# SLAM IV
# Boolean Model Checking

Verification & Testing

Benedikt Maderbacher

## SLAM thus far

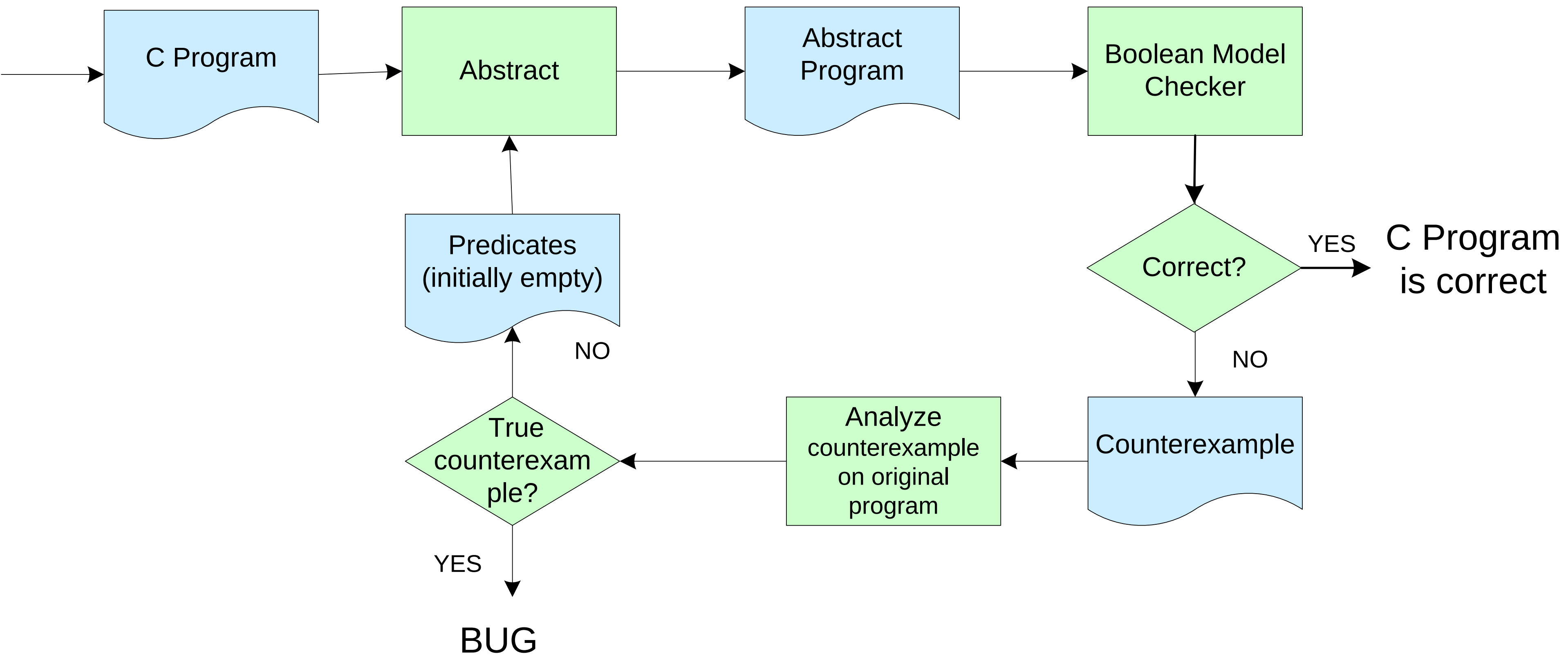
Automatic model checking of C programs

Abstraction/Refinement loop

- Predicate abstractions
- Initial abstraction: no predicates, only control flow
- When abstract program correct, so is concrete program
- When bug found in abstract program, check on concrete program
- If bug is real, stop.
- If bug is not real, add predicates to prove impossibility of path, create new abstraction, and redo

