

Regular, Revisited

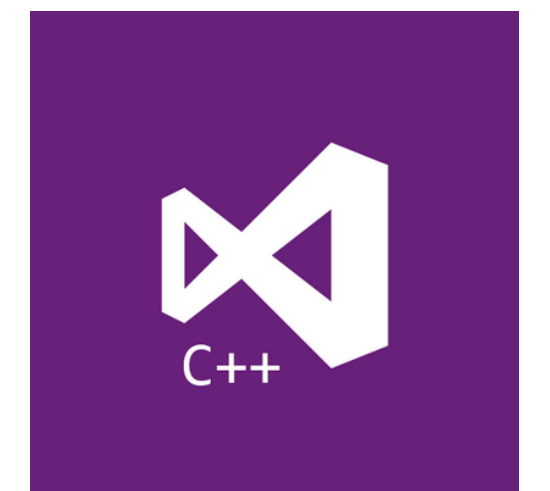
Meeting C++

November 2023

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Visual C++



Abstract

“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.

STL vocabulary types such as `string_view`, `span`, `optional`, `expected` etc., raise new questions regarding values types, whole-part semantics, copies, composite objects, ordering and equality.

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 (plus other concepts) and STL constructs, with examples, common pitfalls and guidance.

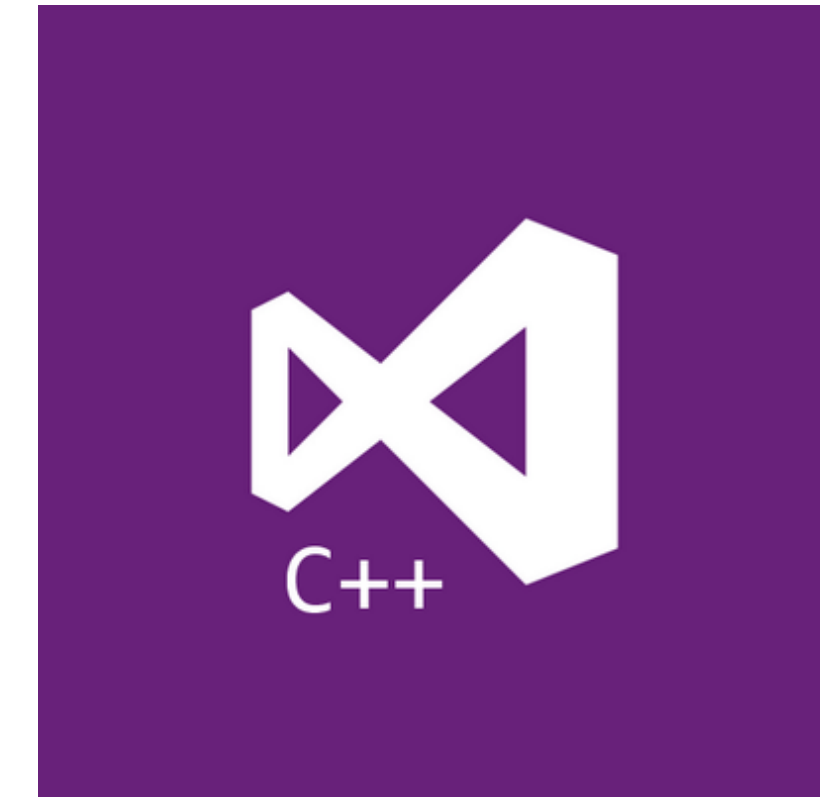
About me



Advanced Installer



Clang Power Tools



Visual C++

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

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Classified

The **classes** we write:


- RAII
- Utility
- Callable
- Wrappers
- Function bundles :(
- Polymorphic types / Hierarchies
- Containers
- Values
- ...



"The Evolution of C++ - A Typescript for C++", Herb Sutter - CppNow 2023 [youtube.com/watch?v=fJvPBHERF2U](https://www.youtube.com/watch?v=fJvPBHERF2U)


Some are more special than others...

cppcon | 2018
THE C++ CONFERENCE • BELLEVUE, WASHINGTON




VICTOR CIURA

Regular Types
and Why Do I Care ?

cppcon 
the c++ conference

Regular Types and Why Do I Care ?

September, 2018



Victor Ciura
Technical Lead, Advanced Installer
www.advancedinstaller.com

Revisiting Regular Types

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](#)

Titus Winters, 2018

abseil.io/blog/20180531-regular-types

Why Regular types ?

Why are we talking about this ?

Why are we talking about this ?

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.

Why are we talking about this ?

Even the [CppCoreGuidelines](#) preach about this thing:

C.11: Make concrete types Regular

Regular types are [easier to understand](#) and reason about than types that are not regular (irregularities requires extra effort to understand and use).

The C++ [built-in types are regular](#), and [so are standard-library classes](#) such as [string](#), [vector](#), and [map](#).

Concrete classes without assignment and equality can be defined, but they [are \(and should be\) rare](#).

isocpp.github.io/CppCoreGuidelines/CppCoreGuidelines#Rc-regular

Why are we talking about this ?

Even the [CppCoreGuidelines](#) preach about this thing:

T.46: Require template arguments to be at least Semiregular

Reason: [Readability](#).

[Preventing surprises and errors](#).

Most uses support that anyway.

isocpp.github.io/CppCoreGuidelines/CppCoreGuidelines#Rt-regular

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”

25 years!

This talk is not just about Regular types

This talk is not just about Regular types

Values

This talk is not just about Regular types

Values

Objects

This talk is not just about Regular types

Values

Objects

Concepts

This talk is not just about Regular types

Values

Objects

Concepts

Ordering
Relations

This talk is not just about Regular types

Values

Objects

Concepts

Ordering
Relations

Requirements

This talk is not just about Regular types

Values

Objects

Concepts

Ordering
Relations

Requirements

Equality

This talk is not just about Regular types

Values

Objects

Whole-part
semantics

Concepts

Ordering
Relations

Requirements

Equality

This talk is not just about Regular types

Values

Objects

Whole-part
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Concepts

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Requirements

Lifetimes

Equality

This talk is not just about Regular types

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Requirements

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Equality

C++ Core
Guidelines

This talk is not just about Regular types

Values

Objects

Whole-part
semantics

C++17

Concepts

Ordering
Relations

Requirements

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This talk is not just about Regular types

Values

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Whole-part
semantics

C++17

Concepts

Ordering
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Requirements

C++20

Lifetimes

Equality

Cpp Core
Guidelines

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

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

Let's start with the beginning...

