Introduction to CBMC

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based on slides by
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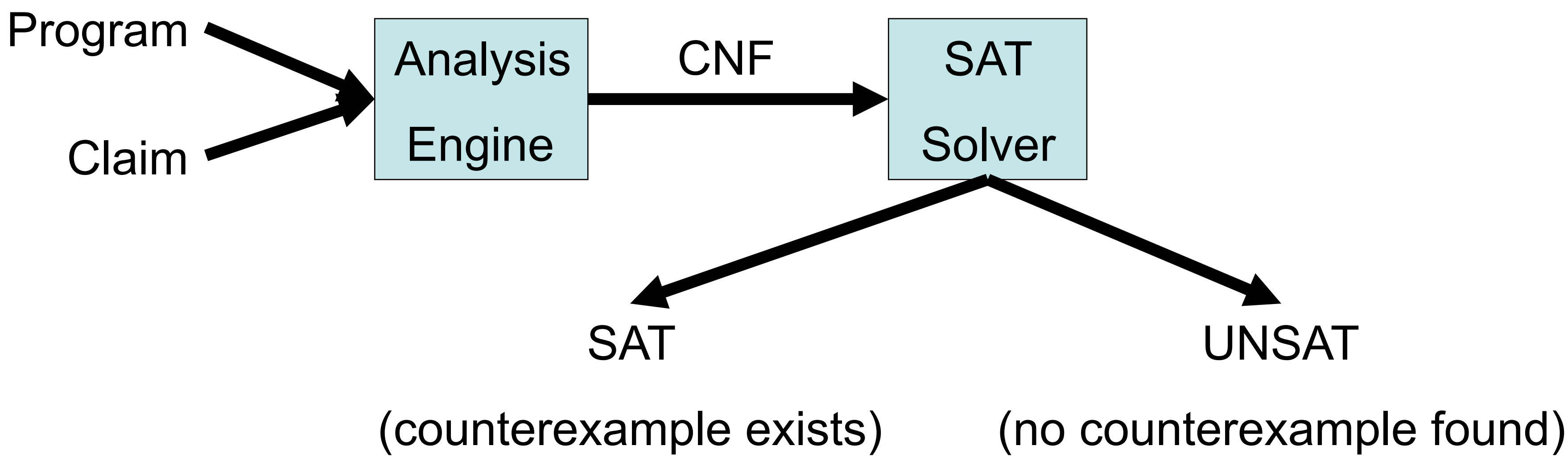
Bug Catching with SAT-Solvers

