FINDING ITERATOR-RELATED ERRORS WITH CLANG STATIC ANALYZER

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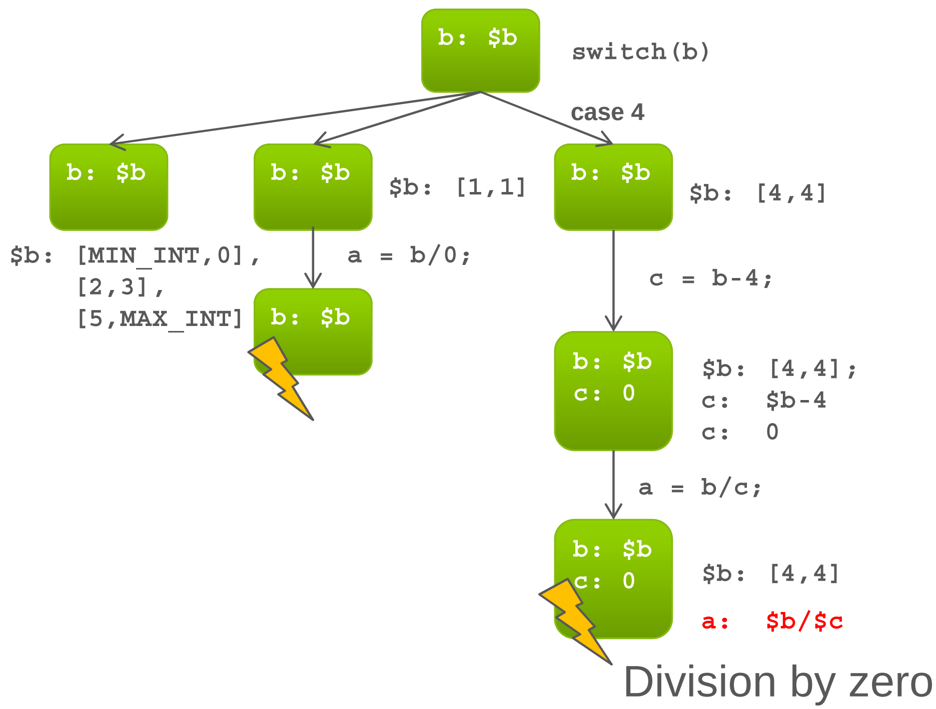
CLANG STATIC ANALYZER

- Symbolic execution of the program to find errors
- Path sensitive walk on the Control Flow Graph
- Simulated execution
  - On every possible path
  - Variables are represented as symbolic values
- Constraints are calculated for symbolic values for each path
- Possible paths are calculated based on the constraints
- Checkers may store additional data for variables in every state
- Checkers may spawn new execution paths or terminate existing ones

SYMBOLIC EXECUTION

```
#include <stdlib.h>
void test(int b)
{
  int a,c;
  switch (b){
    case 1:  a = b / 0; break;
    case 4:
             c = b-4;
             a = b / c; break;
  };
}
```

Nodes are immutable program states



ITERATORS IN C++

- Types that can be used to identify and traverse the elements of a container
- No common ancestor like in Java, C# or Objective-C
- Minimal set of common properties:
  - Copy-constructible, copy-assignable, destructible
  - Can be incremented: operator++(), both prefix and postfix
  - Can be dereferenced: operator*()
- Different categories: input, output, forward, bi-directional, random-access
- **Difficulty for static analysis: how to recognize a type as an iterator?**

DANGERS OF ITERATORS

- Dereferencing an iterator outside of its range
  - Typically dereferencing the past end iterator
- Access of an invalidated iterator
- Mismatch between container and iterator or two iterators
- **All these errors lead to undefined behavior which is hard to debug**
- **Surprisingly, Static Analyzer could not find any of these errors until now**

OUT-OF-RANGE DEREFERENCING AN ITERATOR

Simple Example 1

```
auto i = v.end();
*i; // Oops!
```

Simple Example 2

```
auto i = v.begin();
*--i; // Oops!
```

Typical Example

```
auto first = std::find(V.begin(), V.end(), e);
auto &x = *first; // What if e is not found in V?
```

INVALIDATED ITERATOR ACCESS

Simple Example

```
auto i0 = L.begin();
L.erase(i0);
*i0;
```

Typical Example

```
for (auto i = L.begin(); i != L.end(); ++i) {
  if (dislike(*i))
    L.erase(i);
  }
}
```

ITERATOR MISMATCH

Typical Example 1

```
auto first = std::find(V1.begin(), V1.end(), e);
V2.erase(first); // Undefined behavior
```

