



**Cppcon**  
The C++ Conference

# A Short Life span < > For a Regular Mess



September 15-20  
Aurora, Colorado, USA



 [@ciura\\_victor](https://twitter.com/ciura_victor)

**Victor Ciura**  
*Principal Engineer*  
**CAPHYON**

# *Abstract*

By now you probably heard about “Regular Types and Why Do I Care” :) This would be Part 2 of the journey we’ll take together, where we get a chance to explore `std::span<T>` through our Regular lens. Don’t worry if you’ve missed Part 1; we’ll have plenty of time to revisit the important bits, as we prepare to span our grasp into C++20.

“Regular” is not exactly a new concept. If we reflect back on STL and its design principles, as best described by Alexander Stepanov in his “Fundamentals of Generic Programming” paper, we see that regular types naturally appear as necessary foundational concepts in programming. Why do we need to bother with such taxonomies ? Because STL assumes such properties about the types it deals with and imposes such conceptual requirements for its data structures and algorithms to work properly. C++20 Concepts are based on precisely defined foundational type requirements such as Semiregular, Regular, EqualityComparable, etc.

Recent STL additions such as `std::string_view`, `std::reference_wrapper`, `std::optional`, as well as new incoming types for C++20 like `std::span` or `std::function_ref` raise new questions regarding value types, reference types and non-owning “borrow” types. Designing and implementing regular types is crucial in everyday programming, not just library design. Properly constraining types and function prototypes will result in intuitive usage; conversely, breaking subtle contracts for functions and algorithms will result in unexpected behavior for the caller.

This talk will explore the relation between Regular types (and other concepts) and new STL additions like `std::span<T>` with examples, common pitfalls and guidance.

2019



**Cppcon**  
The C++ Conference

New venue,  
same great C++ conference



September 15-20  
Aurora, Colorado, USA





I have concerns...





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# A Short Life span < > For a Regular Mess



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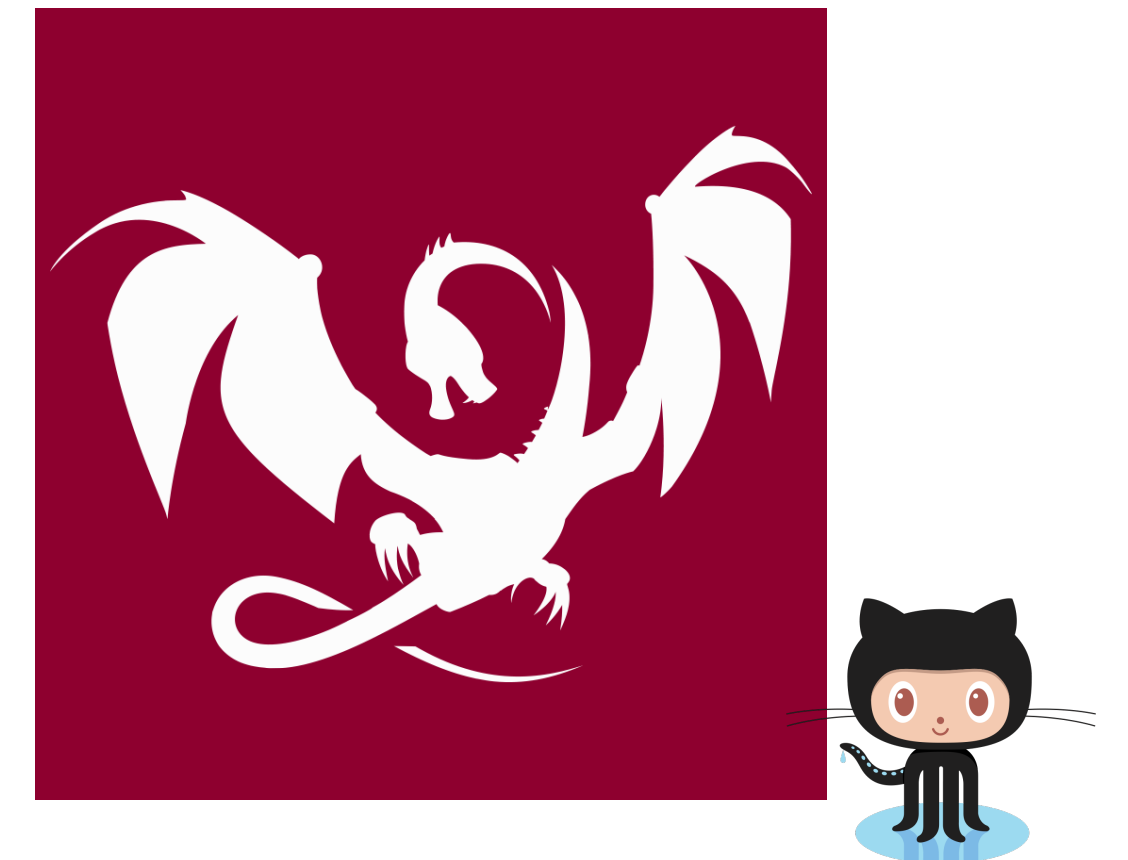
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# Who Am I?



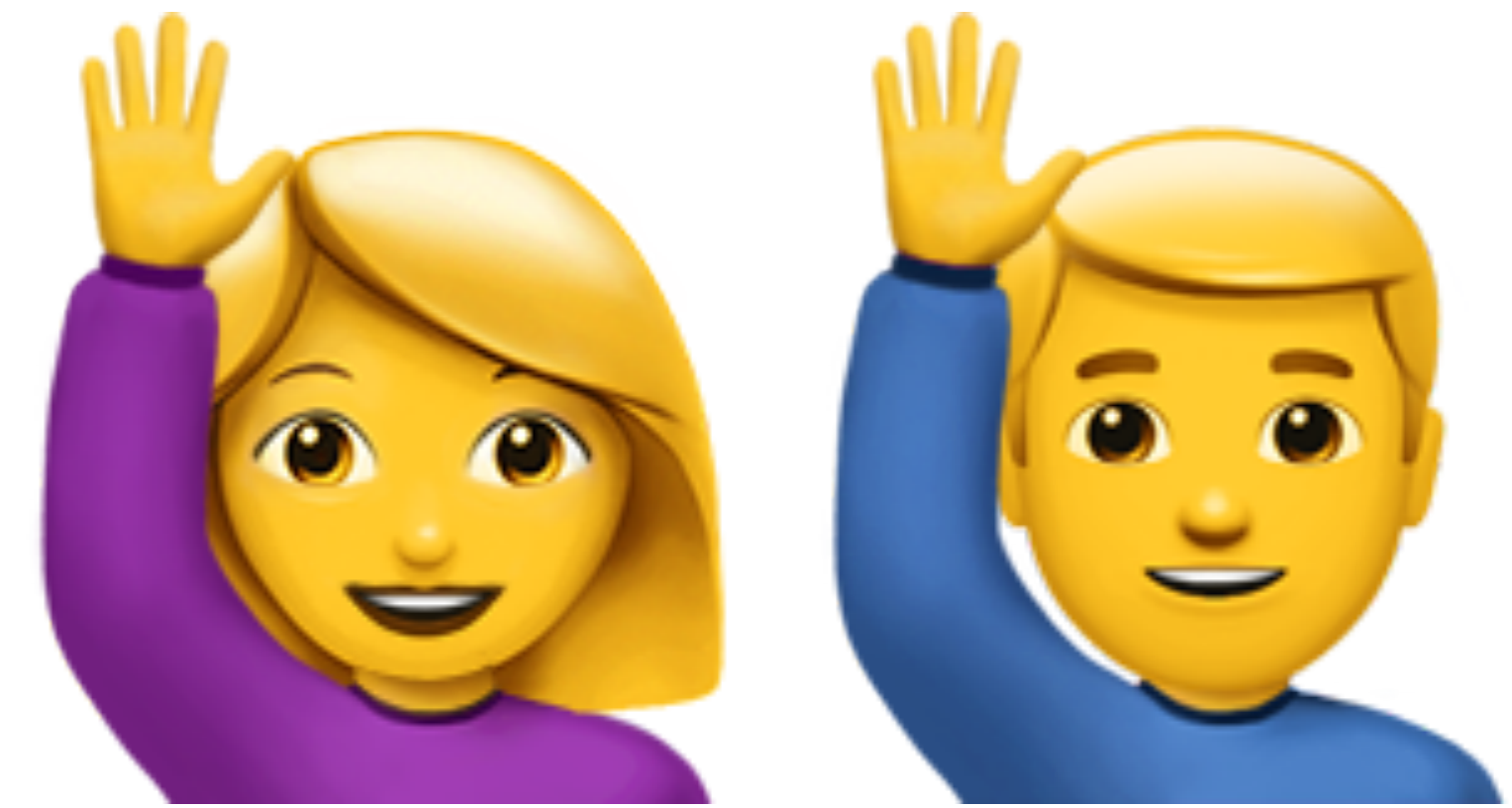
**Advanced Installer**



**Clang Power Tools**

 **@ciura\_victor**





# Regular Types and Why Do I Care ?

CppCon 2018 | Meeting C++ 2018 | ACCU 2019

**Why Regular types ?**

**Why are we talking about this ?**

# This talk is not just about Regular types

A moment to reflect back on **STL** and its **design principles**,  
as best described by Alexander Stepanov in his 1998 paper  
*“Fundamentals of Generic Programming”*

We shall see that **Regular types** naturally appear as necessary foundational concepts in programming and try to investigate how these requirements fit in the ever expanding C++ standard, bringing new data structures & algorithms.

# This talk is not just about Regular types

Values

Objects

Whole-part  
semantics

**C++17**

Concepts

Ordering  
Relations

**C++23~**

Requirements

**C++20**

Lifetimes

Equality

Cpp Core  
Guidelines

`std::span`

# Modern C++ API Design

## **Type Properties**

What properties can we use to describe types ?

## **Type Families**

What combinations of type properties make useful / good type designs ?

