Vec tmp = std::move(a);
    a=std::move(b);
    b=std::move(tmp);
}
int main (){
    Vec f;
    Vec g;
    swap(f,g);
}
```

Output
default constructor
default constructor
move constructor
move assignment
move assignment

0 copies of the vector

Explanation: With std::move an l-value expression can be forced into an x-value. Then move-semantics are applied.

`http://en.cppreference.com/w/cpp/utility/move`

`std::swap` & `std::move`

`std::swap` is implemented as above (using templates)
`std::move` can be used to move the elements of a container into another

```
std::move(va.begin(),va.end(),vb.begin())
```

Conclusion

- Use **`auto`** to infer a type from the initializer.
- X-values are values where the compiler can determine that they go out of scope.
- Use move constructors in order to move X-values instead of copying.
- When you know what you are doing then you can enforce the use of X-Values.
- Subscript operators can be overloaded. In order to write, references are used.
- Behind a ranged **`for`** there is an iterator working.
- Iteration is supported by implementing an iterator following the syntactic convention of the standard library.

5. C++ advanced (II): Templates

Some (converted) slides from Malte Schwerhoff

Generic Programming

Goal: Make code (functions, classes) as widely usable as possible

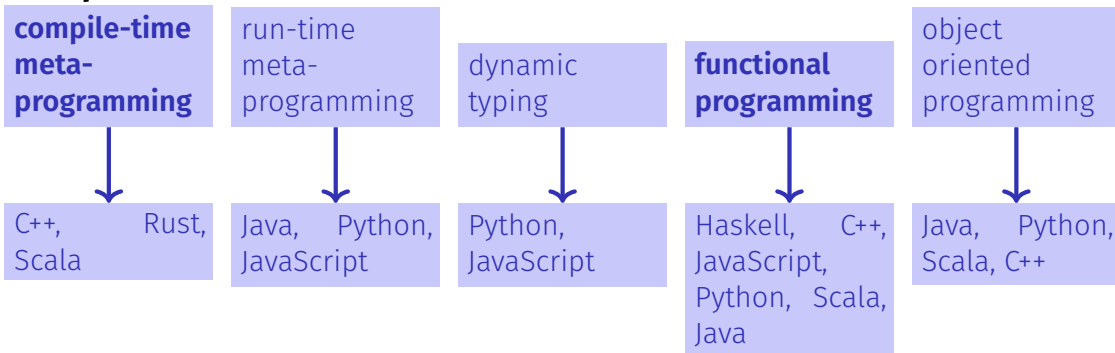
Familiar use-cases:

- `vector`: store objects of any type, e.g. ints, strings, ...
- `std::max(e1, e2)`: return the greater of any two objects
- `Exp* e = new ...; e.eval()`: evaluate any expression (variable, constant, sum, product, ...)

Generic Programming

How: Different languages implement different approaches (and typically more than one), but high-level ideas are often similar.

Examples:



Motivation

Goal: generic vector class and functionality.

```
Vector<double> vd(10);
Vector<int> vi(10);
Vector<char> vi(20);

auto nd = vd * vd; // norm (vector of double)
auto ni = vi * vi; // norm (vector of int)
```

Parametric Polymorphism

Types as template parameters

1. In the concrete implementation of a class replace the type that should become generic (in our example: **`double`**) by a representative element, e.g. **`T`**.
2. Put in front of the class the construct **`template<typename T>`** Replace **`T`** by the representative name).

The construct **`template<typename T>`** can be understood as **"for all types `T`"**.

Types as Template Parameters

```
template <typename ElementType>
class Vector{
    std::size_t size;
    ElementType* elem;
public:
    ...
    Vector(std::size_t s):
        size{s},
        elem{new ElementType[s]}{}
    ...
    ElementType& operator[](std::size_t pos){
        return elem[pos];
    }
    ...
}
```

Template Instances

`Vector<typeName>` generates a type instance `Vector` with `ElementType=typeName`.

