VCC: A Practical System for Verifying Concurrent C

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Introduction

- VCC stands for Verifying C Compiler
- deductive verifier for concurrent C code
- performs static modular analysis and sound verification of functional properties of low-level concurrent C code
- VCC translates annotated C code into BoogiePL
  - Boogie translates BoogiePL into verification conditions
  - Z3 solves them or gives couterexamples

Motivation

- driven by the verification of the Microsoft Hyper-V hypervisor
- the hypervisor turns a single real multi-processor x64 machine into a number of virtual multiprocessor x64 machines
- own concurrency control primitives, complex data structures and dozens of tricky optimizations
- written in no verification in mind (100KLOC of C, 5KLOC of assembly)
- performance was of a great importance

Function Contracts

Specification (Contract) consisting of four kinds of clauses

- preconditions: _(*requires* P)
- postconditions: _(*ensures* Q)
- writes clause: _(*writes* S)
- termination: _(*decreases* T)

Modular – only looks at function specification

Function Contracts

```
int min(int a, int b)
_(requires \true)
_(ensures \result <= a && \result <= b)
_(ensures \result == a || \result == b)
{
  if (a <= b)
  return a;
  else return b;
}
```

Pure functions

```
_(pure) int min(int a, int b) ...
```

- no side effects on programs state
- not allowed to allocate memory
- can only write to local variables
- can be called within VCC annotations

However:

- empty writes clause $\not\Rightarrow$ pure

Pure Ghost functions

- used only in specification
- along with other annotations removed before compilation by preprocessor

```
_(def \bool sorted(int *arr, unsigned len) {
  return \forall unsigned i, j;
    i <= j && j < len ==> arr[i] <= arr[j];
})

void sort(int *arr, unsigned len)
_(writes \array_range(arr, len))
_(ensures sorted(arr, len))
```

Type Invariants

- object invariants can be associated with compound types (structs and unions)
- support for both single and two-state predicates

```
#define SSTR_MAXLEN 100
typedef struct SafeString {
  unsigned len;
  char content[SSTR_MAXLEN + 1];
  _(invariant \this->len <= SSTR_MAXLEN)
  _(invariant content[len] == '\0')
} SafeString;
```

Type Invariants

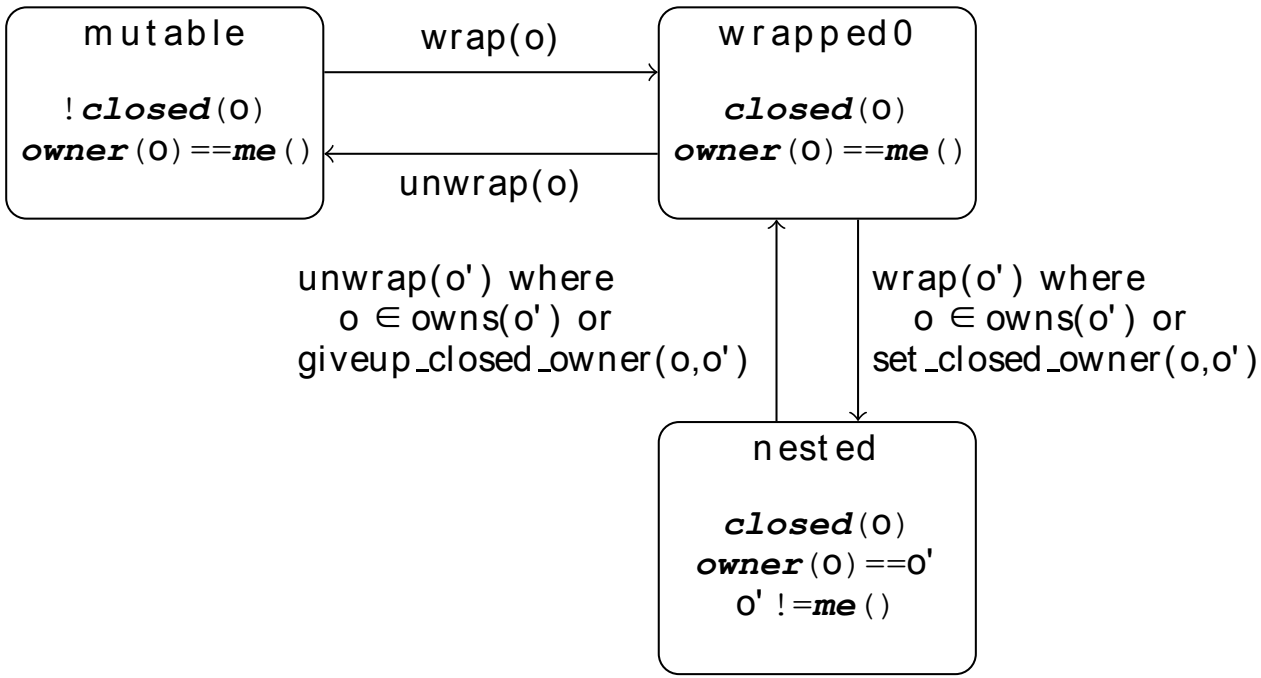
- object invariants cannot hold at all times, e.g.:
  - initialization
  - destruction
  - updates
- an object can be in two states controlled by *closed* ghost field
  - **closed** – invariant holds but non-volatile fields can not be changed
  - **open** – invariant can not be assumed, but fields can be changed
- closedness is manipulated using *wrap* and *unwrap* helper methods
- type invariants are coupled with ownership

