BSSE System and Software Engineering

Potentials of Constraint-based Methods in Software Verification and Validation

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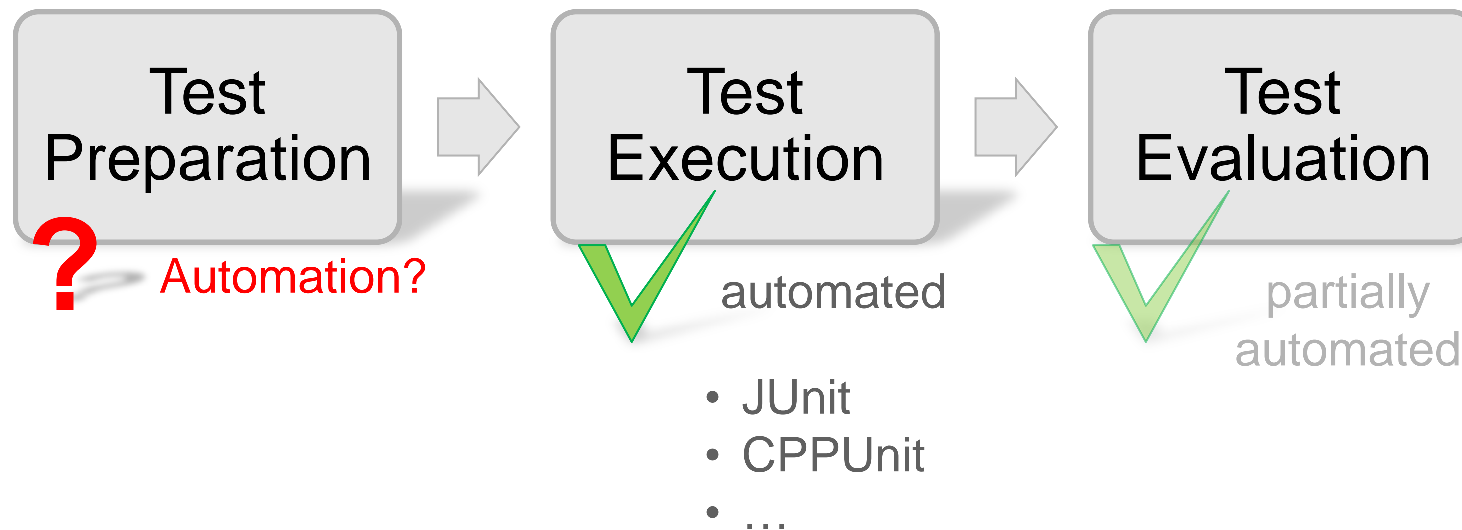
Motivation



- JUnit
- CPPUnit
- …

→Automatic Test Data Generation

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Other applications

Static Analysis and Verification
- Model-Checking
- Abstract Interpretation

Autonomy
- Continuous replanning
- Reconfiguration

Model-based approaches
- Automatic design decisions
- Optimisation
- Model-based Testing

Automatic/Automated Parallelisation (e.g. for multiprocessors or multicores)