2,000 BC



Four Three Algorithmic Journeys



Lectures presented at

A9
(2012)

Spoils of the Egyptians: Lecture 1 Part 1

https://www.youtube.com/watch?v=wrmXDxn_Zuc

Four 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)

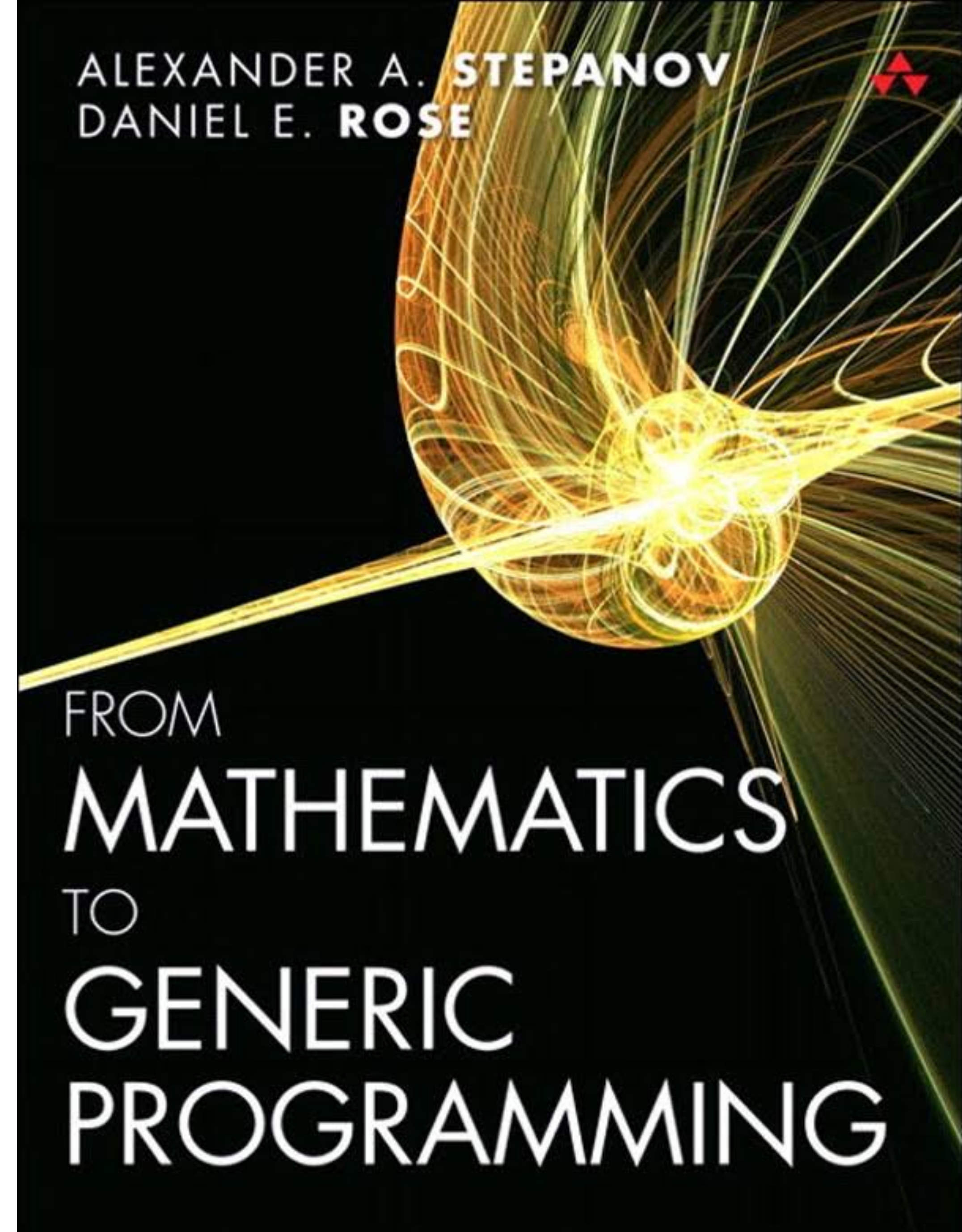
The axioms of natural numbers and their relation to iterators.

Lectures presented at

A9

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**





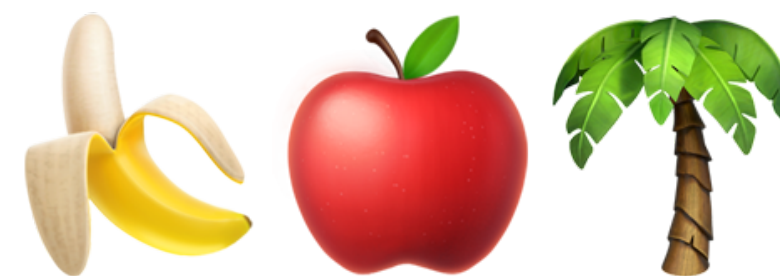
In the beginning there were just 0s and 1s

#define

Datum

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

Can represent anything...



#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

#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*.

#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).

#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.

#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.