Typical Example 2

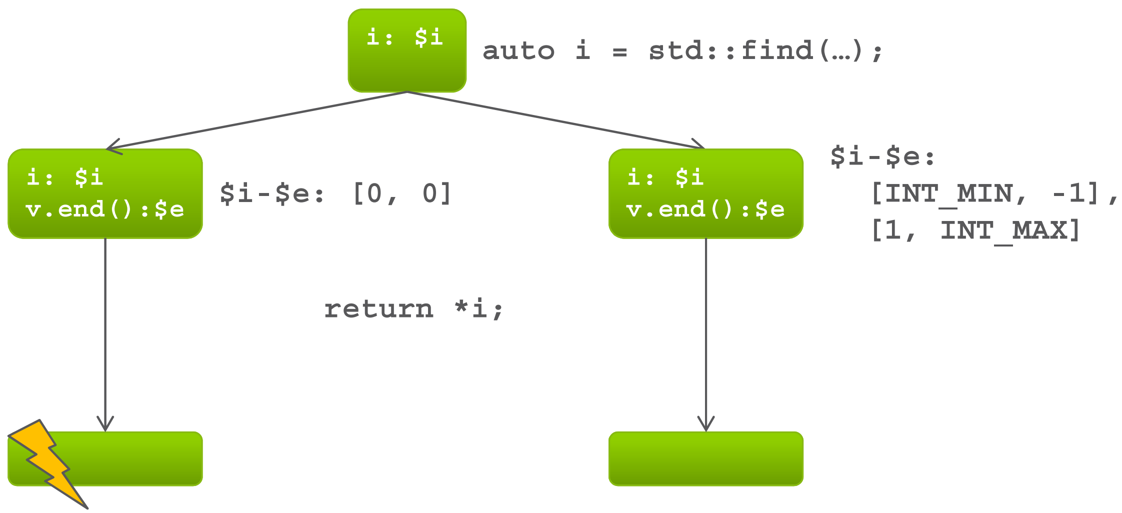
```
auto first = std::find(V1.begin(), V1.end(), e);
if (first == V2.end()) // Always false!!!
  return;
auto &x = *first;
```

OUR SOLUTION

- Combined checker for all three kinds of errors
- Checks for the different kinds of errors can be enabled separately
- Based on STL containers, but also works for custom container types with certain STL like properties:
  - `std::list`-like containers: no subscript operator
  - `std::vector`-like containers: subscript operator and only back-modifiable
  - `std::deque`-like containers: subscript operator and also front-modifiable (e.g. push_front())
- We regard types with `iterator` or `iter` as the suffix in their name as iterators if they fulfill the set of minimal requirements for iterators

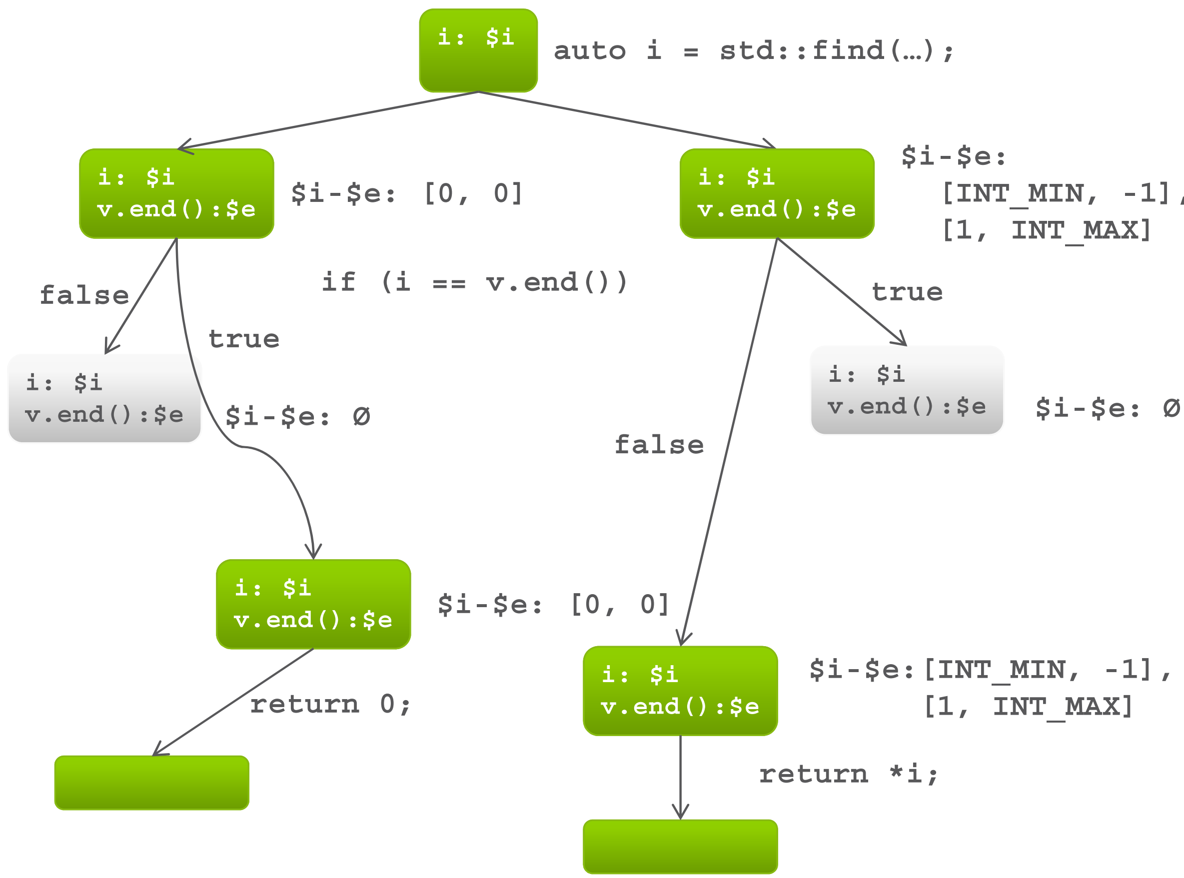
EXAMPLE: PAST-END ACCESS

```
#include <vector>
int test(std::vector<int> v, int n) {
  auto i = std::find(v.begin(), v.end(), n);
  return *i;
}
```