This week: Model checking Boolean Programs

# The Approach



## Model Checking Boolean Programs

**Question**: can Boolean program make nondeterministic decisions such that assertion is violated?

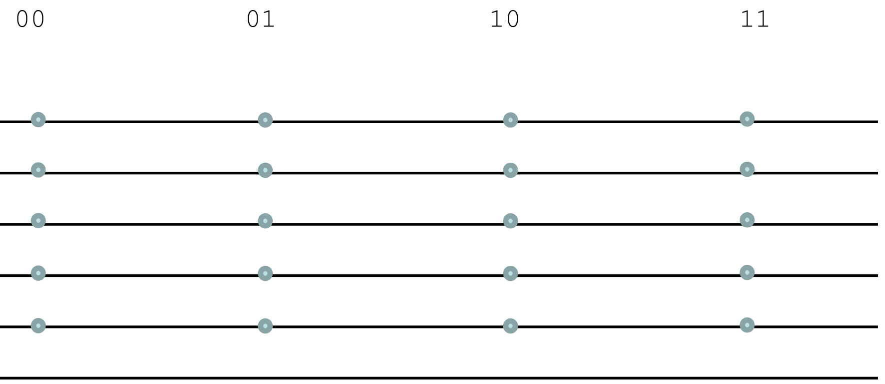
## Example

```
decl g
main(){
   decl h;
   h = !g;
   A(g,h);
   A(g,h);
   assert(!g);
}

A(a1,a2){
   if(a1){

      A(a2,a1);
   }else{

      g = a2;
   }
}
```

# Example

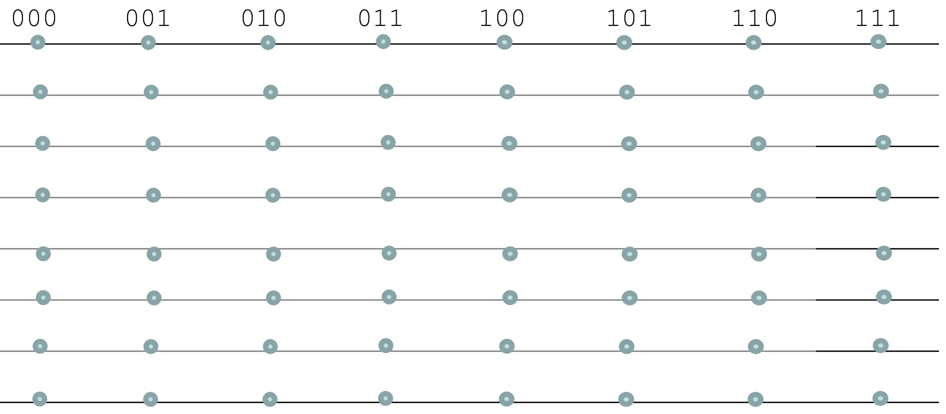
```
01. decl g
02. main(){
03.   decl h;
04.   h = !g;
05.   A(g,h);
06.   A(g,h);
07.   assert(!g);
08. }
```

g h



```
09. A(a1,a2){
10.   if(a1){
11.
12.     A(a2,a1);
13.   }else{
14.
15.     g = a2;
16.   }
17. }
```

g a1 a2



## Some Definitions

A *valuation* gives a value to a set of variables.

The *visible variables* are the global variables plus the local variables that are in scope

