Aliasing

Risks, Opportunities and Techniques

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“All problems in computer science can be solved by another level of indirection"
"... except for the problem of too many levels of indirection"

- David Wheeler

levelofindirection.com

Hi, I'm Roi

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- Not an expert - happy to learn
  - Please - ask questions, make comments

What is Aliasing?

- Definition: two (or more) variables which refer to the same memory location being used together.
- Example:

```
std::string s{“hello, ”};
s += s;
```

- Causes dependencies to exist where the code seems independant
  - Aliasing is NOT about threads and volatile data
  - Reasoning about aliasing can be similar to reasoning about race conditions
- Aliasing considerations impact code correctness and efficiency/speed

Talk Outline

- Examples
  - Correctness, Performance
- Aliasing and the C++ Standard
- Dealing with aliasing pitfalls
  - APIs and implementations
  - Standard vs. compiler specific
- Future of aliasing
- Aliasing based design

Example: Aliased Function Arguments

- Pointers:

```
auto minmax = [](const string& i, const string& j,
                 string* out_min, string* out_max) {
    *out_min = min(i, j); *out_max = max(i, j);
};
array<string, 2> arr{"22222", "11111"};
minmax(arr[0], arr[1], &arr[0], &arr[1]); // try to sort
```

- References:

```
auto concat = [](string& result, const auto&... args) {
    ((result += args), ...);
};
string x{"hello "}, y{"world "};
concat(x, y, x);
```

```cpp
int main() {
    auto minmax = [](const string& i, const string& j, string* out_min,
                     string* out_max) {
        *out_min = min(i, j);
        *out_max = max(i, j);
    };
    array<string, 2> arr{"22222", "11111"};
    // try to sort
    minmax(arr[0], arr[1], &arr[0], &arr[1]);
    cout << "expect 22222 and get " << arr[1] << "\n";
    auto concat = [](string& result, const auto&... args) {
        ((result += args), ...);
    };
    string x{"hello "}, y{"world "};
    concat(x, y, x);
    cout << "expect [hello world hello ] and get [" << x << "]\n";
    return 0;
```

Executor x86-64 clang 14.0.0 (C++, Editor #1)

A | Wrap lines | Libraries (1) | Compilation | Arguments | Stdin | Compiler output

x86-64 clang 14.0.0 | -std=c++20 -O3

```
Program returned: 0
Program stdout
expect 22222 and get 11111
expect [hello world hello ] and get [hello world hello world ]
```

Example: Not Only Arguments

- Member variables:

```
complex<int> x{2, 2};
x *= reinterpret_cast<int*>(&x)[0];  // multiply by real part
```

- Lambda closures:

```
auto add_to_all = [](auto& v, const auto& val) {
    for_each(begin(v), end(v), [&](auto& x) { x += val; });
};
vector<int> v{1, 2, 3};
add_to_all(v, v[0]);
```

```
12  //    members();
13      complex<int> x{2, 2};
14      x *= reinterpret_cast<int*>(&x)[0];  // multiply by real part
15      cout << "expect (4,4) and get " << x << "\n";
16  //    lambdas();
17      auto add_to_all = [](auto& v, const auto& suffix) {
18          for_each(begin(v), end(v), [&](auto& x) { x += suffix; });
19      };
20      vector<int> v{1, 2, 3};
21      add_to_all(v, v[0]);
22      cout << "expected [2,3,4] and got [" << v[0] << "," << v[1] << "," << v[2]
23           << "]\n";
```

Executor x86-64 clang 14.0.0 (C++, Editor #1)

A ▾ | Wrap lines | Libraries (1) | Compilation | Arguments | Stdin | Compiler output

x86-64 clang 14.0.0 ▾ | -std=c++20 -O3

```
Program returned: 0
Program stdout
expect (4,4) and get (4,8)
expected [2,3,4] and got [2,4,5]
```

