Lifetime safety: Preventing common dangling

Abstract

This paper defines the Lifetime profile of the [C++ Core Guidelines]. It shows how to efficiently diagnose many common cases of dangling (use-after-free) in C++ code, using only local analysis to report them as deterministic readable errors at compile time. The approach is to identify variables that are of generalized “Owner” types (e.g., smart pointers, containers, string) and “Pointer” types (e.g., int*, string_view, span, iterators, and ranges), and then use a local simple acyclic control flow graph (ACFG) analysis to track what each Pointer points to and identify when an Owner invalidates a Pointer. The analysis leverages C++’s existing strong notions of scopes, object lifetimes, and const that carry rich information already available in reasonably modern C++ source code. Interestingly, it appears that with minor extension this analysis can also detect uses of local moved-from variables (use-after-move), which are a form of dangling.

The warnings can be deterministically and portably implemented (to give consistent results across implementations, which has been validated by partial implementations in MSVC and Clang) and efficient enough to run during regular compilation (as of this writing, the Clang-based implementation is unoptimized and performs much extra work, such as recomputation of type categories that could readily be memoized and fixed point iteration instead of the more efficient acyclic ACFG specified in this paper, and incurs only about 5% overhead in compiling large LLVM translation units).

Note: De facto vs. de jure

Initially, I did not intend to propose this work in WG21 for Standard C++ for two reasons: First, it’s a grand-but-still-speculative attempt to solve a major 40-year problem, which could fail, especially in its initial stages back in 2015 when there was only one very early proof-of-concept implementation. Second, I believe much of the value of this work can be realized if dangling detection could become de facto implemented in C++ compilers (similar to some other popular-and-common warnings), even if it were never de jure standardized; as long as the major C++ compilers could reliably diagnose these problems as common vendor extensions, it would improve or eliminate C++’s reputation for being a breeding ground for dangling pointers/iterators/string_views/etc.

However, since this work was started, there have been parallel EWG/LEWG proposals from other authors, notably [P0936R0], that propose de jure standardization of widespread annotations in the language and the standard library for cases that are covered by this work (and, in this proposal, typically without annotation; §2.6.2 describes how all examples from [P0936R0] are diagnosed without any annotation). So I thought I should at least submit this work as a WG21 paper and give an evening session about it at a WG21 meeting, possibly in San Diego or in Kona. If there is strong committee interest in standardizing these errors so they are available in the box in all C++ compilers, I could do the additional work to turn this into an actual EWG/LEWG proposal (but even then I would prefer to initially target a TS).
1 Overview

1.1 Summary: Approach and illustrative examples

This paper aims to efficiently diagnose dangling in common cases at build time, by leveraging C++’s existing strong notions of scopes, object lifetimes, and const to identify invaliding operations. The approach works on generalized “Owner” and “Pointer” types, and applies the rules equally to all such types:

- An Owner owns the objects it refers to. Examples: shared_ptr, string, vector.
- A Pointer does not own what it refers to. Examples: int*, string_view, span, vector<T>::iterator.

1.1.1 Track “points-to” information

In this code, a human programmer can see that dereferencing \( p \) is fine on line B, but dangling on line D:

```cpp
int* p = nullptr;
{
    int x = 0;
    p = &x;       // A
    *p = 42;      // B: human says “ok”
}                  // C
*p = 42;        // D: human says “error”
```

How do a human know D is a bug? By following the code and seeing that \( p \) points to \( x \), which went out of scope.

This paper teaches the compiler to “see” that too, by doing the same thing we did in our heads: For each local pointer variable, track the set of things it could point to at any given point in the function’s source code, by following the function’s control flow paths. In this paper, that is called the pset, or “points-to” set, which typically contains the name of local variables, but can also contain the special values null, static, and invalid.

Here is the same example, with the compiler tracking \( p \)’s points-to set through the function. We update \( p \)’s points-to set each time we modify \( p \), and we also update it when something it points to goes out of scope: Here, when \( x \) goes out of scope, we replace “\( x \)” with “invalid” in every points-to set that contains \( x \), which means for any pointer that at that point in the function could have been pointing to \( x \):

```cpp
// godbolt.org/z/szJjnH
int* p = nullptr;    // pset(p) = {null} – records that now p is null
{
    int x = 0;
    p = &x;        // A: set pset(p) = \{x\} – records that now p points to x
    cout << *p;    // B: ok – *p is ok because \{x\} is alive
}                  // C: x destroyed ⇒ replace “x” with “invalid” in all psets
                      // ⇒ set pset(p) = \{invalid\}
cout << *p;       // D: error – because pset(p) contains \{invalid\}
```

We can give useful error messages because we can say what series of pset changes led to invalid. How did invalid enter \( p \)’s pset? Because the set contained \( x \) when \( x \) was invalidated on line C. How did the set get to have \( x \) on line C? Because of the assignment on line A. So we can report something like this:

```cpp
// error: ‘*p’ is illegal, p was invalidated when ‘x’
// went out of scope on line C (path: A→C→D)
```
1.1.2 Generalizing: Pointers

There’s nothing special about built-in * pointers. **All rules apply equally to any generalized “Pointer” type that refers indirectly to another object it doesn’t own**, including iterators, ranges, views, spans, proxies, and more. For example, the identical rules diagnose the identical bug when using a `string_view`:

```cpp
// godbolt.org/z/ytRTKt
string_view s; // pset(s) = {null}
{
    char a[100];
    s = a; // A: pset(s) = {a}
    cout << s[0]; // B: ok
}
// C: x destroyed ⇒ set pset(s) = {invalid}
cout << s[0]; // D: error: ‘s[0]’ is illegal, s was invalidated when ‘a’
// went out of scope on line C (path: A→C→D)
```

1.1.3 Generalizing: Owners

Objects are often owned by other objects. A **generalized “Owner” type is a type that owns another object**, including containers, owning smart pointers, and more. When a Pointer `p` is made to point to data owned by an Owner `o` we set `pset(p) = {o'}`, or “something owned by o.” The main difference is that, in addition to changing `o` to invalid in all psets when `o` goes out of scope, we also set `o'` to invalid when `o` is modified, because modifying `o` can release the data it points to. For example:

```cpp
// godbolt.org/z/1Sc_cE
string_view s; // pset(s) = {null} - records that now p is null
string name = "abcdefghijklmnop";
string sv = s; // A: set pset(s) = {name'} - “data owned by ‘name’”
cout << s[0]; // B: ok – s[0] is ok because {a} is alive
name = "frobozz"; // C: name modified ⇒ set pset(s) = {invalid}
name = "abcdefghijklmnop";
s = name;
// A: pset(s) = {name'} - “data owned by ‘name’”
cout << s[0]; // B: ok – s[0] is ok because {a} is alive
name = "frobozz";
// C: name modified ⇒ set pset(s) = {invalid}
cout << s[0]; // D: error: ‘s[0]’ is illegal, s was invalidated when ‘a’
// went out of scope on line C (path: A→C→D)
```

Note that “modifying `o`” by default simply means any non-const use of `o`, such as calling a non-const member function of `o`. That’s a useful default that works most of the time; where appropriate, it can be overridden to state that functions like `map::insert` that are non-const but don’t actually invalidate (see §2.5.6.10).

This paper’s rules ignore the specific type of an Owner or Pointer; for example, there is no special rule to treat a raw `int*` pointer any differently from (say) a `string_view` or a `span`. Here are some variations of the same example showing different types diagnosed with the same rules, and the expected error quality:

<table>
<thead>
<tr>
<th>View variation: string_view</th>
<th>Proxy variation: vector&lt;bool&gt;::reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>godbolt.org/z/qTle8G</td>
<td>godbolt.org/z/iq5Qja</td>
</tr>
</tbody>
</table>
| `string s = “abcdefghijklmnopqrstuvwxyz”;
  string_view sv = s;
  if (sv[0] == 'a') {} // ok` | `vector<bool> vb{false,true,false,true};
  auto proxy = vb[0];
  if (proxy) {/*...*/} // ok` |
| `s = “xyzy”;
  if (sv[0] == 'a') {} // A: invalidates sv` | `vb.reserve(100);
  if (proxy) {/*...*/} // A: invalidates proxy` |
| `if (sv[0] == 'a') {} // ERROR, sv was invalidated
  // by ‘s =’ (line A)` | `if (proxy) {/*...*/} // ERROR, proxy was invalidated
  // by ‘vb.reserve’ (line A)` |
### Range variation: filter_view (Ranges TS)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>vector&lt;int&gt; ints{0,1,2,3,4,5};</code></td>
<td>Declaration of a vector of integers</td>
</tr>
<tr>
<td><code>auto even = [](int i){ return !(i%2); };</code></td>
<td>Definition of an anonymous function to check if a number is even</td>
</tr>
<tr>
<td>`auto view = ints</td>
<td>view::filter(even);`</td>
</tr>
<tr>
<td><code>cout &lt;&lt; *begin(view);</code></td>
<td>Output the first element of the view</td>
</tr>
<tr>
<td><code>ints.push_back(6);</code></td>
<td>Adding an element to the original vector</td>
</tr>
<tr>
<td><code>cout &lt;&lt; *begin(view);</code></td>
<td>Output the first element of the view after changes</td>
</tr>
</tbody>
</table>

### Iterator variation: regex_iterator

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>string s = &quot;The quick brown fox jumps over;&quot;;</code></td>
<td>Declaring a string</td>
</tr>
<tr>
<td><code>regex r(&quot;[^\s]+&quot;);</code></td>
<td>Defining a regular expression</td>
</tr>
<tr>
<td><code>auto iter = sregex_iterator(s.begin(), s.end(), r);</code></td>
<td>Creating an iterator for the regular expression</td>
</tr>
<tr>
<td><code>cout &lt;&lt; iter-&gt;str();</code></td>
<td>Outputting the first match of the regular expression</td>
</tr>
<tr>
<td><code>s = &quot;the lazy dog&quot;;</code></td>
<td>Updating the string</td>
</tr>
<tr>
<td><code>cout &lt;&lt; iter-&gt;str();</code></td>
<td>Outputting the first match of the regular expression after changes</td>
</tr>
</tbody>
</table>

### 1.1.4 Function calls

Finally, since every function is analyzed in isolation, we have to have some way of reasoning about function calls when a function call returns a Pointer. If the user doesn’t annotate otherwise, by default we assume that a function returns values that are derived from its arguments. For example, given:

```cpp
template<typename T>
const T& min(const T& a, const T& b);
```

by default, `pset(return) = pset(a) ∪ pset(b) —` that is, the returned `T&` refers to one of the two input `T&`s.

Or, given:

```cpp
string_view foo(const string& s1, const string& s2);
```

by default, unless otherwise annotated, `pset(return) = {s1', s2'} —` that is, the returned Pointer (here, a `string_view`) is derived from the inputs (here, the two `string` Owner parameters).

When compiling the callee, the callee assumes inputs are valid and enforces the assumptions on the outputs’ lifetimes. In this example, if the body of `foo` tries to return something different on some path, the programmer gets a compile-time error when `foo` is compiled. For example, this would be an error:

```cpp
string_view foo(const string& s1, const string& s2) {
  static string local;
  return local; // error, pset {local'} is not a subset of {s1',s2'}
}
```

When compiling each caller, the caller ensures the inputs are valid and assumes the resulting outputs’ lifetimes. Each caller knows the psets of the inputs, and can assume the pset of the output based on that. In this example call site, if we pass two temporary `strings`, the caller knows that the returned `string_view` has a lifetime derived from the arguments, whose lifetimes it knows:

```cpp
// godbolt.org/z/1iOvAO
string_view sv;
sv = foo("tmp1", "tmp2"); // C: in: pset(arg1) = {__tmp1'}, pset(arg2) = {__tmp2'}
// ... so assume: pset(sv) = {__tmp1', __tmp2'} [the union]
// ... and then at the end of this statement, __tmp1 and __tmp2 are destroyed, so pset(sv) = {invalid}
cout << sv[0]; // D: error: ‘sv[0]’ is illegal, s was invalidated when // ‘__tmp1’ went out of scope on line C (path: C→D)
```
1.2 Guidance: What we teach users

This approach aims for low false positives in “good” code that follows modern C++ conventions, including:

- Prefer to use RAII Owner types (e.g., shared_ptr, vector) to own other objects. Whenever allocating a new object or raw resource, pass it to an object of such a type that will then own it. (See Guidelines R.1 and R.12.)
- Avoid using unencapsulated owning raw * pointers that require explicit delete, and similar patterns such as raw handles that require explicit free calls. (See Guidelines R.3 and R.11.)
- Prefer to use non-owning Pointer types (e.g., int*, string_view, span) locally, as parameters or local variables. Then this analysis will be able to diagnose common cases of dangling for you at compile time.
  (In cases where you legitimately need to have a non-local Pointer, such as a heap-allocated vector<string_view>, that’s still okay but will not get much compile-time support to diagnose use-after-free dangling bugs.)
- If you write a custom Owner or Pointer class, it will usually be automatically recognized as an Owner or Pointer. If it is not, write a single annotation on its class declaration to tag it as a [[gsl::Owner]] or [[gsl::Pointer]] type, respectively.

