PROGRAMMING WITH TRIGGERS

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OUTLINE

- case-study: an SMT-powered software verifier applied to a commercial operating system
- tools and methods to make this work
  - trigger-engineering
  - tools:
    - Axiom Profiler – postmortem analysis of the search
    - Model Viewers – analysis of counter examples
    - Z3 Inspector – live view of Z3 operation

WINDOWS HYPERVISOR

- virtualization platform
  - thin layer of software between guest operating systems and the hardware
- essentially a small operating system
  - small by OS standards: 100kloc of C, 5kloc x64 asm
- scheduler, memory allocator, etc
  - lock-free data structures
- shipping with Windows Server 2008

Hypervisor Verification (2007 – 2010)

Partners:

- European Microsoft Innovation Center
- Microsoft Research Redmond
- Microsoft's Windows Div.
- Universität des Saarlandes
- German Research Center for Artificial Inteligence

co-funded by the German Ministry of Education and Research

http://www.verisoftxt.de

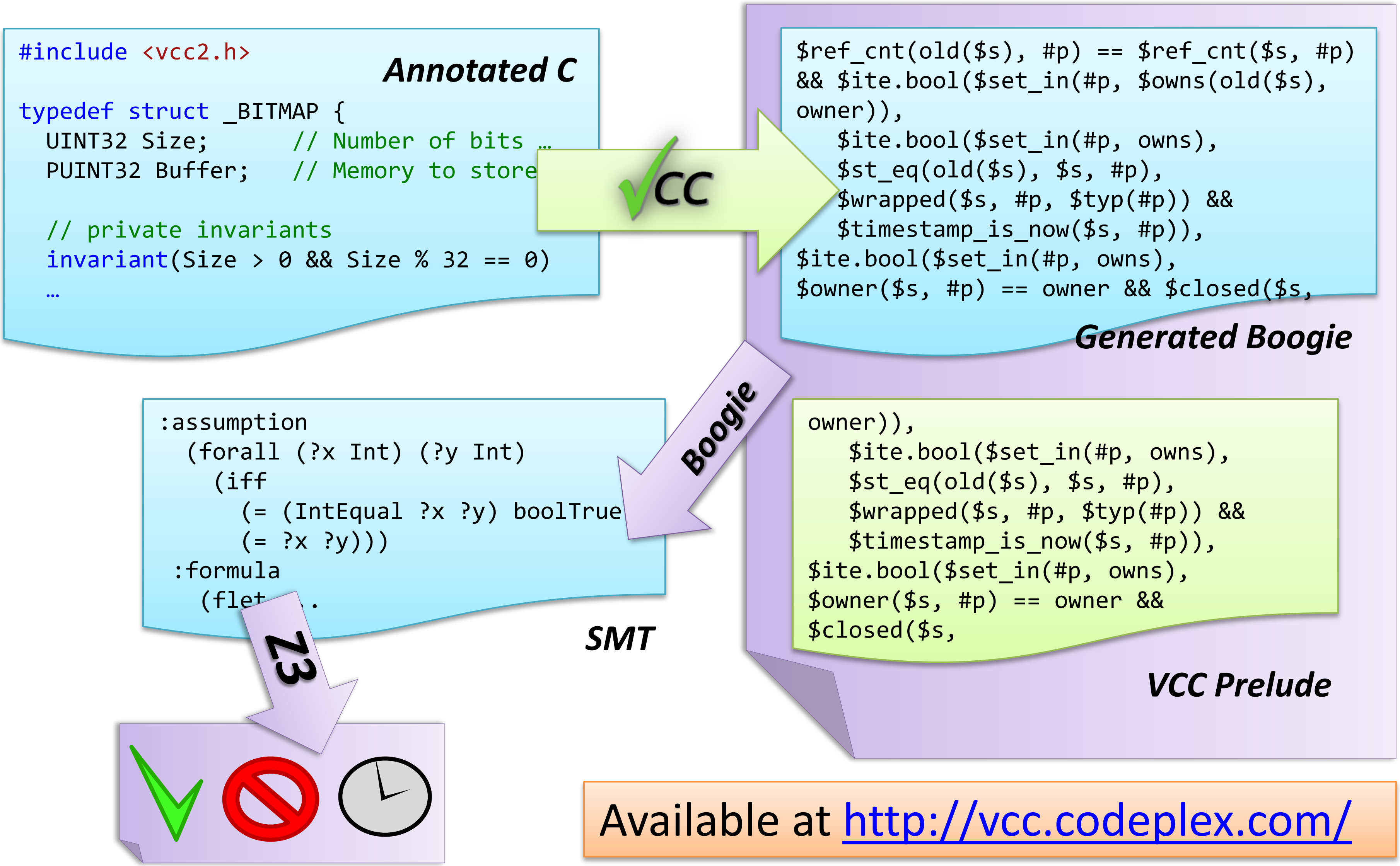
Goal: Full-blown Verification For Everyone

- functional properties
  - but even memory safety depends on functional correctness of complex data structures and concurrency protocols
- automatic
- exercised on real code
  - scalable – modular
  - concurrency
  - not changing existing code
- necessary tool support

VCC

- a deductive verifier for C
- verification methodology centered around
  - two-state invariants
  - ownership system
  - concurrency
- uses Boogie and Z3 (or other Boogie-supported provers)

VCC Architecture



Available at http://vcc.codeplex.com/

A Verification Methodology

- annotation language
  - e.g., first-order logic, higher-order logic, separation logic; + specific features
- specification concepts
  - ownership, type invariants, permissions
- modeling of the programming language semantics
  - how precise, what assumptions, etc.
- specification idioms

Verification Methodology As An SMT Theory

- complex
  - all input language + specification language constructions
- evolving with the verification tool
- not practical to implement as part of SMT solver
- instead encoded using first-order logic