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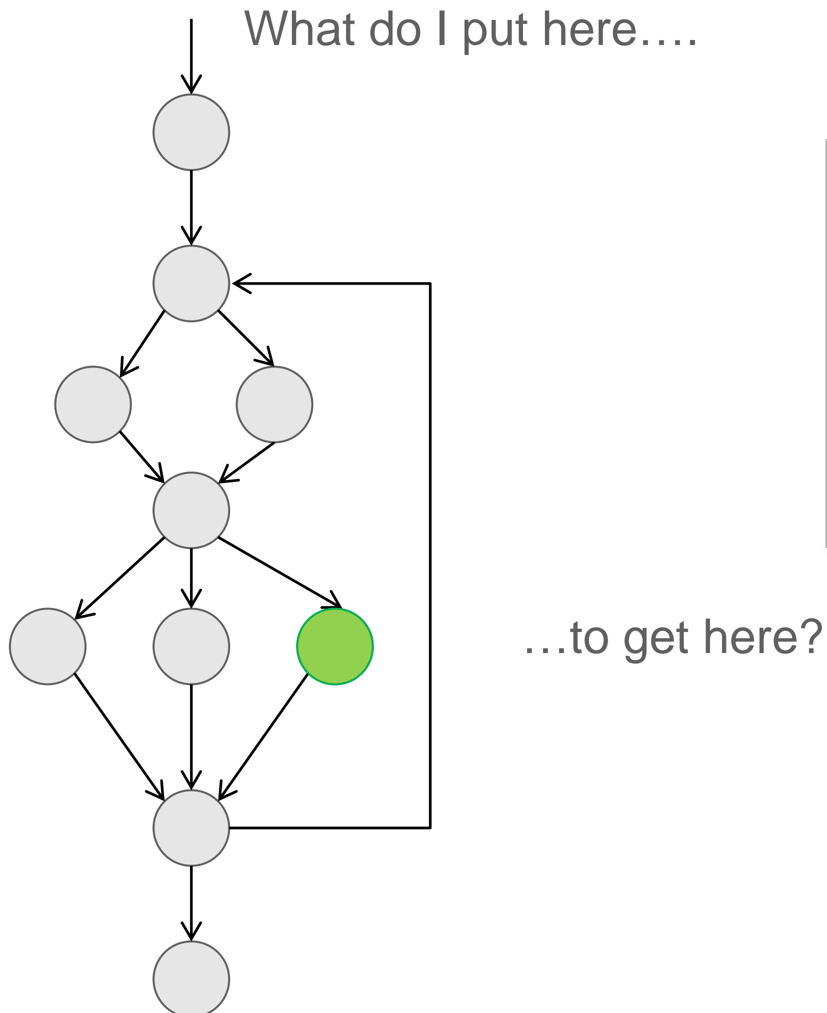
Coverage Testing

What input is required to reach a specific point in the code?



Constraint-based Test Data Generation (CBTDG):

1. Construct a path to the target
2. Execute path symbolically
3. Solve the constraint system

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Symbolic Execution of Paths (Basic Idea)

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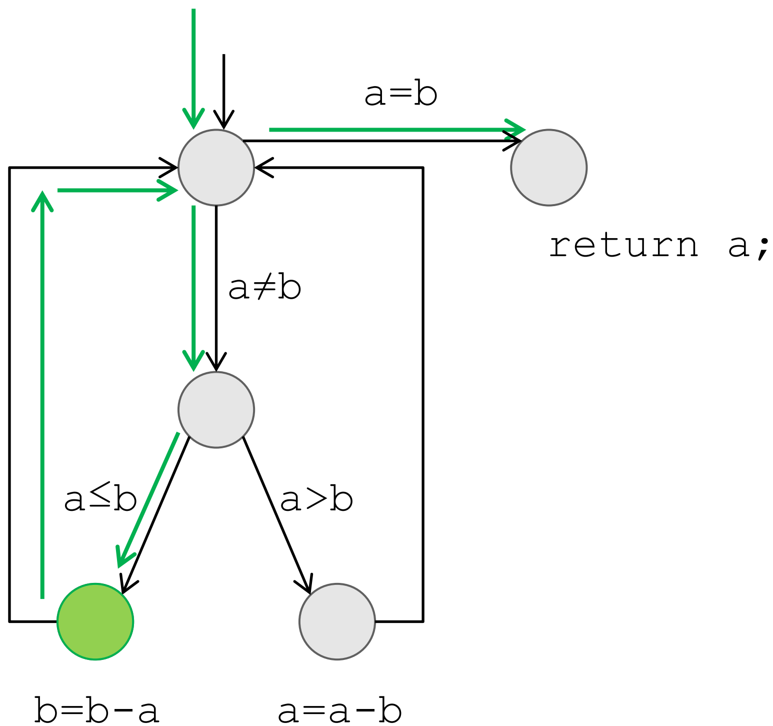
Constructed Path

```
unsigned int gcd(
        unsigned int a,
        unsigned int b)
```



