Trust Me

An exploration of `@trusted` code in D

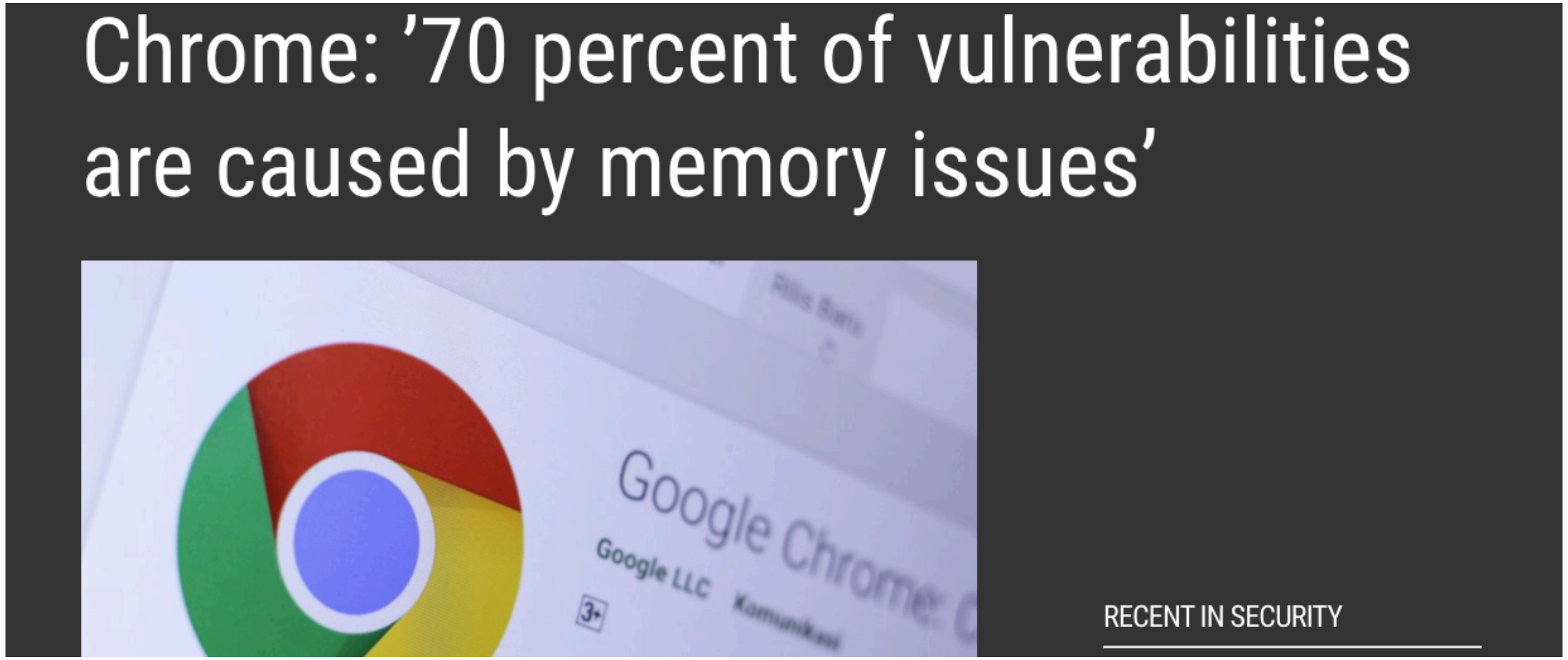
Steven Schveighoffer - DConf Online 2020

Code: https://github.com/schveiguy/dconf2020

Memory Safety!

Memory Safety

Real Problems



Chrome: ’70 percent of vulnerabilities are caused by memory issues’