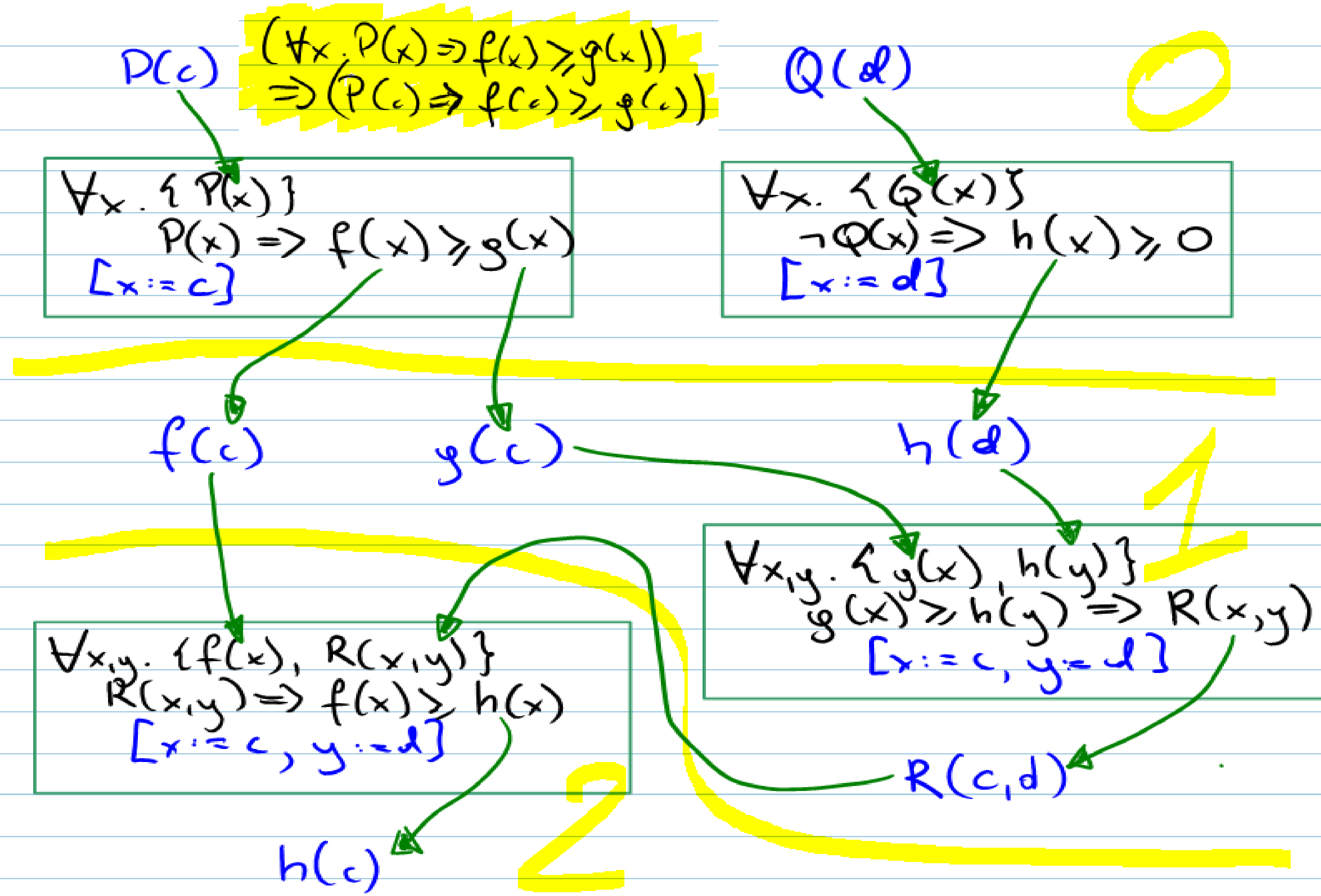
Programming With Triggers

- SMT formulas with quantifiers handled with instantiation
  - guided by E-matching, controlled by trigger annotations
- SMT theory is programmed using triggers

TRIGGERS

- (usually) subterms of the quantified formula, with free variables
- matched against active terms
  - terms with interpretation in the current partial model considered by the SMT solver

CAUSAL DAG


(∀x. P(x) ⇒ f(x) ≥ g(x)) ⇒ (P(c) ⇒ f(c) ≥ g(c))
P(c)
Q(d)
0
∀x. {P(x)} P(x) => f(x) ≥ g(x) [x := c]
∀x. {Q(x)} ¬Q(x) => h(x) ≥ 0 [x := d]
f(c)
g(c)
h(d)
1
∀x,y. {g(x), h(y)} g(x) ≥ h(y) => R(x,y) [x := c, y := d]
∀x,y. {f(x), R(x,y)} R(x,y) => f(x) ≥ h(x) [x := c, y := d]
R(c,d)
2
h(c)

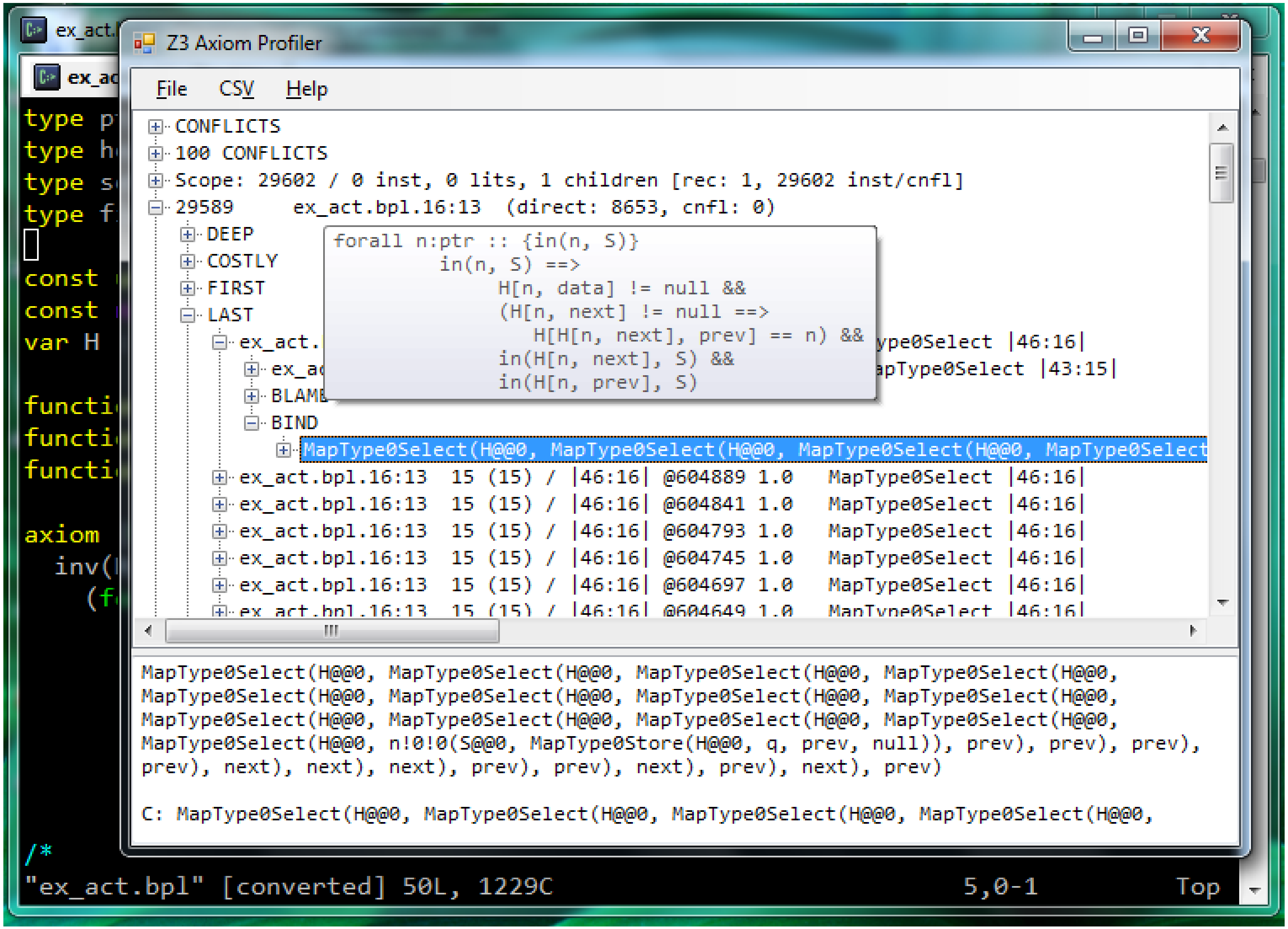
A List Invariant

- `inv(H, S)`: nodes in set S form a doubly-linked list in heap H
  - data is non-null
  - prev link in the next node points back here
  - S is next- and prev-closed

```
(forall H:heap, S:set :: {inv(H, S)}
  inv(H, S) <==>
    (forall n:ptr :: {in(n, S)}
         in(n, S) ==>
              H[n, data] != null &&
              (H[n, next] != null ==>
                 H[H[n, next], prev] == n) &&
              in(H[n, next], S) &&
              in(H[n, prev], S)))
```

DEMO OF THE AXIOM PROFILER

THE AXIOM PROFILER



Prevent Loop By Splitting Next-closedness

```
(forall H:heap, S:set :: {inv(H, S)}
  inv(H, S) <==>
      (forall n:ptr :: {in(n, S)}
        in(n, S) ==>
           H[n, data] != null &&
           (H[n, next] != null ==>
               H[H[n, next], prev] == n))

    && (forall n:ptr :: {in(H[n, next], S)}
         in(n, S) ==> in(H[n, next], S))

    && (forall n:ptr :: {in(H[n, prev], S)}
         in(n, S) ==> in(H[n, prev], S)))
```