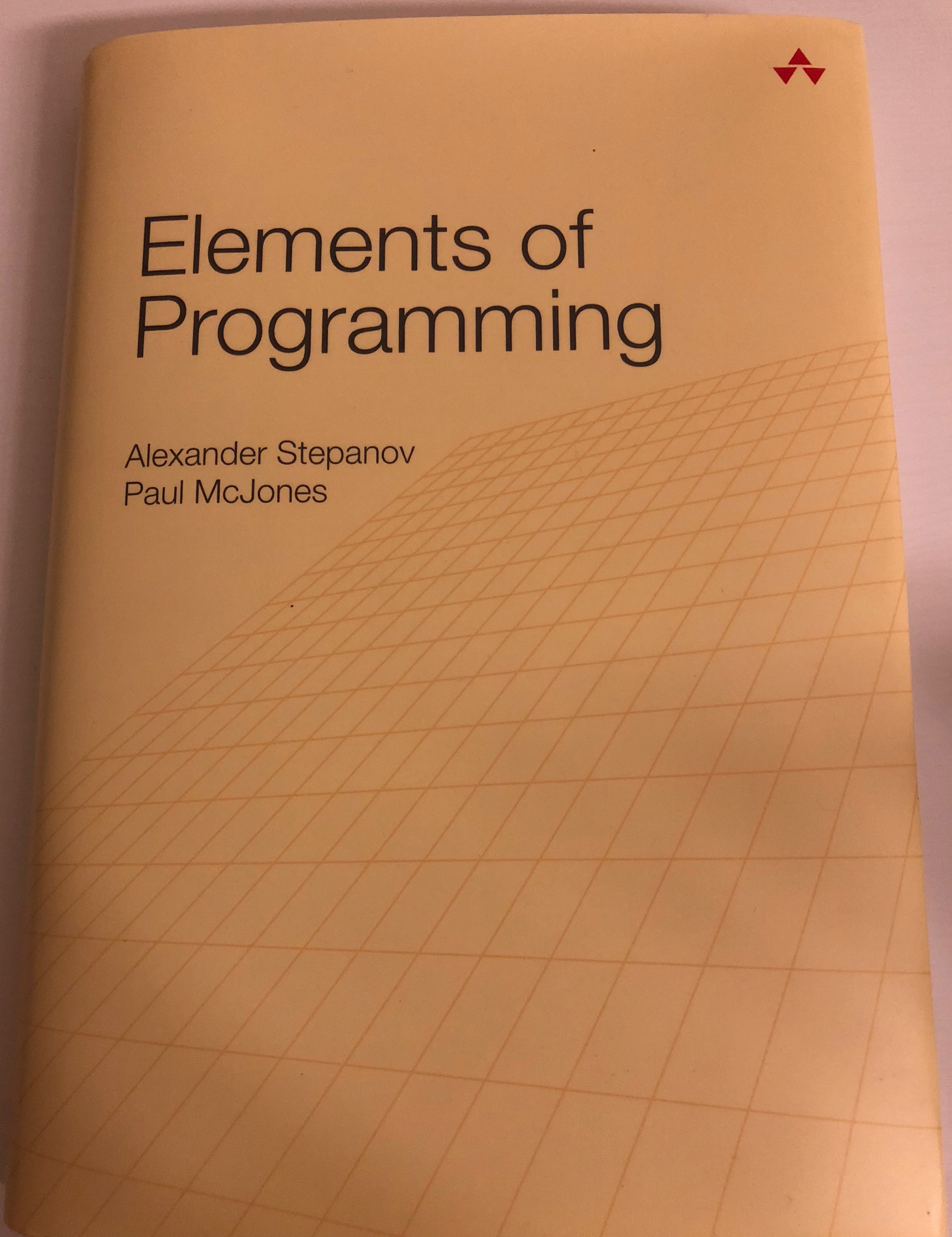
#EoP

#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



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

We can produce an axiomatization of these operators which:

- yields the required **consistency** with built-in types
- matches the **intuitive** expectations of programmers
- reflects our underlying mathematical **expectations**

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

:(

Revisiting Regular Types

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.

Revisiting Regular Types

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**

stepanovpapers.com/stl.pdf

Alexander Stepanov: STL and Its Design Principles 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

whole-part semantics



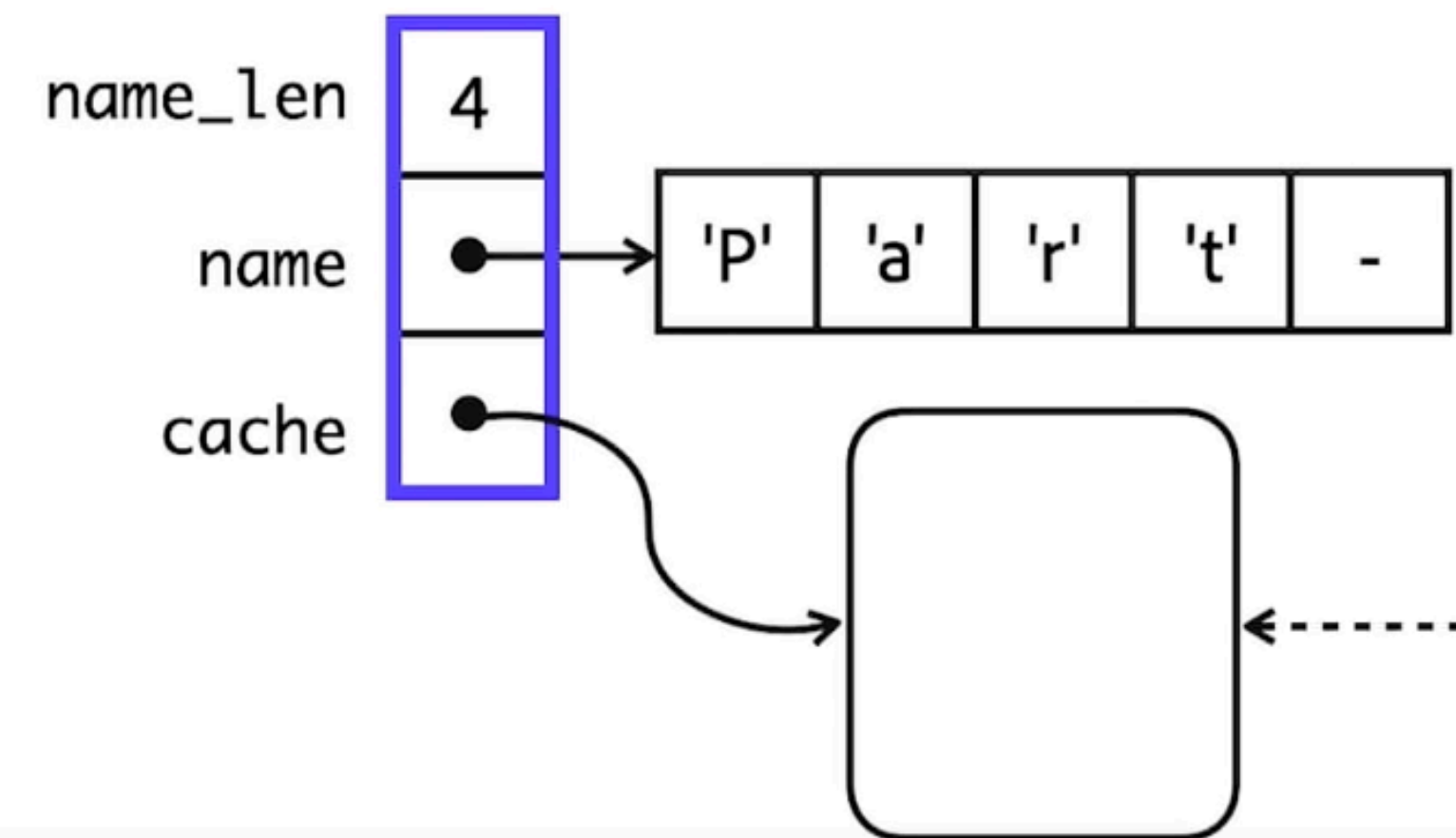
Dave Abrahams

Values: Safety, Regularity, Independence, and the Future of Programming

Achieving value semantics today | decoupling an object graph

What's a value? You decide 🤖

That choice determines the *meaning* of a type.



STL and Its Design Principles

Generic Programming Drawbacks

- abstraction penalty (rarely)
- implementation in the interface
- early binding
- horrible error messages (only in 99% of the cases 😊)
- duck typing
- algorithm could work on some data types, but fail to work/compile on some other new data structures

👉 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

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 have been formalized in **C++20** using **concepts**.