Symbolic Execution

$a_1 \neq b_1$

Index to indicate „version“ of the variable

$a_1 \leq b_1$

$b_2 = b_1 - a_1$

New Index to indicate assignment

$a_1 = b_2$

Always use the latest index

Solve for a_1 and b_1: $b_1 = 2a_1,\ a_1 \leq b_1$

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Infeasible Paths

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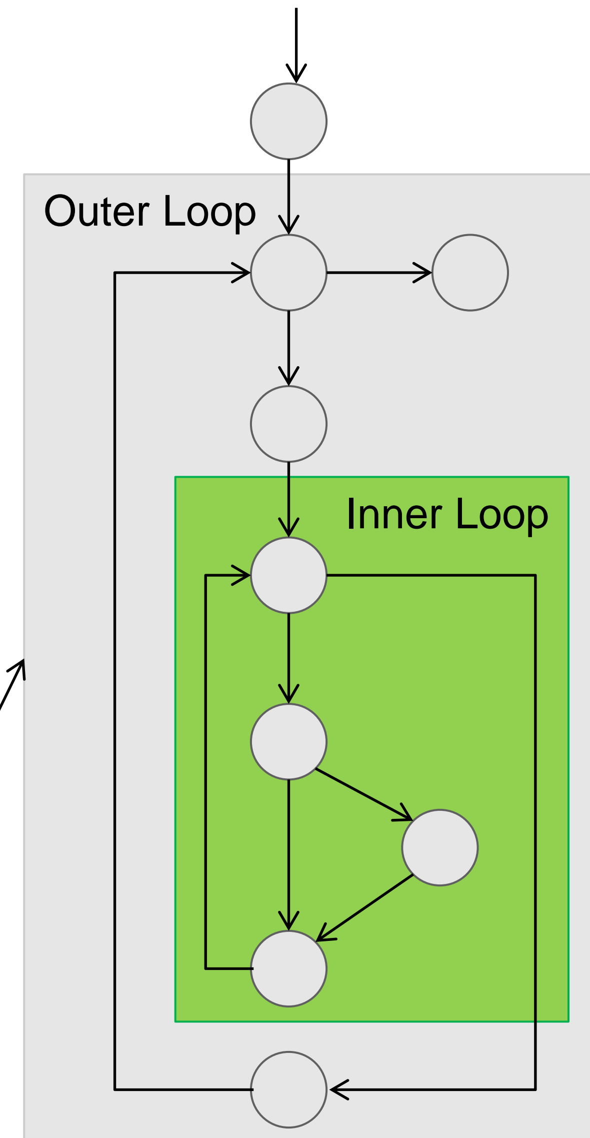
```
void sort(int a[], unsigned int n) {
    unsigned int i,j,min;
    int tmp;

    for (i=0;i<n;i++) {                              n times
        min=i;
        for (j=i+1;j<n;j++) {              n(n-1)/2 times
            if (a[j]<a[min]) {
                min=j;
            }
        }
        tmp = a[i];
        a[i] = a[min];
        a[min] = tmp;
    }
}
```



Inner and outer loop seem to be independent of each other!

Leads to construction of paths that are not possible in actual program!
→ infeasible paths

