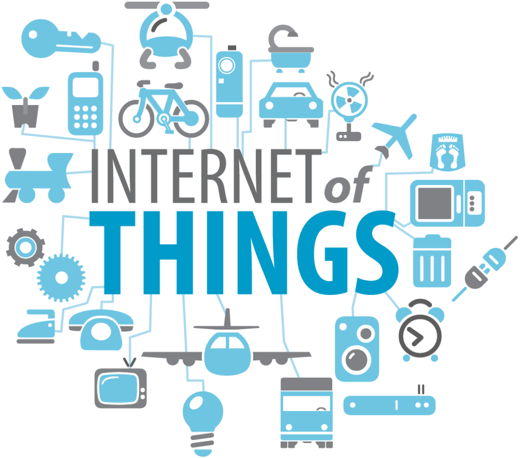
Towards Formal Verification of IoT Operating Systems with Frama-C

Nikolai Kosmatov

joint work with Allan Blanchard, Simon Duquennoy, Frédéric Loulergue, Frédéric Mangano, Alexandre Peyrard, Shahid Raza, ...

Univ. of Twente, December 12, 2019

Internet of Things



(c) Internet Security Buzz

- connect devices and services
- 22 billion IoT devices by 2025
- transport huge amounts of data

And Security?

And Security?

And Security?

By Waqas on October 22, 2016 Email @hackread CYBER ATTACKS MALWARE SECURITY

ANDY GREENBERG SECURITY 07.21.15 06:00 AM

HACKERS REMOTELY KILL A JEEP ON THE HIGHWAY—WITH ME IN IT

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by Tom Spring August 26, 2016 , 2:55 pm

Hacking a computer-aided sniper rifle

Elizabeth Weise | USATODAY
Published 5:56 p.m. UTC Aug 7, 2015

Formal Methods Today

- Improves software quality in 92% of projects

  Source: Formal Methods Practice and Experiments, ACM Comp.Surveys
- More efficient in practice: faster hardware, more memory, more mature verification tools...
- Finding a proof can require significant effort and higher expertise

Formal Verification and the Internet of Things

Formal verification

- can eliminate many exploitable vulnerabilities today
  - exploit kits leverage software errors e.g. buffer overflow, missing bounds checks, integer overflow, invalid array access, memory corruption, ...
- traditionally applied to embedded software in many critical domains
  - avionics, energy, rail, ...
- rarely applied to IoT software

This talk

- promotes the usage of formal verification for IoT software
- illustrates it for an IoT operating system Contiki

Contiki: A lightweight OS for IoT

It provides a lot of features (for a micro-kernel):

- (rudimentary) memory and process management
- networking stack and cryptographic functions
- ...

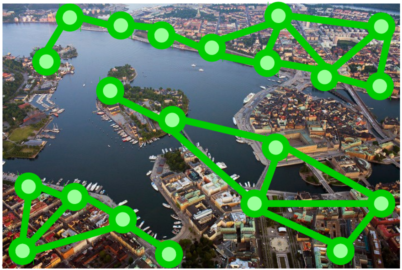
Typical hardware platform:

- 8, 16, or 32-bit MCU (little or big-endian),
- low-power radio, some sensors and actuators, ...

Any invalid memory access can be dangerous: there is *no* memory protection unit.

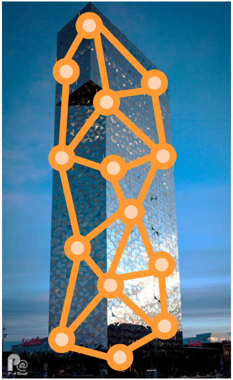
Contiki: Typical Applications

- IoT scenarios: smart cities, building automation, ...
- Multiple hops to cover large areas
- Low-power for battery-powered scenarios
- Nodes are interoperable and addressable (IP)



Traffic lights
Parking spots
Public transport
Street lights
Smart metering
...

Light bulbs
Thermostat
Power sockets
CO2 sensors
Door locks
Smoke detectors
...



Contiki and Formal Verification

- When started in 2003, no particular attention to security
- Later, communication security was added at different layers, via standard protocols such as IPsec or DTLS
- Security of the software itself did not receive much attention
- Continuous integration system does not include formal verification
  - and unit tests are under-represented

Verification goals

For low-level library/system code: ideally functional verification

- highly critical code
- frequently used (memory, lists, ...)