Check a Program

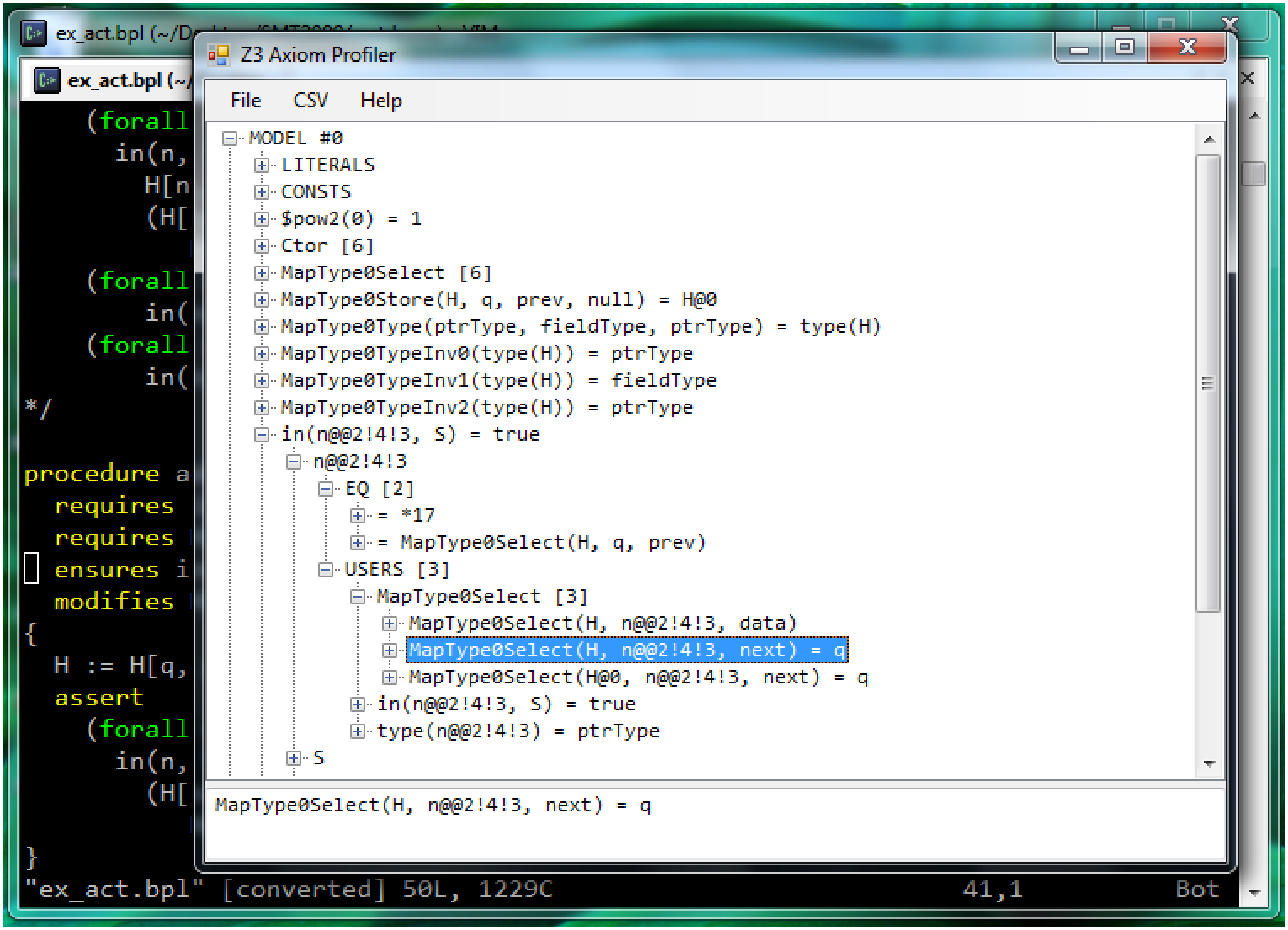
```
procedure add(S:set, q:ptr)
  requires inv(H, S);
  requires H[q, data] == null;
  ensures inv(H, S);
  modifies H;
{
  H := H[q, prev := null];
}
```

Program correct iff formula is UNSAT

```
inv(H, S) &&
H[q, data] == null &&
G == H[q, prev := null] &&
!inv(G, S)
```

DEMO OF THE MODEL VIEWER

THE MODEL VIEWER



WITNESSES

```
(forall n:ptr :: {in(n, S)}
  in(n, S) ==> H[n, data] != null &&
     (H[n, next] != null ==> H[H[n, next], prev] == n)) &&
(forall n:ptr :: {in(H[n, next], S)}
  in(n, S) ==> in(H[n, next], S)) &&
(forall n:ptr :: {in(H[n, prev], S)}
  in(n, S) ==> in(H[n, prev], S)) &&
H[q, data] == null &&
G == H[q, prev := null] &&
!(forall n:ptr :: {in(n, S)}
      in(n, S) ==>
         (G[n, next] != null ==>
            G[G[n, next], prev] == n))
```

```
in(n0, S) &&
G[n0, next] != null &&
G[G[n0, next], prev] != n
```

Z3 thinks that `G[n0, next] == q`

We know: `H[q, data] == null` and `H[n0, next] == G[n0, next]`, and thus we need: `in(G[n0, next], S)` to trigger

But n0 is a skolem constant, so it's hard for the user to introduce it.

ONE STEP AHEAD

```
!(forall n:ptr :: {in(n, S)}
      in(n, S) ==>
        (G[n, next] != null ==>
           G[G[n, next], prev] == n))
```

Whenever proving this thing, look one step ahead, or: i.e., get `in(G[n0, next], S)` activated but don't loop. Please.

Hack the SMT solver to do it :-)

```
!(forall n:ptr :: {in(n, S)}
      {ex_act(in(G[n, next]))}
      in(n, S) ==>
        (G[n, next] != null ==>
           G[G[n, next], prev] == n))
```

