Preface

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Audience: All
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- These are the slides I (Bjarne Stroustrup) presented to the Safety Study Group (SG23) and the Evolution Working Group (EWG) at the February 2023 C++ Standard Committee (ISO SC22/WG21) meeting in Issaquah, Washington State, USA.
- The purpose of my talks was to build a consensus for a direction to allow dramatically improved safety for C++ programs without damaging performance, flexibility, or compatibility where needed. The resulting vote was 47 for and 2 against.
- Please note that this presents a direction/strategy, rather than a completed product. However, it is based on significant previous work; see the references. More experiments and more documentation are in the works.
- A safety profile is a set of guarantees enforced by an implementation. A profile presents the programmer with a set of rules and library components that together delivers the desired guarantees.

Safety Profiles: Type-and-resource Safe programming in ISO Standard C++

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Abstract – Safety Profiles

- Type-and-resource Safe programming in ISO Standard C++
  - You can write C++ with no violations of the type system, no resource leaks, no memory corruption, no garbage collector, no limitation of expressiveness or performance degradation compared to well-written modern C++.
  - We must develop ways of guaranteeing that where guarantees make sense.
  - This can be achieved – and guaranteed – by the applying the strategy from the C++ Core Guidelines: coding rules, simple supporting libraries (mostly the ISC C++ standard library), and enforcement through static analysis.
  - Doing this well requires some standardization and some standardized support: Safety Profiles.
  - Often, this can be done with code that's dramatically simpler than older C++ (and C) code.
  - Examples: RAII, pointer safety, span, range checking, nullptr, initialization, invalidation, casting and variants.

A cause for concern (not panic)

- The overarching software community across the private sector, academia, and the U.S. Government have begun initiatives to drive the culture of software development towards utilizing memory safe languages.
- ...
- NSA advises organizations to consider making a strategic shift from programming languages that provide little or no inherent memory protection, such as C/C++, to a memory safe language when possible. Some examples of memory safe languages are C#, Go, Java, Ruby™, and Swift®.
  - NSA: https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2023/p2739r0.pdf

To contrast (not a cause for complacency)

- **February Headline: C++ still unstoppable**
- Last month, C++ won the TIOBE programming language of the year award for 2022. C++ is continuing its success in 2023 so far. Its current year-over-year increase is 5.93%. This is far ahead of all other programming languages, of which the most popular ones only gain about 1%.

Feb 2023	Feb 2022	Change	Programming Language	Ratings	Change
1	1		Python	15.49%	+0.16%
2	2		C	15.39%	+1.31%
3	4	^	C++	13.94%	+5.93%
4	3	v	Java	13.21%	+1.07%
5	5		C#	6.38%	+1.01%
6	6		Visual Basic	4.14%	-1.09%

- But what does Tiobe measure?
- But this implies that what we do matters to billions of people – for good and bad

We must address the “safety” issue

- There is a real, serious problem for many uses and users
  - Incl. diversion of resources to other languages
  - Incl. discouraging people from learning C++
- Massive improvements are possible in many areas
- C++ has a massive image problem (“C/C++”)
  - And it is getting worse
- Governments and large corporations can coerce

- Ignoring the safety issues would hurt large sections of the C++ community and undermine much of the other work we are doing to improve C++.
  - So would focusing exclusively on safety

References

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We didn't start yesterday

Complete type-and-resource safety

- Is an ideal (aim) of C++
  - From very early on (1979)
  - Also for C: “C is a strongly-typed, weakly checked language” a – DMR
  - “Being careful” doesn’t scale
- Requires judicious programming techniques
  - Supported by libraries
  - Enforced by language rules and static analysis
  - The basic model for achieving that can be found in A brief introduction to C++'s model for type- and resource-safety (2015) and Type-and-resource safety in modern C++ (2021).
- Does not imply limitations of what can be expressed or run-time overhead
  - Compared to traditional C and C++ programming techniques

How?

- Every object is accessed according to the type with which it was defined (type safety)
- Every object is properly constructed and destroyed (resource safety)
- Every pointer either points to a valid object or is the **nullptr** (memory safety)
- Every reference through a pointer is not through the **nullptr** (often a run-time check)
- Every access through a subscripted pointer is in-range (often a run-time check)

- That is
  - just what C++ requires (also C)
  - what most programmers have tried to ensure since the dawn of time
- The enforcement rules are more deduced than invented

Enforcement rules are mutually dependent.
Don't judge individual rules in isolation

Many notions of safety

- **Logic errors**: perfectly legal constructs that don't reflect the programmer's intent, such as using < where a <= or a > was intended.
- **Resource leaks**: failing to delete resources (e.g., memory, file handles, and locks) potentially leading to the program grinding to a halt because of lack of available resources.
- **Concurrency errors**: failing to correctly take current activities into account leading to (typically) obscure problems (such as data races and deadlocks).
- **Memory corruption**: for example, through the result of a range error or by accessing and memory through a pointer to an object that no longer exists thereby changing a different object.
- **Type errors**: for example, using the result of an inappropriate cast or accessing a union through a member different from the one through which it was written.
- **Overflows and unanticipated conversions**: For example, an unanticipated wraparound of an unsigned integer loop variable or a narrowing conversion.
- **Timing errors**: for example, delivering a result in 1.2ms to a device supposedly responding to an external event in 1ms.
- **Termination errors**: a library that terminates in case of "unanticipated conditions" being part of a program that is not allowed to unconditionally terminate.