Example: Aliased Buffers

```
void loopcpy(char* dst, const char* src, int size) {
    while (size--) *dst++ = *src++;
}
```

```
test("loopcpy", loopcpy);
test("strcpy ", [](auto dst, auto src, au
                   strcpy(dst, src); });
test("strncpy", strncpy);
test("memcpy ", memcpy);
test("memmove", memmove);
test("copy_n ",
     [](auto dst, auto src, auto size) {
                  copy_n(src, size, dst); });
```

Clang14	ICC 2021.5.0	Standard
loopcpy [hhhhhh] Bad	[hhhhhh] Bad	Bad
strcpy [helll] Bad	[helll] Bad	UB
strncpy [hello] Good	[hello] Good	UB
memcpy [hello] Good	[helll] Bad	UB
memmove [hello] Good	[hello] Good	Good
copy_n [hello] Good	[hello] Good	ID

https://godbolt.org/z/Er4dfPPqb

Example: STL Algorithms

- Erase (or Erase-Remove) max element with duplicates

```
erase(v, *max_element(begin(v), end(v)));
```

  or (C++20 ranges)

```
erase(v, *ranges::max_element(v));
```

  - (**remove** has documentation about this, **erase** doesn't)
- Copy/Move overlapping regions

```
copy(begin(v),end(v)-1, begin(v)+1);
```

  - (Documented as faulty, **copy_backward** recommended instead)
- Iterators can cause aliasing

```
auto max = ranges::max_element(a);
stable_partition(begin(a),end(a),[=](const auto&x) {return x != *max;});
```

  - (Predicates which modify their argument or the sequence are UB, this case isn't).

```
 7  void erase() {
 8      vector<int> v{1, 4, 2, 1, 4, 3, 4};
 9      erase(v, *max_element(begin(v), end(v)));
10      cout << "erase_max         expected [1,2,1,3]     and got [";
11      copy(begin(v), end(v) - 1, ostream_iterator<int>(cout, ","));
12      cout << v.back() << "]\n";
13      erase(v, *ranges::max_element(v));
14      cout << "erase_ranges::max expected [1,2,1,3]     and got [";
15      copy(begin(v), end(v) - 1, ostream_iterator<int>(cout, ","));
16      cout << v.back() << "]\n";
17  }
```

Executor x86-64 clang 14.0.0 (C++, Editor #1)

A ▾ | Wrap lines | Libraries (1) | Compilation | Arguments | Stdin | Compiler outp

x86-64 clang 14.0.0 | -std=c++20 -O3

```
Program returned: 0
Program stdout
erase_max         expected [1,2,1,3]     and got [1,2,1,4,3,4]
erase_ranges::max expected [1,2,1,3]     and got [1,2,1,3,4]
```

```cpp
void copy() {
    vector<string> v{"b", "c", "d", "e"};
    copy(begin(v), end(v) - 1, begin(v) + 1);
    v[0] = "a";
    cout << "copy              expected [a,b,c,d]     and got [";
    copy(begin(v), end(v) - 1, ostream_iterator<string>(cout, ","));
    cout << v.back() << "]\n";
}

void partition() {
    array a = {1, 4, 2, 4, 3, 4};
    auto max = ranges::max_element(a);
    stable_partition(begin(a), end(a),
                     [=](const auto& x) { return x != *max; });
    cout << "stable_partition  expected [1,2,3,4,4,4] and got [";
    copy(begin(a), end(a) - 1, ostream_iterator<int>(cout, ","));
    cout << a.back() << "]\n";
```

Executor x86-64 clang 14.0.0 (C++, Editor #1)

A | Wrap lines | Libraries (1) | Compilation | Arguments | Stdin | Compiler output

x86-64 clang 14.0.0 | -std=c++20 -O3

```
Program returned: 0
Program stdout
copy              expected [a,b,c,d]     and got [a,b,b,b]
stable_partition  expected [1,2,3,4,4,4] and got [1,2,4,3,4,4]
```