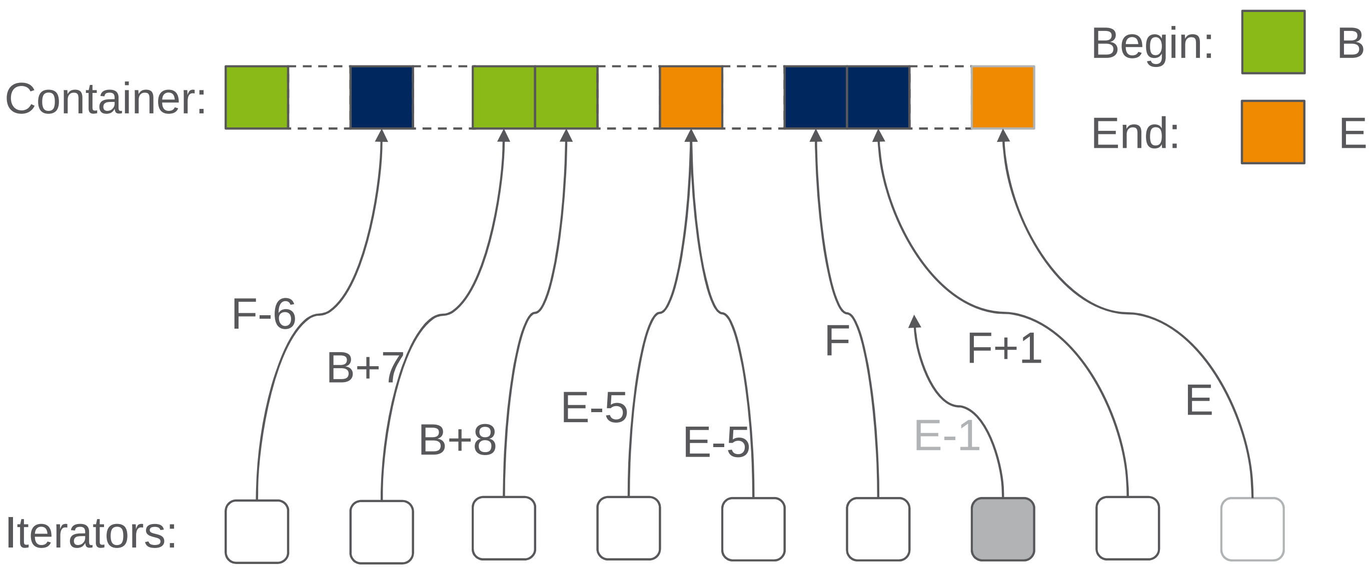


EXAMPLE: NO PAST-END ACCESS

```
#include <vector>
int test(std::vector<int> v, int n) {
  auto i = std::find(v.begin(), v.end(), n);
  if (i == v.end())
    return 0;
  return *i;
}
```



MODELLING ITERATORS



- F was conjured (synthetized) for a return value of a function, e.g. std::find()
- No order known between B, E and F unless assumed in a branch