Constraints on a solution

- C++ must serve wide variety of users/areas
  - One size doesn't fit all
  - C++ is (also) a systems programming language – we can't "outsource" dangerous operations to some other language
- We can't just break billions of lines of existing code
  - Even if we wanted to - major users would insist on compatibility (probably compatibility by default)
- We can't just "upgrade" millions of developers
  - And teaching material, courses, videos, books, articles
- If you want a shiny new language, please go ahead
  - But it won't be C++ or the job of WG21

- But we ***must*** improve

Strategy: Safety Profiles

- We can succeed only if we have a strategy/framework
  - A framework for “details” to fit into
  - Ad hoc, independent “patches” won’t add up to a coherent, complete solution (“Safety”)
    - Even if those “patches” can be immensely useful
- We – WG21 – must be seen to work towards a coherent solution
  - A complete solution will take significant time
  - Until then then, we must be able to point to steady progress
  - Until then then, we must deliver partial solutions

Strategy: Safety Profiles

- Our approach is “a cocktail of techniques” not a single neat miracle cure
- Static analysis
  - to verify that no unsafe code is executed.
- Coding rules
  - to simplify the code to make industrial-scale static analysis feasible.
- Libraries
  - to make such simplified code reasonably easy to write
  - to guarantee run-time checks where needed.

Strategy: Safety Profiles

- This is a strategy
  - Not a finished product
  - Based on significant previous work
    - The C++ Core guidelines (on GitHub)
    - Static checkers
    - Library design
    - and more

Is this strategy "too novel"?

- "People are afraid of new things.
  You should have taken an existing product and put a clock in it."
  – Homer Simpson
- Parts have been tried each individual approach many times before
  - Succeeded for specific tasks
    - E.g., smart pointers, libraries, static analyzers
  - Failed as general solutions
    - Static analysis – doesn't scale to complete safety
    - Guidelines/rules – aren't followed without enforcement
    - Foundation libraries – doesn't give full access to the machine and system
    - Language subsetting – the most dangerous language features are essential (e.g., subscripting of pointers)
- A combined approach is necessary
  - Similar to Ada's safety profiles: https://docs.adacore.com/gnathie_ug-docs/html/gnathie_ug/gnathie_ug/the_predefined_profiles.html#the-predefined-profiles

The C++ Core Guidelines

Caveat: The Core Guidelines does a good, but not complete, job

This talk discusses potential improvements to gain guarantees

- For any reasonable definition of safe
  - We cannot accept arbitrarily complex code while maintaining conventional good performance.
  - Legal != provably safe
- Use a carefully crafted set of programming techniques
  - supported by library facilities
  - enforced by static analysis.
- Available on GitHub
  - https://github.com/isocpp/CppCoreGuidelines/blob/master/CppCoreGuidelines.md
- Many rules checked by the Visual Studio static analyzer and other checkers (Clang, Clion)
- Safety Profiles must go beyond the CG
  - We need some standardization of what's to be checked
  - We need some annotations in the code to specify what is to be checked

C++ Core Guidelines

- You can write type-and-resource-safe C++
  - No leaks
  - No memory corruption
  - No garbage collector
  - No limitation of expressibility
  - No performance degradation
  - ISO C++
  - Tool enforced (eventually)
    - some checking in Visual Studio, Clang tidy, Clion, …
    - A job for the tools SG? For the new Safety SG? Both!
  - For guaranteed type safety, we need range checking and nullptr checking

How to complete the enforcement
Is the key topic here

Safety Profiles go beyond the CG,
e.g., safety requirements in code (slide 24)

Not covered in this talk

- Narrowing conversions and overflow
  - E.g., signed and unsigned mess-ups
- Data races and deadlocks
- Logic errors
  - Including error-prone constructs; e.g., misspelling, missing breaks, and overly complex code
- Performance bugs
  - E.g., copying of large objects, allocations in time-critical code
- Some of this is covered by the Core Guidelines and in existing checkers
  - Rarely systematically
  - Guarantees require systematic checking

Fundamental ideas

- Core Guidelines
  - P.1: Express ideas directly in code
  - P.9: Don't waste time or space
  - P.11: Encapsulate messy constructs, rather than spreading through the code