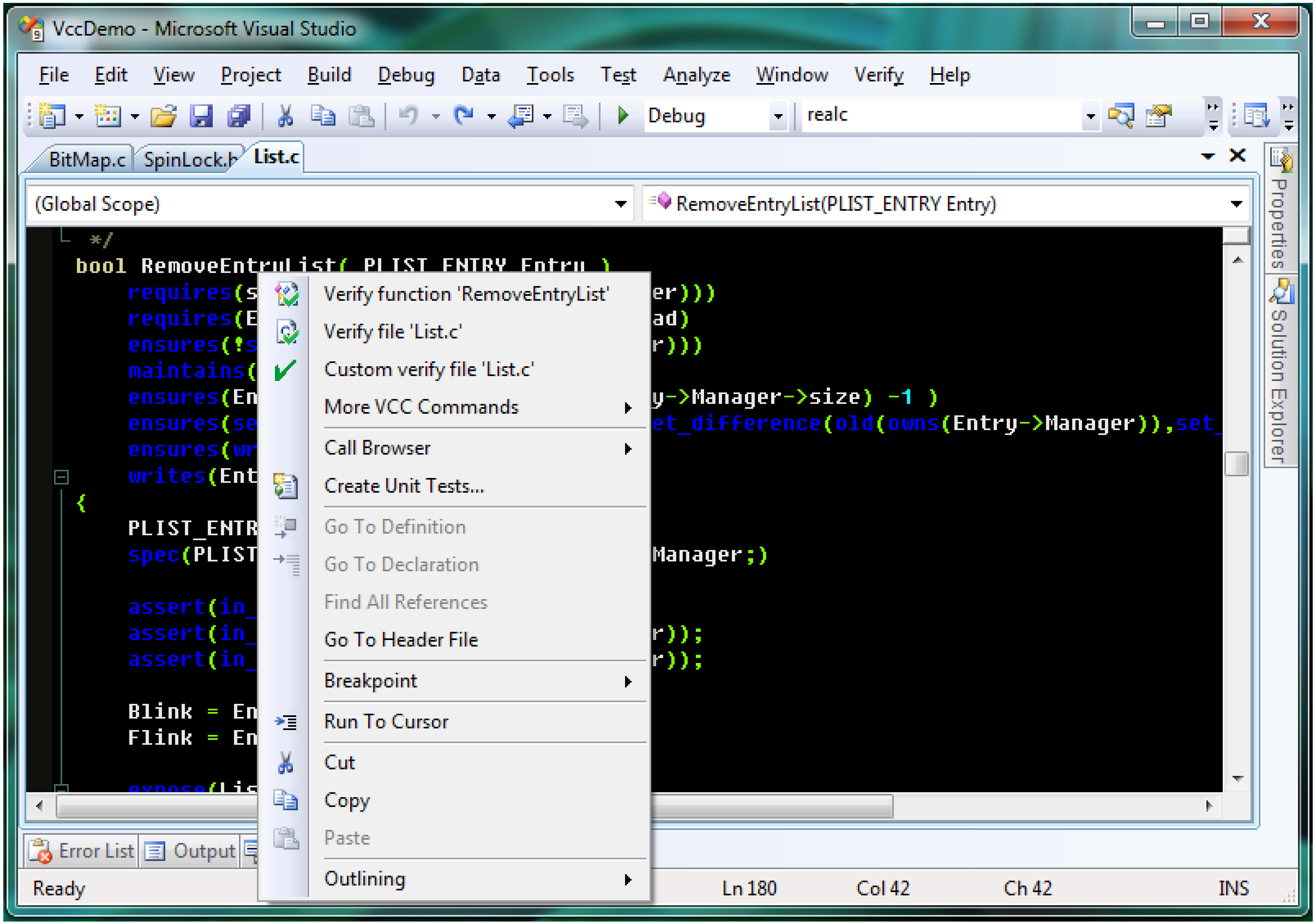
EXISTENTIAL ACTIVATION

When proving this quantifier, use lemma trigged by this

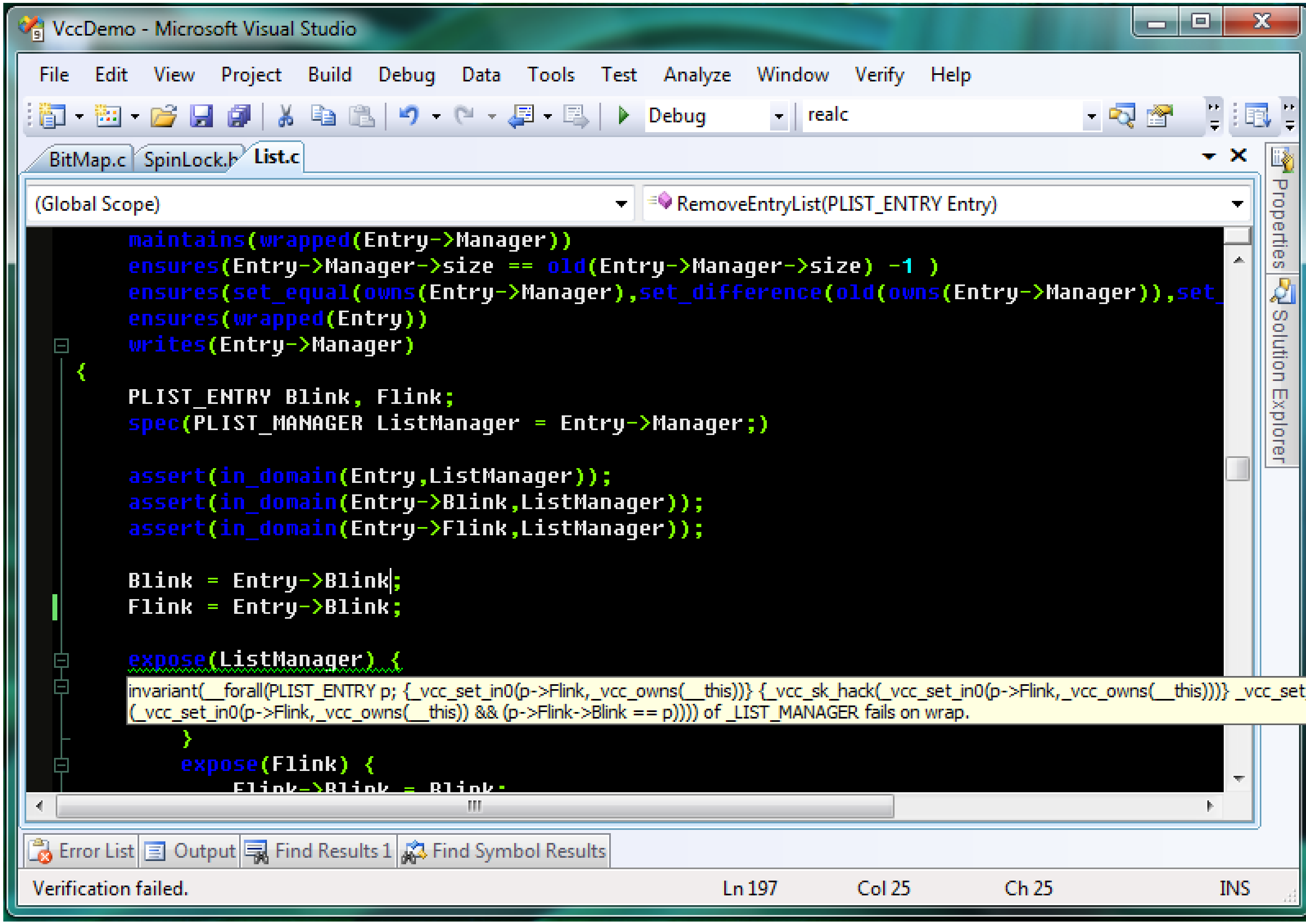
```
(forall H:heap, S:set :: {inv(H,
  inv(H, S) <==>
       (forall n:ptr :: {in(n, S)}
         {ex_act(in(H[n, next], S))}
         in(n, S) ==>
            H[n, data] != null &&
            (H[n, next] != null ==>
                H[H[n, next], prev] == n))

    && (forall n:ptr :: {in(H[n, next], S)}
          in(n, S) ==> in(H[n, next], S))
    && (forall n:ptr :: {in(H[n, prev], S)}
          in(n, S) ==> in(H[n, prev], S)))
```