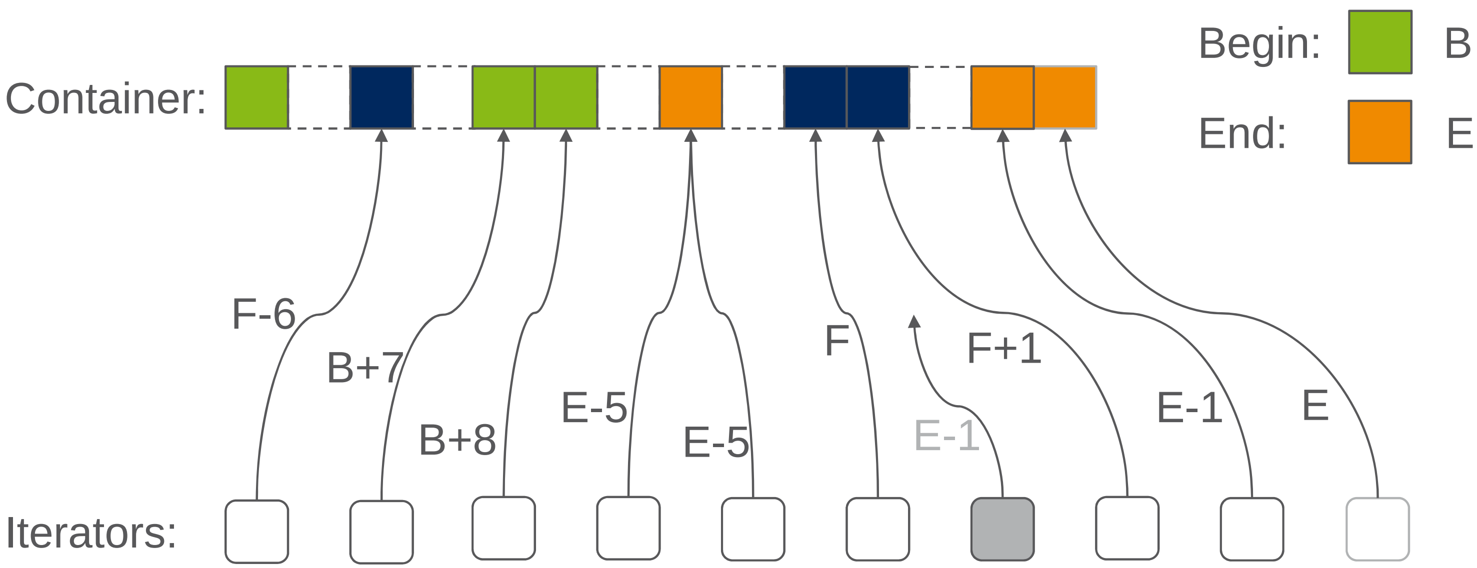
HANDLING BEGIN AND END

- Begin and end position symbols of a container are initially undefined
- A symbol is conjured upon first call to begin() or end() as the iterator’s position
  - Later calls return the same symbol for the iterator’s position
- The begin() and end() symbols are removed from the container data when they become invalidated
  - New value assigned to the container
  - Container’s clear() method is called
  - Data is moved from the container using std::move()

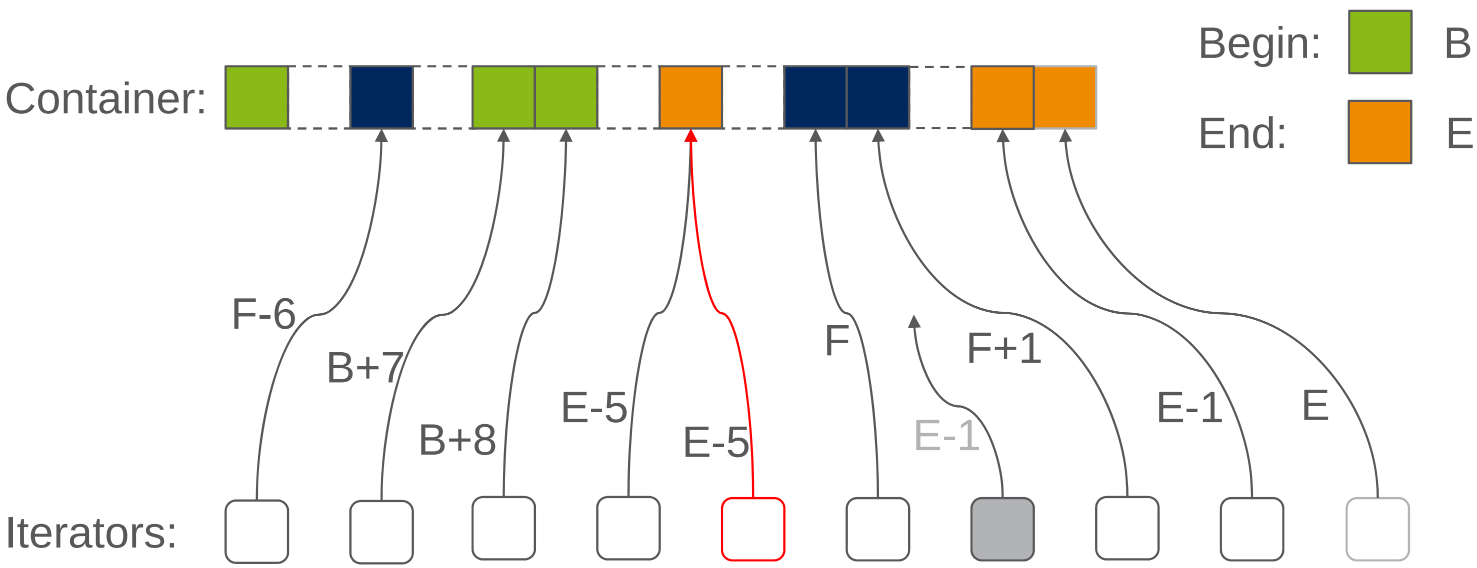
HANDLING MODIFIERS

- Methods modifying the container (not its elements) also affect iterator positions
- Upon insertions and deletions:
  - All iterator positions of the container are checked
  - Some of them are invalidated (according to the standard)
  - The rest is shifted to match the new arrangement
  - If the inserted or deleted position is relative to the begin or end of the container:
    - Shift the begin or end of the container as well