```
Vector<double> x;       // vector of double
Vector<int> y;          // vector of int
Vector<Vector<double>> x; // vector of vector of double
```

Notation: **Type Instantiation**.

Type-checking

Templates are basically replacement rules at instantiation time and during compilation. The compiler always checks as little as necessary and as much as possible.

Example

```
template <typename T>
class Pair{
    T left; T right;
public:
    Pair(T l, T r):left{l}, right{r}{}
    T min(){
      return left < right ? left : right;
    }
};

Pair<int> a(10,20); // ok
auto m = a.min(); // ok
Pair<Pair<int>> b(a,Pair<int>(20,30)); // ok
auto n = b.min(); // no match for operator< !
```

Parametric Polymorphism II

Function Templates

1. To make a concrete implementation generic, replace the specific type (e.g. int) with a name, e.g. `T`,
2. Put in front of the function the construct `template<typename T>` (Replace `T` by the chosen name)

Function Templates

```
template <typename T>
void swap(T& x, T&y){
    T temp = x;
    x = y;
    y = temp;
}
```

The actual parameters' types determine the version of the function that is (compiled) and used:

```
int x=5;
int y=6;
swap(x,y); // calls swap with T=int
```

Safety

```
template <typename T>
void swap(T& x, T&y){
    T temp = x;
    x = y;
    y = temp;
}
```

An inadmissible version of the function is not generated:

```
int x=5;
double y=6;
swap(x,y); // error:  no matching function for ...
```

.. also with operators

```
template <typename T>
class Pair{
    T left; T right;
public:
    Pair(T l, T r):left{l}, right{r}{}
    T min(){ return left < right? left: right; }
    std::ostream& print (std::ostream& os) const{
        return os << "("<< left << "," << right<< ")";
    }
};

template <typename T>
std::ostream& operator<< (std::ostream& os, const Pair<T>& pair){
    return pair.print(os);
}
```

```
Pair<int> a(10,20); // ok
std::cout << a; // ok
```

Useful!

```
// Output of an arbitrary container
template <typename T>
void output(const T& t){
    for (const auto& x: t)
        std::cout << x << " ";
    std::cout << "\n";
}

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

Neat: a generic function that can be applied to all containers.
What are the limits of this function?

- Requirements for T?
- Requirements on Elements of T?

Explicit Type

```
// input of an arbitrary pair
template <typename T>
Pair<T> read(){
  T left;
  T right;
  std::cin << left << right;
  return Pair<T>(left,right);
}
...

auto p = read<double>();
```

If the type of a template instantiation cannot be inferred, it has to be provided explicitly.

Type Inference

- Upon instantiation, template parameters must be provided explicitly – except if the compiler can infer them from provided arguments
- Type inference improved with C++17

```
auto p1 = Pair<int>(1,2); // OK
Pair<int> p2 = Pair(1,2); // C++14: error; C++17: OK
auto p3 = Pair(1,2); // C++14: error; C++17: OK
```

Powerful!

```
template <typename T> // square number
T sq(T x){
    return x*x;
}
template <typename Container, typename F>
void  apply(Container& c, F f){ // x <- f(x) forall x in c
    for(auto& x: c)
        x = f(x);
}
int main(){
  std::vector<int> v={1,2,3};
  apply(v,sq<int>);
  output(v); // 1 4 9
}
```

Conclusion

- Templates improve code reusability, by making classes and functions parametric w.r.t. types
- Implemented via static code-generation (compile-time meta-programming)
  - Advantages
    - No runtime overhead (compared to dynamic solutions, e.g. inheritance or dynamic typing)
    - Compiler can optimise generated code as usual
    - Type-dependent static specialisation possible (see below)
  - Disadvantages
    - Separate compilation (.h vs. .cpp) no longer possible
    - Resulting binary (machine code) larger
    - Delayed type checking, more complex error messages (mitigatable via concepts, see next)

Concepts (C++20)

```
struct Student { ... }; // Lacks == and < operators

template <typename K>
struct BSTNode {
  K key;
  ...
  bool contains(K search_key) {
    if (search_key < key) ...
    else if (search_key == key) ...
    else ...
  }
};

auto n1 = BSTNode(8);
auto n2 = BSTNode("Howdy!");
auto n3 = BSTNode(new int(8));
auto n4 = BSTNode(Student("Omar"));
```

Code compiles just fine

- But should it?
- If it shouldn't, why does it compile?