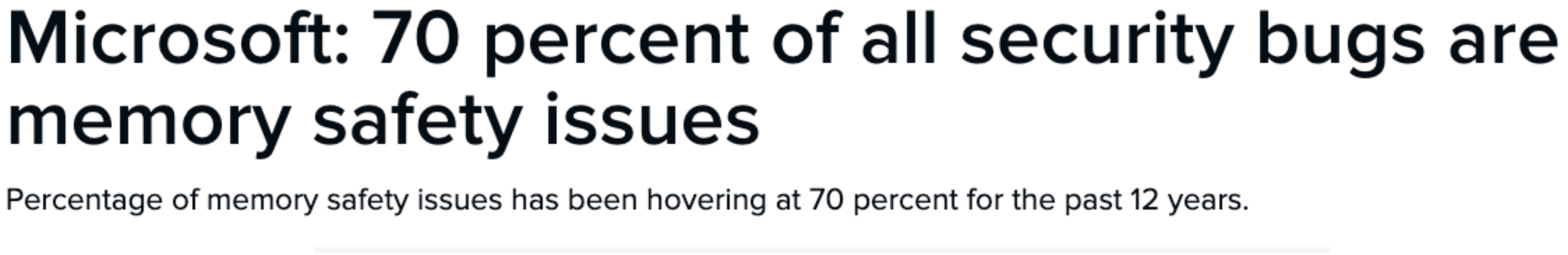
RECENT IN SECURITY

Source: https://www.techzine.eu/news/security/46924/chrome-70-percent-of-vulnerabilities-are-caused-by-memory-issues/

“Developers using C and C++ have full control over how they manage an app’s memory pointers, but these programming languages do not have the capabilities to alert developers when they’re making memory management errors.”

Memory Safety

Real Problems



Microsoft: 70 percent of all security bugs are memory safety issues

Percentage of memory safety issues has been hovering at 70 percent for the past 12 years.

Source: https://www.zdnet.com/article/microsoft-70-percent-of-all-security-bugs-are-memory-safety-issues/

“[Because] Windows has been written mostly in C and C++, two "memory-unsafe" programming languages that allow developers fine-grained control of the memory addresses where their code can be executed. One slip-up in the developers' memory management code can lead to a slew of memory safety errors that attackers can exploit with dangerous and intrusive consequences --such as remote code execution or elevation of privilege flaws.”

Memory Safety

What does “Memory Safe” mean?

Walter Bright (DConf 2017): “I believe memory safety will kill C” (Scott Meyers: “Wow.”)

- Memory safety violations consist of:
    - Accessing memory you should NOT have access to (e.g. buffer overflow)
    - Treating memory that is a scalar type as a pointer type
    - Dangling pointers

Memory Safety

D’s `@safe` implementation

- A `@safe` function:
  - Cannot do pointer math or indexing
  - Cannot access array elements out of bounds
  - Cannot use scalar data re-interpreted as a pointer (i.e. casting or unions)
  - Cannot change mutability type constructors (e.g. immutable -> mutable)
  - Cannot access `__gshared` data
  - Cannot take the address of a local variable
  - Cannot declare uninitialized pointers
  - Cannot call `@system` functions

Unsafety is sexy

Most interesting things are not `@safe`

- Most interesting part of computer programming: i/o!
- A hello world program cannot be fully `@safe` — it *must* use `@system` calls to print to the screen.
- We all want to be dangerous rebels! It's in our code!

Trust Me

Trust Me

`@trusted` functions bridge the gap

- Posix write function is not `@safe`:

```
extern(C) @system ssize_t write(int fd, const scope void* buf, size_t numBytes);
```

- But we can wrap it in a `@safe` D function:

```
@trusted ssize_t safeWrite(int fd, const void[] buf) {
    return write(fd, buf.ptr, buf.length);
}
```

- We can use our knowledge of the POSIX API to prove that this call is safe to use from a `@safe` function.

The Benefit of `@trusted`

Limiting the review

- `@trusted` allows calling `@system` functions.
- But the true benefit is being able to limit what code needs to be checked by hand.
- If `@trusted` functions and APIs are written correctly, then there should be no reason to check `@safe` code.
- This is accomplished by manually verifying the code in `@trusted` functions does not violate memory safety rules

Tagged Union

Writing a `@safe` union of any two types

- Tagged unions are a pairing of a union with a tag to identify the valid member.
- If written properly, tagged unions can be considered memory-safe
- But we want the compiler to help us!

Tagged Union

Issue 20655 (https://issues.dlang.org/show_bug.cgi?id=20655)

- Templates *should* infer `@safe` or `@system`
- [REG: 2.072] attribute inference accepts unsafe union access as `@safe`
- Explicit `@safe`/`@system` tags in implementation (shouldn’t be necessary)

Implementation part 1

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion1.d

```d
module taggedunion;
import std.exception;

struct Tagged(T1, T2) {
    private union Values {
        T1 t1;
        T2 t2;
    }
    private {
        Values values;
        bool tag;
        enum useT1 = false;
        enum useT2 = true;
    }

    this(T1 t1) {
        values.t1 = t1;
        tag = useT1;
    }

    this(T2 t2) {
        values.t2 = t2;
        tag = useT2;
    }
    ...
}
```