**Titus Winters** - Modern C++ API Design  
[youtube.com/watch?v=tn7oVNrPM8I](https://youtube.com/watch?v=tn7oVNrPM8I)

**Let's start with the beginning...**

~2,000 BC



# Three Algorithmic Journeys



Lectures presented at  
**A9**  
2012

Spoils of the Egyptians: Lecture 1 Part 1

[https://www.youtube.com/watch?v=wrmXDxn\\_Zuc](https://www.youtube.com/watch?v=wrmXDxn_Zuc)



# Three Algorithmic Journeys

## I. Spoils of the Egyptians (10h)

How elementary properties of commutativity and associativity of addition and multiplication led to fundamental algorithmic and mathematical discoveries.

## II. Heirs of Pythagoras (12h)

How division with remainder led to discovery of many fundamental abstractions.

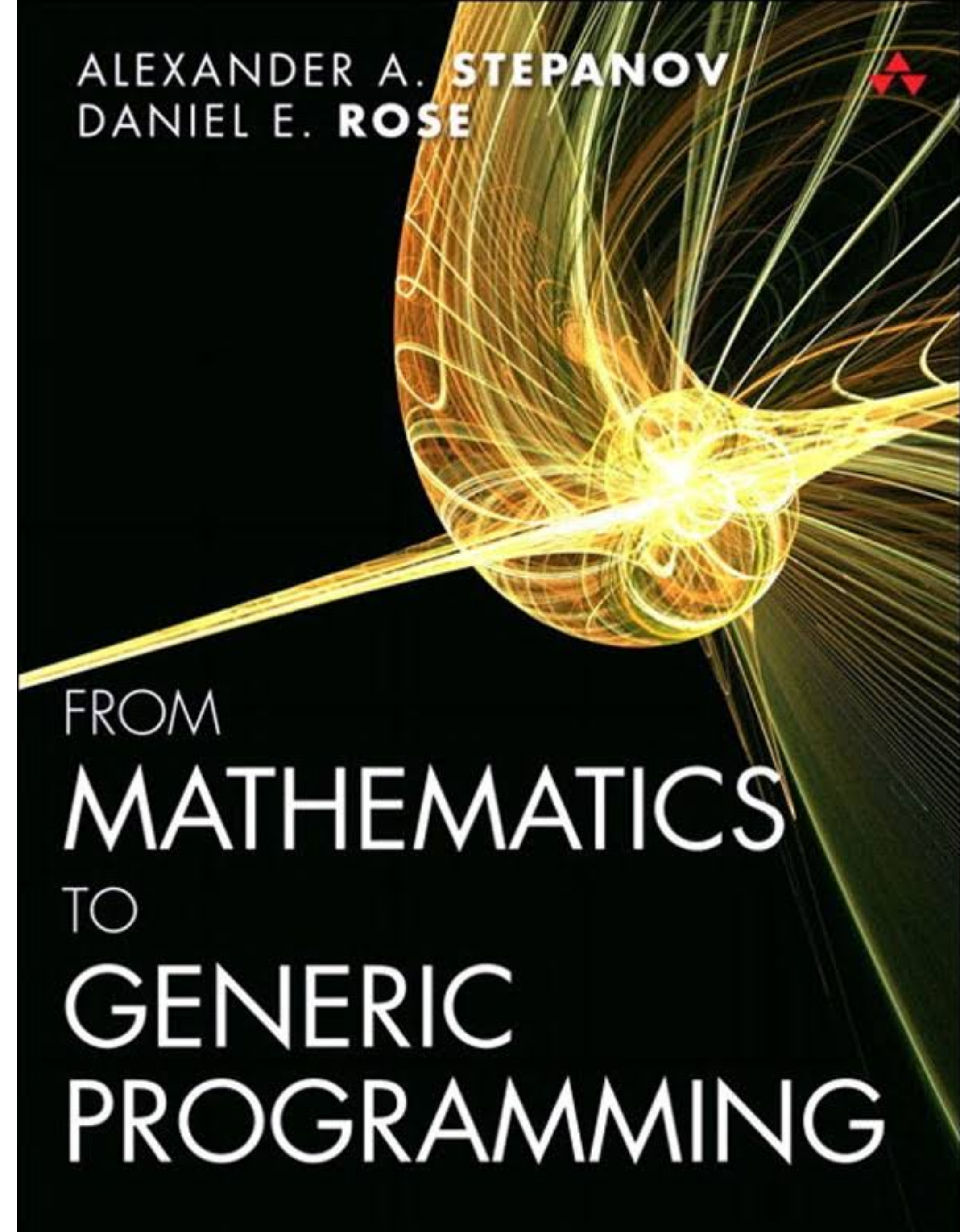
## III. Successors of Peano (10h)

The axioms of natural numbers and their relation to iterators.

Lectures presented at  
**A9**  
2012

[https://www.youtube.com/watch?v=wrmXDxn\\_Zuc](https://www.youtube.com/watch?v=wrmXDxn_Zuc)

- Egyptian multiplication ~ **1900-1650 BC**
- Ancient Greek number theory
- Prime numbers
- Euclid's GCD algorithm
- Abstraction in mathematics
- Deriving generic algorithms
- Algebraic structures
- Programming concepts
- Permutation algorithms
- Cryptology (RSA) ~ **1977 AD**





In the beginning there were just 0s and 1s



#define

# Datum

A **datum** is a finite sequence of **0**s and **1**s

**#EoP**

#define

# Value Type

A **value type** is a correspondence between a species (abstract/concrete) and a *set of datums*.

#EoP

#define

Value

**Value** is a datum together with its *interpretation*.

Eg.

an integer represented in 32-bit two's complement, big endian

**A value cannot change.**

**#EoP**

# Value Type & Equality

## Lemma 1

If a value type is **uniquely** represented,  
equality implies *representational equality*.

## Lemma 2

If a value type is not ambiguous,  
representational equality implies *equality*.

**#EoP**

#define

# Object

An **object** is a representation of a concrete entity as a **value** in computer *memory* (address & length).

An object has a **state** that is a *value* of some value type.

**The state of an object can change.**

**#EoP**



#define

Type

**Type** is a *set of values* with the same interpretation function and operations on these values.

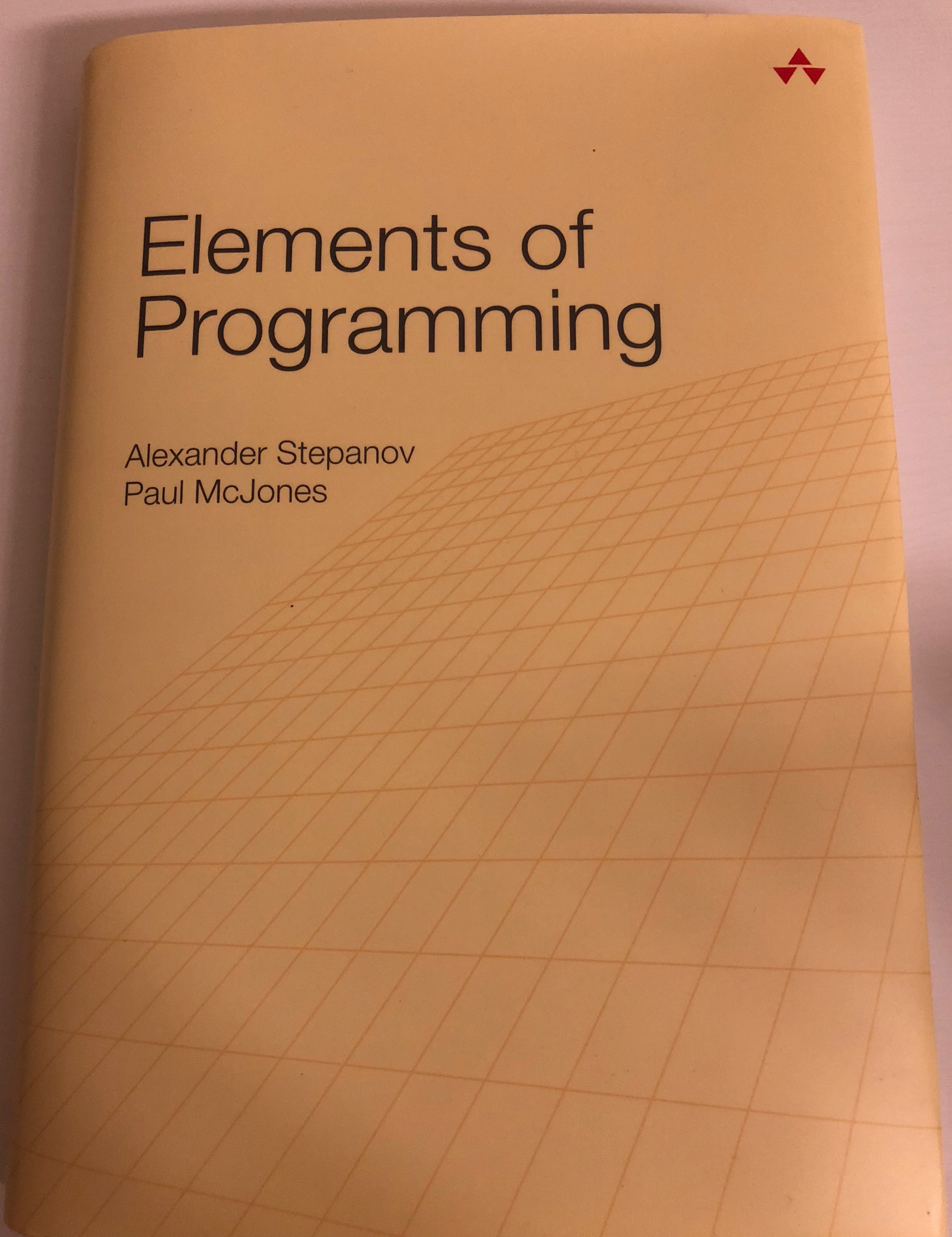
#EoP

#define

# Concept

A **concept** is a collection of similar types.

