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Reply to: Nicolai Josuttis (nico@josuttis.de), Victor Zverovich (victor.zverovich@gmail.com),
Filipe Mulonde (filipemulonde@gmail.com), Arthur O'Dwyer (arthur.j.odwyer@gmail.com)
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Fix the range-based `for` loop, Rev0

This paper was requested by EWG in 2014 when discussing EWG issue 120 (http://wg21.link/ewg120).
as a fix for CWG issue 900 (http://wg21.link/cwg900).

The range-based `for` loop became the most important control structure of modern C++. It is ***the*** loop to deal with all elements of a container/collection/range.

However, due to the way it is currently defined, it can easily introduce lifetime problems in non-trivial but simple applications implemented by ordinary application programmers. This

- is a significant risk in safety-critical contexts
- makes teaching the range-based `for` loop a problem

We have to

- **Hope** that programmers don't fall into the trap
- Teach beginners significant **constraints and security risks of using** the loop
- Teach more experienced programmers about the **details** of the problem:
  - Explain how the loop is defined
  - Explain lifetime rules for references
  - Explain `auto&&`
- Teach programmers how to instrument compilers to detect that problem in their code
- Teach programmers about the alternatives (such as using the range-based `for` loop with initialization) and to mark the alternatives so that they are not accidentally "fixed" introducing the bug again

The far better option is to fix the range-based `for` loop.
This is what this papers proposes.

Tony Table:

Before	**After**
`for (auto e : getTmp().getVals())` // UB if getter returns reference	`for (auto e : getTmp().getVals())` // always OK
`auto tmp = getTemp();` `for (auto e : tmp.getMemByRef())`	`for (auto e : getTmp().getMemByRef())`
// assume we know that we have elements: `for (auto e : getVec()[0]) {` // UB	// assume we know that we have elements: `for (auto e : getVec()[0]) {` // OK
`for (auto e : get<0>(getTuple()))` // UB	`for (auto e : get<0>(getTuple()))` // OK
`for (int i : getOptionalInts().value())` // UB	`for (int i : getOptionalInts().value())` // OK
`for (int i : std::span(getVec().data(), 5))` // UB	`for (int i : std::span(getVec().data(), 5))` // OK

`for (auto e : getColl() | transform(..)`
`                          | filter(..))`
// UB if | would support rvalues
	`for (auto e : getColl() | transform(..)`
	`                          | filter(..))`
	// OK if | would support rvalues

`const auto& tmp = getTmp().getMemByRef();` // UB when using `tmp`	`const auto& tmp = getTmp().getMemByRef();` // still UB when using `tmp` (no change)

Rev0:

First initial version.

Motivation

The symptom

Consider the following code examples when iterating over elements of an element of a collection:

```
std::vector<std::string> createStrings(); // forward declaration
…
for (std::string s : createStrings()) …     // OK

for (char c : createStrings().at(0)) …      // UB (fatal runtime error)
```

While iterating over a temporary return value works fine, iterating over a **reference to a temporary return value** is undefined behavior.
Therefor also:

```
// assume we know that createStrings() is never empty here:
for (char c : createStrings()[0]) …         // UB (fatal runtime error)
for (char c : createStrings().front()) …    // UB (fatal runtime error)
```

For the same reason, iterating over the elements of a returned optional collection, is a runtime error:

```
std::optional<std::vector<int>> createOptInts();
…
for (int i : createOptInts().value()) …     // UB (fatal runtime error)
```

This does not only apply to standard types. When iterating over elements returned by a getter we run into the same problem (yes, if the getters returns by value it would work):

```
class Person {
 private:
  std::vector<int> values{1, 2, 3, 4};
 public:
  const auto& getValues() const {
    return values;
  }
};

Person createPerson();

for (auto elem : createPerson().getValues()) {   // UB (fatal runtime error)
  std::cout << "value: " << elem << "\n";
  break;
}
```

See https://wandbox.org/permlink/ohuuTOyx5k8MWWyh for demonstrating the last problem in a full example. Depending on the compiler and the platform used, the loop might:

- Print "`value: 1`" (assuming the value is still there
- Print "`value: 0`" (printing an arbitrary other value)
- Result in a segmentation fault / core dump

Unfortunately, programmers can run easily into this problem. One recent real-world example by one of the authors is the following:

Improving the following code:

```
struct Person {
  std::vector<int> values;
  …
};

for (auto elem : createPerson().values) {   // OK (lifetime extended)
```

by introducing a getter to have better encapsulation, suddenly caused the undefined behavior:

```
class Person {
 private:
  std::vector<int> values;
  …
 public:
  const auto& getValues() const {
    return values;
  }
};

for (auto elem : createPerson().getValues()) { // UB (fatal runtime error)
```

The Root Cause for the problem

The reason for the undefined behavior above is that according to the current specification, the range-base `for` loop internally is **expanded to multiple statements:**

- First, we have some initializations using the *for-range-initializer* after the colon and
- Then, we are calling a low-level `for` loop

For example, the following call of the range-based `for` loop:

```
for (char c : createStrings().at(0)) …      // UB (fatal runtime error)
```

is defined as equivalent to the following:

```
auto&& rg = createStrings().at(0);      // doesn't extend lifetime of returned vector
auto pos = rg.begin();
auto end = rg.end();
for ( ; pos != end; ++pos ) {
  char c = *pos;
  …
}
```

And the following call of the loop:

```
for (int i : createOptInts().value()) …   // UB (fatal runtime error)
```

is defined as equivalent to the following:

```
auto&& rg = createOptInts().value(); // doesn't extend lifetime of returned optional
auto pos = rg.begin();
auto end = rg.end();
for ( ; pos != end; ++pos ) {
   int i = *pos;
   …
 }
```

And the following call of the loop:

```
for (int i : createPerson().getValues()) …   // UB (fatal runtime error)
```

is defined as equivalent to the following:

```
auto&& rg = createPerson().getValues(); // doesn't extend lifetime of returned Person
auto pos = rg.begin();
auto end = rg.end();
for ( ; pos != end; ++pos ) {
  int i = *pos;
  …
}
```

By rule, all temporary values created during the initialization of the reference `rg` that are not **directly** bound to it are destroyed before the raw `for` loop starts.

Note that references ***do*** extend the lifetime of objects when they refer to sub-objects. That's why without using getters the example above works fine:

```
for (int i : createPerson().values) …   // OK (extends lifetime of returned Person object)
```

Severity of the problem

This ***is*** a serious problem for the following reasons, which we will explain in details in the section:

- The problem was raised several times by multiple people.
- Programmers run into this problem in practice.
- The problem creates significant drawbacks to teach C++.
- The range-based `for` loop becomes a loop style guides more and more warn about.
- Useful API's are not provided due to the danger of this problem.
- The problem reduces the credibility of C++.

A use of the range-based for loop (without using the optional init-statement) looks like **one statement without any semicolons to signal any end of a lifetime** (as we have to signal lifetime issues with init-statements).
Therefore, the problem of the range-base `for` loop is not obvious for its users:

- The ordinary programmer has the impression to be able to iterate safely over all members of the range on the right of the colon.
- Even experienced C++ programmers struggle to see the problem.

But, we teach this as ***the loop*** to use to iterate over all elements (because of its simplicity as we e.g. can't pass a wrong size). So, beginners and even advanced programmers do not see/know that there is a hidden problem in the definition of the loop so that possible code might not work.

Unless a programmer knows all the details of the definition of the loop (including rule for lifetime extensions, universal/forwarding references) it is not obvious that the loop is specified in a way that

a) references are internally used that
b) might limit the lifetime of some of the objects of the expression after the colon.

The loop as a whole acts as one statement and there is no signal in the use of the loop there is a hidden lifetime problem (such as having a semicolon). The average programmer is not aware of the problem. But even worse, the code might run until it gets into production.

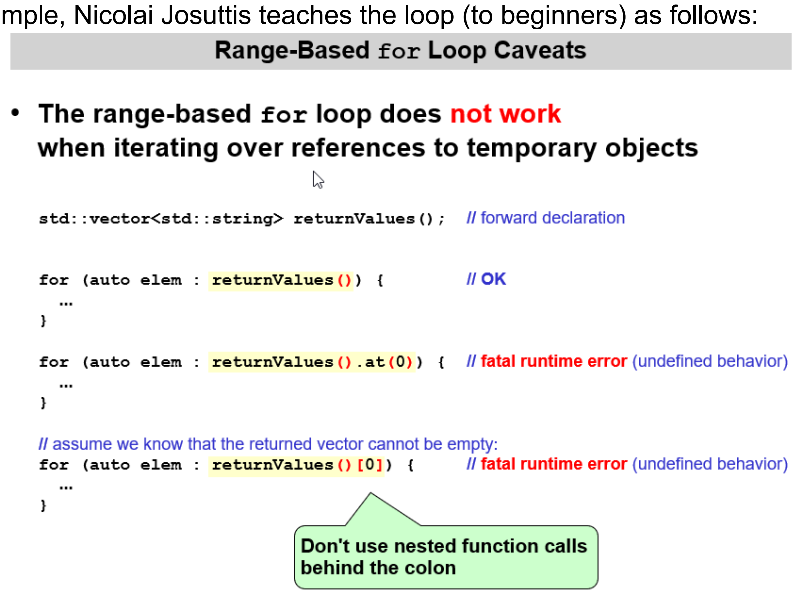
As a consequence of the non-obvious problems of the loop,

