Introduction to CBMC: Part 1

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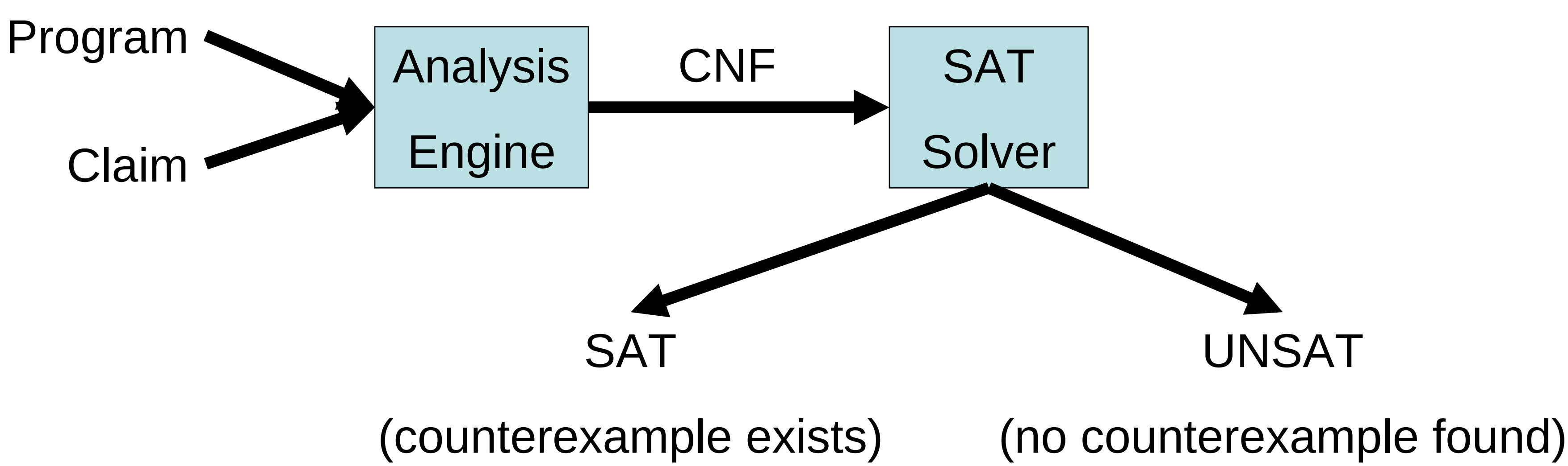
Many slides are courtesy of
Daniel Kroening

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.



