C++ now

2025

Overengineering max(a, b)

Mixed Comparison Functions, Common References, and Rust's Lifetime Annotations

Jonathan Müller

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And we do everything in C++!

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What this talk is about

- We are going to implement `max(a, b)`.

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- We are going to implement `max(a, b)`.
- We are embarking on a journey of accidental and essential complexity.
- We are going to look at the worst feature C++ has ever added.

The maximum function

Definition

The maximum function `max(a, b)` returns the greater of the two arguments.

The maximum function

How hard can it be?

The maximum function

```cpp
int max(int a, int b)
{
    if (a < b)
        return b;
    else
        return a;
}
```

The maximum function

```
int max(int a, int b)
{
    return a < b ? b : a;
}
```

The maximum function

```cpp
[[nodiscard]] constexpr int max(int a, int b) noexcept
{
    return a < b ? b : a;
}
```

Level 0: Let's make it generic

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```cpp
template <typename T>
const T& max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

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Level 0: Let's make it generic

```cpp
template <typename T>
const T& max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

Are we done?

What are the type requirements?

Type requirements

Syntactic requirements

T must provide an `operator<` that returns something contextually convertible to `bool`.

Type requirements

Syntactic requirements

T must provide an `operator<` that returns something contextually convertible to `bool`.

Semantic requirements

The `operator<` must implement a strict total order.

Strict total order

Definition

A strict total order of a set S is a binary relation $< \subseteq S \times S$ that has three properties:

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1. **Irreflexivity**: $a \not< a$ for all $a \in S$.

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2. **Transitivity**: If $a < b$ and $b < c$, then $a < c$ for all $a, b, c \in S$.

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1. **Irreflexivity**: $a \not< a$ for all $a \in S$.
2. **Transitivity**: If $a < b$ and $b < c$, then $a < c$ for all $a, b, c \in S$.
3. **Trichotomy**: For all $a, b \in S$, exactly one of $a < b$, $a = b$, or $b < a$ holds.

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Level 0: Let's make it generic

```
template <typename T>
    // Requires: T has an operator< that implements a strict total order.
const T& max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

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Level 0: Let's make it generic

```
template <typename T>
    // Requires: T has an operator< that implements a strict total order.
const T& max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

Are we done?

Level 0: Let's make it generic

```
struct person {
    int id;
    std::string name;
};
struct person_by_name {
    person& p;
    friend auto operator<=>(person_by_name lhs, person_by_name rhs) {
        return lhs.p.name <=> rhs..p.name;
    }
};

auto result = max(person_by_name{p1}, person_by_name{p2});
```

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Level 0: Let's make it generic

```
auto p1 = person{1, "Jonathan"};
auto p2 = person{2, "Jonathan"};
auto result = max(person_by_name{&p1}, person_by_name{&p2});
```

Level 0: Let's make it generic

```
auto p1 = person{1, "Jonathan"};
auto p2 = person{2, "Jonathan"};
auto result = max(person_by_name{&p1}, person_by_name{&p2});
```

This violates trichotomy.

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1. **Irreflexivity**: $a \not< a$ for all $a \in S$.
2. **Transitivity**: If $a < b$ and $b < c$, then $a < c$ for all $a, b, c \in S$.
3. **Asymmetry**: If $a < b$, then $b \not< a$ for all $a, b \in S$

think-cell

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1. **Irreflexivity**: $a \not< a$ for all $a \in S$.
2. **Transitivity**: If $a < b$ and $b < c$, then $a < c$ for all $a, b, c \in S$.
3. **Asymmetry**: If $a < b$, then $b \not< a$ for all $a, b \in S$
4. **Transitivity of incomparability**: Define $a \sim b$ if neither $a < b$ nor $b < a$. If $a \sim b$ and $b \sim c$, then $a \sim c$ for all $a, b, c \in S$.

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4. **Transitivity of incomparability**: Define $a \sim b$ if neither $a < b$ nor $b < a$. If $a \sim b$ and $b \sim c$, then $a \sim c$ for all $a, b, c \in S$.

A strict weak order of a set S defines a strict total order of the equivalence classes of $\sim$.

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template <typename T>
    // Requires: T has an operator< that implements a strict weak order.
const T& max(const T& a, const T& b)
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    return a < b ? b : a;
}
```

Level 0: Let's make it generic

```cpp
template <typename T>
    // Requires: T has an operator< that implements a strict weak order.
const T& max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

```cpp
auto p1 = person{1, "Jonathan"};
auto p2 = person{2, "Jonathan"};
auto result = max(person_by_name{p1}, person_by_name{p2});
```

Should this be p1 or p2?

think-cell

Level 0: Let's make it generic

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    // Requires: T has an operator< that implements a strict weak order.
const T& max(const T& a, const T& b)
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const T& max(const T& a, const T& b)
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    return b < a ? a : b;
}
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    // Requires: T has an operator< that implements a strict weak order.
const T& max(const T& a, const T& b)
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    return a < b ? b : a;
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```

```
template <typename T>
    // Requires: T has an operator< that implements a strict weak order.
const T& max(const T& a, const T& b)
{
    return b < a ? a : b;
}
```

Let's stick with the first option.

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Level 1: Let's support mixed comparisons

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```
std::string a = "hello";
std::string_view b = "world";
std::print("{}\n", max(a, b)); // error
```

Level 1: Let's support mixed comparisons

```cpp
std::string a = "hello";
std::string_view b = "world";
std::print("{}\n", max(a, b)); // error
```

```cpp
template <typename T>
const T& max(const T& a, const T& b) { … }
```

Level 1: Let's support mixed comparisons

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b)
{
    return a < b ? b : a;
}
```

Level 1: Let's support mixed comparisons

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b) -> std::common_type_t<T, U>
{
    return a < b ? b : a;
}
```

think-cell

Aside: `std::common_type` is weird

`std::common_type_t<T, U>` is essentially:

```
std::decay_t<decltype(
    false
      ? std::declval<std::decay_t<T>>()
      : std::declval<std::decay_t<U>>()
)>;
```

Aside: `std::common_type` is weird

`std::common_type_t<T, U>` is essentially:

```
std::decay_t<decltype(
    false
      ? std::declval<std::decay_t<T>>()
      : std::declval<std::decay_t<U>>()
)>;
```

Plus some weird exception.

Aside: `std::common_type` is user-customizable

You can specialize `std::common_type` for your own types!

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You can specialize `std::common_type` for your own types!

This does not affect `?:`.