Don't destroy maintainability
by lowering the abstraction level
to a subset of C

- Safety Profiles: Beyond (current) Core Guidelines
  - If (local) static analysis cannot prove a construct safe, it's banned
  - Annotations and run-time checks to enforce guarantees
- Rules should help, not hinder
  - No non-essential restrictions on coding style

Suggestions and help
most welcome

High-level rules – "Philosophy"

- Provide a conceptual framework
  - Primarily for humans
- Many can't be checked completely or consistently

  - *P.1: Express ideas directly in code*
  - *P.2: Write in ISO Standard C++*
  - *P.3: Express intent*
  - *P.4: Ideally, a program should be statically type safe*
  - *P.5: Prefer compile-time checking to run-time checking*
  - *P.6: What cannot be checked at compile time should be checkable at run time*
  - *P.7: Catch run-time errors early*
  - *P.8: Don't leak any resource*
  - *P.9: Don't waste time or space*
  - *P.10: Prefer immutable data to mutable data*
  - *P.11: Encapsulate messy constructs, rather than spreading through the code*
  - *P.12: Use supporting tools as appropriate*
  - *P.13: Use support libraries as appropriate*

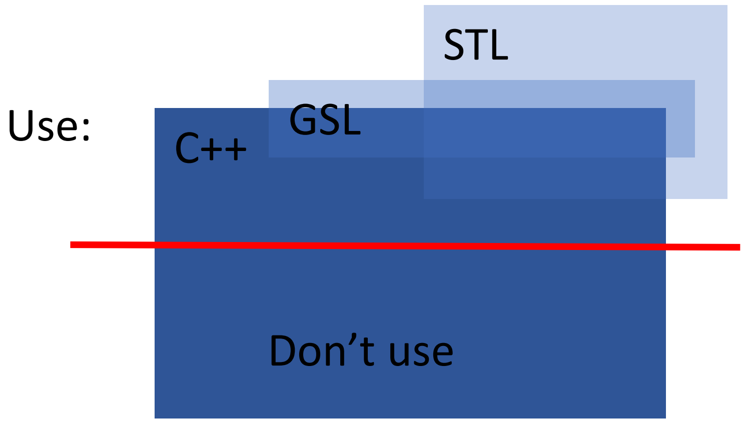
Lower-level rules

- Provide enforcement
  - Many rely on static analysis
  - Some beyond our current tools
  - Often easy to check “mechanically”
- Primarily for tools (static analysis)
  - To allow specific feedback to programmer
- Help to unify style
- Not minimal or orthogonal

- *F.16: Use **T*** or **owner<T*>** to designate a single object*
- *C.49: Prefer initialization to assignment in constructors*
- *ES.20: Always initialize an object*

Subset of superset

- Simple sub-setting doesn't work
  - We need the low-level/tricky/close-to-the-hardware/error-prone/expert-only features
    - For implementing higher-level facilities efficiently
    - Many low-level features can be used well
  - We need the standard library
- Extend language with a few abstractions
  - ***Use*** the STL
  - ***Add*** a small library (the GSL)
    - Messy/dangerous/low-level features can be used to implement the GSL
  - For complete memory safety, enforce range-checking
  - ***Then*** subset
- What we want is "***C++ on steroids***"
  - Simple, safe, flexible, and fast



No change of meaning:
The resulting code is ISO C++

Some rules rely on libraries

- The ISO C++ standard library
  - E.g., **vector<T>** and **unique_ptr<T>**
- The Guideline Support Library
  - E.g., **span<T>** and **not_null<T>**

- Some rules using the GSL and STL
  - *I.11: Never transfer ownership by a raw pointer (**T***)*
    - Use an ownership pointer (e.g., **unique_ptr<T>**) or **owner<T*>**
  - *I.12: Declare a pointer that may not be the **nullptr** as **not_null***
    - E.g., **not_null<int*>**
  - *I.13 Do not pass an array as a single pointer*
    - Use a handle type, e.g., **vector<T>** or **span<T>**

Ideally,
absorb the GSL functionality
into the standard

Static analysis

For safety guidelines only warns

- **If local static analysis cannot prove a construct safe, it's banned**

- To scale, static analysis must be local
  - Constructors and destructors must be considered together
- We need rules to simplify to allow local analysis
  - It is easy to write messy code that cannot be statically determined to be safe
  - Classify: safe, not safe, not sure
  - Reject if not sure ("call a human")

A problem, given multiple analyzers:
How clever should an analyzer required to be?

