Templates

Warning: we will not use slides for this lecture.
This is all meant as a reference.

Summary of Feedback

Likes

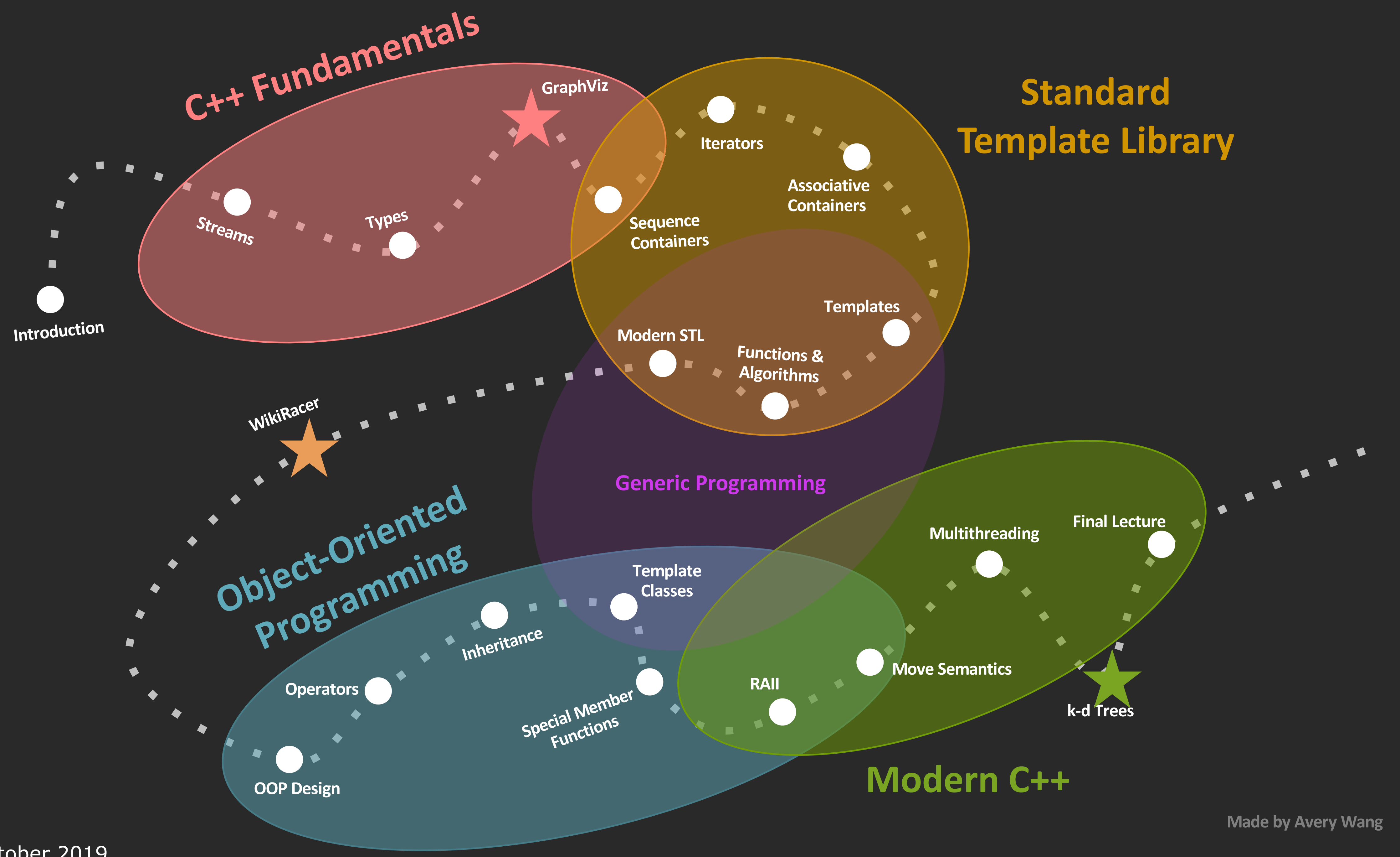
- engaging lectures
- slides look nice
- we’re “nice”
- class is really chill
- amount of questions

Dislikes

- too fast/too much content
- too many slides
- want more practice
- want interactive lectures
- amount of questions

Key Changes

- we’ll post 1-2 practice exercises on Piazza after lecture.
- content/slides will be scaled back by ~30%.
- practice time: can choose between asking questions, or working on the practice exercises.