#EoP



# Elements of Programming

Alexander Stepanov  
Paul McJones

- **Foundations**
- Transformations and Their Orbits
- Associative Operations
- **Linear Orderings**
- Ordered Algebraic Structures
- Iterators
- Coordinate Structures
- Coordinates with Mutable Successors
- Copying
- Rearrangements
- Partition and Merging
- Composite Objects



<http://elementsofprogramming.com>

# Mathematics Really Does Matter



## GCD

One simple algorithm, refined and improved over 2,500 years, while advancing human understanding of mathematics

**SmartFriends U**  
September 27, 2003

Greatest Common Measure: The Last 2500 Years

<https://www.youtube.com/watch?v=fanm5y00joc>



## Hold on !

*"I've been programming for over  $N$  years,  
and I've never needed any **math** to do it.  
I'll be just fine, thank you."*

The reason things **just worked** for you  
is that other people thought long and hard  
about the details of the type system  
and the libraries you are using

... such that it feels **natural** and **intuitive** to you

**4,000 years of mathematics**

**It all leads up to...**

# Fundamentals of Generic Programming

<http://stepanovpapers.com/DeSt98.pdf>

James C. Dehnert and Alexander Stepanov  
1998

- “ Generic programming depends on the *decomposition* of programs into components which may be developed separately and combined arbitrarily, subject only to well-defined **interfaces**.



# Fundamentals of Generic Programming

<http://stepanovpapers.com/DeSt98.pdf>

James C. Dehnert and Alexander Stepanov  
1998

“ Among the *interfaces* of interest, the most *pervasively* and *unconsciously used*, are the fundamental operators *common* to all C++ **built-in types**, as extended to **user-defined types**, eg. *copy constructors*, *assignment*, and *equality*.

# Fundamentals of Generic Programming

<http://stepanovpapers.com/DeSt98.pdf>

James C. Dehnert and Alexander Stepanov  
1998

“ We must investigate the *relations* which must hold among these operators to preserve **consistency** with their semantics for the built-in types and with the *expectations of programmers*.

# Fundamentals of Generic Programming

<http://stepanovpapers.com/DeSt98.pdf>

James C. Dehnert and Alexander Stepanov  
1998

In other words:

We want a foundation powerful enough to support any sophisticated programming tasks, but **simple** and **intuitive** to reason about.

# Fundamentals of Generic Programming

Is simplicity a good goal ?

We're C++ programmers, are we not ?



# Fundamentals of Generic Programming

**Is simplicity a good goal ?**

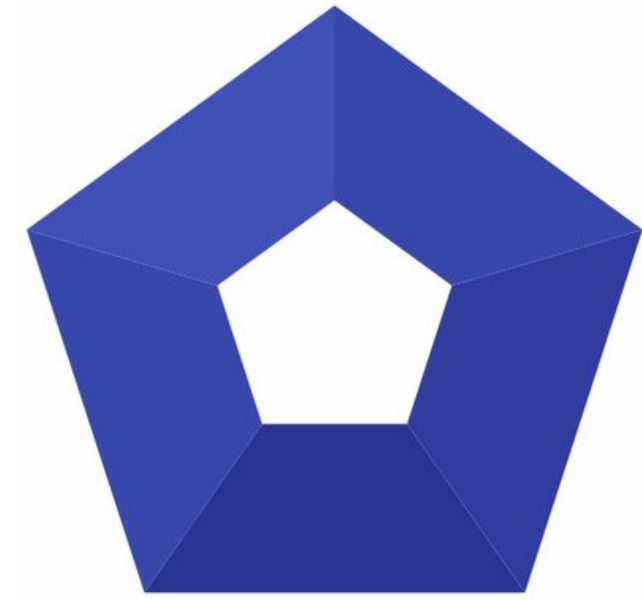
*I hate it when C++ programmers brag about being able to reason about some obscure language construct, proud as if they just discovered some new physical law*

:(

# Is simplicity a good goal ?

- **Simpler** code is more **readable** code
- **Unsurprising** code is more **maintainable** code
- Code that moves complexity to **abstractions** often has less bugs
- Compilers and **libraries** are often much better than you
- Simplicity is an act of **generosity** (to others, to future you)

Kate Gregory, *"It's Complicated"*, Meeting C++ 2017



# Revisiting Regular Types (after 20 years)

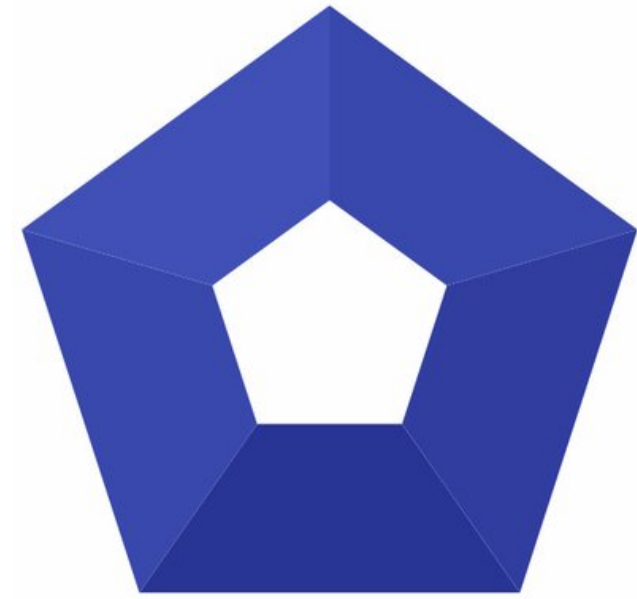
<https://abseil.io/blog/20180531-regular-types>

Titus Winters, 2018

Evokes the **Anna Karenina principle** to designing C++ types:

“ *Good types are all alike; every poorly designed type is poorly defined in its own way.*

- adapted with apologies to [Leo Tolstoy](#)



# Revisiting Regular Types (after 20 years)

<https://abseil.io/blog/20180531-regular-types>

Titus Winters, 2018

This essay is both the best up to date synthesis of the original **Stepanov** paper, as well as an investigation on using *non-values* as if they were **Regular** types.

This analysis provides us some basis to evaluate *non-owning reference parameters types* (like **string\_view** and **span**) in a practical fashion, without discarding **Regular** design.



**Let's go back to the roots...**

# **STL and Its Design Principles**

# STL and Its Design Principles



**Talk presented at Adobe Systems Inc.  
January 30, 2002**

<http://stepanovpapers.com/stl.pdf>

Alexander Stepanov: STL and Its Design Principles

<https://www.youtube.com/watch?v=COuHLky7E2Q>

# STL and Its Design Principles

## Fundamental Principles

- Systematically **identifying** and organizing useful **algorithms** and **data structures**
- Finding the most **general** representations of algorithms
- Using **whole-part value semantics** for data structures
- Using abstractions of addresses (**iterators**) as the interface between algorithms and data structures

# STL and Its Design Principles

- algorithms are associated with a set of ***common properties***

Eg. { +, \*, min, max } => **associative** operations

=> **reorder** operands

=> parallelize + reduction

C++98

std::accumulate()

C++17

std::transform\_reduce()

- natural extension of 4,000 years of mathematics
- exists a generic algorithm behind every **while()** or **for()** loop

# STL and Its Design Principles

## STL data structures

- STL data structures extend the semantics of C structures
- two objects never intersect (they are separate entities)
- two objects have separate lifetimes

# STL and Its Design Principles

## STL data structures have whole-part semantics

- copy of the whole, copies the parts
- when the whole is destroyed, all the parts are destroyed
- two things are equal when they have the same number of parts  
and their corresponding parts are equal

# STL and Its Design Principles

## Generic Programming Drawbacks

- abstraction penalty (rarely)
- implementation in the interface
- early binding
- horrible error messages (no formal specification of interfaces, yet)
- duck typing
- algorithm could work on some data types, but fail to work/compile on some other new data structures (different iterator category, no copy semantics, etc)

 We need to fully specify **requirements** on algorithm types.

# Named Requirements

Examples from STL:

DefaultConstructible, MoveConstructible, CopyConstructible

MoveAssignable, CopyAssignable, Swappable

Destructible

EqualityComparable, LessThanComparable

Predicate, BinaryPredicate

Compare

FunctionObject

Container, SequenceContainer, ContiguousContainer, AssociativeContainer

InputIterator, OutputIterator

ForwardIterator, BidirectionalIterator, RandomAccessIterator

[https://en.cppreference.com/w/cpp/named\\_req](https://en.cppreference.com/w/cpp/named_req)



# Named Requirements

Named requirements are used in the normative text of the C++ standard to define the **expectations** of the standard library.

Some of these requirements are being formalized in **C++20** using **concepts**.

Until then, the **burden is on the programmer** to ensure that library templates are instantiated with template arguments that satisfy these requirements.

[https://en.cppreference.com/w/cpp/named\\_req](https://en.cppreference.com/w/cpp/named_req)

# What Is A **Concept**, Anyway ?

Formal specification of concepts makes it possible to **verify** that template arguments satisfy the **expectations** of a template or function during overload resolution and template specialization (requirements).

Each concept is a **predicate**, evaluated at *compile time*, and becomes a part of the **interface** of a template where it is used as a constraint.