For the netstack: absence of runtime errors

- using value analysis (Frama-C/Eva)
- using minimal contracts and deductive verification (Frama-C/WP) if Eva cannot prove
- using runtime verification if WP cannot prove either

Outline

Frama-C Open-Source Distribution

Software Analyzers

Framework for Analysis of source code written in C

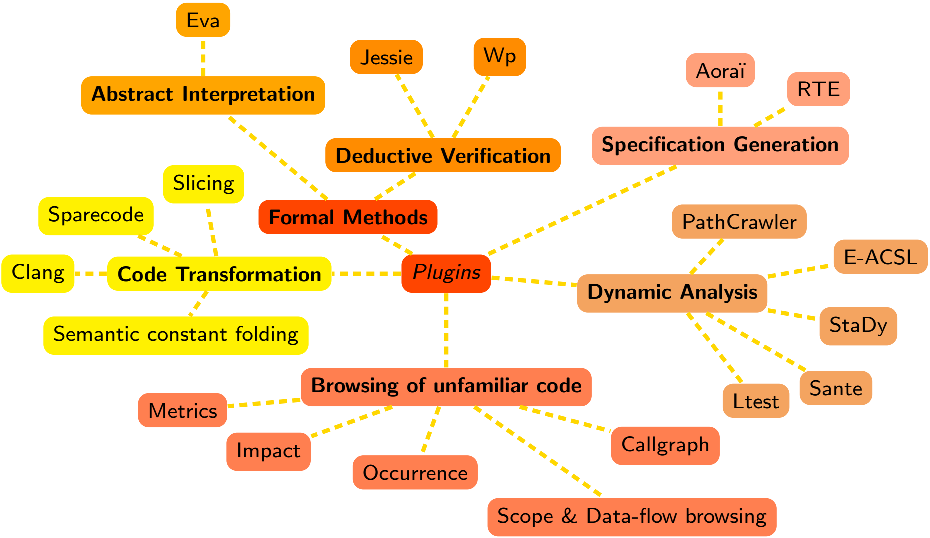
- analysis of C code extended with ACSL annotations
- ACSL Specification Language
  - *langua franca* of Frama-C analyzers
- http://frama-c.com
- targets both academic and industrial usage

Frama-C, a Collection of Tools

Several tools inside a single platform

- plugin architecture like in Eclipse
- tools provided as plugins
  - over 20 plugins in the open-source distribution
  - close-source plugins, either at CEA (about 20) or outside
- a common kernel
  - provides a uniform setting
  - provides general services
  - synthesizes useful information

Frama-C Plugin Gallery



Plugin Frama-C/Eva for Value Analysis

Compute possible values of variables at each program point

- an automatic analysis
- based on abstract interpretation
- reports alarms for potentially invalid operations
- can prove the absence of runtime errors

Plugin Frama-C/WP for deductive verification

- Based on Weakest Precondition calculus [Dijkstra, 1976]
- Goal: Prove that a given program respects its specification
- Requires formal specification

Example: a C Program Annotated in ACSL

```
/*@ requires n>=0 && \valid(t+(0..n-1));
    assigns \nothing;
    ensures \result != 0 <==>
      (\forall integer j; 0 <= j < n ==> t[j] == 0);
*/
int all_zeros(int t[], int n) {
  int k;
  /*@ loop invariant 0 <= k <= n;
      loop invariant \forall integer j; 0<=j<k ==> t[j]==0;
      loop assigns k;
      loop variant n-k;
  */
  for(k = 0; k < n; k++)
    if (t[k] != 0)
      return 0;
  return 1;
}
```

Can be proven with Frama-C/WP

Overview of the `aes-ccm` Modules

- Critical! – Used for communication security
  - end-to-end confidentiality and integrity (e.g. Link-layer security or DTLS)
- Advanced Encryption Standard (AES) is a symmetric encryption algorithm
  - AES replaced in 2002 Data Encryption Standard (DES), which became obsolete in 2005
- Modular API – independent from the OS
- Two modules:
  - AES-128
  - AES-CCM* block cypher mode
  - A few hundreds of LoC
- High complexity crypto code
  - Intensive integer arithmetics
  - Intricate indexing
  - based on multiplication over finite field $\mathrm{GF}(2^8)$

