C++ PROGRAMMING

Lecture 6

Secure Software Engineering Group

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Common mistakes

- Do not confuse the (de)allocation operators

```
void* operator new ( std::size_t count );          // for objects
void operator delete ( void* ptr );                // for objects
void* operator new[]( std::size_t count );         // for arrays
void operator delete[]( void* ptr );               // for arrays
```

- Do not introduce variables before you need them

  `int i; for (i = 0; i < x; ++i)` versus `for (int i = 0; i < x; ++i)`

- Index out of bounds (use address sanitizer, etc.)

```
std::vector<int> v = {1, 2, 3};
for (int i = 0; i < v.size(); ++i) {
  if (v[i] < v[i+1]) { ... }
}
```

- Copy/move assignment operators are called once the variables involved have already been allocated

- `.size()` versus `sizeof()`
- Pointer arithmetic

```
int *array = new int[10]; array[0] = 42; *(array + 1) = 42; delete[] array;
```

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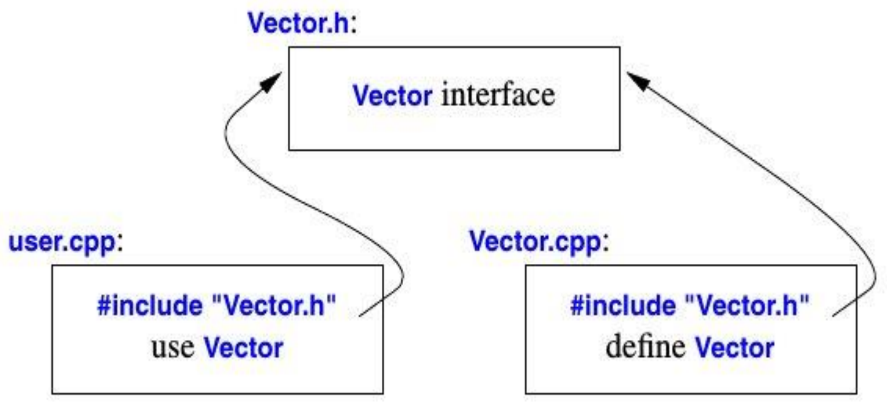
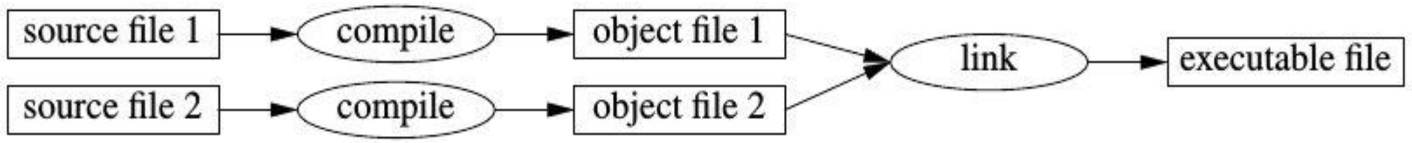
The C/C++ preprocessor: `cpp`

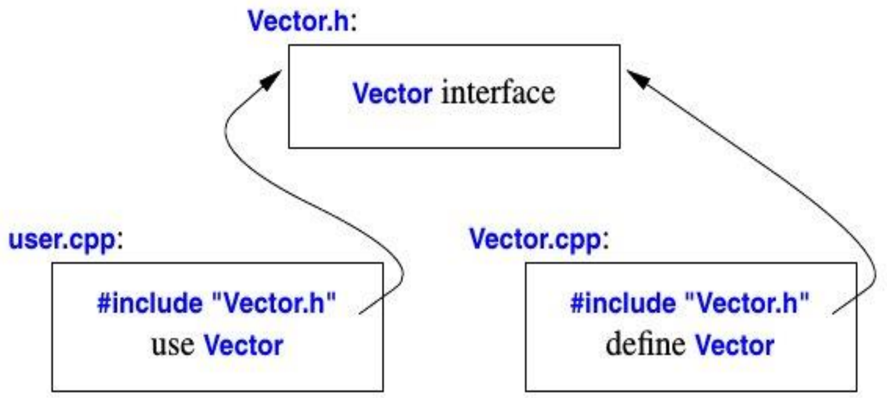
- Remember the `#` directives
- Preprocessor directives are executed by the preprocessor
- `cpp` is just a text processing program
- “Pre” because it processes the program text before the compiler gets it
  - Very powerful
  - Great opportunity to introduce really subtle bugs
- Do not overuse/misuse the preprocessor
  - Only use in rare cases
  - C++ has better mechanisms to replace its uses
- In modern C++ it rarely has to be used anymore
  - “Except” for organizing files: header & implementation files
    - Or use modules in C++20