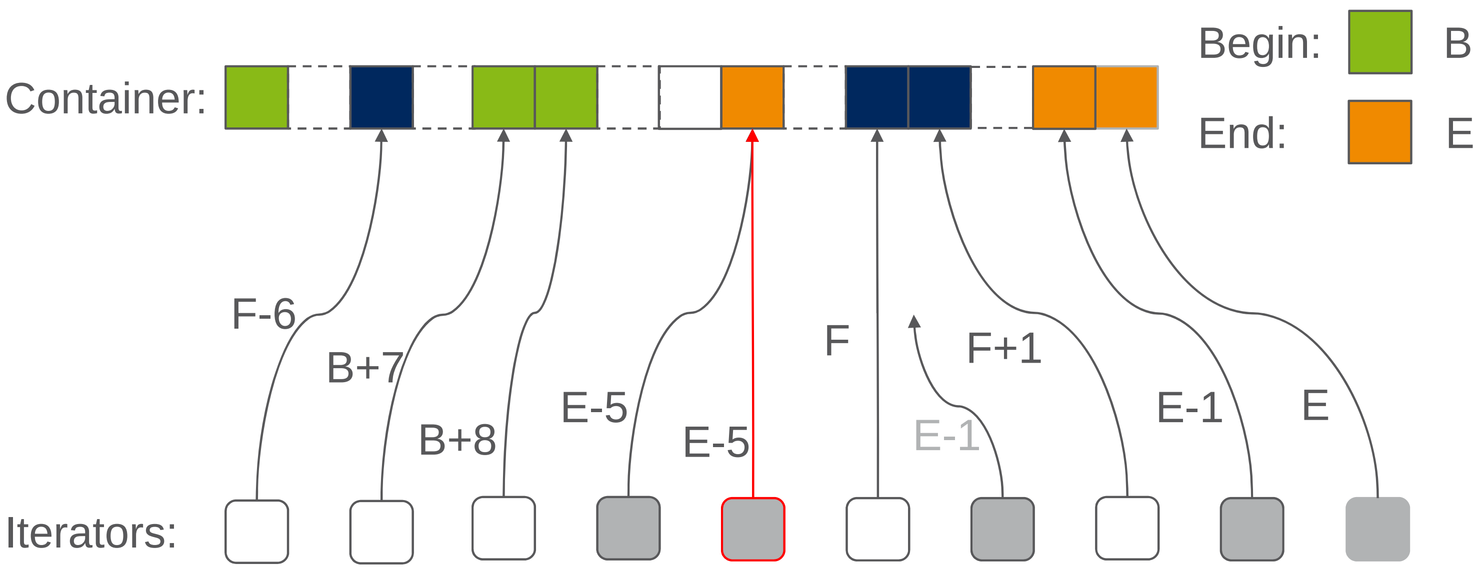
EXAMPLE: INSERT INTO VECTOR



EXAMPLE: INSERT INTO VECTOR

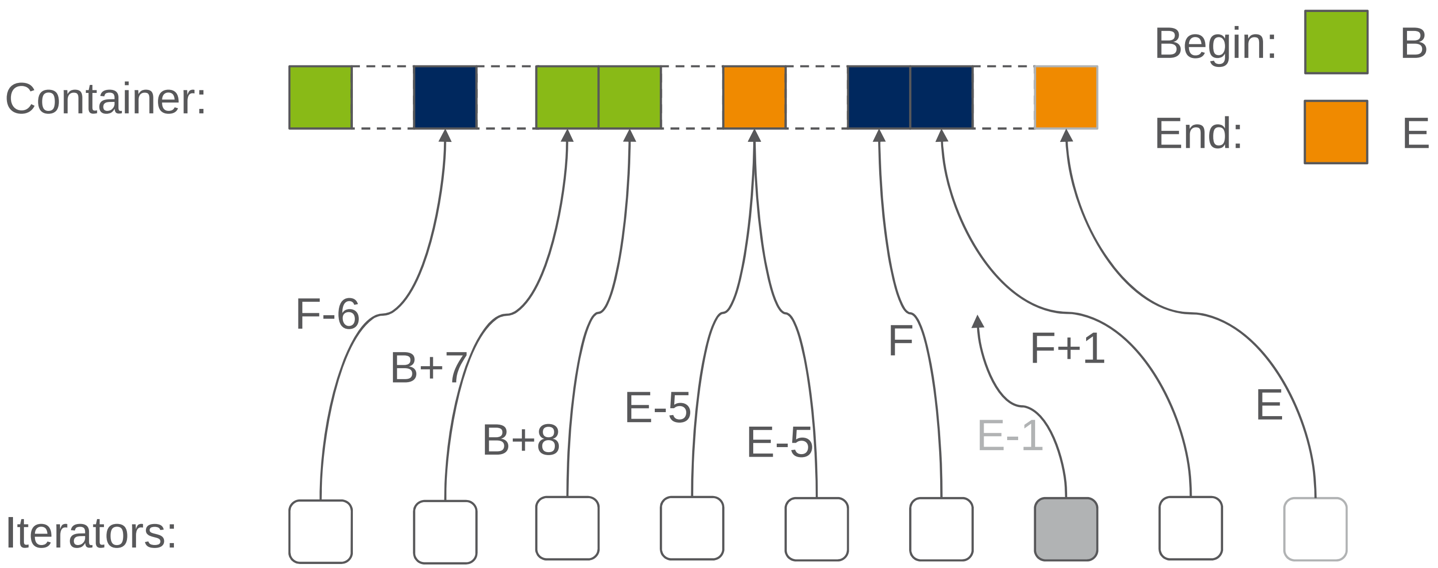


EXAMPLE: INSERT INTO VECTOR



- Note: other positions (e.g. F and F+1) are not invalidated if we do not know whether they are indeed after the insertion
  - If we already have such assumption in the current state, we invalidate them as well