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

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

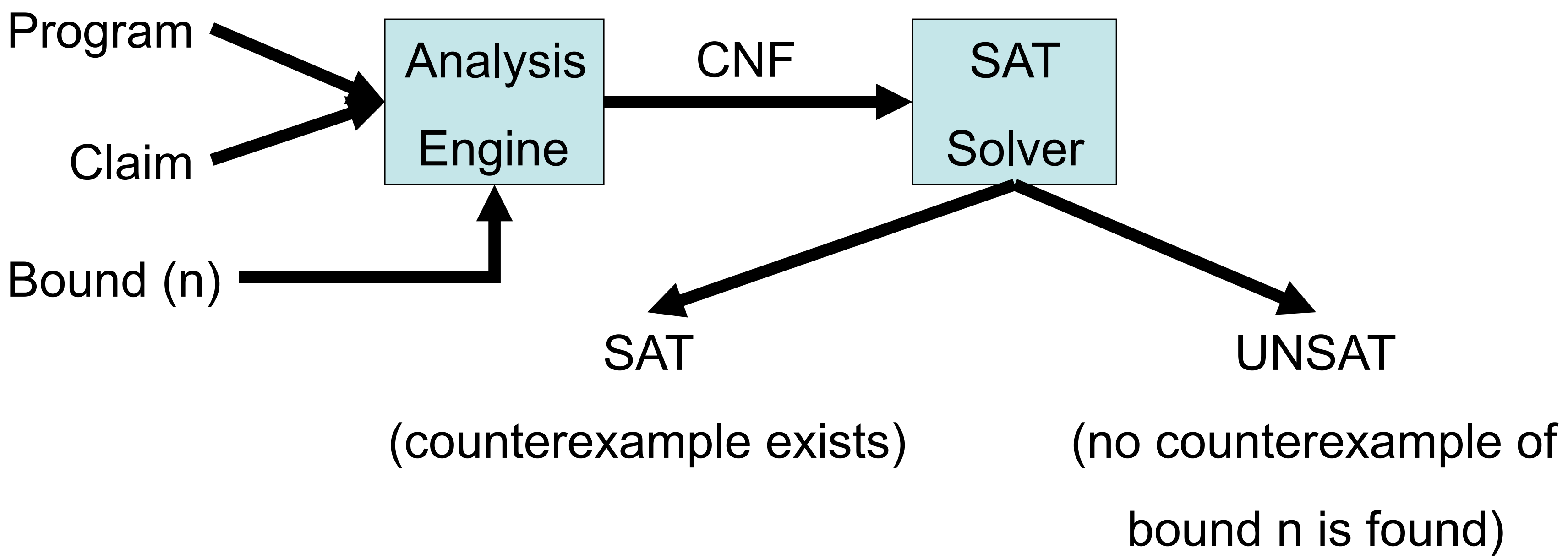
SAT

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 and Ed Clarke
- Available at: http://www.cprover.org/cbmc
  - On Ubuntu: `apt-get install cbmc`
  - `with source code`
- Supported platforms: Windows, Linux, OSX
- Has a command line, Eclipse CDT, and Visual Studio interfaces

- Scales to programs with over 30K LOC
- Found 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