The C/C++ preprocessor



- Remember the language processing system
  - In C++ we use module-wise compilation of implementation files (`.cpp`)
  - Header files (`.h`) are (usually) not compiled at all
    - Header files are only included in implementation files
    - Each implementation file becomes preprocessed and then compiled
  - Preprocessor can be considered a second language ➔ performs text processing/replacement
  - Problem: a programmer has to deal with 2 languages!
    - Template metaprogramming is a 3th language (inside C++)
    - Template metaprogramming is even Turing complete
      - TMP next time
- Why use such a complicated system for modularity?
  - Compatibility: C had this system, so C++ adopted it
  - (Java-like) module-system available in C++20



Preprocessor directives

- Important preprocessor directives
  - `#include`
  - `#define`
  - `#if`
  - `#elif`
  - `#endif`
  - `#else`
  - `#ifdef`
  - `#ifndef`
  - `## // a dark corner`
  - Variadic function arguments aka C-style varargs (macros) `// another dark corner of CPP`

Figure taken from https://c1.staticflickr.com/3/2117/1792490622_5de0a1d609_b.jpg

Preprocessor directives

- `#include` header files

```
#include <iostream>


int main() {
  std::cout << "Hello!\n";
  return 0;
}
```

- `#define` symbols

```
#include <iostream>
#define VALUE 10

int main() {
  std::cout << VALUE << '\n';
  return 0;
}
```

Preprocessor directives

- `#ifdef` example

```
#include <iostream>
// this is one way to define a symbol
#define LINUX
int main() {
#ifdef LINUX
  std::cout << "linux\n";
#elif WINDOWS
  std::cout << "windows\n";
#elif MAC
  std::cout << "mac\n";
#else
  std::cout << "something else\n";
#endif
    return 0;
}
```

- Another way to define a symbol
  - Tell the compiler directly
    - `g++ -DMAC test.cpp -o test`
    - Program produces:
      - `"mac"`
    - `g++ test.cpp -o test`
    - Program produces:
      - `"linux"`
    - Use option –U to undefine a symbol
- Remember preprocessing-only action can be done by calling the `cpp` program
  - Use option `-E` or `-P` (or both)

Preprocessor directives

- `#if` example

```
#include <iostream>
#define VALUE 10

int main() {
#if VALUE == 10
  std::cout << "VALUE is 10\n";
#else
  std::cout << "VALUE is not 10\n";
#endif
  return 0;
}
```

The preprocessor and software product lines

- Using `#if`, `#ifdef`, `#elif`, `#else`, `#endif` …
  - one can build software product lines
  - one can maintain huge software product lines within the same codebase
  - Linux kernel has many `#if` directives
    - Can be compiled for many platforms
  - Almost all larger software projects use the preprocessor to establish SPL's
  - Configurations for CPP symbols are usually maintained in a huge (hopefully documented) table
    - Symbols are looked up for the required product
      - Car system software for model XY of brand Z
      - Use corresponding CPP symbols for XY and compile
      - If software for another model is needed, use the appropriate CPP symbols