Performance Effect of Aliasing

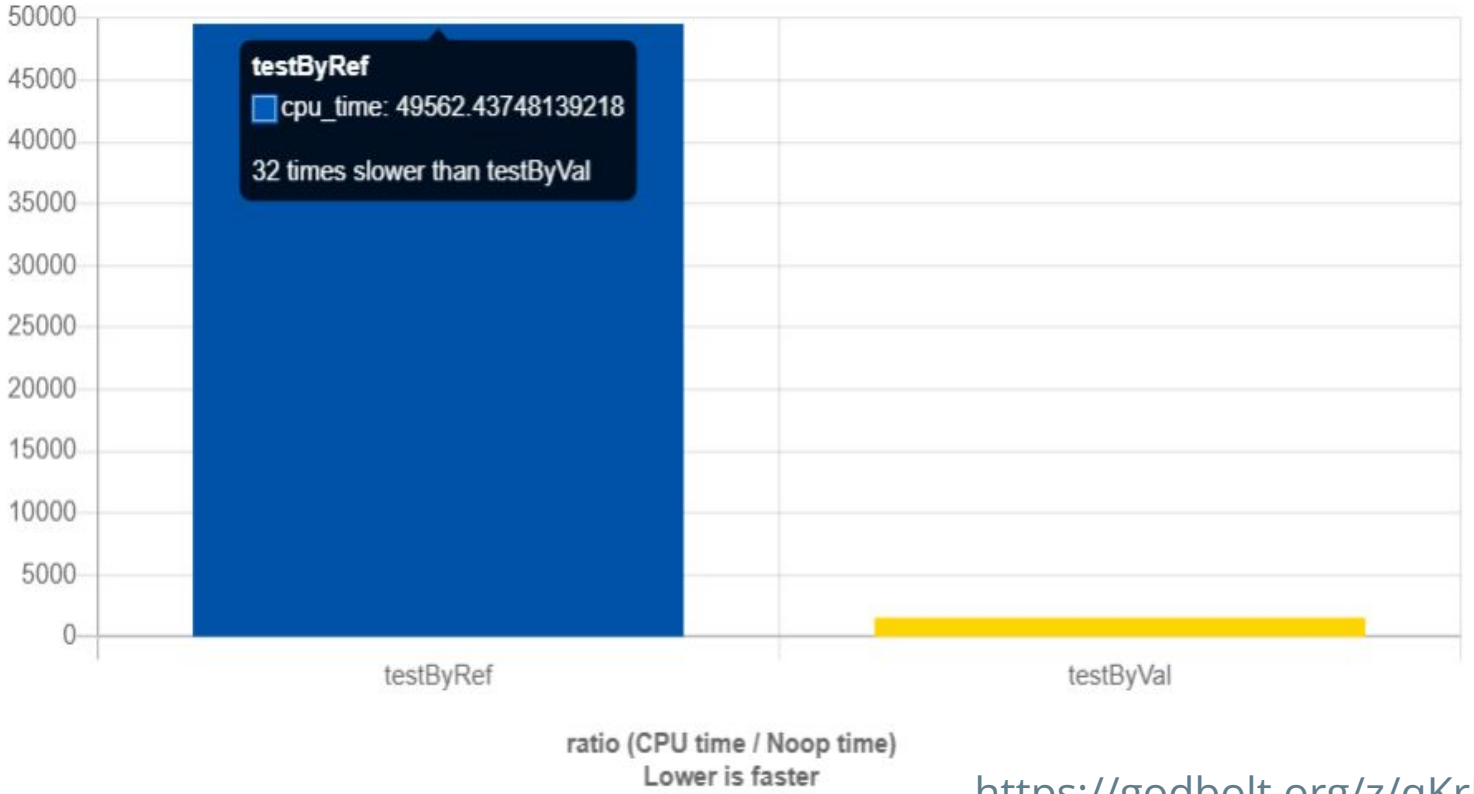
- Extreme example

```
void foo(std::vector<double>& v, const double& coeff) {
  for (auto& item : v) item *= std::sin(coeff);
}
```

- Compiler's missed opportunities:
  - Register <-> memory
  - Vectorization
  - Expression hoisting
- How important can it be...