DEMO

Using CBMC from Command Line

- To see the list of claims

```
cbmc --show-claims -I include file.c
```

- To check a single claim

```
cbmc --unwind n --claim x –I include file.c
```

- For help
    - cbmc --help

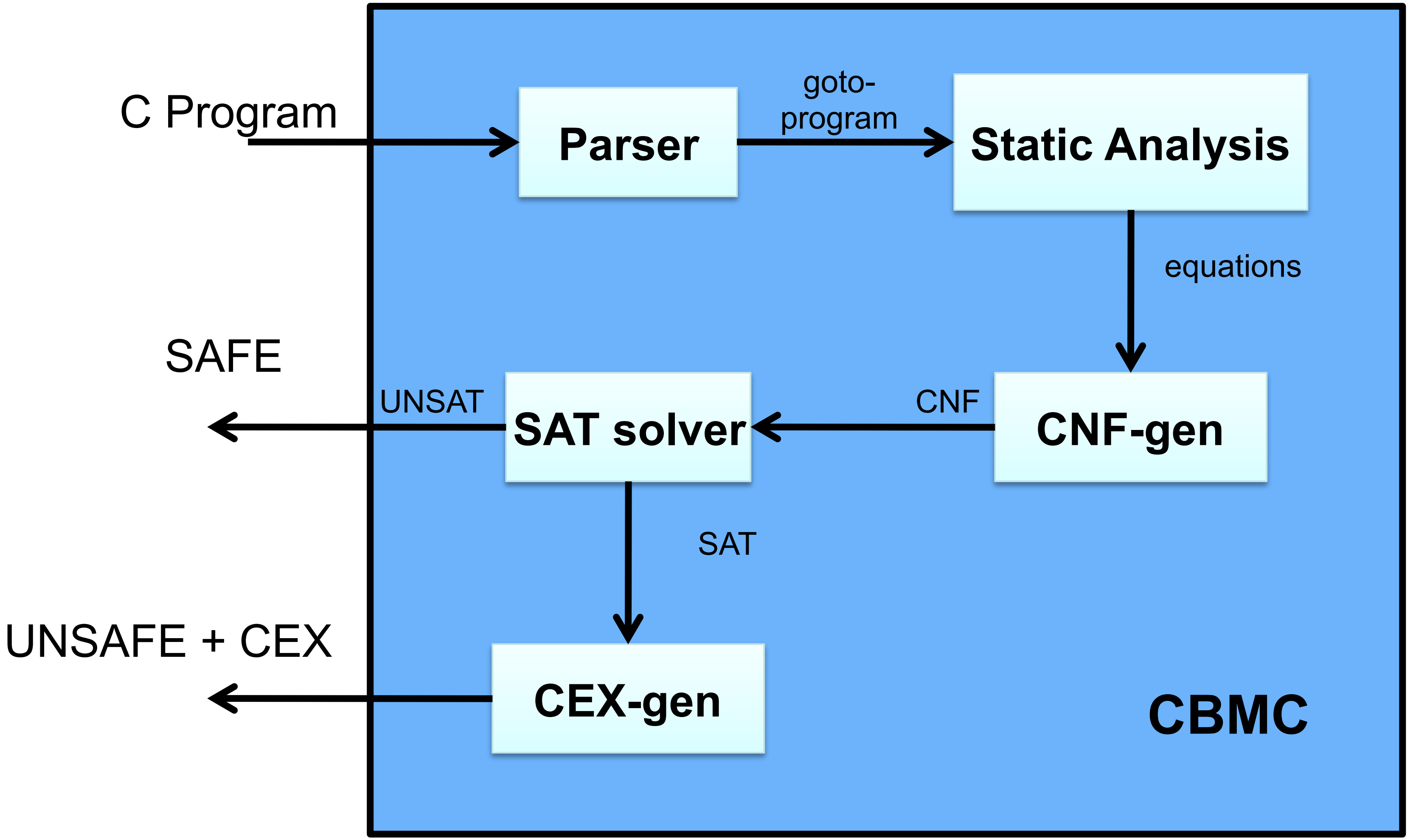
How does it work

Transform a programs into a set of equations

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

CBMC: Bounded Model Checker for C

A tool by D. Kroening/Oxford and Ed Clarke/CMU



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`

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
- Positive correctness result!

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;
}
```

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

$$
\begin{array}{l}
\texttt{if } (v_0)\\
\quad x_0 = y_0;\\
\texttt{else}\\
\quad x_1 = z_0;\\
\\
w_1 = x??;
\end{array}
$$

What should 'x' be?

What about conditionals?

Program	SSA Program
`if (v)`	`if (`v_0`)`
`x = y;`	$x_0 = y_0$;
`else`	`else`
`x = z;`	$x_1 = z_0$;
	$x_2 = v_0$? x_0 : x_1;
`w = x;`	$w_1 = x_2$

ρ

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:

$A_2[2] == 10$ $A_2[1]==5$ $A_2[3] == A_0[3]$

$A_3[2] == (k==2\ ?\ 20 : 10)$

Uses only as much space as there are uses of the array!

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;
char 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

Modeling with CBMC

From Programming to Modeling

Extend C programming language with 3 modeling features

Assertions

- assert(e) – aborts an execution when e is false, no-op otherwise

```
void assert (_Bool b) { if (!b)  exit(); }
```

Non-determinism

- nondet_int() – returns a non-deterministic integer value

```
int nondet_int () { int x; return x; }
```

Assumptions

- assume(e) – “ignores” execution when e is false, no-op otherwise

```
void assume (_Bool e) { while (!e) ;  }
```

Example

```
int x, y;
void main (void)
{
  x = nondet_int ();

  assume (x > 10);
  y = x + 1;

  assert (y > x);
}
```

possible overflow

assertion fails

Using nondet for modeling

Library spec:

"foo is given non-deterministically, but is taken until returned"

CMBC stub:

```
int nondet_int ();
int is_foo_taken = 0;
int grab_foo () {
  if (!is_foo_taken)
    is_foo_taken = nondet_int ();
  return is_foo_taken; }
```

```
void return_foo ()
{ is_foo_taken = 0; }
```

Assume-Guarantee Reasoning (1)

Is `foo` correct?

Check by splitting on the argument of `foo`

```
int foo (int* p) { … }
void main(void) {
  …
  foo(x);
  …
  foo(y);
  …
}
```

Assume-Guarantee Reasoning (2)

(A) Is `foo` correct assuming `p` is not NULL?

```
int foo (int* p) { __CPROVER_assume(p!=NULL); … }
```

(G)Is `foo` guaranteed to be called with a non-NULL argument?

```
void main(void) {
  …
  assert (x!=NULL);// foo(x);
  …
  assert (y!=NULL); //foo(y);
  …}
```

Dangers of unrestricted assumptions

Assumptions can lead to vacuous satisfaction

This program is passed by CMBMC!

