OPERATOR OVERLOADING

HISTORY, PRINCIPLES AND PRACTICE

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FIRST: OPERATORS I'M NOT TALKING ABOUT

- conversions (e.g. `operator int()`)
- `operator new` and `operator delete`
- assignment

I'll mostly be talking about "mathematical" operators (arithmetic, bitwise, equality, etc).

OPERATORS IN C++

They just aren't very good. Things we can't control:

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- arity

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- fixity

OPERATORS IN C++

They just aren't very good. Things we can't control:

- name
- precedence
- associativity
- arity
- fixity
- evaluation semantics

MOTIVATION

The obvious first question:

Why should we use operators at all?

WHY?

WHY?

- for concision?

WHY?

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- for performance?

WHY?

- for concision?
- for performance?
- to take advantage of ADL?

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- because we can?

WHY?

- for concision?
- for performance?
- to take advantage of ADL?
- because we can?
- because we have to (equality/ordering)?

WHY?

Because operators *convey meaning about types* **that named functions don't.**

```
a + b + c;
```

SAY THIS ANOTHER WAY...

"It is probably wise to use operator overloading primarily to mimic conventional use of operators."

– Bjarne Stroustrup, The C++ Programming Language

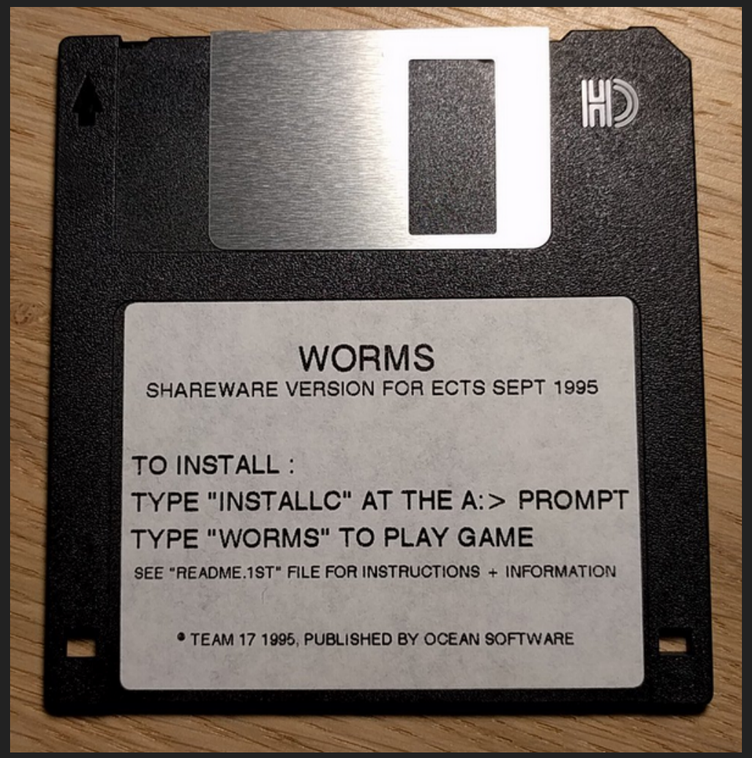
THE HISTORY PART

Or, counterpoint to "stick to convention".

Because things haven't always been this way.

By Joffboff - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=56389131

I 3D-PRINTED A SAVE ICON!



WHAT IS "CONVENTION" IN HISTORY?

What we may think of as "axiomatic" - mathematical notation - is actually changing all the time.

- Nicole Oresme
- Robert Recorde
- William Oughtred
- Gottfried Wilhelm Leibniz

WHAT'S THE ANSWER?

355 / 113 = ?

WHAT'S THE ANSWER?

355 / 113 = ?

Are you sure?

WHAT DO THESE MEAN?

% ^ ~ |

WHAT DO THESE MEAN?

These are really arbitrary and only a little older than me.

REVISED GUIDELINE

When defining our own operators, we are well-advised to stick to conventional or intuitive properties, *where they exist*.

Corollary: study history.