For function calls,

- The *caller* is the calling function
- The *callee* is the called function

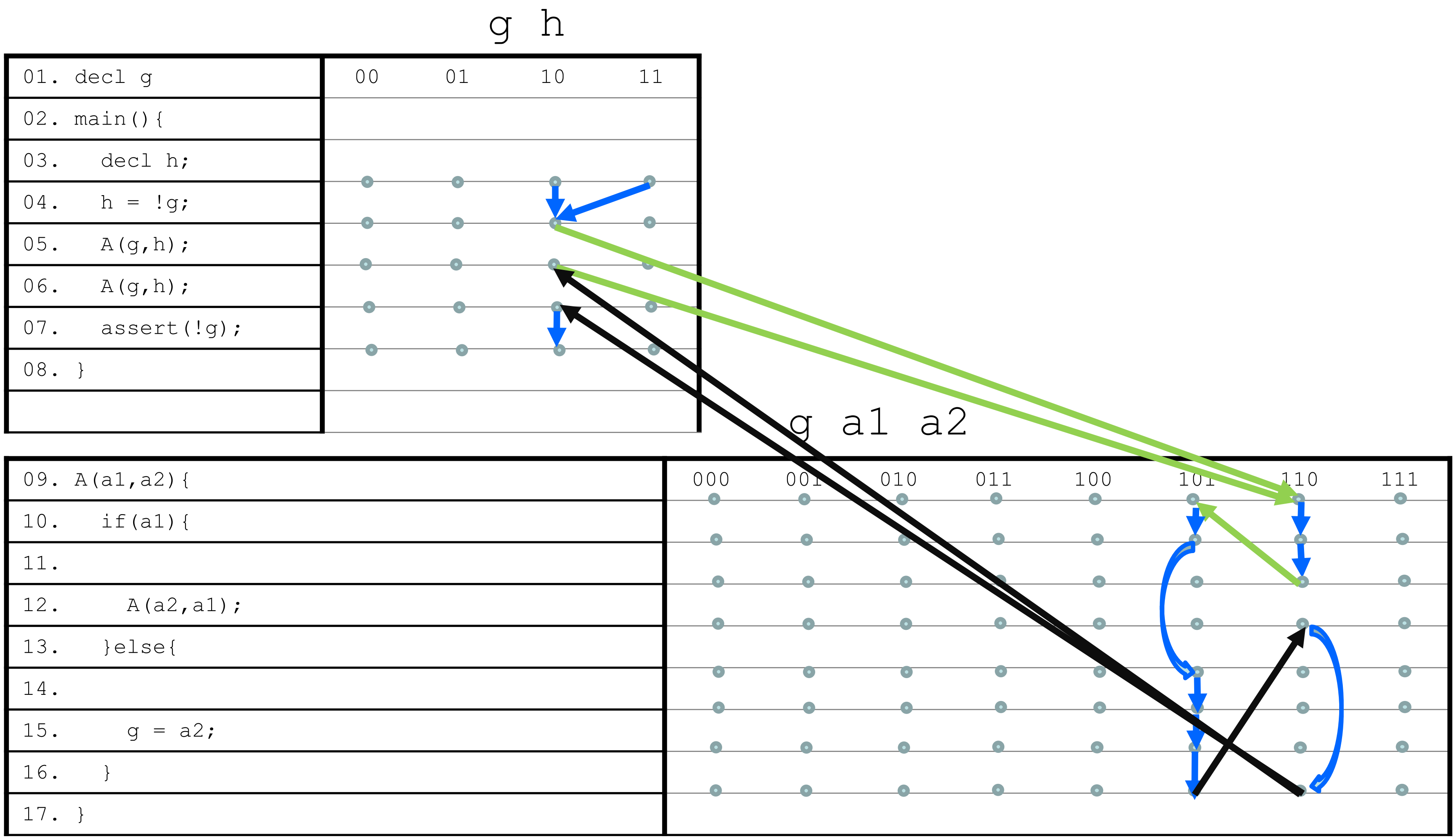
We add *points* to every line

- A point is labeled with a valuation of the visible variables (the valuation after execution of the line)
- A point is marked “done” or “not done”

We add arrows

- blue arrows for control flow
- green arrows for function calls
- black arrows for returns

# Example



```
01. decl g
02. main(){
03.     decl h;
04.     h = !g;
05.     A(g,h);
06.     A(g,h);
07.     assert(!g);
08. }
```

```
09. A(a1,a2){
10.     if(a1){
11.
12.         A(a2,a1);
13.     }else{
14.
15.         g = a2;
16.     }
17. }
```

# Example

```
01. decl g
02. main(){
03.    decl h;
04.    h = !g;
05.    A(g,h);
06.    A(g,h);
07.    assert(!g);
08. }

09. A(a1,a2){
10.    if(a1){
11.
12.       A(a2,a1);
13.    }else{
14.
15.       g = a2;
16.    }
17. }
```