Aside: `std::common_type` is not associative

```
template <typename ... T>
using std::common_type_t = …;
```

Aside: `std::common_type` is not associative

```
template <typename ... T>
using std::common_type_t = …;
```

`std::common_type_t<A, B, C> != std::common_type_t<B, C, A>`.

think-cell

Aside: `std::common_type` is not associative

```
template <typename ... T>
using std::common_type_t = …;
```

`std::common_type_t<A, B, C> != std::common_type_t<B, C, A>`.

```
struct A {};
struct B : A {};
struct C : A {};
```

think-cell

Aside: std::common_type is not associative

```
template <typename ... T>
using std::common_type_t = …;
```

std::common_type_t<A, B, C> != std::common_type_t<B, C, A>.

```
struct A {};
struct B : A {};
struct C : A {};
```

std::common_type_t<std::common_type_t<A, B>, C> is A.

std::common_type_t<std::common_type_t<B, C>, A> does not exist.

Level 1: Let's support mixed comparisons

```
std::string a = "hello";
std::string_view b = "world";
std::print("{}\n", max(a, b));
```

```
world
```

Level 1: Let's support mixed comparisons

```
int      a = -1;
unsigned b = +1;
std::print("{}\n", max(a, b));
```

Level 1: Let's support mixed comparisons

```cpp
int      a = -1;
unsigned b = +1;
std::print("{}\n", max(a, b));
```

```
4294967295
```

Problem #1: Signed/unsigned comparison

`int() < unsigned()` can be implemented in three ways:

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2. Convert both to `int`, then compare two `int`s.

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`int() < unsigned()` can be implemented in three ways:

1. Compare the mathematical value they represent (correct).
2. Convert both to `int`, then compare two `int`s.
3. Convert both to `unsigned`, then compare two `unsigned`s (C++).

think-cell

Problem #1: Signed/unsigned comparison

`int() < unsigned()` can be implemented in three ways:

1. Compare the mathematical value they represent (correct).
2. Convert both to `int`, then compare two `int`s.
3. Convert both to `unsigned`, then compare two `unsigned`s (C++).

`std::cmp_less` does the correct thing.

Problem #2: Signed/unsigned conversion

`std::common_type_t<int, unsigned>` can be one of:

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1. The next larger signed integer type that can fit both types (correct).

think-cell

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1. The next larger signed integer type that can fit both types (correct).
2. `int`.

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1. The next larger signed integer type that can fit both types (correct).
2. `int`.
3. `unsigned` (C++).

think-cell

Problem #2: Signed/unsigned conversion

`std::common_type_t<int, unsigned>` can be one of:

1. The next larger signed integer type that can fit both types (correct).
2. `int`.
3. `unsigned` (C++).
4. invalid (think-cell).

think-cell

think-cell: Safe conversions

```
template <typename Source, typename Target>
concept tc::safely_convertible_to = …;
```

- `std::convertible_to<Source, Target>`, and
- that conversion is “safe”

think-cell: Safe conversions

```
template <typename Source, typename Target>
concept tc::safely_convertible_to = …;
```

- `std::convertible_to<Source, Target>`, and
- that conversion is “safe”

Conversions which are not “safe”:

- `Derived` to `Base` (slicing)
- `int` to `unsigned`

think-cell

think-cell: Safe common type

```cpp
template <typename ... Ts>
using tc::common_type_t = …;
```

`std::common_type_t<Ts...>` provided `tc::safely_convertible_to<Ts, std::common_type_t<Ts...>> && ...`.

Level 1: Let's support mixed comparisons

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b) -> tc::common_type_t<T, U>
{
    return a < b ? b : a;
}
```

Level 1: Let's support mixed comparisons

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
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auto max(const T& a, const U& b) -> tc::common_type_t<T, U>
{
    return a < b ? b : a;
}
```

```
int      a = -1;
unsigned b = 1;
std::print("{}\n", max(a, b)); // error
```

think-cell

Level 2: Let's support perfect forwarding

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```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b) -> tc::common_type_t<T, U> { … }
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think-cell

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auto max(const T& a, const U& b) -> tc::common_type_t<T, U> { … }
```

```
std::string a = "hello";
std::string b = "world";
std::print("{}\n", max(a, b));
```

think-cell

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```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b) -> tc::common_type_t<T, U> { … }
```

```
std::string a = "hello";
std::string b = "world";
std::print("{}\n", max(a, b));
```

Unnecessary copy of the result.

think-cell

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b)
    -> std::conditional_t<
          std::same_as<T, U>,
              const T&, tc::common_type_t<T, U>
    >
{ … }
```

Level 2: Let's support perfect forwarding

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template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b)
    -> std::conditional_t<
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{ … }
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```
std::string a = "hello";
std::string b = "world";
std::print("{}\n", max(a, b));
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think-cell

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    -> std::conditional_t<
          std::same_as<T, U>,
              const T&, tc::common_type_t<T, U>
    >
{ … }
```

```
std::string a = "hello";
std::string b = "world";
std::print("{}\n", max(a, b));
```

No copy of the result.

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b)
    -> std::conditional_t<
          std::same_as<T, U>,
              const T&, tc::common_type_t<T, U>
    >
{ … }
```

```
std::print("{}\n", max("hello", std::string("world")));
```

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```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(const T& a, const U& b)
    -> std::conditional_t<
          std::same_as<T, U>,
              const T&, tc::common_type_t<T, U>
    >
{ … }
```

```
std::print("{}\n", max("hello", std::string("world")));
```

Unnecessary copy of the result, should be a move.

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
    requires requires { typename tc::common_type_t<T, U>; }
decltype(auto) max(T&& a, U&& b)
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
    requires requires { typename tc::common_type_t<T, U>; }
decltype(auto) max(T&& a, U&& b)
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

What if `std::remove_cvref_t<T>` and `std::remove_cvref_t<U>` are the same type?

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What does the ternary operator do?

?:	T&	const T&	T&&	const T&&
T&	T&	const T&	T	T
const T&	const T&	const T&	T	T
T&&	T	T	T&&	const T&&
const T&&	T	T	const T&&	const T&&

think-cell

What does the ternary operator do?

?:	T&	const T&	T&&	const T&&
T&	T&	const T&	T	T
const T&	const T&	const T&	T	T
T&&	T	T	T&&	const T&&
const T&&	T	T	const T&&	const T&&

`?:` is a prvalue when mixing an lvalue and an rvalue reference.

think-cell

Level 2: Let's support perfect forwarding

```cpp
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
    requires requires { typename tc::common_type_t<T, U>; }
decltype(auto) max(T&& a, U&& b)
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decltype(auto) max(T&& a, U&& b)
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

```
std::print("{}\n", max("hello", std::string("world")));
```

Result will be moved.

Level 2: Let's support perfect forwarding

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    requires requires { typename tc::common_type_t<T, U>; }
decltype(auto) max(T&& a, U&& b)
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

```
std::print("{}\n", max("hello", std::string("world")));
```

Result will be moved.