Implementation part 1

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion1.d

```
module taggedunion;
import std.exception;

struct Tagged(T1, T2) {
    ...

    void opAssign(T1 t1) {
        if(tag == useT2)
            destroy(values.t2);
        values.t1 = t1;
        tag = useT1;
    }

    void opAssign(T2 t2) {
        if(tag == useT1)
            destroy(values.t1);
        values.t2 = t2;
        tag = useT2;
    }

    ...
}
```

Implementation part 1

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion1.d

```
module taggedunion;

struct Tagged(T1, T2) {
    ...

    ~this() {
        if(tag == useT2)
            destroy(values.t2);
        else
            destroy(values.t1);
    }

    ref get(T)() if (is(T == T1) || is(T == T2)) {
        import std.exception : enforce;
        enforce((tag == useT2) == is(T == T2),
                "attempt to get wrong type from tagged union of "
                ~ T1.stringof ~ ", " ~ T2.stringof);
        static if(is(T == T2))
            return values.t2;
        else
            return values.t1;
    }
}
```

Implementation part 1

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion1.d

```
module taggedunion;

struct Tagged(T1, T2) {
    ...
}

// not @safe yet
unittest {
    import std.exception : assertThrown;
    alias TU = Tagged!(int, int *);
    auto tu = TU(1);
    assert(tu.get!int == 1);
    assertThrown(tu.get!(int *));
    int *x = new int(1);
    tu = x;
    assert(tu.get!(int *) == x);
    assertThrown(tu.get!int);
}
```

Let's run it!

```
% rdmd -main -unittest taggedunion1.d
1 modules passed unittests
```

Is it @safe?

Safety of `Tagged`

is it `@safe`?

- Using Tagged cannot result in a memory violation.
  - No access to memory we don’t own
  - No treating scalars as pointers
  - No dangling pointers
  - Very similar to memory allocation.

Compiler: “not safe!”

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion2.d

```
@safe unittest {
    ...
}
```

```
% rdmd -main -unittest taggedunion2.d
taggedunion2.d(59): Error: @safe function taggedunion.__unittest_L56_C7 cannot call @system destructor taggedunion.Tagged!
(int, int*).Tagged.~this
taggedunion2.d(38):        taggedunion.Tagged!(int, int*).Tagged.~this is declared here
taggedunion2.d(59): Error: @safe function taggedunion.__unittest_L56_C7 cannot call @system destructor taggedunion.Tagged!
(int, int*).Tagged.~this
taggedunion2.d(38):        taggedunion.Tagged!(int, int*).Tagged.~this is declared here
taggedunion2.d(60): Error: @safe function taggedunion.__unittest_L56_C7 cannot call @system function taggedunion.Tagged!
(int, int*).Tagged.get!int.get
taggedunion2.d(45):        taggedunion.Tagged!(int, int*).Tagged.get!int.get is declared here
taggedunion2.d(61): Error: @safe function taggedunion.__unittest_L56_C7 cannot call @system function taggedunion.Tagged!
(int, int*).Tagged.get!(int*).get
taggedunion2.d(45):        taggedunion.Tagged!(int, int*).Tagged.get!(int*).get is declared here
taggedunion2.d(63): Error: @safe function taggedunion.__unittest_L56_C7 cannot call @system function taggedunion.Tagged!
(int, int*).Tagged.opAssign
taggedunion2.d(31):        taggedunion.Tagged!(int, int*).Tagged.opAssign is declared here
taggedunion2.d(64): Error: @safe function taggedunion.__unittest_L56_C7 cannot call @system function taggedunion.Tagged!
(int, int*).Tagged.get!(int*).get
taggedunion2.d(45):        taggedunion.Tagged!(int, int*).Tagged.get!(int*).get is declared here
taggedunion2.d(65): Error: @safe function taggedunion.__unittest_L56_C7 cannot call @system function taggedunion.Tagged!
(int, int*).Tagged.get!int.get
taggedunion2.d(45):        taggedunion.Tagged!(int, int*).Tagged.get!int.get is declared here
```

Compiler: “not safe!”

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion2.d

- Because every function’s safety is inferred, instead of seeing the actual part that makes the code unsafe, you see just the “cannot call `@system` function” error messages

- Use explicit `@safe` tags to further diagnose those errors.

Compiler: “not safe!”