https://godbolt.org/z/qKrEfWe7Y

Performance Benchmark Results



https://godbolt.org/z/qKrEfWe7Y

Lesson Learned - Aliasing is Tricky

- Humans rarely consider it → Strange unexpected bugs
  - We expect independence of different variables
- Compilers can't ignore it → Unexpected performance loss
  - Learn more in Ofek Shilon's talk about optimization remarks from Wednesday
- Library writers should document it → users should read documentation
  - Misuse often leads to 'happens to work' code
- *"All problems in computer science can be solved by another level of indirection"*
  "... except for the problem of too many levels of indirection"

- Questions and comments are welcome…

Aliasing in Other Languages

- The C language had a surge of (non-assembly) aliasing issues
  - Pointers were used as primitive substitutes to arrays, matrices, strings
  - C99 introduced the `restrict` keyword
    - A code block with a `restrict` pointer/array can only change the pointed data through that pointer/array. Otherwise: undefined behavior
    - Most C++ compilers have some non-standard support for `restrict`
- Fortran typically treats aliases as undefined behavior
  - with compiler switches to assume aliasing
- Swift and Rust track reference creation aiming to prohibit the risk of aliasing

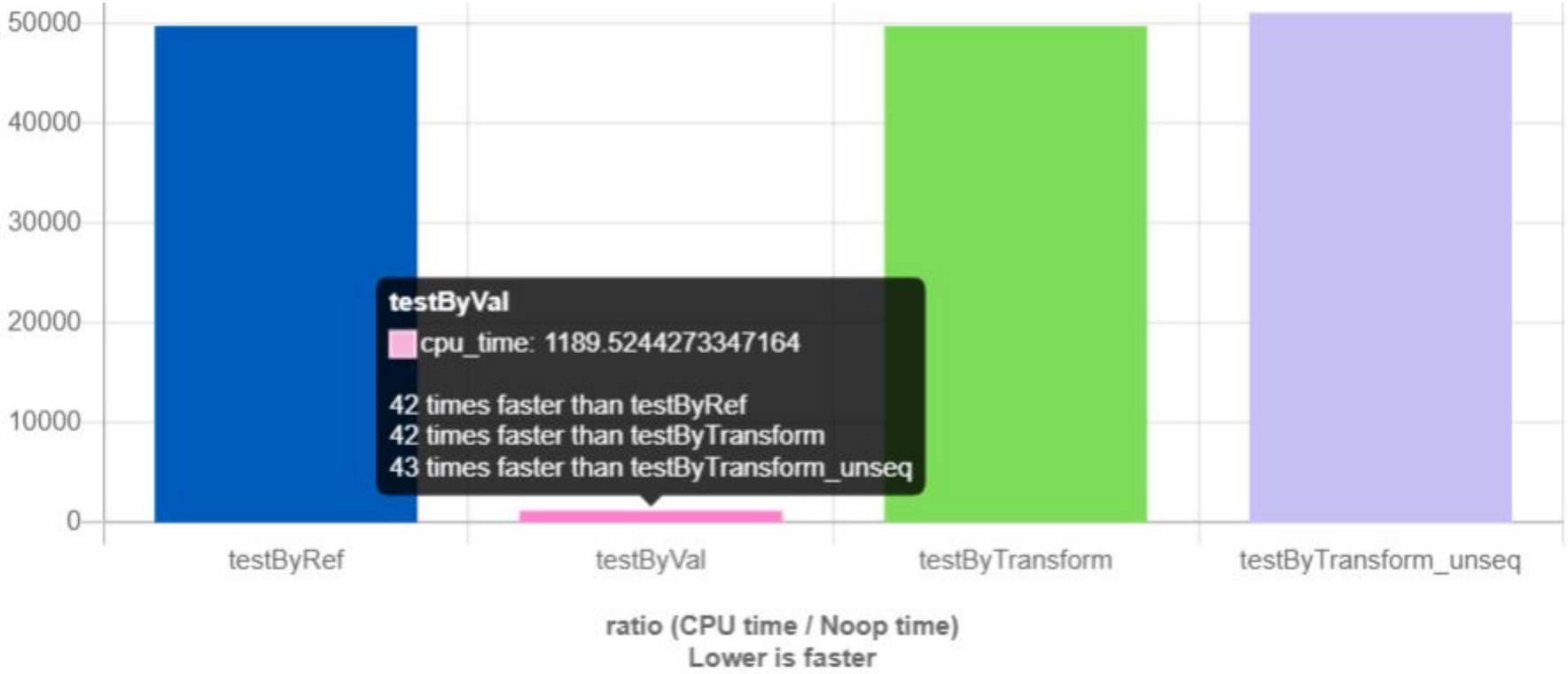
Aliasing in the C++ Standard

- C++ hasn't adopted the **`restrict`** keyword (yet?)
  - Seems more tricky: function-signature qualifiers, templates, functors/lambdas
- Aliasing *should* be type-based - known as "strict aliasing"
  - Only similar types are technically allowed to alias each other (and **`char`**, **`std::byte`**)
    - Similar types - changes to const/volatile/signed, or base-derived relationship
    - Otherwise - undefined behavior
  - Strong-typedefs can reduce risk and improve performance !
  - Most compiler-optimizers relax the rules - favoring predictability over performance
    - Still - compilers try to prove whether aliasing is impossible.
- Some objects are easier to reason about
  - Local variables - locally live on the stack
  - Temporary values

Aliasing in the C++ Standard Library (STL)

- The STL tries to document the effect of aliasing and sometimes mitigates them
