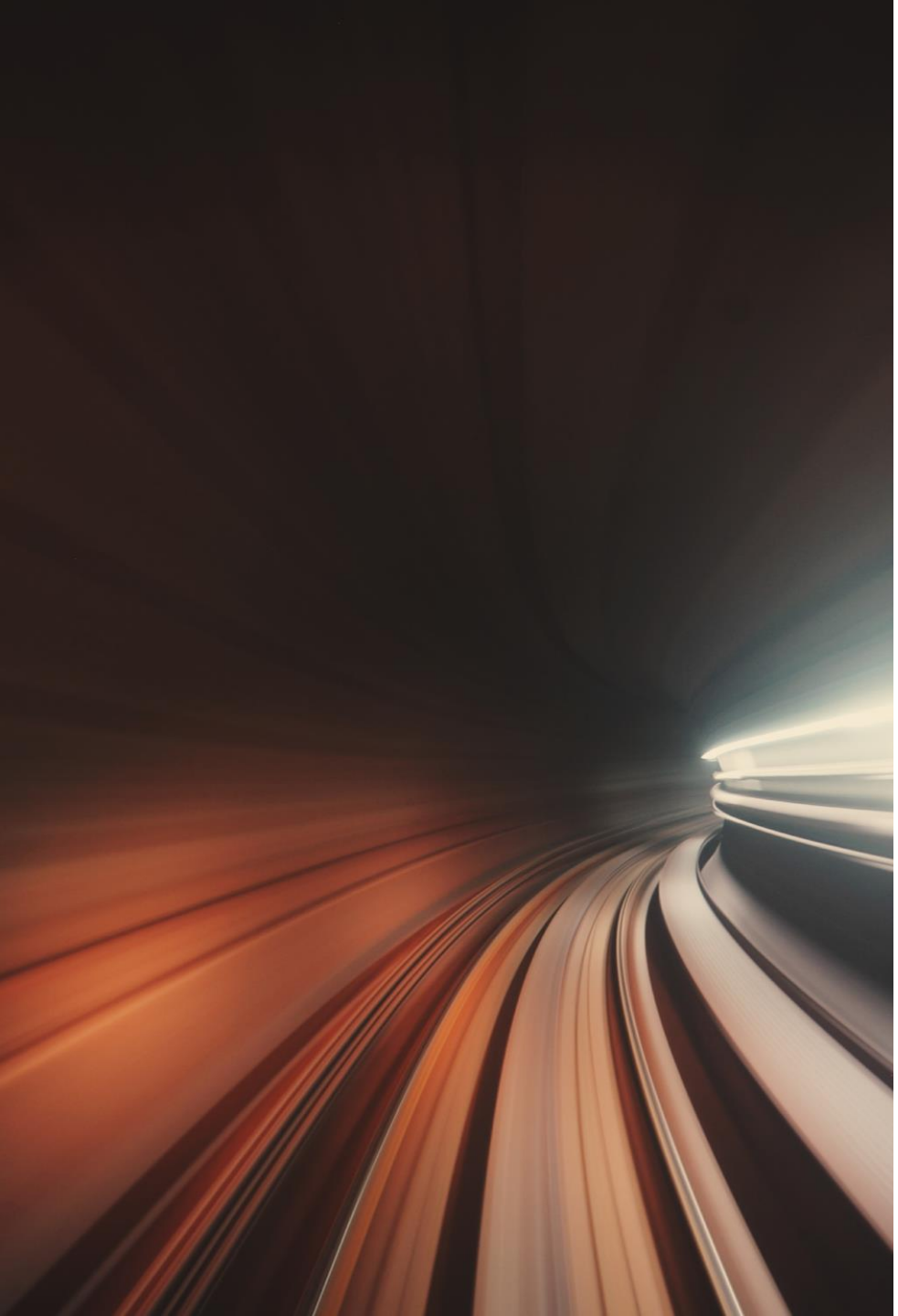
C++ Tutorial

TIM STRAUBINGER – CPSC 427 – FALL 2021



Talk Outline

BRIEF TOUR OF C++

TEMPLATES

UNDEFINED BEHAVIOUR

Additional Resources

isocpp.org/get-started

- Recommended book list
- high-level explanations, tutorials, and design guidance