```
auto a = std::string("world");
std::print("{}\n", max(std::string("hello"), a));
```

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Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
    requires requires { typename tc::common_type_t<T, U>; }
decltype(auto) max(T&& a, U&& b)
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

```
std::print("{}\n", max("hello", std::string("world")));
```

Result will be moved.

```
auto a = std::string("world");
std::print("{}\n", max(std::string("hello"), a));
```

Unnecessary copy of a.

think-cell

Level 2: Let's support perfect forwarding

```
template <typename ... Ts>
using std::common_reference_t = …;
```

- If `std::remove_cvref_t<T>` and `std::remove_cvref_t<U>` are the same type, figure out the correct cv-ref qualification.
- Otherwise, use `std::common_type_t<T, U>`.

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Level 2: Let's support perfect forwarding

```
template <typename ... Ts>
using std::common_reference_t = …;
```

- If `std::remove_cvref_t<T>` and `std::remove_cvref_t<U>` are the same type, figure out the correct cv-ref qualification.
- Otherwise, use `std::common_type_t<T, U>`.

Crucially: not `decltype( false ? … : … )`.

think-cell

What does `std::common_reference` do?

`std::common_reference`	`T&`	`const T&`	`T&&`	`const T&&`
`T&`	`T&`	`const T&`	`const T&`	`const T&`
`const T&`	`const T&`	`const T&`	`const T&`	`const T&`
`T&&`	`const T&`	`const T&`	`T&&`	`const T&&`
`const T&&`	`const T&`	`const T&`	`const T&&`	`const T&&`

think-cell

What does `std::common_reference` do?

`std::common_reference`	`T&`	`const T&`	`T&&`	`const T&&`
`T&`	`T&`	`const T&`	`const T&`	`const T&`
`const T&`	`const T&`	`const T&`	`const T&`	`const T&`
`T&&`	`const T&`	`const T&`	`T&&`	`const T&&`
`const T&&`	`const T&`	`const T&`	`const T&&`	`const T&&`

`std::common_reference` is a `const` lvalue reference when mixing an lvalue and an rvalue reference.

think-cell

Aside: Implicit conversions of references

$$\begin{tikzcd}
\texttt{T\&} \arrow[r] & \texttt{const T\&} \\
\texttt{T\&\&} \arrow[r] \arrow[ur] & \texttt{const T\&\&} \arrow[u]
\end{tikzcd}$$

Binds to:	Temporary	`const`
`T&`	no	no
`const T&`	yes	yes
`T&&`	yes	no
`const T&&`	yes	yes

Thus:

- The common reference is `const T&` as that is the universal receiver.
- Functions that don't care about lifetime or mutation, use `const T&`.

think-cell

Aside: Implicit conversions of references

Is that ideal?

Aside: Implicit conversions of references

Is that ideal?

Binds to	Temporary	`const`
`T&`	no	no
`const T&`	yes	yes
`T&&`	yes	no
`const T&&`	yes	yes

think-cell

Aside: Implicit conversions of references

Is that ideal?

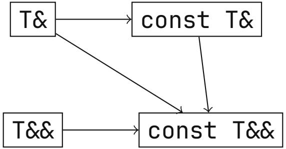
Binds to	Temporary	`const`
`T&`	no	no
`const T&`	yes	yes
`T&&`	yes	no
`const T&&`	yes	yes

We are missing “no” + “yes”!

think-cell

Aside: Implicit conversions of references

C++Better



Binds to:	Temporary	`const`
`T&`	no	no
`const T&`	no	yes
`T&&`	yes	no
`const T&&`	yes	yes

Then:

- The common reference is `const T&&` as that is the universal receiver.
- Functions that don't care about lifetime or mutation, use `const T&&`.

think-cell

think-cell: Better common reference

```
template <typename ... Ts>
using tc::common_reference_t = …;
```

- `tc::common_reference_t<int&, int&&>` is `const int&&`, not `const int&`.
- Uses `tc::common_type_t` not `std::common_type_t`.

think-cell

think-cell: Better common reference

tc::common_reference	T&	const T&	T&&	const T&&
T&	T&	const T&	const T&&	const T&&
const T&	const T&	const T&	const T&&	const T&&
T&&	const T&&	const T&&	T&&	const T&&
const T&&	const T&&	const T&&	const T&&	const T&&

think-cell

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

`?:` is a prvalue when mixing lvalues and rvalues!

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    if (a < b)
        return std::forward<U>(b);
    else
        return std::forward<T>(a);
}
```

think-cell

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    if (a < b)
        return static_cast<tc::common_reference_t<T, U>>(
            std::forward<U>(b)
        );
    else
        return static_cast<tc::common_reference_t<T, U>>(
            std::forward<T>(a)
        );
}
```

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    return tc_conditional_rvalue_as_ref(
        a < b,
        std::forward<U>(b),
        std::forward<T>(a)
    );
}
```

think-cell

tc_conditional_rvalue_as_ref

```
#define tc_conditional_rvalue_as_ref(cond, lhs, rhs) \
  ((cond) \
      ? (tc::common_reference_t<decltype((lhs)), decltype((rhs))>)(lhs) \
      : (tc::common_reference_t<decltype((lhs)), decltype((rhs))>)(rhs))
```

think-cell

Aside: Better base class conversion

```
struct A {};

struct B : A { using base = A; }
struct C : A { using base = A; }
struct D : C { using base = C; }

B b;
D d;
A& ref = tc_conditional_rvalue_as_ref(cond, b, d);
```

think-cell

Aside: Better base class conversion

```
struct A {};

struct B : A { using base = A; }
struct C : A { using base = A; }
struct D : C { using base = C; }

B b;
D d;
A& ref = tc_conditional_rvalue_as_ref(cond, b, d);
```

Fun TMP challenge: Given `T` and `U` find the most-derived common base class by walking `::base`.