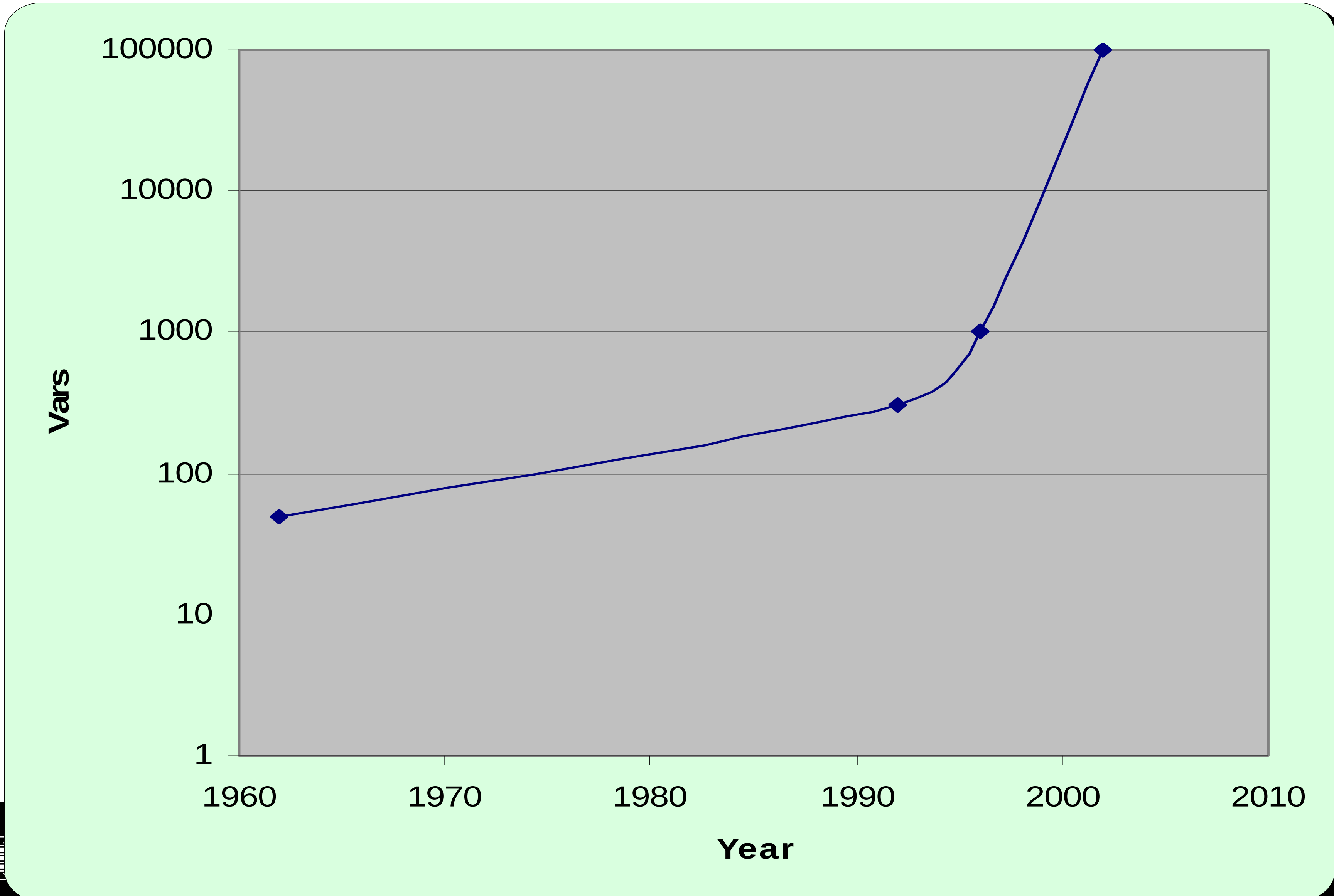
Programs and Claims

- 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

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

Constraints

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)