A History of Mathematical Notations **by Florian Cajori**

OPERATOR OVERLOADING ADVICE

> *"When in doubt, do as the `int`s do."*
>
> *– Scott Meyers, More Effective C++*

OPERATOR OVERLOADING

When in doubt, do what `operator+` does?

`operator+` PROPERTIES

Property	Math(s)	C++

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Property	Math(s)	C++
Closed	✔	

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Has Identity	✔	

`operator+` PROPERTIES

Property	Math(s)	C++
Closed	✔	✗ (overflow)
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Property	Math(s)	C++
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Commutative	✔	✗ (strings)
Has Identity	✔	✔ ✔(+0.0, -0.0!)

OPERATORS IN COMPILER HISTORY

(from https://jeffreykegler.github.io/personal/timeline_v3)

1956: The IT Compiler

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But it didn't have operator precedence as we know it today.

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1956: The IT Compiler

> *"…the first really useful compiler."*

– Donald E Knuth

But it didn't have operator precedence as we know it today.

> *"The lack of operator priority … in the IT language was the most frequent single cause of errors by the users of that compiler."*

– Donald E Knuth

WHY?

Because operators convey meaning that names don't.

- associativity/commutativity
- precedence
- distributive law

Because operators allow concision/readability.

Because operators allow expressions to be manipulated.

MATHEMATICAL PRINCIPLES

Which mathematical conventions should we follow, then?

A selection, in approximate order of importance…

PROBABLY THE MOST IMPORTANT

- Logical contrariety of == and !=

Break this one at your peril!

```
bool operator==(const T& x, const T& y) noexcept
{
  ...
}

bool operator!=(const T& x, const T& y) noexcept
{
  return !(x==y);
}
```

VERY IMPORTANT

- Associativity of + and *

```
assert((a + b) + c == a + (b + c));
```

Almost all mathematical objects we work with in C++ obey this, so if you violate this, your code could be very surprising.

STILL FAIRLY IMPORTANT

- Law of the excluded middle

Either a given proposition is true, or its negation is true.

tertium non datur

```
assert(a > b || a <= b);
```

Mostly true (but notably not for `float`).

NICE TO HAVE

- **Commutativity of `+`**

I think it's *probably* too late to "fix" `std::string` by giving it `operator*`.

(ಠ_ಠ at `std::reduce`)

NICE TO HAVE

- Distribution of * over +

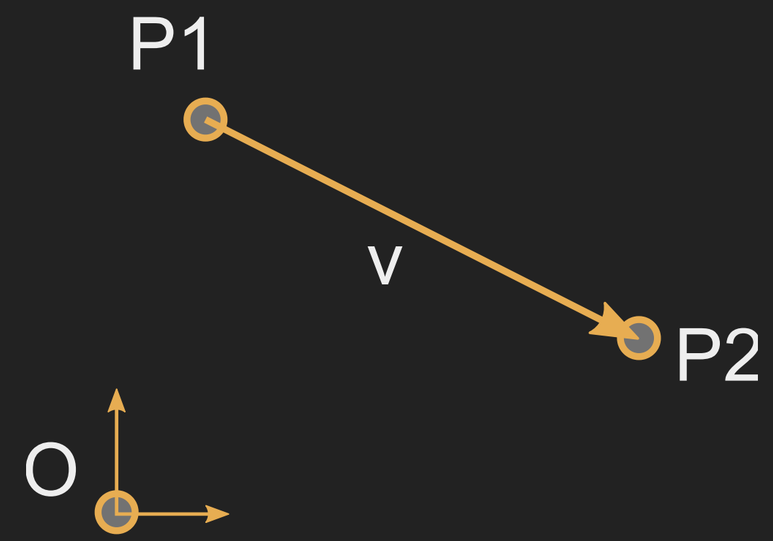
This (or something similar) helps users of your code to manipulate expressions.

CAN GO EITHER WAY

- Closedness of +

But if you don't have closure over your type, you had better know why.

AFFINE SPACES



AFFINE SPACES

Types and operators working together as a team.