See also Sunny Chatterjee's CppCon'21 talk on static analysis of C++

Profile controls

- The (current) Core Guidelines are controlled using compiler/build options
- Some users and some organizations insist on annotations in the code
  - E.g., "This code type-and-resource safe."
    - Must be enforced
  - E.g., "this is unverified, trusted code"
    - Something like that is in every "safe" language
- Maybe also compiler/build options
- How do we handle programs composed out of fragments with different requirements?
  - Very difficult problem
  - Unavoidable (in any language)
  - See P2687R0 (Stroustrup and Dos Reis 2022)

Examples

- Type safety
  - Initialization, construction, destruction
- Pointer safety
  - Every pointer points to a valid object or is the nullptr
- Ownership
  - No littering
- Invalidation
  - Aliases
- Run-time checks
  - Span, not_null, not_end
- Memory pools
  - A tricky set of problems
- Concurrency rules

For a much more detailed paper:
P2687R0 and in particular P2687R1 (in the works)

Every object is accessed according to the type with which it was defined

- **ES.20: Always initialize an object**
  - To a meaningful value
  - Just “zero out all objects” isn’t enough
- Prevent
  - Unsafe casting
    - Restrict casting to converting untyped data (bytes) into typed objects
    - **dynamic_cast** is safe and accepted
  - Unsafe uses of **unions**
    - Use alternatives, e.g., **variant**
  - Unsafe use of pointers
    - E.g., subscripting
    - Use alternatives, e.g., **span**

Always initialize an object

Yes, we could be more clever,
but simplicity is valuable

```
int f(int x)
{
        int y;              // Not OK: uninitialized
        if (x) y = g(x);
        return y;
}
```

```
Message read(int n)          // we need buffers for low-level input: std::byte
{
        [[uninitialized]] std::byte buf[n];          // uninitialized buffer
        return fill_message(buf,n);          // fill and convert to correct type
                                             // (had better check the value of n)
}
```

One possibility

Yes, we could close all loopholes,
but for real-world problems we can't be purists

Every object is properly constructed and destroyed

- [P.8: Don't leak any resources]
- Resources – Entities that must be acquired and later released
  - represented as objects with destructors doing the release
  - often with constructors that do the acquisition as part of establishing an invariant (RAII)
  - This scope-based resource management ensures predictability and minimizes resource retention
- The language guarantees that destructors are invoked
  - Except for objects pointed to only by static variables
- Using copy elision or move operations, objects can be safely moved between scopes.
  - Moved objects will be destroyed in their new scope or moved further
  - The CG insist that a moved-from object be assignable
- Prevent the creation of uninitialized objects
  - Buffers of uninitialized **unsigned char**s are acceptable

Every pointer either points to an object or is the nullptr

- Aka “no dangling pointers”

- When I say “pointer” I mean anything that refers to an object
  - References
  - Containers of pointers
  - Smart pointers
  - Lambda captures of pointers
  - …

Turning simple logical rules
into detailed enforceable rules
is a lot of hard work

Dangling pointers – the worst problem

- One nasty variant of the problem

```
void f(X* p)
{
	// …
	delete p;		// looks innocent enough (not OK)
}

void g()
{
	X* q = new X;	// looks innocent enough (not OK)
	f(q);
	// … do a lot of work here …
	q->use();		// Ouch! Read/scramble random memory
}
```

Dangling pointers

- We ***must*** eliminate dangling pointers ***or***
  - type safety is compromised
  - memory safety is compromised
  - resource safety is compromised
- Eliminated by a combination of rules
  - Distinguish owners from non-owners
    - Annotation **gsl::owner<int*>**
    - Something that holds an owner is an owner
    - Don’t forget **malloc()**, etc.
  - Assume raw pointers to be non-owners
  - Catch every attempt for a pointer to “escape” into a scope enclosing its owner’s scope
    - **return**, **throw**, out-parameters, lambda captures, long-lived containers, …

Dangling pointer rules

- A pointer can be returned from a scope ***iff***
  - It was passed into the scope (e.g., as an argument or retrieved from an object external to the scope)
  - It points to an object external to the scope (e.g., it was initialized by **new**)
- If static analysis cannot prove that, the pointer cannot be returned
  - This implies limitations to the complexity of the flow of control leading to the return of a pointer value

A problem, given multiple analyzers:
How clever should an analyzer required to be?

*Ownership and invalidation rules guarantee that pointers points to an object or are the nullptr

Example: Pointer to deleted object

```
int* f()
{
        int* p = new int {7};
        int* q = p;
        delete p;
        *q = 9;              // not OK: detected by local static analysis
        return q;            // not OK: returning pointer to deleted object
}
```

We need to address aliasing in general

Static analysis must involve flow analysis

Example: Escaping pointers

```
int glob = 9;
int* glob2 = &glob;                   // OK: global pointer to global

int* confused(int i, int* arg)
{
        int loc = 0;

        switch (i) {
        case 1:   return &loc;           // not OK: pointer to local
        case 2:   return new int{7};     // OK: pointer to free-store object (but ownership problem)
        case 3:   return &glob;          // OK: pointer to global
        case 4:   return arg;            // OK: returning what we received as an argument
        case 5:   return glob2;          // OK: returning what someone stored globally
        }
}
```

ES.65: Don't dereference an invalid pointer

- A pointer can be made not dereferenceable in several ways:
  - Uninitialized
    - Forget to initialize a pointer
  - Dangling pointer
    - Point to an object after it has gone out of scope (e.g., return a pointer to a local variable from a function)
    - Retain a pointer to a **delete**d object.
    - Violate the type system by placing a value that does not refer to an object into a pointer (e.g., a cast, misuse of union, or range error)
  - Invalidation
    - Retain a pointer to an object that has been deleted or moved (so that the object pointed to have been deleted or now hold a value that is logically different from the one expected).
  - Be the **nullptr**.
  - Point to one-past-the-end of a sequence (such a pointer may not be dereferenced).

