CS4414 Recitation 10

All about templates

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Metaprogramming with templates

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- With templates, we write a template for the actual source code

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- With templates, we write a template for the actual source code

```
template <class T>
void print(std::vector<T> vec) {
    for(const T& t : vec) {
        std::cout << t << "\n";
    }
}

int main() {
  std::vector<int> nums{1, 3, 5, 7, 9};
  print(nums);
}
```

Metaprogramming with templates

- The compiler generates code, in this case a function print that takes a std::vector<int> (since print is called on a std::vector<int>)
- This is called **template instantiation**
- If print was called on a std::vector<std::string>, another function print (overload) will be generated with T = std::string

```
void print(std::vector<int> vec) {
    for(const int& t : vec) {
        std::cout << t << "\n";
    }
}
```

Templates enable generic programming

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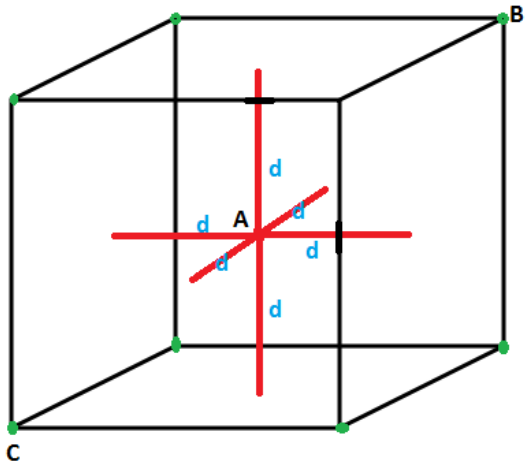
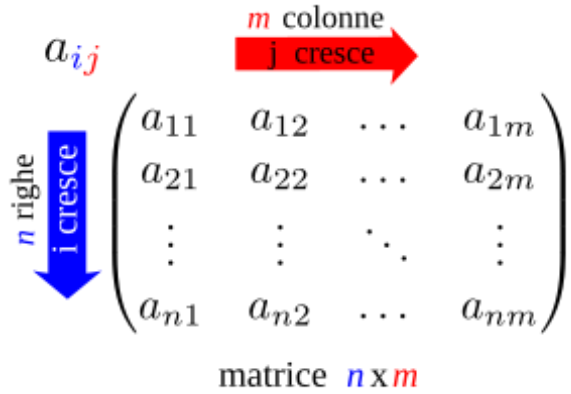




std::vector<T> can store	T=
a finite sequence of integers	int
a point in the n-dimensional space	double
a collection of traffic controllers in a city	controller::traffic_controller
fields in a line of a csv file	std::string
a real matrix	std::vector<double>

Templates in the perspective of programming

- One larger goal of programming is to automate tasks. Reflexively, we want to avoid code copying in programming itself
- Functions are blocks of organized, reusable code that model a particular action
- Classes model similar set of objects
- Libraries provide a consistent set of features
- With templates, we can write functions or classes or variables that can work with different types. Templates *abstract away* the type.

Three types of templates

- Variable templates

```
namespace math {
template<class T>
T pi = 3.14159265359;
}

int main() {
    std::cout << math::pi<int> << "\n"      // prints 3
              << math::pi<float> << "\n"    // prints 3.14159
              << math::pi<double> << "\n"; // prints 3.14159
}
```

Three types of templates

- Function templates

```
template <class T>
void print(std::vector<T> vec) {
    for(const T& t : vec) {
        std::cout << t << "\n";
    }
}

int main() {
  std::vector<int> nums{1, 3, 5, 7, 9};
  print(nums); // or print<int>(nums);
}
```

Three types of templates

- Class templates

```
template <class T>
class my_vector {
public:
    my_vector(size_t _size);
    T& operator[](size_t i);
    const T& operator[](size_t i) const;
    size_t size() const;
private:
    T* elem;
    size_t _size;
    size_t cap;
};
```

Implementation of a template class function cannot be in .cpp files, in general!