- **We have to warn about the use of the range-based `for` loop**,

And:

- We have to explain how the range-based for loop is implemented and what this means
  - Show how the range-based `for` loop is defined in detail
  - Explain references
  - Explain auto&&
  - Explain the lifetime extension rules of references in detail

For example, Nicolai Josuttis teaches the loop (to beginners) as follows:



There are already **style guides that mark the use of the range-based `for` loop as unsafe**:

- See for example the categorization of the range-based for loop as “Conditionally Safe” in “Embracing Modern C++ Safely” by Rostislav Khlebnikov and John Lakos (Bloomberg, 2018).
- https://abseil.io/tips/107 gives a warning about using the range-based for loop that way (without explaining that the problem is the way the loop is defined).

And due to the flaws revealed by this loop (and as consideration of lifetime issues in C++ in general), we can’t implement:

```
for (int val : getVector() | rng::views::transform(…))
                           | rng::views::filter(…)) {   // doesn’t compile
    …
}
```

While the following works (even when declaring `vec` as reference):

```
auto vec = getVector();
for (int val : vec | rng::views::transform(…))
                   | rng::views::filter(…)) {   // OK
    …
}
```

As another example for restrictions caused by this problem consider using `std::as_const()` in a range-based `for` loop:

```
std::vector<int> vec;
for (auto&& val : std::as_const(getVector())) {
    …
}
```

Both std::ranges with operator | and `std::as_const()` have a deleted overload for rvalues to disable this and similar uses. With the proposed fix things like that could be possible. We can definitely discuss the usability of such examples, but it seems that there are more example than we thought where the problem causes to `=delete` function calls for rvalues.

Why is the Severity higher than in other places with dangling references?

You might argue that even with a fix we can still get easily into trouble with

```
const auto& str = get<0>(getTuple());
```

or

```
const std::string& str = getStrings()[0];
```

or

```
auto&& sp = std::span(getValues().data(), 5);
```

or

```
for (const auto& v = getColl().getValue(); auto elem : v)
```

However, the key difference to the problem inside the range-based `for` loop is that in all these examples **the risk is visible**, because usually two visible things are necessary to have a potential risk with references to deleted temporary objects:

- A reference declaration (& or && or `decltype(auto)`)
- A semicolon (;)

The range-base `for` loop is **the only place** in the C++ standard where this problem occurs without a visible reference and without a visible semicolon.

And the discussion of http://wg21.link/cwg900 agrees:

> This [fix] also removes **the only place** where binding a reference to a temporary extends its lifetime implicitly, **unseen** by the user.

Proposed Solution

We propose to fix this problem of the range-based `for` loop by a modification of the way the loop is specified. The internal initialization of the range as universal/forwarding reference shall no longer act as a separate statement that ends lifetimes before the internal `for` loop is entered.

Taking the last motivating example, a statement such as

```
for (auto elem : foo().bar().getValues()) …
```

should be expanded **equivalent** to the following:

```
auto&& tmp1 = foo();          // lifetime of all temporaries extended
auto&& tmp2 = tmp1.bar();     // lifetime of all temporaries extended
auto&& rg = tmp2.getValues();
auto pos = rg.begin();
auto end = rg.end();
for ( ; pos != end; ++pos ) {
  auto elem = *pos;
  …
}
```

The question is how to formulate that without introducing new (lifetime) rules for C++.

One idea for the wording of the fix is to use a lambda:

```
[&](auto&& rg) {
  auto pos = rg.begin();
  auto end = rg.end();
  for ( ; pos != end; ++pos ) {
    auto elem = *pos;
    …    // special return, goto, co_yield, co_return handling
  }
}(foo().bar().getValues()); // all temporary return values valid until the end of the loop
```

See https://wandbox.org/permlink/KRecfQhE696LD4DC for an example without and with this fix.