Ownership

- An owner is something responsible for invoking a destructor
  - A scope
  - An object
- Something holding an owner is an owner
  - Container (vector, map, array, pointer to pointer, …)
- **operator new** returns an owner
- Ownership annotation
  - **template<typename T> using owner = T;**
  - Used by static analysis
  - Useful in code reviews
  - Doesn’t affect ABI

Prefer ownership abstractions

- Such as
  - **vector**, **map**, **unique_ptr**, **fstream**, **jthread**, …
- **owner** annotations is for
  - Implementation of ownership abstractions
    - E.g., **vector**, **map**, **unique_ptr**, **fstream**, **jthread**, …
  - Avoiding ABI breaks
    - E.g., C-style functions with pointers
- **owner**s in application code is a sign of a problem
  - Usually, C-style interfaces
  - "Lots of annotations" doesn't scale
    - Becomes a source of errors

Low-level ownership rules

- To keep static analysis local, use **gsl::owner** annotations
  - A pointer returned by **new** is an **owner** and must be **delete**d
    - unless stored in static storage to ensure that it lives “forever”
  - Only a pointer known to be an **owner** can be **delete**d
    - a pointer passed into a scope as an **owner** must be **delete**d in that scope or passed to another scope as an **owner**.
  - A pointer passed to another scope as an **owner** and not passed back as an **owner** is invalidated
    - cannot be used again in its original scope (since it will have been **deleted**).

Example: Ownership

```
void f(int* pp)
{
        // …
        delete pp;                  // Not OK: can’t delete non-owner
        // …
}

void use();
{
        int* p = new int{99};       // Not OK: assigns owner to non-owner
        // …
        f(p);
        // …
        *p = 7;                     // dangling pointer; but we’ll never get here
}
```

Example: Ownership

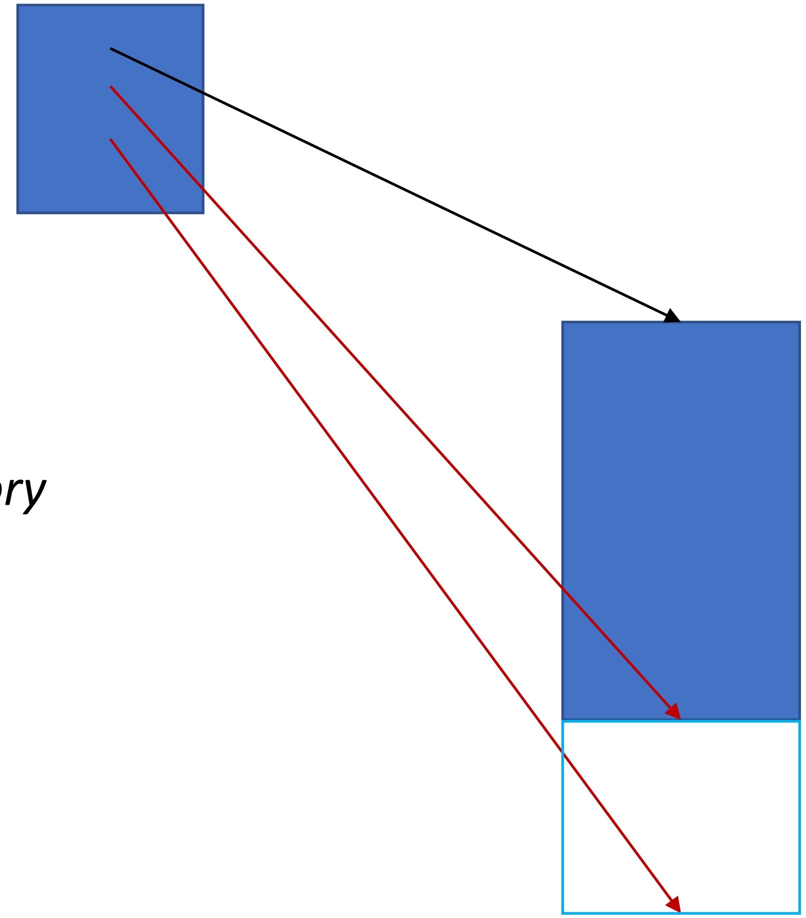
```
void f(owner<int*> pp)
{
        // …
        delete pp;                     // OK: f() must delete owner (or pass it along)
        // …
}

void use();
{
        owner<int*> p = new int{99};           // OK: assigns owner to owner
        // …
        f(p);                                  // OK: pass owner along
        // …
        *p = 7;                                // dangling pointer; but we'll never get here
}
```