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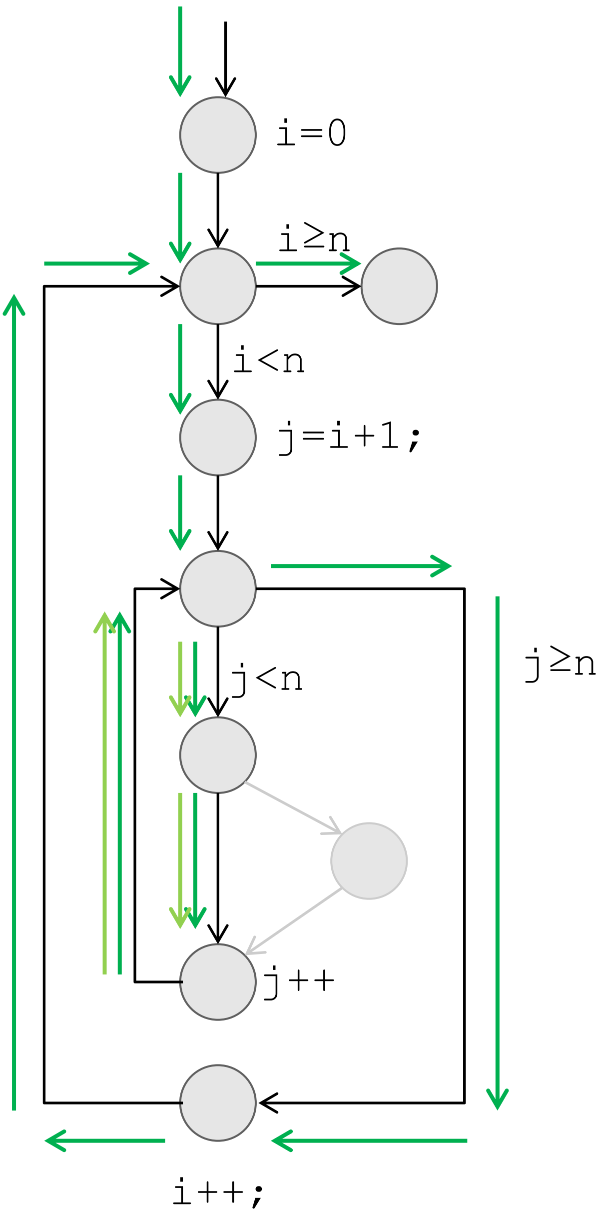
Detecting Infeasible Paths



Contradiction!

$i_1=0$	
$i_1<n$	0<n
$j_1=i_1+1$	
$j_1<n$	1<n
$j_2=j_1+1$	
$j_2<n$	2<n
$j_3=j_2+1$	
$j_3\geq n$	3≥n
$i_2=i_1+1$	
$i_2\geq n$	1≥n

```
void sort(int a[], unsigned int n) {
    unsigned int i,j,min;
    int tmp;

    for (i=0;i<n;i++) {
        min=i;
        for (j=i+1;j<n;j++) {
            if (a[j]<a[min]) {
                min=j;
            }
        }
        tmp = a[i];
        a[i] = a[min];
        a[min] = tmp;
    }
}
```

Cannot be solved by brute force trial-and-error!

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Solution of systems of linear inequations by Joseph Fourier (1768-1830) and Theodore Motzkin (1908-1970).

1. Transform into upper and lower bounds for x:

$$\begin{array}{c} 1 < 4x + 3y < 5 \\ -1 < 2x - y < 2 \end{array} \Rightarrow \begin{array}{c} 1 - 3y < 4x < 5 - 3y \\ -1 + y < 2x < 2 + y \end{array} \Rightarrow \begin{array}{c} 1 - 3y < 4x < 5 - 3y \\ -2 + 2y < 4x < 4 + 2y \end{array}$$

2. Recombine upper and lower bounds:

$$\begin{array}{c} 1 - 3y < 4 + 2y \\ -2 + 2y < 5 - 3y \end{array} \Rightarrow \begin{array}{c} -3 < 5y \\ 5y < 7 \end{array} \Rightarrow -\frac{3}{5} < y < \frac{7}{5}$$

3. Find a solution by selecting a value for y:

$$y = 0 \Rightarrow \begin{array}{c} 1 < 4x < 5 \\ -1 < 2x < 2 \end{array} \Rightarrow \begin{array}{c} \frac{1}{4} < x < \frac{5}{4} \\ -\frac{1}{2} < x < 1 \end{array} \Rightarrow \frac{1}{4} < x < 1 \Rightarrow x = \frac{1}{2}$$

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All issues solved?

So existing solvers for rational numbers should be sufficient for CBTDG, right?