- a set of points (values of type 1)
- difference between two points is a vector (value of type 2)
- operations that relate points to vectors
- no need for an origin

chrono: time_point AND duration

In chrono, time is a one-dimensional affine space.

- time_point **is a point**
- duration **is a vector**

chrono AS AN AFFINE SPACE

Thinking of it this way helps us to define the operations that make sense.

```
time_point operator+(time_point, duration);
time_point operator-(time_point, duration);

duration operator-(time_point, time_point);

duration operator+(duration, duration);
duration operator-(duration, duration);
duration operator*(duration, rep);
duration operator/(duration, rep);

duration operator%(duration, duration);
```

WHY OVERLOAD CONVENTIONALLY?

Helps users with:

- intuition
- manipulation
- properties

WHY OVERLOAD CONVENTIONALLY?

Helps implementers/designers identify:

- a complete basis
- minimality vs convenience
- efficiency
- in general, the space of types and operations

WHY BE CONVENTIONAL?

It helps us take advantage of compositionality built into the standard library and the language.

- `std::accumulate`, `std::reduce`, etc
- fold expressions

NEW STUFF IN C++17

FOLD EXPRESSIONS

In C++17, *fold expressions* fold (reduce) a parameter pack over a binary operator.

```
template <typename... Args>
auto output(Args&&... args) {
  return (std::cout << ... << args);
}
```

FOLD EXPRESSIONS

Choosing left- or right- fold is usually about commutativity rather than associativity.

```
template <typename Matrix, typename... Args>
auto multiply_on_right(Matrix&& m, Args&&... args) {
  return (m * ... * args);
}

template <typename Matrix, typename... Args>
auto multiply_on_left(Matrix&& m, Args&&... args) {
  return (args * ... * m);
}
```

FOLD EXPRESSIONS

Unary fold expressions also exist...

But are mostly useful with operators that shouldn't really be overloaded.

NEW EVALUATION SEMANTICS

C++17 changed semantics for overloading:

- `operator&&`
- `operator||`
- `operator,`

Evaluation order guarantees **P0145**

OPERATORS IN C++17

- Associativity is important for leveraging fold expressions
- Non-commutativity affects the choice of fold
- You probably still don't want to mess with `&&` `||` and `,`

RIGHT-FOLD, OLD-STYLE

Something like this.

```
// Assuming we have a class Foo with a non-commutative operation

struct right_multiplies {
  template <typename T>
  T operator()(T t1, T t2) const {
    return operation(t2, t1);
  }
};

template <template <class> typename Container = std::initializer_list>
Foo right_fold_old(Foo init, Container<Foo> c) {
    return std::accumulate(std::crbegin(c), std::crend(c), init, right_multiplies{});
}

auto sum = right_fold_old(foo_init, {foo1, foo2, foo3});
```

RIGHT-FOLD, NEW-STYLE

Something like this.

```
// Assuming we have a class Foo with a non-commutative operator*

template <typename... Args>
Foo right_fold_new(Foo init, Args&&... args) {
    return (args * ... * init);
}

auto sum = right_fold_new(foo_init, foo1, foo2, foo3);
```

NEW IN C++20

We get a whole new operator!

The three-way comparison operator.

`operator<=>`

AKA "the spaceship operator". [expr.spaceship]

`operator<=>` 101

`#include <compare>` to get 5 types [cmp.categories]:

- `std::strong_equality`
- `std::weak_equality`
- `std::strong_ordering`
- `std::weak_ordering`
- `std::partial_ordering`

A call to `operator<=>` returns a value of one of these types.

