“Modular and Verified Automatic Program Repairs”

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presenter name(s) removed for FERPA considerations
Introduction

Your programs will have bugs!
    ...and it would be useful to catch these bugs before running your program.

There exist automatic design time programs that report bugs to the developer.
    ...but they do not automatically provide the repairs for those bugs.

Wouldn’t it be easier if code repairs were automatically suggested to you as you write buggy code?
Research Questions

How do we verify a satisfactory code repair?

Can code repairs be generated for every type of bug found?

Are the code repairs being suggested fast enough to be useful in an active development use case?
The Approach

During design time, automatically suggest code repairs that address bug warnings reported by static analyzers at design time.

- Repairs need to be “verified” for correctness
- Framework needs to be “modular” and work off of different static analyzers
- No program runs or test-suites
- Works on incomplete code
Contributions

Defined the notion of a “verified” repair.

Proposed sound algorithms for suggesting verified code repairs that address bugs at design time.

Evaluated implementation to be accurate and fast enough for use in IDE.
We already know what this is...
These are already used in practice.
cccheck: a static analyzer

Static analysis that will automatically detect buggy code during design time. (No program runs or test suite needed)

- Missing contracts
- Incorrect locals
- Incorrect object initialization
- Wrong conditionals
- Buffer overruns
- Arithmetic overflows
- Incorrect floating point comparisons
Will extending cccheck to include repair work?
Trace Semantics

“Traces are a sequence of states…”

Runs

What it means to be a good or bad run
Verified Program Repair

What makes a repair a “good” repair?
Repair should mean greater good runs and fewer bad runs.
Verified Assertion Repair

Abstracting what verified repair means

How can you determine an improved assertion?
System Diagram

Design Time

Developer \rightarrow \text{Code} \quad \text{Accept/Decline Repair}

\text{Modular Verified Repair} \rightarrow \text{Static Analyzer} \quad \text{Warnings}

Program Repairs from a Static Analyzer

So does the repair program actually work with a static analyzer?

(1) “cccheck” does not require program runs and does not require test-suites.

(2) By construction, any verified code repair will not break your code (assuming that your assertions are defined correctly).

(3) The verified code repairs are design-time suggestions, and are not applied unless the developer approves it.

(4) Authors claim the repair program can be generalized for ALL static analyzers.
cccheck: Static Analysis Phases (part 1/2)

(1) Gather assertions
   - Provided as the developer codes
   - Can also be inferred by language semantics

(2) Infer facts
   - Abstract interpretation in the abstract domains of heap abstraction, null checks, scalable numerical analysis, universally and existentially quantified properties, and floating point comparisons
cccheck: Static Analysis Phases (part 2/2)

(3) Prove assertions
   - Four possible outcomes:
     1. *True*, the assertion holds for all executions that reach it
     2. *False*, the assertion does not hold for all executions that reach it
     3. *Bottom*, the assertion is not reached in any execution
     4. *Top*, the assertion holds only sometimes or the analysis is imprecise

(4) Report warnings and suggest repairs
   - Rank the warnings based on severity
Forwards and Backwards Analysis

Verified repairs are property specific.

Verified repairs are inferred by the process of either:
(1) Backwards *must* analysis: to specifically provide repairs involving new contracts, initializations, and guards
(2) Forwards *may* analysis: to specifically provide repairs involving off-by-one, floating point exceptions, and arithmetic overflows
Backwards analysis

Backwards analysis is treated as a function which computes the under-approximation of semantics by computing fixed points at loops.

Begin with a known failing assertion and analyze backwards until a point where the preconditions for the failing assertion do not hold.

Specifically provide repairs for failing assertions with properties involving new contracts, initializations, and guards.
Seeing how it works: Repair by contract

```csharp
int[] ContractRepairs(int index)
{
    var length = GetALength(); // (1)
    var arr = new int[length];
    arr[index] = 9876;
    return arr;
}
```

Assertions: $0 \leq index$ and $index < arr.Length$
Seeing how it works: Repair by contract

```csharp
int[] ContractRepairs(int index)
{
    var length = GetALength(); // (1)
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Assertions: $0 \leq \text{index}$ and $\text{index} < \text{arr.Length}$
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    return arr;
}
```

Assertions: $0 \leq index$ and $index < arr.Length$

- $B_{\text{entry}}(0 \leq index) = 0 \leq index$ is suggested as precondition.
- It is necessary as else underflow shall occur.
- It isn’t sufficient (array in bounds isn’t ensured)
Seeing how it works: Repair by contract

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int[] ContractRepairs(int index)
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Assertions: $0 \leq \text{index}$ and $\text{index} < \text{arr.Length}$
Seeing how it works: Repair by contract

```csharp
int[] ContractRepairs(int index)
{
    var length = GetALength(); // (1)
    var arr = new int[length];
    arr[index] = 9876;
    return arr;
}
```