cppreference.com/w/

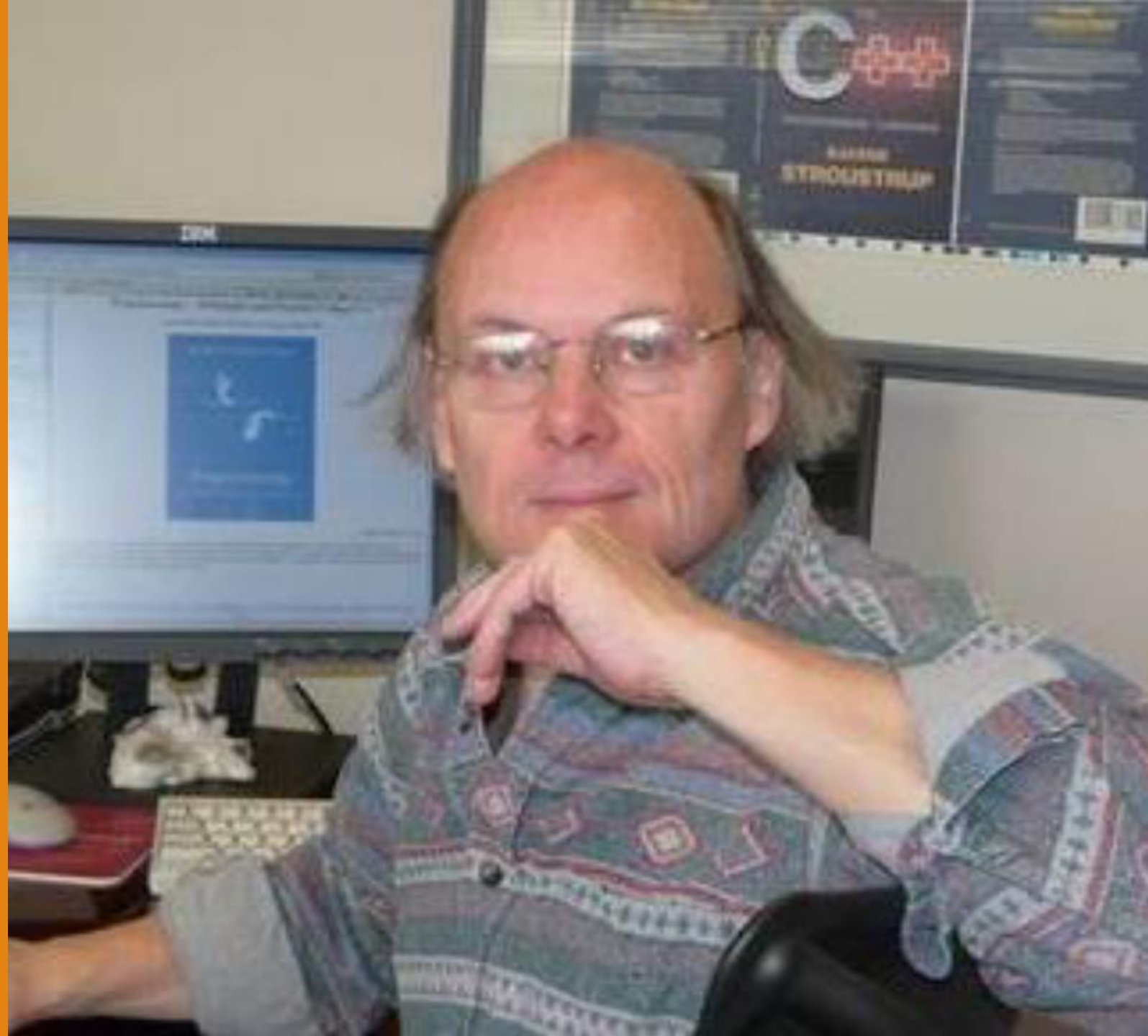
- Language and standard library documentation

coliru.stacked-crooked.com

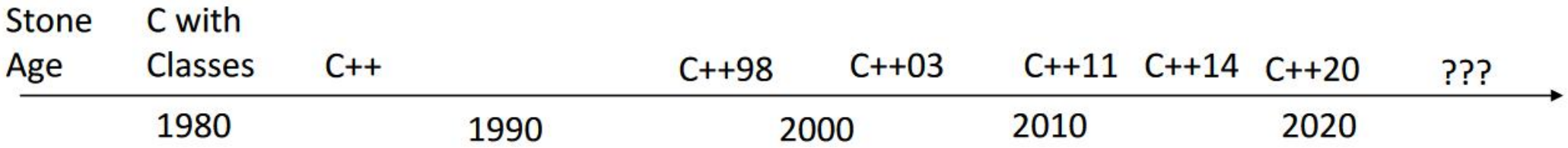
- Free online compiler (great for small exercises)

A Brief Tour of C++

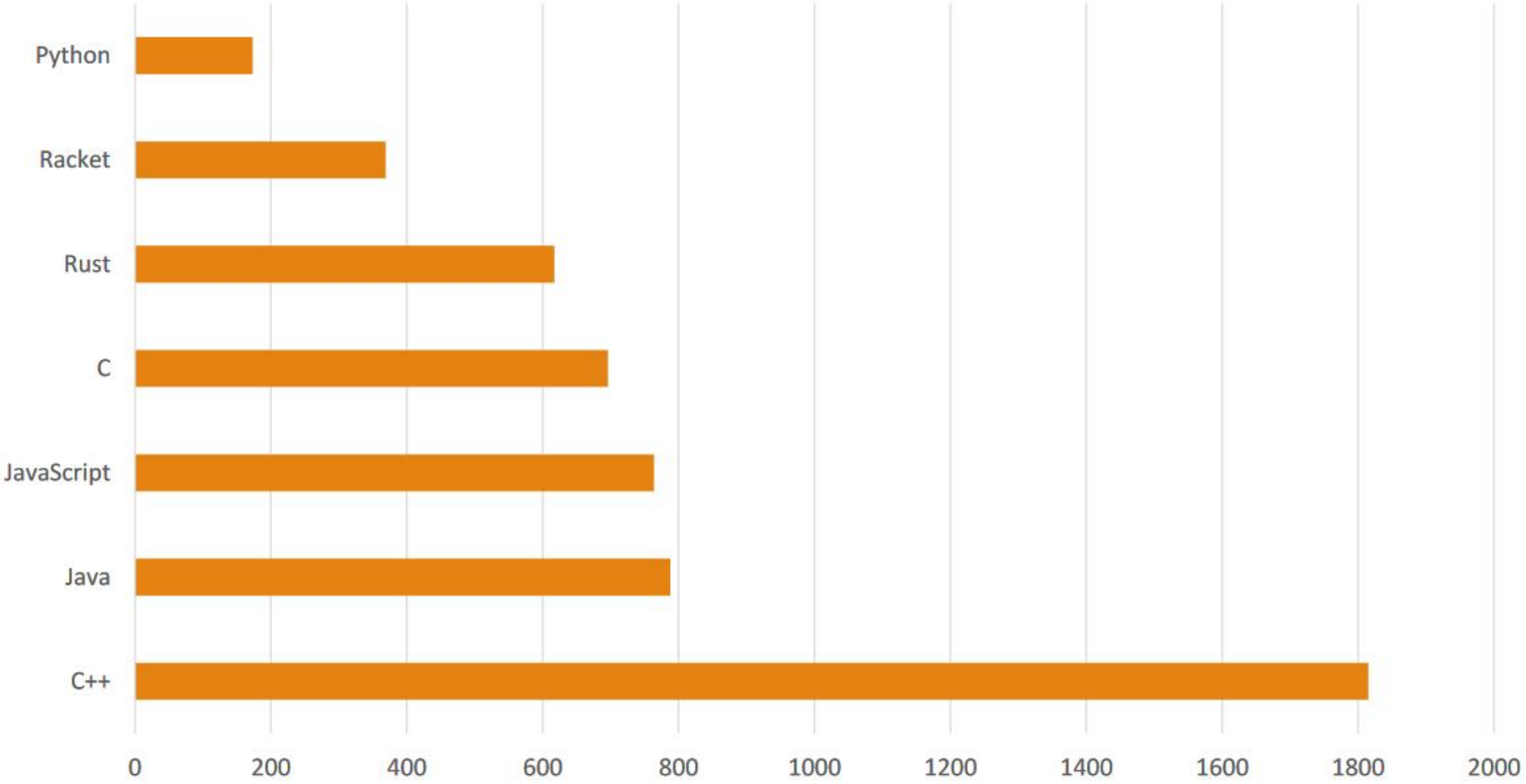
C++ **began** being invented in 1979 by Danish computer scientist **Bjarne Stroustrup** (pictured right)