EQUALITY

`std::strong_equality` means values that are `equal` are indistinguishable.

```
std::strong_equality operator<=>(std::type_info a, std::type_info b);
```

`std::weak_equality` means values that are `equivalent` may be distinguishable.

```
std::weak_equality operator<=>(std::filesystem::path a, std::filesystem::path b);
```

ORDERING

A *total* ordering means exactly one of the following is true:

- a > b
- a == b
- a < b

`std::strong_ordering` is a total ordering *with* substitutability.

```
template <typename T>
std::strong_ordering operator<=>(typename std::vector<T>::iterator a,
                                 typename std::vector<T>::iterator b);
```

`std::weak_ordering` is a total ordering *without* substitutability.

```
std::weak_ordering operator<=>(const CIString& a, const CIString& b);
```

ORDERING

`std::partial_ordering` means it's possible that none of the following is true:

- a > b
- a == b
- a < b

```
std::partial_ordering operator<=>(float a, float b);
```

CASE STUDY: LAST YEAR'S SCM CHALLENGE

Challenge: write a case insensitive string class that implements all 6 comparison operations.

```
struct ci_compare_equal {
    bool operator()(char x, char y) const {
        return std::toupper(x) == std::toupper(y);
    }
};
struct ci_compare_less {
    bool operator()(char x, char y) const {
        return std::toupper(x) < std::toupper(y);
    }
};

inline bool operator==(const CIString& x, const CIString& y) {
    return std::equal(x.s.cbegin(), x.s.cend(),
        y.s.cbegin(), y.s.cend(), ci_compare_equal{});
}
inline bool operator<(const CIString& x, const CIString& y) {
    return std::lexicographical_compare(x.s.cbegin(), x.s.cend(),
        y.s.cbegin(), y.s.cend(), ci_compare_less{});
}
```

CASE STUDY - CONTINUED

```
inline bool operator!=(const CIString& x, const CIString& y) {
    return !(x == y);
}

inline bool operator>(const CIString& x, const CIString& y) {
    return y < x;
}

inline bool operator<=(const CIString& x, const CIString& y) {
    return !(y < x);
}

inline bool operator>=(const CIString& x, const CIString& y) {
    return !(x < y);
}
```

SO HOW DID THIS CHANGE WITH C++20?

```
inline std::weak_ordering operator<=>(const CIString& x, const CIString& y) {
    return std::lexicographical_compare_3way(
        x.s.cbegin(), x.s.cend(), y.s.cbegin(), y.s.cend(),
        [] (char x, char y) {
            const auto diff = std::toupper(x) - std::toupper(y);
            return diff < 0 ? std::weak_ordering::less :
              diff > 0 ? std::weak_ordering::greater :
              std::weak_ordering::equivalent;
        });
}
```

`operator<=>` GUIDELINES

It's too new to switch to it yet (obviously - it's C++20).

- library support is only just being figured out
- no real implementations yet
- issues with generic code/composition have to be worked out
- perf pitfalls with sequence containers + naive usage

STRAYING FROM CONVENTION

"When I use a word," Humpty Dumpty said, in rather a scornful tone, "it means just what I choose it to mean—neither more nor less." "The question is," said Alice, "whether you can make words mean so many different things." "The question is," said Humpty Dumpty, "which is to be master—that's all."

– Lewis Carroll, Through the Looking Glass

DSLS

The primary use of a DSL is in the construction of (otherwise) complex objects.

- terser
- simpler
- manipulable

The use of template expressions may also provide performance gains.

UDLs are a natural fit for DSLs.

READABILITY

```cpp
std::vector<int> v;
v.reserve(5);
v.push_back(1);
v.push_back(2);
v.push_back(3);
v.push_back(4);
v.push_back(5);
```

VS

```cpp
std::vector<int> v{1,2,3,4,5};
```

chrono **DATES**

A DSL with one operator and two UDLs.

```
using namespace std::chrono;

constexpr auto today_us = September/25/2018;
constexpr auto today_uk = 25d/September/2018;
constexpr auto today = 2018y/September/25;
```

filesystem::path

A DSL with one operator.

```
using namespace std::filesystem;

auto home_prefix = path{"/home"};
auto my_home_dir = home_prefix / "bdeane";
```

[BOOST.]SML

(Disclaimer: SML isn't a Boost library)

```
struct tcp_release final {
  auto operator()() const {
    using namespace sml;
    return make_transition_table(
      *"established"_s + event<release>          / send_fin  = "fin wait 1"_s,
       "fin wait 1"_s  + event<ack> [ is_valid ]             = "fin wait 2"_s,
       "fin wait 2"_s  + event<fin> [ is_valid ] / send_ack  = "timed wait"_s,
       "timed wait"_s  + event<timeout>                      = X
    );
  }
};
```

OPERATORS AND MONADS

What's the biggest problem with monads?