Example: ownership abstraction implementation

- How do we implement ownership abstractions?

```
template<semiregular T>
class vector {
public:
        // …
private:
        owner<T*> elem;          // this anchors the allocated memory
        T* space;                // just a position indicator
        T* end;                  // just a position indicator
        // …
};
```

- **owner<T*>** is just an alias for **T***



Invalidation

- Any operation that may reallocate the elements of a container invalidates all operations on it
- Deleting a container invalidates all operations on it
  - See “ownership”

- Container: anything that holds a pointer
  - Classes with pointer members
  - Lambdas (they are classes, and remember capture-by-reference)
  - Pointers to pointers
  - References to pointers
  - Arrays of pointers
  - **unique_ptr** and **shared_ptr**
  - Threads with pointer arguments

```
int x = 7;
int* p = &x;
int** pp = &p;
cout << **pp;        // 7
p = nullptr;
cout <<  **pp;       // not OK
```

Example: Invalidation

```
void f(vector<int>& vi)
{
	vi.push_back(9);		// may relocate vi's elements
}

void g()
{
	vector<int> vi { 1,2 };
	auto p = vi.begin();		// point to first element of vi
	f(vi);
	*p = 7;				// not OK, may appear to work correctly
}
```

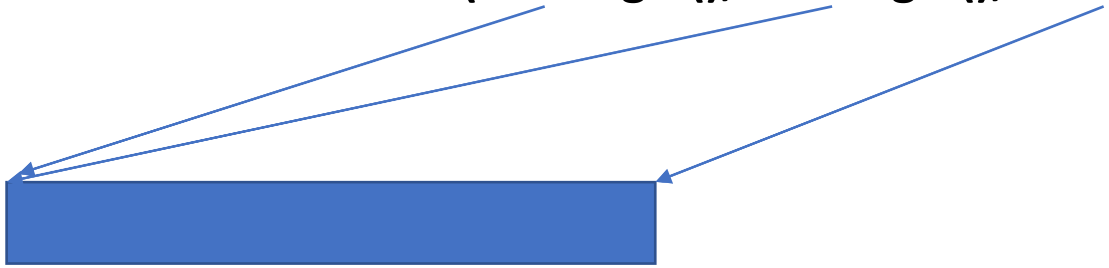
Invalidation

- Currently
  - Any non-**const** member function invalidates (see [Sutter'19])
  - Any function with a non-**const** pointer argument invalidates
  - Note: **Con.2: By default, make member functions const**
- Suggested (not implemented)
  - The current rule is simple and safe, but overly conservative
  - Some important functions are not non-const yet don't invalidate
    - E.g., **vector::swap()** and **vector::operator[]()**.
  - Mark those **[[not_invalidating]]**
    - **[[not_invalidating]]** is a testable optimization of a safe default
  - **ES.2x: Don't use pointers to pointers or references to pointers**

Example: Invalidation

- Aliasing problems are subtle
  - Best left to tools (compilers, static analyzers)
- Consider

```
vec.insert(vec.begin(), vec.front());    // OK, guaranteed by standard
                                         // (may have to copy *vec.front())
vec.insert(vec.begin(), {4,5,6});        // OK, add a range
vec.insert(vec.begin(), vec.begin(),vec.end()); // likely disaster: for some allowed implementations
                                                //      allocate more space for elements
                                                //      copy old elements
                                                //      delete old allocation
                                                //      copy elements from old allocation
                                                // caught by CG invalidation check
lst.insert(lst.begin(), lst.begin(), lst.end());  // OK (lists don't  relocate elements)
```



Library support

- **gsl::dynarray**
  - Like **vector**, but no resizing
  - No invalidation
- **std::unique_ptr** (and **std::shared_ptr**)
  - Use static analysis to prevent **get()** or introduce **gsl::unique_ptr**
  - Prevent unnecessary aliasing
- In general, we may need restricted versions of library facilities to simplify static analysis

Low-level code

- C++ is extensively used for low-level manipulation of memory and other system resources
  - Making C++ safe by eliminating all direct access to “raw” memory is not an option
  - Languages that ban such unsafe access, typically have ways of allowing unsafe code or delegate such manipulation to code written in C or C++.
- Currently
  - Selective use of static analysis
    - E.g., CG “profiles”
- Suggestion (unimplemented)
  - Annotate necessarily messy code **[[unverified]]**
    - E.g., fundamental data structures, concurrency primitives, etc.
    - Possibly using “profiles” **[[unverified lifetime]]**
  - Discourage use of **[[unverified]]**
    - It will be overused

Some run-time checks are unavoidable

- Access that depend on values not known until run time
  - **nullptr**
    - Use **gsl::not_null**
  - Range errors
    - Use **gsl::span**
  - One-past-the-end pointers