Level 2: Let's support perfect forwarding

```
template <typename T, typename U>
    // Requires: T and U have a common operator< that
    // implements a strict weak order.
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    return tc_conditional_rvalue_as_ref(
        a < b,
        std::forward<U>(b),
        std::forward<T>(a)
    );
}
```

```
auto a = std::string("world");
std::print("{}\n", max(std::string("hello"), a));
```

No unnecessary copy of a

Level 3: `clamp(v, lo, hi)`

think-cell

Level 3: `clamp(v, lo, hi)`

```
template <typename T, typename U>
auto max(T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return tc_conditional_rvalue_as_ref(
        a < b,
        std::forward<U>(b), std::forward<T>(a)
    );
}
```

think-cell

Level 3: clamp(v, lo, hi)

```
template <typename T, typename U>
auto max(T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return tc_conditional_rvalue_as_ref(
        a < b,
        std::forward<U>(b), std::forward<T>(a)
    );
}
```

```
template <typename T, typename U>
auto min(T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return tc_conditional_rvalue_as_ref(
        a > b,
        std::forward<U>(b), std::forward<T>(a)
    );
}
```

Level 3: `clamp(v, lo, hi)`

```cpp
template <typename T, typename U, typename V>
decltype(auto) clamp(T&& v, U&& lo, V&& hi)
{
    return min(
        max(std::forward<T>(v), std::forward<U>(lo)),
        std::forward<V>(hi)
    );
}
```

Level 3: `clamp(v, lo, hi)`

```
template <typename T, typename U, typename V>
decltype(auto) clamp(T&& v, U&& lo, V&& hi)
{
    return min(
        max(std::forward<T>(v), std::forward<U>(lo)),
        std::forward<V>(hi)
    );
}
```

```
std::string lo = "a";
std::string hi = "z";
std::string v = "h";
auto clamped = clamp(v, lo, hi); // ok
```

think-cell

Level 3: `clamp(v, lo, hi)`

```cpp
template <typename T, typename U, typename V>
decltype(auto) clamp(T&& v, U&& lo, V&& hi)
{
    return min(
        max(std::forward<T>(v), std::forward<U>(lo)),
        std::forward<V>(hi)
    );
}
```

```cpp
std::string_view lo = "a";
std::string_view hi = "z";
std::string v = "h";
auto clamped = clamp(v, lo, hi); // crash!
```

think-cell

Level 3: `clamp(v, lo, hi)`

```
template <typename T, typename U, typename V>
decltype(auto) clamp(
      T&& v,  // std::string&
      U&& lo, // std::string_view&
      V&& hi  // std::string_view&
    )
{
    return min(
        max(std::forward<T>(v), std::forward<U>(lo)),
        std::forward<V>(hi)
    );
}
```

think-cell

Level 3: `clamp(v, lo, hi)`

```cpp
template <typename T, typename U, typename V>
decltype(auto) clamp(
        T&& v,  // std::string&
        U&& lo, // std::string_view&
        V&& hi  // std::string_view&
    )
{
    return min(
        max(std::forward<T>(v), std::forward<U>(lo)), // std::string_view
        std::forward<V>(hi)
    );
}
```

think-cell

Level 3: `clamp(v, lo, hi)`

```
template <typename T, typename U, typename V>
decltype(auto) clamp(
      T&& v,  // std::string&
      U&& lo, // std::string_view&
      V&& hi  // std::string_view&
    )
{
    return min(
        max(std::forward<T>(v), std::forward<U>(lo)), // std::string_view
        std::forward<V>(hi)                            // std::string_view&
    );
}
```

Level 3: `clamp(v, lo, hi)`

```cpp
template <typename T, typename U, typename V>
decltype(auto) clamp(
      T&& v,  // std::string&
      U&& lo, // std::string_view&
      V&& hi  // std::string_view&
    )
{
    return min(
        max(std::forward<T>(v), std::forward<U>(lo)), // std::string_view
        std::forward<V>(hi)                            // std::string_view&
    ); // const std::string_view&&
}
```

think-cell

Level 3: `clamp(v, lo, hi)`

Whose fault is it?

think-cell

Whose fault is it?

Projection A function that returns a reference whose lifetime is tied to one of the arguments.

Composed Projection A projection built by composing multiple projections.

Whose fault is it?

Projection A function that returns a reference whose lifetime is tied to one of the arguments.

Composed Projection A projection built by composing multiple projections.

Problem: If projections return rvalue references to prvalue arguments, composing them can lead to returning dangling references.

Level 3: `clamp(v, lo, hi)`

Solution 1: A projection never returns an rvalue reference.

Level 3: `clamp(v, lo, hi)`

Solution 1: A projection never returns an rvalue reference.

```
template <typename T>
using decay_rvalue_t = std::conditional_t<
    std::is_rvalue_reference_v<T>, std::decay_t<T>, T
>;
```

```
template <typename T, typename U>
auto max(T&& a, U&& b)
    -> decay_rvalue_t<tc::common_reference_t<T, U>>
{
    return tc_conditional_rvalue_as_ref(
        a < b, std::forward<U>(b), std::forward<T>(a)
    );
}
```

think-cell

Level 3: `clamp(v, lo, hi)`

Solution 1: A projection never returns an rvalue reference.

```
template <typename T>
using decay_rvalue_t = std::conditional_t<
    std::is_rvalue_reference_v<T>, std::decay_t<T>, T
>;
```

```
template <typename T, typename U>
auto max(T&& a, U&& b)
    -> decay_rvalue_t<tc::common_reference_t<T, U>>
{
    return tc_conditional_rvalue_as_ref(
        a < b, std::forward<U>(b), std::forward<T>(a)
    );
}
```

Problem: Too aggressive.

think-cell

Level 3: `clamp(v, lo, hi)`

Solution 2: A projection never returns an rvalue reference to a prvalue argument.

Level 3: `clamp(v, lo, hi)`

Solution 2: A projection never returns an rvalue reference to a prvalue argument.

```
template <typename T, typename ... Args>
using decay_if_prvalue_t = ???;
```

```
template <typename T, typename U>
auto max(T&& a, U&& b)
    -> decay_if_prvalue_t<tc::common_reference_t<T, U>, T, U>
{
    return tc_conditional_rvalue_as_ref(
        a < b, std::forward<U>(b), std::forward<T>(a)
    );
}
```

think-cell

Level 3: `clamp(v, lo, hi)`

Solution 2: A projection never returns an rvalue reference to a prvalue argument.

```
template <typename T, typename ... Args>
using decay_if_prvalue_t = ???;
```

```
template <typename T, typename U>
auto max(T&& a, U&& b)
    -> decay_if_prvalue_t<tc::common_reference_t<T, U>, T, U>
{
    return tc_conditional_rvalue_as_ref(
        a < b, std::forward<U>(b), std::forward<T>(a)
    );
}
```

Problem: Not actually implementable.

think-cell

Aside: Forwarding references

```cpp
template <typename T>
void f(T&& t);
```

Category	T	T&&
lvalue	U&	U&
xvalue	U	U&&
prvalue	U	U&&

think-cell

Aside: Forwarding references

```
template <typename T>
void f(T&& t);
```

Category	T	T&&
lvalue	U&	U&
xvalue	U	U&&
prvalue	U	U&&

A function cannot distinguish between prvalues and xvalue arguments.

think-cell

Aside: Forwarding references

C++Better

```
template <typename T>
void f(T&& t);
```

Category	T	T&&
lvalue	U&	U&
xvalue	U&&	U&&
prvalue	U	U&&

think-cell

Aside: Forwarding references

C++Better

```
template <typename T>
void f(T&& t);
```

Category	T	T&&
lvalue	U&	U&
xvalue	U&&	U&&
prvalue	U	U&&

A function could actually distinguish between prvalues and xvalue arguments!