C++ is Not Done Being Invented



Length of Language Specification (Number of Pages)



Why do C++ programmers like C++?

- **Runtime performance** 
  - Zero-cost abstractions
  - Compiler optimizations
  - Easy and efficient resource management
  - Compile-time programming (for advanced users)

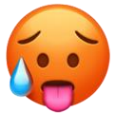
- **Type Safety**
  - Many bugs are eliminated at compile time *

- **Expressiveness**
  - Many diverse tools are provided by the C++ language
  - Many styles of programming are possible and can be mixed
    - Generic, object-oriented, functional, imperative, procedural, compile-time, template meta-programming, etc

* but not all

Why **don't** C++ programmers like C++?

- **Undefined Behaviour**
  - C++ gives you the freedom to hurt yourself
  - **You are responsible** for preventing bugs
  - **The language does not protect you from yourself**

- **Complexity**
  - The C++ language is **huge** 
  - C++ programmers readily over-engineer 
  - Reasoning about C++ easily causes headaches 
- Compilation speed
  - Begin a C++ compiler is not easy 

C++ is a very diverse landscape

Image credit: http://fearlesscoder.blogspot.com/2017/02/the-c17-lands.html

C++ is a very diverse landscape

Different communities use different subsets of the language in different ways for different goals

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Different communities use different subsets of the language in different ways for different goals

Video game programming is **just one** of countless ways of using C++

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C++ is a very diverse landscape

Different communities use different subsets of the language in different ways for different goals

Video game programming is **just one** of countless ways of using C++

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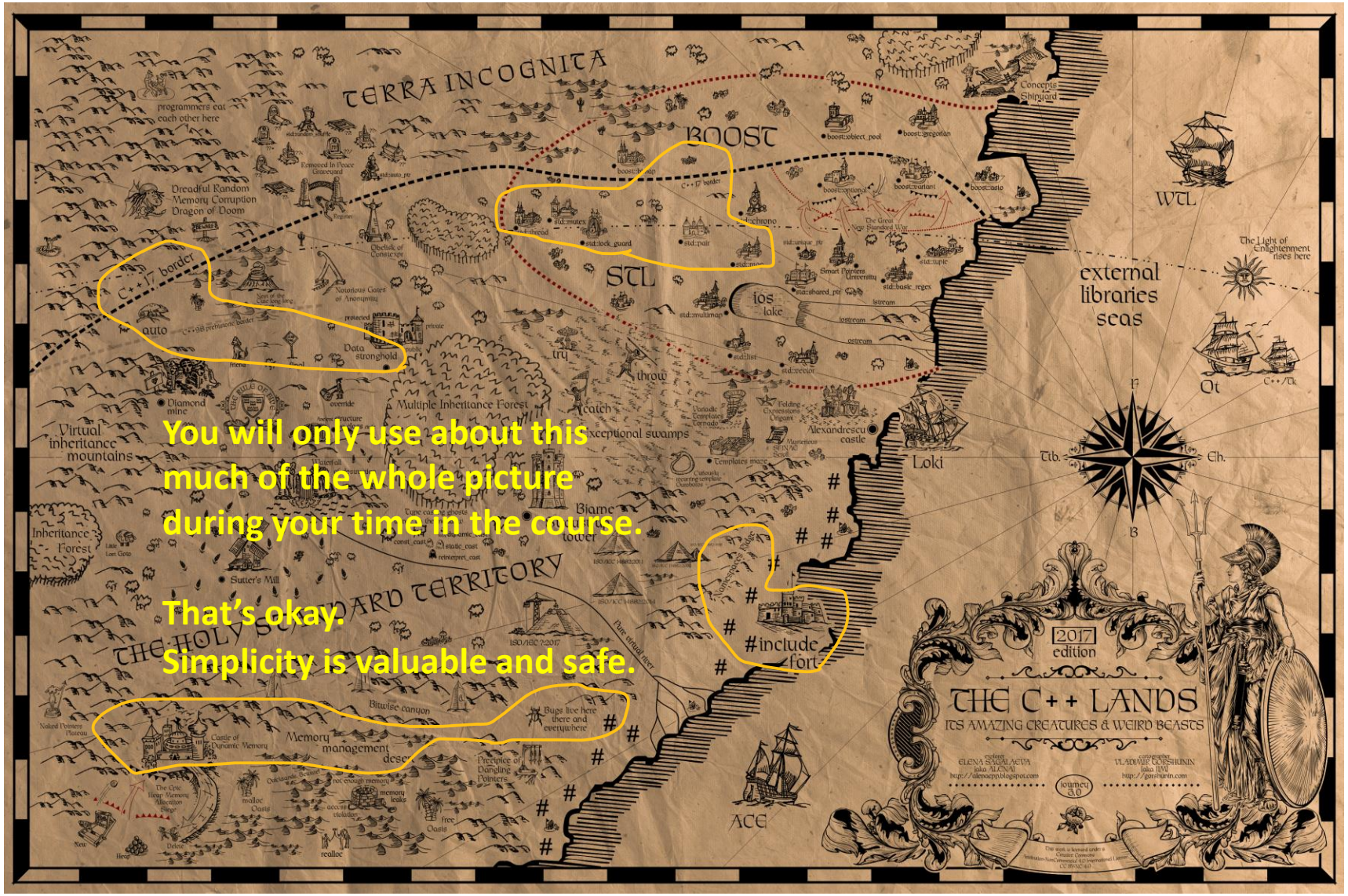