Run-time checks are allowed by the standard,
but needs to be enforced for safety guarantees

Example: range checks

- Use raw pointers only for pointing
  - F.22: Use T* or owner<T*> to designate a single object
- Then what?
  - ES.71: Prefer a range-for-statement to a for-statement when there is a choice
  - F.24: Use a span<T> or a span_p<T> to designate a half-open sequence
  - R.14: Avoid [] parameters, prefer span
  - SL.con.1: Prefer using STL array or vector instead of a C array
- For example:

```
void f(int* p, span<int> s)
{
    p[7] = 9;                       // not OK
    s[7] = 9;                       // OK (might throw)
    for (int x : s)  x=f(x);        // better: no runtime check
}
```

Note: using span is simpler than (pointer,count) argument pairs

Example: **nullptr** problems

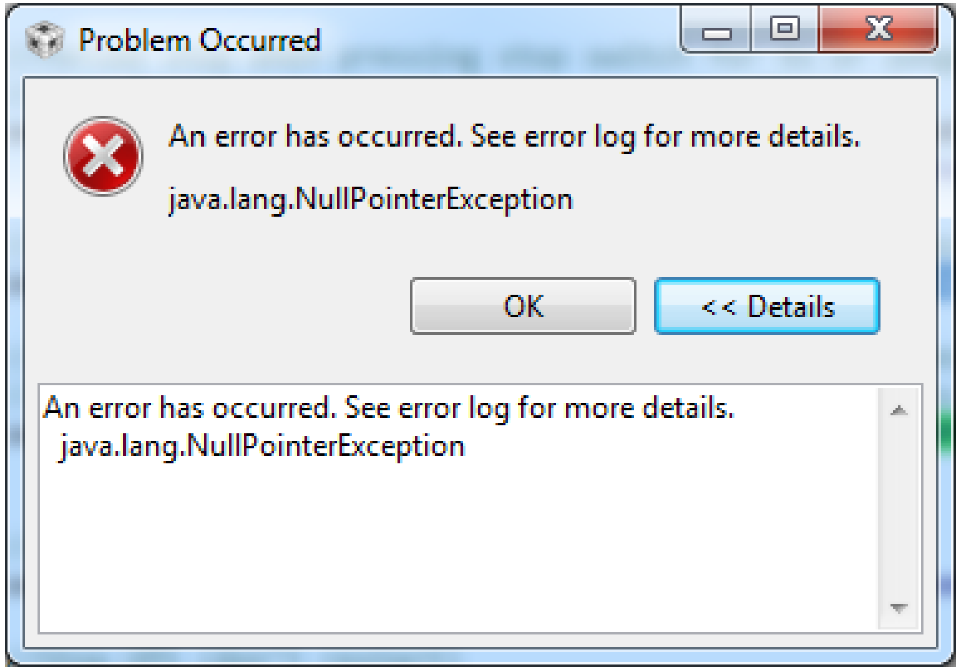
- Mixing **nullptr** and pointers to objects
  - Causes confusion
  - Requires (systematic) checking
- Caller

```
void f(char*);

f(nullptr);                // OK?
```

- Implementer

```
void f(char* p)
{
        if (p==nullptr)    // necessary?
        // …
}
```

- Can you trust the documentation?
- Compilers don't read manuals, or comments
- Complexity, errors, and/or run-time cost



Example: **not_null<T>** use

- **not_null** in interfaces

```
void f(not_null<char*> p)
{
	if (p==nullptr) *p = 'c';	// OK (but redundant – warn)
	*p = 'c';			// OK
	// …
}

void user(char* q)
{
	f(nullptr);		// not OK: detected or throws
	f(q);			// OK: might throw
	if (q) f(q);		// OK: won't throw
}
```

Example: **not_null<T>** use

- Not using **not_null** implies that tests are required

```
void f(char* p)
{
        *p = 7;                         // not OK
        if (p!=nullptr)  *p = 7         // OK
        // …
}

void user(char* q)
{
        f(nullptr);             // OK: f() is supposed to check
        f(q);                   // OK: q might be nullptr but f() is supposed to check
        if (q) f(q);            // OK: redundant check
}
```

One-past-the-end pointers

- Can be formed, but not dereferenced

```
vector<int> v;             // fill v
auto p = find(v,42);       // p becomes v.end()
*p = 9;                    // disaster
if (p!=v.end()) *p=9;      // allowed
```

- Hard for static analyzers
  - Exactly what pointers are one-past-the-end – not just **std**
- Suggestion (not implemented)
  - Introduce **gsl::not_end(p,v)** overloaded on **p** (pointer) and **v** (container)
    - to help analyzers and human readers

```
*p = 9;                         // not OK
if (not_end(p,v)) *p = 9;       // OK
```