... out of few components

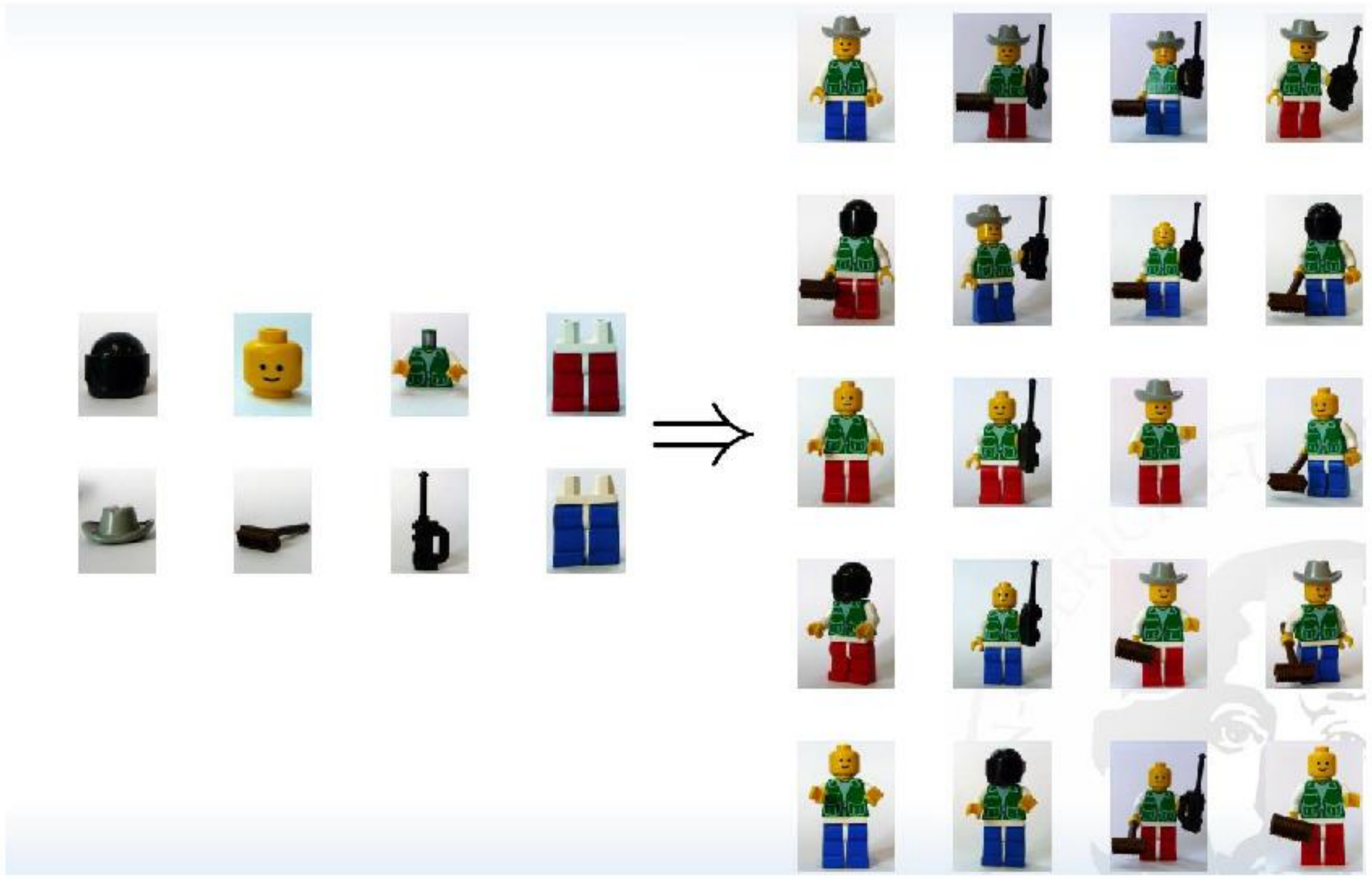


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Image courtesy Thomas Thüm

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Feature model restricts valid configurations

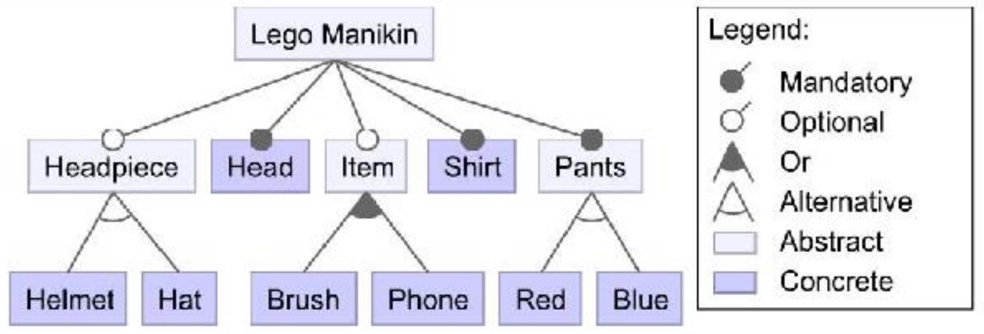

Image courtesy Thomas Thüm

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Finding bugs and testing SPL's

- Welcome to hell
- It is just a program, right?
  - No!
  - Every use of `#if` or `#ifdef` leads to two different programs
    - One program that contains the code "inside" `#if`
    - One program that does not contain the code "inside" `#if`
  - There are 2^n different versions of your program
    - n is the number of preprocessor `#if`s used
  - What does that mean?