EXAMPLE: PUSH FRONT INTO LIST



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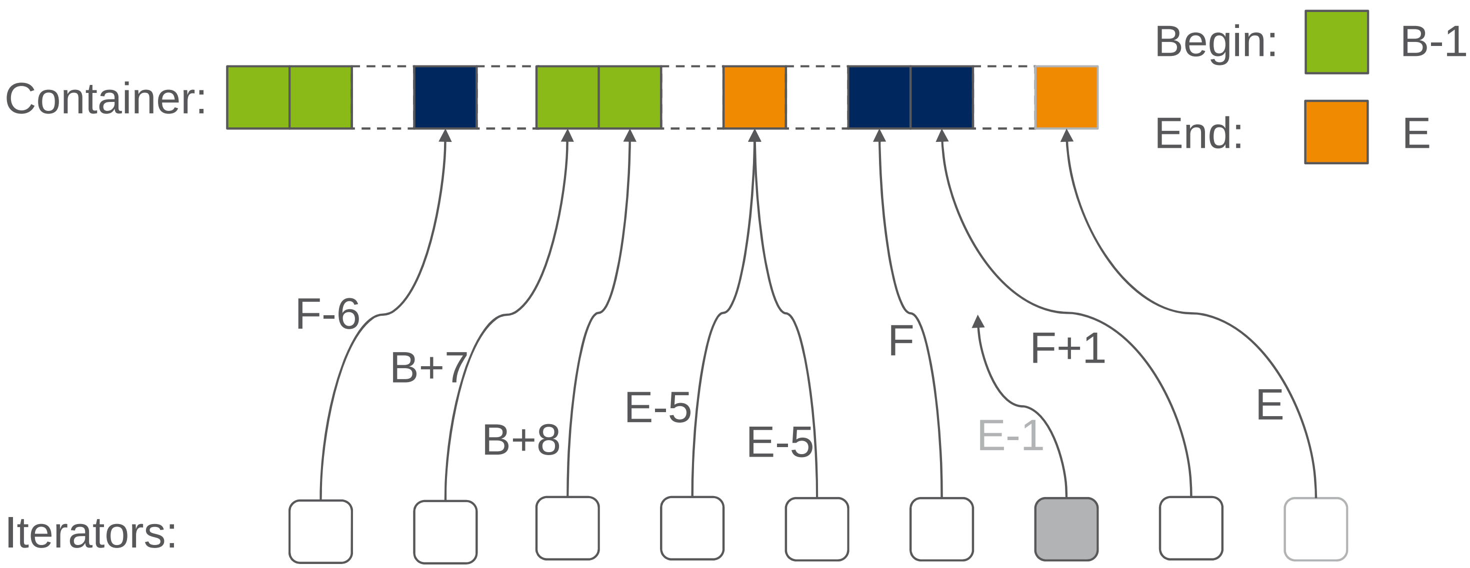
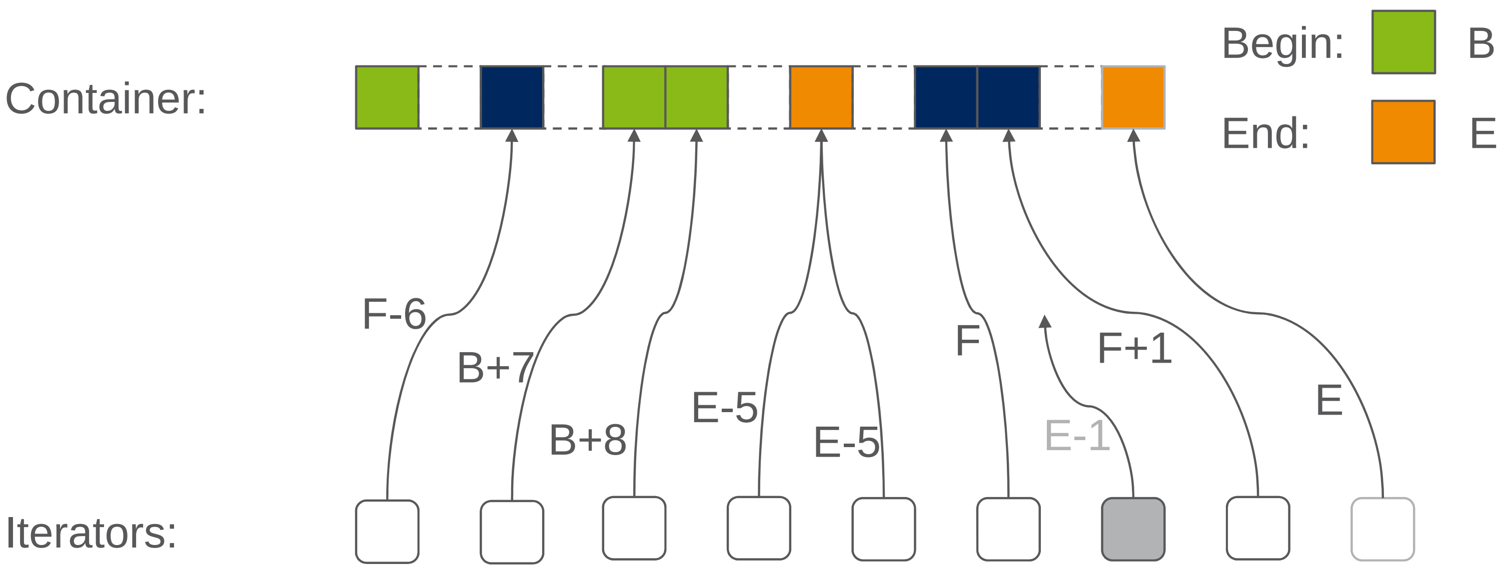