Memory pools

- Not all memory is directly managed by **new** and deleted by **delete**
  - E.g., **malloc()/free()**
- We must handle user-managed “memory pools”
  - Problem: there is no standard memory pool abstraction
  - **<memory_resource>** is not yet widely used
- Alternative strategies (for using pointers to members of a pool)
  - Disallow members to be deleted or relocated
    - Requires **[[not_invalidating]]** annotations unless all pointers to elements are **const**
  - Disallow pointers to members to escape
  - Invalidate all pointers to elements if a potentially deleting or relocating operation is invoked
    - **std::vector** is an example
    - Must be communicated to the static analyzer: non-**const** and **[[not_invalidating]]**

Example of memory pools: Graphs

- Consider a general graph:

```
struct Tree_node {                    // a node owns its subnodes
        Value val;
        unique_ptr<Tree_node> left;
        unique_ptr<Tree_node> right;
};

struct Tree {
        unique_ptr<Tree_node> head;
        // …
};
```

- Not OK: can lead to loops, implying resource leaks
  - Conservative strategy: reject **Tree_node** because ownership loops and leaks are possible
  - **Shared_ptr** would not solve this
- Extracting **Tree_node***s from **unique_ptr<Tree_node>**s would cause a lot of invalidation

Example of memory pools: Graphs

- One solution: separate ownership from access

```
struct Tree_node2 {                    // a node doesn't own any other node; it just points
        Value val;
        Tree_node2* left;
        Tree_node2* right;
};

struct Tree2 {
        vector<unique_ptr<Tree_node2>> nodes;
        Tree_node2* head;
        // …
};
```

- Accessor loops are acceptable
- Ownership loops are not OK (and detectable)

Concurrency

- The Core Guideline rules are incomplete (but still helpful)

  - CP.20: Use RAII, never plain **lock()/unlock()**
  - CP.21: Use **lock()** or **scoped_lock** to acquire multiple mutexes
  - CP.22: Never call unknown code while holding a lock (e.g., a callback)
  - CP.23: Think of a **jthread** as a scoped container
  - CP.24: Think of a thread as a global container (implies invalidation checks against aliasing)
  - CP.25: Prefer **jthread** over **thread**
  - CP.26: Don't **detach()** a thread

  - std::jthread is a “joining thread”, obeying RAII

For more suggested CG concurrency rules see Michael Wong’s CppCon’21 MISRA C++ talk

Why not enforcement *exclusively* through language rules?

- Stability/compatibility
  - Billions of lines of code
- Different domains have different definition of “safety”
  - Basic type-and-resource safety should be common
- Gradual adoption
  - Essential
  - Many of the Core Guidelines checks are in use “at scale”

- Most desirable
  - Platform-independent static analyzer
  - Uniform adoption of the basic type-and-resource safety rules
  - Compiler and build options for invoking the static analyzer

Many notions of safety

- **Logic errors**: perfectly legal constructs that don’t reflect the programmer’s intent, such as using < where a <= or a > was intended.
- **Resource leaks**: failing to delete resources (e.g., memory, file handles, and locks) potentially leading to the program grinding to a halt because of lack of available resources.
- **Concurrency errors**: failing to correctly take current activities into account leading to (typically) obscure problems (such as data races and deadlocks).
- **Memory corruption**: for example, through the result of a range error or by accessing and memory through a pointer to an object that no longer exists thereby changing a different object.
- **Type errors**: for example, using the result of an inappropriate cast or accessing a union through a member different from the one through which it was written.
- **Overflows and unanticipated conversions**: For example, an unanticipated wraparound of an unsigned integer loop variable or a narrowing conversion.
- **Timing errors**: for example, delivering a result in 1.2ms to a device supposedly responding to an external event in 1ms.
- **Termination errors**: a library that terminates in case of “unanticipated conditions” being part of a program that is not allowed to unconditionally terminate.

Why Safety Profiles?

- Arbitrary C or C++ code is too complex for static analysis
  - Halting problem
  - Dynamic linking
  - Cost of global analysis
- Arbitrary C or C++ forces us to deal with too low an abstraction level
  - Ends up chasing complexities in messy old-style code
  - Backwards looking
- We care about performance as well as type-and-resource safety
- Eventually much higher productivity

Why Safety Profiles?

- We need a coherent set of rules
  - Not just a lot of unrelated tests
- Profile: a coherent sets of rules yielding a guarantee
  - Current: bounds, type, memory
  - E.g., type-and-resource-safe, safe-embedded, safe-automotive, safe-medical, performance-games, performance-HPC, EU-government-regulation
  - Must be visible in code
    - To indicate intent
    - To trigger analysis

Strategy: Safety Profiles

- Our approach is “a cocktail of techniques” not a single neat miracle cure

- Static analysis
  - to verify that no unsafe code is executed.
- Coding rules
  - to simplify the code to make industrial-scale static analysis feasible.
- Libraries
  - to make such simplified code reasonably easy to write
  - to guarantee run-time checks where needed.