- Suppose we define the my_vector class in **my_vector.hpp**. Then, I implement the functions my_vector::size and my_vector::operator[] etc. in **my_vector.cpp**
- Then, I use a my_vector<int> in **main.cpp** which includes **my_vector.hpp**
- This will not compile. Let's see why.

First, let's see how to implement template class functions outside the class

```
#include "my_vector.hpp"
template <class T>
my_vector<T>::my_vector(size_t _size)
        : elem(new T[_size]),
          _size(_size) {
}
template <class T>
size_t my_vector<T>::size() const {
    return size;
}
template <class T>
T& my_vector<T>::operator[](size_t i) {
    return elem[i];
}
template <class T>
const T& my_vector<T>::operator[](size_t i) const {
    return elem[i];
} // contents of my_vector.cpp
```

We get a linking error at compile time

```
-*- mode: compilation; default-directory: "/tmp/" -*-
Compilation started at Fri Oct 29 13:10:46

g++ -std=c++2a main.cpp my_vector.cpp -o main
/usr/bin/ld: /tmp/ccn3SsTO.o: in function `main':
main.cpp:(.text+0x28): undefined reference to `my_vector<int>::my_vector(unsigned long)'
collect2: error: ld returned 1 exit status

Compilation exited abnormally with code 1 at Fri Oct 29 13:10:46
```

Why do we get an error?

- Recall that a template class is not a class, but a template for creating a class.
- When the compiler creates an object file from **my_vector.cpp** which includes **my_vector.hpp**, my_vector<int> is never used. So, code is not generated for the class my_vector<int>
- When **main.cpp** is compiled to an object file, the compiler generates code for the definition of my_vector<int>
- When **main.o** is linked against **my_vector.o**, the implementation of functions of my_vector<int> is, therefore, not found
- **Fun fact**: If your template code is not used, it will not be instantiated with real types. You can even have syntactic errors in such code!

What's the fix?

- In my_vector.cpp, add the following line:

```
template class my_vector<int>;
```

- This requires my_vector.cpp to know that T = int will be used.
- What if the user supplies the template parameter for our library class? For e.g., what if we wanted std::vector<traffic_controller>?
- The entire implementation must be in the header file ☹

A practical workaround ☺

- Implement the functions in my_vector_impl.hpp (or my_vector.tpp)
- At the end of my_vector.hpp, include my_vector_impl.hpp