C++20 Concepts

Core language concepts

Defined in header [<concepts>](#)

same_as (C++20)

derived_from (C++20)

convertible_to (C++20)

common_reference_with (C++20)

common_with (C++20)

integral (C++20)

signed_integral (C++20)

unsigned_integral (C++20)

floating_point (C++20)

assignable_from (C++20)

swappable
swappable_with (C++20)

destructible (C++20)

constructible_from (C++20)

default_initializable (C++20)

move_constructible (C++20)

copy_constructible (C++20)

Comparison concepts

Defined in header [<concepts>](#)

boolean-testable (C++20)

equality_comparable
equality_comparable_with (C++20)

totally_ordered
totally_ordered_with (C++20)

Defined in header [<compare>](#)

three_way_comparable
three_way_comparable_with (C++20)

Object concepts

Defined in header [<concepts>](#)

movable (C++20)

copyable (C++20)

semiregular (C++20)

regular (C++20)

Callable concepts

Defined in header [<concepts>](#)

invocable
regular_invocable (C++20)

predicate (C++20)

relation (C++20)

equivalence_relation (C++20)

strict_weak_order (C++20)

+ concepts in the [iterators](#) library, [algorithms](#) library, [ranges](#) library cppreference.com/w/cpp/concepts

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.

cppreference.com/w/cpp/language/constraints

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

What's the Practical Upside ?

Using STL algorithms & data structures

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

Using STL - Compare Requirements

Eg.

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


Using STL - Compare Requirements

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Using STL - Compare Requirements

Eg.

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template<class RandomIt, class Compare>  
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What are the requirements for a Compare type ?