C++ Fundamentals
Standard Template Library
Introduction
Streams
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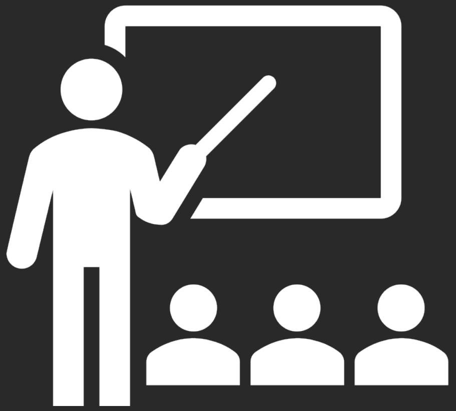
Multithreading
Final Lecture
k-d Trees
Modern C++
Made by Avery Wang

Game Plan



- template functions
- varadic templates
- concept lifting
- implicit interfaces & concepts

Write a minmax function which returns a pair {min, max} of parameters.

```
int main() {
  auto [min, max] = my_minmax(4, 7);
  cout << min << endl; // 4
  cout << max << endl; // 7
}
```

Write a minmax function which returns a pair {min, max} of parameters.

```
pair<int, int> my_minmax(int a, int b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

What if we wanted to handle different types?

```
int main() {
  auto [min, max] = my_minmax(4.2, -7.9);
  cout << min << endl; // -7.9
  cout << max << endl; // 4.2
}
```

What if we wanted to handle different types?

```
int main() {
  auto [min, max] = my_minmax("Anna", "Avery");
  cout << min << endl; // Avery
  cout << max << endl; // Anna
}
```

template functions

Classic C-solution: write separate functions.

```
pair<int, int> my_minmax_int(int a, int b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<double, double> my_minmax_double(double a, double b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<string, string> my_minmax_string(string a, string b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Problem: each function has a different name!

Slightly better: overloaded functions.

```
pair<int, int> my_minmax(int a, int b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<double, double> my_minmax(double a, double b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<string, string> my_minmax(string a, string b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Problem: you have to write a function for every single type.

Slightly better: overloaded functions.

```
pair<int, int> my_minmax(int a, int b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<double, double> my_minmax(double a, double b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<string, string> my_minmax(string a, string b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Bigger problem: how do you handle user defined types?

An observation: the highlighted parts are identical.

```
pair<int, int> my_minmax(int a, int b) {
  if (a < b) return {a, b};
  else return {b, a};
}
---------------------------------------------------
pair<double, double> my_minmax(double a, double b) {
  if (a < b) return {a, b};
  else return {b, a};
}
---------------------------------------------------
pair<string, string> my_minmax(string a, string b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Only the types are different.

```
pair<int, int> my_minmax(int a, int b) {
  if (a < b) return {a, b};
  else return {b, a};
}
--------------------------------------------------------------
pair<double, double> my_minmax(double a, double b) {
  if (a < b) return {a, b};
  else return {b, a};
}
--------------------------------------------------------------
pair<string, string> my_minmax(string a, string b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Let’s write a general form in terms of a type T.

```
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

```
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Let’s write a general form in terms of a type T.

```
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

We have a generic function!

```
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Be sure to inform the compiler that T is a type.

```
template <typename T>
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Explicit instantiation: specify the type T.