think-cell

Level 3: `clamp(v, lo, hi)`

```
return min(
    max(std::forward<T>(v), std::forward<U>(lo)),
    std::forward<V>(hi)
); // dangling
```

Level 3: `clamp(v, lo, hi)`

```
return min(
    max(std::forward<T>(v), std::forward<U>(lo)),
    std::forward<V>(hi)
); // dangling
```

```
some_function(min(
    max(std::forward<T>(v), std::forward<U>(lo)),
    std::forward<V>(hi)
)); // fine
```

think-cell

Level 3: `clamp(v, lo, hi)`

```
return min(
    max(std::forward<T>(v), std::forward<U>(lo)),
    std::forward<V>(hi)
); // dangling
```

```
some_function(min(
    max(std::forward<T>(v), std::forward<U>(lo)),
    std::forward<V>(hi)
)); // fine
```

The user of a composed projection should be responsible for preventing dangling references!

think-cell

Level 3: `clamp(v, lo, hi)`

Solution 3: A composed projection never returns a reference to an intermediate prvalue.

Level 3: `clamp(v, lo, hi)`

Solution 3: A composed projection never returns a reference to an intermediate prvalue.

```
template <typename T>
auto decay_rvalue(T&& v) -> decay_rvalue_t<T&&> {
    return std::forward<T>(v);
}
```

```
template <typename T, typename U, typename V>
decltype(auto) clamp(T&& v, U&& lo, V&& hi) {
    return decay_rvalue(min(
        max(std::forward<T>(v), std::forward<U>(lo)),
        std::forward<V>(hi)
    ));
}
```

think-cell

Level 3: `clamp(v, lo, hi)`

Solution 3: A composed projection never returns a reference to an intermediate prvalue.

```
template <bool Cond, typename T>
auto decay_if(T&& v)
    -> std::conditional_t<Cond, std::decay_t<T>, T&&> {
    return std::forward<T>(v);
}
```

```
template <typename T, typename U, typename V>
decltype(auto) clamp(T&& v, U&& lo, V&& hi) {
    using max_t = decltype(max(std::forward<T>(v), std::forward<U>(lo)));
    return decay_if<!std::is_reference_v<max_t>>(min(
        max(std::forward<T>(v), std::forward<U>(lo)),
        std::forward<V>(hi)
    ));
}
```

Level 4: Generic compositions

Level 4: Generic compositions

```cpp
template <typename F, typename G, typename H>
struct dovekie
{
    F f;
    G g;
    H h;

    template <typename T, typename U>
    decltype(auto) operator()(T&& t, U&& u) const
    {
        return f(g(std::forward<T>(t)), h(std::forward<U>(u)));
    }
};
```

think-cell

Level 4: Generic compositions

```
template <typename F, typename G, typename H>
struct dovekie
{
    F f;
    G g;
    H h;

    template <typename T, typename U>
    decltype(auto) operator()(T&& t, U&& u) const
    {
        return decay_if<g_or_h_returns_prvalue>(
            f(g(std::forward<T>(t)), h(std::forward<U>(u)))
        );
    }
};
```

Level 4: Generic compositions

```cpp
template <typename F, typename G, typename H>
struct dovekie
{
    F f;
    G g;
    H h;

    template <typename T, typename U>
    decltype(auto) operator()(T&& t, U&& u) const
    {
        return decay_if<f_returns_an_rvalue_to_prvalue_of_g_or_h>(
            f(g(std::forward<T>(t)), h(std::forward<U>(u)))
        );
    }
};
```

Level 4: Generic compositions

C++ isn't a particularly great language, but all problems in C++ can be fixed with more C++.

think-cell

`tc::temporary` - A new reference type

Idea: Introduce a special “reference to temporary” type.

tc::temporary - A new reference type

```
template <typename T> requires std::is_object_v<T>
class temporary {
    T&& m_ref;
public:
    template <std::same_as<T&> U>
    explicit temporary(U ref) noexcept : m_ref(ref) {}
    template <std::same_as<T&&> U>
    temporary(U ref) noexcept : m_ref(std::move(ref)) {}

    operator T&() const& noexcept {
      return m_ref;
    }
    operator T&&() const&& noexcept {
      return std::move(m_ref);
    }
};
```

Creating a temporary

```
template <typename T>
using prvalue_as_temporary_t = std::conditional_t<
    std::is_reference<T>::value || tc::is_temporary<T>,
        T,
        tc::temporary<T>
>;

#define tc_prvalue_as_temporary(...) \
    static_cast<tc::prvalue_as_temporary_t<decltype((__VA_ARGS__))>> \
        (__VA_ARGS__)
```

Creating a temporary

```
int f();
int object = 0;
```

```
tc_prvalue_as_temporary(object)              // int&
```

Creating a temporary

```
int f();
int object = 0;
```

```
tc_prvalue_as_temporary(object)                // int&
```

```
tc_prvalue_as_temporary(std::move(object))  // int&&
```

Creating a temporary

```
int f();
int object = 0;
```

```
tc_prvalue_as_temporary(object)                  // int&
```

```
tc_prvalue_as_temporary(std::move(object))  // int&&
```

```
tc_prvalue_as_temporary(42)                      // tc::temporary<int>
```

think-cell

Creating a temporary

```cpp
int f();
int object = 0;
```

```cpp
tc_prvalue_as_temporary(object)                // int&
```

```cpp
tc_prvalue_as_temporary(std::move(object))     // int&&
```

```cpp
tc_prvalue_as_temporary(42)                    // tc::temporary<int>
```

```cpp
tc_prvalue_as_temporary(f())                   // tc::temporary<int>
```

Creating a temporary

```
#define tc_prvalue_as_temporary(...) \
    static_cast<tc::prvalue_as_temporary_t<decltype((__VA_ARGS__))>> \
        (__VA_ARGS__)
```

Is there overhead?

think-cell

Aside: Copy elision

```
static_cast<decltype((expr))>(expr)
```

- If `expr` is an lvalue or xvalue, casts it to an lvalue or rvalue reference.
- If `expr` is a prvalue, copy-elision keeps it as a prvalue.

Aside: Copy elision

```
static_cast<decltype((expr))>(expr)
```

- If `expr` is an lvalue or xvalue, casts it to an lvalue or rvalue reference.
- If `expr` is a prvalue, copy-elision keeps it as a prvalue.

→ no-op

think-cell

Aside: Copy elision

```
static_cast<decltype((expr))>(expr)
```

- If `expr` is an lvalue or xvalue, casts it to an lvalue or rvalue reference.
- If `expr` is a prvalue, copy-elision keeps it as a prvalue.