#ifdef occurrences in OpenSSL

__cplusplus
OPENSSL_SYS_VMS
OPENSSL_FIPS
CHARSET_EBCDIC
KSSL_DEBUG
CRYPTO_MDEBUG
OPENSSL_SYS_NETWARE
OPENSSL_SYS_WINDOWS
REF_PRINT
TLSEXT_TYPE_opaque_prf_input
SIGALRM
OPENSSL_SYS_WIN32
OPENSSL_NO_EC
TIMES
LINT
FIPS_ALGVS
TEST
ZLIB
LEVITTE_DEBUG_MEM
OPENSSL_SYS_WIN16

391 different Features ⇒ $5 \cdot 10^{117}$ Combinations

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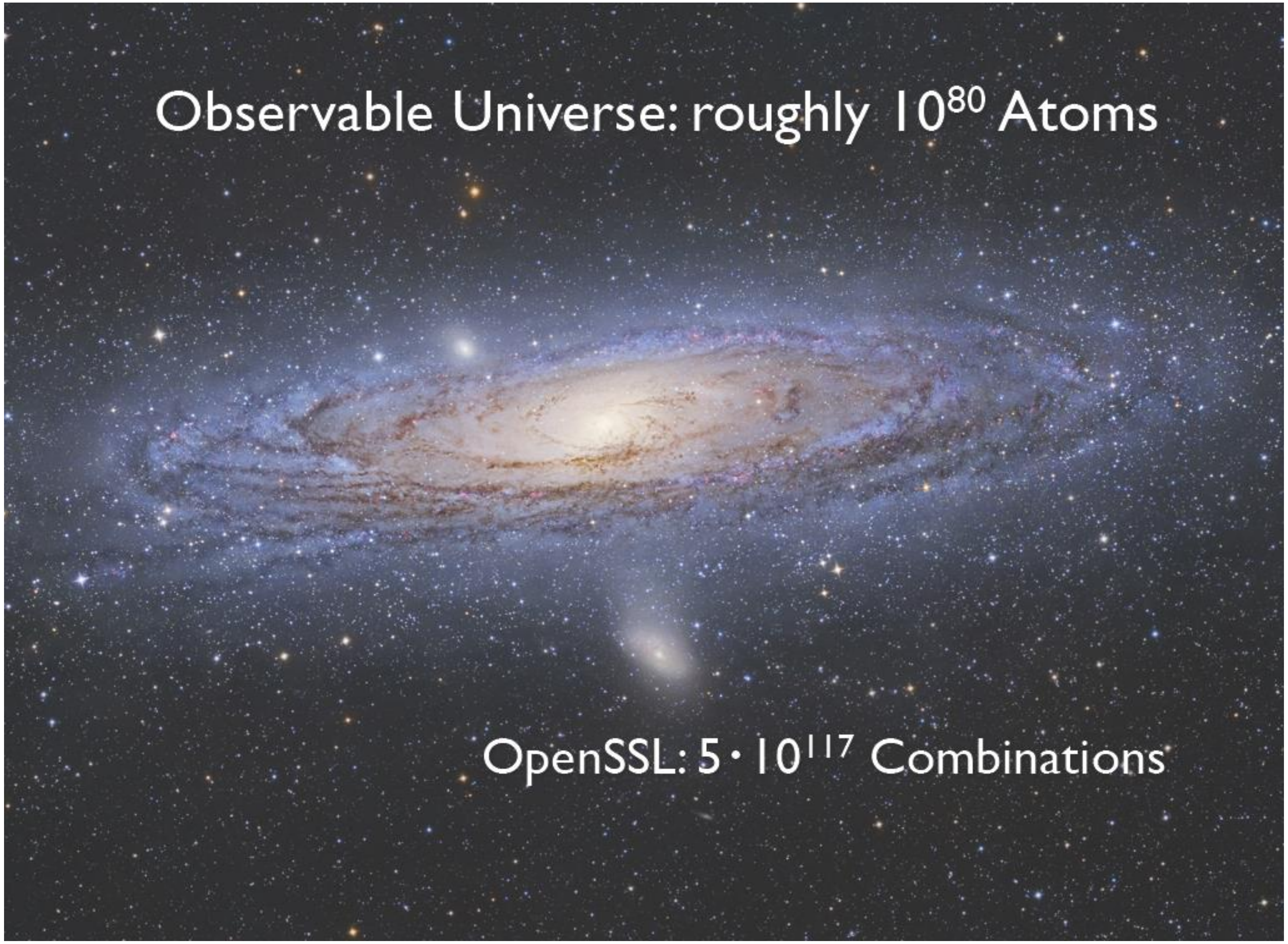
Observable Universe: roughly 10^{80} Atoms
OpenSSL: $5 \cdot 10^{117}$ Combinations