Because the expression we initialize `rg` with is now no longer a separate statement, the lifetime of all prvalues returned in the expression that is the initial range remain valid until the end of the whole loop.

However, in that case we have to specify special handling for `return`, `goto`, and co-routine statements because they have to leave the scope where the loop is called.

It is probably easier to provide plain wording or extend the equivalent-to section with a statement that

- All stack-based destructor calls of the for-range-initializer are deferred until the end of the loop
- The semicolons operate like commas not ending the statement.

Here, we need CWG's help.

The overall goal of the fix is:

- We introduce/update wording so that the lifetimes of all values returned in subexpressions of the *for-range-initializer* end with the end of the loop (as if we would pass the whole expression like a function argument).
- We do not modify or introduce any new (lifetime) rule a C++ programmer can use or has to learn.

Note that we do ***not*** propose to extend the lifetime of the optional initialization in the range-based `for` loop. Thus

```
for (auto&& x = foo().bar(); auto elem : x.getValues()) …
```

should still be expanded **equivalent** to the following:

```
auto&& x = foo().bar();    // yes, still problem with reference to temporary
auto&& rg = x.getValues();
auto pos = rg.begin();
auto end = rg.end();
for ( ; pos != end; ++pos ) {
  auto elem = *pos;
  …
}
```

Q&A

Do we have evidence that this is a major problem in practice?

This ***is*** a problem we see in practice.

For example:

- At a major IT company the internal development platform has multiple posts of lifetime problems with the range-base `for` loop.
- One authors of this paper personally run into this problem just recently when replacing a direct member access to using a getter (as Unfortunately,).
- Designs are already changed to avoid the possibility to run into this problem.
- Style guides warn already about the range-based `for` loop.
- The internet has discussions about this issue. For example:
  - https://stackoverflow.com/questions/51436155/range-based-for-loop-on-a-temporary-range
  - https://softwareengineering.stackexchange.com/questions/262215/who-is-to-blame-for-this-range-based-for-over-a-reference-to-temporary/262243

It is for sure a **significant problem in teaching**, because you either have to constrain the use without explanation or show details of the definition of the range-based `for` loop understandable only by experts. It's surprising how many developers are surprised by this issue even in advanced trainings.

Finally, with new classes and functions with reference semantics, we get more and more problems like this.

Consider the motivating example with `std::optional` (C++17) and using `std::span` (C++20) as follows:

```
for (auto elem : std::span{getColl().data(), 5}) { // UB (fatal runtime error)
   …
}
```

This lowers the credibility of C++, especially for beginners.

But don't we have the same problem with initializers in loops?

You can argue that we have the same problem in code like this:

```
for (const auto& v = createPerson().getValues(); !v.is_empty(); …) …
```

However: In this code there is a **significant difference** to the problem raised:
Programmers can see that there might be a critical partial lifetime extension:

- **a semicolon signals the end of a statement**
- **a reference is used**

That is, at all other places, we usually have two signals for possible problems.

In code like

```
for (int i : foo().bar()) …   // OOPS: different lifetime extensions in one statement
```

the programmer has to know that **the lifetime of objects extends differently inside the same expression** in a context where there is no signal for an end of a statement. We are not aware of any other location in the C++ standard where we have a situation like this. And the discussion of http://wg21.link/cwg900 agrees:

> This [fix] also removes **the only place** where binding a reference to a temporary extends its lifetime implicitly, **unseen** by the user.

Programmers tend to read the code above as being no more dangerous than performing a nested function call:

```
loopOver(foo().bar());          // OK, looks like equally safe
```

But don't we break the zero-overhead principle?