Example: Function set_key

```
static void set_key(const uint8_t *key)
{
  uint8_t i;
  uint8_t j;
  uint8_t rcon;

  rcon = 0x01;
  memcpy(round_keys[0], key, AES_128_KEY_LENGTH);
  for(i = 1; i <= 10; i++) {
    round_keys[i][0] = sbox[round_keys[i - 1][13]]
      ^ round_keys[i - 1][0] ^ rcon;
    round_keys[i][1] = sbox[round_keys[i - 1][14]]
      ^ round_keys[i - 1][1];
    round_keys[i][2] = sbox[round_keys[i - 1][15]]
      ^ round_keys[i - 1][2];
    round_keys[i][3] = sbox[round_keys[i - 1][12]]
      ^ round_keys[i - 1][3];
    for(j = 4; j < AES_128_BLOCK_SIZE; j++) {
      round_keys[i][j] = round_keys[i - 1][j]
        ^ round_keys[i][j - 4];
    }
    rcon = galois_mul2(rcon);
  }
}
```

Verification of aes-ccm with Frama-C/Eva

- Proof of absence of runtime errors (and security vulnerabilities) for all possible cases
- Example for AES: we run Eva on the most general context built for AES:

```
int main() {
  uint8_t key[16];
  uint8_t data[16];
  int i;
  for(i=0; i<16; i++) {
    key[i]=Frama_C_interval(0,255);
    data[i]=Frama_C_interval(0,255);
  }
  aes_128_set_key(key);
  aes_128_encrypt(data);
}
```

- If Eva does not prove, one can use WP with minimal contracts

Example: Function set_key

```
/*@ requires \valid_read(key+ (0 .. (AES_128_KEY_LENGTH - 1)));
    assigns round_keys[0][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[1][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[2][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[3][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[4][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[5][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[6][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[7][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[8][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[9][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[10][0 .. (AES_128_KEY_LENGTH - 1)];
*/
static void
set_key(const uint8_t *key)
{
    uint8_t i;
    uint8_t j;
    uint8_t rcon;
    rcon = 0x01;
    for(i = 0; i < AES_128_KEY_LENGTH; i++) {
        round_keys[0][i] = key[i];
    }
    for(i = 1; i <= 10; i++) {
        round_keys[i][0] = sbox[round_keys[i - 1][13]] ^ round_keys[i - 1][0] ^ rcon;
        round_keys[i][1] = sbox[round_keys[i - 1][14]] ^ round_keys[i - 1][1];
        round_keys[i][2] = sbox[round_keys[i - 1][15]] ^ round_keys[i - 1][2];
        round_keys[i][3] = sbox[round_keys[i - 1][12]] ^ round_keys[i - 1][3];
        for(j = 4; j < AES_128_BLOCK_SIZE; j++) {
            round_keys[i][j] = round_keys[i - 1][j] ^ round_keys[i][j - 4];
        }
        rcon = galois_mul2(rcon);
    }
}
```

```
/*@ loop invariant 0 <= i <= AES_128_KEY_LENGTH;
    loop assigns i, round_keys[0][0 .. (AES_128_KEY_LENGTH - 1)];
    loop variant AES_128_KEY_LENGTH - i;
*/
```

```
/*@ loop invariant 1 <= i <= 11;
    loop assigns i, rcon, j, round_keys[1][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[2][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[3][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[4][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[5][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[6][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[7][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[8][0 .. (AES_128_KEY_LENGTH - 1)], round_keys[9][0 .. (AES_128_KEY_LENGTH - 1)],
    round_keys[10][0 .. (AES_128_KEY_LENGTH - 1)];
    loop variant 11 - i;
*/
```

```
/*@ loop invariant 4 <= j <=
AES_128_BLOCK_SIZE;
    loop assigns j, round_keys[i][4 ..
(AES_128_KEY_LENGTH - 1)];
    loop variant 16 - j;
*/
```

Specification and Verification with Frama-C/WP

- Specification of “minimal” contracts of each function
  - $\sim$300 lines of C code
  - $\sim$100 lines of ACSL spec
  - 467 proof obligations (proved within $\sim$50 sec.)
- Proof of absence of RTE with Frama-C/WP
- Validation of contracts of a test file
  - to get confidence that the contracts are OK

Reference: A.Peyrard, N.Kosmatov, S.Duquennoy, S.Raza.
Towards Formal Verification of Contiki OS: Analysis of the AES-CCM Modules with Frama-C.* In RED-IoT 2018, part of EWSN 2018, ACM.