  - `vec.push_back(v.front());` always works (with a performance cost)
  - `std::bind()` holds its 'closure' by-value and avoids aliasing
- **`std::valarray`** is specifically required to have no aliasing
  - The expression `addressof(a[i]) != addressof(b[j])` evaluates to `true` for any two arrays `a` and `b` and for any `size_t i` and `size_t j` such that `i < a.size()` and `j < b.size()`. [valarray.access]
- **`std::execution::par/unseq`** inherently (implicitly) treats many forms of aliasing as *undefined behavior*.

Performance - `std::execution::unseq`



https://godbolt.org/z/9qsafxfvb

Strong Typedefs

- Types that encapsulate and behave like other types, but are different and don't automatically convert to/from them
  - No standard implementation, but a few libraries mimic the behavior
- Motivating example:

```
struct A { int i; };
struct B { int i; };

int mayAlias(auto& a, const auto& b) {
    a.i += b.i;
    if (b.i == 2) return 0;
    return 1;
}

template int mayAlias(A&, const A&);
template int mayAlias(A&, const B&);
```

```
int mayAlias<A, A>(A&, A const&):
        mov     eax, DWORD PTR [rsi]
        add     DWORD PTR [rdi], eax
        xor     eax, eax
        cmp     DWORD PTR [rsi], 2
        setne   al
        ret
int mayAlias<A, B>(A&, B const&):
        mov     eax, DWORD PTR [rsi]
        add     DWORD PTR [rdi], eax
        cmp     eax, 2
        setne   al
        movzx   eax, al
        ret
```

https://godbolt.org/z/4dKfah7c5

How to Avoid Aliasing Pitfalls

- Pass arguments by value
  - Value semantics are all the rage
  - Move semantics and copy-elision can make this relatively cheap
  - Consider supporting **`std::reference_wrapper`** (i.e. **`std::ref()`**)
- Use strong typedefs and unit libraries
  - clearer code for humans, compilers might optimize it as well
- Document your code's aliasing assumptions (contract)
  - Read other people's documentation
- For a large user base - write defensive code
  - Verify your contract - assert/throw/etc.
  - Widen your contract (e.g. **`vec.push_back(v.front())`**)
  - Let users control the contract

Defensive Code

- Basic function

```
template <typename Value, typename BinOp>
void unsafe_apply(std::span<Value> s, const Value& v, BinOp op) {
    for (auto& item : s) item = op(item, v);
}
```