Programmers should not pay for things they don't need. Usually this means, code from using a feature should not be slower or bigger than code not using this feature. However, when the risk of a problem is severe and we have a simple way ***not*** to get the overhead, we prefer safety (especially for features for non-experts). For example:

- We pass parameters to threads by value (unless otherwise specified)

And if it is worth it, we even change C++ accordingly. For example:

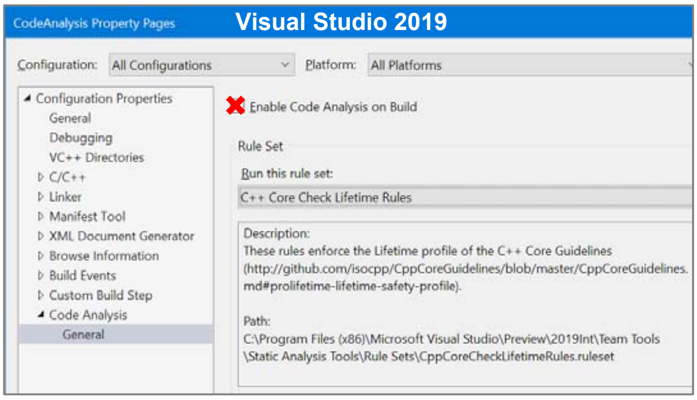
- We introduced a defined evaluation order for additional operators in C++17

This fix clearly falls into this category: We avoid severe errors (undefined behavior) and we have easy workarounds if it might introduce a performance issue.

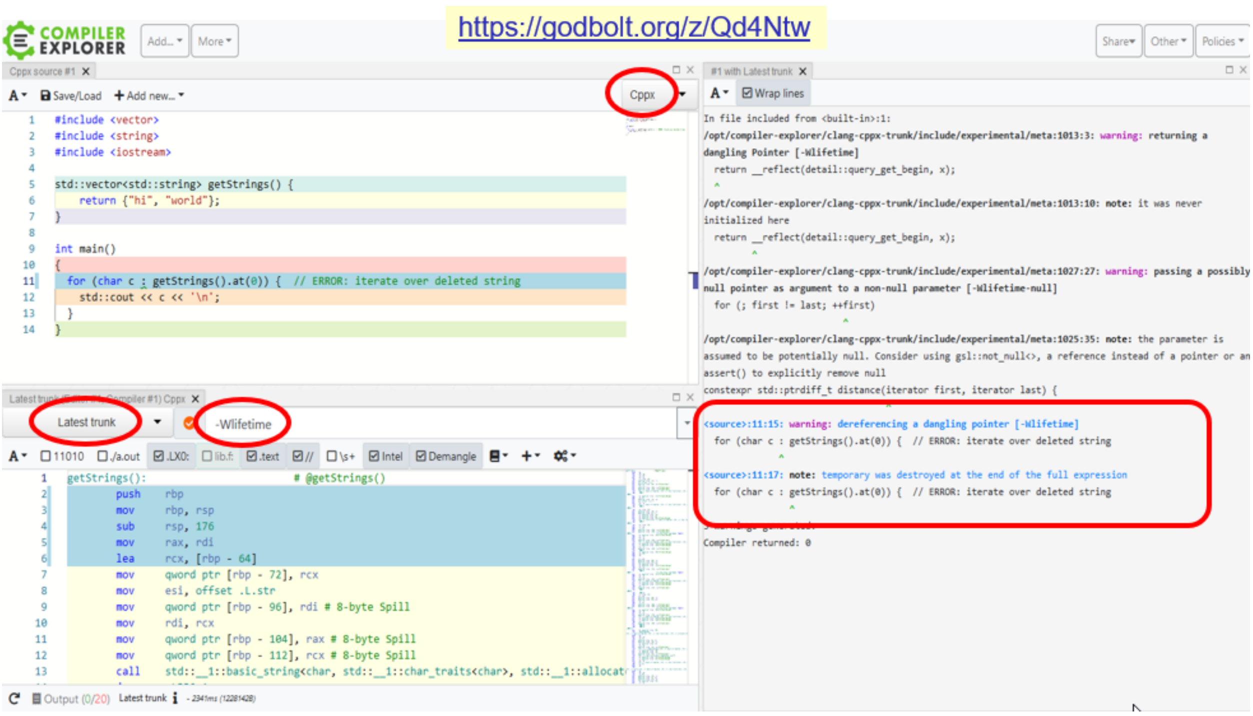
Note especially that the range-based `for` loop is ***not*** a low level feature. It is already a layer on top of the basic `for` loop. **Such a layer should have fewer security risks, not more.**

But don't we have tools to detect such lifetime problems?