Note that most of this is what we already teach as well-written modern C++.

1.3 Goals and scope

A primary goal is to define a simple analysis that is easy for compilers to implement efficiently and programmers to reason about clearly. The analysis is local each to function (no whole program analysis), linear and single-pass (suitable for implementation in a C++ front-end compiler rather than a separate expensive analysis step), and directly corresponds to the visible structure of the source code (linearly follows the function’s nested blocks).

This paper focuses on the following as target “common cases”:

- Local variables (stack variables, parameters, and return values) and local analysis of each individual function’s body, composed across opaque function calls by using defaulted (mostly) or annotated (occasionally) lifetime semantics for parameter/return values that are Owners and Pointers.
- Single-level Pointers (e.g., *, & string_view, vector<int>::iterator). Multi-level Pointers (e.g., **, span<widget>*, vector< span< int > >:: iterator) are also supported but get more conservative invalidation results.

This excludes the following:

- We do not attempt to check after the end of main, during static destruction.
- We do not attempt to address all aliasing cases or make concurrency safety guarantees. Programmers are still responsible for eliminating race conditions.
- We do not currently attempt to check of the internals of Owner types, including that we do not attempt to validate the correctness of pointer-based data structures. Each Owner type is assumed to be correctly implemented, and we check the common uses which greatly outnumber the Owner’s own functions. In this version, implementations are expected to skip analysis member functions of Owner types.
1.4 Design principles

**Note** These principles apply to all design efforts and aren’t specific to this paper. Please steal and reuse.

The primary design goal is conceptual integrity [Brooks 1975], which means that the design is coherent and reliably does what the user expects it to do. Conceptual integrity’s major supporting principles are:

- **Be consistent**: Don’t make similar things different, including in spelling, behavior, or capability. Don’t make different things appear similar when they have different behavior or capability. — This proposal does not invent special rules that are specific to only raw pointers or specific smart pointers, but uses the same rules for all Pointer types so that the same errors diagnosed for a dangling T* are also diagnosed consistently for a dangling iterator, `string_view`, `span`, or other user-defined Pointer type.

- **Be orthogonal**: Avoid arbitrary coupling. Let features be used freely in combination. — This proposal allows arbitrary Owner and Pointer types to be used in combination. This proposal also follows the [C++ Core Guidelines] guidance to permit the same `[[gsl::suppress(tag)]]` portable warning suppression syntax that works for all Guidelines warnings.

- **Be general**: Don’t restrict what is inherent. Don’t arbitrarily restrict a complete set of uses. Avoid special cases and partial features. — This proposal treats all non-`const` operations on Owner types as potentially invalidating by default, and does not rely on recognizing a specific preset list of “known” operators.

These also help satisfy the principles of least surprise and of including only what is essential, and result in features that are additive and so directly minimize concept count (and therefore also redundancy and clutter).

Additional design principles include: Make important things and differences visible. Make unimportant things and differences less visible. — This proposal makes deliberate violations of Lifetime checks visible in source code, so that if the code actually fails, then during debugging the programmer can grep and audit the places where `[[gsl::suppress(lifetime)] occurs, unlike today where common lifetime-unsafe operations are invisible and compile silently. However, this proposal also intentionally selects defaults that fit the most common cases so that visible annotation is unnecessary most of the time.

1.5 Acknowledgments and implementation notes

Thank you especially to Neil MacIntosh and Kyle Reed for the Visual C++ extension implementation, and to Matthias Gehre and Gábor Horváth for the Clang-based compiler implementation (linked to throughout this paper).

**Note** Both are partial in-progress implementations that implement many of the core examples, but parts of this paper are not yet implemented in both or either. For example, null checking is in Clang but not VC++ as of this writing.

Thank you also to all of the following for their comments and feedback on these ideas and/or drafts of this paper: Andrei Alexandrescu, Steve Carroll, Pavel Curtis, Gabriel Dos Reis, Joe Duffy, Daniel Frampton, Anna Gringauze, Chris Hawblitzel, Nicolai Josuttis, Leif Kornstaedt, Aaron Lahanman, Ryan McDougall, Gor Nishanov, Andrew Pardoe, Jared Parsons, Dave Sielaff, Richard Smith, Jim Springfield, and Bjarne Stroustrup.

1.6 Revision history

**R0**: Initial “1.0” revision (September 2018). Major changes: Made the analysis rules rigorous, generalized Owner and Pointer type deduction to use requirements/concepts from the standard and Ranges TS, generalized move support to include diagnosing common use-after-move cases.

**Initial incomplete draft**: “Lifetimes I and II – v0.9.1”: Presented with live prototype demos at CppCon 2015.
2 Proposal

2.1 Type categories: Owner, Pointer, Indirection, Value, Aggregate

An **Owner** owns another object (cannot dangle). An Owner type is expressed using the annotation ```[[gsl::Owner(DerefType)]]``` where DerefType is the owned type (and (Dereftype) may be omitted and deduced as below). For example:

```cpp
template<class T> class [[gsl::Owner(T)]] my_smart_pointer;
```

The following standard or other types are treated as-if annotated as Owners, if not otherwise annotated:

- Every type that satisfies the standard Container requirements and has a user-provided destructor. (Example: `vector`.) DerefType is `::value_type`.
- Every type that provides unary * and has a user-provided destructor. (Example: `unique_ptr`.) DerefType is the ref-unqualified return type of `operator*`.
- Every type that is publicly derived from an Owner type.

Additionally, for convenient adoption without modifying existing standard library headers, the following well-known standard types are treated as-if annotated as Owners: `stack`, `queue`, `priority_queue`, `optional`, `variant`, `any`, and `regex`.

An **Pointer** is not an Owner and provides indirect access to an object it does not own (can dangle). A Pointer type is expressed using the annotation ```[[gsl::Pointer(DerefType)]]``` where DerefType is the pointed-to type (and (Dereftype) may be omitted and deduced as below). For example:

```cpp
template<class T> class [[gsl::Pointer(T)]] my_span;
```

The following standard or other types are treated as-if annotated as Pointer, if not otherwise annotated and if not Owners:

- Every type that satisfies the standard Iterator requirements. (Example: `regex_iterator`.) DerefType is the ref-unqualified return type of `operator*`.
- Every type that satisfies the Ranges TS Range concept. (Example: `basic_string_view`) DerefType is the ref-unqualified type of `*begin()`.
- Every type that satisfies the following concept. DerefType is the ref-unqualified return type of `operator*`.

```cpp
template<typename T>
concept TriviallyCopyableAndNonOwningAndDereferenceable =
    std::is_trivially_copyable_v<T> &&
    std::is_copy_constructible_v<T> &&
    std::is_copy_assignable_v<T> &&
    requires(T t) { *t; };
```

- Every closure type of a lambda that captures by reference or captures a Pointer by value. DerefType is `void`.
- Every type that is publicly derived from a Pointer type.
Additionally, for convenient adoption without modifying existing standard library headers, the following well-known standard types are treated as-if annotated as Pointers, in addition to raw pointers and references: `reference_wrapper`, and `vector<bool>::reference`.

**Note** Points follow copy semantics, and if there is a move from a Pointer we assume it does not change the source. As a QoI issue, we could warn if the user opts-in to being a Pointer a type that has user-declared move operations.

An **Indirection** is a type that is either a Pointer or an Owner. For an Indirection type `I`, `DerefType(I)` is:

- If `I` has a DerefType `R` that is user-specified or is part of automatic deduction as an Owner or Pointer as specified above, then `R`.
- Otherwise, if `I` has unary `operator*` with return type `R&`, then `R`. (Note: This includes raw pointer of type `R*`, and raw reference of type `R&` which is treated as `R*` in this analysis.)
- Otherwise, if `I` has `operator->` with return type `R*`, then `R`.
- Otherwise, if `I` has `operator[]` with return type `R&`, then `R`.
- Otherwise, if `I` has `begin()` with return type `R` where `R` is a Pointer, then `DerefType(R)`.
- Otherwise, if `I` is declared as a template with template parameter list `<typename R /*, ...*/>`, then `R`.
- Otherwise, not defined.

For example, `DerefType(unique_ptr<int>)` is `int`, and `DerefType(variant<int,string>)` is not defined.

An **Aggregate** is a type that is not an Indirection and is a class type with public data members none of which are references (`&` or `&&`) and no user-provided copy or move operations, and no base class that is not also an Aggregate. The **elements** of an Aggregate are its public data members.

**Notes** Aggregates are types we will “explode” (consider memberwise) at local scopes, because the function can operate on the members directly. They are similar to the standard “aggregate” concept but simpler; for this analysis we just need a name for types that have public data and default copy/move.

In the future we could consider fixed-length arrays as well, but the difference for arrays is that whereas a K-member struct will always have its members accessed with names that are known statically (e.g., `s.m1`, `s.m2`), a K-element array can have its elements accessed not only with statically known names (e.g., `a[0]`, `a[1]`) but also with statically unknown names (e.g., `a[i]`).

A **Value** is a type that is neither an Indirection nor an Aggregate.

**Note** Sum types like `variant` and `any` are Values. They are not Aggregates because they are not product types, and they are not Owners or Pointers because they do not have a single `DerefType`.

### 2.2 Local variables and control flow

“Function entry” means the beginning of the function, including the mem-init-list for constructors. “Function return” means a return statement or the implicit return at the end of the function body. A “local variable” means any parameter, local variable, member variable (if in a member function), or temporary object in the scope of a function definition; for a local variable of Aggregate type each element is treated as a distinct variable; and for each lambda function defined in the function body each data member (capture) is treated as a distinct variable. A “local Pointer” is a local variable of Pointer type. A “local Owner” is a local variable of Owner type.
Local struct members are treated as individual variables because that’s what they are to the function body, which accesses them directly and individually. For example, this code

```c
void test() {
    struct { int* p1; int* p2; int i; } s; // will be exploded
}
```

is treated as if it had been written using five distinct local variables

```c
void test() {
    int* s__p1; // exploded out
    int* s__p2;
    int  s__i;
}
```

I don’t currently include uncaught exceptional paths in “function exit” because they do not result in any communication of valid Pointer results to the caller, so there’s no postcondition to enforce.

A function’s “acyclic control flow graph (ACFG)” means the function’s normal local CFG minus backward edges, which are removed by simplifying all for/while/do loops as described in §2.4.9, simplifying all try/catch blocks as described in §2.4.10, and ignoring continue and backward goto statements. A “node” has its usual meaning in a CFG except that each subexpression that mentions a local variable (including its declaration or destruction) or any global variable of Pointer or Owner type is treated as a distinct node (rather than combined in larger basic blocks); every initialized local variable has at least three nodes, for its declaration, initialization, and destruction, respectively. A “noexcept node” is a node corresponding to a subexpression that is unconditionally noexcept by language rule (e.g., built-in integer assignment) or by function declaration. A “not-noexcept node” is a node that is not a noexcept node (this includes an explicit throw statement). A “path” is a connected directed path in a function’s ACFG.

“Use” of a local variable var means a node corresponding to a mention of var’s name that accesses var’s value (not its declaration, not just taking its address). A “const use” means a use that only reads var (e.g., a read of a fundamental type, calling a function that treats its var argument as const) or using var as an argument to a function parameter explicitly annotated as [[gsl::lifetime_const]] (to annotate the this parameter of a function the attribute is in the same position as override). A “non-const use” means a use that is not a const use (e.g., a write or read-modify-write of a fundamental type, or passing var to a function that takes it via reference to non-const so that it is a function output). “Copy from” and “copy to” have their usual meanings. “Move from” var means to use var as an argument to a & (rvalue reference or forwarding reference) parameter (this includes but is not limited to the parameter of a move constructor or move assignment operator). “Move to” var means to use var as the argument to the this parameter of a move constructor or move assignment operator.