Bug:

```
03. g=1, h=0
04. g=1, h=0
  09. g=1, a1=1, a2=0
  11. g=1, a1=1, a2=0
    09. g=1, a1=0, a2=1
    14. g=1, a1=0, a2=1
    15. g=1, a1=0, a2=1
  12. g=1, a1=1, a2=0
  16. g=1, a1=1, a2=0
05. g=1, h=0
09. g=1, a1=1, a2=0
  11. g=1, a1=1, a2=0
    09. g=1, a1=0, a2=1
    14. g=1, a1=0, a2=1
    15. g=1, a1=0, a2=1
  12. g=1, a1=1, a2=0
  16. g=1, a1=1, a2=0
06. g=1, h=0
07. assert(false)!
```

## Example

```
decl g
main(){
   decl h;
   h = !g;
   A(g,h);
   A(g,h);
   assert(!g);
}

A(a1,a2){
   if(a1){

      A(a2,a1);
   }else{

      g = a2;
   }
}
```

Note:

Example is deterministic (no *)

Example has an infinite loop.

- This is not a bug
- The model checker should still finish

# Model Checking

*We perform forward analysis and build graph. Nodes: combination of line number and valuation of variables. Arrows: blue (normal execution) and green (function calls).*

At beginning of main, add point for every valuation

For every point p not marked *done*:

- If next statement is
  - **assignment:** compute new valuations, add point q to next line, label with each valuation. (Nondeterminism can cause multiple valuations)
  - **if:** Add point q with same valuation to beginning of then or else branch. (or both if condition is *)
  - **while statement:** Like if
  - **end of function f:** For all p' with green arrow to the start of f and path of blue arrows from start of f to p (calls to f that end in p), compute new valuation of caller and add point q with this valuation.
  - **assert:** Condition false? Bug! Otherwise, create q with same valuation after assert.
- Mark p done. If not at end of function, add blue arrow from p to q
- If next statement is **function call:** compute valuation local to function, add point q to start of callee, add green arrow from p to q

All points marked done and no bug found? program is correct!

## Function Calls

Function calls are call-by-value (like in C)

When calling a function,

- Value of globals in callee = value of globals in caller before call
- Value of formal parameters in callee = value of actual parameters in caller before call

When returning

- Value of globals in caller after call = value of globals in callee at end of function
- Value of locals in caller after call = value of locals in caller before call

## Example, Notes

For a given function and valuation there may be

- No call with that valuation: ignored
- A call but no returns: infinite loop
- A call and one return: deterministic
- A call and multiple returns.
- The last case happens if there is nondetermism in the function. Every return is propagated to caller. Try replacing if(a1) by if(*) in example.

There may be multiple callers for every valuation

We avoid infinite loops by keeping track of valuations we have seen before.

## Another Example: nondeterminism

| | |
|---|---|
| `01. decl g` | |
| `02. main(){` | |
| `03.    A(g,g)` | |
| `04.    assert(g);` | |
| `05. }` | |
| | |
| `06. A(a1,a2){` | |
| `07.    if(*){` | |
| `08.       g = a1;` | |
| `09.    } else {` | |
| `10.       g = !a1` | |
| `11.    }` | |
| `13. }` | |
| | |

# Another Example: nondeterminism

| | |
|---|---|
| `01. decl g` | |
| `02. main(){` | |
| `03.    A(g,g)` | |
| `04.    assert(g);` | |
| `05. }` | |
| | |
| `06. A(a1,a2){` | |
| `07.    if(*){` | |
| `08.       g = a1;` | |
| `09.    } else {` | |
| `10.       g = !a1` | |
| `11.    }` | |
| `13. }` | |
| | |

Note:

Nondeterminism causes two outgoing transitions for each point on line 7 and line 3.

For instance:

- In line 7 with (g,a1,a2)=(0,0,0), we can go to line 8 with (0,0,0) or line 10 with (0,0,0).
- In line 3 with g = 0 we can go to line 4 with g = 0 or line 4 with g = 1.

## Concluding

Model checking a Boolean program

It’s simple, just keep track of what you’ve done