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

Using STL - Compare Requirements

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);
```

Using STL - Compare Requirements

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 ?



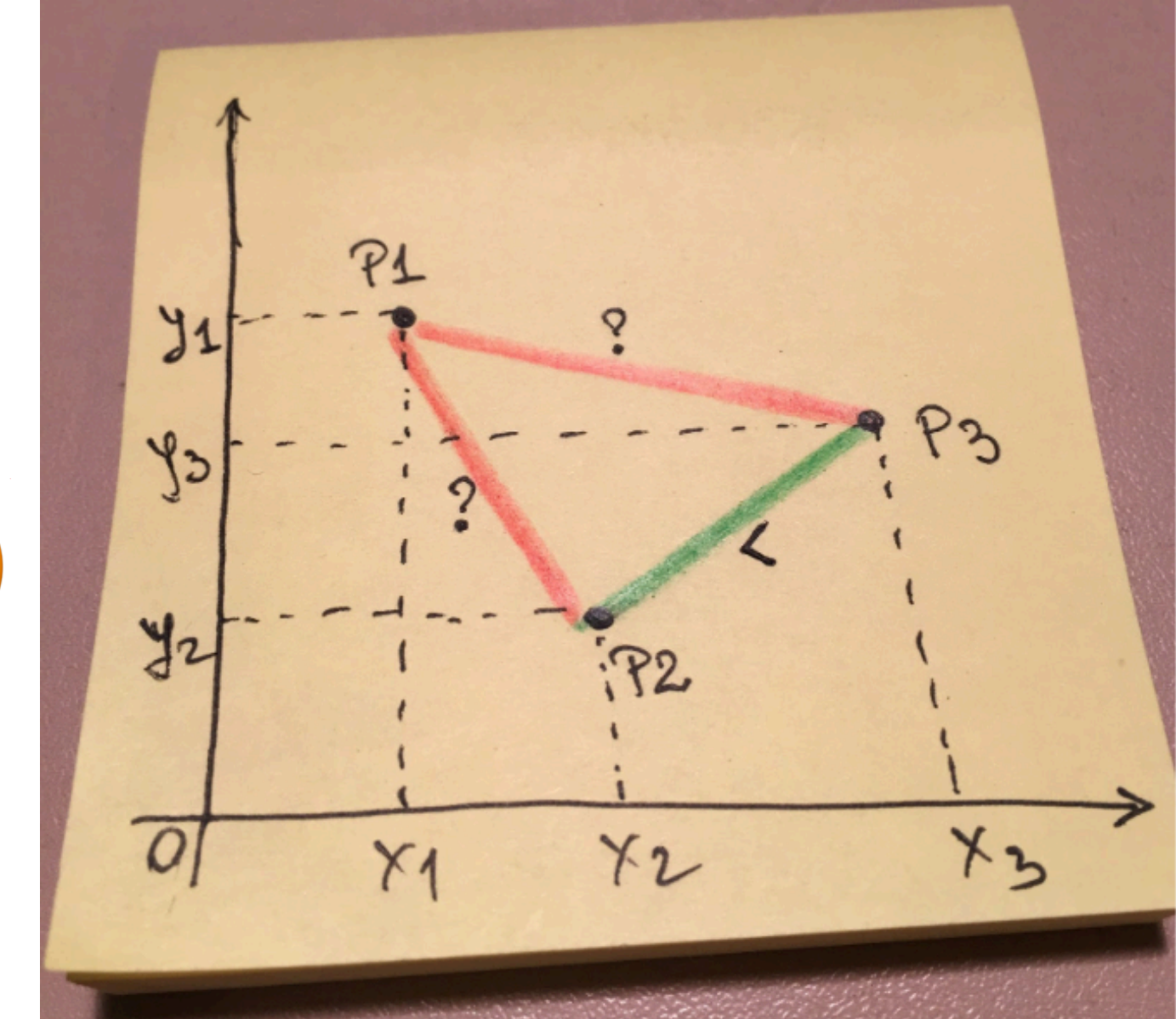
cppreference.com/w/cpp/named_req/Compare

Compare Requirements

Partial ordering relationship is not enough



Compare needs a *stronger* constraint

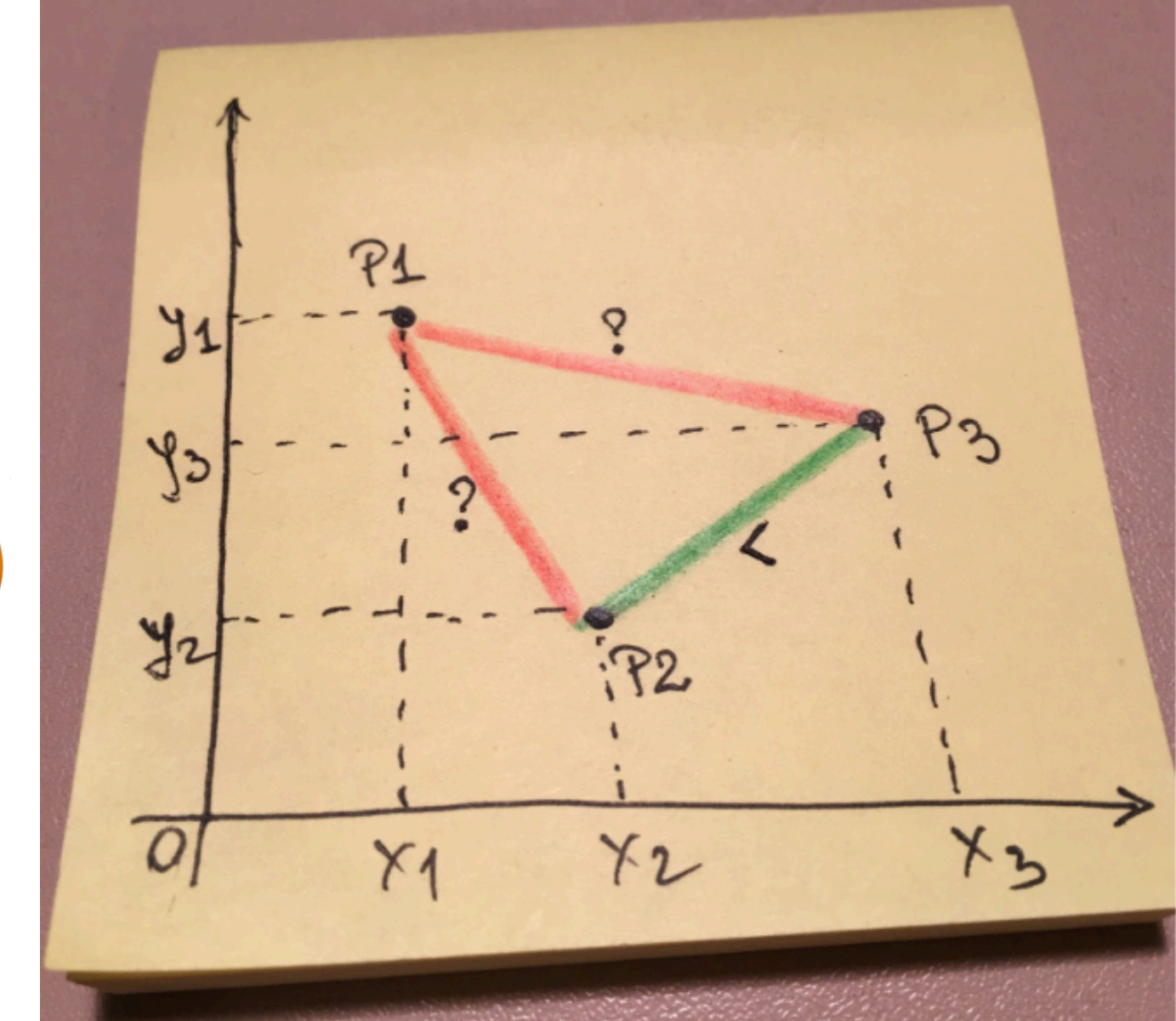


 $(a.x < b.x) \ \&\& \ (a.y < b.y)$

Compare Requirements

Partial ordering relationship is not enough 🤔

Compare needs a *stronger* constraint



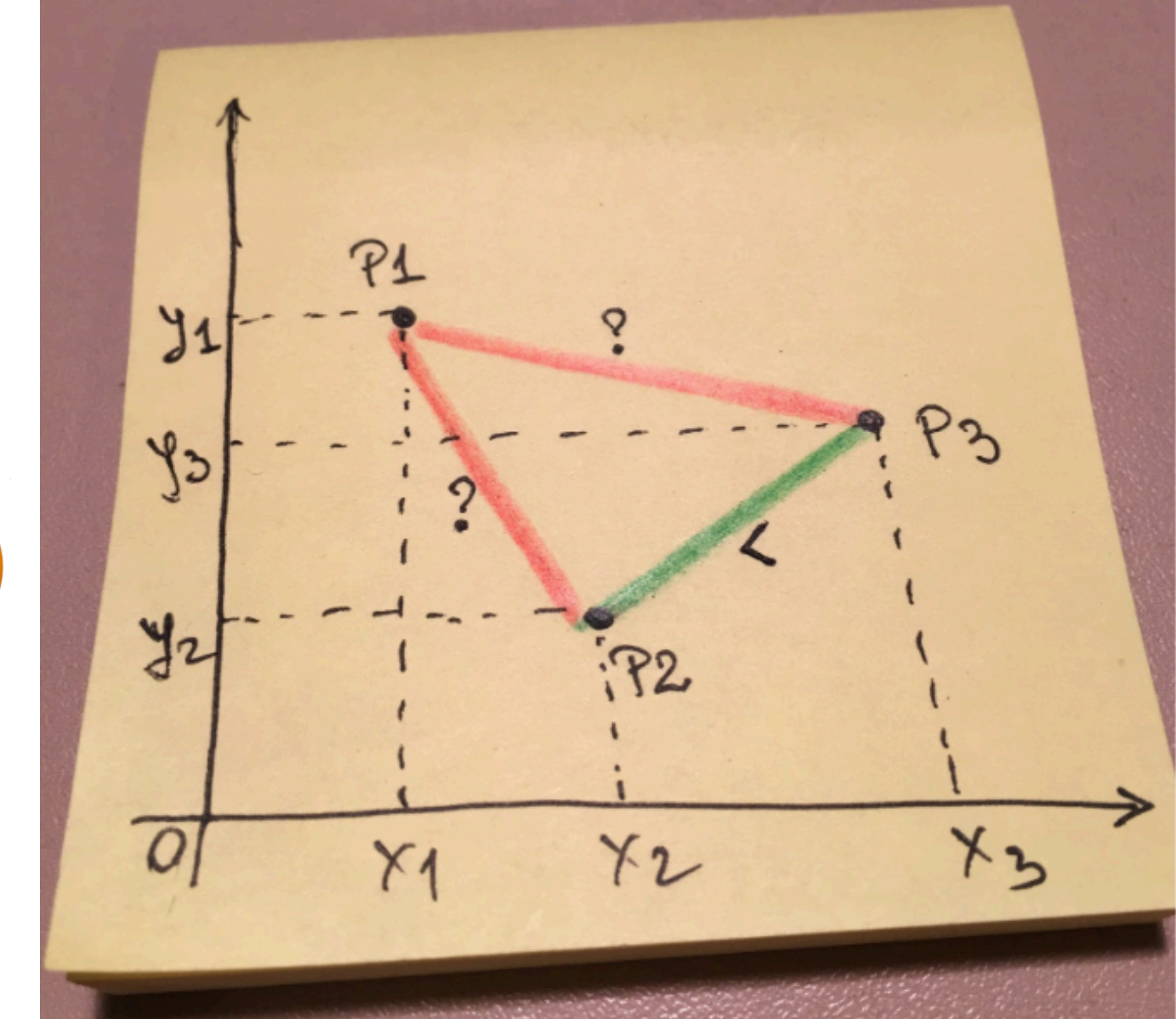
🔥 $(a.x < b.x) \ \&\& \ (a.y < b.y)$

Strict weak ordering = **Partial ordering** + **Transitivity of Equivalence**

Compare Requirements

Partial ordering relationship is not enough 🤔

Compare needs a *stronger* constraint



🔥 $(a.x < b.x) \ \&\& \ (a.y < b.y)$

Strict weak ordering = **Partial ordering** + **Transitivity of Equivalence**

where:

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

Strict weak ordering

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:

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

Concept: *Strict weak ordering*

std::strict_weak_order

Defined in header `<concepts>`