### 2.3 Points-to map (pmap) and Points-to set (pset)

Compilation of a function definition maintains a pmap (“points-to map”) for each ACFG path. At each node (subexpression) in the function body source code, the path’s pmap contains:

- one tuple \((x, \text{pset}(x))\) for every local variable \(x\) currently in scope, where the set \(\text{pset}(x)\) denotes what \(x\) could refer to at that point in the source code (e.g., for a Pointer, what it can point to); and
- special entries, notably \((\text{static}, \{\text{static}\})\), \((\text{null}, \{\text{null}\})\) and \((\text{nullptr}, \{\text{null}\})\).

Each element in a \(\text{pset}(x)\) set is one of the following:
<table>
<thead>
<tr>
<th>Meaning</th>
<th>A pset entry is invalidated</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>var</code> p currently refers to local variable <code>var</code></td>
<td>when <code>var</code> is destroyed</td>
</tr>
<tr>
<td><code>static</code> p currently refers to a static variable, or an object owned directly by a <code>const</code> static Owner object</td>
<td>never (until the end of <code>main</code>; may inject additional checking after <code>main</code> ends)</td>
</tr>
<tr>
<td><code>o'</code> p currently refers to an object owned directly by Owner <code>o</code></td>
<td>when <code>o</code> is destroyed or modified by non-<code>const</code> use</td>
</tr>
<tr>
<td><code>o''</code> (etc.) p currently refers to an object owned by an object that is owned by <code>o</code></td>
<td>when <code>o'</code> is modified by non-<code>const</code> use</td>
</tr>
<tr>
<td><code>null</code> p is invalid for any use until tested to be not equal to the null pointer constant</td>
<td>when used without removing <code>null</code> from the list via a not-null branch</td>
</tr>
<tr>
<td><code>invalid</code> p is already invalid</td>
<td>always</td>
</tr>
</tbody>
</table>

The set entries are interpreted as “or’d.” For example, for a Pointer `p`, `pset(p) == {a,null}` denotes that `p` either points to the object `a` or is null. A variable `x` is said to be:

- “possibly null” if `pset(x)` contains `null`; and
- “invalid” if `pset(x)` contains `invalid` (and putting `invalid` into `pset(x)` is said to `invalidate` `x`).

### QoI

As a quality of implementation (QoI) matter, implementations are encouraged, but not required, to track sources of `null` and `invalid` by extending the `pmap` tuples to contain two additional sets for each `p`: `null_history(p)` and `invalid_history(p)`. This enables higher quality diagnostics with source line attributions identifying paths that lead to possibly null and invalid Pointers. Later “QoI” notes refer to these additional sets. The “(line #)” sample diagnostic messages refer to these histories.

- `pset(p) = rhs` means to change `pmap` by removing any existing tuple `(p, *)` and inserting the tuple `(p, rhs)`.
- `pset(list)` means `U pset(e) | e ∈ list`, the union of the psets of each element in `list`.
- `pset(p)'` means `{ e | e ∈ pset(p) where e is an Owner}, to add ' to each Owner mentioned in the list.
- `pset(o')` is `{o''}`, `pset(o'')` is `{o'''}`, etc.

For a non-local Pointer `g`, there is no `pmap` entry. Whenever `pset(g)` is mentioned, it means `{static}`.

- `KILL(x)` means to replace all occurrences of `x` and `x'` and `x''` (etc.) in the `pset` with `invalid`. For example, if `pmap` is `{(p1,{a}), (p2,{a'})}`, `KILL(a')` would invalidate only `p2`, and `KILL(a)` would invalidate both `p1` and `p2`.

### QoI

For each `p` for which `pset(p)` that was modified by the `KILL`, additionally append the current node to `invalid_history(p)` to record the source location that caused the invalidation.

- `JOIN({pmap_1,...,pmap_n})` means `{ (p, pset_1(p) ∪ ... ∪ pset_n(p)) | (p, *) ∈ pmap_1 ∪ ... ∪ pmap_n }`.

For two `psets` from and `to`, from is “substitutable for” to if from is no more `invalid` than to, no more `null` than to, and no more ininvalidatable than to. If from is `{static}`, it is substitutable for any to. Otherwise, from is substitutable for to if all of the following must be true, where `o` is an Owner:

- If from includes `invalid`, then to must include `invalid`.
- If from includes `null`, then to must include `null`.
- If from includes `o'`, then to must include `o'` or `o`.
• If \texttt{from} includes \texttt{o''} (etc.), then \texttt{to} must include \texttt{o''} or \texttt{o'} or \texttt{o} (etc.).
• If \texttt{to} is \{\texttt{static}\}, then \texttt{from} must be \{\texttt{static}\}.

For example:

• \{a\} (points to \texttt{a}, invalidated by the end of lifetime of \texttt{a}) is substitutable for \{a,b\} (points to either \texttt{a} or \texttt{b}, invalidated by the end of lifetime of either \texttt{a} or \texttt{b}).
• \{x\} is substitutable for \{y\} if \texttt{x} and \texttt{y} are declared in that order so that \texttt{x}'s lifetime is longer than \texttt{y}'s.
• \{\texttt{static}\} is substitutable for \{\texttt{static,}\null\}.
• \{o,o2'\} is substitutable for \{o',o2'\}.

In the following examples:

• \textcolor{green}{\texttt{green}} highlights legal uses of valid Pointers;
• \textcolor{red}{\texttt{x}} highlights the point at which an invalidation occurs; and
• \textcolor{red}{\texttt{red}} highlights subsequent illegal uses of invalidated Pointers (when those are allowed to be formed).

2.4 Analysis rules by node type

2.4.1 Function entry and exit

On function entry, \texttt{pmap} contains the special entries \{\texttt{static,}\{\texttt{static}\}\}, \{\texttt{null,}\{\texttt{null}\}\} and \{\texttt{nullptr,}\{\texttt{null}\}\} and one entry for each parameter as described in §2.5.

On function exit, \texttt{pmap} is discarded after performing the checks described in §2.5.

2.4.2 Local variable declaration, use, and scope

“Declaration” means the explicit declaration of a named variable, the implicit declaration of an rvalue, the explicit or implicit appearance of a member variable in the mem-init-list (if in a constructor), or a Pointer value created by a type-unsafe cast (in which case the source of the cast is ignored and not treated as an initializer).

\textbf{Note} When the type safety profile is also enforced, then the last case (type-unsafe casting) cannot happen unless the type safety rule is explicitly [[\texttt{[\texttt{supress]}]]]-ed.

As a possible extension (which as of this writing is partly implemented in the MSVC implementation), we could additionally consider giving useful Pointer lifetime guarantees for even such type-unsafe code that performs pointer/reference casting; for example, when casting from one Pointer type to another, we could optimistically copy the pset even though the types do not match, as if it were a Pointer copy. This gives useful tracking in the case of casting \texttt{byte*} to \texttt{SomeLayout*} which actually are equivalent for Lifetime purposes (just not for Type profile purposes).

When a non-parameter non-member Pointer \texttt{p} is declared, add \{(p, \{\texttt{invalid}\})\} to \texttt{pmap}. If the declaration includes an initialization, the initialization is treated as a separate operation; for example, \texttt{int* p = expr}; is treated as \texttt{int* p /!*= uninitialized*/}; (governed by this section) followed by \texttt{p = expr}; (copying governed by §2.4.4). If the initialization is default initialization or zero initialization, set \texttt{pset(p) = \{\texttt{null}\}}; for example, \texttt{int* p;} results in \texttt{pset(p) == \{\texttt{invalid}\}}, whereas \texttt{int* p{};} or \texttt{string_view p;} results in \texttt{pset(p) == \{\texttt{null}\}}.

When a local Value \texttt{x} is declared, add \{(x, \{x\})\} to \texttt{pmap}.

When a local Owner \texttt{x} is declared, add \{(x, \{x'\})\} to \texttt{pmap}.
Note In a member function of an Owner type, this includes the generated deref__this (see §2.5).

On co_await or co_yield, for every Pointer parameter p, KILL(p). This makes p invalid if it still contains its initial value. For coroutines, the assumption that an argument outlives the call holds until a co_await or co_yield.

On every non-const use of a local Owner o, KILL(o').

On every dereference of a Pointer p, enforce that p is not invalid:

**Rule (lifetime.1)** It is an error to dereference an invalid Pointer.

On every use of a non-Pointer x that has a precondition (e.g., passing it to a function with an [[expects]] contract that mentions x), enforce that x is not invalid:

**Rule (lifetime.1a)** It is an error to use a moved-from object.

When a local variable x goes out of scope, KILL(x) and remove (x, *) from pmap.

Note For a lifetime-extended temporary, as usual it goes out of scope at the end of the lifetime of the reference rather than at the end of the full-expression.

### 2.4.2.1 Example

For example:

```c
// godbolt.org/z/g9C8G6
void f(string param) {
    int* p; // A: pset(p) = {invalid}
    *p = 1; // ERROR (lifetime.1), p is invalid (line A)
    int** pp; // B: pset(pp) = {invalid}
    *pp = &p; // ERROR (lifetime.1), pp is invalid (line B)
    if (cond) {
        // ...
        int x;
        // ...
    } // KILL(x) – invalidates any Pointer to x
    while (cond) {
        // ...
        string s; // KILL(s') – invalidates any Pointer to s’s data
        // (the non-const operation could move s’s buffer)
        // ...
    } // KILL(s) – invalidates any Pointer to s
    // ...
} // KILL(param) – invalidates any Pointer to param
```

### 2.4.3 Unary & (address-of)

Taking the address of a global variable, or public data member or array element thereof, creates a temporary tmp that points to a variable whose duration lasts longer than this function, and so sets pset(tmp) = {static}. 

Taking the address of a local variable \(x\), or public data member or array element thereof, creates a temporary \(tmp\) that points to \(x\), and so sets \(\text{pset}(\text{tmp}) = \{x\}\).

2.4.3.1 Example
For example:

```c
static int i = 0;
void f() {
    &i; // pset(tmp1) = \{static\}
    int j = 1;
    &j; // pset(tmp2) = \{j\}
}
```

2.4.4 Pointer arithmetic

The Lifetime safety profile requires the following rule from the Bounds safety profile:

| Rule | (bounds.1) Raw pointer arithmetic is not allowed. For a raw pointer \(p\) and some other variable \(x\), the following are errors: \(p+x, x+p, p[x], p+=x, ++p, p++, p-x, x-p, p-=x, --p, p--.\) |

Any of these expressions that results in a pointer sets that pointer's \(\text{pset}\) to \{invalid\}. For example:

```c
int x;
int* p = &x;
*p = 1; // ok
int* q = p+1; // ERROR (bounds.1), pointer arithmetic is not allowed
// pset(q) = pset(p+1) which is \{invalid\}
*q = 1; // ERROR (lifetime.1), q is invalid (line A)
```

2.4.5 Copying and moving

When an Aggregate \(a\) is copied or moved from \(\text{rhs}\), the semantics are to copy or move \(a.m\) from \(\text{rhs}.m\) for each element \(m\) of \(a\).

When a Pointer \(p\) is copied from \(\text{rhs}\), set \(\text{pset}(p) = \text{pset}(\text{rhs})\). The Pointer copy is an error if \(p\) has type \text{not_null<>} and \(\text{pset}(\text{rhs})\) contains \text{null}. The Pointer copy is an error if \(p\) is non-local and \(\text{pset}(\text{rhs})\) contains values other than \text{null} and/or \text{static}. If \(\text{rhs}\) has no known \(\text{pset}\) (e.g., is derived from a parameter, in examples like \(p = p->next;\)) assume it is \{static\} (that is, assume \(\text{rhs}\) is valid).

| Rule | (lifetime.1b) It is an error to copy a possibly-null Pointer to a Pointer \(p\) that is declared \text{not_null}. |
| Rule | (lifetime.1c) It is an error to copy a Pointer that could refer to something other than \text{null} or \text{static} to a non-local Pointer. |

| QoI | When copying the \(\text{pset}\), also copy both histories and add the current node to the history if propagating \text{null} or \text{invalid} respectively: |

- Copy \(\text{null_history}(p) = \text{null_history}(\text{rhs})\), then if \(\text{pset}(\text{rhs})\) contains \text{null} additionally append the current node to \(\text{null_history}(p)\). |
- Copy \(\text{invalid_history}(p) = \text{invalid_history}(\text{rhs})\), then if \(\text{pset}(\text{rhs})\) contains \text{invalid} additionally append the current node to \(\text{invalid_history}(p)\). |
Note: Binding a reference \( T & r = \text{rhs}; \) is treated as \( T* r = \&\text{rhs}; \) — i.e., declaring \( r \), taking the address of \( \text{rhs} \), and copying \( \text{pset(tmp)} \) to \( \text{pset(r)} \).