Overview of the `memb` Module

- No dynamic allocation in Contiki
  - to avoid fragmentation of memory in long-lasting systems
- Memory is pre-allocated (in arrays of blocks) and attributed on demand
- The management of such blocks is realized by the `memb` module

The `memb` module API allows the user to

- initialize a `memb` store (i.e. pre-allocate an array of blocks),
- allocate or free a block,
- check if a pointer refers to a block inside the store
- count the number of allocated blocks

memb is critical!

- Contiki's main memory allocation module
- about 100 lines of critical code
- kernel and many modules rely on memb
  - used for HTTP, CoAP (lightweight HTTP), IPv6 routes, CSMA, the MAC protocol TSCH, packet queues, network neighbors, the file system Coffee or the DBMS Antelope

- memb is one of the most critical elements of Contiki

A flaw in memb could result in attackers reading or writing arbitrary memory regions, crashing the device, or triggering code execution

The memb Store

- An array of blocks with a given block size and number of blocks
- Defined by an instance of `struct memb`
- Created by a macro for a given block type and number of blocks
  - since there is no polymorphism in C
  - blocks are manipulated as `void*` pointers
- Refers to global definitions added by preprocessing

```c
/* file memb.h */
struct memb {
  unsigned short size; // block size
  unsigned short num;  // number of blocks
  char *count;         // block statuses
  void *mem;           // array of blocks
};
#define MEMB(name, btype, num)...
// macro used to decrare a memb store for
// allocation of num blocks of type btype

void  memb_init(struct memb *m);
void *memb_alloc(struct memb *m);
char  memb_free(struct memb *m, void *p);
...
```

```c
/* file demo.c */
#include "memb.h"
struct point {int x; int y};

// before preprocessing,
// there was the following macro:
// MEMB(pblock, struct point, 2);

// after preprocessing, it becomes:
static char pblock_count[2];
static struct point pblock_mem[2];
struct struct memb pblock = {
  sizeof(struct point), 2,
  pblock_count, pblock_mem };
...
```

Contract of the Allocation Function memb_alloc

```
/*@
  requires valid_memb(m);
  ensures valid_memb(m);
  assigns m→count[0 .. (m→num - 1)];
  behavior free_found:
    assumes ∃ ℤ i; 0 ≤ i < m→num ∧ m→count[i] == 0;
    ensures ∃ ℤ i; 0 ≤ i < m→num ∧ \old(m→count[i]) == 0 ∧ m→count[i] == 1 ∧
      \result == (char*) m→mem + (i * m→size) ∧
      ∀ ℤ j; (0 ≤ j < i ∨ i < j < m→num) ⟹ m→count[j] == \old(m→count[j]);
    ensures \valid((char*) \result + (0 .. (m→size - 1)));
    ensures _memb_numfree(m) == \old(_memb_numfree(m)) - 1;
  behavior full:
    assumes ∀ ℤ i; 0 ≤ i < m→num ⟹ m→count[i] ≠ 0;
    ensures ∀ ℤ i; 0 ≤ i < m→num ⟹ m→count[i] == \old(m→count[i]);
    ensures \result == NULL;
  complete behaviors;
  disjoint behaviors;
*/
void *memb_alloc(struct memb *m);
```

Proven
in Frama-C/WP

Specification in ACSL

We specify the contract of each function and prove it in Frama-C

For instance, the contract of `memb_alloc` has two behaviors

1. If the store is full, then leave it intact and return NULL (lines 12-15)
2. If the store has a free block, then return a free block *b* such that:
   - *b* is properly aligned in the block array (line 8)
   - *b* was marked as free, and is now marked as allocated (line 7)
   - *b* is valid, i.e. points to a valid memory space of a block size that can be safely read or written to (line 10)
   - the states of the other blocks have not changed (line 9)
   - the number of free blocks is decremented (line 11)

These behaviors are disjoint and complete.