Ownership

- ownership is expressed by adding a ghost field to every object and making it point to object owner
- the roots of trees in the ownership forest are objects representing threads of execution.
  - threads are always closed, and own themselves
- the set of objects directly or transitively owned by an object is called the ownership domain of that object

Ownership

- type invariants are coupled with ownership
- if an object is owned by a thread, only that thread can change its (nonvolatile) fields (and then only if the object is open), wrap or unwrap it, or change its owner to another object



Wrapping & Unwrapping Example

```
1  void sstr_append(struct SafeString *s, char c)
2    _(maintains \wrapped(s))
3    _(requires s->len < SSTR_MAXLEN)
4    _(ensures s->len == \old(s->len) + 1)
5    _(ensures s->content[\old(s->len)] == c)
6    ...
7    _(writes s)
8  {
9    _(unwrap s)
10   s->content[s->len++] = c;
11   s->content[s->len] = '\0';
12   _(wrap s)
13 }
```

Verifying Concurrent Programs

- coarse-grained concurrency - ownership based
- fine-grained concurrency - atomic actions on volatile fields

Volatile fields

C meaning:

- value can be changed from "outside"
- prevents compiler from storing value in registers

VCC meaning:

- field can be modified while the object is closed, as long as the update occurs inside an explicit atomic action that preserves the object invariant
- thread forgets the values of these fields when it makes an impure function call and just before an atomic action

Spin-lock

- ownership used to control access to shared resource

```
_(volatile_owns) struct Lock {
volatile int locked;
_(ghost \object protected_obj;)
_(invariant locked == 0 ==> \mine(protected_obj))
};
```

Spin-lock - Initialization

```
void InitializeLock(struct Lock *l
                    _(ghost \object obj))
_(requires \wrapped(obj))
_(ensures \wrapped(l) && l->protected_obj == obj )
_(ensures \nested(obj))
_(writes \span(l), obj)
{
  l->locked = 0;
  _(ghost {
    l->protected_obj = obj;
    l->\owns = {obj};
    _(wrap l)
  })
}
```

Spin-lock - Acquire

```
void Acquire(struct Lock *l)
_(maintains \wrapped(l))
_(ensures l->locked == 1)
_(ensures \wrapped(l->protected_obj) && \fresh(l->protected_obj))
{
  int stop = 0;
  do {
    _(atomic l) {
      stop = InterlockedCompareExchange(&l->locked, 1, 0) == 0;
      _(ghost if (stop) l->\owns -= l->protected_obj)
    }
  } while (!stop);
}
```

Spin-lock - Release

```
void Release(struct Lock *l)
_(maintains \wrapped(l))
_(requires l->locked == 1)
_(requires \wrapped(l->protected_obj))
_(ensures l->locked == 0
_(ensures \nested(l->protected_obj))
_(writes l->protected_obj)
{
  _(atomic l) {
    l->locked = 0;
    _(ghost l->\owns += l->protected_obj)
  }
}
```

Spin-lock - Problems

- acquire and release require that the lock is closed

```
void Acquire(struct Lock *l)
_(requires \wrapped(l)) ...
```

- definition of wrapped:

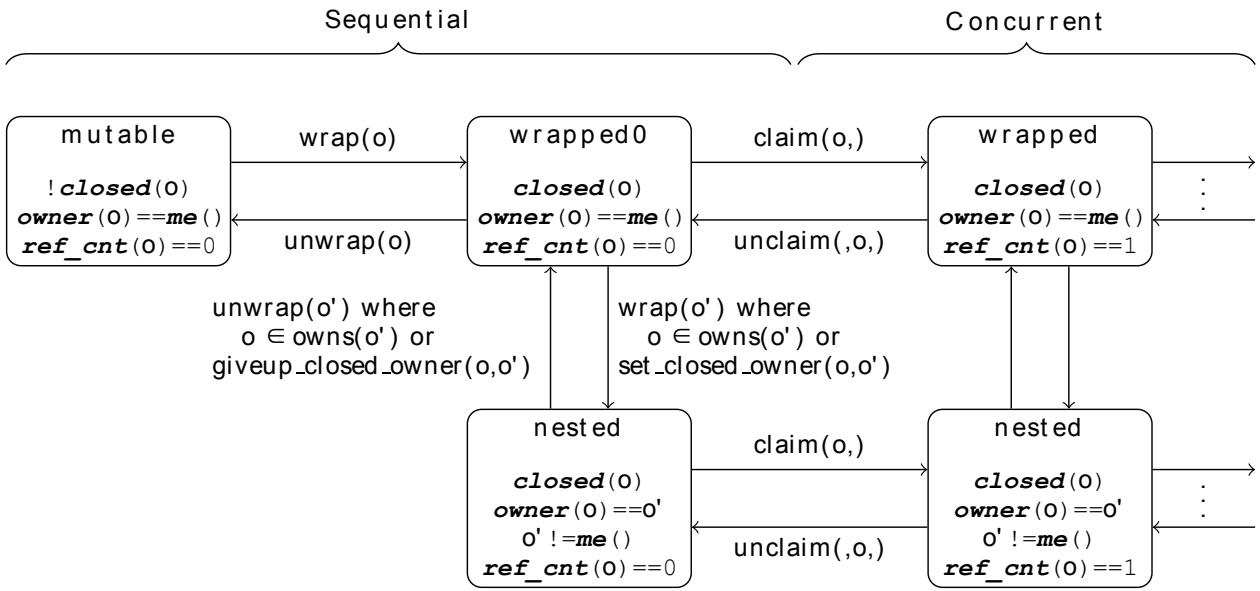
```
\bool \wrapped(\object o)
_(ensures \result <==> o->\owner == \me && o->\closed)
```

- $o \rightarrow \backslash owner == \backslash me$ is satisfiable by only single thread

Claims

```
_(ghost typedef struct {
  \ptrset claimed;
  _(invariant \forall \object o; o \in claimed ==> o->\closed)
} \claim; )
```

- Ownership meta-states updated:



Spin-lock revisited

```
void Release(struct Lock *l _(ghost \claim c))
_(maintains \wrapped(c) && \claims_object(c, l))
_(requires l->locked == 1 )
_(requires \wrapped(l->protected_obj))
_(ensures l->locked == 0 )
_(ensures \nested(l->protected_obj))
_(writes l->protected_obj)
{
  _(atomic c, l) {
    l->locked = 0;
    _(ghost l->\owns += l->protected_obj)
  }
}
```

Invariant contraints

- what part of state are invariants allowed to mention
- how to make sure that updates dont break out of scope invariants?
- VCC allows invariants to mention arbitrary parts of the state, but requires them to be admissible
- VCC checks that no object invariant can be broken by invariant-preserving changes to other objects

```
struct Counter {
int n;
_(invariant n = old(n) ||
            n = old(n) + 2)
};
```

```
struct Low {
Counter cnt;
int floor;
_(invariant floor <= cnt.n)
};

struct High {
Counter cnt;
int ceiling;
_(invariant cnt.n <= ceiling)
};
```

Locally checked invariant

- VCC enforces that all invariants are **reflexive**.

$$refl(\tau) \equiv \forall p, h_o, h.type(p) = \tau \wedge inv_\tau(h_o, h, p) \Rightarrow inv_\tau(h, h, p)$$

- an action is **legal** iff it preserves the invariants of updated objects

$$legal(h_o, h) \equiv safe(h_o) \Rightarrow \forall p.h_o[p] = h[p] \vee inv(h_o, h, p)$$