When a Pointer \( p \) is copied from \( \text{rhs} \), and \( p \) is a reference or a non-local variable, \( \text{rhs} \) must not be invalid:

**Rule** *(lifetime.2)* It is an error to copy an invalid Pointer to a Pointer \( p \) that is a reference or a non-local variable.

**Note** Normally these rules diagnose dereferencing an invalid Pointer, not forming one, because this allows local Pointer variable reuse. For a reference, we should make even creating the unusable reference be a build-time error, because the reference is unusable and cannot be rebound to make it usable, so there is no reason to allow this.

When an Owner \( o \) is moved from another Owner \( \text{rhs} \), the ownership moves from \( \text{rhs} \) to \( o \), and so in all psets replace \( \text{rhs} \) with \( o \).

**Note** This is generally useful for STL containers and smart pointers, but will give false negatives (fail to warn on invalidations) for an Owner type whose move does not fully transfer ownership of all internally owned state, such as \( \text{std::string} \) when it performs the small string optimization (for small strings, the buffer does not move to the new object). In the future we can add an annotation for such an Owner to opt out, and state that moving from such an object invalidates all Pointers into the moved-from owner object, instead of tracking them as now pointing into the moved-to owner object.

When an Owner \&\& parameter is invoked so that the \&\& has a pset of \( \{x'\} \), the \&\& is bound to \( x \) and \( x \)'s data will be moved from, so as a postcondition (after the function call) \text{KILL}(x')\).

When a Pointer \( p \) is moved from, the operation is always treated as a copy.

**Note** Pointers follow copy semantics. If there is a move from a Pointer, it is assumed not to change the source.

When a non-Pointer \( x \) is moved from, set \( \text{pset(x)} = \{\text{invalid}\} \) as a postcondition of the function call.

When an Owner \( x \) is copied to or moved to or passed by lvalue reference to non-\text{const} to a function that has no precondition that mentions \( x \), set \( \text{pset(x)} = \{x'\} \). When a Value \( x \) is copied to or moved to or passed by lvalue reference to non-\text{const} to a function that has no precondition that mentions \( x \), set \( \text{pset(x)} = \{x\} \). These pset resets are done before processing the function call (§2.5) including preconditions.

2.4.5.1 Example

For example:

```c
// godbolt.org/z/G3BCOR

void f() {
    int* p = nullptr;       // A: \text{pset(p)} = \text{pset(nullptr)} \text{ which is } \{\text{null}\}
    *p = 1;                 // \text{ERROR (lifetime.1), p is null (line A)}
    int* p2;                // \text{pset(p2)} = \{\text{invalid}\}
    
    {                       // \text{pset(p)} = \text{pset(temp)} = \{s.i\}, p now points to s.i
        struct { int i; } s = \{0\};
        p = \&s.i;
    }
}
```
p2 = p;
*p = 1;
*p2 = 1;
}

*p = 1;
*p2 = 1;

p = nullptr;

int x[100];
p2 = &x[10];
*p2 = 1;
p2 = p;
*p2 = 1;
p2 = &x[10];
*p2 = 1;
int** pp = &p2;
*pp = p;

}  

2.4.5.2 Example: Owner move
For example:

vector<int> v1(100);
int* pi = &v1[0];
auto v2 = std::move(v1);
// pset(pi) = {v1'}
consume(std::move(v1));
// A: pset(iter) = {invalid}, pset(v) = {invalid}
*iter;  
// error, iter was invalidated on line A
v[100];
// error, v is moved-from and [] has a precondition

2.4.5.3 Example: && parameter
For example:

void consume(vector<int>&&);

void test() {
    vector<int> v(1000);
    auto iter = v.begin();  
    // pset(iter) = {v'}
    consume(std::move(v));
    // A: pset(iter) = {invalid}, pset(v) = {invalid}
    *iter;
    // error, iter was invalidated on line A
    v[100];
    // error, v is moved-from and [] has a precondition
}

2.4.6 Local Pointer dereferencing
When a Pointer p is dereferenced using unary * or ->, if pset(p) contains more than one location, processing of the rest of the expression continues distributively with respect to the locations. If a multi-location Pointer value is copied to, the effect is of appending (rather than replacing) the psets. For example:
When a local Pointer `p` is dereferenced using unary `*` or `->` to create a temporary `tmp`, then if `pset(pset(p))` is nonempty, set `pset(tmp) = pset(pset(p))` (i.e., `tmp` is itself a Pointer). Otherwise, set `pset(tmp) = {tmp}`.

QoI If `pset(tmp)` is nonempty, then also copy the `null_history` and `invalid_history` and add the current node to the respective history if `pset(tmp)` contains `null` or `invalid`.

This tracks the second-level points-to set of `p` when `p` is a Pointer to Pointer. For example, given this `pmap`:

```c
{( p, {x, y} ),          // p points to x or y
 ( x, {a, b, c} ),      // x points to a, b, or c
 ( y, {null} )          // y points to null (nothing)
}
```

and that we are processing an ACFG node for the expression `*p`, we insert a new `pmap` tuple:

```c
(tmp, {a, b, c, null} )  // tmp points to a, b, c, or null
```

2.4.6.1 Example

For example:

```c
int* p1 = nullptr;
int* p2 = nullptr;
int* p3 = nullptr;
int* p4 = nullptr;
```

```c
{
    int   i = 0;
    int&  ri = i;                     // pset(ri) = {i}
    p1 = &ri;                         // pset(p1) = {i}
    *p1 = 1;                          // ok
    int*  pi = &i;                     // pset(pi) = {i}
    p2 = pi;                          // pset(p2) = {i}
    *p2 = 1;                          // ok
    int** ppi = &pi;                  // pset(ppi) = {pi}
    **ppi = 1;                        // ok, modifies i
    int* pi2 = *ppi;                  // pset(pi2) = pset(pset(ppi)) which is {i}
    p3 = pi2;                         // pset(p3) = {i}
    *p3 = 1;                          // ok
}
```

```c
{
    int   j = 0;
    pi = &j;                           // pset(pi) = {j} (note: so *ppi now points to j)
    pi2 = *ppi;                        // pset(pi2) = pset(pset(ppi)) but which is now {j}
```
**p1 = 1; // ok
**p2 = 1; // ok
**p3 = 1; // ok
**p4 = 1; // ok

A: KILL(j) → pset(pi) = {invalid},
    pset(p4) = {invalid}, and pset(pi2) = {invalid}

**p1 = 1; // ok
**p2 = 1; // ok
**p3 = 1; // ok
**p4 = 1; // ok

Not that **p1 is never modified after initialization, and so its pset records that it always points only to p1. However, we track that *ppi points first to i and then to j through the changes to pset(pi).

2.4.6.2 Example: Invalidation by modifying Owners

For example:

```c++
auto s = make_shared<int>(0);
int* pi3 = s.get(); // pset(pi3) = {s'} [more on this later]
auto sv = make_shared<vector<int>>(100);
shared_ptr<vector<int>>* sv2 = &sv; // pset(sv2) = {sv}
vector<int>* vec = &*sv; // pset(vec) = {sv'}
int* ptr = &(*sv)[5]; // pset(ptr) = {sv''}
*ptr = 1; // ok
```

```
// track pset of: sv2 vec ptr
//       ----- ----- ------
// IN: sv sv' sv''
vec-> // same as "(*vec)." → pset(*vec) == {sv''}
Lifetime safety: Preventing common dangling

2.4.6.3 Example: Container of containers

Here is a variation on Chris Hawblitzel’s example showing a container of containers.

```
vector<vector<int>> vv;
vector<vector<int>>* vv2 = &vv;  // pset(vv2) = vv
vector<int>* vec = &vv[0];       // pset(vec) = vv'
int* ptr = &(*vec)[5];          // pset(ptr) = vv''
*ptr = 0;                       // ok

// track pset of:     vv  vec  ptr
//                   ---- ---- ----
// IN:     vv  vv'  vv''

vec->push_back(1);             // same as "(*vec)."  → pset(*vec) == {vv''}

// KILL(vv'') because non-const operation
// OUT:     vv  vv'  invalid

*ptr = 1;                      // ERROR, invalidated by push_back
ptr = &(vv[0])[5];            // back to previous state to demonstrate an alternative...
*ptr = 0;                      // ok

vv2->clear();                  // same as "(*vv2)."  → pset(*vv2) == {vv'}

// KILL(vv') because non-const operation
// OUT:     vv  invalid  invalid

*ptr = 2;                      // ERROR, invalidated by clear
```
2.4.7 Branches (fork and join nodes)

Every if scope begins with a “fork node” that has two outbound ACFG edges (true path and false path), and ends with a “join node” where the true and false inbound paths converge (if reachable; that is, unless either or both path unconditionally leads to a function exit before the join).

At each fork node, make a copy of the current pmap for each outbound path.

At each join node, \( pmap = \text{JOIN}(pmap_{\text{true}}, pmap_{\text{false}}) \).

QoI And similarly for null_history and invalid_history.

An if that has no else is treated as if it has an empty else{} block.

A switch\((\text{cond})\) is treated as if it were an equivalent series of non-nested if statements with single evaluation of cond; for example, switch(a){ case 1:/*1*/ case 2:/*2*/ break; default:/*3*/} is treated as if(auto\& a=a; a=1)//*1*/ else if(a=1||a=2)//*2*/ else/*3*/.

A ternary expression \(a?b:c\) is treated as if it were an equivalent if\((a)\){/*b*/}else/*c*/ for path purposes. The language-semantic result of the expression is unchanged (it is still an expression that evaluates to either \(b\) or \(c\)). For example, \(p = \text{cond}?p2:p3\) is treated as if\((\text{cond}) p=p2; \) else \(p=p3\). For example, \(\text{cond}?p2:p3 = p\) is treated as \(p = \text{cond} p2=p; \) else \(p3=p\). For example, auto \(p = \text{cond}?p2:p3\) is treated as auto \(p = /*uninitialized*/; \) if\((\text{cond}) /*\text{construct p from p2}*/; \) else /*construct p from p3*/;

2.4.7.1 Example: Invalidation in both branches

Both branches could invalidate. For example:

```c
// godbolt.org/z/RjQogH
int* p = nullptr; // pset(p) = {null}
if(cond) {
  int i = 0;
  p = &i; // pset(p) = {i}
  *p = 42; // ok
} // A: KILL(i) \rightarrow pset(p) = {invalid}
else {
  int j = 1;
  p = &j; // pset(p) = j
  *p = 42; // ok
} // B: KILL(j) \rightarrow pset(p) = {invalid}
// merge \rightarrow pset(p) = {invalid}
*p = 42; // ERROR, p was invalidated when i went out of scope
// at line A or j went out of scope at line B.
// Solution: increase i's and j's lifetimes, or
// reduce p's lifetime
```

2.4.7.2 Example: Invalidation in one branch

Invalidation on only one branch allows the possibility of “could be invalidated.” For example:

```c
// godbolt.org/z/WqK1wT
int* p = nullptr; // pset(p) = {null}
```
int i = 0;
if (cond) {
    p = &i; // pset(p) = {i}
    *p = 42; // ok
} // no invalidation
else {
    int j = 1;
    p = &j; // pset(p) = {j}
    *p = 42; // ok
} // A: KILL(j) → pset(p) = {invalid}
// merge → pset(p) = {invalid}
*p = 1; // ERROR, p was invalidated when j went out of scope
// at line A. Solution: increase j’s lifetime, or
// reduce p’s lifetime
if (cond) *p = 2; // ERROR, (same diagnostic) even if cond is unchanged

Note The case if (cond) *p; is still an error because the rules must be portable (they must give the same
answer for the same code across implementations without requiring implementations to perform
data-dependent reasoning or be omniscient) and the fix is simple in most cases (increase or de-
crease the lifetime of a specifically named local variable).

2.4.7.3 Example: Invalidation in neither branch
A pointer can be assigned differently on different branches and still be valid after the branches merge. For ex-
ample:

// godbolt.org/z/uXExWo
int* p = nullptr; // pset(p) = {null}
int i = 0;
{
    int j = 1;
    if (cond) {
        p = &i; // pset(p) = {i}
        *p = 42; // ok
    } // no invalidation
    else {
        p = &j; // pset(p) = {j}
        *p = 42; // ok
    } // no invalidation
    // merge → pset(p) = {i,j}
    *p = 42; // ok
}
2.4.8 Null/not-null tests and assertions/branches

For a Pointer $p$:

- a $p$-is-not-null-test means an explicit test that $p$ is not null by comparing it $!=$ to a Pointer $p_2$ for which $pset(p_2) = \{null\}$ only (such as a null pointer constant, `nullptr`) or by using $p$’s conversion to `bool` returning `true`, possibly in combination with other tests using `&`.
- a $p$-is-null-test means an explicit test that $p$ is null by comparing it `==` to a Pointer $p_2$ for which $pset(p_2) = \{null\}$ only (such as a null pointer constant, `nullptr`) or by using $p$’s conversion to `bool` returning `false`, possibly in combination with other tests using `&`.

When a branch can be entered only on success of a Pointer $p$-is-not-null-test, remove null (if present) from $pset(p)$ in that branch path; if testing $p$’s nullness was the entire condition, additionally set $pset(p) = \{null\}$ in the alternate branch path. For example, if($p$) and if($p$==nullptr) and if($p$==0 && cond) remove null from $pset(p)$ in the true branch (and the first two additionally set $pset(p) = \{null\}$ in the false branch), but if($p$==0 || cond) does not.

When a branch can be entered only on success of a Pointer $p$-is-not-null-test, set $pset(p) = \{null\}$ in that branch path; if testing $p$’s nullness was the entire condition, additionally remove null (if present) from $pset(p)$ in the alternate branch path. For example, if($!p$) and if($p$==nullptr) and if($p$==0 && cond) set $pset(p) = \{null\}$ in the true branch (and the first two additionally remove null from $pset(p)$ in the false branch), but if($p$==0 || cond) does not.

When a Pointer $p$-is-not-null test or a $p$-is-null-test “test” is part of a compound if statement condition where the rest will be short-circuited if the test fails (i.e., of the form `if(test && rest)`), the condition is treated as if written `if(test) if(rest)`. This implies that $pset(p)$ will be adjusted as above for the rest expression. For example, given initially $pset(p) = \{null,x\}$, then performing `if(p && p->x)` is as if written `if(p) if(p->x)`, which is valid because at the point of the second condition $pset(p) = \{x\}$.

When an `assert` or `[[assert: ]]` can succeed only on success of a Pointer $p$-is-not-null-test, remove null (if present) from $pset(p)$. For example, `assert(p)` and `[[assert: p!=nullptr]]` and `assert(p==0 && cond)` remove null from $pset(p)$, but `[[assert: p==0 || cond]]` does not.

When an `assert` or `[[assert: ]]` can succeed only on success of a Pointer $p$-is-null-test, set $pset(p) = \{null\}$. For example, `[[assert: !p]]` and `assert(p==nullptr)` and `[[assert: p==0 && cond]]` set $pset(p) = \{null\}$, but `assert(p==0 || cond)` does not.

2.4.8.1 Example: Removing null from a pset to dereference successfully

For example, if a Pointer might be null, code can test for non-null and then use the pointer:

```c
// godbolt.org/z/4dTX9n

int* p = nullptr;  // A: pset(p) = {null}
int i = 0;
if(cond) {
    p = &i;  // pset(p) = {i}
}  // merge: pset(p) = {null,i}

*p = 42;  // ERROR, p could be null from line A
```
if(p) {
    // remove null in this branch → pset(p) = {i}
    *p = 42;
    // ok, pset(p) == {i}
}
// here, outside the null testing branch, pset(p) is still {null,i}

2.4.8.2 Example: Replacing null in a pset with a valid object
For example, if a Pointer might be null, code can test for null and replace it with non-null.

```cpp
// godbolt.org/z/Q-4zwP
int i = 0, j = 0;
int* p = cond ? &i : nullptr; // A: pset(p) = {i, null}
*p = 42; // ERROR, p could be null from line A
if(!p) {
    p = &j; // in this branch, pset(p) = {null}
    // pset(p) = {j}
}
// NOTE: in implicit “else”, pset(p) = {i}
// merge pset(p) = {j} ∪ {i}
*p = 1; // ok, pset(p) = {i,j}, does not contain null
```

2.4.9 Loops
A loop is treated as if it were the first two loop iterations unrolled using an if. For example,
for(/*init*/; /*cond*/; /*incr*/){/*body*/} is treated as if(/*init*/; /*cond*/){/*body*/; /*incr*/}
if(/*cond*/){/*body*/}.

A range-based for loop is treated as if it were textually expanded to its semantic definition in ISO C++
[stmt.ranged] in terms of a non-range-based for loop, then treated as an ordinary for loop as above.

**Note** There are only three paths to analyze: never taken (the loop body was not entered), first taken (the
first pass through the loop body, which begins with the loop entry pmap), and subsequent taken
(second or later iteration, which begins with the loop body exit pmap and so takes into account any
invalidations performed in the loop body on any path that could affect the next loop).

This ensures that a subsequent loop iteration does not use a Pointer that was invalidated during a
previous loop iteration.

Because this analysis gives the same answer for each block of code (always converges), all loop itera-
tions after the first get the same answer and so we only need to consider the second iteration, and
so the analysis algorithm remains linear, single-pass.

As an optimization, if the loop entry pmap is the same as the first loop body exit pmap, there is no
need to perform the analysis on the second loop iteration; the answer will be the same.
2.4.9.1 Example: Loops that do not change psets

Some loops do not change psets used in the loop. For example:

```c
p = &a[0]; // pset(p) = {a}
for( /*...whatever...*/ ) {
    // ...
    if( /*...whatever...*/ ) {
        // ...
        p = &a[i]; // pset(p) = {a}
        // ...
    }
    // ...
}
// merge: pset(p) = {a} /*before loop*/ \cup {a} /*after loop body*) = {a}
*p;
```

In this case, the set of dependencies on input and output did not change and no further action is needed.

2.4.9.2 Example: Loops that do change psets

If instead `p` could be pointed to another object during the loop, we would take the exit pset and then process the loop exactly one more time treating them as entry dependencies to ensure the loop body did not rely on an invalidatable dependency. For example:

```c
p = &a[0]; // pset(p) = {a}
for( /*...whatever...*/ ) {
    // ...
    if( /*...whatever...*/ ) {
        // ...
        p = &b[i]; // pset(p) = {b}
        // ...
    }
    // ...
}
// merge → pset(p) = {a,b}
// ...
merge: pset(p) = {a} /*before loop*/ \cup {b} /*in loop body*) = {a,b}
```

// that’s different from entry, so process loop one more time with {a,b}:

```c
for( /*...whatever...*/ ) {
    // ...
    if( /*...whatever...*/ ) {
        // ...
        p = &b[i]; // pset(p) = {b}
        // ...
    }
    // merge → pset(p) = {a,b} again/still
    // ...
}
```

// pset(p) = {a,b} still
2.4.9.3 Example: Loops that invalidate
If the loop body could invalidate, we get a possibly invalid exit dependency:

```cpp
// godbolt.org/z/_midIP
p = &a[0];  // pset(p) = {a}
for( /*...whatever...*/ ) {
    *p = 42;
    p = nullptr;  // A: pset(p) = {null}
    // ...
    if( /*...whatever...*/ ) {
        // ...
        p = &b[i];  // pset(p) = {b}
        // ...
    }
    // merge \rightarrow pset(p) = {null,b}
    // ...
}
// pset(p) = {null,a,b}  // that’s different from entry, so process loop one more time with {null,a,b}:
for( /*...whatever...*/ ) {
    *p = 42;  // ERROR, could be null from assignment to p at line A in a previous iteration
    p = nullptr;  // A: pset(p) = {null}
    // ...
    if( /*...whatever...*/ ) {
        // ...
        p = &b[i];  // pset(p) = {b}
        // ...
    }
    // merge \rightarrow pset(p) = {null,b}
    // ...
}
// pset(p) = {null,a,b} still
```

2.4.9.4 Example: Loops that allocate (and `owner<>` vs. `unique_ptr`)
Some loop bodies allocate:

```cpp
p = &a[0];  // pset(p) = {a}
bool must_delete = false;
for( /*...whatever...*/ ) {
    // ...
    if( /*...whatever...*/ ) {
        // ...
        p = new A  // A: pset(p) = {temp'}
            ;  // KILL(temp) \rightarrow pset(p) = {invalid}
        must_delete = true;
        // ERROR: no delete of owner<> returned from new
```
if (must_delete)
    delete p;     // ERROR, delete of non-owner<> is not lifetime-safe

Solution: Have more than one pointer. In this case a unique_ptr is appropriate and replaces the explicit flag, so we net out to zero additional variables (and less code since we can omit the explicit fragile delete check).

    p = &a[0];       // pset(p) = {a}
    unique_ptr<A> up;  // initially null
    for (/*...whatever...*/ ) {
        // ...
        if (/*...whatever...*/) {
            // ...
            up = make_unique<int>();
            p = up.get();       // ok, pset(p) = {up'}
            // ...
        }
        // merge: pset(p) = {a, up'}
        // ...
    }
    // merge: pset(p) = {a} /*before loop*/ ⊖ {a, up'} /*loop body*/ = {a, up'}

    // that's different from entry, so process loop one more time with {a,up'}:
    for (/*...whatever...*/ ) {
        // ...
        if (/*...whatever...*/) {
            // ...
            p = (up = new A).get();       // ok, pset(p) = {up'}
            // ...
        }
        // merge: pset(p) = {a,up'}
        // ...
    }
    // pset(p) = {a,up'} still

    if (p)
        *p = 42;         // ok
2.4.10 **try and catch**

A `try {/*1*/} catch {/*2*/} {/*3*/}` block is treated as if it were a branch of the form `/*1*/ if (invented bool condition) {/*3*/}`. In particular, if control flow could proceed normally out of block 3 because an exception has been handled, the `pmaps` at the end of blocks 1 and 3 are JOINed.

Additionally, within a `try` block, at every non-noexcept node `n` take a copy `pmap_n` of the current `pmap`. Apply any KILL operation within or at the end of the `try` block to all `pmaps`. On entry of the corresponding `catch` block, `pmap = JOIN(pmap_1, ..., pmap_n`.

Note  The `catch` block as if it could have been entered from every point in the `try` block where an exception could have been raised. As an optimization, instead of taking full copies of the `pmap`, an implementation could store deltas.

This case is a clear win and we expect this to catch many mistakes.

For an exception caught by reference via `catch(cv-qualified E& e)`, the reference is treated as a raw pointer and has pset `{static}`.

2.4.10.1 **Example: catch**

For example:

```cpp
int i = 0;
int *p1 = &i, *p2 = p1;
try {
    int j = 0;
    p1 = &j;
    could_throw();
    p1 = &i;
    could_throw();
    p2 = &j;
    could_throw();
} // // A: pset(p1) = {j}
    // pset(p1) = {i}
    // B: pset(p2) = {j}

    // KILL(j) → kills j in all pmap copies

    catch(...) {
        // join: pset(p1) == pset(p2) == {i, invalid}
        // ERROR, invalidated by assignment to p1 on line A
        *p1 = 42; // ERROR, invalidated by assignment to p2 on line B
        *p2 = 42;
    }
```

2.4.10.2 **Example: throw**

Unlike a `return`, the type of an `throw` object cannot be carried through function signatures. Therefore, do not throw a `Pointer` with lifetime other than `static`. For example:

```cpp
// godbolt.org/z/p_QjCR
static int gi = 0;
void f() {
    int i = 0;

    throw &i; // ERROR
    throw &gi; // OK
}
```
2.5 Calling functions

When the analysis sees a function call, apply the following model to simulate an output behavior that is consistent with the Lifetime rules for the callee.

#### Note
All defaults are only for convenience to minimize annotation in the common case. Defaults are never central to the analysis method, and so they can use heuristics.

The following rules are applied consistently when separately analyzing each side of the function call:

- When analyzing the call site, the rules apply to arguments, and the call site enforces preconditions and assumes postconditions.
- When analyzing the callee definition, the rules apply to parameter, and the callee definition assumes preconditions and enforces postconditions. Postconditions are enforced after every parameter \( x \)’s end-of-scope \( \text{KILL}(x) \) has been done but before \( x \)’s tuple is removed from \( \text{pmap} \).

Definitions and general rules:

- \( \text{argument}(x) \) means the name at a given call site for the argument to the function input \( x \) or a function output \( x \). For a generated \( \text{deref__param} \) parameter, \( \text{argument(deref__param)} \) means \( \ast \text{argument(param)} \) at the call site.
- Treat a parameter declared as \( \ast \)\[gsl::lifetime_const\] \( X \& \) as if declared \( \text{const} X \& \).
- Treat \( \text{this} \) (if present) as if it were declared with \( \text{not_null} \).
- For each reference parameter, treat the reference as if it were a \( \text{not_null} \) pointer.
- \&\& intentionally means both rvalue references and forwarding references.

2.5.1 Expand parameters and returns: Aggregates, nonstatic data members, and Pointer dereference locations

For each Aggregate parameter \( \text{agg} \) passed by value, \( \ast \), or \&, treat it as if it were additionally followed by a series of generated element parameters \( \text{agg__m} \) for each element \( m \) of \( \text{agg} \). (Note: This includes \( \text{this} \) when the type of \( \ast \text{this} \) is an Aggregate.) For example, given \text{struct Agg} \{ \text{int} i; \text{char}\ast p; \}, we expand:

- \( f(\text{Agg a}) \) to \( f(\text{Agg a, int} \ a.i, \text{char}\ast \ a.p) \)
- \( f(\text{Agg} \ast a) \) to \( f(\text{Agg} \ast a, \text{int}\ast \ a.i, \text{char}\ast\ast \ a.p) \)
- \( f(\text{Agg}& a) \) to \( f(\text{Agg}& a, \text{int}& \ a.i, \text{char}\&\& \ a.p) \)

If the type of \( \ast \text{this} \) is not an Aggregate, treat each nonstatic data member \( m \) of \( \ast \text{this} \) as a parameter passed by value if in a constructor (and on function entry they are treated as described in §2.4.2) or by reference otherwise (and on function entry they are treated as described in this section).

For each Pointer parameter \( p \), treat it as if it were additionally followed by a generated \( \text{deref__p} \) parameter of the same type as \( \ast p \). These are treated as distinct parameters.

Apply recursively to nested Aggregates’ by-value data members.

For an Aggregate return value returned by value (not by \( \ast \) or \&), treat it as if it were multiple return values, one for each element \( m \) of \( \text{agg} \) that is a Pointer.
2.5.2 Create the input sets

The set Input includes:

- Every parameter of any type X that is passed by value, X&, const X&, X&&, or as the X* this parameter.
- Every reference (for X&, const X&, X&& parameters), treated as a Pointer.

Note that, for a Pointer type P and the function signature f(const P&), Input contains the P and the & treated as a Pointer.

For example:

```cpp
void f(int a, int* b, int& c, int** d, int*& e); // {a, b, c, deref_c, d, e, deref_e}
void m(T* this); // {this, deref_this}
```

The sets Pin and OIn (Pointer and Owner Inputs) includes:

- Every parameter in Input that has type Pointer or Owner, respectively, except:
  - not if it is annotated [[gsl::lifetime_out]]
  - not if it is the Owner or the reference of Owner&& or const Owner& (i.e., neither Owner, nor its & or && treated as a Pointer)

**Note** Includes this so that member functions that return class references work. Includes the deref location of this for Pointer or Owner member functions, which allows Owner/Pointer member functions like data() to work.

For example:

```cpp
void f(Owner o, Owner& ro, const Owner& cro) // OIn = {ro, deref_ro}
```

The set OIn_weak includes (these are “weak rvalue magnets” because they can bind to rvalue arguments):

- The Owner and reference of every const Owner& parameter in Input (i.e., the Owner, and the & treated as a Pointer).

**Notes** This allows functions to return a Pointer to the Owner itself or to the data owned by the Owner.

The point of treating an Owner this way in the function inputs is that we only care about Owners that will outlive the call, and a reference to Owner is the idiomatic way to refer to an Owner in the scope of the caller. We strip the reference off because we only care about the Owner’s identity at the call site. If in the future we add the concept of a SharedOwner, for example to model shared_ptr distinctly from unique_ptr, then it would make sense to consider SharedOwner parameters passed by value, since Pointers derived from them can still sensibly outlive the function call.

For example:

```cpp
void f(Owner o, Owner& ro, const Owner& cro) // OIn_weak = {cro, deref_cro}
```

The set Vin includes:

- All the elements of Input that are Values.
On function entry, for every $p \in \text{Pin}$, a Pointer function input can be lifetime-annotated with \([\text{gsl::lifetime}(p,\{x\})]\) where $x \in \text{Pin} \cup \text{0in} \cup \{\text{static}\} \cup \{\text{null}\} - \{p\}$. The annotation may appear on the parameter, in which case “$p$,” can be omitted, or on the function itself. This expresses that $p$ must have the same lifetime as $x$. For example, void $f(int^* p, int^* p2 [[\text{gsl::lifetime}(\{p\})]])$ expresses that $p2$ must point to the same thing as $p$.

On function entry, for every $p \in \text{Pin}$:

- If $p$ is explicitly lifetime-annotated with $x$, then each call site enforces the precondition that $\text{argument}(p)$ is a valid Pointer and $\text{pset}(\text{argument}(p)) \equiv \text{pset}(\text{argument}(x))$ and both $\text{psets}$ have a single entry, and in the callee on function entry set $\text{pset}(p) = \text{pset}(x)$.
- Otherwise, if $p$ is a generated element parameter $\text{agg\_m}$ and $\text{agg}$ is a Pointer, then it behaves as if annotated $\text{agg\_m, \{\text{agg}\}}$. For example, given struct $\text{Agg}$\{ int* $p$; int i; \}; and applying all the foregoing rules, the signature $f(\text{Agg\_agg, int* agg\_p [[\text{gsl::lifetime}(\{\text{agg}\})]]})$ is treated as if written $f(\text{Agg\_agg, Agg deref\_agg, int* agg\_p [[\text{gsl::lifetime}(\{\text{agg}\})]], int* deref\_agg\_p, int* agg\_i [[\text{gsl::lifetime}(\{agg\})]], int deref\_agg\_i)$.
- Otherwise, each call site enforces the precondition that $\text{argument}(p)$ is valid, and in the callee on function entry set $\text{pset}(p) = \{\text{deref\_p}, \text{null}\}$.

Then in all cases:

- If $p$ is declared \text{not\_null}, then each call site enforces the precondition that $\text{pset}(\text{argument}(p))$ must not contain \text{null}, and in the callee remove \text{null} (if present) from $\text{pset}(p)$.
- Each call site enforces the precondition that no entry in $\text{pset}(\text{argument}(p))$ refers to a non-\text{const} global Owner, a local Owner being passed by reference to non-\text{const} to the same function call, or a local Owner mentioned in a $\text{pset}$ of another Pointer being passed to the same function call; and in the callee on function entry record the additional entry $\text{pset}(p: \text{in}) = \text{pset}(p)$.

On function entry, for every other $v \in \text{Vin}$:

- Each call site enforces the precondition that, if this function has a precondition that mentions $v$, $\text{pset}(\text{argument}(v))$ must be valid. (Note: For Owners and Values, this verifies they have not been moved-from.)

\begin{itemize}
  \item \textbf{Rule (lifetime.3)} Except for the this parameter of a Pointer constructor, it is an error to pass a Pointer as a function argument if it is invalid, if it violates the parameter’s $\text{[gsl::lifetime]}$ precondition, or if its $\text{pset}$ refers to a non-\text{const} global Owner, a local Owner being passed by reference to non-\text{const} to the same function call, or a local Owner mentioned in a $\text{pset}$ of another Pointer being passed to the same function call.
\end{itemize}

\begin{itemize}
  \item \textbf{Note} Note that if a Pointer parameter $p$'s $\text{pset}(p)$ refers to Owner inputs (e.g., $\text{[gsl::lifetime}(\{p\}), o]$) $f(int^* p, \text{string}\& o)$, its input value can be invalidated as usual by modifications of Owner inputs in the function body (e.g., if the first line in $f$'s body modifies $o$, $p$'s initial value is invalidated).
\end{itemize}
2.5.4 Create the output sets

The set Output means the empty set for a constructor, otherwise includes:

- All return values.
- All parameters passed by Pointer to non-const where the top-level Pointer is not a &amp;&amp; reference (and is not considered to include the top-level Pointer, because the output is the pointee).

Note Parameters passed by &amp;&amp; are excluded because they are assumed to be moved/forwarded on entry or during the body of the function.

For example, void f(int&amp;) and void f(int**) are each considered to have a single function output of type int*, just the same as int* f(); For example, void f(vector&lt;deque&lt;int&gt;&gt;::iterator) is considered to have one function output of type deque&lt;int&gt;&gt;::iterator.

The set Pout is the set of function outputs that are Pointers.

The set Oout is the set of function outputs that are Owners.

2.5.5 Validate outputs: Enforce in callee, assume in caller

For every Owner o in Oout, at each call site reset pset(argument(o)) = {o’}.

Notes Includes this so that calls to an Owner’s non-const member function resets the Owner.

A Pointer function output ret can be lifetime-annotated with [[gsl::lifetime(ret, {s})]] where s \subseteq Pin \cup Oin \cup \{static\} \cup \{null\}. To refer to the return value, ret is return; to refer to a dereferenced Pointer to Pointer parameter p, ret is *p. This expresses that ret points to what one of s points to. For example, int* f(int* p, int* p2, string o) [[gsl::lifetime{return, {p, o}}]] expresses that the returned pointer points to either what p pointed to on input or data that o owned on input. For a set s, s:in means \{x:in \mid x \in s\}. For every ret \in Pout:

- In the callee on function exit, enforce that pset(ret) is substitutable for pset(s:in).

Rule (lifetime.4) It is an error on function exit for a Pointer function output to be invalid or to violate its postcondition.

Note Because only parameters and static can be referred to as postcondition requirements, typically this means pset(ret) \subseteq pset(s:in) or pset(ret) == \{static\}.

- Each call site uses the postcondition by setting pset(argument(ret)) = pset(argument(s)).

If a ret \in Pout is not explicitly lifetime-annotated, then it is treated as if annotated as follows, where Pin_{ret}, Oin_{ret}, and Oin_{weak_{ret}} are the respective subsets of Pin, Oin, and Oin_{weak} that have the same type as ret or are convertible to the type of ret:

- If Pin_{ret} and Oin_{ret} are not both empty, then as if declared [[gsl::lifetime{ret, {Pin_{ret} \cup Oin_{ret}}}]].

  For example, for int* f(int x, int* p, string_view sv, string&amp; s, const string&amp; s2, the return value is as if declared [[gsl::lifetime{return, {p}}]]. That is, by default the Pointer function output is assumed to be either a copy of one of its Pointer inputs of the same type or to point to data owned by one of its Owner inputs owning the same type.
• Otherwise, if \( \text{Pin\_weak} \) is not empty, then as if declared \([gsl\::\text{lifetime}(\text{ret},{\text{Pin\_weak}\_\text{ret}})])]. For example, for \( \text{char* f} (\text{x, const string& s2}) \), the return value is as if declared \([gsl\::\text{lifetime} (\text{return,\{s2\}})])]. That is, the next fallback is that the Pointer function output is assumed to point to data owned by one of its weak rvalue magnet inputs of the same type (the actual argument is not necessarily an rvalue, and when it is an rvalue the caller will diagnose that).

• Otherwise, if \( \text{Pin} \) and \( \text{Oin} \) are not both empty, then as if declared \([gsl\::\text{lifetime}(\text{ret},{\text{Pin} \cup \text{Oin}})])]. That is, the Pointer function output is assumed to be either a copy of one of its Pointer inputs or to point to data owned by one of its Owner inputs, without matching types.

• Otherwise, if \( \text{Oin\_weak} \) is not empty, then as if declared \([gsl\::\text{lifetime}(\text{ret},{\text{Oin\_weak}})])]. That is, the Pointer function output is assumed to point to data owned by one of its weak rvalue magnet inputs, without matching types.

• Otherwise, \{static\}. That is, since there are no Pointer or Owner whose lifetimes are known at the call site, every Pointer function output is assumed to point to a global variable.

Notes The goal of these defaults is to minimize total annotation by recognizing that functions commonly return values derived from their inputs.

If a parameter is both an input and an output (e.g., a Pointer type’s this parameter), do not allow it to bind to itself. This would cause invalid to flow through Pointer constructor calls.

Each call site applies the postcondition that for every \( \text{ret} \in \text{Pout} \), on function exit record \( \text{pset} (\text{argument(ret)}) = \text{pset}(\text{ret}) \).

2.5.6 Examples

2.5.6.1 Example default output psets

For example:

```cpp
// The default pset for the return value is:

int* f();                        // {static}
int* f(int* p, int* p2);         // pset(p) \cup pset(p2)
int* f(shared_ptr<X>& o);        // \{o'\}
int* f(vector<X>& o, string& o2); // \{o', o2'\}
```

For example:

```cpp
template<class T> int* f(const T&);
auto sp = make_shared<vector<int>>(100);
f(sp);                          // pass: shared_ptr<vector<int>>& with pset=={sp}
   // return: pset = {sp'}
f(*sp);                          // pass: vector<int>& with pset == {sp'}
   // return: pset = {sp''}
f(sp->begin());                  // pass: vector<int>::iterator& with pset=={sp''}
   // return: pset = {sp'''}
f((*sp)[5]);                      // pass: int& with pset == {sp''}
   // return: pset = {sp'''}
```
2.5.6.2  Example: Owners

For example, consider \texttt{shared_ptr\langle int\rangle::get()}, where the only argument is the \texttt{this} pointer to an Owner:

\begin{verbatim}
// godbolt.org/z/1xAGOH
auto sp = make_shared<int>(0);
int* p = sp.get();       // pset(p) = pset(sp.get()) which is \{sp'
*p = 42;              // ok
sp = make_shared<int>(1);  // KILL(sp') \rightarrow pset(p) = \{invalid
*p = 42;              // ERROR
\end{verbatim}

2.5.6.3  Example: \texttt{std::move} and \texttt{std::forward}

\textbf{Note}  The parameters of \texttt{std::move} and \texttt{std::forward} should be annotated [[\texttt{gsl::lifetime\_const}]].

See §2.5.6.10 Note.

Consider a function template like \texttt{std::move} that returns a parameter. (\texttt{std::forward} is handled similarly.)

\begin{verbatim}
template<class T> constexpr typename
    // if T is not an Owner
    std::remove_reference<T>::type&&
    // pset(ret) = pset(t) = \{t
move([[\texttt{lifetime\_const}]] T&& t)
    { return t; }       // ok, \{t\} is substitutable for \{t
\end{verbatim}

Calling code can reason on the lifetime that flows through \texttt{move}:

\begin{verbatim}
string_view s1, s2;
s1 = move(s2);       // ok, pset(s1) = pset(ret) = pset(arg) = pset(s2)
\end{verbatim}

2.5.6.4  Example: \texttt{std::min} and \texttt{std::max}

Consider \texttt{std::min}, which returns one of its input references. (\texttt{std::max} is handled similarly.)

\begin{verbatim}
template<class T>
    // if T is not an Owner
    const T&
    // pset(ret) = \{a,b\},
min(const T& a, const T& b) {
    return b < a
    ? b
    : a;         // ok, \{b\} is substitutable for \{a,b
\end{verbatim}

In calling code, this prevents known lifetime errors, including improving existing C++ code. For example, here is a problem reported by a number of people including Andrei Alexandrescu: Because \texttt{std::min} returns a reference, if a call to \texttt{min(x,y)} might change under maintenance to \texttt{min(x,y+1)} we could get a dangling reference if \texttt{min} returns a reference to \texttt{y+1}, which would be invalidated when the temporary is destroyed after the end of the call expression in which it appears:

\begin{verbatim}
// godbolt.org/z/1C4t8m
int main() {
    auto x=10, y=2;
    auto& good = min(x,y);       // ok, pset(good) == \{x,y
    cout << good;              // ok, 2
    auto& bad = min(x,y+1)   // A: IN: pset(\texttt{arg1})==\{x,
    //      pset(\texttt{arg2})==\{temp(y+1)
    //      \texttt{min()} returns temp2
\end{verbatim}
In normal C++, this code compiles but has undefined behavior.

**Note** In practice, on the three major compilers (gcc, VC++, clang) this code does not crash and appears to work. That’s because one manifestation of “undefined behavior” can be “happens to do what you expect.” Nevertheless, this is undefined and its appearance of working makes the error more pernicious, not less so; slightly different examples will visibly break.

If this code had instead used `max` instead of `min`, therefore returning a reference to the first argument, there would have been no undefined behavior in normal C++ but these rules (I think rightly) would still reject it as statically unsound, having data-dependent safety.

### 2.5.6.5 Example: Meyers Singleton

Consider the classic Meyers Singleton, where the default returned `pset` is `{static}` because there are no Pointer or Owner parameters:

```cpp
// godbolt.org/z/sKIltx
widget& get_widget() {
    static widget w;
    return w;
}
```

### 2.5.6.6 Example: Return Pointer that must be invalid (e.g., to local)

In a function body, it is a lifetime error to return a pointer that must be invalid, either as a return value or through an inout/out parameter.

```cpp
// godbolt.org/z/vC5g6G
int* f() {
    int i = 0;
    return &i; // pset(&i) = {i}, then KILL(i) → pset(ret) = {invalid}
    // ERROR, {invalid} is not substitutable for {static}
}

void g(int*& pi) {
    int i = 0;
    pi = &i; // KILL(i) → pset(pi) = {invalid}
    // ERROR, pi is non-const& so pset(pi) checked on exit,
    // and {invalid} is not substitutable for {static}
}
2.5.6.7 Example: Return indirection that may be invalid (e.g., to local)
In a function body, it is a lifetime error to return a pointer that could be invalid, either as a return value or through an inout/out parameter.

```c
// godbolt.org/z/53qeAD
int* f(int* pi) {
    int i = 0;
    return cond ? pi : &i;  // pset(expr)={pi,i}, KILL(i) → pset(expr)={invalid}
    // ERROR, {invalid} is not substitutable for {pi}
}
void g(int*& pi, int* pi2) {
    int i = 0;
    pi = cond ? pi2 : &i;
    // pset(pi)={invalid}
    // ERROR, pi is non-const& so pset(pi) checked on exit
    // and {invalid} is not substitutable for {pi2}
```

2.5.6.8 Example: Calling a function that returns an indirection
For example:

```c
// godbolt.org/z/-exrN7
int* f();  // pset(ret) = {static}
int main() {
    int* p = f();  // pset(p) = {static}
    *p = 42;  // ok
}
```

2.5.6.9 Example: Passing indirections
Non-const Pointer parameters can be reused as usual in the function body:

```c
// In function bodies
//
void f(int* p) {  // pset(p) = {p}
    p = something_else;  // ok, now points to something else
    // ...
}
void g(shared_ptr<int>& s, int* p) {  // pset(s) = {s'}, pset(p) = {p}
    s = something_else;  // KILL(s') → no local effect, does not kill p
    // ...
    // pset(p) == {p}, unchanged
}
```

// At call sites
//
int gi = 0;
shared_ptr<int> gsp = make_shared<int>();
int main() {

// passing global and local objects
f(&gi);         // ok, pset(arg) == {static}
int i = 0;
f(&i);          // ok, pset(arg) == {i}
f(gsp.get());   // ERROR (lifetime.3), pset(arg) == {gsp'}, gsp is global
auto sp = gsp;
f(sp.get());    // ok, pset(arg) == {sp'}, sp's address has not been taken
g(sp, sp.get()); // ERROR (lifetime.3), pset(arg2) == {sp'}, sp being passed
g(gsp, sp.get()); // ok, pset(arg2) == {sp'}, sp not being passed
}

Note  This diagnoses the #1 correctness error using smart pointers, and with a clear message highlighting the key variable names. (The #1 performance error using smart pointers is covered under the foundation coding guidelines profile, which diagnoses needlessly passing smart pointer copies.)

2.5.6.10  Example: Explicitly overriding defaults
Sometimes you want to override the defaults. For example, consider two standard container member functions:

- The insert-with-hint insert(iter,t) assumes that the iterator is into this container, which is not the default (and would not be allowed by the earlier rule that iter could be invalidated by this insert). We can express this using [[gsl::lifetime(iter,{this})]].
- The range-based insert insert(iter1,iter2) assumes that the passed iterators are not into this container, which is the default. It also assumes that iter1 and iter2 have the same lifetime, which is not the default; we can express this using [[gsl::lifetime(iter2,{iter1})]].

Result:

template<class Key, class T, /*...etc...*/>
class map {
public:
  iterator insert(const_iterator pos [[gsl::lifetime({this})]],
                  const value_type&);

  template <class InputIterator>
  void insert(InputIterator first,
              InputIterator last [[gsl::lifetime({first})]]);

    // ... more insert overloads and other functions ... 
};

map<int,string> m = {{1,"one"}, {2,"two"}}, m2;
m.insert(m2.begin(), {3,"three"});  // ERROR, pset(m2.begin()) != {m'}
m.insert(m.begin(), {3,"three"});   // ok, pset(m.begin()) == {m'}
m.insert(m.begin(), m.end());      // ERROR, psets=={m'}, and m is passed as non-const&
m.insert(m2.begin(), m.end());     // ERROR, psets are not equal
m.insert(m2.begin(), m2.end());    // ok, pset == {m2'}, and m2 is not passed to insert
Notes This statically diagnoses several common classes of STL iterator bugs.

There are patterns, notably iterator pairs. For example, every standard library function that has Pointer (iterator) parameters named `first` and `last` should annotate `last` `[[gsl::lifetime(last,{first})]]`.

Non-const `begin()` and `end()`, non-member `std::begin()` and `std::end()`, and the parameters of `std::move` and `std::forward`, should be annotated `[[gsl::lifetime_const]]`.

For containers where insertion (if available) does not invalidate iterators, likely all non-const member functions except `erase` should be additionally annotated `[[gsl::lifetime_const]]`. This includes `array`, `forward_list`, `list`, `set`, `multiset`, `map`, `multimap`, `unordered_set`, `unordered_multiset`, `unordered_map`, `unordered_multimap`.

The `this` parameter of a constructor or assignment operator is always treated as if annotated `[[gsl::lifetime_out]]`.

We should make a list of all the annotations we want for standard library functions, and then for convenient adoption without modifying existing standard library headers, treat those standard library functions as if they were so annotated (as in §2.1 for Owner and Pointer types).

2.5.6.11 Example: Pointer swap

Another example of overriding the defaults is for `std::swap` for Pointers.

```cpp
template<Pointer T> // assumes a Pointer concept
[[gsl::lifetime(*a,{*b})]] [[gsl::lifetime(*b,{*a})]] swap(T& a, T& b)
{ T tmp = a; a = b; b = tmp; } // no need for std::move, Pointers are copyable
```

2.5.6.12 Example: Lifetime-const

The lifetime-annotation `[[gsl::lifetime_const]]` on a member function of an Owner type means to treat this Owner object argument as if declared `const` for the purpose of lifetime invalidation, and on a reference parameter of Owner type means to treat the argument as if declared `const` for the purpose of lifetime invalidation.

Note We don’t have a use case yet for going the other way, but we could also provide the opposite annotation `[[gsl::lifetime_mutable]]` if we ever find an example where a `const` Owner parameter `o` may actually invalidate data owned by `o` (which seems weird).

For example, given a `vector<T>` consider two non-const member functions, one of which invalidates pointers/iterators into the vector and one of which doesn’t:

```cpp
void push_back(const T& t) { // can move storage
    if (/* need to grow */) {
        // ...
        data = /* some new buffer, and copy old data */;
        // ...
    }
    // ...
}

T& operator[](size_t n) [[gsl::lifetime_const]] { // won’t move storage
    return data[n];
}
```
We benefit by annotating `operator[]` to treat it as though it were `const`, because even though it is a non-`const` operation, `operator[]` does not perform non-`const` operations on its structure—and therefore does not invalidate references previously obtained from `operator[]` (or equivalently `front()`, etc.). If this is communicated to the caller, then a caller that has a Pointer `int* pi` referring to an `int` inside a `vector<int> v` can know that calling `v[0]` does not invalidate `pi`, whereas calling `v.push_back(42)` does invalidate `pi`.

**Note**  It is debatable whether STL made the right design decision in not distinguishing structure from contents—that is, failing to treat the container’s own structure distinctly from the contained elements. But STL isn’t alone here, and many C++ libraries have followed such a convention; the lifetime annotation provides a way to tactically add the arguably “missing” `const`. The STL might be a better library if it treated `vector<int>` and `vector<const int>` distinctly; that is, the constness of the elements is distinct from the constness of the container. Then `vector` would mark `operator[]` as a `const` function; and a `vector<int>::iterator` could be allowed to convert to a `vector<const int>::iterator`, avoiding the need for the `const_iterator` oddity. Something to think about for STLv2.

Granted, this complaint does not apply equally to `map`, which we consider next.

Similarly, given a node-based container `map<T>`, consider two non-`const` member functions, one of which invalidates pointers/iterators into the map and one of which doesn’t:

```cpp
/*...*/ erase(const T& t) { // can invalidate
  // ...
}
/*...*/ insert(const T& t) [[gsl::lifetime_const]] { // won’t invalidate
  return data[n];
}
```

**Note**  This is not the same structure-vs-contents situation as `vector`, but rather a node-based lifetime semantics situation. However, the approach works the same way for lifetime invalidation purposes; by saying “consider `insert` as a const operation for lifetime invalidation purposes” we express the correct semantics, that `erase` is a function that should be assumed to invalidate pointers and iterators into the container, but `insert` is not.