this has been

A Brief Tour of C++

thank you for watching

C++ Templates

Avoiding Manual Code Duplication

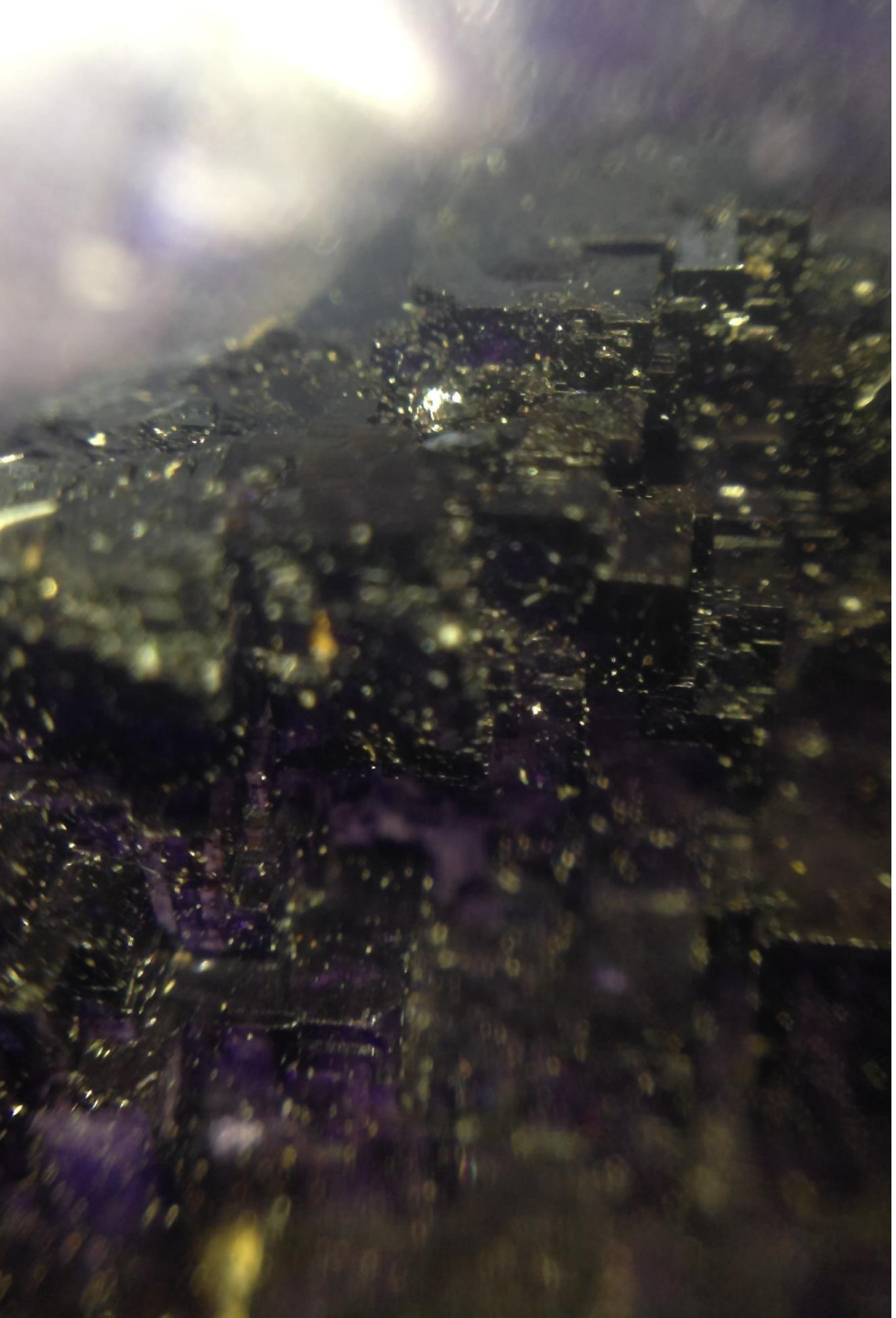
Does this code style look familiar to you?

```
int add_int(int x, int y) {
    int result = x + y;
    return result;
}

double add_double(double x, double y) {
    double result = x + y;
    return result;
}

std::string add_string(std::string x, std::s
    std::string result = x + y;
    return result;
}

float add_float(float x, float y) {
    float result = x + y;
    return result;
}
```

Templates to the rescue!