```
if (x > 0) {
  __CPROVER_assume (x < 0);
  assert (0); }
```

Assume must either be checked with assert or used as an idiom:

```
x = nondet_int ();
y = nondet_int ();
__CPROVER_assume (x < y);
```

Example: Prophecy variables

```
int x, y, v;
void main (void)
{
  v = nondet_int ();
  x = v;

  x = x + 1;
  y = nondet_int ();
  assume (v == y);

  assert (x == y + 1);

}
```

v is a *prophecy* variable

it guesses the future value of y

assume blocks executions with a wrong guess

syntactically: x is changed *before* y

semantically: x is changed *after* y

Context-Bounded Analysis with CBMC

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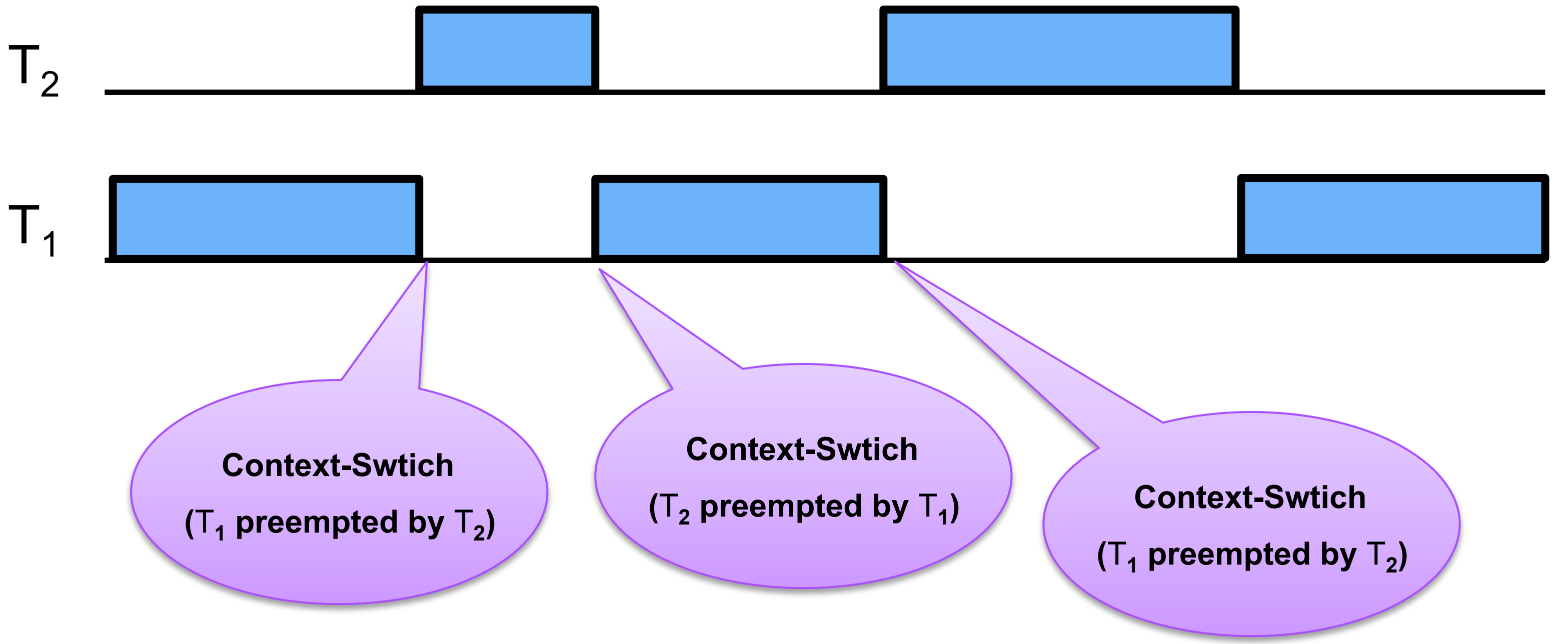
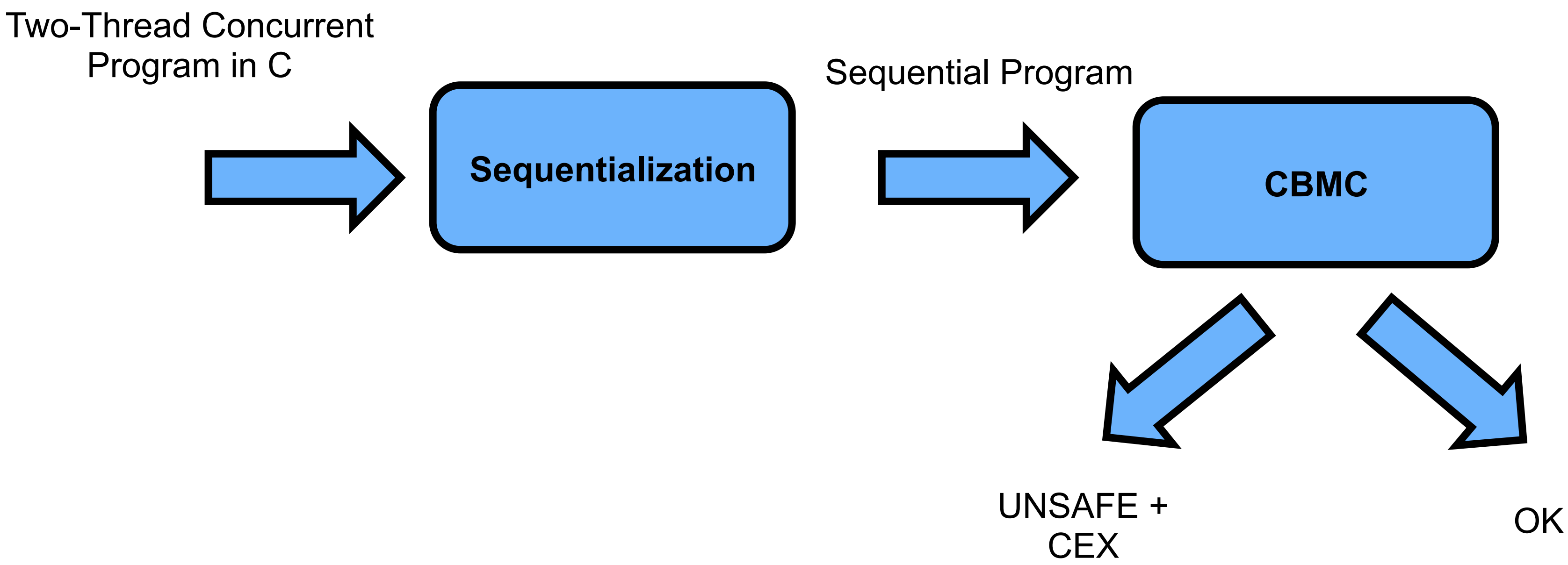
Context-Bounded Analysis (CBA)

Explore all executions of TWO threads that have at most R context-switches (per thread)



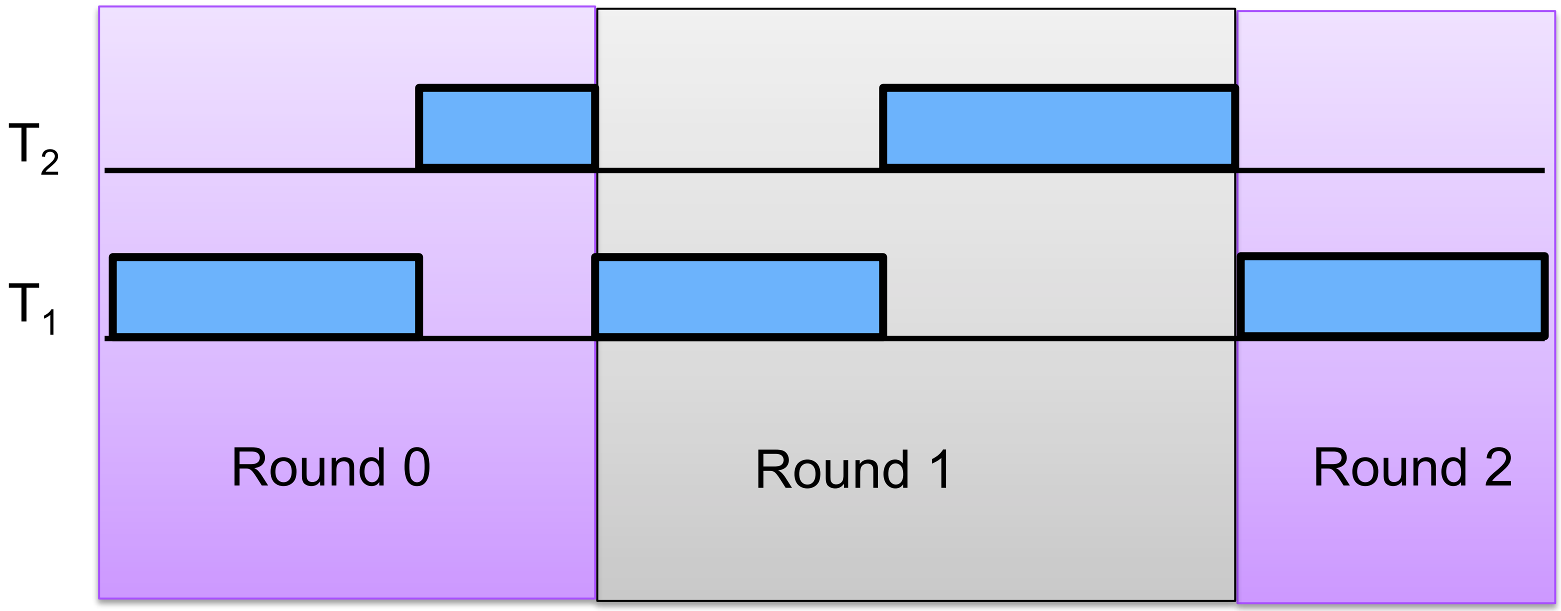
CBA via Sequentialization

1. Reduce concurrent program P to a sequential (non-deterministic) program P' such that "P has error" iff "P' has error"
2. Check P' with CBMC