<https://en.cppreference.com/w/cpp/language/constraints>

# C++20 Renaming concepts from Pascal/CamelCase to snake\_case

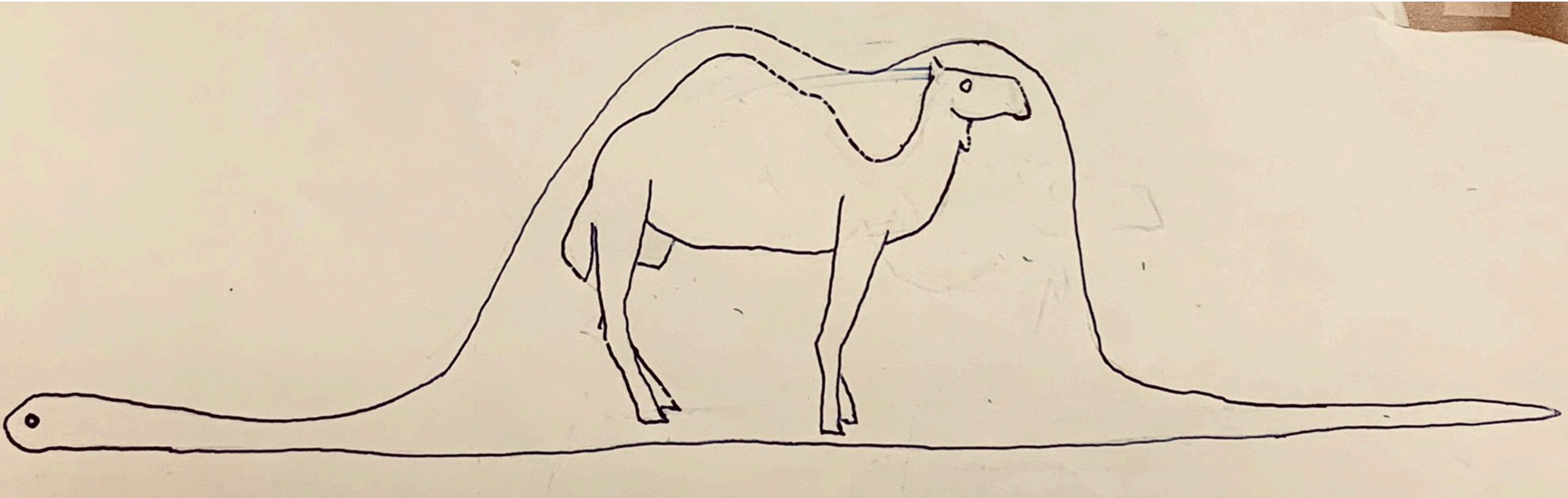
<https://wg21.link/p1754>

Boolean	boolean	SizedSentinel	sized_sentinel_for
EqualityComparable	equality_comparable	InputIterator	input_iterator
EqualityComparableWith	equality_comparable_with	OutputIterator	output_iterator
StrictTotallyOrdered	totally_ordered	ForwardIterator	forward_iterator
StrictTotallyOrderedWith	totally_ordered_with	BidirectionalIterator	bidirectional_iterator
Movable	movable	RandomAccessIterator	random_access_iterator
Copyable	copyable	ContiguousIterator	contiguous_iterator
Semiregular	semiregular	IndirectUnaryInvocable	indirectly_unary_invocable
Regular	regular	IndirectRegularUnaryInvocable	indirectly_regular_unary_invocable
Invocable	invocable	IndirectUnaryPredicate	indirect_unary_predicate
RegularInvocable	regular_invocable	IndirectRelation	indirect_relation
Predicate	predicate		

**VOTED**

# C++20 Renaming concepts from Pascal/CamelCase to snake\_case

<https://wg21.link/p1754>



Adults lack imagination...

Photo: @AdiShavit

With apologies to [Antoine de Saint-Exupéry](#) (The Little Prince)

# C++20 Renaming concepts from Pascal/CamelCase to snake\_case

<https://wg21.link/p1754>

I liked the original PascalCase because:

- it's desirable to make concepts **Stand Out** (they are *policies* rather than types)
- **concepts are not types** and should thus be named differently from standard types
- of consistency with standard **template parameters**  
eg.  

```
template<class CharT, class Traits, class Allocator>  
class basic_string;
```
- confusion with **type traits**:  
eg. having both `std::copy_constructible` and `std::is_copy_constructible`  
mean different things and give subtly different answers in some cases  
=> creates user confusion and pitfalls

# What's the Practical Upside ?

If I'm not a library writer 🧐,  
Why Do I Care ?

# What's the Practical Upside ?

Using STL algorithms & data structures

Designing & exposing your own **vocabulary types**  
(interfaces, APIs)

# Using STL - Compare Concept

Eg.

```
template<class RandomIt, class Compare>  
constexpr void std::sort(RandomIt first, RandomIt last, Compare comp);
```

What are the requirements for a Compare type ?

Compare << BinaryPredicate << Predicate << FunctionObject << Callable

```
bool comp(*iter1, *iter2);
```

But what kind of *ordering* relationship is needed for the *elements* of the collection ?



[https://en.cppreference.com/w/cpp/named\\_req/Compare](https://en.cppreference.com/w/cpp/named_req/Compare)



# Strict weak ordering

[https://en.wikipedia.org/wiki/Weak\\_ordering#Strict\\_weak\\_orderings](https://en.wikipedia.org/wiki/Weak_ordering#Strict_weak_orderings)

Irreflexivity	$\forall a, \text{comp}(a,a) == \text{false}$
Antisymmetry	$\forall a, b, \text{if } \text{comp}(a,b) == \text{true} \Rightarrow \text{comp}(b,a) == \text{false}$
Transitivity	$\forall a, b, c, \text{if } \text{comp}(a,b) == \text{true} \text{ and } \text{comp}(b,c) == \text{true} \Rightarrow \text{comp}(a,c) == \text{true}$
Transitivity of equivalence	$\forall a, b, c, \text{if } \text{equiv}(a,b) == \text{true} \text{ and } \text{equiv}(b,c) == \text{true} \Rightarrow \text{equiv}(a,c) == \text{true}$

where:

$\text{equiv}(a,b) : \text{comp}(a,b) == \text{false} \ \&\& \ \text{comp}(b,a) == \text{false}$

# < LessThanComparable

[https://en.cppreference.com/w/cpp/named\\_req/LessThanComparable](https://en.cppreference.com/w/cpp/named_req/LessThanComparable)

Irreflexivity	$\forall a, (a < a) == \text{false}$
Antisymmetry	$\forall a, b, \text{if } (a < b) == \text{true} \Rightarrow (b < a) == \text{false}$
Transitivity	$\forall a, b, c, \text{if } (a < b) == \text{true} \text{ and } (b < c) == \text{true} \Rightarrow (a < c) == \text{true}$
Transitivity of equivalence	$\forall a, b, c, \text{if } \text{equiv}(a, b) == \text{true} \text{ and } \text{equiv}(b, c) == \text{true} \Rightarrow \text{equiv}(a, c) == \text{true}$

where:

$\text{equiv}(a, b) : (a < b) == \text{false} \ \&\& \ (b < a) == \text{false}$

# Named Requirements

<http://wg21.link/p0898>

Examples from STL:

DefaultConstructible, MoveConstructible, CopyConstructible

MoveAssignable, CopyAssignable, Swappable

Destructible

LessThanComparable, EqualityComparable

Predicate, BinaryPredicate

Compare

FunctionObject

Container, SequenceContainer, ContiguousContainer, AssociativeContainer

InputIterator, OutputIterator

ForwardIterator, BidirectionalIterator, RandomAccessIterator

[https://en.cppreference.com/w/cpp/named\\_req](https://en.cppreference.com/w/cpp/named_req)

#define

SemiRegular

DefaultConstructible, MoveConstructible, CopyConstructible  
MoveAssignable, CopyAssignable, Swappable  
Destructible

<http://wg21.link/p0898>

#define

Regular

(aka "Stepanov Regular")

SemiRegular

DefaultConstructible, MoveConstructible, CopyConstructible

MoveAssignable, CopyAssignable, Swappable

Destructible

+

EqualityComparable

<http://wg21.link/p0898>

# Regular

(aka "Stepanov Regular")

STL assumes **equality** is always defined (at least, equivalence relation)

STL algorithms assume **Regular** data structures

The STL was written with *Regularity* as its basis

Also, see the **Palo Alto TR**

<http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2012/n3351.pdf>

<http://wg21.link/p0898>

# EqualityComparable

Reflexivity	$\forall a, (a == a) == \text{true}$
Symmetry	$\forall a, b, \text{if } (a == b) == \text{true} \Rightarrow (b == a) == \text{true}$
Transitivity	$\forall a, b, c, \text{if } (a == b) == \text{true} \text{ and } (b == c) == \text{true} \Rightarrow (a == c) == \text{true}$

The type must work with `operator==` and the result should have ***standard semantics***.

# Equality vs. Equivalence

For the types that are both `EqualityComparable` and `LessThanComparable`, the STL makes a clear **distinction** between **equality** and **equivalence**

where:

`equal(a,b)` : `(a == b)`

`equiv(a,b)` : `(a < b)==false && (b < a)==false`

**Equality** is a special case of **equivalence**



# Equality

Defining **equality** is hard 🙄

# Equality

“although it still leaves room for judgement”

Ultimately, **Stepanov** proposes the following *definition*:

- Two objects are **equal** if their corresponding *parts* are equal (applied recursively), including remote parts (but not comparing their addresses), excluding inessential components, and excluding components which identify related objects.



