Introduction to CBMC: Part 1

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Many slides are courtesy of
Daniel Kroening
Bug Catching with SAT-Solvers

**Main Idea:** Given a program and a claim use a SAT-solver to find whether there exists an execution that violates the claim.

![Diagram showing the process of Bug Catching with SAT-Solvers.](image)
Programs and Claims

• Arbitrary ANSI-C programs
  • With bitvector arithmetic, dynamic memory, pointers, …

• Simple Safety Claims
  • Array bound checks (i.e., buffer overflow)
  • Division by zero
  • Pointer checks (i.e., NULL pointer dereference)
  • Arithmetic overflow
  • User supplied assertions (i.e., `assert (i > j)`)
  • etc
Why use a SAT Solver?

• SAT Solvers are very efficient

• Analysis is completely automated

• Analysis as good as the underlying SAT solver

• Allows support for many features of a programming language
  • bitwise operations, pointer arithmetic, dynamic memory, type casts
SAT made some progress…
A (very) simple example (1)

Program

```c
int x;
int y=8, z=0, w=0;
if (x)
    z = y – 1;
else
    w = y + 1;
assert (z == 7 ||
w == 9)
```

Constraints

```c
y = 8,
z = x ? y - 1 : 0,
w = x ? 0 : y + 1,
z != 7,
w != 9
```

UNSAT

no counterexample

assertion always holds!
A (very) simple example (2)

```c
int x;
int y=8, z=0, w=0;
if (x)
    z = y – 1;
else
    w = y + 1;
assert (z == 5 ||
        w == 9);
```

**Constraints**

```plaintext
y = 8,
z = x ? y – 1 : 0,
w = x ? 0 : y + 1,
z != 5,
w != 9
```

SAT

counterexample found!

```
y = 8, x = 1, w = 0, z = 7
```
What about loops?!

- SAT Solver can only explore finite length executions!
- Loops must be bounded (i.e., the analysis is incomplete)

Program → Analysis Engine → CNF → SAT Solver

Claim

Bound (n)

SAT: (counterexample exists)

UNSAT: (no counterexample of bound n is found)
CBMC: C Bounded Model Checker

• Developed at CMU by Daniel Kroening et al.
• Available at: http://www.cs.cmu.edu/~modelcheck/cbmc/
• Supported platforms: Windows (requires VisualStudio’s `CL), Linux
• Provides a command line and Eclipse-based interfaces

• Known to scale to programs with over 30K LOC
• Was used to find previously unknown bugs in MS Windows device drivers
CBMC: Supported Language Features

ANSI-C is a low level language, not meant for verification but for efficiency

Complex language features, such as

- Bit vector operators (shifting, and, or,…)
- Pointers, pointer arithmetic
- Dynamic memory allocation: malloc/free
- Dynamic data types: `char s[n]`
- Side effects
- `float / double`
- Non-determinism
Introduction to CBMC: Part 2

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How does it work

1. Simplify control flow
2. Convert into Single Static Assignment (SSA)
3. Convert into equations
4. Unwind loops
5. Bit-blast
6. Solve with a SAT Solver
7. Convert SAT assignment into a counterexample
Control Flow Simplifications

- All side effect are removed
  - e.g., \( j = i++ \) becomes \( j = i; i = i + 1 \)

- Control Flow is made explicit
  - `continue, break` replaced by `goto`

- All loops are simplified into one form
  - `for, do while` replaced by `while`
Transforming Loop-Free Programs Into Equations (1)

Easy to transform when every variable is only assigned once!

```
x = a;
y = x + 1;
z = y - 1;
```

Program

```
x = a &
y = x + 1 &
z = y - 1 &
```

Constraints
Transforming Loop-Free Programs Into Equations (2)

When a variable is assigned multiple times, use a new variable for the RHS of each assignment.

**Program**

\[
\begin{align*}
x &= x + y; \\
x &= x \times 2; \\
a[i] &= 100;
\end{align*}
\]

**SSA Program**

\[
\begin{align*}
x_1 &= x_0 + y_0; \\
x_2 &= x_1 \times 2; \\
a_1[i_0] &= 100;
\end{align*}
\]
What about conditionals?

Program

```
if (v)
    x = y;
else
    x = z;

w = x;
```

SSA Program

```
if (v_0)
    x_0 = y_0;
else
    x_1 = z_0;

w_1 = x_0;
```

What should ‘x’ be?
What about conditionals?