The examples in this paper are **partially** diagnosed by Herb Sutter's Lifetime rules spec in the C++ Core Guidelines, which is now partially part of clang and can be used in Visual Studio as follows:



In fact, the first two examples get useful diagnoses with this extension. You get messages like the following:



See

- https://godbolt.org/z/Qd4Ntw
- https://godbolt.org/z/76v4v6

However,
this lifetime extension does not solve the general problem raised here for the following reasons:

- These lifetime extensions are not standardized yet and need special compiler support.
- When not using standard library types (such as the motivating type `Person`), you have to specify the corresponding lifetime dependencies. This means that for each and every getter (and other function) returning a reference to a member, we have to provide the corresponding lifetime dependencies for each and every static-analysis tool.
- We still have to explain why we get the error and how to avoid it.
- Unfortunately, the lifetime extension only gives a warning, not an error and many projects ignore warnings (due to the problem that several warnings are not severe and that we have too much).

  And making it an error would create false positives. For example:

```
class Person {
  std::string name
 public:
  const std::string& getName() const {
    return name;
  }
  const std::string& getAnswer() const {
    static std::string s{"42"};
    return s;
  }
};

for (char c : getPersonByValue().getName())     // ERROR
for (char c : getPersonByValue().getAnswer())   // OK
```

  If the getters are not inline defined, a compiler has no way to find out that one usage of it in the range-base for loop is safe, while the other is not.
  The programmer would have to instrument the compiler somehow (or we introduce a syntax to specify lifetime dependencies or lifetime dependency exceptions).

Thus, the lifetime extensions helps to lower the severity of the consequences of this problem. But still we have the problem and have to warn about using the range-based `for` loop, explain why, and discuss alternatives.

But don't we have a workaround with the initializing range-based `for` loop?

Since C++20, we can avoid the problems of the range-based for loop by using the range-based for loop with initialization (see http://wg21.link/p0614):

Instead of

```
for (char c : createStrings().at(0)) …      // UB (fatal runtime error)
```

we can implement

```
for (auto rg{createStrings()}; char c : rg.at(0)) …      // OK
```

or

```
for (auto&& rg{createStrings()}; char c : rg.at(0)) …      // OK
```

However,
this new language feature does not solve the problem raised here for the following reasons:

- We still have to explain why we get the error when using the ordinary range-based `for` loop.
- The code becomes significantly more clumsy.
- We have to teach lifetime extension of references to understand this workaround.

In fact, without careful comments, programmers might even “improve” the workaround by turning it into code using the ordinary range-based `for` loop (not knowing that they introduced a severe runtime error).

Shouldn’t we fix lifetime extension for references in general?

Instead of fixing the range-based for loop, we could also change the general rules for extending the lifetime objects references refer to.

This was proposed earlier a couple of times for C++, but it was always rejected for good reasons. To quote Bjarne Stroustrup here:

> Way back in the 1980s, the lifetime of an object declared in the for-initializer extended to the end of the block (you can find that in the ARM). Initially, I thought that safer, but changed my mind after many complaints. The most serious was the long life of matrix temporaries that basically rendered initialization in for-statements useless. Be very careful when trying to extend lifetimes; the results can be surprising and costly.

When the issue was discussed as EWG issue 120 there were also significant concerns about introducing a new lifetime model as well as extending lifetimes in general due to extended memory footprint (see http://wiki.edg.com/bin/view/Wg21rapperswil2014/EvolutionWorkingGroup).

It might be great to solve lifetime issues in some more general way, but that doesn't mean we couldn't/shouldn’t solve this one directly.

Note that this problems only occurs due to **the way** we specify the behavior of the range-based `for` loop. If we would provide the behavior more like a black box of function call, we wouldn’t have this problem and the loop would match the expectations of the programmers.

Are there other places in the language that have similar (theoretical or real) problems?

Not that we are aware of.
Again, as the discussion of http://wg21.link/cwg900 states:

> This [fix] also removes **the only place** where binding a reference to a temporary extends its lifetime implicitly, **unseen** by the user.

See Why is the Severity higher than in other places with dangling references? for details.

What are the drawbacks of such a fix?

A fix like this would usually not break existing code, because we would extend just the lifetime of a few temporary objects a bit longer (yes, there are ways that such an extensions breaks functional behavior with very subtle programming).