Automated code duplication!

```
2727    template<typename T>
2728    T add(T x, T y) {
2729        T result = x + y;
2730        return result;
2731    }
2732
2733
2734
2735
2736
2737
2738
2739
2740
2741
2742
2743
2744
2745
2746
```



C++ templates versus other languages

member access in Python

Nearly everything is checked at **runtime!**

Lots of testing required 😢

```python
def foo(x):
    print(x.bar)

class A:
    def __init__(self):
        self.bar = "Blab"

a = A()
b = 99
foo(a)
foo(b)
```

member access in **C++ templates**

Templates are checked **at compile time!**

```
template<typename T>
void foo(T t){
    std::cout << t.bar << std::endl;
}

struct A {
    std::string bar = "Blab";
};

int main(){
    auto a = A{};
    auto b = 99;
    foo(a);
    // foo(b); ERROR: request for member 'bar' in 't',
    //                which is of non-class type 'int'

    return 0;
}
```

Generic factory functions in **Java**

Only one function is generated!

Types are **erased** 😔

Simple things are impossible 😭

```java
public static <T> T create() {
    T t = new T();
    return t;
}
```

```
Main.java:11: error: unexpected type
        T t = new T();
                  ^
  required: class
  found:    type parameter T
  where T is a type-variable:
    T extends Object declared in method <T>create()
```

Template factory functions in **C++**

Types can be provided explicitly for **great good**

Our ECS system uses this extensively
Take a look 😉

```
template<typename T>
T create(){
    auto t = T{};
    return t;
}


int main(){
    auto i = create<int>();
    auto d = create<double>();
    auto s = create<std::string>();

    return 0;
}
```

Templates in C++

C++ is **statically typed**, and **all types must be known at compile time**

So how do templates work in C++?

- **Automated code duplication!** (*technically called monomorphization)*

Each time you provide a template function/class with a different type, **a different function/class is generated by the compiler!**

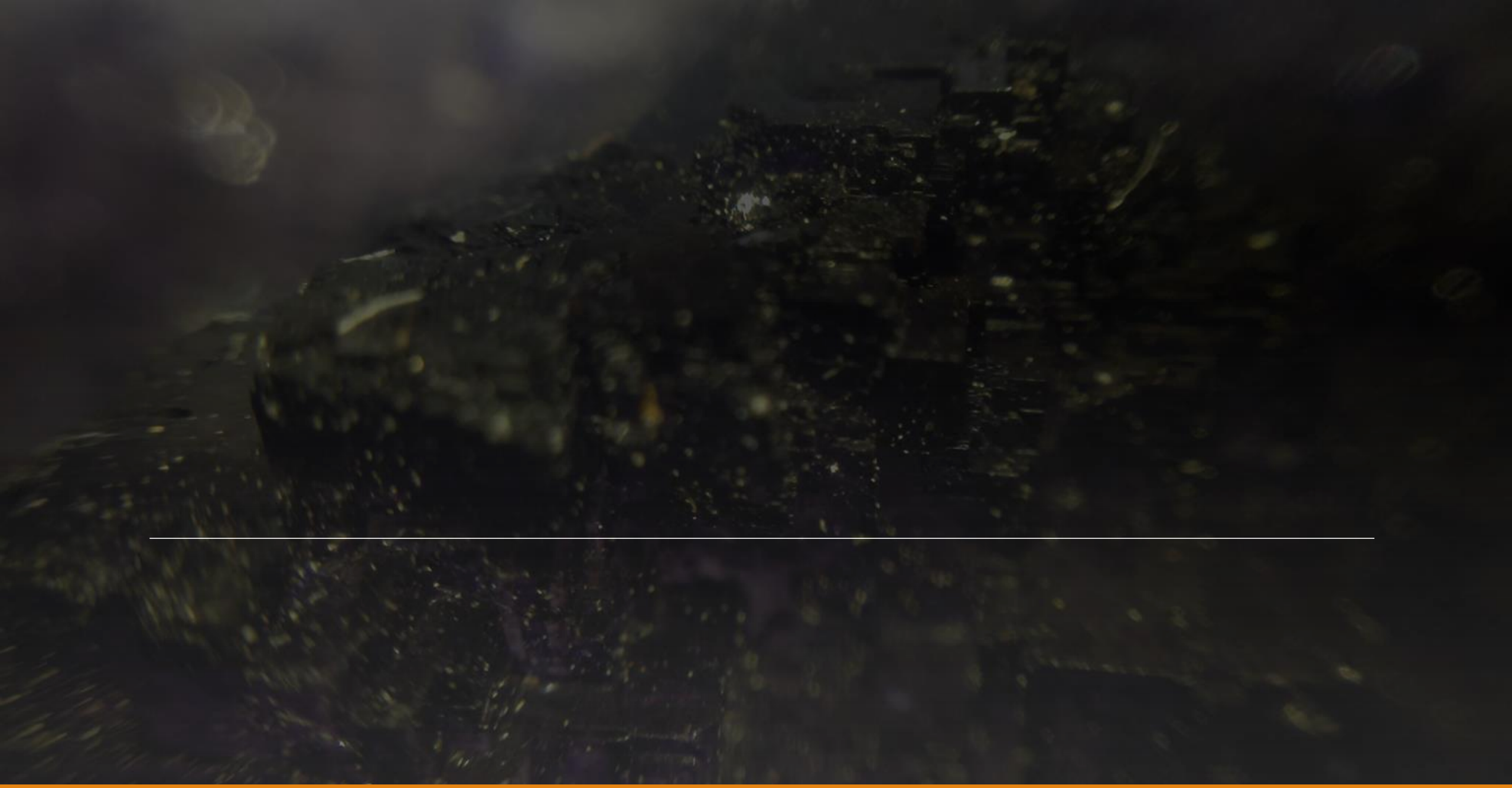
In other words, a template **is not** a class or function **until** you specify a type *(technically called instantiation)*