→ no-op

```
static_cast<decltype(expr)>(expr)
```

- If `expr` is a non-identifier, as above.
- If `expr` is an identifier referring to an lvalue reference or object, casts it to an lvalue reference.
- If `expr` is an identifier referring to an rvalue reference, casts it to an rvalue reference.

Aside: Copy elision

```
static_cast<decltype((expr))>(expr)
```

- If `expr` is an lvalue or xvalue, casts it to an lvalue or rvalue reference.
- If `expr` is a prvalue, copy-elision keeps it as a prvalue.

→ no-op

```
static_cast<decltype(expr)>(expr)
```

- If `expr` is a non-identifier, as above.
- If `expr` is an identifier referring to an lvalue reference or object, casts it to an lvalue reference.
- If `expr` is an identifier referring to an rvalue reference, casts it to an rvalue reference.

→ `std::forward`

think-cell

Handling a temporary

Rule: A `tc::temporary` must never be returned from a function.

Handling a temporary

Rule: A `tc::temporary` must never be returned from a function.

```
template <typename T>
using return_temporary_t = std::conditional_t<
    tc::is_temporary<T>,
        tc::decay_t<T>,
        T
>;

#define tc_return_temporary(...) \
    return static_cast<tc::return_temporary_t<decltype((__VA_ARGS__))>>( \
        __VA_ARGS__ \
    )
```

Handling a temporary

```cpp
int object;
tc_return_temporary(object);
```

Equivalent to: `return static_cast<int&>(object);`

Handling a temporary

```
int object;
tc_return_temporary(object);
```

Equivalent to: `return static_cast<int&>(object);`

```
int object;
tc_return_temporary(std::move(object));
```

Equivalent to: `return static_cast<int&&>(std::move(object));`

think-cell

Handling a temporary

```
int object;
tc_return_temporary(object);
```

Equivalent to: `return static_cast<int&>(object);`

```
int object;
tc_return_temporary(std::move(object));
```

Equivalent to: `return static_cast<int&&>(std::move(object));`

```
tc_return_temporary(42);
```

Equivalent to: `return static_cast<int>(42);` (copy-elision!)

think-cell

Handling a temporary

```
int object;
tc_return_temporary(object);
```

Equivalent to: `return static_cast<int&>(object);`

```
int object;
tc_return_temporary(std::move(object));
```

Equivalent to: `return static_cast<int&&>(std::move(object));`

```
tc_return_temporary(42);
```

Equivalent to: `return static_cast<int>(42);` (copy-elision!)

```
tc_return_temporary(tc::temporary(42));
```

Equivalent to: `return static_cast<int>(tc::temporary(42));`

think-cell

Level 4: Generic compositions

```cpp
template <typename F, typename G, typename H>
struct dovekie
{
    F f;
    G g;
    H h;

    template <typename T, typename U>
    decltype(auto) operator()(T&& t, U&& u) const
    {
        tc_return_temporary(f(
            tc_prvalue_as_temporary(g(std::forward<T>(t))),
            tc_prvalue_as_temporary(h(std::forward<U>(u)))
        ));
    }
};
```

Better invoke

Let's teach it to `invoke`:

```
#define tc_invoke(f, ...) \
    tc::invoke_impl(f, /* wrap arguments in tc_prvalue_as_temporary */)
```

Better invoke

Let's teach it to `invoke`:

```
#define tc_invoke(f, ...) \
    tc::invoke_impl(f, /* wrap arguments in tc_prvalue_as_temporary */)
```

```
template <typename T, typename U>
decltype(auto) operator()(T&& t, U&& u) const
{
    tc_return_temporary(
        tc_invoke(f,
            tc_invoke(g, std::forward<T>(t)),
            tc_invoke(h, std::forward<U>(u))
        )
    );
}
```

Level 4: Generic compositions

Consequence: Projections need to be aware of `tc::temporary`.

Level 4: Generic compositions

Consequence: Projections need to be aware of `tc::temporary`.

```
template <typename T, typename U>
tc::common_reference_t<T, U> f(T&& t, U&& u);
```

Must return a `tc::temporary` if at least one argument is a temporary.

Level 4: Generic compositions

Consequence: Projections need to be aware of `tc::temporary`.

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template <typename T, typename U>
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Must return a `tc::temporary` if and only if the first argument is a temporary.

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template <typename T, typename U>
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```
template <typename T, typename U>
T&& f(T&& t, U&& u);
```

Must return a `tc::temporary` if and only if the first argument is a temporary.

```
template <typename T, typename U>
tc::common_type_t<T, U> f(T&& t, U&& u);
```

Must never return a `tc::temporary`.

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Level 4: Generic compositions

```
template <typename T, typename U>
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    // Implicit conversion of tc::temporary -> T& if necessary.
    return tc_conditional_rvalue_as_ref(
        a < b, std::forward<U>(b), std::forward<T>(a)
    );
}
```

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Level 4: Generic compositions

```
template <typename T, typename U>
auto max(T&& a, U&& b)
    -> tc::common_reference_t<T, U>
{
    // Implicit conversion of tc::temporary -> T& if necessary.
    return tc_conditional_rvalue_as_ref(
        a < b, std::forward<U>(b), std::forward<T>(a)
    );
}
```

```
template <typename T>
decltype(auto) get_foo(T&& obj)
{
    return std::forward<T>(obj).foo; // no implicit conversion!
}
```

Unwrapping temporaries

```
template <typename T>
using unwrap_temporary_t = std::conditional_t<
    tc::is_temporary<T>,
        tc::decay_t<T>&&, T
>;

#define tc_unwrap_temporary(...) \
    static_cast<tc::unwrap_temporary_t<decltype((__VA_ARGS__))>>( \
        __VA_ARGS__ \
    )
```

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Unwrapping temporaries

```
template <typename T>
decltype(auto) get_foo(T&& obj)
{
    return tc_unwrap_temporary(std::forward<T>(obj)).foo;
}
```

think-cell

Unwrapping temporaries

```
template <typename T>
decltype(auto) get_foo(T&& obj)
{
    return tc_unwrap_temporary(std::forward<T>(obj)).foo;
}
```

No `tc::temporary` annotation on the result.

Rewrapping temporaries

```
template <typename Result, typename ... Args>
using rewrap_temporary_t = std::conditional_t<
    std::is_rvalue_reference_v<Result> && (tc::is_temporary<Args> || ...),
        tc::temporary<std::remove_reference_t<Result>>,
        Result
>;

#define tc_rewrap_temporary(Args, ...) \
    static_cast<tc::rewrap_temporary_t<decltype((__VA_ARGS__)), Args>( \
        __VA_ARGS__ \
    )
```

If the result is an rvalue reference and any of the arguments is a `tc::temporary`, wrap it in a `tc::temporary`.

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Rewrapping temporaries