VCC IN ACTION

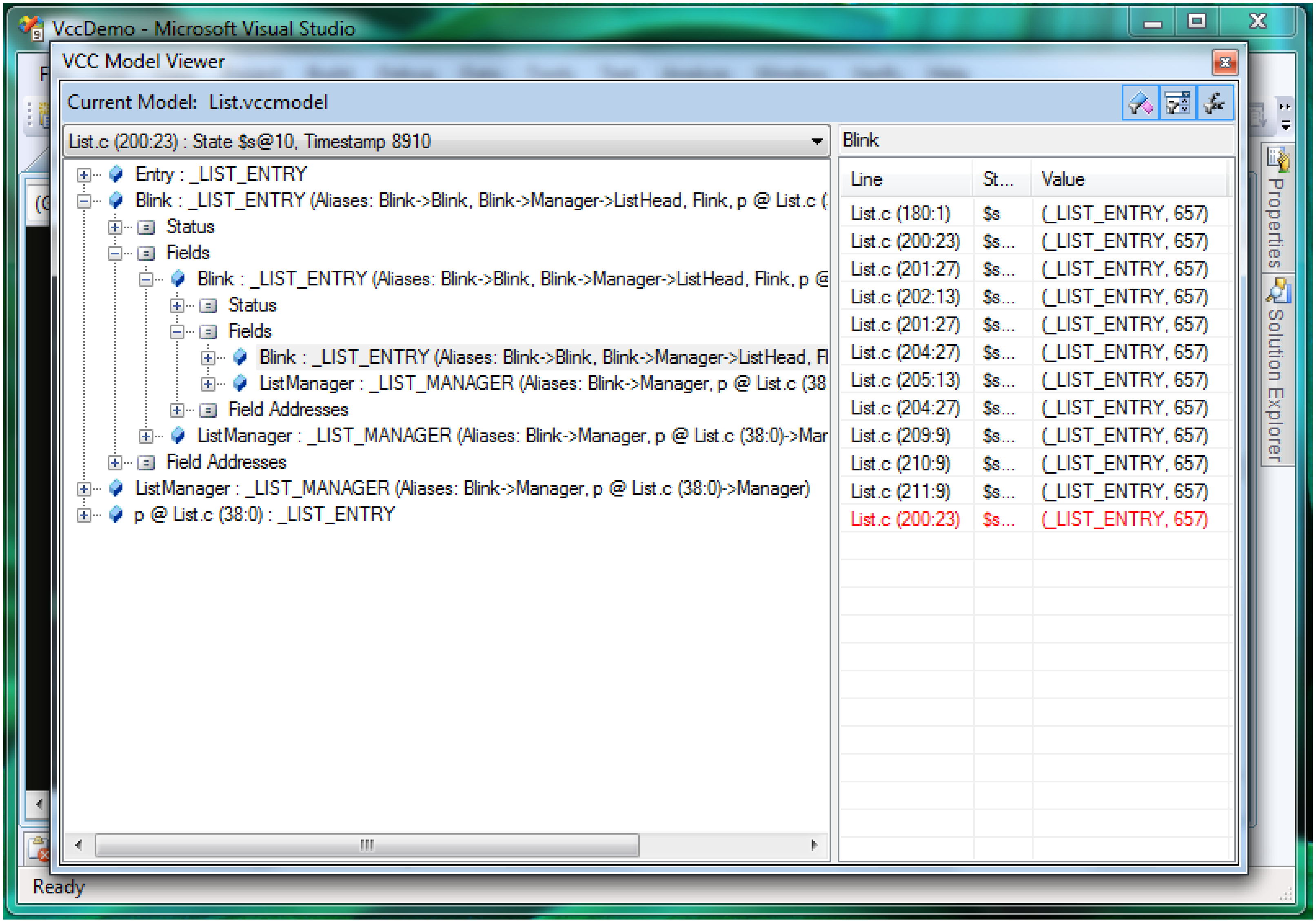
VCC Visual Studio Plugin



VCC: Failed Verification Attempt



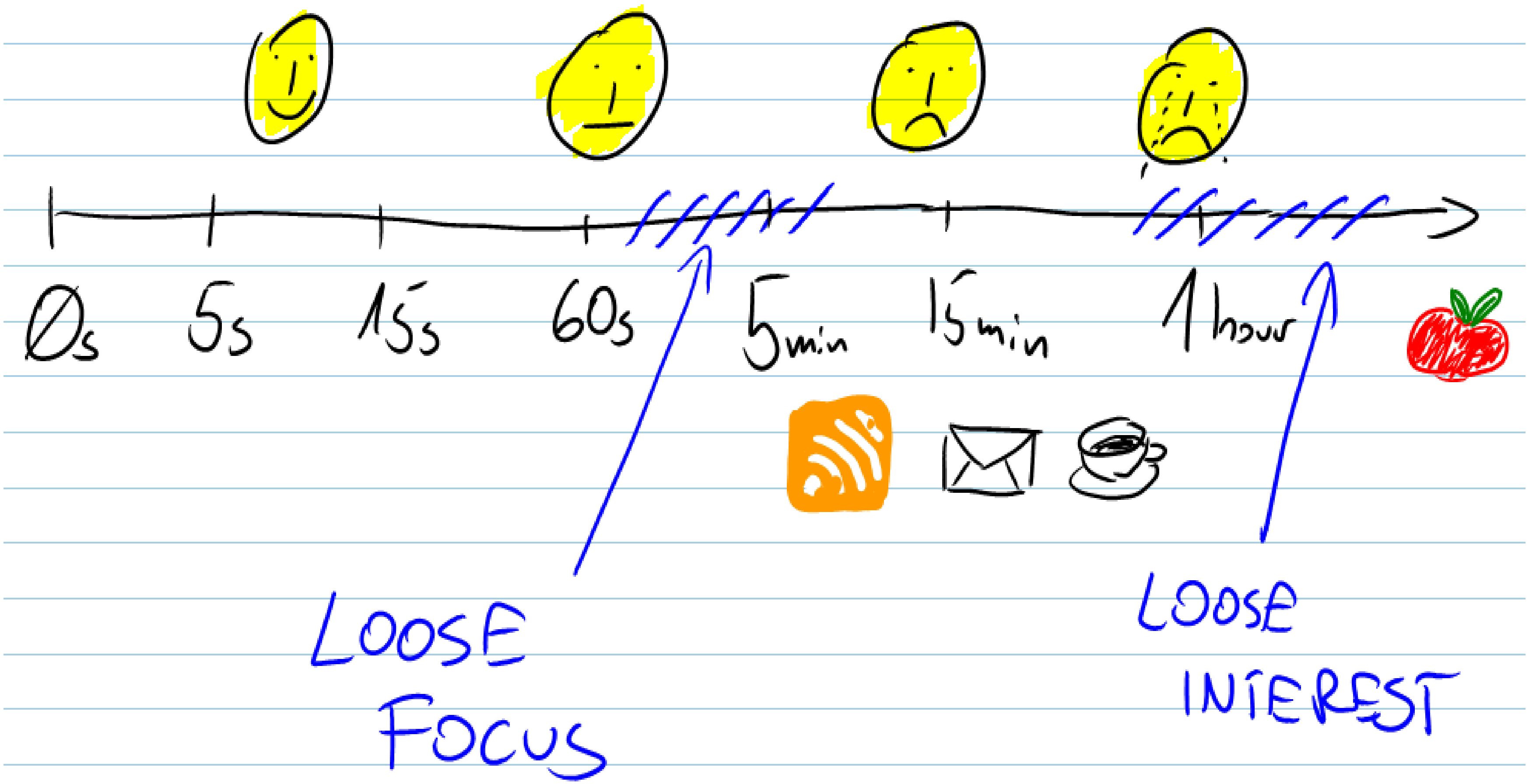
VCC-Specific Model Viewer



Working With VCC

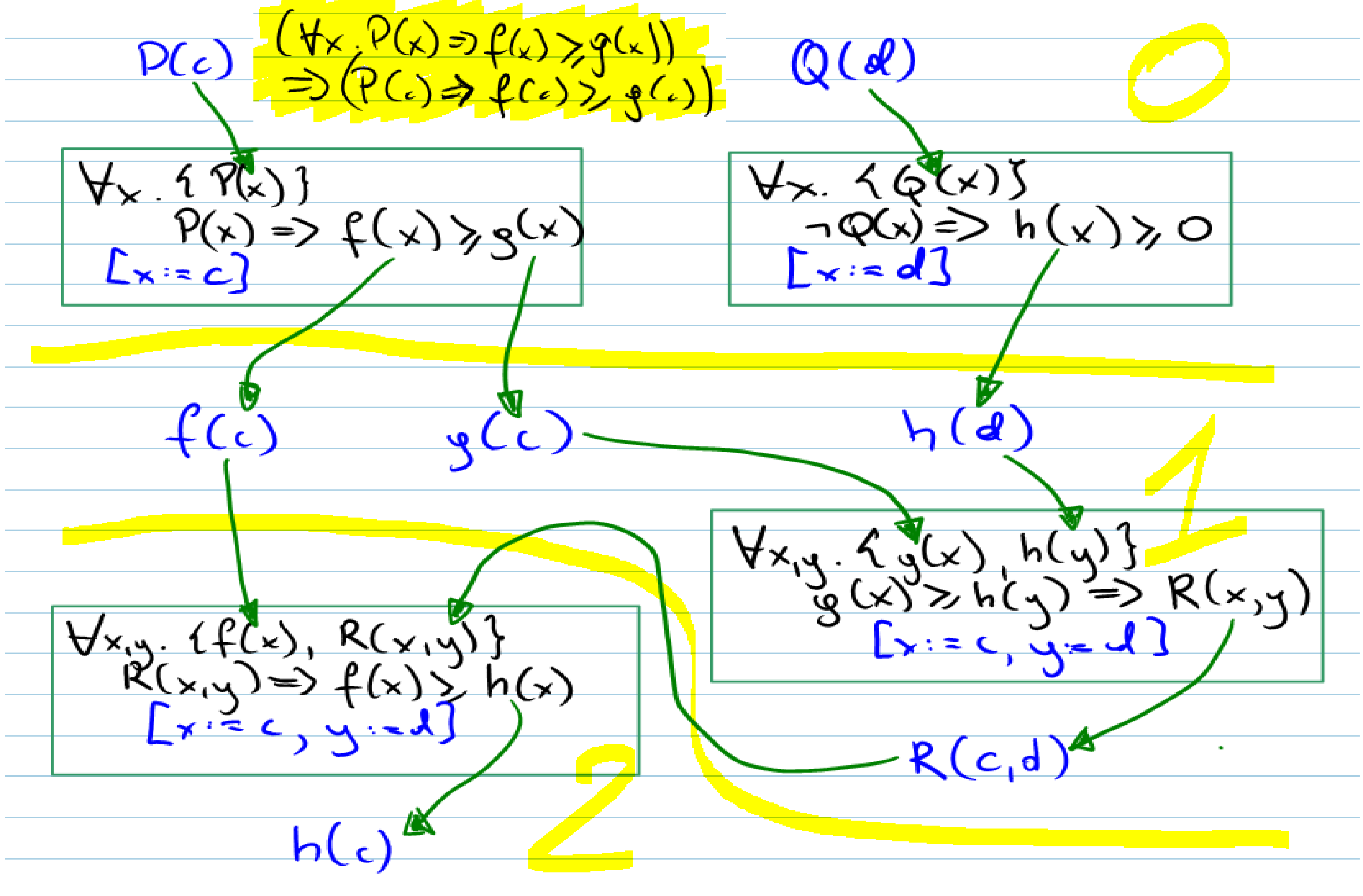
- write a version of the spec
- verify, fail
- add assertions or look at the model to see why it failed
  - for bigger functions, do it a couple of lines at a time, moving focus window down
- repeat