[Slide taken from “Designing Code Analysis”, Eric Bodden]

Preprocessor macros

- Writing a macro

```
#include <iostream>
#define FACTORIAL(X,R) {              \
    R = 1;                            \
    while (X > 0) {                   \
     R *= X;                          \
     --X;                             \
    }                                 \
  }

int main() {
  int i = 5;
  int result;
  FACTORIAL(i, result);
  std::cout << result << '\n';
  return 0;
}
```

- Do not abuse macros for function inlining!
- This leads to subtle bugs
  - Compiler only sees the expanded macro
    - Programmer sees the unexpanded one
  - Type information is missing
- Use C++ keyword `inline` instead
- Macro expands to:

```
int main() {
  int i = 5;
  int result;
  { result = 1; while (i > 0) {
        result *= i; --i; } };
  std::cout << result << '\n';
  return 0;
}
```

Macros gone wrong

- Very subtle bugs

```
#include <iostream>
#define ABS(X) ((X) < 0) ? -(X) : X;
int main() {
  int i = ABS(-42);
  int j = ABS(42);
  int t = 10;
  int k = ABS(--t);
  std::cout << i << '\n';
  std::cout << j << '\n';
  std::cout << k << '\n';
  return 0;
}
```

- What will be printed?

```
int main() {
  int i = (-42 < 0) ? - -42 : -42;;
  int j = (42 < 0) ? -42 : 42;;
  int t = 10;
  int k = (--t < 0) ? - --t : --t;;
  std::cout << i << '\n';
  std::cout << j << '\n';
  std::cout << k << '\n';
  return 0;
}
```

- Output: 42, 42, 8

Predefined preprocessor macros

- Predefined macros

```
#include <iostream>
int main()  {
  std::cout << "File : " << __FILE__ << '\n';
  std::cout << "Date : " << __DATE__ << '\n';
  std::cout << "Time : " << __TIME__ << '\n';
  std::cout << "Line : " << __LINE__ << '\n';
  return 0;
}
```

```
int main()  {
  ERROR(1, "uups");
  return 0;
}
```

- Output

```
File : myfile.cpp
Date : Jun 05 2020
Time : 09:09:16
Line : 8
```

```
#include <iostream>
#include <cstdlib>
#define ERROR(BOOL_EXPR, MESSAGE) {                                           \
  if (BOOL_EXPR) {                                                          \
    std::cout << "Detected unrecoverable error: " << MESSAGE << '\n';       \
    std::cout << "File : " << __FILE__ << '\n';                             \
    std::cout << "Abort program!" << '\n';                                  \
    std::abort();                                                           \
  };                                                                        \
}
```

Notes on the preprocessor

- Include mechanism is completely fine
  - Header file

```
#ifndef MODULE_H
#define MODULE_H
  // … some code
#endif
```

  - Implementation file

```
#include <iostream>
#include "MyFile.h"
```

- Other than that, try to avoid using CPP’s

```
#define
#if
```

  as much as possible

Templates

- Templates allow abstraction from a concrete type
- Templates are handled by the compiler, not the preprocessor
  - Compiler can use the type system
- “A template is a C++ entity that defines one of the following:
  1. a family of classes/structs (class template), which may be nested classes
  2. a family of functions (function template), which may be member functions
  3. an alias to a family of types (alias template)
  4. a family of variables (variable template)
  - Templates are parameterized by one or more template parameters of three kinds:
    1. type template parameters
    2. non-type template parameters
    3. template template parameters” [http://en.cppreference.com/w/cpp/language/templates]
- If template parameters are specified (template instantiation) one obtains a template specialization