```
template <typename Result, typename ... Args>
using rewrap_temporary_t = std::conditional_t<
    std::is_rvalue_reference_v<Result> && (tc::is_temporary<Args> || ...),
        tc::temporary<std::remove_reference_t<Result>>,
        Result
>;

#define tc_rewrap_temporary(Args, ...) \
    static_cast<tc::rewrap_temporary_t<decltype((__VA_ARGS__)), Args>( \
        __VA_ARGS__ \
    )
```

If the result is an rvalue reference and any of the arguments is a `tc::temporary`, wrap it in a `tc::temporary`.

This is a heuristic.

Unwrapping and rewrapping temporaries

```
template <typename T>
decltype(auto) get_foo(T&& obj)
{
    return tc_rewrap_temporary(T&&,
          tc_unwrap_temporary(std::forward<T>(obj)).foo
    );
}
```

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Level 4: Generic compositions

```
template <typename T, typename U>
decltype(auto) operator()(T&& t, U&& u) const
{
    tc_return_temporary(
        tc_invoke(f,
            tc_invoke(g, std::forward<T>(t)),
            tc_invoke(h, std::forward<U>(u))
        )
    );
}
```

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Level 4: Generic compositions

```cpp
template <typename T, typename U>
decltype(auto) operator()(T&& t, U&& u) const
{
    tc_return_temporary(
        tc_invoke(f,
            tc_invoke(g, std::forward<T>(t)),
            tc_invoke(h, std::forward<U>(u))
        )
    );
}
```

What if `t` or `u` is already a `tc::temporary`?

Temporary with lifetime

```
template <typename T, unsigned Lifetime>
class temporary { … };
```

- `Lifetime == 0`: true temporary, need to decay in `tc_return_temporary`
- `Lifetime > 0`: only a temporary in some parent scope
- `tc::common_reference_t`, `tc_rewrap_temporary`: minimum lifetime of all temporaries

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Temporary with lifetime

```
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- `Lifetime == 0`: true temporary, need to decay in `tc_return_temporary`
- `Lifetime > 0`: only a temporary in some parent scope
- `tc::common_reference_t`, `tc_rewrap_temporary`: minimum lifetime of all temporaries

```
#define tc_increment_lifetime(...) …
#define tc_decrement_lifetime(...) …
```

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Temporary with lifetime

```
template <typename F, typename ... Args>
decltype(auto) invoke_impl(F&& f, Args&&... args) {
    return tc_decrement_lifetime(std::forward<F>(f)(
        tc_increment_lifetime(std::forward<Args>(args))...
    ));
}
```

This approach works.

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- Composed projections use `tc_invoke` and `tc_return_temporary` → never returns a dangling reference.
- Tracking of `tc::temporary` is accurate → no unnecessary decay.

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This approach works.

- Composed projections use `tc_invoke` and `tc_return_temporary` → never returns a dangling reference.
- Tracking of `tc::temporary` is accurate → no unnecessary decay.

But: all templated projections need to be aware of `tc::temporary`.

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Level 4: Generic compositions

Insight: `tc::temporary` is only relevant for projections that can return an rvalue reference.

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```
template <typename F, typename ... Args>
decltype(auto) invoke_impl(F&& f, Args&&... args) {
    if constexpr (std::is_rvalue_reference_v<decltype(
        std::forward<F>(f)(
            tc_unwrap_temporary(std::forward<Args>(args))...
        )
    )>)
        return tc_decrement_lifetime(std::forward<F>(f)(
            tc_increment_lifetime(std::forward<Args>(args))...
        ));
    else
        return std::forward<F>(f)(
            tc_unwrap_temporary(std::forward<Args>(args))...
        );
}
```

Other temporary complexities

- `tc::temporary<const T, Lifetime>`

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  - `tc::temporary<T, Lifetime>&` $\longrightarrow$ `T&`

Other temporary complexities

- `tc::temporary<const T, Lifetime>`
- Reference collapsing rules:
  - `tc::temporary<T, Lifetime>&` → `T&`
  - `tc::temporary<T, Lifetime>&&` → `tc::temporary<T, Lifetime>`

Level 4: Generic compositions

`tc::temporary` is being used in production:

- It is only necessary for function objects in generic code.

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Level 4: Generic compositions

`tc::temporary` is being used in production:

- It is only necessary for function objects in generic code.
- Composed projections handle temporaries appropriately.
- Generic library projections handle temporaries appropriately.
- There isn't a single projection in user code that needs to handle temporary.

Level 4: Generic compositions

Most common projection:

```
#define tc_member(...) \
    []<typename T>(T&& obj) -> decltype(auto) { \
        return tc_rewrap_temporary(T&&, \
            tc_unwrap_temporary(std::forward<T>(obj)) __VA_ARGS__ \
        ); \
    }
```

```
tc::transform(rng, tc_member(.foo));
```

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Level 4: Generic compositions

Most common projection:

```
#define tc_member(...) \
    []<typename T>(T&& obj) -> decltype(auto) { \
        return tc_rewrap_temporary(T&&, \
            tc_unwrap_temporary(std::forward<T>(obj)) __VA_ARGS__ \
        ); \
    }
```

```
tc::transform(rng, tc_member(.foo));
```

Similar: `tc_mem_fn(.size)`.

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Level 5: New language design

Requirements

Projections:

- No unnecessary copies.
- No unnecessary moves.

Composed Projections:

- Don’t return reference to intermediate temporary.

Requirements

Projections:

- No unnecessary copies.
- No unnecessary moves.

Composed Projections:

- Don't return reference to intermediate temporary.

Problem: How to track whether a resulting reference is tied to an argument?

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Rust approach: Built-in lifetime annotations

Mark the lifetime of the output reference (if it is one).

```
template <typename T, typename U>
auto max(T&&/l a, U&&/l b)
    -> tc::common_reference_t<T, U>/l
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

Rust approach: Built-in lifetime annotations

Mark the lifetime of the output reference (if it is one).

```
template <typename T, typename U>
auto max(T&&/l a, U&&/l b)
    -> tc::common_reference_t<T, U>/l
{
    return a < b ? std::forward<U>(b) : std::forward<T>(a);
}
```

Automatically decay references to dangling temporary in return.

```
template <typename T, typename U>
decltype(auto) operator()(T&&/l a, U&&/l b) const
{
    return f(g(std::forward<T>(t)), h(std::forward<U>(u)));
}
```

Level 5: New language design

This is still unnecessary complexity!

Level 5: New language design

Why does Rust require lifetime annotations in the signature?

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To ensure that you don't change the signature accidentally during internal refactorings.

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To ensure that you don't change the signature accidentally during internal refactorings.

But: For a projection, the lifetime follows from the behavior!