Verification Attempt Time vs Satisfaction and Productivity



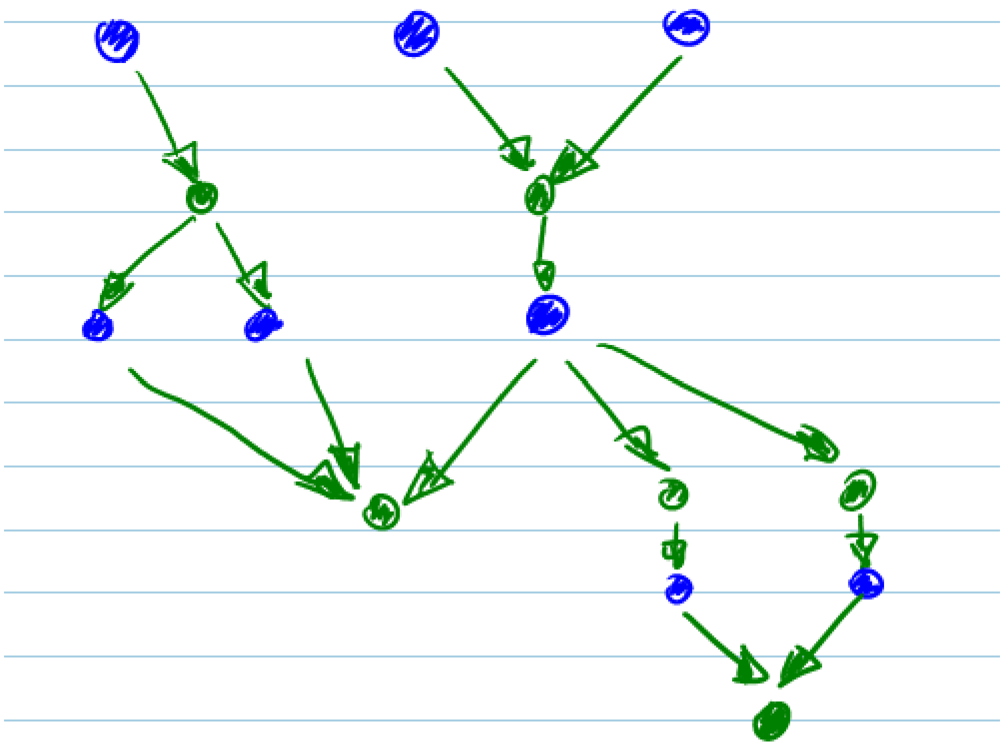
WANT IT TO GO FASTER?
PROFILE!

CAUSAL DAG

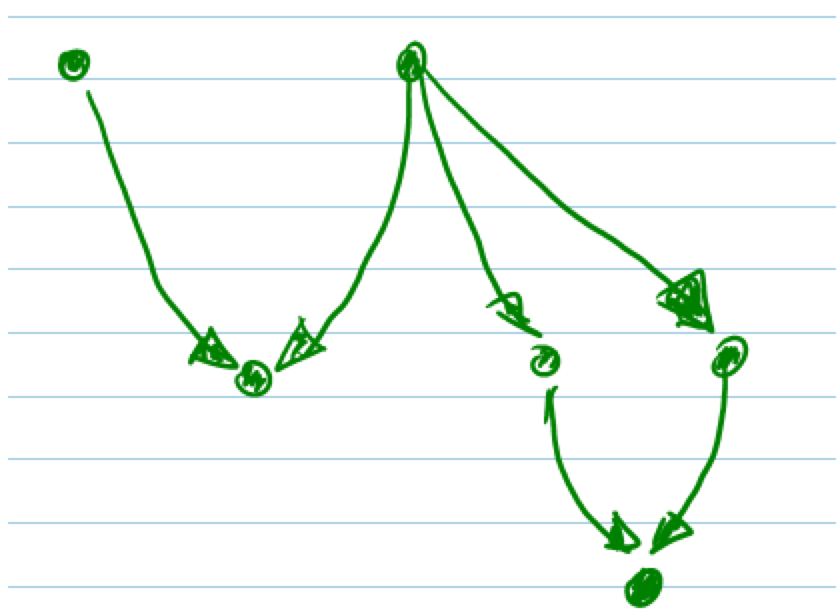


(∀x. P(x) ⇒ f(x) ≥ g(x)) ⇒ (P(c) ⇒ f(c) ≥ g(c))
P(c)
Q(d)
0
∀x. {P(x)}
P(x) => f(x) ≥ g(x)
[x := c]
∀x. {Q(x)}
¬Q(x) => h(x) ≥ 0
[x := d]
f(c)
g(c)
h(d)
1
∀x,y. {g(x), h(y)}
g(x) ≥ h(y) => R(x,y)
[x := c, y := d]
∀x,y. {f(x), R(x,y)}
R(x,y) => f(x) ≥ h(x)
[x := c, y := d]
R(c,d)
2
h(c)