In both cases, we will flag potential false positives: For `vector`, when `push_back` does not really invalidate because of a careful earlier `reserve` we diagnose invalidation anyway, but such code is arguably has data-dependent correctness so we feel correct in diagnosing it. For `map`, when `erase` removes only one node (or a few) we diagnose invalidation of all pointers and iterators into the map, not just ones to those nodes; this is a stronger conservatism and source of false positives.
2.6 Additional examples

2.6.1 From StackOverflow

Back in 2015, an hour before I was about to add a usage example here of how the above rules and implementation of `unique_ptr` detect lifetime errors, the following was posted on StackOverflow, so let’s use this example.

```cpp
unique_ptr<A> myFun()
{
    unique_ptr<A> pa(new A());
    return pa;
}
const A& rA = *myFun();
```

This code compiles but `rA` contains garbage. Can someone explain to me why is this code invalid?

Under this lifetime profile, the rules mechanically diagnose the problem and give the answer. The convention in this paper is to diagnose the problem at the point the code attempts to use the invalidated local pointer or reference, and so we have the ability to diagnose:

```cpp
// godbolt.org/z/4G-8H-
const A& rA = *myFun();
```

In the first line, `myFun` returns a temporary `unique_ptr` (call it `temp_up`), then unary * returns a temporary reference `temp_ref` with `pset(temp_ref) = temp_up`, then `temp_up` is destroyed which implies `KILL(temp_up) → pset(temp_ref) = invalid`, and finally that is copied to initialize `pset(rA) = invalid`.

As noted earlier, we diagnose the error at the creation of the unusable reference, since references cannot be reseated and so this initialization is just always nonsense.

The poster added a coda:

**Note: if I assign the return of `myFun` to a named `unique_ptr` variable before dereferencing it, it works fine.**

Indeed it does:

```cpp
auto local = myFun(); // ok, local assumes ownership
const A& rA = *local; // ok, pset(rA) = {local}
use(rA); // ok, we know that local is keeping rA alive
```
2.6.2 From P0936R0 (Richard Smith, Nicolai Josuttis)
The examples in [P0936R0] are diagnosed by this proposal without annotation. Note that we deliberately diagnose only when attempting to actually use an invalid Pointer, because it is common for a Pointer to be temporarily invalidated and then set to a valid value before being used again.

2.6.2.1 Example: string_view initialized from string literal
This example is correctly diagnosed by this proposal without annotation. (basic_string meets the Container requirements and so is automatically recognized as an Owner type, and basic_string_view meets the Range requirements and so is automatically recognized as a Pointer type.)

```cpp
// godbolt.org/z/dymV_C
std::string_view s = "foo"s;   // A
s[0];                      // ERROR (lifetime.3): ‘s’ was invalidated when // temporary ‘"foo"s’ was destroyed (line A)
```

2.6.2.2 Example: string_view initialized from temporary string
This example is correctly diagnosed by this proposal without annotation. (basic_string meets the Container requirements and so is automatically recognized as an Owner type, and basic_string_view meets the Range requirements and so is automatically recognized as a Pointer type.)

```cpp
// godbolt.org/z/0aeHPp
std::string operator+ (std::string_view s1, std::string_view s2) {
    return std::string{s1} + std::string{s2};
}
std::string_view sv = “hi”;    // A
sv = sv + sv;                  // ERROR (lifetime.3): ‘sv’ was invalidated when // temporary ‘"foo"s’ was destroyed (line A)
```

2.6.2.3 Example: string_view initialized from temporary string via template
This example is correctly diagnosed by this proposal without annotation. (basic_string meets the Container requirements and so is automatically recognized as an Owner type, and basic_string_view meets the Range requirements and so is automatically recognized as a Pointer type.)

Note that the diagnosis happens even earlier than P0936 asks for, because we notice the dangling pointer during instantiation of template add<std::string_view>.

```cpp
// godbolt.org/z/IsPG8P
std::string operator+ (std::string_view s1, std::string_view s2) {
    return std::string{s1} + std::string{s2};
}
template<typename T>
T add(T x1, T x2) {  // for T == string_view, pset(ret) = {x1,x2}, // pset(x1) = {x1}, pset(x2) = {x2}  // A: ERROR (lifetime.4): {tmp} was invalidated  // when temporary ‘x1 + x2’ was destroyed (line A)
    return x1 + x2;
}
sv = add(sv, sv);
```

For a variation of this example, see also std::min in §2.5.6.4.
2.6.2.4 Example: Returned reference to parameter
This example is correctly diagnosed by this proposal without annotation (and without error, the code is fine).

```cpp
// godbolt.org/z/wncC9a
struct X { int a, b;};
int& f(X& x) { return x.a; } // ok, pset(ret) == pset(x)
```

For a variation of this example, see also `std::move` in §2.5.6.3

2.6.2.5 Example: Returned reference to temporary argument
This example is correctly diagnosed by this proposal without annotation. (`basic_string` meets the Container requirements and so is automatically recognized as an Owner type.)

```cpp
// godbolt.org/z/AqXDYp
char& c = std::string("hello my pretty long string")[0];
cout << c; // A: ERROR (lifetime.2): illegal to initialize a
// reference 'c' with an invalid pointer, pointer
// was invalidated with temporary string was
// destroyed (line A)
```

2.6.2.6 Example: Reversed ranges
This example is correctly diagnosed by this proposal without annotation. (This assumes `reversed_range` meets the Range requirements and so is automatically recognized as a Pointer type.)

```cpp
// Use either of the following definitions for reversed() — both definitions are valid
template<Range R>
reversed_range reversed(R&& r) { // pset(ret) = pset(r) = {r}
    return reversed_range{r}; // ok, pset(ret) == pset(r)
}

template<Range R>
reversed_range reversed(R r) { // pset(ret) = pset(r) = {r}
    return reversed_range{r}; // ok, pset(ret) == pset(r)
}
```

// Now do a range-for, which expands per [stmt.ranged] (see §2.4.9)
```
for (auto x : reversed(make_vector())) // A: ERROR (lifetime.1): __begin was invalidated
// when temporary ‘make_vector()’ was destroyed
// (line A)
```

2.6.2.7 Example: “A classical bug”
This example is correctly diagnosed by this proposal without annotation.

**Note** Because the search values happen to be also Owners, the default lifetime annotation
`{m',key',defvalue'}` is stricter than the one the user would likely have written by hand, namely
`{m',key,defvalue}` or `{key,defvalue}`. That’s okay in the function body because `{key,defvalue}
and `{m',key,defvalue}` are substitutable for `{m',key',defvalue'}`, and it’s okay to diagnose this
call site because the destruction of the temporary `defvalue` also invalidates `defvalue'`.)
Lifetime safety: Preventing common dangling – Sutter

```cpp
// const V& findOrDefault(const std::map<K,V>& m, const K& key, const V& defvalue);
// because K and V are std::string (an Owner),
// pset(ret) = {m',key',defvalue'}

std::map<std::string, std::string> myMap;
const std::string& s = findOrDefault(myMap, key, "none");
    // A: pset(s) = {mymap', key', tmp'}
    // tmp destroyed → pset(s) = {invalid}

s[0]; // ERROR (lifetime.3): ‘s’ was invalidated when temporary "none" was destroyed (line A)
```

For a variation of this example, see also `std::min` in §2.5.6.4.

2.6.3 From Ryan McDougall

2.6.3.1 Example: Eigen expression templates (reported by Chris Patton)

This example is correctly diagnosed by this proposal, with light annotation: The Eigen library should annotate its expression template `Cwise*Op` types as `[[gsl::Owner]]`. (The specific type being used in this example is `CwiseBinaryOp`.)

```
Note If we can identify a reliable heuristic for automatically identifying expression template ‘reference’ types, we can add that to the list of automatically recognized Pointer types in §2.1 and then this type would not need to be annotated.
```

```
class Type {
    Eigen::Vector3d calculateVector(); // Matrix<double,3,1>
};

auto point = // A: captures an expression template object
    (src.calculateVector() + dst.calculateVector()) * 0.5;

Eigen::Vector3d point2 = point; // ERROR (lifetime.3): ‘point’ was invalidated when temporary ‘...’ was destroyed (line A)

const Eigen::Vector3d point3 = // no dangling references
    (src.calculateVector() + dst.calculateVector()) * 0.5;
```

2.6.3.2 Example: Parameter use-after-move

This example is correctly diagnosed by this proposal without annotation.

```
class Foo {
    Foo(Bar&& bar)
        : bar_(std::move(bar)) { // A
                bar.set_safety_critical(true); // oops, typo: meant bar_
            // ERROR (lifetime.1): ‘bar’ was invalidated when moved from (line A)

        }
    // ...
};
```
2.6.3.3 Example: Expected use-after-move

This example is correctly diagnosed by this proposal the annotation of the Expected type as a [[gsl::Owner]].

The API for this Expected type doesn't make clear whether the user should use the value in-place (simpler), or move it out before use (cleaner), so the result is you get users doing both:

```cpp
template <typename T>
class Expected {
    T& get() { return value_; }
    T value_;  
    // ...
};

void take_it(Baz&&);

Expected<Baz> result = baz();
do_some_work(result.get()); // pset(tmp) = {result'}
take_it(std::move(result.get())); // A: added recently in a rush
    // pset(tmp) = {result'}, passed to rref param,
    // → KILL(result') and pset(result) = {invalid}
do_other_work(result.get()); // ERROR (lifetime.1): ‘result’ was invalidated when
    // its data was moved from (line A)
```
3 Bibliography


4 Future notes

4.1 Nullable owners
Should we add a NullableOwner concept? For example, containers like vector are always \{o’\} even if default-constructed, whereas unique_ptr wants to be nullable if default-constructed. Perhaps a default detection heuristic would be for owners that have * and -\(\rightarrow\) (i.e., offer explicit access to contained data) be assumed to be nullable by default, which would include smart pointers but exclude containers.

4.2 Namespace-scope static variables (aka “global”)
The primary thing we teach people about such global variables is “avoid them.” This analysis focuses on locals, and only needs enough support for globals to reason about the locals, such as when copying from a global Pointer to a local one.

Trying to reason about global variables is inherently in tension with local analysis. For example, any function call could modify a global, and we don’t want to have to compute and communicate the set of global variables that a caller and callee might have in common in order to treat them as additional parameters.

But then there are...

4.3 Function local static variables
... which have “global” lifetime but only local visibility. These, we could reason about. If we wanted to, here is an extension we could contemplate for function local statics.

Process the function twice, “first time through function” and “not-first time through the function” separately, similarly to what we do for loops. For a function local static Pointer variable \(p\):

- In the “first time” analysis, \(p\) is treated exactly like a local. In particular, we set the initial \(\text{pset}(p)\) from its initializer.
- In the “non-first time” analysis, we ignore the initializer and instead set the initial \(\text{pset}(p) = \{\text{static}\}\) (valid for lifetime of function) if \(p\)’s type is not\_null, otherwise set \(\text{pset}(p) = \{\text{null,static}\}\). (Allowing null will cause warnings in some existing code, to silence the warning just make the type not\_null or assert(p).)

4.4 Pointers to member pointers
Pointers to members whose pointed-at type is itself a pointer type are just a variation on Pointers to Pointers. However, they are rare enough (and discouraged enough) that I would like to put them in the “future” section and see whether we can avoid having to acknowledge and support them. In case we add it, this section documents the design.

A pointer to member can treated the same as a Pointer to Pointer. For a Pointer to Pointer \(pp\) that can point to multiple things (e.g., \(\text{int}** pp = \text{rand()}\%2 ? \&p1 : \&p2;\) so that \(\text{pset}(pp) = \{p1,p2\}\), the dereferenced Pointer has the union of the pointees’ \(psets\) (e.g., \(\text{pset}(p) = \text{pset}(p1) \cup \text{pset}(p2)\)). Similarly, when following a pointer to member whose type is a pointer, and if there is more than one matching data member, take the union of the \(psets\) of the members. For example:
struct Agg { int* p1; int* p2; };

Agg a; // pset(p1) = pset(p2) = {invalid}
int i;
a.p1 = &i; // pset(p1) = {i}
int* Agg::*memptr = something(); // could point to .p1 or .p2
cout << *(a.*memptr); // error, pset is {i,invalid}