Level 5: New language design

Why do C++/Rust require explicit opt-in to call by reference?

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Level 5: New language design

Why do C++/Rust require explicit opt-in to call by reference?

Because it has consequences for lifetime tracking.

Why do C++/Rust require explicit opt-in to call by reference?

Because it has consequences for lifetime tracking.

But: For a projection, there is an obvious choice.

Better approach: Just write the projection

Specify that it is a projection, and the compiler does the right thing.

```
template <typename T, typename U>
projection auto max(T a, U b)
    -> tc::common_type_t<T, U>
{
    return a < b ? b : a;
}
```

Better approach: Just write the projection

Specify that it is a projection, and the compiler does the right thing.

```
template <typename T, typename U>
projection auto max(T a, U b)
    -> tc::common_type_t<T, U>
{
    return a < b ? b : a;
}
```

```
template <typename T, typename U>
projection auto operator()(T a, U b) const
{
    return f(g(a), h(b));
}
```

First-class references are the worst feature C++ has ever added.

- Complexity in function arguments.

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- `T&` vs. `T&&` vs. `auto&&`.

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- Dangling references.

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First-class references are the worst feature C++ has ever added.

- Complexity in function arguments.
- `T&` vs. `T&&` vs. `auto&&`.
- Temporary lifetime extension.
- Dangling references.
- So much complexity for every language feature that interacts with them.

Parameter passing modes are much better.

- `in` vs. `out` vs. `inout` vs. regular parameters.
- Compiler figures out how to pass stuff.

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Level 5: New language design

Hylo: References aren't a thing.

- Value semantics only.
- Pass by reference as parameter passing optimization.
- Subscripts implement "projections".

Hylo: References aren't a thing.

- Value semantics only.
- Pass by reference as parameter passing optimization.
- Subscripts implement "projections".

This is a much cleaner design!

Conclusion

Is this really necessary?

If you want to avoid unnecessary moves yes, you need `tc::temporary` like tracking

If you are fine with unnecessary moves no, always decay rvalues

Is this really necessary?

If you want to avoid unnecessary moves yes, you need `tc::temporary` like tracking

If you are fine with unnecessary moves no, always decay rvalues

But really: We need different language design.

Bonus: Bells and whistles for `max`

Bonus: Bells and whistles for max

```
template <typename T, typename U>
auto max(T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return tc_conditional_rvalue_as_ref(
        a < b,
        std::forward<U>(b), std::forward<T>(a)
    );
}
```

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Custom predicate

```
template <typename Better, typename T, typename U>
auto best(Better&& better, T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return tc_conditional_rvalue_as_ref(
        better(tc::as_const(b), tc::as_const(a)),
        std::forward<U>(b), std::forward<T>(a)
    );
}
```

Custom predicate

```
template <typename Better, typename T, typename U>
auto best(Better&& better, T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return tc_conditional_rvalue_as_ref(
        better(tc::as_const(b), tc::as_const(a)),
        std::forward<U>(b), std::forward<T>(a)
    );
}
```

```
template <typename T, typename U>
auto max(T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return best(std::greater<>{}, std::forward<T>(a), std::forward<U>(b));
}
```

Custom predicate

```
template <typename Better, typename T, typename U>
auto best(Better&& better, T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return tc_conditional_rvalue_as_ref(
        better(tc::as_const(b), tc::as_const(a)),
        std::forward<U>(b), std::forward<T>(a)
    );
}
```

```
template <typename T, typename U>
auto max(T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return best(std::greater<>{}, std::forward<T>(a), std::forward<U>(b));
}
```

```
template <typename T, typename U>
auto min(T&& a, U&& b) -> tc::common_reference_t<T, U> {
    return best(std::less<>{}, std::forward<T>(a), std::forward<U>(b));
}
```

Compile-time predicate

```
template <typename Better, typename T, typename U>
    // Requires: Better implements a strict weak ordering.
decltype(auto) best(Better&& better, T&& a, U&& b) {
    auto result = better(tc::as_const(b), tc::as_const(a));
    if constexpr (std::same_as<decltype(result), std::true_type>) {
        return std::forward<U>(b);
    } else if constexpr (std::same_as<decltype(result), std::false_type>) {
        return std::forward<T>(a);
    } else {
        return tc_conditional_rvalue_as_ref(
            result, std::forward<U>(b), std::forward<T>(a)
        );
    }
}
```

Compile-time predicate

```
#define tc_conditional_rvalue_as_ref(b, lhs, rhs) \
  [&]() -> decltype(auto) { \
      if constexpr (std::same_as<decltype(b), std::true_type>) \
          return lhs; \
      else if constexpr (std::same_as<decltype(b), std::false_type>) \
          return rhs; \
      else \
          return …; \
  }()
```

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Compile-time predicate

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#define tc_conditional_rvalue_as_ref(b, lhs, rhs) \
  [&]() -> decltype(auto) { \
      if constexpr (std::same_as<decltype(b), std::true_type>) \
          return lhs; \
      else if constexpr (std::same_as<decltype(b), std::false_type>) \
          return rhs; \
      else \
          return …; \
  }()
```

But: intermediate stack frame.

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Compile-time predicate

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#define tc_conditional_rvalue_as_ref(b, lhs, rhs) \
  [&]() -> decltype(auto) { \
      if constexpr (std::same_as<decltype(b), std::true_type>) \
          return lhs; \
      else if constexpr (std::same_as<decltype(b), std::false_type>) \
          return rhs; \
      else \
          return …; \
  }()
```

But: intermediate stack frame.

Wish list: `constexpr ?:` or `do` expressions

Compile-time predicate

```
auto biggest_size = best(
    [](const auto& lhs, const auto& rhs) {
        return std::bool_constant<sizeof(lhs) > sizeof(rhs)>{};
    },
    3.14, "hello world"
);
```

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Variadic

```
template <typename Better, typename T, typename U, typename ... Tail>
    // Requires: Better implements a strict weak ordering.
decltype(auto) best(Better&& better, T&& a, U&& b, Tail&&... tail) {
    auto result = better(tc::as_const(b), tc::as_const(a));
    if constexpr (std::same_as<decltype(result), std::true_type>) {
        return best(better, std::forward<U>(b), std::forward<Tail>(tail)...);
    } else if constexpr (std::same_as<decltype(result), std::false_type>) {
        return best(better, std::forward<T>(a), std::forward<Tail>(tail)...);
    } else {
        return tc_conditional_rvalue_as_ref(result,
            best(better, std::forward<U>(b), std::forward<Tail>(tail)...)
            best(better, std::forward<T>(a), std::forward<Tail>(tail)...)
        );
    }
}
```

Every problem in C++ can be solved with more C++.

But maybe it shouldn't.

We're hiring: think-cell.com/career/dev

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