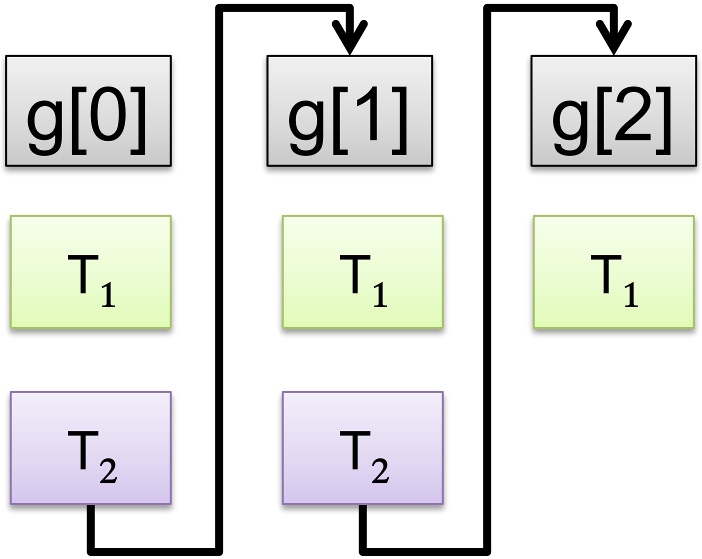


Key Idea

1. Divide execution into rounds based on context switches
2. Execute executions of each context separately, starting from a symbolic state
3. Run all parts of Thread 1 first, then all parts of Thread 2
4. Connect executions from Step 2 using assume-statements



Sequentialization in Pictures



Guess initial value of each global in each round

Execute task bodies

- T_1
- T_2

Check that initial value of round i+1 is the final value of round i

CBA Sequentialization in a Nutshel

Sequential Program for execution of R rounds (i.e., context switches):

1. for each global variable g, let g[r] be the value of g in round r
2. execute thread bodies sequentially
   - first thread 1, then thread 2
   - for global variables, use g[r] instead of g when running in round r
   - non-deterministically decide where to context switch
   - at a context switch jump to a new round (i.e., inc r)
3. check that initial value of round r+1 is the final value of round r
4. check user assertions

CBA Sequentialization 1/2