```
int main() {
  auto [min1, max1] = my_minmax<double>(4.2, -7.9);
  auto [min2, max2] = my_minmax<string>(“Avery”, “Anna”);
  auto [min3, max3] = my_minmax<int>(3, 3);
  auto [min4, max4] = my_minmax<double>(2, 2.3);
  auto [min5, max5] = my_minmax<vector<int>>({1, 2}, {3, 1});
}
```

Let’s walk through what the compiler does!

```
int main() {
  auto [min1, max1] = my_minmax<double>(4.2, -7.9);
  auto [min2, max2] = my_minmax<string>("Anna", "Avery");
  auto [min3, max3] = my_minmax<int>(3, 3);
  auto [min4, max4] = my_minmax<double>(2, -6.2);
  auto [min5, max5] = my_minmax<vector<int>>({1, 2}, {3, 1});
}
```

```
template <typename T>
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

We have a template that looks like that!

Let’s walk through what the compiler does!

```
int main() {
  auto [min1, max1] = my_minmax<double>(4.2, -7.9);
  auto [min2, max2] = my_minmax<string>("Anna", "Avery");
  auto [min3, max3] = my_minmax<int>(3, 3);
  auto [min4, max4] = my_minmax<double>(2, -6.2);
  auto [min5, max5] = my_minmax<vector<int>>({1, 2}, {3, 1});
}
```

```
template <typename double>
pair<double, double> my_minmax(double a, double b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Let’s replace the T’s.
We have our function!

And just in case the type is a large collection.

```
template <typename T>
pair<T, T> my_minmax(T a, T b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

And just in case the type is a large collection.

```
template <typename T>
pair<T, T> my_minmax(const T& a, const T& b) {
  if (a < b) return {a, b};
  else return {b, a};
}
```

Your turn: make this function generic!

```
int getInteger(const string& prompt, const string& reprompt) {
  while (true) {
    cout << prompt;
    string line; int result; char extra;
    if (!getline(cin, line))
      throw domain_error("[shortened]");
    istringstream iss(line);
    if (iss >> result && !(iss >> extra)) return result;
    cout << reprompt << endl;
  }
}
```

Your turn: make this function generic!

```
template <typename T>
T getInteger(const string& prompt, const string& reprompt) {
  while (true) {
    cout << prompt;
    string line; T result; char extra;
    if (!getline(cin, line))
      throw domain_error("[shortened]");
    istringstream iss(line);
    if (iss >> result && !(iss >> extra)) return result;
    cout << reprompt << endl;
  }
}
```

(optional)
varadic templates

skipped during lecture, but really cool.

C++11

Generic Programming and Lifting

Concept Lifting

Looking at the assumptions you place on the parameters, and questioning if they are really necessary.

Can you solve a more general problem by relaxing the constraints?

Why write generic functions?

Count how many times 3 appears in a vector<int>.
Count how many times 4.7 appears in a vector<double>.
Count how many times ‘X’ appears in a string.
Count how many times ‘X’ appears in a deque<char>.
Count how many times 5 appears in the second half of a list<string>.
Count how many elements in the second half of a list<string> are at most 5.

How many times does the integer [val] appear in a vector of integers?

```
template <>
int countOccurences(const vector<int>& vec,
                                        int val) {
   int count = 0;
   for (size_t i = 0; i < vec.size(); ++i) {
     if (vec[i] == val) ++count;
   }
   return count;
}
```

What unnecessary assumption does the function make?

How many times does the integer [val] appear in a vector of integers?

```
template <>
int countOccurences(const vector<int>& vec,
                                          int val) {
   int count = 0;
   for (size_t i = 0; i < vec.size(); ++i) {
      if (vec[i] == val) ++count;
   }
   return count;
}
```

What unnecessary assumption does the function make?

How many times does the [type] [val] appear in a vector of [type]?

```
template <typename DataType>
int countOccurences(const vector<DataType>& vec,
                                      DataType val) {
  int count = 0;
  for (size_t i = 0; i < vec.size(); ++i) {
    if (vec[i] == val) ++count;
  }
  return count;
}
```

What unnecessary assumption does the function make?