Summary

- The `memb` module specified and formally verified with Frama-C/WP
  - 115 lines of annotations
  - 32 additional assertions
  - 126 verification conditions (i.e. proven properties)
- A few client functions proven as expected
  - Proof fails for out-of-bounds access attempts
- A potentially harmful situation reported (and fixed)
  - `count--;` used instead of `count=0;`

Reference: F.Mangano, S.Duquennoy and N.Kosmatov.
A Memory Allocation Module of Contiki Formally Verified with Frama-C. A Case Study. In CRiSIS 2016, LNCS, vol.10158, 114–120. Springer.

The LIST module - Overview

- Provides a generic list API for linked lists.
  - about 176 LOC (excl. MACROS)
  - required by 32 modules of Contiki
  - more than 250 calls in the core part of Contiki
- Some special features:
  - no dynamic allocation
  - does not allow cycles
  - maintains item unicity

The LIST module - A rich API

```
struct list {
  struct list *next;
};
typedef struct list ** list_t;

void list_init(list_t pLst);
int  list_length(list_t pLst);
void * list_head(list_t pLst);
void * list_tail(list_t pLst);
void * list_item_next(void *item);
void * list_pop (list_t pLst);
void list_push(list_t pLst, void *item);
void * list_chop(list_t pLst);
void list_add(list_t pLst, void *item);
void list_remove(list_t pLst, void *item);
void list_insert(list_t pLst, void *previtem, void *newitem);
void list_copy(list_t dest, list_t src);
```

The LIST module - A rich API

Observers

```
struct list {
  struct list *next;
};
typedef struct list ** list_t;

void list_init(list_t pLst);
int  list_length(list_t pLst);
void * list_head(list_t pLst);
void * list_tail(list_t pLst);
void * list_item_next(void *item);
void * list_pop (list_t pLst);
void list_push(list_t pLst, void *item);
void * list_chop(list_t pLst);
void list_add(list_t pLst, void *item);
void list_remove(list_t pLst, void *item);
void list_insert(list_t pLst, void *previtem, void *newitem);
void list_copy(list_t dest, list_t src);
```

The LIST module - A rich API

Observers

Update list beginning

```
struct list {
  struct list *next;
};
typedef struct list ** list_t;

void list_init(list_t pLst);
int  list_length(list_t pLst);
void * list_head(list_t pLst);
void * list_tail(list_t pLst);
void * list_item_next(void *item);
void * list_pop (list_t pLst);
void list_push(list_t pLst, void *item);
void * list_chop(list_t pLst);
void list_add(list_t pLst, void *item);
void list_remove(list_t pLst, void *item);
void list_insert(list_t pLst, void *previtem, void *newitem);
void list_copy(list_t dest, list_t src);
```

The LIST module - A rich API

Observers

Update list beginning

Update list end

```
struct list {
  struct list *next;
};
typedef struct list ** list_t;

void list_init(list_t pLst);
int  list_length(list_t pLst);
void * list_head(list_t pLst);
void * list_tail(list_t pLst);
void * list_item_next(void *item);
void * list_pop (list_t pLst);
void list_push(list_t pLst, void *item);
void * list_chop(list_t pLst);
void list_add(list_t pLst, void *item);
void list_remove(list_t pLst, void *item);
void list_insert(list_t pLst, void *previtem, void *newitem);
void list_copy(list_t dest, list_t src);
```

The LIST module - A rich API

```
struct list {
  struct list *next;
};
typedef struct list ** list_t;

void list_init(list_t pLst);
int  list_length(list_t pLst);
void * list_head(list_t pLst);
void * list_tail(list_t pLst);
void * list_item_next(void *item);
void * list_pop (list_t pLst);
void list_push(list_t pLst, void *item);
void * list_chop(list_t pLst);
void list_add(list_t pLst, void *item);
void list_remove(list_t pLst, void *item);
void list_insert(list_t pLst, void *previtem, void *newitem);
void list_copy(list_t dest, list_t src);
```