Concepts (C++20)

```
auto n4 = BSTNode(Student("Omar"));
n4.contains(Student("Ida")); // Error!
```

Code fails to compile

```
test.cpp:29:
  In instantiation of
  'bool BSTNode<K>::contains(K)
  [with K = Student]':
test.cpp:21:
  no match for 'operator<' (operand types
  are 'Student' and 'Student')
     21 |     if (search_key < key)
        |
```

Problems:

- Instantiation of **`BSTNode<Student>`** already nonsensical, but accepted by the compiler
- Requirement on concrete **`K`**s scattered across code, not part of declaration

Concepts (C++20)

Better: explicit requirement, prevent nonsensical instantiations.

```
struct Student { ... }; // Lacks < operators

template <typename T>
concept Comparable = requires(T t1, T t2) {
  { t1 < t2 };
};
template <Comparable K>
struct BSTNode {
  K key;
     ...
    bool contains(K search_key) { ... }
};

auto n4 = BSTNode(Student("Omar")); // Error
```

```
test.cpp:43:
  In substitution of 'template<class K>
  BSTNode(K)-> BSTNode<K> [with K = Student]:
test.cpp:23:
  template constraint failure for
  'template<class K> requires Comparable<K>
  struct BSTNode
test.cpp:4:
  required for the satisfaction of Comparable<K>
  [with K = Student]
```

Concepts (C++20)

```
#include <algorithm>
#include <vector>
#include <list>

template <typename Iter>
void clever_sort(Iter begin, Iter end) {
  if (!is_sorted(begin, end))
    std::sort(begin, end);
}

int main() {
  std::vector<int> data1 = {3,-1,10};
  clever_sort(data1.begin(), data1.end());

  std::list<int> data2 = {3,-1,10};
  clever_sort(data2.begin(), data2.end());
}
```

```
In file included from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/algorithm:62,
                 from <source>:1:
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_algo.h: In instantiation of 'void std::__sort(
      _RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = std::_List_iterator<int>;
      _Compare = __gnu_cxx::__ops::_Iter_less_iter]':
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_algo.h:4842:18: required from 'void std::sort(_RAIter, _RAIter)
      [with _RAIter = std::_List_iterator<int>]'
<source>:10:14: required from 'void clever_sort(Iter, Iter) [with Iter = std::_List_iterator<int>]'
<source>:18:14: required from here
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_algo.h:1955:50: error: no match for 'operator-' (operand types
      are 'std::_List_iterator<int>' and 'std::_List_iterator<int>')
 1955 |                               std::__lg(__last - __first) * 2,
      |                                         ~~~~~~~^~~~~~~~
In file included from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_algobase.h:67,
                 from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/algorithm:61,
                 from <source>:1:
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_iterator.h:560:5: note: candidate: 'template<class _IteratorL,
      class _IteratorR> constexpr decltype ((__y.base() - __x.base())) std::operator-(const std::reverse_iterator<_Iterator
      R>&, const std::reverse_iterator<_IteratorR>&)'
  560 |     operator-(const reverse_iterator<_IteratorL>& __x,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_iterator.h:560:5: note: template argument deduction/
      substitution failed:
In file included from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/algorithm:62,
                 from <source>:1:
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_algo.h:1955:50: note: 'std::_List_iterator<int>' is not derived
      from 'const std::reverse_iterator<_Iterator>'
 1955 |                               std::__lg(__last - __first) * 2,
      |                                         ~~~~~~~^~~~~~~~
In file included from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_algobase.h:67,
                 from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/algorithm:61,
                 from <source>:1:
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_iterator.h:1639:5: note: candidate: 'template<class _IteratorL,
       class _IteratorR> constexpr decltype ((__x.base() - __y.base())) std::operator-(const std::move_iterator<_IteratorL>&,
      const std::move_iterator<_IteratorR>&)'
 1639 |     operator-(const move_iterator<_IteratorL>& __x,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_iterator.h:1639:5: note: template argument deduction/
      substitution failed:
In file included from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/algorithm:62,
                 from <source>:1:
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_algo.h:1955:50: note: 'std::_List_iterator<int>' is not derived
      from 'const std::move_iterator<_IteratorL>'
 1955 |                               std::__lg(__last - __first) * 2,
      |                                         ~~~~~~~^~~~~~~~
```