How many times does the [type] [val] appear in a vector of [type]?

```
template <typename DataType>
int countOccurences(const vector<DataType>& vec,
                    DataType val) {
  int count = 0;
  for (size_t i = 0; i < vec.size(); ++i) {
    if (vec[i] == val) ++count;
  }
  return count;
}
```

What unnecessary assumption does the function make?

How many times does the [type] [val] appear in a [collection] of [type]?

```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                                    DataType val) {
  int count = 0;
  for (size_t i = 0; i < list.size(); ++i) {
    if (list[i] == val) ++count;
  }
  return count;
}
```

This code does not work. Why?

How many times does the [type] [val] appear in a [collection] of [type]?

```
list<int> list = {1.1, 3.14, 3.14, 3.14, 1.1};
int count = countOccurences(list, 3.14);
```

Sample code calling our function that won't work.

How many times does the [type] [val] appear in a [collection] of [type]?

```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                                                  DataType val) {
  int count = 0;
  for (size_t i = 0; i < list.size(); ++i) {
    if (list[i] == val) ++count;
  }
  return count;
}
```

We are indexing through a potentially unindexable collection.

Recall: iterators offer a “standardized” way of traversing a container.

```
for (auto iter = container.begin();
          iter != container.end(); ++iter) {
  cout << *iter << ‘\n’;
}
```

No matter what container is, this prints the elements of that container.

How many times does the [type] [val] appear in a [collection] of [type]?

```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                                     DataType val) {
   int count = 0;
   for (auto iter = list.begin(); iter != list.end(); ++iter) {
     if (*iter == val) ++count;
   }
   return count;
}
```

Solved using iterators!

How many times does the [type] [val] appear in a [collection] of [type]?

```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                                DataType val) {
  int count = 0;
  for (auto iter = list.begin(); iter != list.end(); ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

This still makes one last assumption.

How many times does the [type] [val] appear in [a range of elements]?

```
template <typename InputIterator, typename DataType>
int countOccurences(InputIterator begin, InputIterator end,
                                   DataType val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

We even give control of where the start and end should be.

Why write generic functions?

Count how many times 3 appears in a vector<int>.
Count how many times 4.7 appears in a vector<double>.
Count how many times ‘X’ appears in a string.
Count how many times ‘X’ appears in a deque<char>.
Count how many times 5 appears in the second half of a list<int>.
Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
```

Count how many times 4.7 appears in a vector<double>.
Count how many times ‘X’ appears in a string.
Count how many times ‘X’ appears in a deque<char>.
Count how many times 5 appears in the second half of a list<int>.
Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
```

Count how many times 4.7 appears in a vector<double>.

Count how many times ‘X’ appears in a string.

Count how many times ‘X’ appears in a deque<char>.

Count how many times 5 appears in the second half of a list<int>.

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
```

Count how many times ‘X’ appears in a string.

Count how many times ‘X’ appears in a deque<char>.

Count how many times 5 appears in the second half of a list<int>.

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
```

Count how many times 'X' appears in a string.

Count how many times 'X' appears in a deque<char>.

Count how many times 5 appears in the second half of a list<int>.

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
countOccurences(s.begin(), s.end(), ‘X’);
```

Count how many times ‘X’ appears in a deque<char>.

Count how many times 5 appears in the second half of a list<int>.

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
countOccurences(s.begin(), s.end(), ‘X’);
```

Count how many times ‘X’ appears in a deque<char>.

Count how many times 5 appears in the second half of a list<int>.

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
countOccurences(s.begin(), s.end(), ‘X’);
countOccurences(d.begin(), d.end(), ‘X’);
```

Count how many times 5 appears in the second half of a list<int>.

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
countOccurences(s.begin(), s.end(), ‘X’);
countOccurences(d.begin(), d.end(), ‘X’);
```

Count how many times 5 appears in the second half of a list<int>.