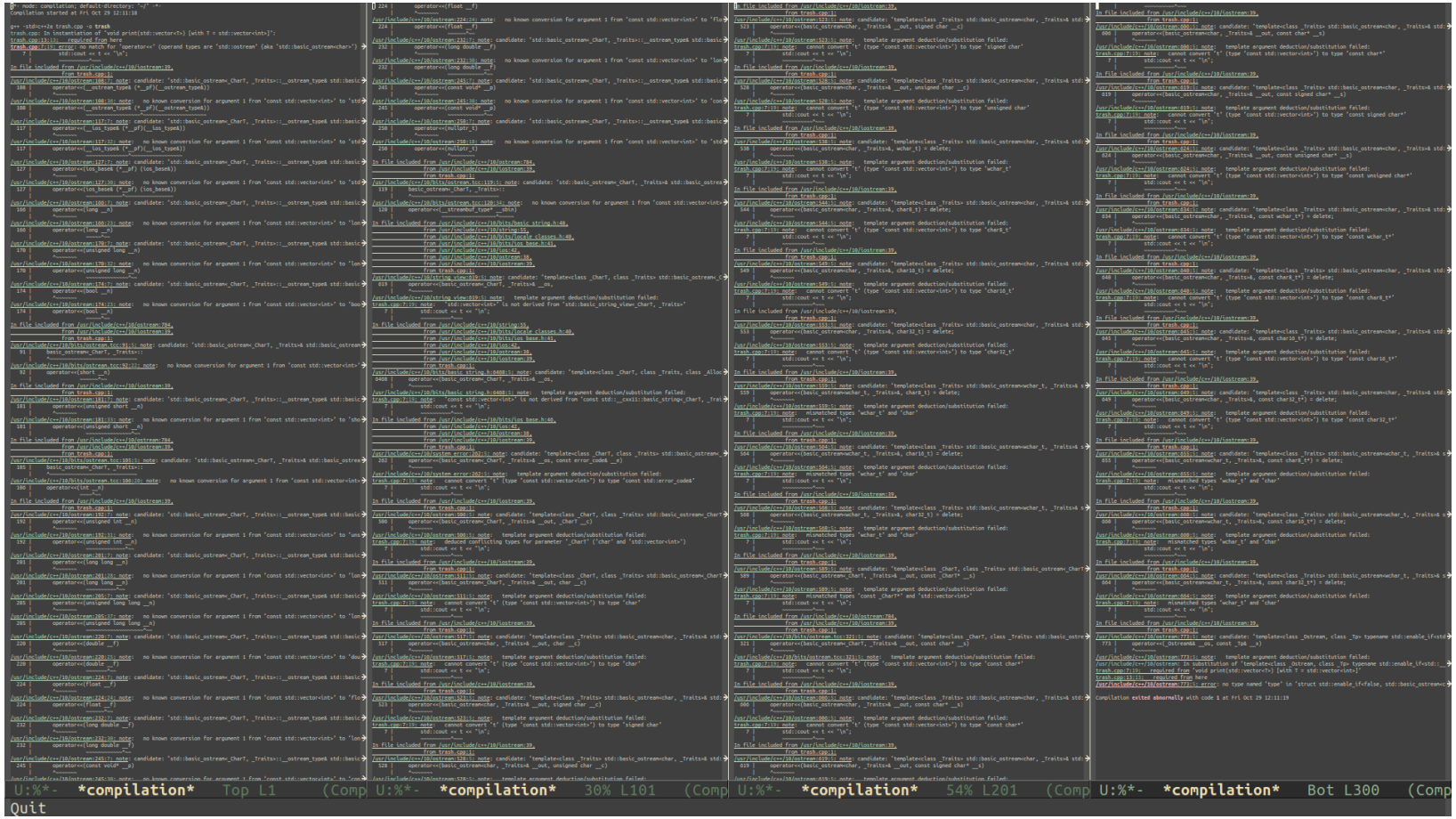
```
template <class T>
class my_vector {
public:
    my_vector(size_t _size);
    T& operator[](size_t i);
    const T& operator[](size_t i) const;
    size_t size() const;
private:
    T* elem;
    size_t _size;
    size_t capacity;
};
#include "my_vector_impl.hpp"
```

Question: What happens if I call my print function with an std::vector<std::vector<int>>?

```
template <class T>
void print(std::vector<T> vec) {
    for(const T& t : vec) {
        std::cout << t << "\n";
    }
}

int main() {
  std::vector<std::vector<int>> nums{{1, 3}, {5, 7}, {9}};
  print(nums);
}
```

The compiler writes me an essay (400 lines, 4 pages with very tiny font size, 15-inch Dell XPS)



g++-10 with –std=c++2a

Concepts: Model constraints on template parameters (C++-20)

- We want the type T to work with the ostream (<<) operator
- We write a Streamable concept requiring just that
- The print function is then templated on a Streamable T

```
template <class T>
concept Streamable = requires(std::ostream& os, T t) {
    { os << t } -> std::convertible_to<std::ostream&>;
};
template <Streamable T>
void print(std::vector<T> vec) {
    for(const T& t : vec) {
        std::cout << t << "\n";
    }
}
```

```
-*- mode: compilation; default-directory: "~/" -*-
Compilation started at Fri Oct 29 12:30:54

g++ -std=c++2a trash.cpp -o trash
trash.cpp: In function ‘int main()’:
trash.cpp:18:15: error: use of function ‘void print(std::vector<T>) [with T = std::vector<int>]’ with unsatisfied constraints
   18 |     print(nums);
      |               ^
trash.cpp:10:6: note: declared here
   10 | void print(std::vector<T> vec) {
      |      ^~~~~
trash.cpp:10:6: note: constraints not satisfied
trash.cpp: In instantiation of ‘void print(std::vector<T>) [with T = std::vector<int>]’:
trash.cpp:18:15:   required from here
trash.cpp:5:9:   required for the satisfaction of ‘Streamable<T>’ [with T = std::vector<int, std::allocator<int> >]
trash.cpp:5:22:   in requirements with ‘std::ostream& os’, ‘T t’ [with T = std::vector<int, std::allocator<int> >]
trash.cpp:6:10: note: the required expression ‘(os << t)’ is invalid
    6 |     { os << t } -> std::convertible_to<std::ostream&>;
      |       ~~~^~~~
cc1plus: note: set ‘-fconcepts-diagnostics-depth=’ to at least 2 for more detail

Compilation exited abnormally with code 1 at Fri Oct 29 12:30:55
```