Concepts (C++20)

```
#include <algorithm>
#include <vector>
#include <list>
#include <iterator>

template<std::random_access_iterator Iter>
void clever_sort(Iter begin, Iter end) {
  if (!is_sorted(begin, end))
    std::sort(begin, end);
}

int main() {
  std::vector<int> data1 = {3,-1,10};
  clever_sort(data1.begin(), data1.end());

  std::list<int> data2 = {3,-1,10};
  clever_sort(data2.begin(), data2.end());
}
```

```
In function 'int main()':
<source>:18:14: error: no matching function for call to 'clever_sort(std::__cxx11::list<int>::
    iterator, std::__cxx11::list<int>::iterator)'
   18 |   clever_sort(data2.begin(), data2.end());
      |   ~~~~~~~~~~^~~~~~~~~~~~~~~~~~~~~~~~~~~~~
<source>:8:6: note: candidate: 'template<class Iter> requires random_access_iterator<Iter>
    void clever_sort(Iter, Iter)'
    8 | void clever_sort(Iter begin, Iter end) {
      |      ^~~~~~~~~~
<source>:8:6: note: template argument deduction/substitution failed:
<source>:8:6: note: constraints not satisfied
In file included from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/compare:39,
                 from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/stl_pair.h:65,
                 from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/utility:70,
                 from /opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/algorithm:60,
                 from <source>:1:
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/concepts: In substitution of 'template<
    class Iter> requires random_access_iterator<Iter> void clever_sort(Iter, Iter) [with Iter
     = std::_List_iterator<int>]':
<source>:18:14:  required from here
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/concepts:67:13: required for the
    satisfaction of 'derived_from<typename std::__detail::__iter_concept_impl<_Iter>::type,
    std::random_access_iterator_tag>' [with _Iter = std::_List_iterator<int>]
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/bits/iterator_concepts.h:660:13:
    required for the satisfaction of 'random_access_iterator<Iter>' [with Iter = std::
    _List_iterator<int>]
/opt/compiler-explorer/gcc-11.2.0/include/c++/11.2.0/concepts:67:28: note: 'std::
    random_access_iterator_tag' is not a base of 'std::bidirectional_iterator_tag'
   67 |     concept derived_from = __is_base_of(_Base, _Derived)
      |                            ^~~~~~~~~~~~~~~~~~~~~~~~~~~~~
          ~~~~~~~^~~~~~~~~
```

Specialization

- Basic idea: general implementation for arbitrary types, but specialised (usually: more efficient) implementation for specific types
- Applicable to data structures (e.g. more space-efficient internal representation) and algorithms (e.g. more efficient sorting)
- Examples:
  - General `vector<T>`, but space-compressed `vector<bool>`
  - Quicksort for a random-access container, Mergesort otherwise

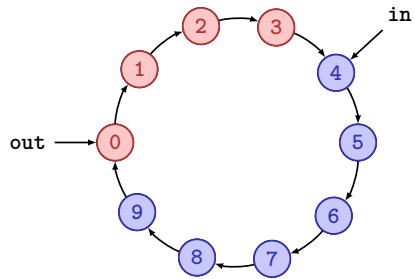
Specialization

```
template <>
class Pair<bool>{
    short both;
public:
    Pair(bool l, bool r):both{(l?1:0) + (r?2:0)} {};
    std::ostream& print (std::ostream& os) const{
        return os << "("<< both % 2 << "," << both /2 << ")";
    }
};
```

```
Pair<int> i(10,20); // ok -- generic template
std::cout << i << std::endl; // (10,20);
Pair<bool> b(true, false); // ok -- special bool version
std::cout << b << std::endl; // (1,0)
```

Template Parameterization with Values

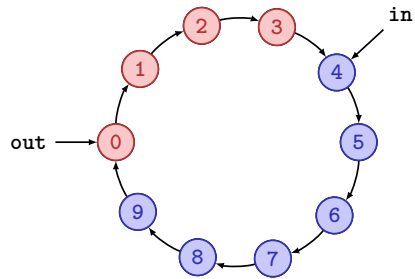
```
template <typename T, int size>
class CircularBuffer{
  T buf[size] ;
  int in; int out;
public:
  CircularBuffer():in{0},out{0}{};
  bool empty(){
    return in == out;
  }
  bool full(){
    return (in + 1) % size == out;
  }
  void put(T x); // declaration
  T get();    // declaration
};
```



Template Parameterization with Values

```
template <typename T, int size>
void CircularBuffer<T,size>::put(T x){
    assert(!full());
    buf[in] = x;
    in = (in + 1) % size;
}

template <typename T, int size>
T CircularBuffer<T,size>::get(){
    assert(!empty());
    T x = buf[out];
    out = (out + 1) % size;
    return x;
}
```



Potential for optimization if size $= 2^k$.

Specialisation

Specialisation has many different use cases, and can come in different forms:

- Optimization by specialisation of types: e.g. **`vector<T>`** generic, and **`vector<bool>`** specific
- Optimisation by specialisation for values: e.g. **`std::array<T, n>`**
- Type-specifict implementation via specialisations: e.g. **`std::hash<T>`**, used e.g. by **`std::unordered_set`**.
  This idea is the base of traits.