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion3.d

```
struct Tagged(T1, T2) {

    @safe:
    ...
}
```

```
taggedunion3.d(20): Error: field Values.t2 cannot access pointers in @safe code that overlap other fields
taggedunion3.d(26): Error: field Values.t2 cannot access pointers in @safe code that overlap other fields
taggedunion3.d(34): Error: field Values.t2 cannot access pointers in @safe code that overlap other fields
taggedunion3.d(40): Error: field Values.t2 cannot access pointers in @safe code that overlap other fields
taggedunion3.d(58): Error: template instance taggedunion.Tagged!(int, int*) error instantiating
```

Compiler: “not safe!”

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion3.d

- As expected, all the problems stem from accessing the union pointer member that overlaps the non-pointer member.

- However, our tag tells us which one is valid. So we can mark `@trusted` the portions of the code that determine which value is valid, and provide a reference to that value.

Extract trusted portions

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion4.d

```
struct Tagged(T1, T2) {
    ...
    @trusted private ref accessValue(bool expectedTag)()
    {
        import std.exception;
        enforce(tag == expectedTag, "attempt to get wrong type from tagged union of "
                ~ T1.stringof ~ ", " ~ T2.stringof);
        static if(expectedTag == useT2)
            return values.t2;
        else
            return values.t1;
    }

    @trusted private void setTag(bool newTag)
    {
        if(tag != newTag)
        {
            if(tag == useT2)
                destroy(values.t2);
            else
                destroy(values.t1);
        }
        tag = newTag;
    }
    ...
}
```

Extract trusted portions

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion4.d

```
struct Tagged(T1, T2) {
    ...
    this(T1 t1) {
        setTag(useT1);
        accessValue!useT1 = t1;
    }

    this(T2 t2) {
        setTag(useT2);
        accessValue!useT2 = t2;
    }

    void opAssign(T1 t1) {
        setTag(useT1);
        accessValue!useT1 = t1;
    }

    void opAssign(T2 t2) {
        setTag(useT2);
        accessValue!useT2 = t2;
    }

    ~this() {
        setTag(!tag);
    }
    ...
}
```

Extract trusted portions

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion4.d

```
struct Tagged(T1, T2) {
    ...

    ref get(T)() if (is(T == T1) || is(T == T2)) {
        static if(is(T == T2))
            return accessValue!useT2;
        else
            return accessValue!useT1;
    }
}
```

Is it @safe?

It’s safe! But…

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion5.d

- Running destructors might not be safe, but we have it trusted.
- Easy to fix!

```
/* @safe inferred */
private void setTag(bool newTag)
{
    if(tag != newTag)
    {
        if(tag == useT2)
            destroy(accessValue!useT2);
        else
            destroy(accessValue!useT1);
    }
    tag = newTag;
}
```

Are we done?

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion5.d

- How do we know the code is `@safe`?
- Is reviewing `@trusted` function enough?

```
/* @safe */
private void setTag(bool newTag)
{
    if(tag != newTag)
    {
        if(tag == useT2)
            destroy(accessValue!useT2);
        else
            destroy(accessValue!useT1);
    }
    tag = newTag;
}
```

- Must review entire module, including `@safe` functions!

Mitigation

Attempt 1: Tag in the union

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion6.d

```d
module taggedunion;

struct Tagged(T1, T2) {
    private struct T1Val
    {
        bool tag;
        T1 val;
    }
    private struct T2Val
    {
        bool tag;
        T2 val;
    }
    private union Values {
        T1Val t1;
        T2Val t2;
        bool tag;
        int *poison;
    }
    ...
}
```

Attempt 1: Tag in the union

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion6.d

```
struct Tagged(T1, T2) {
    ...
    @trusted private ref accessValue(bool expectedTag)() {
        import std.exception;
        enforce(values.tag == expectedTag, "attempt to get wrong type from tagged union of "
                ~ T1.stringof ~ ", " ~ T2.stringof);
        static if(expectedTag == useT2)
            return values.t2.val;
        else
            return values.t1.val;
    }

    /* @safe */
    private void setTag(bool newTag) {
        if(values.tag != newTag) {
            if(values.tag == useT2)
                destroy(accessValue!useT2);
            else
                destroy(accessValue!useT1);
        }
        values.tag = newTag; // not @safe!
    }
    ...
}
```

Attempt 1: Tag in the union

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion6.d

```
% rdmd -main -unittest taggedunion6.d
1 modules passed unittests
```