Templates

- Templates are code generators (compare to C's abs implementation: `fabs`, `fabsf`, `fabsl`, `abs`, `labs`, `llabs`)
- Caution: template code cannot be compiled up-front
  - A concrete template instantiation is required
  - (Usually) put template code in header files
  - Include headers where you need the template code
- Always prefer templates over some macro directives
- Use templates …
  - if you do not know information up-front
  - if a class/function/variable can be used in a more general way (like sorting – in the exercises)

- **Can be abused to compute values at compile time: template meta-programming** (next lecture)
  - Since C++11/C++14 prefer `constexpr` functions

Class and function templates

```
#include <iostream>
#include <type_traits>

template<typename A, typename B>
struct Tuple {
  A first;
  B second;
  Tuple(A a, B b) : first(a),
                    second(b) {}
};

template<typename T>
T add(T a, T b)  {
  static_assert(
    std::is_arithmetic<T>::value,
    "wrong");
  return a + b;
}
```

```
int main() {
  Tuple<int, string> t(5, "Hello!");
  std::cout << t.first << '\n';
  std::cout << t.second << '\n';
  int result_int = add<int>(5, 5);
  double result_double = add<double>(1.11,
                                     2.22);
  double result_double_deduced = add(3.33,
                                     4.44);
  std::cout << result_int << '\n';
  std::cout << result_double << '\n';
  std::cout << result_double_deduced << '\n';
  return 0;
}
```

- Templates are code generators
- Program will contain one `Tuple` type and two different version of the `add` function

Variable template

- Note: only integer types can be used as variable templates

- Implement your own safe static array type (carrying size information)

```
#include <iostream>
#include <algorithm>
#include <cassert>
template<typename T, size_t S>
class MyArray {
 private:
  static constexpr size_t elements = S;
  T data[S];

 public:
  MyArray() {}
  MyArray(T ival) {
    std::fill(&data[0], &data[elements], ival)
  }
  size_t size() const { return elements; }
  T& operator[] (size_t idx) {
    assert(idx < elements);
    return data[idx];
  }
  const T& operator[] (size_t idx) const {
    assert(idx < elements);
    return data[idx];
  }
  friend std::ostream& operator<< (
    std:: ostream& os,
    const MyArray& a){
    for (size_t i = 0; i < a.elements; ++i) {
      os << a.data[i] << " ";
    }
    return os;
  }
};

int main() {
  MyArray<int, 10> a;
  MyArray<double, 5> b(1.11);
  std::cout << a << '\n';
  std::cout << b << '\n';
  return 0;
}
```

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One of C++'s many oddities

```
template<typename T>
class MyClassTemplate {
      // ...
};
```

versus

```
template<class T>
class MyClassTemplate {
      // ...
};
```

- "Summary: Stroustrup originally used class to specify types in templates to avoid introducing a new keyword. Some in the committee worried that this overloading of the keyword led to confusion. Later, the committee introduced a new keyword typename to resolve syntactic ambiguity, and decided to let it also be used to specify template types to reduce confusion, but for backward compatibility, class kept its overloaded meaning."

Variadic function arguments

- More flexibility for function parameters
- How can we pass arbitrary many parameters to a function?

```
void print_ints(int i) { cout << i << '\n'; }
void print_ints(int i, int j) { cout << i << " " << j << '\n'; }
```

- Do not use C-style vararg macros!
- Better solution
  - Use `std::initializer_list`

    ```
    void print_ints(initializer_list<int> varargs);
    ```

    - The user can pass arbitrary many integers to `print_ints()`
    - But caution
      - You have to pass arguments using the `std::initializer_list`'s curly braces `{ }`

Variadic function arguments

```
#include <iostream>
#include <initializer_list>
void print_ints(
  std::initializer_list<int> args) {
  for (int i : args) {
    std::cout << i << " ";
  }
}

template<typename T>
void print_generic(
  std::initializer_list<T> args) {
  for (const T &arg : args) {
    std::cout << arg << " ";
  }
}
```

```
int main() {
  print_ints({1, 2, 3, 4});
  print_ints({1, 2});
  print_generic({1.111, 2.222, 3.333});
  return 0;
}
```

- Use `std::initializer_list` for variable argument list
  - Cleanest way to achieve flexibility
- Another way is possible
  - C-style varargs (involves preprocessor macros)
    - Hard to read
    - Hard to understand → **NO!**
- Next time: variadic arguments of different types

  → involves template meta programming

Function object or functor

- A functor is a class or struct that implements `operator()`
  - The (function) call operator
- A variable of that type can be called like a function
  - A functor is a function that can store variables and data
    - It has state
    - You can wrap tasks into functors
    - Fits perfectly into object oriented programming and concurrent programming (later on)