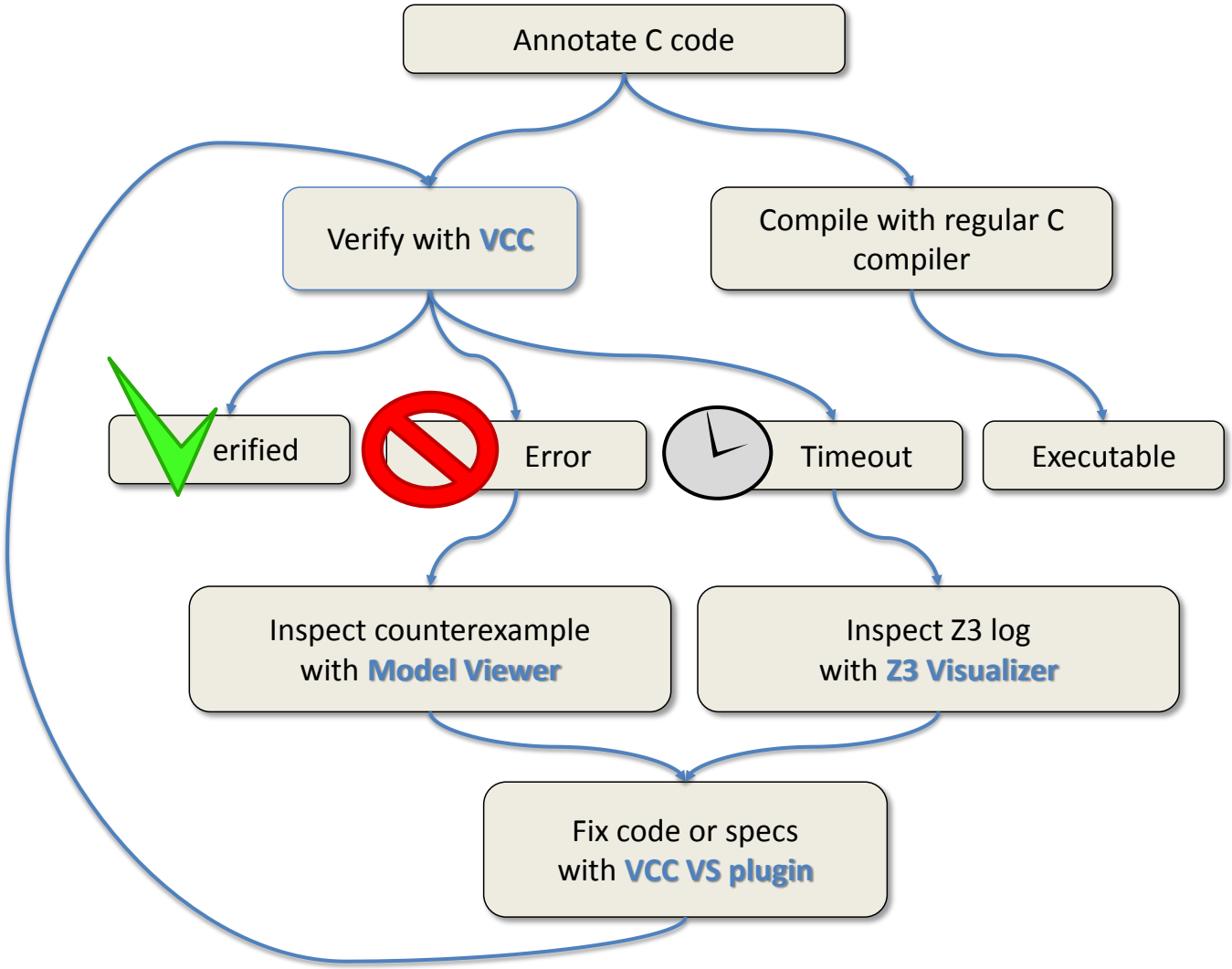
- a **stable** invariant is one that cannot be broken by legal actions

$$stable(\tau) \equiv \forall p, h_o h.type(p) = \tau \wedge safe(h_o) \wedge legal(h_o, h) \Rightarrow inv_\tau(h_o, h, p)$$

- An **admissible** invariant is one that is stable and reflexive

$$adm(\tau) \equiv stable(\tau) \wedge refl(\tau)$$

VCC Workflow



source: http://research.microsoft.com/en-us/projects/vcc/

Microsoft Hyper-V hypervisor Experience

- implementation of the SPT algorithm contains $\approx$ 700 lines of C code
- $\approx$ 4000 lines of the annotations
- overall proof time is $\approx$ 18 hours on one core of 2GHz Intel Core 2 Duo machine
- most functions in 0.5 to 500 seconds with an average of $\approx$ 25 seconds
- estimated person effort is $\approx$ 1.5 person-years, including VCC learning period

Conclusion

- VCC follows largely the design of Spec#
- expressive enough for industrial program verification
- lot's of helper methods
- up to the user to guarantee that access annotated as \atomic is indeed atomic
- assumes sequential consistency

Future work

- incorporate x86 memory model
- annotation overhead
- performance

References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