Benefits of Templates in C++

- **Type checking**
  - The compiler can inspect types and perform all the normal safety and correctness checks
- **Optimization**
  - The compiler can generate faster code that is specific to each type
- **Expressivity**
  - Templates are *extremely* powerful at doing many different things

Downsides of Templates in C++

- **Slow compile times**
  - Templates add extra work for the compiler
- **Code bloat**
  - “automatic code duplication” is exactly that – the size of compiled programs increases for every new template instantiation
- **Complexity**
  - Template code compiles differently from normal code – understanding and fixing errors can be difficult



The Dark Side of C++

Undefined Behaviour

C++ is **not safe**

- C++ **lets you break the rules** of the language
- When you break the rules, ***anything*** can happen
- A good C++ programmer knows **how not to break the rules**

```
1   #include <iostream>
2
3   int main() {
4       std::cout << "Start ---" << std::endl;
5       char ch; // Oops! Forgot to initialize :-)
6       std::cout << ch << std::endl;
7       std::cout << "Finish ---" << std::endl;
8       return 0;
9   }
10
11
12
13
14
15
16
```

```
Start ---
Finish ---
```

Undefined Behaviour means:

Your code *may* do nothing

```cpp
#include <iostream>

int main(){
    int i;
    double d;
    bool b;
    uint8_t u;
    std::cout << i << '\n';
    std::cout << d << '\n';
    std::cout << b << '\n';
    std::cout << u << '\n';
}
```

```
0
0
0
```

Undefined Behaviour means:

Your code *may* do what you believe it should

```
1   #include <iostream>
2
3   int main(){
4       int i;
5       double d;
6       bool b;
7       uint8_t u;
8       std::cout << i << '\n';
9       std::cout << d << '\n';
10      std::cout << b << '\n';
11      std::cout << u << '\n';
12  }
```

```
0
6.95255e-310
0
```

Undefined Behaviour means:

Your code *may* do what you believe it should

…until you change your compiler settings

```
1   #include <iostream>
2
3   int main(){
4       int i;
5       double d;
6       bool b;
7       uint8_t u;
8       std::cout << i << '\n';
9       std::cout << d << '\n';
10      std::cout << b << '\n';
11      std::cout << u << '\n';
12  }
```

```
718172376
0
0
```

Undefined Behaviour means:

Your code *may* do what you believe it should

…until you change your compiler settings
…or try a different compiler

```
// Entry point
int main() {
    int* ptr = nullptr;
    std::cout << *ptr;
```

Exception Thrown

Exception thrown: read access violation.
ptr was nullptr.

Copy Details

Exception Settings

- [x] Break when this exception type is thrown

Except when thrown from:

Undefined Behaviour means:

YOUR CODE MAY CRASH WITH A HELPFUL ERROR MESSAGE

```
48
49
50
51    // Entry point
52    int main() {
53        return 0;
54    }
55
56
57
```

Undefined Behaviour means:

YOUR CODE MAY CRASH FOR NO EXPLAINABLE REASON

xhash

salmon | std::_Hash<_Traits> | _Find_hint<_Keyty>(const _Nodeptr _Hint, const _Keyty & _Ke

```
1650  protected:
1651      template <class _Keyty>
1652      _NODISCARD _Hash_find_last_result<_Nodeptr> _Find_last(const _Keyty& _Keyval, const size_t _Hashval) const {
1653          // find the insertion point for _Keyval and whether an element identical to _Keyval is already in the container
1654          const size_type _Bucket = _Hashval & _Mask;
1655          _Nodeptr _Where         = _Vec._Mypair._Myval2._Myfirst[(_Bucket << 1) + 1]._Ptr;
1656          const _Nodeptr _End     = _List._Mypair._Myval2._Myhead;
1657          if (_Where == _End) {
1658              return {_End, _Nodeptr{}};
1659          }
1660
1661          const _Nodeptr _Bucket_lo = _Vec._Mypair._Myval2._Myfirst[_Bucket << 1]._Ptr;
1662          for (;;) {
1663              // Search backwards to maintain sorted [_Bucket_lo, _Bucket_hi] when !_Standar
1664              if (!_Traitsobj(_Keyval, _Traits::_Kfn(_Where->_Myval))) {
1665                  if _CONSTEXPR_IF (!_Traits::_Standard) {
1666                      if (_Traitsobj(_Traits::_Kfn(_Where->_Myval), _Keyval)) {
1667                          return {_Where->_Next, _Nodeptr{}};
1668                      }
1669                  }
1670
1671                  return {_Where->_Next, _Where};
1672              }
1673
1674              if (_Where == _Bucket_lo) {
1675                  return {_Where, _Nodeptr{}};
```

Exception Thrown

Exception thrown: read access violation.
this->_Vec._Mypair._Myval2._**Myfirst** was 0x11101110111011A.