<http://stepanovpapers.com/DeSt98.pdf>



## C++20 Three-way comparison

**Bringing consistent comparison operations...**

operator  $\langle == \rangle$

```
(a  $\langle == \rangle$  b) < 0 if a < b  
(a  $\langle == \rangle$  b) > 0 if a > b  
(a  $\langle == \rangle$  b) == 0 if a and b are equal/equivalent
```

<http://wg21.link/p0515>



## C++20 Three-way comparison

The comparison categories for: `operator <=>`



**It's all about *relation strength***



# C++20 Three-way comparison

**The Mothership Has Landed**

**Adding `operator<=>` to the whole **STL****

Barry Revzin

2019-07 Cologne ISO C++ Committee Meeting

<https://wg21.link/P1614>



# C++20 Three-way comparison

## Simplify Your Code With Rocket Science



**Sy Brand**

<https://blog.tartanllama.xyz/spaceship-operator/>

**Cameron DaCamara**

<https://devblogs.microsoft.com/cppblog/simplify-your-code-with-rocket-science-c20s-spaceship-operator/>

**Before we get too far with C++20**

**let's spend a few minutes on an interesting C++17 type**

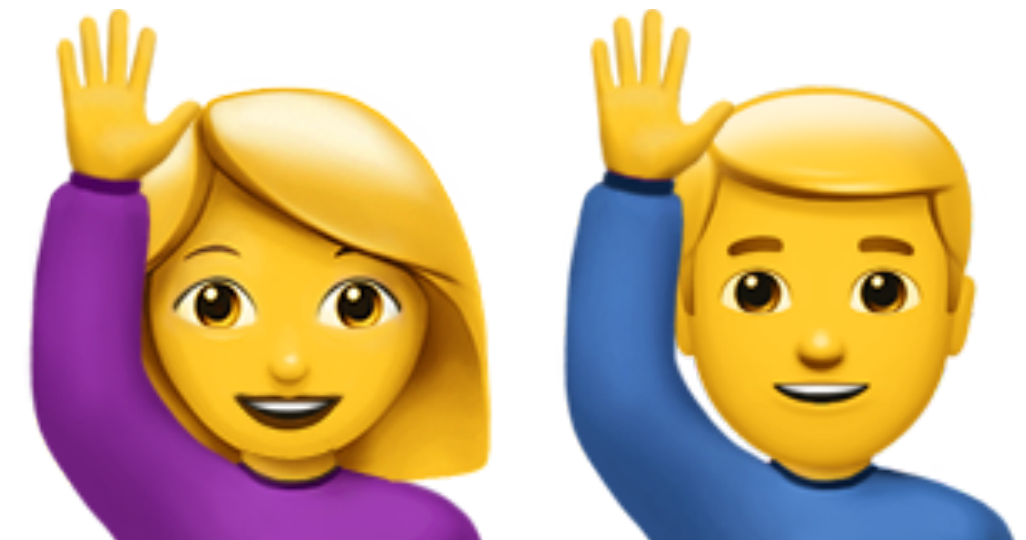
**C++17**

# `std::string_view`

An object that can refer to a **constant**  
*contiguous* sequence of `char`-like objects

A `string_view` does not manage the **storage** that it refers to

Lifetime management is up to the user





**I have a whole talk just on C++17 `std::string_view`**

# Enough `string_view` to hang ourselves

**CppCon 2018**

[https://www.youtube.com/watch?v=xwP4YCP\\_0q0](https://www.youtube.com/watch?v=xwP4YCP_0q0)



`std::string_view` is a *borrow type*

- Arthur O'Dwyer

<https://quuxplusone.github.io/blog/2018/03/27/string-view-is-a-borrow-type/>

# `std::string_view` is a borrow type



`string_view` succeeds admirably in the goal of “*drop-in replacement*” for `const string &` parameters.

## The problem:

The two relatively **old** kinds of types are **object types** and **value types**

The new kid on the block is the ***borrow type***

`string_view` is the first “mainstream” ***borrow type***

<https://quuxplusone.github.io/blog/2018/03/27/string-view-is-a-borrow-type/>

**Borrow types** are essentially “*borrowed*” references to existing objects

- they **lack ownership**
- they are **short-lived**
- they generally can do without an **assignment operator**
- they generally appear only in **function parameter** lists
- they generally **cannot be stored in data structures** or **returned** safely from functions (no ownership semantics)

# `std::string_view` is a borrow type



`string_view` is *assignable*: `sv1 = sv2`

Assignment has *shallow* semantics (of course, the viewed strings are *immutable*)

Meanwhile, the comparison `sv1 == sv2` has *deep* semantics (lexicographic comp)

# std::string\_view

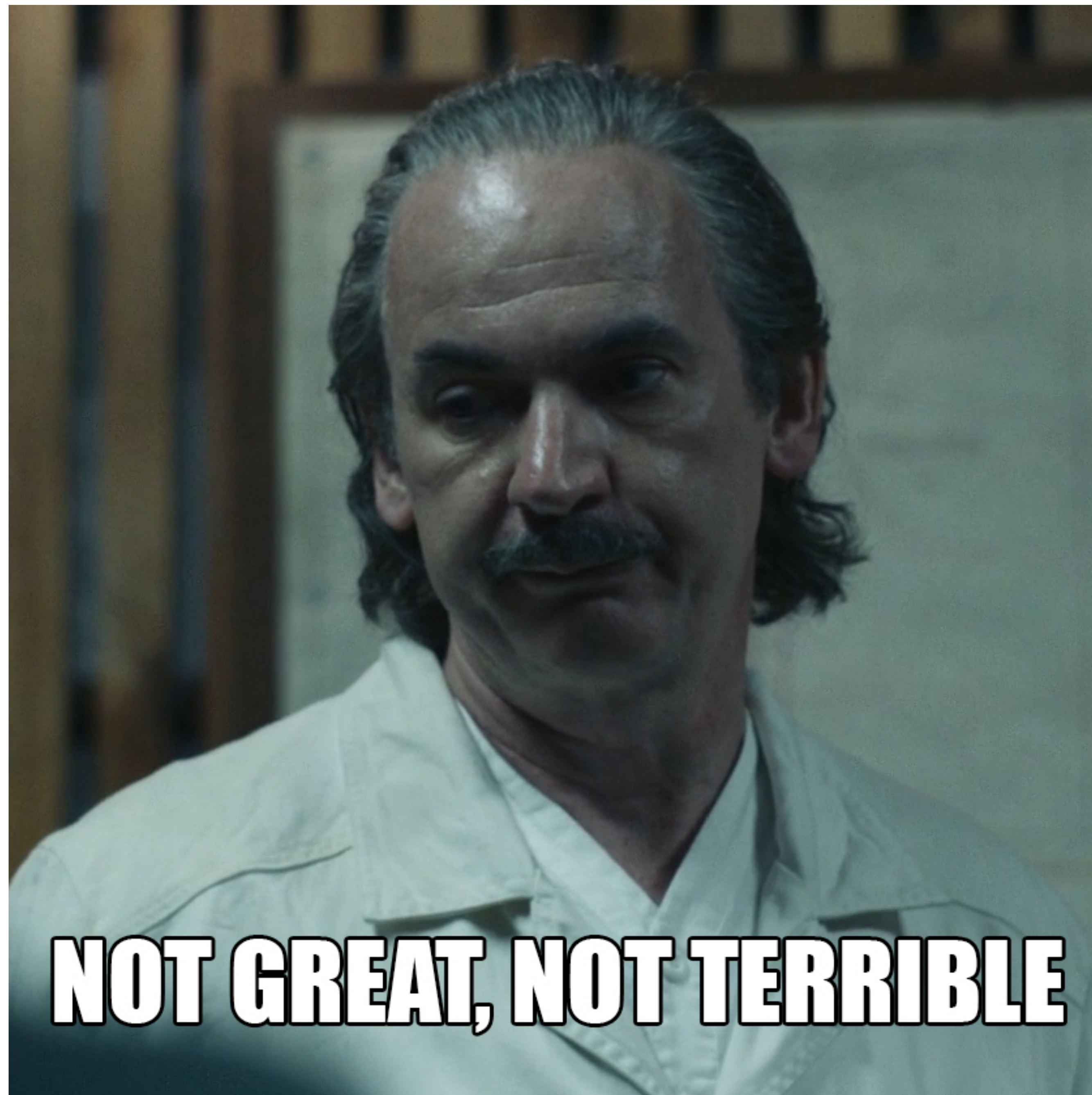
## Non-owning reference type

When the underlying data is **extant** and **constant**  
we can determine whether the rest of its usage still **looks Regular**

When used properly (eg. *function parameter*),

`string_view` works well...

as if it is a **Regular** type



**C++20** `std::span<T>`

I give you `std::span`

the very confusing type that the world's best C++  
experts are not quite sure what to make of

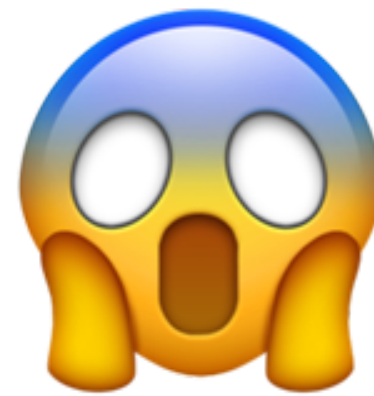


<https://en.cppreference.com/w/cpp/container/span>



**C++20** `std::span<T>`

Think "array\_view" as in `std::string_view`,  
but **mutable** on underlying data



<https://en.cppreference.com/w/cpp/container/span>

**C++20** `std::span<T>`

A `std::span` does not manage the **storage** that it refers to

Lifetime management is up to the user

<https://en.cppreference.com/w/cpp/container/span>

# Historical Background



## C++ Core Guidelines

[github.com/isocpp/CppCoreGuidelines](https://github.com/isocpp/CppCoreGuidelines)

Editors:

- [Bjarne Stroustrup](#)
- [Herb Sutter](#)

**F.24:** Use a `span<T>` or a `span_p<T>` to designate a half-open sequence

[CppCoreGuidelines.md#Rf-range](#)

**Pro.bounds:** Bounds safety profile

[CppCoreGuidelines.md#SS-bounds](#)

# C++ Core Guidelines

## F.24: Use a `span<T>` or a `span_p<T>` to designate a half-open sequence

**Reason: Informal/non-explicit ranges are a source of errors**

**Ranges** are extremely common in C++ code.

Typically, they are **implicit** and their correct use is very hard to ensure.