Only if the lifetime extension is a problem (such as when a subexpression of the initialization temporarily holds a lock and that lock is extended), we might get into trouble. For example:

```
for (auto elem : lockedAccess{obj, objMx}->getValues()) {
  …
}
```

With a type such as `boost::synchronized_value` even deadlocks might occur:

```
boost::synchronized_value syncObj{obj};
for (auto elem : syncObj->getValues()) {
  if (…elem…)
    syncObj->getName()   // deadlock with the fix
}
```

However, note that this code above turns into a data race, when using references instead:

```
boost::synchronized_value syncObj{obj};
for (const auto& elem : syncObj->getValues()) {
  if (…elem…)     // data race even without the proposed fixed:  unsynchronized access to obj
    syncObj->getName()   // deadlock with the fix
}
```

The question is, how likely code is where we iterate over copies of multiple elements of an object and then inside deal with the object again and knowing that the whole code is broken if the declaration of an element uses a reference instead (which might easily happen accidentally if others see this code).

We consider this close to a pathologic example,

We also see no ABI break because object code compiled with the old behavior could coexist with object code having the new behavior.

Regarding performance. First, running time should not be affected. We would only extend the lifetime of prvalues in initializers of the range-based `for` loop until the end of the loop. That is, we only delay a destruction to a later timepoint but do not execute additional code.

However, when temporary objects live longer than expected, programs might temporarily need more memory. That is, when a function returns an expensive value, the resource is hold while possible additional resources are used. This might in rare cases extend memory limits.

Note that **usually** (in all cases where we just have one expression on the right side of a range-based `for` loop, **the proposed change would have no effect at all**.

Note also that a programmer still can avoid any overhead of the range-based `for` loop by using the optional initializer of the loop or using an ordinary `for` loop.

What was discussed about this problem before?

This problem was raised and discussed a couple of time. Unfortunately, we never got a resolution.

Core issue 900 (http://wg21.link/cwg900) and core issue 1498 (http://wg21.link/cwg1498) raised exactly this problem in 2009 and 2012, which then 2014 became EWG issue 120 (http://wg21.link/ewg120).

The comment by CWG on issue 900 was:

> Notes from the February, 2017 meeting:
>
> CWG felt were **inclined to accept the suggested change** but felt that EWG involvement was necessary prior to such a decision.

The comment in EWG was:

> Discussed in Rapperswil 2014. **EWG wants a solution**, and welcomes a paper tackling the issue. Vandevoorde raised concerns introducing any new lifetime models. Stroustrup pointed out that the end-of-full-expression rule came about to reduce memory footprint compared to the end-of-block rule and is good for RAII uses. Is it possible to solve the issue by just modifying the specification of a range-for loop?

We want to point out that **the proposed solution covers all concerns raised in EWG**:

- We don't introduce a new lifetime model for C++. We only change the guarantees the range-based `for` loop gives to programmers.
- We don't modify the end-of-full-expression rule.

Proposed Wording

(All against N4835)

CWG should come up with wording based on the proposed wording and **overall goal of the fix** above.

Note: There are different ways for a modified definition of the range-based for loop

a) Use black-box wording
b) Use the current wording and state that the internal initializations in the definition of the range-based for loop are not statement that end the lifetime of subexpressions in the for-range-initializer
c) Come with a different as-if clause using a lambda

A change with option a) might look as follows:

> Iterates over all elements of the range [*begin-expr*, *end-expr*) while using the *for-range-declaration* as initial declaration of each element inside the body of the loop.

This way to specify the behavior of the loop has the advantage that we do not have to reveal a new general language feature or lifetime rule (beside specifying the new feature here).

A change with option b) might look as follows:

Change **8.6.4 The range-based for statement [stmt.ranged]** as follows:

- All stack-based destructor calls of the for-range-initializer are deferred until the end of the loop.

Or:

- The semicolons in the initializations before the raw for loop operate like the comma operator in the sense that they do not end the statement.

A change with option c) might look as follows:

Change **8.6.4 The range-based for statement [stmt.ranged]** as follows

> The range-based for statement
>
> `for` (*init-statement*$_{opt}$ *for-range-declaration* : *for-range-initializer*) *statement*
>
> is equivalent to

```
 {
   init-statementopt
   ~~auto && range = for-range-initializer;~~
   [&](auto&& range) {
     auto begin = begin-expr ;
     auto end = end-expr ;
     for ( ; begin != end ; ++begin ) {
       for-range-declaration = * begin ;
       statement   // a return or goto or or co- statement applies to the loop as a whole
     }
   }( for-range-initializer );
}
```

> where each `return`, `goto`, `co_return`, and `co_yield` statement, inside the lambda is equivalent to or propagated to a corresponding statement outside the lambda.

Feature Test Macro

New macro or do we have a versioned range-based `for` loop macro?

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