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
countOccurences(s.begin(), s.end(), ‘X’);
countOccurences(d.begin(), d.end(), ‘X’);
countOccurences((l.begin()+l.end())/2, l.end(), 5);
```

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
countOccurences(s.begin(), s.end(), ‘X’);
countOccurences(d.begin(), d.end(), ‘X’);
countOccurences((l.begin()+l.end())/2, l.end(), 5);
```

Count how many elements in the second half of a list<int> are at most 5.

Why write generic functions?

```
countOccurences(v.begin(), v.end(), 3);
countOccurences(v.begin(), v.end(), 4.7);
countOccurences(s.begin(), s.end(), ‘X’);
countOccurences(d.begin(), d.end(), ‘X’);
countOccurences((l.begin()+l.end())/2, l.end(), 5);
```

Count how many elements in the second half of a list<int> are at most 5.

We’ll tackle this one next time!

Your turn:
lift this function to its most generic form.

```
int main() {
   vector<int> v1{1, 2, 3, 4};
   vector<int> v2{1, 2, 4, 6};
   vector<int> v3{1, 2, 3, 4};
   vector<int> v4{1, 2, 3};

   auto [match, l1, l2] = mismatch(v1, v2); // {false, 3, 4}
   auto [match, r1, r3] = mismatch(r1, r3); // {true, 0, 0}
   auto [match, k1, k4] = mismatch(k1, k4); // undefined
}
```

Your turn:
lift this function to its most generic form.

```
tuple<bool, int, int> mismatch(const vector<int>& vec1,
                               const vector<int>& vec2)
  size_t i = 0;
  while (i < vec1.size() && vec1[i] == vec2[i]){
    ++i;
  }
  if (i == vec1.size()) return {true, 0, 0};
  else return {false, vec1[i], vec2[i]};
}
```

Your turn:
lift this function to its most generic form.

```
tuple<bool, int, int> mismatch(const vector<int>& vec1,
                               const vector<int>& vec2)
  size_t i = 0;
  while (i < vec1.size() && vec1[i] == vec2[i]){
    ++i;
  }
  if (i == vec1.size()) return {true, 0, 0};
  else return {false, vec1[i], vec2[i]};
}
```

Can you get rid of the boolean?

Your turn:
lift this function to its most generic form.

```
template <??>
pair<??, ??> mismatch(???)




}
```

Your turn:
lift this function to its most generic form.

```
template <typename InputIt1 typename InputIt2>
pair<int, int> mismatch(InputIt1 first1, InputIt1 last1,
                        InputIt2 first2)
  while (first1 != last1 && *first1 == *first2){
    ++first1; ++first2;
  }

  return {first1, first2};
}
```

Implicit Interfaces and Concepts

The compiler literally replaces each template parameter with whatever you instantiate it with.

```
vector<int> v1{1, 2, 3, 1, 2, 3};
vector<int> v2{1, 2, 3};
countOccurences(v1.begin(), v1.end(), v2.begin());
```

Suppose I write the code above.

The compiler literally replaces each template parameter with whatever you instantiate it with.

```cpp
template <typename InputIterator, typename DataType>
int countOccurences(InputIterator begin,
                    InputIterator end,
                    DataType val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

The compiler literally replaces each template parameter with whatever you instantiate it with.

```
template <typename InputIterator, typename DataType>
int countOccurences(vector<int>::input_iterator begin,
                    vector<int>::input_iterator end,
                    vector<int>::input_iterator val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

The compiler literally replaces each template parameter with whatever you instantiate it with.

```
template <typename InputIterator, typename DataType>
int countOccurences(vector<int>::input_iterator begin,
                    vector<int>::input_iterator end,
                    vector<int>::input_iterator val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

The problem is here: *iter has type int, and can't be compared to an iterator.

A template function defines an implicit interface that each template parameter must satisfy.

```
template <typename InputIterator, typename DataType>
int countOccurences(InputIterator begin, InputIterator end,
                    DataType val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

What must be true of InputIterator and DataType?