```
template< class R, class T, class U >
concept strict_weak_order = std::relation<R, T, U>;    (since C++20)
```

The concept `strict_weak_order<R, T, U>` specifies that the `relation` `R` imposes a strict weak ordering on its arguments.

Semantic requirements

A relation `r` is a strict weak ordering if

- it is irreflexive: for all `x`, `r(x, x)` is `false`;
- it is transitive: for all `a`, `b` and `c`, if `r(a, b)` and `r(b, c)` are both `true` then `r(a, c)` is `true`;
- let `e(a, b)` be `!r(a, b) && !r(b, a)`, then `e` is transitive: `e(a, b) && e(b, c)` implies `e(a, c)`.

Under these conditions, it can be shown that `e` is an equivalence relation, and `r` induces a strict total ordering on the equivalence classes determined by `e`.

cppreference.com/w/cpp/concepts/strict_weak_order

< LessThanComparable

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

wg21.link/p0898

Examples from STL

DefaultConstructible, MoveConstructible, CopyConstructible

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< LessThanComparable, EqualityComparable

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Container, SequenceContainer, ContiguousContainer, AssociativeContainer

InputIterator, OutputIterator

ForwardIterator, BidirectionalIterator, RandomAccessIterator

cppreference.com/w/cpp/named_req

EqualityComparable

cppreference.com/w/cpp/named_req/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***.

wikipedia.org/wiki/Equivalence_relation

Concept: EqualityComparable

cppreference.com/w/cpp/concepts/equality_comparable

```
template< class T, class U >
concept __WeaklyEqualityComparableWith =
    requires(const std::remove_reference_t<T>& t,
             const std::remove_reference_t<U>& u) {
        { t == u } -> boolean-testable;
        { t != u } -> boolean-testable;
        { u == t } -> boolean-testable;
        { u != t } -> boolean-testable;
    };
```

```
template< class T >
concept equality_comparable = __WeaklyEqualityComparableWith<T, T>;
```

wikipedia.org/wiki/Equivalence_relation

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

Equality is a special case of **equivalence**

Equality is both an *equivalence relation* and a *partial order*.

Total ordering relationship

Total ordering relationship

$\text{comp}()$ induces a *strict total ordering* on the equivalence classes determined by $\text{equiv}()$

Total ordering relationship

$\text{comp}()$ induces a **strict total ordering** on the equivalence classes determined by $\text{equiv}()$

The equivalence relation and its equivalence classes partition the elements of the set, and are **totally ordered** by $<$

< LessThanComparable

cppreference.com/w/cpp/named_req/LessThanComparable

```
template< class T, class U >
concept __PartiallyOrderedWith =
    requires(const std::remove_reference_t<T>& t,
             const std::remove_reference_t<U>& u) {
        { t < u } -> boolean-testable;
        { t > u } -> boolean-testable;
        { t <= u } -> boolean-testable;
        { t >= u } -> boolean-testable;
        { u < t } -> boolean-testable;
        { u > t } -> boolean-testable;
        { u <= t } -> boolean-testable;
        { u >= t } -> boolean-testable;
    };

template< class T >
concept totally_ordered = std::equality_comparable<T> &&
    __PartiallyOrderedWith<T, T>;
```

A Concept Design for the STL

Palo Alto TR

open-std.org/jtc1/sc22/wg21/docs/papers/2012/n3351.pdf

A. Stepanov et al.

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

STL algorithms assume **Regular** data structures

The STL was written with *Regularity* as its basis

wg21.link/p0898

`#define`

`SemiRegular`

`DefaultConstructible, MoveConstructible, CopyConstructible`
`MoveAssignable, CopyAssignable, Swappable`
`Destructible`

#define

SemiRegular

```
template <class T>
concept semiregular = std::copyable<T> &&
                    std::default_initializable<T>;
```

```
template <class T>
concept copyable =
    std::copy_constructible<T> &&
    std::movable<T> &&
    std::assignable_from<T&, T&> &&
    std::assignable_from<T&, const T&> &&
    std::assignable_from<T&, const T>;
```

```
template<class T>
concept default_initializable =
    std::constructible_from<T> &&
    requires { T{}; } &&
    requires { ::new T; };
```

cppreference.com/w/cpp/concepts/semiregular

#define

Regular

(aka "Stepanov Regular")

SemiRegular {

DefaultConstructible, MoveConstructible, CopyConstructible

MoveAssignable, CopyAssignable, Swappable

Destructible

}

+

EqualityComparable

#define

Regular

```
template <class T>
concept regular = std::semiregular<T> &&
                 std::equality_comparable<T>;
```

```
template< class T, class U >
concept __WeaklyEqualityComparableWith =
    requires(const std::remove_reference_t<T>& t,
             const std::remove_reference_t<U>& u) {
        { t == u } -> boolean-testable;
        { t != u } -> boolean-testable;
        { u == t } -> boolean-testable;
        { u != t } -> boolean-testable;
    };
```