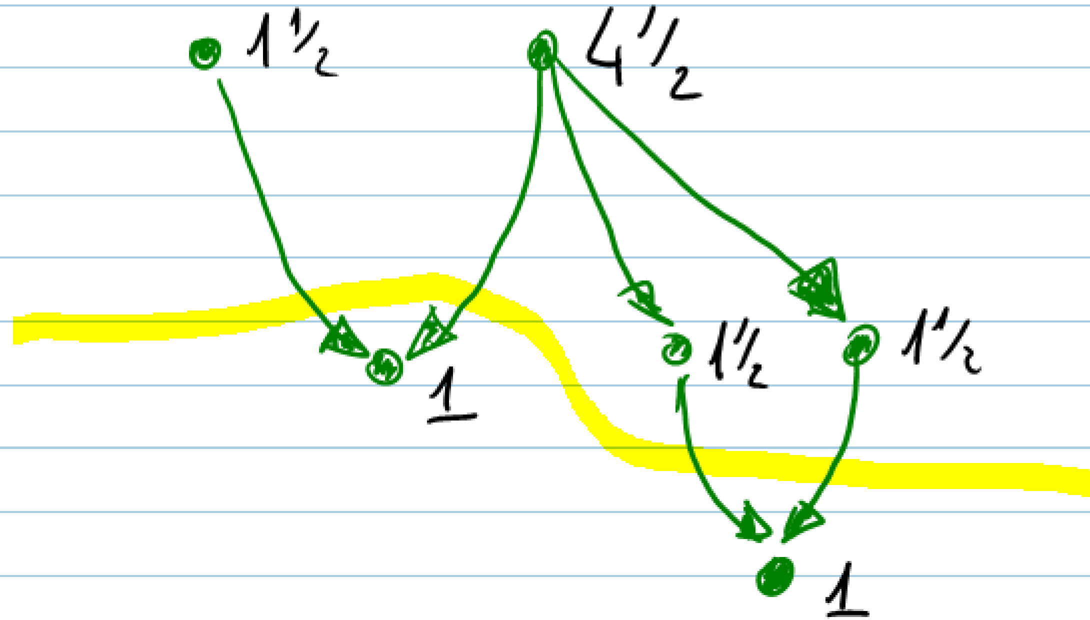
Cost In The Causal DAG



Cost In The Causal DAG

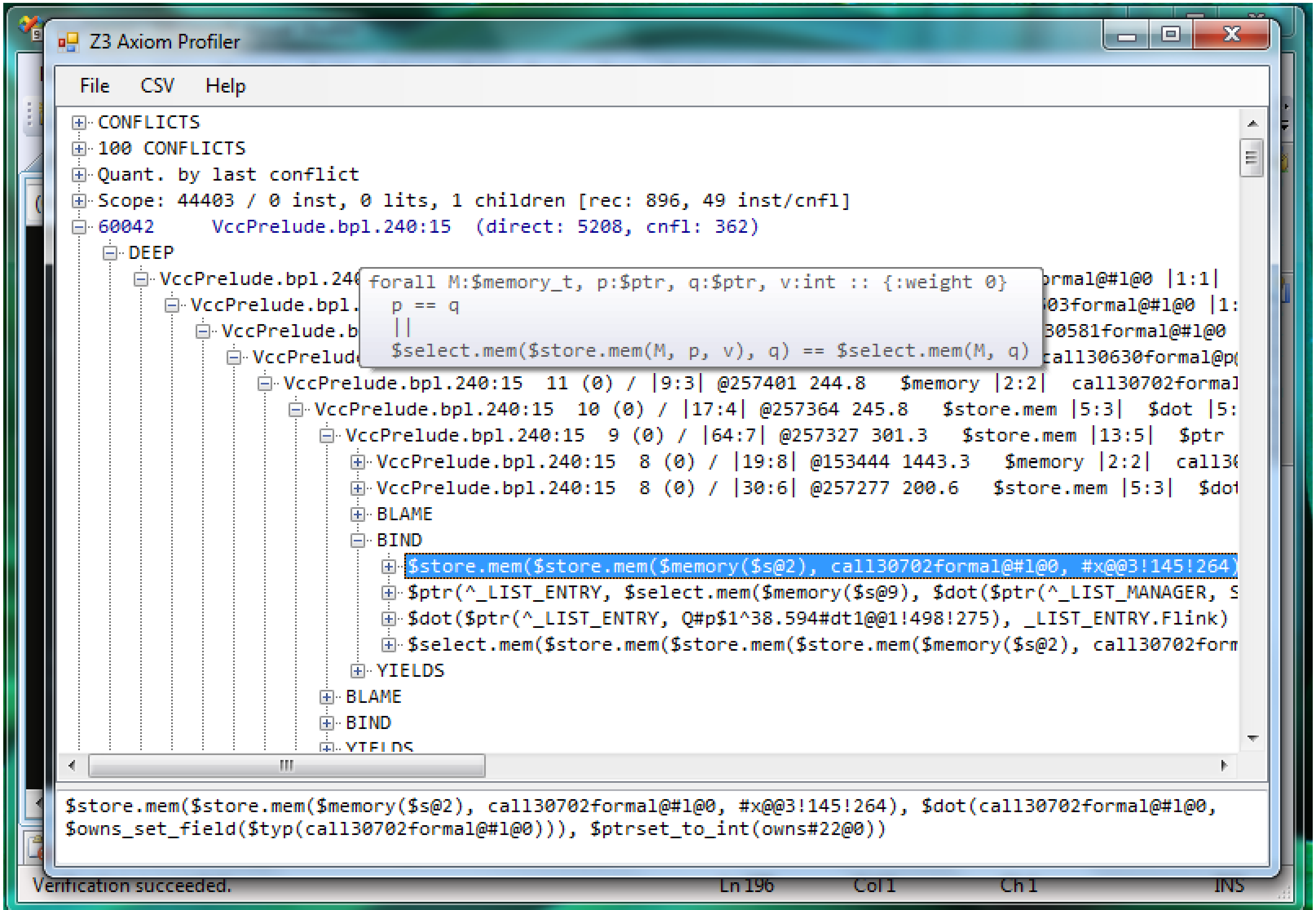


Cost In The Causal DAG



$$c(n) = 1 + \sum_{n \to m} \frac{c(m)}{\mathrm{indeg}(m)}$$

Browsing The Causal DAG

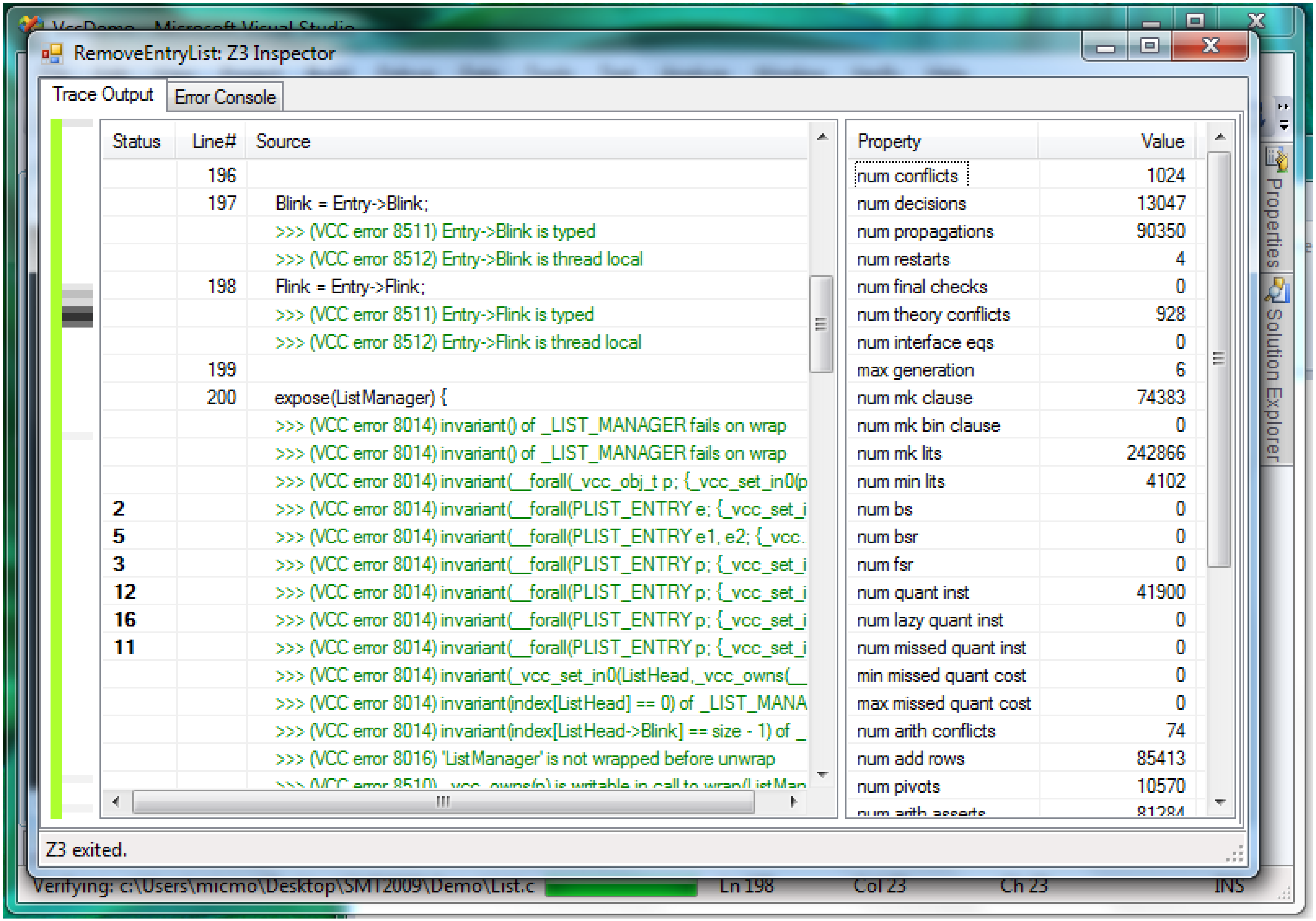


THE INSPECTOR:
CONTROL TO THE PEOPLE

THE INSPECTOR

- ask Z3 to state the current model from time to time
  - in forms of labels
- translate such models to error messages
- display all possible error message and blink the current one