Assertions: $0 \leq \text{index}$ and $\text{index} < \text{arr.Length}$

- $B_{entry}(\text{index} < \text{arr.Length}) = \text{True}$ but $B_1(\text{index} < \text{arr.Length}) = \text{index} < \text{length}$ must be true for GetALength.
- Repair: Contract.Assume ($\text{index} < \text{length}$)
void P(int[] a)
{
    for (var i = 0; i < a.Length; i++)
        a[i - 1] = 110;
}

void P'(int[] a)
{
    Contract.Requires(a != null);
    for (var i = 1; i < a.Length; i++)
        a[i - 1] = 110;
}

• Necessary condition $1 \leq i$, but $i = 0$. So suggest fix as $i = 1$. 
string GetString(string key)
{
    var str = GetString(key, null);
    if (str == null)
    {
        var args = new object[1];
        // (*)
        args[1] = key;
        throw new ApplicationException(args);
    }
    return str;
}
void ValidateOwnerDrawRegions(
    ComboBox c, Rectangle updateRegionBox)
{
    if (c == null)
    {
        var r = new Rectangle(0, 0, c.Width); // (*)
        // use r and c
    }
}
Seeing how it works: Initialization fixes (3)

void ValidateOwnerDrawRegions(ComboBox c, Rectangle updateRegionBox)
{
    if (c == null)
    {
        var r = new Rectangle(0, 0, c.Width); // (*)
        // use r and c
    }
}

Change to (c != null)

Not reached ever!
Seeing how it works: Repairing object initialize

```
public class MyClass
{
    private readonly SomeObj s;

    public MyClass(SomeObj s)
    {
        Contract.Requires(s != null);
        this.s = s;
    }

    public MyClass()
    {
    }

    public int Foo()
    {
        return this.s.f;
    }
    // ...
}
```

(this.s != null) should be true always.

As else:

```java
x = new MyClass();
x.Foo();
```

fails invariably.
Seeing how it works: Repairing object initialize

this.s is private hence can’t be made precondition of foo. It should be established during creation.
Seeing how it works: Repairing object initialize

either initialize this.s to a non-null value in MyClass() or add an object invariant to avoid the null dereference of s in Foo.
Forwards analysis

Forwards analysis evaluates repairs using the semantic facts inferred by abstract domains.

Specifically provide repairs for failing assertions with properties involving off-by-one, floating point exceptions, and arithmetic overflows.
Seeing how it works: Repairing off-by-one

```csharp
string GetString(string key)
{
    var str = GetString(key, null);
    if (str == null)
    {
        var args = new object[1];
        ```args[1] = key; ```// (*)
        throw new ApplicationException(args);
    }
    return str;
}
```

Infer: $1 \leq \text{args.Length} = 1$, so suggest 0 as the new index.
Seeing how it works: Repairing floating-point

```java
class FloatingPoint
{
    double d;

    [ContractInvariantMethod]
    void ObjectInvariant()
    {
        Contract.Invariant(this.d != 0.0);
    }

    public void Set(double d0)
    {
        // here d0 may have extended double precision
        if (d0 != 0.0)
            this.d = d0; // d0 can be truncated to 0.0
        
    }
}
```

Comparing against constants. Repair with typecast: `((double)d0 != 0.0)`
Forward analysis on arithmetic overflows is defined over a set of rules.
int BinarySearch(int[] array, int value)
{
    Contract.Requires(array != null);
    int inf = 0, sup = array.Length - 1

    while (inf <= sup)
    {
        var index = (inf + sup) / 2;  // (*)
        var mid = array[index];

        if (value == mid) return index;
        if (mid < value) inf = index + 1;
        else
            sup = index - 1;
    }
    return -1;
}
This can overflow! Repair by replacing with half sums:
inf + (sup - inf) / 2
void ThreadSafeCopy(char* sourcePtr, char[] dest, int destIndex, int count)
{
    if (count > 0)
        if ((destIndex > dest.Length)
            || (count + destIndex) > dest.Length)
            throw new ArgumentOutOfRangeException();
{ // ... }
}

Fix using: count > dest.Length - destIndex
Evaluation

80.9% of assertion warnings reported by cccheck had at least one verified repair suggested.

Time spent generating repairs is very small relative to time spent generating warnings.

On integration with Visual Studio, the program analyzed:

6+ methods/second and infers 7.5 repairs/second
10x faster with cccheck caching
Conclusion

The authors produced a design time solution for automatic suggestion of verified program repair.

- The program to be repaired does not need to be run (or even complete)
- Developer does not need to provide a test suite
- The strict definition of verified repair implies correctness for all suggestions
- Repairs are local and can handle loops/infinite states
- Can be used as an extension of static analyzers with little added overhead
- Full functionality operates with reasonable speed and completeness
Discussion 1

What kind of bugs can we fix using this?
Discussion 2

Does it actually bridge the gap between static analyzers and dynamic analyzer?
Discussion 3

Can it repair automatically?
Discussion 4

The program requires a set of regular expressions to capture arithmetic errors. Can this be exhaustive?
Discussion 5

What else can be added to this to make it more robust and user independent?