- Oops! should not have compiled

Attempt 1: Tag in the union FAILED

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion6.d

```
% rdmd -main -unittest taggedunion6.d
1 modules passed unittests
```

- Oops! should not have compiled
- Compiler allows access to non-pointer union data, *even if it overlaps a pointer.*

Attempt 2: Use a specialized tag

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion7

```
module systemtag;

struct SystemTag
{
    private bool _tag;
    @system opAssign(bool newValue) {
        _tag = newValue;
    }
    @system opAssign(SystemTag st) {
        this._tag = st._tag;
    }
    @safe tag() {
        return _tag;
    }

    alias tag this;
}
```

Attempt 2: Use a specialized tag

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion7

```
module taggedunion;
import systemtag;

struct Tagged(T1, T2) {
    private union Values {
        T1 t1;
        T2 t2;
    }
    private {
        Values values;
        SystemTag tag;
        enum useT1 = false;
        enum useT2 = true;
    }

    ...
}
```

Attempt 2: Use a specialized tag

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion7

```
struct Tagged(T1, T2) {
    ...
    /* @safe */
    private void setTag(bool newTag)
    {
        if(tag != newTag)
        {
            if(tag == useT2)
                destroy(accessValue!useT2);
            else
                destroy(accessValue!useT1);
        }
        tag = newTag;
    }
    ...
}
```

```
% rdmd -main -unittest taggedunion7/taggedunion.d
taggedunion7/taggedunion.d(48): Error: @safe function taggedunion.Tagged!(int, int*).Tagged.setTag cannot call
@system function systemtag.SystemTag.opAssign
```

Use a specialized tag PASS

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion7

```
struct Tagged(T1, T2) {
    ...
    /* @safe */
    private void setTag(bool newTag)
    {
        if(tag != newTag)
        {
            if(tag == useT2)
                destroy(accessValue!useT2);
            else
                destroy(accessValue!useT1);
        }
        () @trusted {tag = newTag;} ();
    }
    ...
}
```

```
% rdmd -main -unittest taggedunion7/taggedunion.d
1 modules passed unittests
```

Use a specialized tag PASS-ish

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion7

```
struct Tagged(T1, T2) {
    ...
    /* @safe */
    private void setTag(bool newTag)
    {
        if(tag != newTag)
        {
            if(tag == useT2)
                destroy(accessValue!useT2);
            else
                destroy(accessValue!useT1);
        }
        tag.tupleof[0] = newTag;
    }
    ...
}
```

```
% rdmd -main -unittest taggedunion7/taggedunion.d
1 modules passed unittests
```

Attempt 3: Travel into the future (DIP1035)

DIP: https://github.com/dlang/DIPs/blob/master/DIPs/DIP1035.md

- Be able to tag data as only accessible to `@system` or `@trusted` functions
- Use the compiler to enforce our semantics
- Eliminates back doors

```
@system int x;

void foo() @safe {
    x = 5; // Error
}
```

Attempt 3: Use DIP1035

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion8.d

```
module taggedunion;

struct Tagged(T1, T2) {
    private union Values {
        T1 t1;
        T2 t2;
    }
    private {
        @system Values values;
        @system bool _tag;
        @trusted bool tag() { return _tag; }
        enum useT1 = false;
        enum useT2 = true;
    }
    ...
}
```

- Probably works…

Make `@safe` no-review

- Attempt 1: tag inside union.
  - FAIL — Compiler doesn’t stop us from accessing
- Attempt 2: Specialized “system only” tag
  - PASS-ish — Add `.tupleof` as another problem to look for.
- Attempt 3: DIP1035
  - PASS — Compiler now helps us by restricting access to the tag without extra effort or wrappers.

But are we done? Really done?…

Lifetime Problems

```
import taggedunion;

@safe:
void foo(ref int x, ref int* ptr) {
    import std.stdio;
    x += 4; // malicious pointer increment
    writeln(*ptr);
}

int publicVal = 1;
private int secretVal = 42;

void main() {
    auto item = Tagged!(int, int *)(5);
    void helper(ref int x) {
        item = &publicVal;
        foo(x, item.get!(int *));
    }

    helper(item.get!int);
}
```

```
% dmd lifetime.d taggedunion.d
% ./lifetime
42
```

Lifetime Problems

- Need to enforce when a reference becomes invalid
- Or limit utility of the union (disallow changing types mid-program)
- Or disallow reassignment to a different type while a reference is held

Ownership solution?