SCREENSHOT


RemoveEntryList: Z3 Inspector
Trace Output
Error Console
Status
Line#
Source
196
197
Blink = Entry->Blink;
>>> (VCC error 8511) Entry->Blink is typed
>>> (VCC error 8512) Entry->Blink is thread local
198
Flink = Entry->Flink;
>>> (VCC error 8511) Entry->Flink is typed
>>> (VCC error 8512) Entry->Flink is thread local
199
200
expose(ListManager) {
>>> (VCC error 8014) invariant() of _LIST_MANAGER fails on wrap
>>> (VCC error 8014) invariant() of _LIST_MANAGER fails on wrap
>>> (VCC error 8014) invariant(__forall(_vcc_obj_t p; {_vcc_set_in0(p
2
>>> (VCC error 8014) invariant(__forall(PLIST_ENTRY e; {_vcc_set_i
5
>>> (VCC error 8014) invariant(__forall(PLIST_ENTRY e1, e2; {_vcc.
3
>>> (VCC error 8014) invariant(__forall(PLIST_ENTRY p; {_vcc_set_i
12
>>> (VCC error 8014) invariant(__forall(PLIST_ENTRY p; {_vcc_set_i
16
>>> (VCC error 8014) invariant(__forall(PLIST_ENTRY p; {_vcc_set_i
11
>>> (VCC error 8014) invariant(__forall(PLIST_ENTRY p; {_vcc_set_i
>>> (VCC error 8014) invariant(_vcc_set_in0(ListHead,_vcc_owns(__
>>> (VCC error 8014) invariant(index[ListHead] == 0) of _LIST_MANA
>>> (VCC error 8014) invariant(index[ListHead->Blink] == size - 1) of _
>>> (VCC error 8016) 'ListManager' is not wrapped before unwrap
Property
Value
num conflicts 1024
num decisions 13047
num propagations 90350
num restarts 4
num final checks 0
num theory conflicts 928
num interface eqs 0
max generation 6
num mk clause 74383
num mk bin clause 0
num mk lits 242866
num min lits 4102
num bs 0
num bsr 0
num fsr 0
num quant inst 41900
num lazy quant inst 0
num missed quant inst 0
min missed quant cost 0
max missed quant cost 0
num arith conflicts 74
num add rows 85413
num pivots 10570
Properties
Solution Explorer
Z3 exited.
Verifying: c:\Users\micmo\Desktop\SMT2009\Demo\List.c
Ln 198
Col 23
Ch 23
INS

SOME NUMBERS

LIMITS ON MATCHING DEPTH

- matching depth on one of the list functions
  - 10 heap related (10 heap updates in the function)
  - 6 user-defined (different levels of expansion of the invariant)
  - total of 17
- the looping example shows that number of instances can be easily exponential with depth

SCALE OF PROBLEMS

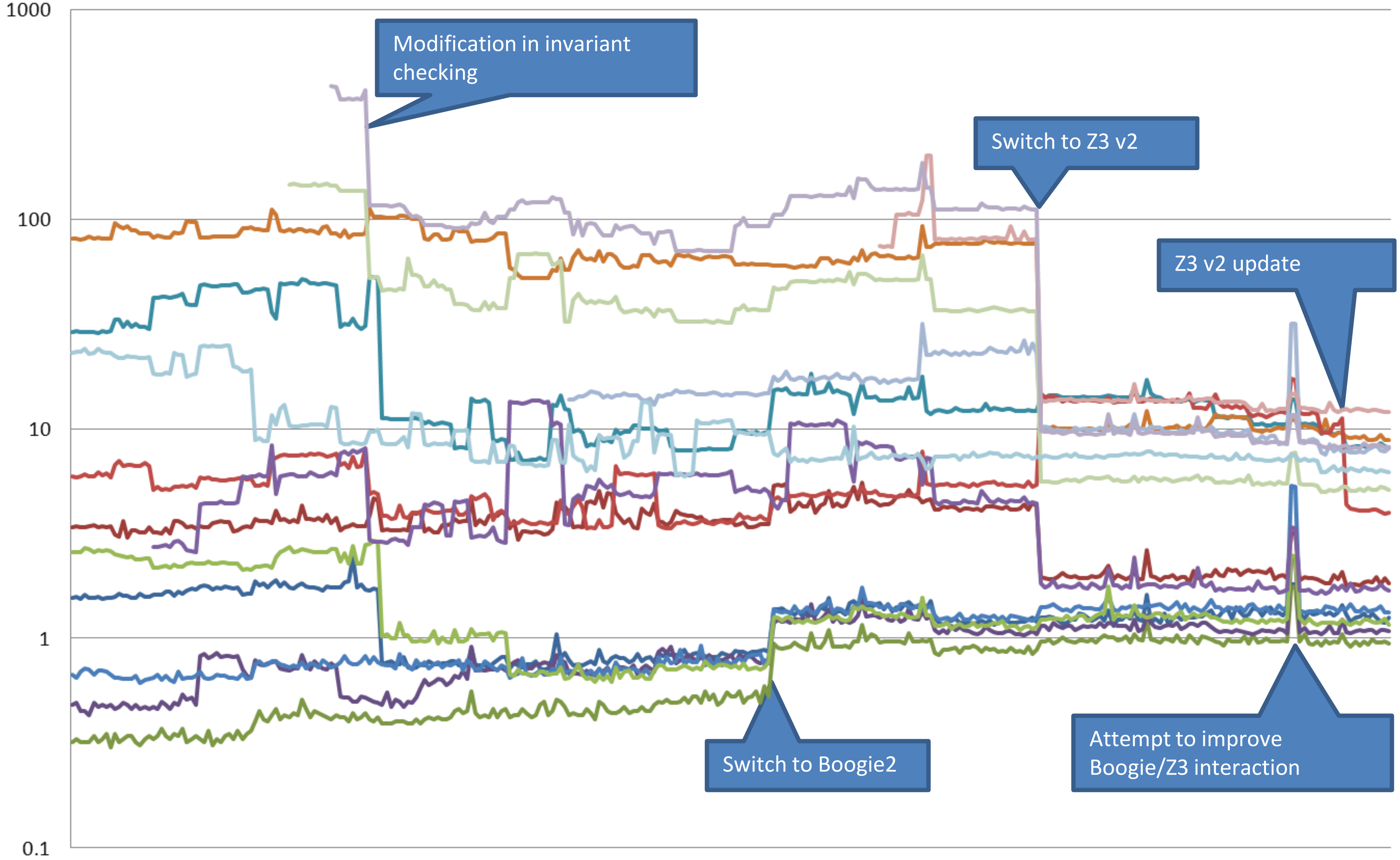
- prelude: 300 quantifiers, 50 multi-triggers
- Hypervisor program-specific background predicate:
  - 300 types, 1500 fields => 13000 axioms
  - type description dwarfs VC for the function itself
- even Z3 E-matching indices didn't take that lightly
- without proper guidance any SMT solver is likely to be lost

PERFORMANCE, PERFORMANCE, PERFORMANCE

Experience from the Hyper-V verification

- **successful** verifications:
  - typical: 0.5–500s, average 25s
  - current max: 2 500s
  - all time max: 50 000s (down to 1 000s with Z3v2)
- acceptable time for **interactive** work: < 30s
- annotations (since Nov 2008):
  - 15 000 lines
  - 400 functions
  - ca. 20% of codebase verified

VCC Performance Trends Nov 08 – Mar 09



SUMMARY

SUMMARY

- program a custom theory for the SMT solver
- like for a “normal” programming language
  - debug models (model viewers)
  - profile traces (axiom profiler)
  - profile with sampling (the inspector)
- but:
  - lack of clear semantics
  - possibly not the best programming model

VCC Is Available!

- source code available for non-commercial purposes at http://vcc.codeplex.com/
  - includes the SMT tools!
- further information linked from there

THANK YOU!