HANDLING MOVE SEMANTICS

- Standard: upon move constructor or move assignment, the existing iterators remain valid, but refer to the element in the new container, **except the past-end iterators**
- Upon move:
  - Move the begin-symbol to the new container
  - Reassign all iterators to the new container
  - Create a new end-symbol for the new container
  - Replace the end-symbol in the reassigned symbolic expressions

EXAMPLE: MOVE SEMANTICS



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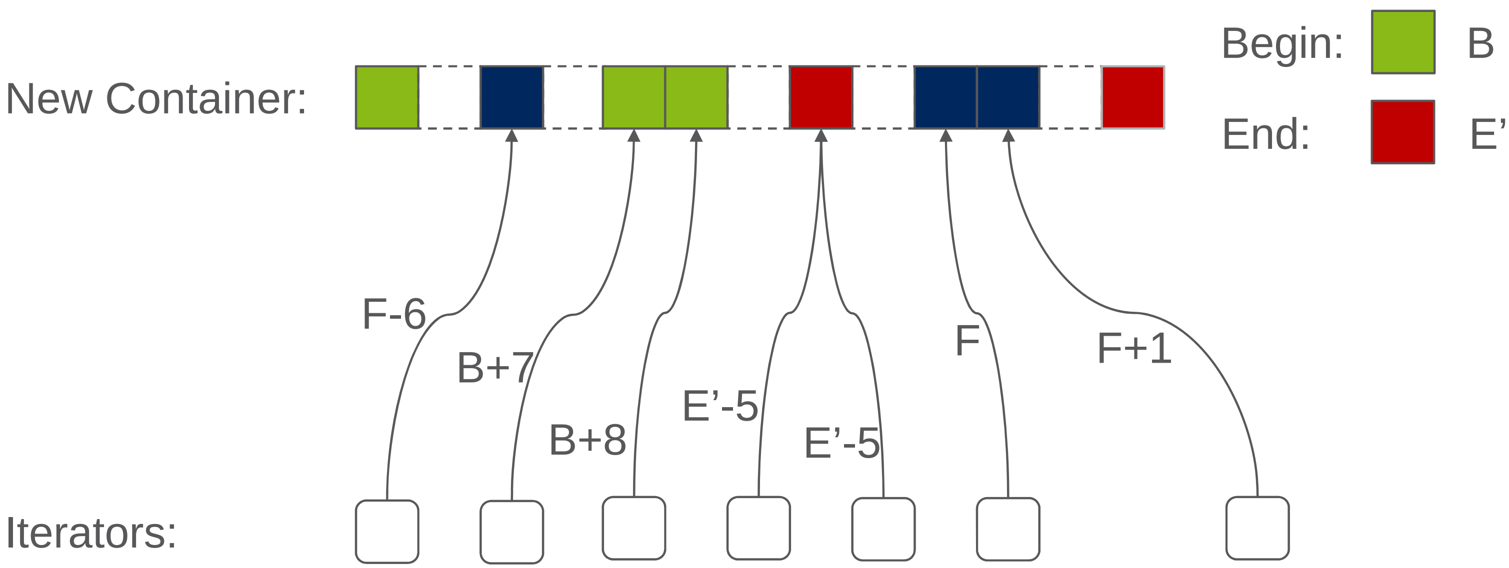
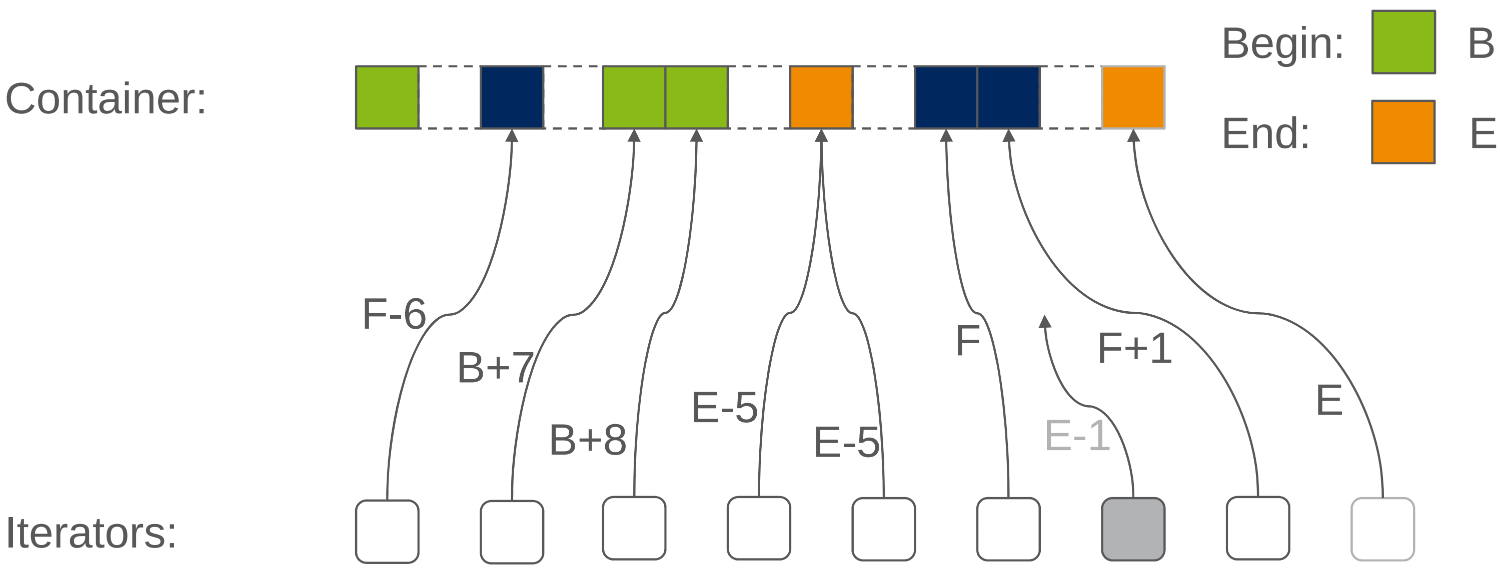
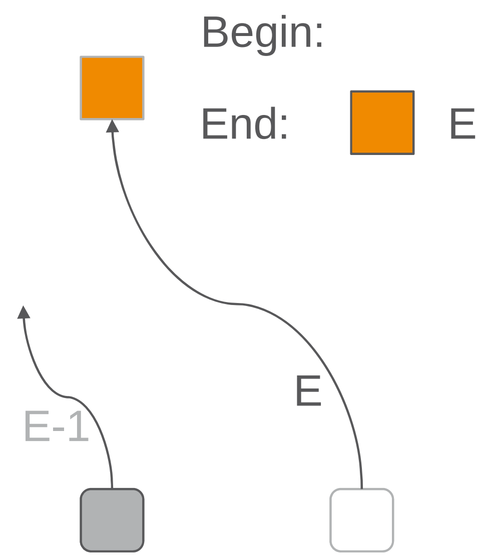