Given a pair of arguments  $(p, n)$  designating an array  $[p:p+n)$ ,

it is in general impossible to know if there really are  $n$  elements to access following  $*p$

**GSL** `span<T>` and `span_p<T>` were designed to solve this problem, by given an **explicit** context

# C++ Core Guidelines

## Pro.bounds: Bounds safety profile

- Don't use pointer arithmetic; use **span** instead
- Only index into arrays using constant expressions
- No array-to-pointer decay
- Don't use standard-library functions and types that are not bounds-checked

Pass pointers to single objects (only) and Keep pointer arithmetic simple

Use the standard library in a type-safe manner

# Historical Background



## **GSL: Guidelines Support Library**

[github.com/microsoft/GSL](https://github.com/microsoft/GSL)

The library includes types like `span`, `string_span`, `owner` and others

[github.com/Microsoft/GSL/blob/master/include/gsl/span](https://github.com/Microsoft/GSL/blob/master/include/gsl/span)

(circa 2017)

# Historical Background

## `std::span`

“ Comes directly from the **C++ Core Guidelines**' **GSL** and is intended to be a replacement especially for unsafe C-style (pointer, length) parameter pairs.

We expect to be used pervasively as a vocabulary type for function parameters in particular.


**span: bounds-safe views for sequences of objects**

[wg21.link/p0122](https://wg21.link/p0122) Neil MacIntosh & Stephan T. Lavavej

<https://herbsutter.com/2018/04/02/trip-report-winter-iso-c-standards-meeting-jacksonville/>

# Automatic Checkers

## Use the C++ Core Guidelines checkers

- core guideline checkers are installed by default in **Visual Studio 2017** and **Visual Studio 2019**  
[docs.microsoft.com/en-us/visualstudio/code-quality/using-the-cpp-core-guidelines-checkers](https://docs.microsoft.com/en-us/visualstudio/code-quality/using-the-cpp-core-guidelines-checkers)
- LLVM **clang-tidy** `-checks='-* ,cppcoreguidelines-*'`  
[clang.llvm.org/extra/clang-tidy/checks/list.html](https://clang.llvm.org/extra/clang-tidy/checks/list.html)
- ClangPowerTools  (powered by **clang-tidy**)  
[clangpowertools.com](https://clangpowertools.com)



# Automatic Checkers

- **LLVM clang-tidy**

[clang.llvm.org/extra/clang-tidy/checks/cppcoreguidelines-pro-bounds-array-to-pointer-decay.html](http://clang.llvm.org/extra/clang-tidy/checks/cppcoreguidelines-pro-bounds-array-to-pointer-decay.html)

This check flags all array to pointer decays. Pointers should not be used as arrays. `span<T>` is a bounds-checked, safe alternative to using pointers to access arrays.

[clang.llvm.org/extra/clang-tidy/checks/cppcoreguidelines-pro-bounds-pointer-arithmetic.html](http://clang.llvm.org/extra/clang-tidy/checks/cppcoreguidelines-pro-bounds-pointer-arithmetic.html)

This check flags all usage of pointer arithmetic, because it could lead to an invalid pointer. **Subtraction** of two pointers is **not flagged** by this check.

Pointers should only refer to single objects, and pointer arithmetic is fragile and easy to get wrong. `span<T>` is a bounds-checked, safe type for accessing arrays of data.

# Automatic Checkers

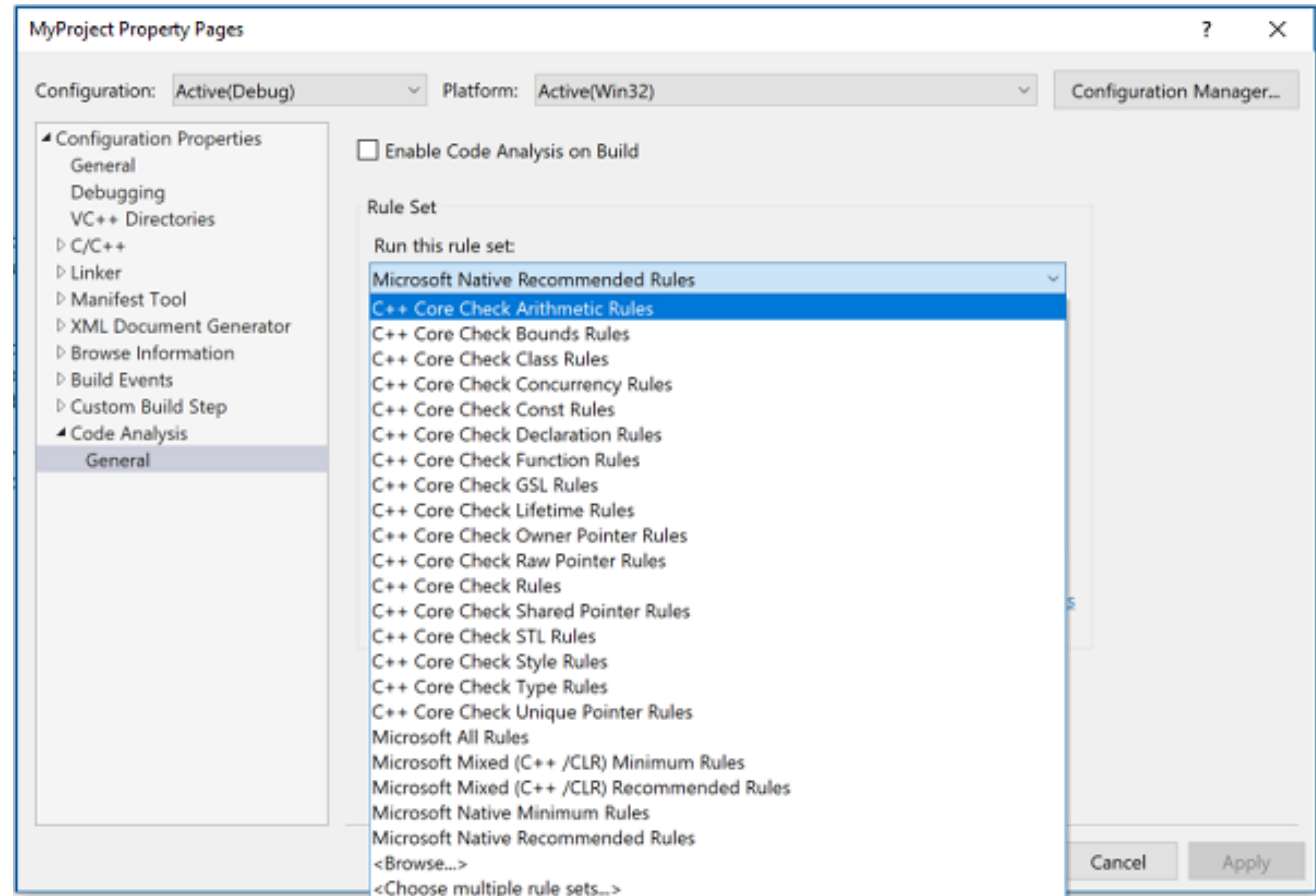
- Visual Studio 2017/2019

C26485

Bounds.3: No array-to-pointer decay.

C26481

Bounds.1: Don't use pointer arithmetic.  
Use span instead.



[docs.microsoft.com/en-us/visualstudio/code-quality/using-the-cpp-core-guidelines-checkers](https://docs.microsoft.com/en-us/visualstudio/code-quality/using-the-cpp-core-guidelines-checkers)

# Automatic Checkers

- Visual Studio 2017/2019

```
int arr[10];           // warning C26494
int * p = arr;        // warning C26485
```

```
[[gsl::suppress(bounds.1)]] // This attribute suppresses Bounds rule #1
{
    int * q = p + 1; // warning C26481 (suppressed)
    p = q++;        // warning C26481 (suppressed)
}
```

C26494

Type.5: Always initialize an object

C26485

Bounds.3: No array-to-pointer decay

C26481

Bounds.1: Don't use pointer arithmetic  
Use span instead

# Automatic Checkers

```
static unsigned char* encodeBytesGroup(unsigned char* data, const unsigned char* buffer, int bits)
{
    assert(bits >= 1 && bits <= 8);

    if (bits == 1)
        return data;

    if (bits == 8)
    {
        memcpy(data, buffer, kByteGroupSize);
        return data + kByteGroupSize;
    }

    size_t byte_size = 8 / bits;
    assert(kByteGroupSize % byte_size == 0);

    // fixed portion: bits bits for each value
    // variable portion: full byte for each out-of-range value (using 1...1 as sentinel)
```



26481: Don't use pointer arithmetic. Use span instead (bounds.1).

<https://twitter.com/zeuxcg/status/1088686771037122560?s=21>

# Automatic Checkers

```
for (size_t i = 0; i < kByteGroupSize; ++i)  
{  
    if (buffer[i] >= sentinel)  
    {  
        *data  
    }  
}
```

const unsigned char \*buffer  
26481: Don't use pointer arithmetic. Use span instead (bounds.1).

```
return data;
```



<https://twitter.com/zeuxcg/status/1088686771037122560?s=21>

# std::span

Defined in header `<span>`

```
template<
    class T,
    std::size_t Extent = std::dynamic_extent
> class span;
```

an object that can refer to a **contiguous** sequence of objects with the first element of the sequence at position zero

A typical implementation holds only two members:

- a pointer to T
- a size

A span can either have:

- a **static extent** (number of elements is known and encoded in the type)
- a **dynamic extent**

# Construct a span

```
constexpr span() noexcept;
```

```
constexpr span(pointer ptr, index_type count);
```

```
constexpr span(pointer first, pointer last);
```

```
template <std::size_t N>  
constexpr span(element_type (&arr)[N]) noexcept;
```

```
template <std::size_t N>  
constexpr span(std::array<value_type, N>& arr) noexcept;
```

```
template <std::size_t N>  
constexpr span(const std::array<value_type, N>& arr) noexcept;
```



```
template <class Container>  
constexpr span(Container& cont);
```

```
template <class Container>  
constexpr span(const Container& cont);
```

```
template <class U, std::size_t N>  
constexpr span(const std::span<U, N>& s) noexcept;
```

```
constexpr span(const span& other) noexcept = default;
```

# Notable functions

constexpr reference `front()` const;

constexpr reference `back()` const;

constexpr reference `operator[]`(index\_type idx) const;

constexpr pointer `data()` const noexcept;