- User controlled version

```
template <typename T> struct ByRef { using type = const T&; };
template <typename T> struct ByVal { using type = T; };

template <typename Value, typename BinOp, typename PassBy = ByRef<Value>>
void user_apply(std::span<Value> s, const Value& v_ref, BinOp op, PassBy = {}) {
    typename PassBy::type v{v_ref};
    for (auto& item : s) item = op(item, v);
}
```


https://godbolt.org/z/T15odT8Ks

Defensive Code

- Safe version

```
template <typename Value, typename BinOp>
void safe_apply(std::span<Value> s, const Value& v, BinOp op) {
    if (!s.empty() && std::less_equal{}(&s.front(), &v) &&
        std::less_equal{}(&v, &s.back()))
    {
        user_apply(s, v, op, ByVal<Value>{});
        return;
    }
    user_apply(s, v, op, ByRef<Value>{});
}
```

- Sometimes bounds/alias checking isn't as easy
- Questions and comments are welcome…

Proposals on Aliasing in the C++ Standard

- The `restrict` keyword signal to users and compiler that aliasing is UB
  - Many compilers have some support for it, but standardization isn't likely
- [[alias_set]] (2014) - annotate the relationship between variables
  - has some similarities with Rust lifetime annotations
- span<T, std::restrict_access> (2018) - property-based 'qualifier' for added semantics
- std::disjoint (2018) - meant for *contracts* to convey aliasing consistently
- Lifetime safety (2019) - Core guidelines and static analysis which "default to banning passing non-owning Pointers that alias".

Tricking the Compiler ?

- **`union`** is a mechanism for several object types to reside in the same address.
- At any time one type is *active* and accessing a different type is *typically* UB
  - **`variant`** is a type safe STL class that enforces correct access
- C++ does allow some accesses to non-active types - and aliasing
  - Types need to be *StandardLayoutType* and accessed members need to be in their common prefix. **`std::is_corresponding_member`** checks for this condition.
- This implies that “strict aliasing” has limits
  - I might be wrong, or this might be a bug in the standard/compilers

Aliasing of Standard Layout Types

- Accessing aliased union members is sometimes allowed:

  "In a standard-layout union with an active member of struct type `T1`, it is permitted to read a non-static data member `m` of another union member of struct type `T2` provided `m` is part of the common initial sequence of `T1` and `T2`; the behavior is as if the corresponding member of `T1` were nominated." [class.mem.general]

- Example from the standard:

```
struct T1 { int a, b; };
struct T2 { int c; double d; };
union U { T1 t1; T2 t2; };
int f() {
  U u = { { 1, 2 } };    // active member is t1
  return u.t2.c;         // OK, as if u.t1.a were nominated
}
```

Motivating Example

- Implement a C++ Conference:

```
struct CppPerson {
    std::string name; double expertise;
    //... more fields, methods
};
//Precondition - teacher and students
can't alias
void teach(span<CppPerson*> students,
           const CppPerson& teacher) {
    for (auto pStudent : students)
      pStudent->expertise +=
       std::max(teacher.expertise,100.0);
};
```

- Can we use unions to express non-aliasing to the compiler ?