EXAMPLE: MOVE SEMANTICS



EXAMPLE: MOVE SEMANTICS

Old Container:



Iterators:

Handling Search Algorithms

- Symbolic execution of search algorithms (e.g. std::find()) is too complex
  - The analyzer usually cannot determine whether the element is found
  - Lots of different execution paths generated
- Simplification: we model the search functions of the STL
  - Only two paths: the element is found or not
  - When found, we conjure a new symbol
  - When not found, we return the argument which stores the end of the range
- False not-found states?
  - Yes, but (as we mentioned it), full execution does not help
  - The programmer can use assertions if the element is surely to be found

INFRASTRUCTURE LIMITATIONS

- Tracking of complex structures
  - Static Analyzer can track Symbols or Memory Regions
  - Complex structures may appear as any of them
- Static Analyzer's default constraint manager only handles integer ranges
  - Microsoft's Z3 is an option, but it increases analysis time by more than a whole magnitude!
  - We need to compare iterator positions which are symbolic expressions
    - Example: compare iterator positions to past-end iterator position
    - Symbolic expressions: symbol plus/minus constant is enough
    - Record the relation of two positions in the state and use it for subsequent assumptions

TRACKING COMPLEX STRUCTURES

- Assign iterator positions for both symbols and regions behaving as iterators
- Track every assignment in the checker and copy the state manually
- Hooks: after constructors, upon value bindings, **after temporary creation**
- There is no hook after temporary creation
  - Analyzer extended by such hook
  - Useful for every future checker that tracks complex structures

EXPRESSION REARRANGEMENT

- We have an expression `M + a @ N + b`
  - M and N are symbols, a and b concrete integers and `@` is a comparison operator
- Rearrange it to `M – N @ b – a`
  - Constraint manager can store an integer range for `M – N` now
- What about overflow cases?
  - Type extension disables correct handling of intentional overflow cases
  - Solution: only do the rearrangement if `M`, `N`, `a` and `b` are signed and inside `(MIN/4..MAX/4)`
  - This limitation is acceptable not only for the iterator checkers, but also other checkers, e.g. array out-of-range checkers
- Side effect: also do the rearrangement if `@` is an additive operator
  - No limitation in this case

DIFFERENCE NEGATION

- If we store a range for `M - N` in the constraint manager, it still cannot reason about `N - M`
- Solution: if constraint manager cannot find a range for `N - M`, then try to find it for `M - N` and then negate the range as well
- It can later be extended to a more generic solution for other negation cases

CURRENT STATUS

- Checker is under review on the Phabricator in 10 parts
  - First part is accepted
  - Some other parts tentatively accepted (dependent on yet unaccepted parts)
- Infrastructure patches (except difference negation) already in Clang
- Whole checker is internally used inside Ericsson

OPEN ISSUES

- Problems causing these false-positives:
  - Container’s length() is not simulated
  - Random-access iterators are not specially handled
  - Difficult to determine whether two containers are indeed different

CONCLUSION

- New checker developed to detect the 3 most typical error using iterators
- Clang Static Analyzer core infrastructure improved
- Existing checkers benefit from core infrastructure improvements
- New checkers may be developed based on these improvements

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