- Walter’s `@live` solution: https://dlang.org/blog/2019/07/15/ownership-and-borrowing-in-d/
- Solution isn’t viable for a tagged union, because it’s not enough to require const, we also must require the type doesn’t change.
- Possible to enhance to allow more user semantics? e.g. `opBorrow`

Solve Lifetime with reference counting

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion9.d

```
module taggedunion;

struct BorrowedRef(T) {
    this(T* val, int *cnt) {
        this.val = val;
        this.count = cnt;
        ++(*this.count);
    }

    private int *count;
    private T *val;

    @disable this(this); // disable copying
    ~this() { --(*count); }

    @property ref T _get() { return *val; }
    alias _get this;

    void opAssign(V)(auto ref V v) { *val = v; } // bug 16426
}
```

Solve with reference counting

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion9.d

```
struct Tagged(T1, T2) {
    private union Values {
        T1 t1;
        T2 t2;
    }
    private {
        Values values;
        bool tag;
        int borrowers;
        enum useT1 = false;
        enum useT2 = true;
    }

    this(this) { borrowers = 0;}
    ...
}
```

Solve with reference counting

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion9.d

```
struct Tagged(T1, T2) {
    ...
    @trusted private @property accessValue(bool expectedTag)() {
        import std.exception;
        enforce(tag == expectedTag, "attempt to get wrong type from tagged union of "
                ~ T1.stringof ~ ", " ~ T2.stringof);
        static if(expectedTag == useT2)
            return BorrowedRef!T2(&values.t2, &borrowers);
        else
            return BorrowedRef!T1(&values.t1, &borrowers);
    }

    private void setTag(bool newTag)
    {
        if(tag != newTag)
        {
            import std.exception;
            enforce(borrowers == 0, "Cannot change type when someone has a reference");
            if(tag == useT2)
                destroy(accessValue!useT2._get);
            else
                destroy(accessValue!useT1._get);
        }
        () @trusted { tag = newTag; } ();
    }
    ...
}
```

Solve with reference counting

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion9.d

```
struct Tagged(T1, T2) {
    ...
    this(T1 t1) {
        setTag(useT1);
        accessValue!useT1() = t1;
    }

    this(T2 t2) {
        setTag(useT2);
        accessValue!useT2() = t2;
    }

    void opAssign(T1 t1) {
        setTag(useT1);
        accessValue!useT1() = t1;
    }

    void opAssign(T2 t2) {
        setTag(useT2);
        accessValue!useT2() = t2;
    }
    ...
}
```

Oh the bugs!

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion9.d

```
import taggedunion;

@safe:
void foo(ref int x, ref int* ptr) {
    import std.stdio;
    x += 4; // next integer
    writeln(*ptr);
}

int publicVal = 1;
private int secretVal = 42;

void main() {
    auto item = Tagged!(int, int *)(5);
    void helper(ref int x) {
        item = &publicVal;
        foo(x, item.get!(int *)._get); // bug 21369
    }

    helper(item.get!int._get); // bug 21369
}
```

Result

code: https://github.com/schveiguy/dconf2020/blob/master/taggedunion9.d

```
% dmd -g lifetime2.d taggedunion9.d
% ./lifetime2
object.Exception@taggedunion9.d(64): Cannot change type when someone has a reference
----------------
lifetime2.d:18 pure @safe void std.exception.bailOut!(Exception).bailOut(immutable(char)[], ulong, scope
const(char)[]) [0x1007ca08a]
lifetime2.d:18 pure @safe bool std.exception.enforce!().enforce!(bool).enforce(bool, lazy const(char)[],
immutable(char)[], ulong) [0x1007ca006]
lifetime2.d:18 pure @safe void taggedunion.Tagged!(int, int*).Tagged.setTag(bool) [0x1007ca2a5]
lifetime2.d:18 pure @safe void taggedunion.Tagged!(int, int*).Tagged.opAssign(int*) [0x1007ca49f]
lifetime2.d:16 @safe void lifetime2.main().helper(ref int) [0x1007c974f]
lifetime2.d:20 _Dmain [0x1007c963c]

Line 16:        item = &publicVal;
```

Conclusion

- Writing `@trusted` code is not as easy as it seems
- Still a long way to go to allow “no need for review” `@safe` code
- DIP1035 would help!
- Lifetime issues not very easy to solve, not helped by compiler bugs
- BUT there is a path to where the compiler helps enforce the semantic guarantees we want!