Observers

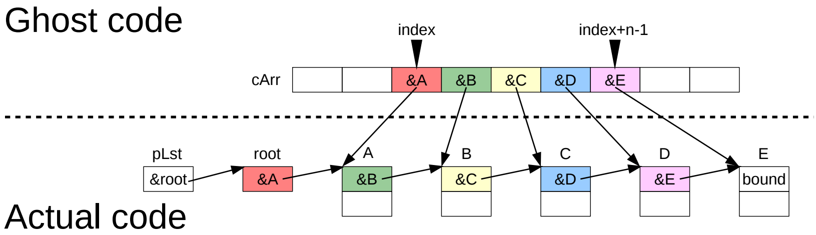
Update list beginning

Update list end

Update list anywhere

Formalization approach

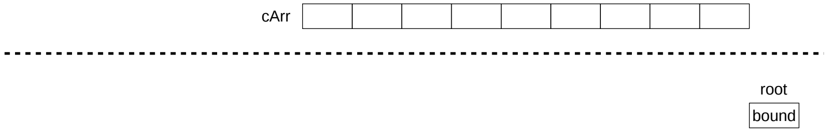
Maintain a companion ghost array that stores the addresses of list cells



Define an inductive predicate linking the list and the array

Formalization approach - Base case

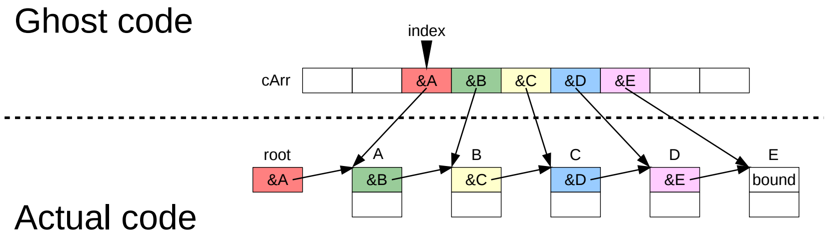
Ghost code



Actual code

```
inductive linked_n{L}(struct list *root, struct list **cArr,
                      integer index, integer n, struct list *bound) {
case linked_n_bound{L}:
  \forall struct list **cArr, *bound, integer index;
    0 <= index <= MAX_SIZE ==> linked_n(bound, cArr, index, 0, bound);
// ...
}
```

Formalization approach - Induction




```
inductive linked_n{L}(struct list *root, struct list **cArr,
                      integer index, integer n, struct list *bound) {
// ...
case linked_n_cons{L}:
  \forall struct list *root, **cArr, *bound, integer index, n;
    /*indexes properties*/ ==> \valid(root) ==> root == cArr[index] ==>
    linked_n(root->next, cArr, index + 1, n - 1, bound) ==>
      linked_n(root, cArr, index, n, bound);
}
```

Formalization approach - Advantages

The companion array allows us to easily reason about the list contents:

```
predicate unchanged{L1, L2}(struct list **array, int index, int size) =
  \forall integer i ; index <= i < index+size ==>
    \at(array[i]->next, L1) == \at(array[i]->next, L2);
```

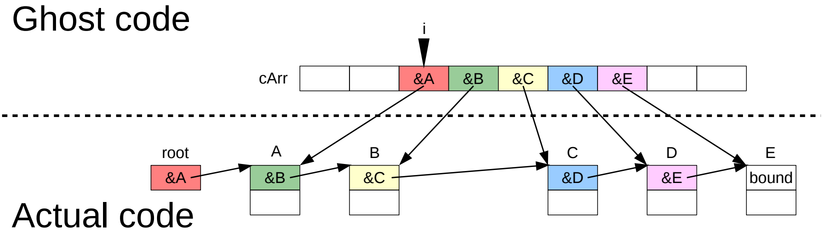
We have to update the array (in ghost code) when the list is modified

Example of required lemma: split a list into two segments

```
/*@
lemma linked_split_segment:
  \forall struct list *root, **cArr, *bound, *AddrC, integer i, n, k;
    n > 0 ==> k >= 0 ==>
    AddrC == cArr[i + n - 1]->next ==>
    linked_n(root, cArr, i, n + k, bound) ⇒
      (linked_n(root, cArr, i, n, AddrC) &&
       linked_n(AddrC, cArr, i + n, k, bound));
*/
```

Example of required lemma: split a list into two segments

```
/*@
lemma linked_split_segment:
  \forall struct list *root, **cArr, *bound, *AddrC, integer i, n, k;
    n > 0 ==> k >= 0 ==>
    AddrC == cArr[i + n - 1]->next ==>
    linked_n(root, cArr, i, n + k, bound) ⇒
      (linked_n(root, cArr, i, n, AddrC) &&
       linked_n(AddrC, cArr, i + n, k, bound));
*/
```