```
var
  int round;                       // current round
  int g[R], i_g[R];                // global and initial global
  Bool saved_assert = 1;           // local assertions
```

```
void main ()
  initShared ();
  initGlobals();

  for t in [0,N) : // for each thread
      round = 0;
      T'_t();
  checkAssumptions ();
  checkAssertions ();
```

```
initShared ()
 for each global var g, g[0] = init_value (g);
```

```
initGlobals ()
  for r in [1,R): //for each round
    for each global g: g[r] = i_g[r] = nondet();
```

```
checkAssumtpions ()
  for r in [0,R-1):
    for each global g:
      assume (g[r] == i_g[r+1]);
```

```
checkAssertions ()
  assert (saved_assert);
```

CBA Sequentialization: Task Body 2/2

```
void T'_t ()
  Same as T_t, but each statement 'st' is replaced with:
     contextSwitch (t); st[g ← g[round]];
  and 'assert(e)' is replaced with:
     saved_assert = e;
```

```
void contextSwitch ()
  int oldRound;

  if (nondet ()) return;  // non-det do not context switch

  oldRound = round;
  round = nondet_int ();
  assume (oldRound < round <= R-1);
```

For more details, see

Akash Lal and Tom Reps. "Reducing Concurrent Analysis Under a Context Bound to Sequential Analysis", in Proceedings of Computer Aided Verification, 2008.

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