```
template< class T >
concept equality_comparable = __WeaklyEqualityComparableWith<T, T>;
```

cppreference.com/w/cpp/concepts/regular

Equality

Defining **equality** is hard 🤔

Equality

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.



stepanovpapers.com/DeSt98.pdf

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.



stepanovpapers.com/DeSt98.pdf



C++20 Three-way comparison

Bringing consistent comparison operations...

operator $\langle == \rangle$

$(a \langle == \rangle b) < 0$ if $a < b$

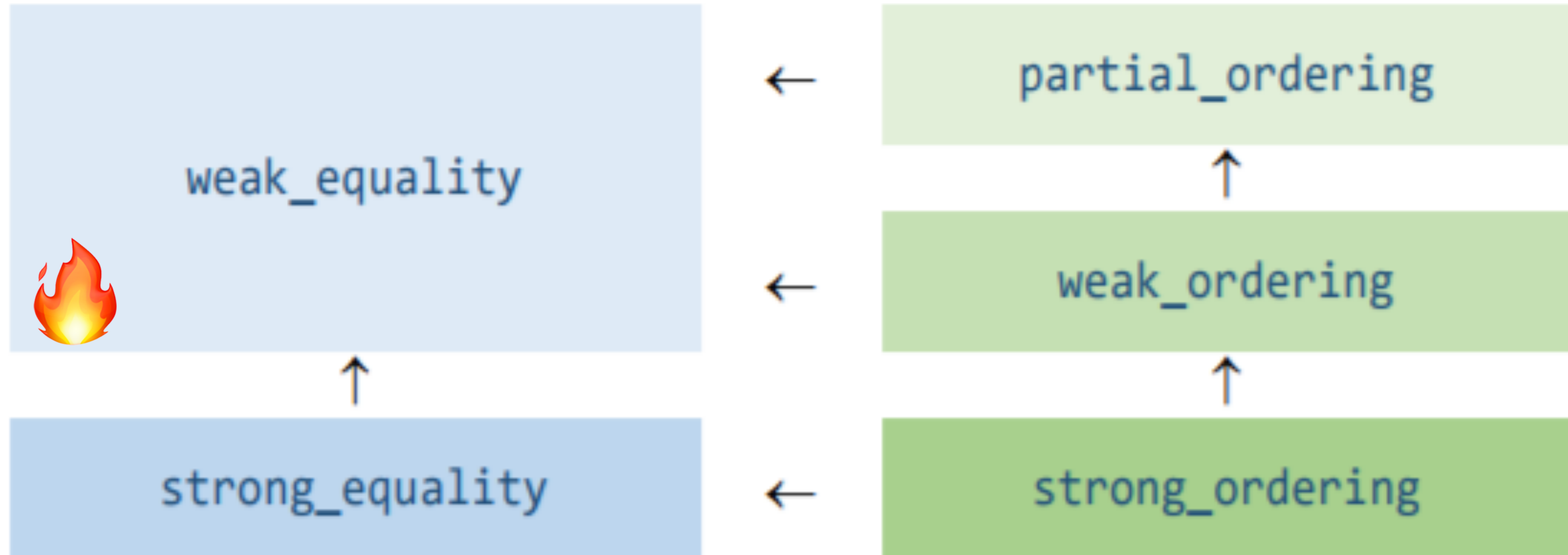
$(a \langle == \rangle b) > 0$ if $a > b$

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



C++20 Three-way comparison

The comparison categories for: `operator <=>`



It's all about *relation strength*



C++20 Three-way comparison

<, <=, >, >= synthesized from operator<=>
!= synthesized from operator==

Convenience

operator<=>

operator!=

operator==

Efficiency ?

The problem: implement <=> **optimally** for "wrapper" types

```
struct S {  
    vector<string> names;  
    auto operator<=>(S const&) const = default;  
};
```

wg21.link/P1185



C++20 Three-way comparison

Cppcon | 2019
The C++ Conference | cppcon.org



Using C++20's Three-way Comparison $\langle = \rangle$
Jonathan Müller — @foonathan — CC BY 4.0



Jonathan Müller

Using C++20's
Three-way
Comparison $\langle = \rangle$

Jonathan Müller — @foonathan — CC BY 4.0 Using C++20's Three-way Comparison $\langle = \rangle$ CppCon 2019-09-20 0

youtube.com/watch?v=8jNXy3K2Wpk

Sometimes,
you just want a **value**

```
Point2D: @value type = {  
  // data members  
  // private by default  
  // with default values  
  x: i32 = 0;  
  y: i32 = 0;  
  // ...  
}
```

Example from Apr 30 blog post
herbsutter.com/2023/04/30/cppfront-spring-update/

```
// Point2D is declaratively a value type: it is guaranteed to have  
// default/copy/move construction and <=> std::strong_ordering  
// comparison (each generated with memberwise semantics  
// if the user didn't write their own, because "@value" explicitly  
// opts in to ask for these functions), a public destructor, and  
// no protected or virtual functions. the word "value" carries  
// all that meaning as a convenient and readable opt-in, but  
// without hardwiring "value" specially into the language
```