For each join point, add new variables with selectors.
Adding Unbounded Arrays

\[
\nu_\alpha[a] = \epsilon \\
\nu_\alpha = \lambda i : \begin{cases} 
\rho(e) & : i = \rho(a) \\
\nu_{\alpha-1}[i] & : \text{otherwise}
\end{cases}
\]

Arrays are updated “whole array” at a time

\[
\begin{align*}
A[1] &= 5; & A_1 &= \lambda i : i == 1 \ ? \ 5 : A_0[i] \\
A[2] &= 10; & A_2 &= \lambda i : i == 2 \ ? \ 10 : A_1[i] \\
A[k] &= 20; & A_3 &= \lambda i : i == k \ ? \ 20 : A_2[i]
\end{align*}
\]

Examples:

\[
\begin{align*}
A_2[2] &= \_?\_ \\
A_2[1] &= \_?\_ \\
A_2[3] &= \_?\_
\end{align*}
\]

\[
y = A_3[2] \Rightarrow \_?\_
\]
Example

```
int main() {
    int x, y;
    y = 8;
    if(x)
        y--;  
    else
        y++;

    assert
        (y == 7 ||
         y == 9);
}
```

```
int main() {
    int x, y;
    y1 = 8;
    if(x0)
        y2 = y1 - 1;
    else
        y3 = y1 + 1;

    y4 = x0 ? y2 : y3;
    assert
        (y4 == 7 ||
         y4 == 9);
}
```

```
( y1 = 8
∧ y2 = y1 - 1
∧ y3 = y1 + 1
∧ y4 = x0 ? y2 : y3 )
⇒ (y4 = 7 ∨ y4 = 9)
```
Pointers

While unwinding, record right hand side of assignments to pointers

This results in very precise points-to information

- Separate for each pointer
- Separate for each instance of each program location

Dereferencing operations are expanded into case-split on pointer object (not: offset)

- Generate assertions on offset and on type

Pointer data type assumed to be part of bit-vector logic

- Consists of pair <object, offset>
Pointer Typecast Example

```c
void *p;
int i;
int c;
int main (void) {
    int input1, input2, z;
p = input1 ? (void*)&i : (void*) &c;
if (input2)
z = *(int*)p;
else
z = *(char*)p; }
```
Dynamic Objects

Dynamic Objects:

- `malloc`/`free`
- Local variables of functions

Auxiliary variables for each dynamically allocated object:

- Size (number of elements)
- Active bit
- Type

`malloc` sets size (from parameter) and sets active bit

`free` asserts that active bit is set and clears bit

Same for local variables: active bit is cleared upon leaving the function
Loop Unwinding

- All loops are unwound
  - can use different unwinding bounds for different loops
  - to check whether unwinding is sufficient special “unwinding assertion” claims are added

- If a program satisfies all of its claims and all unwinding assertions then it is correct!

- Same for backward goto jumps and recursive functions
Loop Unwinding

while() loops are unwound iteratively
Break / continue replaced by goto

```c
void f(...) {
    ...
    while (cond) {
        Body;
    }
    Remainder;
}
```
Loop Unwinding

void f(...) {
    ...
    if(cond) {
        Body;
        while(cond) {
            Body;
        }
    }
    Remainder;
}
Loop Unwinding

```c
void f(...) {
    ...
    if (cond) {
        Body;
        if (cond) {
            Body;
            while (cond) {
                Body;
            }
        }
    }
    Remainder;
}
```

- while() loops are unwound iteratively
- Break / continue replaced by goto
Unwinding assertion

while() loops are unwound iteratively

Break / continue replaced by goto

Assertion inserted after last iteration: violated if program runs longer than bound permits

```c
void f(...) {
    ...
    if(cond) {
        Body;
        if(cond) {
            Body;
            if(cond) {
                Body;
                while(cond) {
                    Body;
                }
            }
        }
    }
    Remainder;
}
```
Unwinding assertion

while() loops are unwound iteratively
Break / continue replaced by goto
Assertion inserted after last iteration: violated if program runs longer than bound permits

```c
void f(...) {
  ...
  if(cond) {
    Body;
    if(cond) {
      Body;
      if(cond) {
        Body;
        assert(!cond);
        }
      }
    }
  }
  }
  Remainder;
}
```
Example: Sufficient Loop Unwinding

void f(...) {
    j = 1
    while (j <= 2)
        j = j + 1;
    Remainder;
}

unwind = 3
**Example: Insufficient Loop Unwinding**

```c
void f(...) {
    j = 1
    while (j <= 10)
        j = j + 1;
    Remainder;
}
```

`unwind = 3`

```c
void f(...) {
    j = 1
    if(j <= 10) {
        j = j + 1;
        if(j <= 10) {
            j = j + 1;
            if(j <= 10) {
                j = j + 1;
                assert(!(j <= 10));
            }
        }
    }
    Remainder;
}
```
Convert Bit Vector Logic Into Propositional Logic