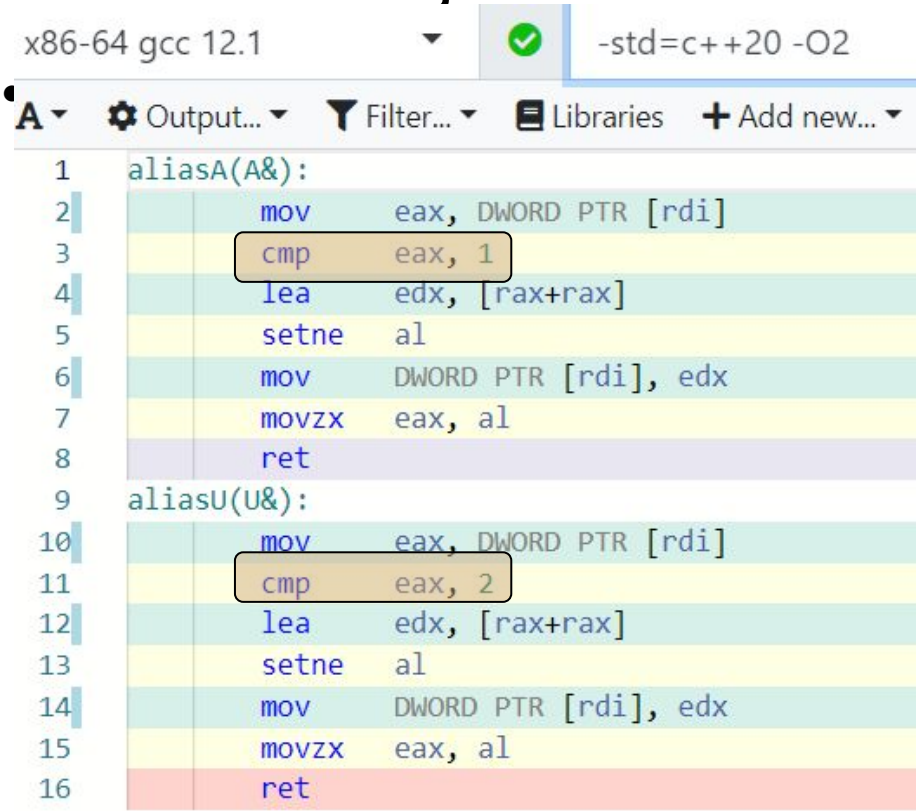
- Suggested approach:

```
struct Student : CppPerson {};
struct Teacher : CppPerson {};
static_assert(std::is_layout_compatible_v<
Student, Teacher>);
union Attendee {
    Student student;
    Teacher teacher;
};
void teach(span<Student*> students,
           const Teacher& teacher) {
    for (auto pStudent : students)
      pStudent->expertise +=
       std::max(teacher.expertise,100.0);
};
```

- Is this UB ??

https://godbolt.org/z/5coxPxxdf

Strict Aliasing and `union`



- Let's add unions:

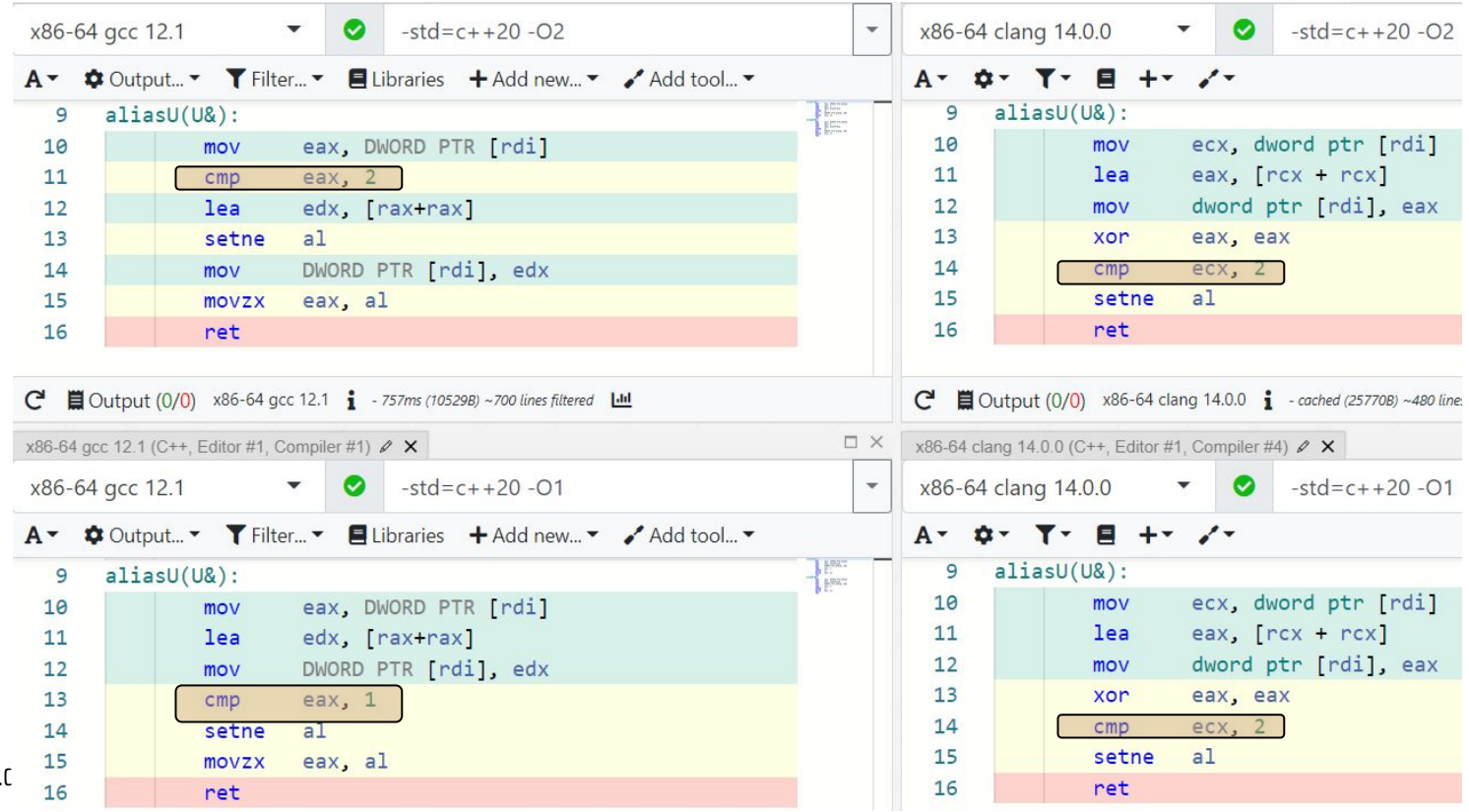
```
union U {
    A a;
    B b;
};

int aliasA(A& a) {
    return mayAlias(a, a);
};

int aliasU(U& u) {
    return mayAlias(u.a, u.b);
};
```

https://godbolt.org/z/d71Mjaxz7

Different Optimizers, Different Worlds



`variant` State Machines

- State machine is a typical case for using `variant`
  - At any point only one state is valid
- Changing the state to `T` is done via `operator=(T&&)` or `emplace<T>()`
- Different states commonly share information
  - `variant<WorkingPerson, RestingPerson>` - both states typically have a name, might inherit from `Person`.
  - Semantic strong typedefs might be identical in structure, e.g. `variant<Cat, HappyCat>`
- Sadly, state changing functions aren't allowed (UB) to read the previous state (especially relevant for `emplace<T>()`)
  - Previous state gets destructed before the new state constructor is invoked
  - STL chose performance over safety (unlike most containers).

`variant` State Changes

- Undefined/unexpected behavior:

```
variant<filesystem::path, string> v{"some_long_file_name"s};
v = std::move(v); //Bad on non-variants as well
v.emplace<filesystem::path>(std::move(get<string>(v)));
v.emplace<filesystem::path>(get<string>(v));
```

- The proper (no copy) way is to use temporaries, and rely on move semantics:

```
v.emplace<filesystem::path>(
                        string{std::move(get<string>(v))})
```

Summary

- Aliasing is tricky - people assume independence
- Value semantics makes life simpler
- Strong typedefs can assist
- Implement and document your code with care
- Smart people in the committee are working on improvements
- Know how to communicate with others and the compiler

Thank You !!

- Happy coding !
- Questions/comments are welcome

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References / Acknowledgements

- OptView2 - https://youtu.be/nVc439dnMTk
- [[alias_set]] - https://wg21.link/n3988
- span<T, std::restrict_access> - https://wg21.link/p0856
- std::disjoint - https://wg21.link/p1296
- Lifetime safety - https://wg21.link/p1179

Thank You !!