```
Point2D: @value type = {  
  x: i32 = 0; // data members (private by default)  
  y: i32 = 0; // with default values  
  // ...  
}
```


Before we get too far with C++20

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

std::optional<T>

Any time you need to express:

- *value or not value*
- *possibly an answer*
- *object with delayed initialization*

Using a common **vocabulary type** for these cases raises the *level of abstraction*, making it easier for others to understand what your code is doing.

std::optional<T>

optional<T> extends T's ordering operations:

< > <= >= == !=

an **empty** optional compares as **less than** any optional that *contains* a T

=> you can use it in some contexts exactly *as if* it were a T

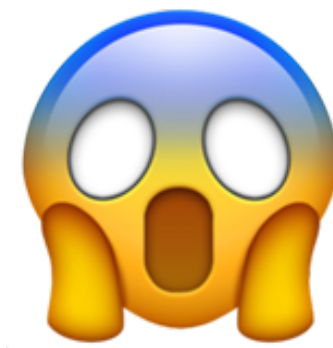
std::optional<T>

Using `std::optional` as *vocabulary type* allows us to simplify code and compose functions easily.

Write waaaaay less error checking code

But, wait...

`std::optional<T&>`



`operator=`
`operator==`

std::optional<T&>

- **References for Standard Library Vocabulary Types - an optional<> case study**

wg21.link/p1683

- **To Bind and Loose a Reference**

the-phd.dev/to-bind-and-loose-a-reference-optional

 Recommendation:

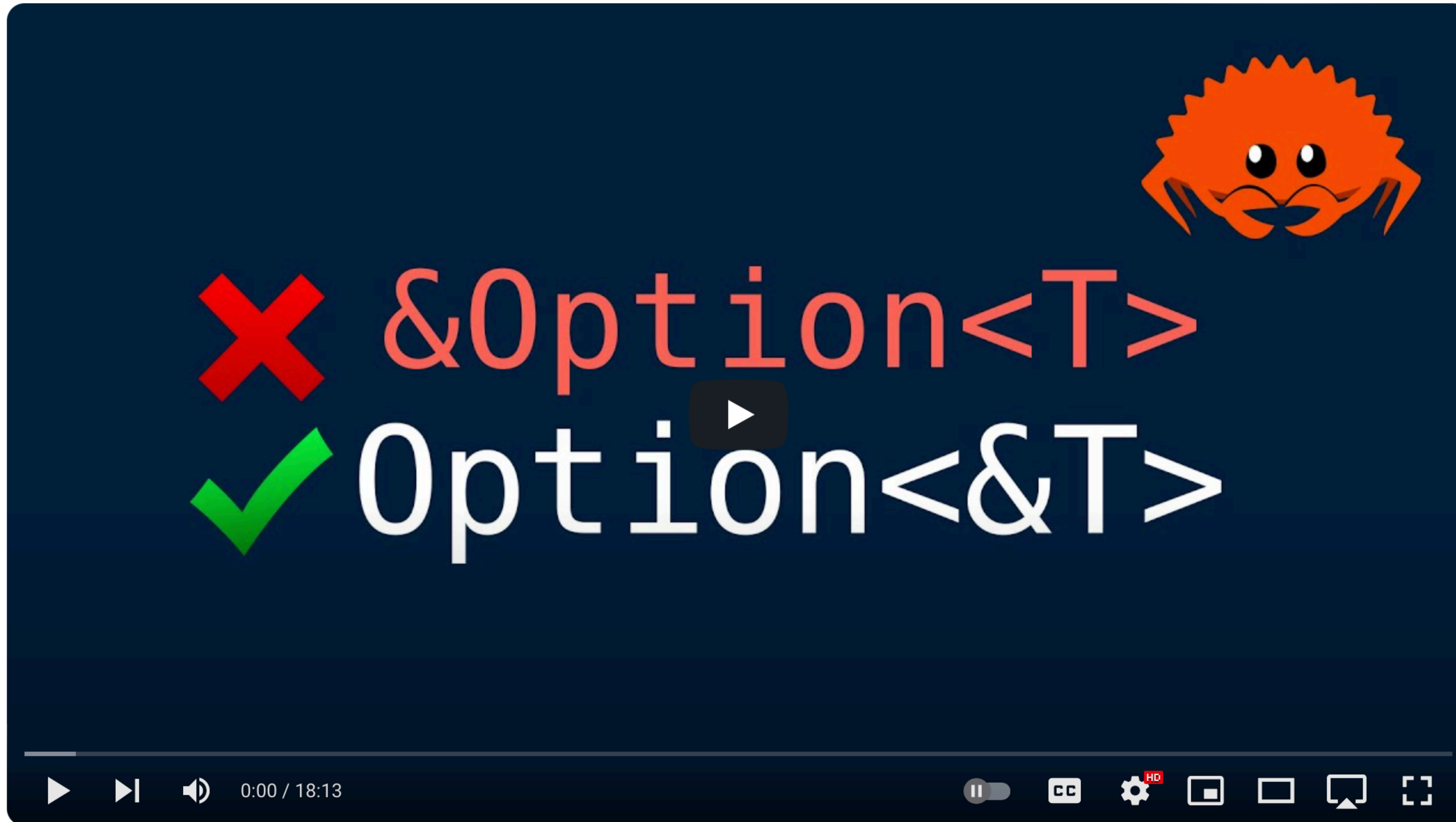
- **rebinding**
- **shallow const**
- **deep comparison**

 **rebinding** optional reference

This is the solution that is seen as a step up from the conservative solution.

It is the version used in **boost::optional** for over 15 years + many other implementations.

std::optional<T&>



Choose the Right Option



Logan Smith
15.7K subscribers

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3.1K



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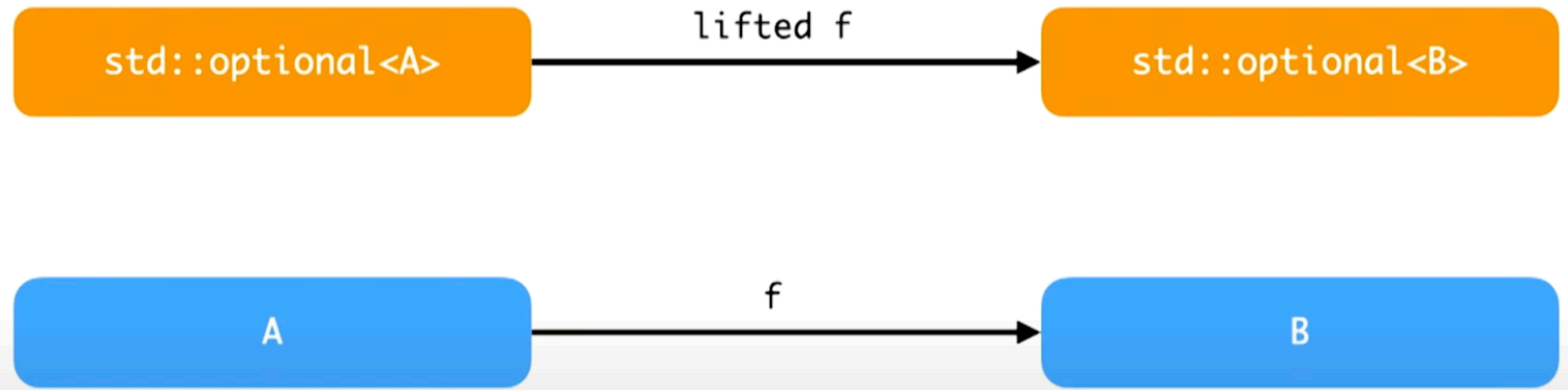
Clip

Save



youtube.com/watch?v=6c7pZYP_iE

Lifting any function



Victor Ciura

2023 Victor Ciura | @ciura_victor - And Then() Some(T) 53

cppnorth.ca 24:24 / 56:48

⏸ CC ⚙️ HD 📺 📱 🗨️ 🗲

And Then() Some(T) Functional Adventures With C++23 `std::optional` and `std::expected` - Victor Ciura

youtube.com/watch?v=06VNq_tC-I0

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

`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` was our first “mainstream” ***borrow type***

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

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- 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**

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>`

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

`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

WWSD

WWSD

What Would **Stepanov** Do?

Should Span be Regular?

wg21.link/p1085

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

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- **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**)

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wg21.link/p1085

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- `operator=` (copy) is **shallow** (just **pointer** and **size** are copied)

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- `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**

Should Span be Regular?

wg21.link/p1085

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wg21.link/p1085

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APPROVED

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 :(

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

C++20

`std::span<T>`



Photo credit: Corentin Jabot

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

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 Name() {  
    return std::string("some long runtime value string");  
}
```

```
const string & str = Name();  
std::print("{} ", str);
```

```
string_view sv = Name();  
std::print("{} ", sv);
```

- `const lvalue ref` binds to rvalue and provides `lifetime extension`
- `string_view` doesn't extend the lifetime of the rvalue



For short strings this issue might be hard to detect due to SSO.
Problem becomes obvious with longer dynamically allocated strings.



Call To Action



Call To Action

Make your value types **Regular**



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



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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`



Call To Action



Call To Action

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



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Call To Action

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

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

Regular, Revisited

Meeting C++

November 2023

 @ciura_victor

 @ciura_victor@hachyderm.io

Victor Ciura
Principal Engineer
Visual C++