# Notable functions

```
constexpr index_type size_bytes() const noexcept  
{  
    return size() * sizeof(element_type);  
}
```

```
template<class T, std::size_t N>  
auto as_bytes(std::span<T, N> s) noexcept  
{  
    return std::span(reinterpret_cast<const std::byte*>(s.data()), s.size_bytes());  
}
```

```
template<class T, std::size_t N>  
auto as_writable_bytes(std::span<T, N> s) noexcept  
{  
    return std::span(reinterpret_cast<std::byte*>(s.data()), s.size_bytes());  
}
```

# Subviews

```
template<size_t Count>  
constexpr span<element_type, Count> first() const;  
  
constexpr span<element_type, std::dynamic_extent> first(size_t Count) const;
```

```
template<size_t Count>  
constexpr span<element_type, Count> last() const;  
  
constexpr span<element_type, std::dynamic_extent> last(size_t Count) const;
```

```
template<size_t Offset, size_t Count = std::dynamic_extent>  
constexpr span<element_type, CountOrDiff> subspan() const;  
  
constexpr std::span<element_type, std::dynamic_extent> subspan(  
    size_t Offset, size_t Count = std::dynamic_extent) const;
```

# Usability Enhancements for `std::span`

[wg21.link/p1024](http://wg21.link/p1024)

- Add `front()` and `back()` member functions
  - improve consistency with standard library containers
- Mark `empty()` as `[[nodiscard]]`
- Remove `operator()`
  - vestigial traces from the `array_view` multidimensional genesis
- *Structured bindings* support for fixed-size spans
  - `std::get<N>()`
  - `tuple_element / tuple_size`

# WWSD

## What Would **Stepanov** Do?

## Should Span be Regular?

[wg21.link/p1085](https://wg21.link/p1085)

Tony Van Eerd

### "Copy or copy not; there is no shallow" - Master Yoda

- *overloading operators* can be dangerous when you change the **common meaning** of the operator
- the meaning of **copy construction** and **copy assignment** is to **copy the value** of the object
- the meaning of **==** and **<** is to **compare the value** of the object
- **copy**, **assignment**, **equality** are expected to go together (act as built-in types -- *intuitively*)
- when designing a class type, where possible it should be a **Regular** type (see **EoP**)

<https://herbsutter.com/2018/11/13/trip-report-fall-iso-c-standards-meeting-san-diego/>

## Should Span be Regular?

[wg21.link/p1085](https://wg21.link/p1085)

Tony Van Eerd

- `operator=` (copy) is **shallow** (just **pointer** and **size** are copied)
- we could make `operator==` **deep** (elements in the span are compared with `std::equal()`), just like `std::string_view`
  - however `string_view` **can't modify** the elements it points at (**const**)  
=> the shallow copy of `string_view` is similar to a *copy-on-write optimization*
  - but is span a **value** ? do we need a **deep** compare ?
- `std::span` is trying to act like a collection of the elements over which it spans
  - but it's not **Regular** !
- basically `std::span` has **reference semantics**

<https://herbsutter.com/2018/11/13/trip-report-fall-iso-c-standards-meeting-san-diego/>

## Should Span be Regular?

[wg21.link/p1085](https://wg21.link/p1085)

Tony Van Eerd

- **deep operator==** also implies **deep const** (logical const) - extend protection to all parts (**EoP**)
  - all parts of the type that constitute its **value** (eg. participate in **==** and **copy**)
  - **deep equality** means the *value* of span are the **elements** it spans, not `{ ptr + size }`
- if we want span to act like a *lightweight* representation of the elements it references:
  - => we need to have a **shallow operator==** (*just like smart pointers*)
    - **shallow const** => **shallow operator==**
- but **shallow operator==** might be really confusing to users (especially because of `string_view`)
- final decision was to REMOVE **operator==** completely

**APPROVED**

<https://herbsutter.com/2018/11/13/trip-report-fall-iso-c-standards-meeting-san-diego/>

# A Strange Beast

`std::span` - a case of unmet expectations...

- Users of the STL can reasonably expect `span` to be a *drop-in replacement* for `std::vector` | `std::array`
- And that happens to be mostly the case...
- Until of course, you try to **copy** it or change its **value**, then it stops acting like a container :(

`std::span` is ~~Regular~~ **SemiRegular**

<https://cor3ntin.github.io/posts/span/>



C++20

`std::span<T>`



Photo credit: Corentin Jabot

<https://cor3ntin.github.io/posts/span/>

Non-owning reference types  
like `string_view` or `span`

You need more **contextual** information when working  
on an instance of this type

Things to consider:

- shallow copy ?
- shallow / deep compare ?
- const / mutability ?
- `operator==`

Non-owning reference types  
like `string_view` or `span`

Have reference semantics,  
but without the “magic” that can make references safer  
(for example *lifetime extension*)

# std::string\_view cheatsheet

## Lifetime with std::string\_view (C++17)

std::string\_view isn't a drop-in replacement  
for const std::string&

```
std::string str() {  
    return std::string("long_string_helps_to_detect_issues");  
}
```

```
const std::string& s = str();  
std::cout << s << '\n';
```

**lifetime extended**  
**prints the correct result**



```
std::string_view sv = str();  
std::cout << sv << '\n';
```

**lifetime not extended**  
**prints nonsense**



**const lvalue reference** binds to rvalue and provides lifetime extension. But there is no lifetime extension for std::string\_view.

For short strings this issue might be hard to detect due to short string optimization (SSO). The problem becomes obvious with longer (dynamically allocated) strings.

@walletfox





# clang-tidy bugprone-dangling-handle



Detect dangling references in value handles like `std::string_view`

These dangling references can be a result of constructing handles from **temporary** values, where the temporary is destroyed **soon** after the handle is created.

## Options:

### HandleClasses

A semicolon-separated list of class names that should be treated as handles. By default only `std::string_view` is considered.

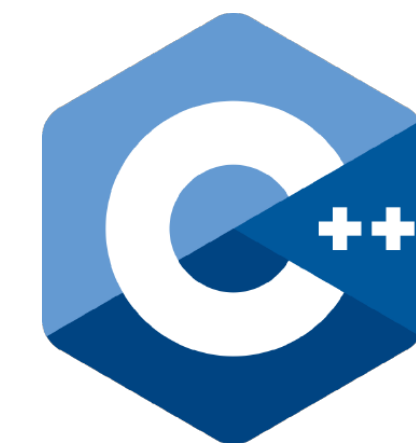
`std::span` 🙌

<https://clang.llvm.org/extra/clang-tidy/checks/bugprone-dangling-handle.html>

# Lifetime profile v1.0

## Lifetime safety: Preventing common dangling

This is important because it turns out to be **easy** to convert **[by design]** a `std::string` to a `std::string_view`, or a `std::vector/array` to a `std::span`, so that **dangling is almost the default behavior**.



CppCoreGuidelines

<https://github.com/isocpp/CppCoreGuidelines/blob/master/docs/Lifetime.pdf>

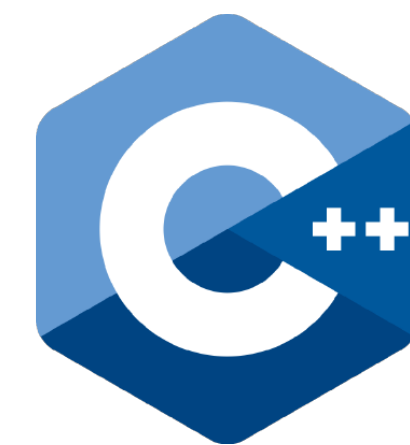
# Lifetime profile v1.0

## Lifetime safety: Preventing common dangling

```
void example()
{
    std::string_view sv = std::string("dangling"); // A
    std::cout << sv; // ERROR (lifetime.3): 'sv' was invalidated when
} // temporary was destroyed (line A)
```

clang **-Wlifetime**

Experimental



CppCoreGuidelines

<https://github.com/isocpp/CppCoreGuidelines/blob/master/docs/Lifetime.pdf>



# Lifetime safety: Preventing common dangling

`[-Wdangling-gsl]` diagnosed by default in Clang 10

**warning:** initializing pointer member to point to a temporary object whose lifetime is shorter than the lifetime of the constructed object

```
void example()
{
    std::string_view sv = std::string("dangling");
    // warning: object backing the pointer will be destroyed
    // at the end of the full-expression [-Wdangling-gsl]
    std::cout << sv;
}
```

<https://clang.llvm.org/docs/DiagnosticsReference.html#wdangling-gsl>





# Lifetime safety: Preventing common dangling

`[-Wdangling-gsl]` diagnosed by default in Clang 10

**warning:** initializing pointer member to point to a temporary object whose lifetime is shorter than the lifetime of the constructed object

```
void example()
{
    std::span sp = std::vector{1,2,3,4}; // warning: 🙅 WIP... (PR)

    for (auto e : sp)
        std::cout << e << " ";
}
```

<https://clang.llvm.org/docs/DiagnosticsReference.html#wdangling-gsl>

# Simple rules for borrow types

**Borrow types** must appear *only as function parameters* or *for-loop control variables*



We can make an **exception** for function *return types*:

- a function may have a borrow type as its return type  
(the function must be explicitly **[annotated]** as returning a potentially dangling reference)
- the result returned ***must not be stored*** into any named variable,  
except passed along to a function parameter or for-loop control variable

# Say What You Mean

If you decide to make an **exception** to these best practices, strongly consider **explicitly annotating** your intent in code.