So I thought ~2 years ago, when I started implementing a CBTDG tool. Unfortunately, …

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Limitations: Integers are Rationals, but…

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$$1 < 4x + 3y < 5$$
$$-1 < 2x - y < 2$$

Fourier-Motzkin-Elimination tells us:

$$-\frac{3}{5} < y < \frac{7}{5}$$

So, y=0 and y=1 may be integer solutions…

…but none of them is!

$$y = 0 \Rightarrow \frac{1}{4} < x < 1$$
$$y = 1 \Rightarrow 0 < x < \frac{1}{2}$$

There is an algorithm (Omega Test by Pugh, 1991).
It may be computationally costly (exponentially with the number of variables).

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Limitations: Floats are Rationals, but…

We assume that…

$$\forall x, y: y > 0 \Rightarrow x + y > x$$

Not for float!

```
float x;
for (x=x0;x<limit;x+=inc) {
    /* … */
}
```

Seems like this loop will terminate in any case, …

…but if `x(<limit)` is sufficiently large compared to `inc`, we get…

$$x + inc = x$$

…although `inc` is greater than 0!

Floating-Point operations are fundamentally different from rational arithmetic due to rounding!

Current solver approaches (Botella et al, 2006) use domain filtering, which suffers from bad convergence.

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Linearisation of Bitwise Operations

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Basic approach: bit-vector

$$x = \sum_{i=0}^{n-1} x_i 2^i \qquad (0 \leq x_i \leq 1)$$

$$x \sqcap y = \sum_{i=0}^{n-1} (x_i \sqcap y_i) 2^i$$

Many additional variables

Nonlinear

But most of the time, one operand is constant!

$$y = x \& 12$$

$$y = 4x_2 + 8x_3$$

Bit 2 of x, Bit 3 of x

$$x = c_1 + 4c_2 + 16c_3$$

$$y = 4c_2$$

$$0 \leq c_1 < 4$$

$$0 \leq c_2 < 4$$

$$c_1 = x_0 + 2x_1$$

$$c_2 = x_2 + 2x_3$$

$$c_3 = \sum_{i=0}^{n-5} x_i 2^i$$

Exact linear representation!

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Integer arithmetic traps

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```
unsigned int a,b,c;
/* … */

c=a-b;
```

Is this classical arithmetics over integers?

No, it's not!

$$c = a - b + 2^{32}s$$

$$0 \le c \le 2^{32} - 1$$

```
void foo(int l, int u) {
        int i;
        if ((u-l)<100) {
                for (i=l;i<u;i++) {
                        /* … */
                }
        }
}
```

Is the iteration count of this loop really limited to 100?

No, it's not!

$$l = -2^{31} + 1$$

$$u = 1$$

$$u - l = 2^{31} \equiv -2^{31} < 100$$

Sometimes, even i+1=0, although i>0!

```
for (j=0;j<n;j+=i+1) { … }
```

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Avoidance of Bias

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Software test cannot prove absence of bugs, only their presence.

So software test is really a scientific experiment, testing the hypothesis: „The program is correct.“

Selection of test cases influences the validity of the result greatly.

When there is more than one test case fulfilling the same test objective, which one to use? (→Bias)

Simple algorithms are easier to rid of bias (e.g. in selecting paths to execute) than complex algorithms…

…and constraint solution is a pretty complex matter!

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Recommendations: Coding for CBTDG

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Recommendations to simplify constraint-based program analysis:

- Separate hardware interaction from logic (functional H/W I/F)
- Avoid memory overlays, `memcpy`, `memmove` and `union`
- Use small, well-specified functions for specific purposes
- Solver support for fixed-point is much better than for floating point

Recommendations to simplify automatic test-data generation:

- First test randomly, then complement by constraint-based methods
- Restrict parameter types as far as possible

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Conclusions and Outlook

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Not any solver is able to properly solve the problems coming up in static analysis of software.

In theory everything works, in practice…

Some static analysis tasks are still difficult to solve and the results may be surprising – or not, if they are masked by bias.

Ongoing research is expected to bring important advances in all areas, e.g.

- handling floating point
- parallelisation of constraint calculations
- parallelisation in software
- …

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Thank you for your Attention!

Any Questions?

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