Copy Details

Exception Settings

- [x] Break when this exception type is thrown
  Except when thrown from:
  - [ ] salmon.exe

Open Exception Settings | Edit Conditions

Undefined Behaviour means:

YOUR CODE MAY CRASH FOR NO EXPLAINABLE REASON

```
1   #include <iostream>
2
3   bool fn() {
4       // Oops! Forgot to return :-)
5   }
6
7   int main() {
8       std::cout << "Start ---" << std::endl;
9       if (fn()) {
10          std::cout << "fn() returned true\n";
11      } else {
12          std::cout << "fn() returned false\n";
13      }
14      std::cout << "Finish ---" << std::endl;
15      return 0;
16  }
```

```
Start ---
Start ---
bash: line 7:  1737 Segmentation fault      (core dumped) ./a.out
```

Undefined Behaviour means:

Your code may run and do something **completely unexplainable**

```c
#ifndef OPENSSL_NO_HEARTBEATS
int
tls1_process_heartbeat(SSL *s)
        {
        unsigned char *p = &s->s3->rrec.data[0], *pl;
        unsigned short hbtype;
        unsigned int payload;
        unsigned int padding = 16; /* Use minimum padding */

        /* Read type and payload length first */
        hbtype = *p++;
        n2s(p, payload);
        pl = p;

        if (s->msg_callback)
                s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
                        &s->s3->rrec.data[0], s->s3->rrec.length,
                        s, s->msg_callback_arg);
```

This is a pointer to an array

This *should* be the length of that array. It is not.

Undefined Behaviour means:

YOUR CODE MIGHT RUN FINE, BUT HACKERS CAN STEAL YOUR PASSWORDS

The code will crash if I read an array out of bounds, right? 😉 😉 😉

```c
#ifndef OPENSSL_NO_HEARTBEATS
int
tls1_process_heartbeat(SSL *s)
        {
        unsigned char *p = &s->s3->rrec.data[0], *pl;
        unsigned short hbtype;
        unsigned int payload;
        unsigned int padding = 16; /* Use minimum padding */

        /* Read type and payload length first */
        hbtype = *p++;
        n2s(p, payload);
        pl = p;

        if (s->msg_callback)
                s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
                        &s->s3->rrec.data[0], s->s3->rrec.length,
                        s, s->msg_callback_arg);
```

This is a pointer to an array

This *should* be the length of that array. It is not.

Undefined Behaviour means:

YOUR CODE MIGHT RUN FINE, BUT HACKERS CAN STEAL YOUR PASSWORDS

answer:
Hard maybe

The Heartbleed Bug

The Heartbleed Bug is a serious vulnerability in the popular OpenSSL cryptographic software library. This weakness allows stealing the information protected, under normal conditions, by the SSL/TLS encryption used to secure the Internet. SSL/TLS provides communication security and privacy over the Internet for applications such as web, email, instant messaging (IM) and some virtual private networks (VPNs).

The Heartbleed bug allows anyone on the Internet to read the memory of the systems protected by the vulnerable versions of the OpenSSL software. This compromises the secret keys used to identify the service providers and to encrypt the traffic, the names and passwords of the users and the actual content. This allows attackers to eavesdrop on communications, steal data directly from the services and users and to impersonate services and users.

Undefined Behaviour means:

YOUR CODE MIGHT RUN FINE, BUT HACKERS CAN STEAL YOUR PASSWORDS

Reading an array out of bounds **does not guarantee anything**

Definitions of Undefined Behaviour

- **“Renders the entire program meaningless** if certain rules of the language are violated.” [1]
- “There are **no restrictions on the behaviour of the program**” [1]
- “**Compilers are not required to diagnose undefined behaviour** […], and the compiled program **is not required to do anything meaningful**.” [1]
- “Because **correct C++ programs are free of undefined behaviour**, compilers may produce unexpected results when a program that actually has UB is compiled with optimization enabled” [1]
- If a program encounters UB when given a set of inputs, there are no requirements on its behaviour, **“not even with regard to operations preceding the first undefined operation”** [2]

[1] https://en.cppreference.com/w/cpp/language/ub

[2] C++20 Working Draft, Section 4.1.1.5

Undefined Behaviour in simpler terms

If you do something wrong in C++, **<u>literally anything</u>** can happen your code runs.

This includes:

- Your code runs and does nothing 🤔
- Your code runs as you expect it to 🙂
- Your code crashes with a helpful error message 🥲
- Your code crashes for no explainable reason 😖
- Your code runs and does something ***weird*** 😵
- Your code runs as you expect it to, but fails later at the worst possible moment 🤮
- Your code passes all tests, but hackers can steal your passwords 😭
- Demons will coming flying out of your nose

Common causes of **Undefined Behaviour**

- Reading from an **uninitialized variable**
- Reading an array **out of bounds**
- **Dereferencing a null pointer**
- **Dereferencing an invalid pointer** that doesn't point to any object
- Dereferencing a pointer to an object with an incompatible type
- Forgetting to return a value from a non-`void` function
- `delete`-ing dynamically allocated memory twice

Many infamous software bugs and vulnerabilities are due to Undefined Behaviour!

Why does C++ have Undefined Behaviour? This sounds **terrible**!

- Undefined Behaviour *simplifies* compilation (and language design)
  - Compilers can (and do!) assume that Undefined Behaviour never happens
  - Compilers don't need to do extra work to ensure safety
  - The concept of Undefined Behaviour was inherited from C
  - Detecting all types of Undefined Behaviour in C++ is **impossible.**

What Undefined Behaviour means for **you**

- **The C++ language cannot be learned by trial-and-error.**
- Read **good C++ books** and **reliable documentation** to best learn to avoid Undefined Behaviour
  - See https://isocpp.org/get-started for introductions, examples, tutorials, guidance, and books
  - See https://en.cppreference.com/w/ for language and standard library documentation
- If you **write safe code** to begin with, you will **waste less time debugging** 
- **Read compiler warnings** and **increase your compiler's warning level**
  - We've already turned on extra warnings in the starter code for you
- **When in doubt,** write your own safety checks