The error after formally defining the streamable constraint on type T

Template specialization

- Our print function does not work with a vector of vectors
- I can write a specialization of print for a vector of vector of ints
- Another use case: What if I wanted to prints a vector of strings with spaces between them (like a sentence), but a vector of integers with new line?

Template specialization

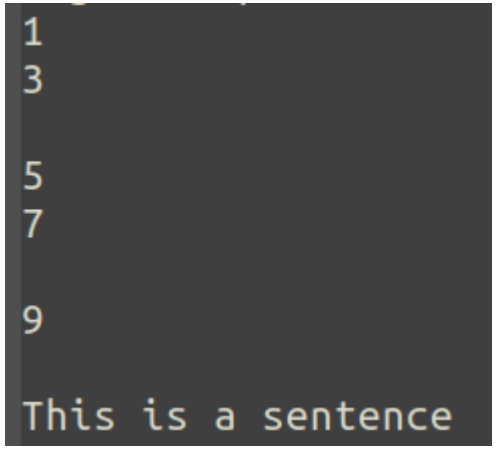
```
template <>
void print(std::vector<std::string> vec) {
    for(const std::string& s : vec) {
        std::cout << s << " ";
    }
    std::cout << "\n";
}
```

```
template <>
void print(std::vector<std::vector<int>> vec) {
    for(const std::vector<int>& inner_vec : vec) {
        for(const int i : inner_vec) {
            std::cout << i << "\n";
        }
        std::cout << "\n";
    }
}
```

```
template <class T>
void print(std::vector<T> vec) {
    for(const T& t : vec) {
        std::cout << t << "\n";
    }
}
```

Template specialization

```
std::vector<std::vector<int>> nums{{1, 3}, {5, 7}, {9}};
print(nums);
std::vector<std::string> strs{"This", "is", "a", "sentence"};
print(strs);
```



The SFINAE rule (Substitution Failure is Not An Error)

- If multiple overloads of function templates exist and substitution fails for one particular specialization, a compile time error is not produced. Instead, the compiler tries to match with the next specialization.
- If no specialization matches the invocation, then the compiler (of course) gives an error
- What if there are multiple matches? The compiler picks the *most specialized* version. If there is a tie, again you get an error.

Value template arguments

```
template<
    class T,
    std::size_t N
> struct array; // defined in C++'s header array

std::array<int, 27> arr; // in user code, e.g., main
```

Default template arguments

- Ever wondered why

```
std::priority_queue<controller::traffic_controller> queue;
```

  works if controller::traffic_controller defines the **operator <**?

- But, otherwise, you supply a comparator functions like this:

```
std::priority_queue<controller, std::vector<controller>, compare> queue;
```

Default template arguments

- This is because std::priority_queue specifies default arguments for the second and the third template parameter
- It works as long as std::less which invokes the < operator is defined for the type

```
template<
    class T,
    class Container = std::vector<T>,
    class Compare = std::less<typename Container::value_type>
> class priority_queue;
```

Variadic templates

```
class car {
public:
    int price;
    car(int price) : price(price) {}
};
class pc {
public:
    int price;
    pc(int price) : price(price) {}
};
class pen {
public:
    int price;
    pen(int price) : price(price) {}
};
```

Variadic templates

```
int sum() {
    return 0;
}

template <typename T, typename... Args>
int sum (T item, Args... rest) {
    return item.price + sum(rest...);
}


int main() {
  car c(100);
  pc pc(10);
  pen p(1);
  std::cout << "The sum is " << sum(c, pc, p);
}
```