A template function defines an implicit interface that each template parameter must satisfy.

```
template <typename InputIterator, typename DataType>
int countOccurences(InputIterator begin, InputIterator end,
                    DataType val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

begin must be copyable.

A template function defines an implicit interface that each template parameter must satisfy.

```
template <typename InputIterator, typename DataType>
int countOccurences(InputIterator begin, InputIterator end,
                    DataType val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

iter must be equality comparable to end.

A template function defines an implicit interface that each template parameter must satisfy.

```
template <typename InputIterator, typename DataType>
int countOccurences(InputIterator begin, InputIterator end,
                    DataType val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

You must be able to increment iter.

A template function defines an implicit interface that each template parameter must satisfy.

```
template <typename InputIterator, typename DataType>
int countOccurences(InputIterator begin, InputIterator end,
                    DataType val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

You must be able to dereference iter and equality compare it to val.

Each template parameter must have the operations the function assumes it has.

InputIterator must support

- copy assignment (iter = begin)
- prefix operator (++iter)
- comparable to end (begin != end)
- dereference operator (*iter)

DataType must support

- comparable to *iter

Nasty compile errors if instantiated type does not support these.

More practice: what is the implicit interface?

```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                                      DataType val) {
  int count = 0;
  for (size_t i = 0; i < list.size(); ++i) {
    if (list[i] == val) ++count;
  }
  return count;
}
```

More practice: what is the implicit interface?

```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                                 DataType val) {
  int count = 0;
  for (size_t i = 0; i < list.size(); ++i) {
    if (list[i] == val) ++count;
  }
  return count;
}
```

Collection must have a method size() that returns an integer.

More practice: what is the implicit interface?

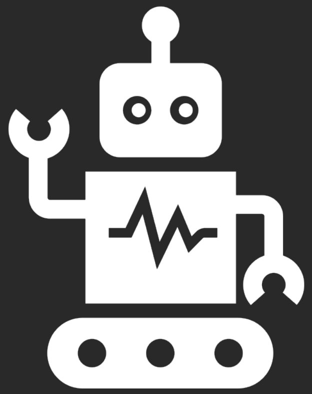
```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                    DataType val) {
  int count = 0;
  for (size_t i = 0; i < list.size(); ++i) {
    if (list[i] == val) ++count;
  }
  return count;
}
```

Collection must support the subscript operator ([ ])

More practice: what is the implicit interface?

```
template <typename Collection, typename DataType>
int countOccurences(const Collection<DataType>& list,
                                DataType val) {
  int count = 0;
  for (size_t i = 0; i < list.size(); ++i) {
    if (list[i] == val) ++count;
  }
  return count;
}
```

Furthermore, that return value must be equality comparable to DataType.



Example

When templates go wrong.

C++20 Concepts: named requirements on the template arguments

```
template <typename It, typename Type>
   requires Input_Iterator<It> && Iterator_of<It> &&
            Equality_comparable<Value_type<It>,Type>
int countOccurences(It begin, It end, Type val) {
  int count = 0;
  for (auto iter = begin; iter != end; ++iter) {
    if (*iter == val) ++count;
  }
  return count;
}
```

The Standard library has a concepts you can use, or you can write your own!

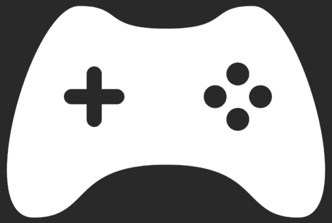
A concept is a predicate, evaluated at compile-time, that is a part of the interface.

```
template <typename It, typename Type>
   requires Input_Iterator<It> && Iterator_of<It> &&
            Equality_comparable<Value_type<It>,Type>
int countOccurences(It begin, It end, Type val);
```

The client can easily see the concepts It and Type must satisfy.

Further Reading on Concepts

https://meetingcpp.com/mcpp/slides/2018/C++%20Concepts%20and%20Ranges%20-%20How%20to%20use%20them.pdf



Next time

Functions and Algorithms