Program

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

Constraints

y = 8,

z = x ? y – 1 : 0,

w = x ? 0 :y + 1,

z != 5,

w != 9

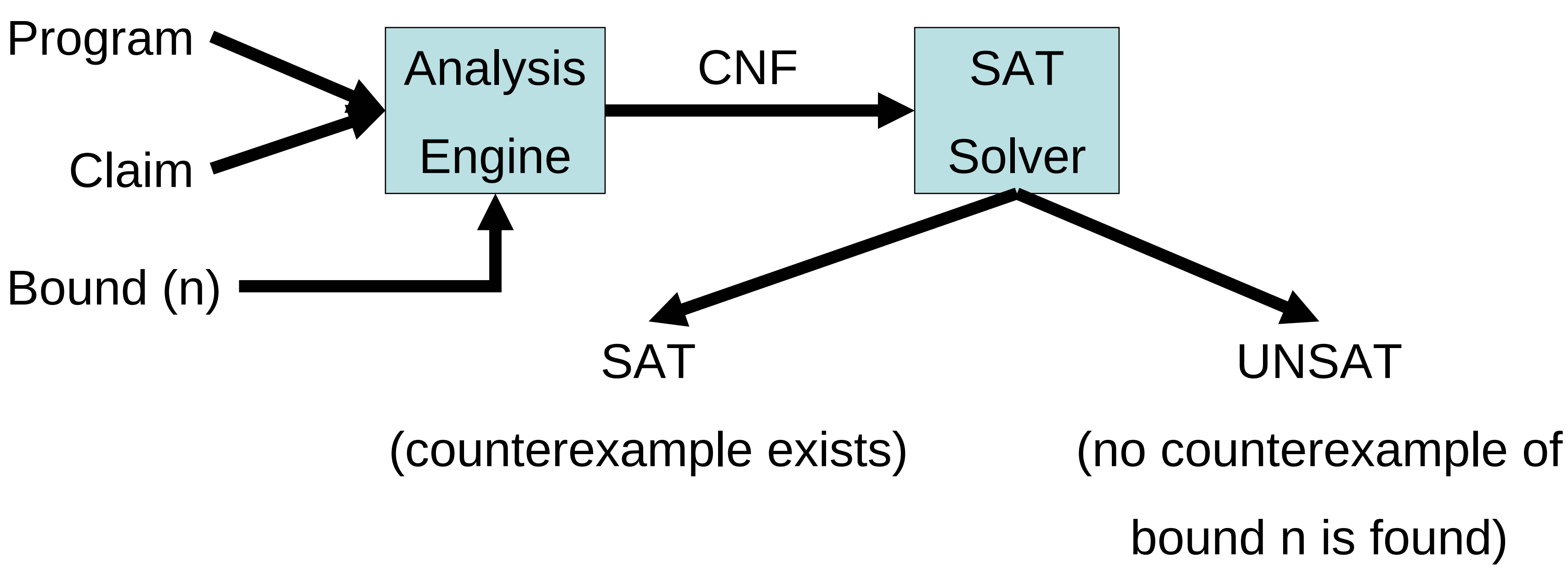
SAT

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)



CBMC: C Bounded Model Checker

- Developed at CMU by Daniel Kroening et al.
- Available at: http://www.cs.cmu.edu/~modelcheck/cbmc/
- Supported platfoms: 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!

Program

```
x = a;
y = x + 1;
z = y – 1;
```

Constraints

x = a &&

y = x + 1 &&

z = y – 1 &&

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

```
x=x+y;
x=x*2;
a[i]=100;
```

ρ

SSA Program

$x_1 = x_0 + y_0;$

$x_2 = x_1 * 2;$

$a_1[i_0] = 100;$

What about conditionals?

Program

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

w = x;
```

ρ

SSA Program

$\texttt{if } (v_0)$

$\quad x_0 = y_0;$

$\texttt{else}$

$\quad x_1 = z_0;$

$w_1 = x??;$

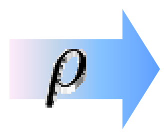
What should ‘x’ be?

What about conditionals?

Program

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

w = x;
```



SSA Program

$\texttt{if}\ (v_0)$

$\quad x_0 = y_0;$

$\texttt{else}$

$\quad x_1 = z_0;$

$x_2 = v_0\ ?\ x_0 : x_1;$

$w_1 = x_2$

For each join point, add new variables with selectors

Adding Unbounded Arrays

$$v_\alpha[a] = e \quad \xrightarrow{\rho} \quad v_\alpha = \lambda i : \begin{cases} \rho(e) & : \ i = \rho(a) \\ v_{\alpha-1}[i] & : \ \text{otherwise} \end{cases}$$

Arrays are updated "whole array" at a time

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]

Examples: A_2[2] == ?? A_2[1]==?? A_2[3] == ??

y=A_3[2] =>??

Example

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

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

ρ →

```
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);
}
```

→

$$
\begin{aligned}
(\quad & y_1 = 8 \\
\wedge \quad & y_2 = y_1 - 1 \\
\wedge \quad & y_3 = y_1 + 1 \\
\wedge \quad & y_4 = x_0 \,?\, y_2 : y_3 \;) \\
\Longrightarrow \quad & (y_4 = 7 \vee y_4 = 9)
\end{aligned}
$$

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

```
void *p;
int i;
int c;
int main (void) {
  int input1, intput2, 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

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

while() loops are unwound iteratively

Break / continue replaced by goto

Loop Unwinding

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

while() loops are unwound iteratively

Break / continue replaced by goto

Loop Unwinding

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

while() loops are unwound iteratively

Break / continue replaced by goto

Unwinding assertion

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

while() loops are unwound iteratively

Break / continue replaced by goto

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

Unwinding assertion

```
void f(...) {
  ...
  if(cond) {
    Body;
    if(cond) {
      Body;
      if(cond) {
        Body;
        assert(!cond);

      }
    }
  }
  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

Example: Sufficient Loop Unwinding

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

unwind = 3

```
void f(...) {
  j = 1
  if(j <= 2) {
    j = j + 1;
    if(j <= 2) {
      j = j + 1;
      if(j <= 2) {
        j = j + 1;
        assert(!(j <= 2));
      }
    }
  }
  Remainder;
}
```

Example: Insufficient Loop Unwinding

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

unwind = 3

```
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