OPERATORS AND MONADS

What's the biggest problem with monads?

- understanding them?

OPERATORS AND MONADS

What's the biggest problem with monads?

- understanding them?
- explaining them?

OPERATORS AND MONADS

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- CT wonks?

OPERATORS AND MONADS

What's the biggest problem with monads?

- understanding them?
- explaining them?
- CT wonks?
- the sudden urge to try to make everything monadic?

THE MAIN PROBLEM WITH MONADS

In C++, `operator>>=` is *right associative*!

What operator overloads are we going to use is we want to compose things monadically?

OPERATOR OVERLOADING AND FUTURES


```
// imaginary-ish code
my_future<A> f(X);
my_future<B> g1(A);
my_future<C> g2(A);
my_future<D> h(B, C);
```

OPERATOR OVERLOADING AND FUTURES

OPERATOR OVERLOADING AND FUTURES

```
auto fut = f();
auto split1 = fut.then(g1);
auto split2 = fut.then(g2);
auto fut2 = when_all(split1, split2).then(h);
```

OPERATOR OVERLOADING AND FUTURES

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auto fut = f();
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```
auto fut = f() >= (g1 & g2) >= h;
```

OPERATOR OVERLOADING AND FUTURES

```
auto fut = f();
auto split1 = fut.then(g1);
auto split2 = fut.then(g2);
auto fut2 = when_all(split1, split2).then(h);
```

```
auto fut = f() >= (g1 & g2) >= h;
```

Operator overloading can clarify the computational structure when combining futures/promises.

MECHANICS

FREE OR NOT?

```
struct Foo {
  Foo operator+(const Foo& other);
};
```

```
struct Foo {
};

Foo operator+(const Foo& x, const Foo& y);
```

FREE AND NON-FREE

```
struct Foo {
  Foo& operator+=(const Foo& other);
};

Foo operator+(const Foo& x, const Foo& y) {
  Foo r{x};
  r += y;
  return r;
}
```

DON'T FORGET QUALIFIERS

Operators are functions, so you should apply all the normal rules of writing functions.

- `constexpr`
- `const`
- `noexcept`
- parameter types
- return type

GUIDELINES REDUX

Let's recap.

WHEN TO USE OPERATOR OVERLOADING

Use operators when:

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- you want users to be able to manipulate expressions
- you want to make complex construction easier

WHEN TO USE OPERATOR OVERLOADING

Use operators when:

- you have a natural binary function that combines your types
- your types obey mathematical principles (associativity, etc)
- you want users to be able to manipulate expressions
- you want to make complex construction easier
- you want users to intuit properties of your types

WHEN NOT TO USE OPERATOR OVERLOADING

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Don't use (only) operators when:

- you can provide better perf with an n-ary function

WHEN NOT TO USE OPERATOR OVERLOADING

Don't use (only) operators when:

- you can provide better perf with an n-ary function
- they aren't yet ready for primetime (`operator<=>`)

DON'T

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- break contrariety of `operator==` and `operator!=`

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DON'T

- break contrariety of `operator==` and `operator!=`
- break associativity
- be afraid to overload just one operator, if it makes sense (`operator/`)
- overload `operator&&` `operator||` `operator,` even with P0145
- pick weird operators if your type *is* mathematical

DO

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- **use conventions *other* than mathematical ones**

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- consider distinguishing your types to leverage affine spaces

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- use conventions *other* than mathematical ones
- consider distinguishing your types to leverage affine spaces
- use operators for non-commutative operations to leverage fold expressions
- use UDLs as a counterpart to operators to help with construction
- provide the whole set of related operators if you provide one

THANK YOU

THANK YOU

Questions?

THANK YOU

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~~Comments thinly disguised as questions?~~

THANK YOU

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Pitchforks & torches?