Avoiding Undefined Behaviour with safety checks

Using the `assert()` macro

Documentation: https://en.cppreference.com/w/cpp/error/assert

Use `assert(condition)` to test your assumptions

- In **debug mode**, halts the program *immediately* with a helpful error message if `condition` is false
  - **Use your debugger!** It will take you right to the problem!
- In **release mode**, does **nothing.**
  - Useful for optimization (fast code)
  - **Not useful for input validation!**
- Use `assert` to **test your assumptions** about your own code and to find **unrecoverable errors**
- For problems that can be fixed, such as a user pressing the wrong button, use a different error reporting mechanism (e.g. returning error codes)

```
1   #include <iostream>
2
3
4   int main() {
5       int x = 88;
6       int* ptr = nullptr;
7       for (int i = 0; i < 100 && !ptr; ++i) {
8           for (int j = 0; j < 100 && !ptr; ++j) {
9               if (i*i + j*j == x) {
10                  ptr = &x;
11              }
12          }
13      }
14      std::cout << *ptr << std::endl;
15      return 0;
16  }
17
```

```
bash: line 7: 29756 Segmentation fault      (core dumped) ./a.out
```

```cpp
#include <iostream>
#include <cassert>

int main() {
    int x = 88;
    int* ptr = nullptr;
    for (int i = 0; i < 100 && !ptr; ++i) {
        for (int j = 0; j < 100 && !ptr; ++j) {
            if (i*i + j*j == x) {
                ptr = &x;
            }
        }
    }
    assert(ptr != nullptr);
    std::cout << *ptr << std::endl;
    return 0;
}
```

```
a.out: main.cpp:14: int main(): Assertion `ptr != nullptr' failed.
bash: line 7: 30544 Aborted                 (core dumped) ./a.out
```

```
1   #include <iostream>
2   #include <vector>
3
4
5   class A {
6   public:
7       A() : m_items{1, 2, 3, 5, 7, 11, 13, 17, 19} {}
8       int getItem(int index){
9
10          return m_items[index];
11      }
12  private:
13      std::vector<int> m_items;
14  };
15
16  int main() {
17      auto a = A{};
18      std::cout << a.getItem(0) << std::endl;
19      std::cout << a.getItem(13) << std::endl;
20      return 0;
21  }
```

```
1
0
```

```cpp
#include <iostream>
#include <vector>
#include <cassert>

class A {
public:
    A() : m_items{1, 2, 3, 5, 7, 11, 13, 17, 19} {}
    int getItem(int index){
        assert(index >= 0 && index < m_items.size());
        return m_items[index];
    }
private:
    std::vector<int> m_items;
};

int main() {
    auto a = A{};
    std::cout << a.getItem(0) << std::endl;
    std::cout << a.getItem(13) << std::endl;
    return 0;
}
```

```
1
a.out: main.cpp:9: int A::getItem(int): Assertion `index >= 0 && index < m_items.size()' failed.
bash: line 7: 32109 Aborted                 (core dumped) ./a.out
```

```cpp
#include <iostream>
#include <cmath>
#include <exception>

int main() {
    auto x = 0.0;
    std::cin >> x;
    std::cout << "x is " << x << std::endl;



    std::cout << "sqrt(x) is " << std::sqrt(x) << std::endl;
    return 0;
}

```

```
x is -22
sqrt(x) is -nan
```

```cpp
#include <iostream>
#include <cmath>
#include <exception>

int main() {
    auto x = 0.0;
    std::cin >> x;
    std::cout << "x is " << x << std::endl;
    if (x < 0.0) {
        throw std::runtime_error("Oops! Please enter a non-negative number, thanks! :-)");
    }
    std::cout << "sqrt(x) is " << std::sqrt(x) << std::endl;
    return 0;
}

```

```
x is -22
terminate called after throwing an instance of 'std::runtime_error'
  what():  Oops! Please enter a non-negative number, thanks! :-)
bash: line 7:  3873 Done                    echo "-22"
      3874 Aborted                 (core dumped) | ./a.out
```

```cpp
24 int main() {
25     showLoginPrompt();
26     if (getUserCommand() == DatabaseAction::Drop){
27         auto uc = getUserCredentials();
28         std::cout << "LOG: " << uc << " wants to delete the database" << std::endl;
29         assert(uc == User::Admin);
30         deleteTheEntireDatabase();
31     }
32     return 0;
33 }
```

```
Welcome to Database Management System (Development Version 9.04.12)
LOG: Guest wants to delete the database
a.out: main.cpp:29: int main(): Assertion `uc == User::Admin' failed.
bash: line 7: 14871 Done
     14872 Aborted                 (core dumped) | ./a.out
```

```
24 int main() {
25     showLoginPrompt();
26     if (getUserCommand() == DatabaseAction::Drop){
27         auto uc = getUserCredentials();
28         std::cout << "LOG: " << uc << " wants to delete the database" << std::endl;
29         assert(uc == User::Admin);
30         deleteTheEntireDatabase();
31     }
32     return 0;
33 }
```

```
Welcome to Database Management System (Release 10.05.71)
LOG: Guest wants to delete the database
LOG: The database was successfully deleted. Everything is gone.
```

```
24 int main() {
25     try {
26         showLoginPrompt();
27         if (getUserCommand() == DatabaseAction::Drop){
28             auto uc = getUserCredentials();
29             std::cout << "LOG: " << uc << " wants to delete the database" << std::endl;
30             if (uc != User::Admin) {
31                 throw AuthenticationError{};
32             }
33             deleteTheEntireDatabase();
34         }
35     } catch (const std::exception& e){
36         std::cout << "ERROR: " << e.what() << std::endl;
37     }
38     return 0;
39 }
```

```
Welcome to Database Management System (Release 10.05.71)
LOG: Guest wants to delete the database
ERROR: Authentication failed
```

In conclusion:

- C++ is not safe
- *Undefined Behaviour* is weird
- *Undefined Behaviour* must be avoided
- Learn before you code
- Safety checks make life better


C++