Functor

- Example function object

```
#include <iostream>
class Task {
private:
  int i;
  int j;
  // perform extensive task of adding
  // two numbers
  int do_hard_work() { return i + j; }

public:
  Task(int i, int j) : i(i), j(j) {}
  int operator() () {
    return do_hard_work();
  }
};
```

```
int main() {
  // set up a task
  Task t(100, 200);
  // start solving the task
  int result = t();
  std::cout << result << '\n';
  return 0;
}
```

Lambda functions

- “A lambda function is an unnamed function object capable of capturing variables in scope”
  [http://en.cppreference.com/w/cpp/language/lambda]
- Syntax

  1. [capture-list] (params) -> ret { body }
  2. [capture-list] (params) { body }
  3. [capture-list] { body }
- What is a capture-list?
  - A comma-separated list of zero or more captures

    [a,&b] where *a* is captured by value and *b* is captured by reference.
    [this] captures the **this** pointer by value
    [&] captures all automatic variables odr-used in the body of the lambda by reference
    [=] captures all automatic variables odr-used in the body of the lambda by value
    [] captures nothing

Lambda functions

```cpp
#include <iostream>
#include <functional>

int bin_operation(
  int a,
  int b,
  std::function<int(int,int)> f) {
  return f(a, b);
}
```

```cpp
int main() {
  int result = bin_operation(2, 3, [](int a, int b) {
                    return a + b; });
  int other = bin_operation(2, 3, [](int a, int b) {
                    return a * b; });
  std::function<int(int)> f_sq = [](int a) {
                    return a * a; };
  // or use auto to be shorter
  auto f_sub = [](int a, int b) { return a - b; };
  std::cout << f_sq(10) << '\n';
  std::cout << f_sub(10, 5) << '\n';
  std::cout << result << '\n';
  std::cout << other << '\n';
  return 0;
}
```

Lambda functions

- Example using `std::for_each()` algorithm (which is a fully generic function)

```
#include <iostream>
#include <vector>
#include <algorithm>
#include <functional>

int main() {
  std::vector<int> v = {1, 2, 3, 4, 5, 6};
  std::for_each(v.begin(), v.end(), [](int &i) { i *= i; });
  std::for_each(v.begin(), v.end(), [](int i) { std::cout << i << " "; });
  std::cout << '\n';
  return 0;
}
```

Lambda functions

- Now we can introduce easy-to-use predicates
- Example binary predicate

```
#include <iostream>
#include <vector>
#include <functional>
#include <cassert>
bool check_pred(
  std::vector<int>& v1,
  std::vector<int>& v2,
  std::function<bool(int,int)> pred){
  assert(v1.size() == v2.size());
  for (size_t i = 0; i < v1.size(); ++i) {
    if (!pred(v1[i], v2[2])) {
      return false;
    }
  }
  return true;
}
```

```
int main() {
  std::vector<int> v1(5, 1);
  std::vector<int> v2 = {1, 1, 1, 1, 1};
  bool equal = check_pred(v1, v2,
                   [](int a, int b) {
                     return a == b; });
  std::cout << equal << '\n';
  return 0;
}
```

Lambda functions

```
#include <iostream>
#include <vector>
#include <algorithm>
#include <functional>
int main() {
  std::vector<int> from(10);
  std::vector<int> to(10);
  // fills with 1, 2, ... , 10
  std::iota(from.begin(), from.end(), 1);
  std::for_each(from.begin(),
                from.end(),
                [](int i) {
                 std::cout << i << ' '; }
                );
  std::cout << '\n';
```

```
int epsilon = 5;
std::transform(from.begin(),
  from.end(),
  to.begin(),
  [epsilon](int d) {
    if (d <= epsilon) {
      return 0;
    }
    return d;
  });
  std::for_each(to.begin(),
    to.end(),
    [](int i) {
    std::cout << i << ' '; });
  std::cout << '\n';
  return 0;
}
```

Recap

- C/C++'s preprocessor
- Modularity in C++
- Software Product Lines (SPLs)
- Exponential `#ifdef` variability
- Macros
- Macros gone wrong
- Predefined macros
- Templates
- Variadic function arguments
- Functor: function objects
- Lambda functions

Thank you for your attention
Questions?