*Custom attributes ?*



`[[magic]]`

`[[trust_me_on_this_one]]`

`[[i_am_very_sorry]]`

`[[it_works_on_my_machine]]`

`[[beware_of_dangling_reference]]`

<https://en.cppreference.com/w/cpp/language/attributes>

Credit: **Ólafur Waage**  
@olafurw

# Compiler Support

<https://godbolt.org/z/FRHiPR>

The screenshot shows the Compiler Explorer interface. On the left, a C++ source file is open with the following code:

```
1
2 #include <vector>
3 #include <span>
4 #include <iostream>
5
6 int main()
7 {
8     std::vector<int> v = {1, 2, 3, 4, 5};
9     std::span<int> sp = v;
10
11     for (auto & i : sp)
12         std::cout << i << " ";
13
14     return 0;
15 }
```

On the right, the 'Conformance viewer' shows a table of compiler configurations:

Compiler	Flags	Status
x86-64 gcc 9.2	-Werror -Wall -Wextra -std=c++2a	✗
x86-64 gcc (trunk)	-Werror -Wall -Wextra -std=c++2a	✗
x86-64 clang 8.0.0	-Werror -Wall -Wextra -std=c++2a <u>-stdlib=libstdc++</u>	✗
x86-64 clang 7.0.0	-Werror -Wall -Wextra -std=c++2a <u>-stdlib=libc++</u>	✓
x64 msvc v19.22	/WX /W4 /std:c++latest	✗

Below the table, a red error message is displayed:

```
fatal error: span: No such file or directory
3 | #include <span>
```

[https://en.cppreference.com/w/cpp/compiler\\_support](https://en.cppreference.com/w/cpp/compiler_support)

# Span Evolution

Initial <code>std::span</code> spec	<a href="http://wg21.link/p0122">wg21.link/p0122</a>	Clang libc++ <b>7.0</b>
Remove comparison operators of <code>std::span</code>	<a href="http://wg21.link/p1085">wg21.link/p1085</a>	Clang libc++ <b>8.0</b>
Usability enhancements for <code>std::span</code>	<a href="http://wg21.link/p1024">wg21.link/p1024</a>	Clang libc++ <b>9.0</b>
<code>std::ssize()</code> and unsigned extent for <code>std::span</code>	<a href="http://wg21.link/p1227">wg21.link/p1227</a>	Clang libc++ <b>9.0</b>

# Span Evolution (cont)

<https://wg21.link/p1394> **Range** constructor for `std::span`

<https://wg21.link/p1391> **Range** constructor for `std::string_view` (Bonus)

<https://wg21.link/p448> A **stringstream** replacement using `span<charT>` as buffer



[github.com/cplusplus/papers/issues?q=span](https://github.com/cplusplus/papers/issues?q=span)

# Can't Wait ?

Want an implementation of `std::span` to match the **C++20** CD ?


Clang libc++ 9.0

<https://github.com/tcbrindle/span>

by **Tristan Brindle**

[github.com/chromium/chromium/base/containers/span.h](https://github.com/chromium/chromium/base/containers/span.h)

# The Five Phases Of Joy

 **Timur Doumler**  
@timur\_audio

The five phases of joy:

- 1 🥵 Refactoring some audio code
- 2 😎 In the process, adding a cool modern C++ feature
- 3 😭 Realising that it's a C++20 feature and my compiler doesn't do that yet
- 4 🤔 Trying to work around this limitation
- 5 😊 Discovering a defect in the C++20 working draft

9:36 AM · Aug 10, 2019 · [Twitter for iPhone](#)

14 Retweets 143 Likes

Can you guess what was  
the C++20 feature ?

`std::span`

**lacks a feature test macro**

[https://twitter.com/timur\\_audio/status/1160092474259443712?s=21](https://twitter.com/timur_audio/status/1160092474259443712?s=21)



# The Five Phases Of Joy

`std::span` lacks a feature test macro



Can't you use `__has_include` for that?

new header: `<span>`

**libc++** always has all the headers it's implemented, but those headers are **empty** unless you have the right standard enabled. So that doesn't work.

## Why do I care ?

In case you want to use *another* **span** implementation, until the *standard* one becomes available (same API)

[https://twitter.com/timur\\_audio/status/1160092474259443712?s=21](https://twitter.com/timur_audio/status/1160092474259443712?s=21)

# Double or Nothing

```
int main(std::span<std::string_view> args);
```

**Two of my favorite pet peeves, combined into one glorious disaster**

**What if the implementation expects a [null-terminated string](#) ?  
(eg. calling some old system C API)**

# Beyond `std::span`

C++ 23-26

## Possible areas of focus:

- `stride_view`
- `slice_view`
- `sliding_view`
- `cycle_view`
- `chunk_view`

**It's all about ranges !**

# OTHER DIMENSIONS...

C++ 23-26

mdspan

A Non-Owning Multidimensional Array Reference

[wg21.link/p0009](https://wg21.link/p0009)

mdarray

An Owning Multidimensional Array Analog of mdspan

[wg21.link/p1684](https://wg21.link/p1684)

Hear more about it:

<https://cppcast.com/bryce-leibach-mdspan/>

Early implementation by **David Hollman**:

<https://github.com/kokkos/mdspan>

#defining data layout

in memory

HP computing, graphics



## Call To Action

Make your value types **Regular**

The best Regular types are those that model built-ins most closely and have no dependent preconditions.

Think `int` or `std::string` or `std::vector`

<https://github.com/cplusplus/LEWG/blob/master/library-design-guidelines.md>



## Call To Action

For non-owning reference types like `string_view` or `span`

You need more **contextual** information when working on an instance of this type

Try to restrict these types to **SemiRegular** to avoid confusion for your users



**Cppcon**  
The C++ Conference

# A Short Life span < > For a Regular Mess



September 15-20  
Aurora, Colorado, USA



 [@ciura\\_victor](https://twitter.com/ciura_victor)

**Victor Ciura**  
*Principal Engineer*  
**CAPHYON**

# References I encourage you to study

**Alexander Stapanov, Paul McJones**

Elements of Programming (2009)

<http://elementsofprogramming.com>

**Alexander Stapanov, James C. Dehnert**

Fundamentals of Generic Programming (1998)

<http://stepanovpapers.com/DeSt98.pdf>

**Alexander Stepanov**

STL and Its Design Principles - presented at Adobe Systems Inc., January 30, 2002

<https://www.youtube.com/watch?v=COuHLky7E2Q>

<http://stepanovpapers.com/stl.pdf>

**Bjarne Stroustrup, Andrew Sutton, et al.**

A Concept Design for the STL (2012)

<http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2012/n3351.pdf>



# References I encourage you to study

## **Titus Winters**

Revisiting Regular Types

<https://abseil.io/blog/20180531-regular-types>

## **Corentin Jabot (cor3ntin)**

A can of span

<https://cor3ntin.github.io/posts/span/>

RangeOf: A better span

<https://cor3ntin.github.io/posts/rangeof/>

## **Christopher Di Bella**

Prepping Yourself to Conceptify Algorithms

<https://www.cjdb.com.au/blog/2018/05/15/prepping-yourself-to-conceptify-algorithms.html>

## **Tony Van Eerd**

Should Span be Regular?

<http://wg21.link/P1085>

# References I encourage you to study

## Barry Revzin

Non-Ownership and Generic Programming and Regular types, oh my!

<https://medium.com/@barryrevzin/non-ownership-and-generic-programming-and-regular-types-oh-my>

Should Span Be Regular?

<https://medium.com/@barryrevzin/should-span-be-regular-6d7e828dd44>

span: the best span

<https://brevzin.github.io/c++/2018/12/03/span-best-span/>

Implementing the spaceship operator for optional

<https://medium.com/@barryrevzin/implementing-the-spaceship-operator-for-optional-4de89fc6d5ec>

# References I encourage you to study

## Sy Brand

Functional exceptionless error-handling with optional and expected  
<https://blog.tartanllama.xyz/optional-expected/>

Spaceship Operator  
<https://blog.tartanllama.xyz/spaceship-operator/>

Monadic operations for std::optional  
<https://wg21.tartanllama.xyz/monadic-optional>

# References I encourage you to study

## Arthur O'Dwyer

Default-constructibility is overrated

<https://quuxplusone.github.io/blog/2018/05/10/regular-should-not-imply-default-constructible/>

Comparison categories for narrow-contract comparators

<https://quuxplusone.github.io/blog/2018/08/07/lakos-rule-for-comparison-categories/>

std::string\_view is a borrow type

<https://quuxplusone.github.io/blog/2018/03/27/string-view-is-a-borrow-type/>



# References I encourage you to study

**Jonathan Müller**

## **Mathematics behind Comparison**

#1: Equality and Equivalence Relations

<https://foonathan.net/blog/2018/06/20/equivalence-relations.html>

#2: Ordering Relations in Math

<https://foonathan.net/blog/2018/07/19/ordering-relations-math.html>

#3: Ordering Relations in C++

<https://foonathan.net/blog/2018/07/19/ordering-relations-programming.html>

#4: Three-Way Comparison

<https://foonathan.net/blog/2018/09/07/three-way-comparison.html>

#5: Ordering Algorithms

<https://foonathan.net/blog/2018/09/07/three-way-comparison.html>

# **BONUS SLIDES**

# Object Relocation

One particularly sensitive topic about handling C++ **values** is that they are all conservatively considered **non-relocatable**

<https://github.com/facebook/folly/blob/master/folly/docs/FBVector.md#object-relocation>

# Object Relocation

In contrast, a **relocatable value** would preserve its invariant, even if its bits were moved arbitrarily in memory

For example, an `int32` is relocatable because moving its **4 bytes** would preserve its actual value, so the address of that value does not matter to its integrity.

<https://github.com/facebook/folly/blob/master/folly/docs/FBVector.md#object-relocation>



# Object Relocation



<https://github.com/facebook/folly/blob/master/folly/docs/FBVector.md#object-relocation>

# Object Relocation

C++'s assumption of **non-relocatable values** hurts everybody  
for the benefit of a few questionable designs

<https://github.com/facebook/folly/blob/master/folly/docs/FBVector.md#object-relocation>

# Object Relocation

Only a *minority* of objects are genuinely non-relocatable:

- objects that use internal **pointers**
- objects that need to update **observers** that store pointers to them

<https://github.com/facebook/folly/blob/master/folly/docs/FBVector.md#object-relocation>

# Object Relocation



**"Object relocation in terms of move plus destroy"**

Arthur O'Dwyer

<https://wg21.link/p1144>