Verification Results

- Code written and specification
  - 46 lines for ghost functions
  - 500 lines for contracts
  - 240 lines for logic definitions and lemmas
  - 650 lines of other annotations
- It generates 798 proof obligations
  - 772 are automatically discharged by SMT solvers
  - 24 are lemmas proved with Coq
  - 2 assertions proved with Coq
  - 2 assertions proved using TIP
- Discharging all PO requires about an hour of computation.

Reference: A.Blanchard, N.Kosmatov and F.Loulergue.
Ghosts for Lists: A Critical Module of Contiki Verified in Frama-C. In NFM 2018, LNCS. Springer.

Bug found in `list_insert` (now fixed)

List: list_insert bug #254

Closed **simonduq** opened this issue on 15 Dec 2017 · 4 comments

simonduq commented on 15 Dec 2017 • edited

Owner

The function `list_insert` in `list.c` is buggy: when `previtem` is null, it pushes the new element (which (1) removes any old instance and then (2) inserts the new element). But when `previtem` is non-null, it just adds the new item without removing any old instance. Could in duplicate elements in the latter case.

Only reporting as `bug/low` because the function is currently not used in the codebase.

(report by Nikolai Kosmatov)

Bug found in `list_insert` (now fixed)

List: list_insert bug #254

Closed **simonduq** opened this issue on 15 Dec 2017 · 4 comments

simonduq commented on 15 Dec 2017 • edited ▾ Owner

The function `list_insert` in `list.c` is buggy: when `previtem` is null, it pushes the new element (which (1) removes any old instance and then (2) inserts the new element). But when `previtem` is non-null, it just adds the new item without removing any old instance. Could in duplicate elements in the latter case.

Only reporting as `bug/low` because the function is currently not used in the codebase.

(report by Nikolai Kosmatov)

g-oikonomou commented on 16 Dec 2017 • edited ▾ Owner

For the record, things are actually worse than having the same element in the list twice: This bug will corrupt the list.

Conclusion

Frama-C successfully used to formally verify several critical modules

- functional verification of memory allocation (MEMB)
- absence of security flaws in cryptography (AES-CCM and CCM*)
- functional verification of a key kernel module (LIST)
- other studies in progress

Absence of security related errors verified in all cases

End-to-end confidentiality and integrity (via AES-CCM)

Basic module for memory separation of various tasks

Several errors or incoherencies detected

New: Continuous integration framework for formal verification of Contiki is online [submitted]

Further reading

Tutorial papers:

- A. Blanchard, N. Kosmatov, and F. Loulergue. A Lesson on Verification of IoT Software with Frama-C (HPCS 2018)
- on deductive verification:
  N. Kosmatov, V. Prevosto, and J. Signoles. A lesson on proof of programs with Frama-C (TAP 2013)
- on runtime verification:
  - N. Kosmatov and J. Signoles. A lesson on runtime assertion checking with Frama-C (RV 2013)
  - N. Kosmatov and J. Signoles. Runtime assertion checking and its combinations with static and dynamic analyses (TAP 2014)
- on test generation:
  N. Kosmatov, N. Williams, B. Botella, M. Roger, and O. Chebaro. A lesson on structural testing with PathCrawler-online.com (TAP 2012)
- on analysis combinations:
  N. Kosmatov and J. Signoles. Frama-C, A collaborative framework for C code verification: Tutorial synopsis (RV 2016)

Further reading

More details on the verification of Contiki:

- on the MEMB module:
  F. Mangano, S. Duquennoy, and N. Kosmatov. A memory allocation module of Contiki formally verified with Frama-C. A case study (CRiSIS 2016)
- on the AES-CCM* module:
  A. Peyrard, S. Duquennoy, N. Kosmatov, and S. Raza. Towards formal verification of Contiki: Analysis of the AES–CCM* modules with Frama-C (RED-IoT 2017)
- on the LIST module:
  - A. Blanchard, F. Loulergue and N. Kosmatov. Ghosts for lists: A critical module of contiki verified in Frama-C (NFM 2018)
  - F. Loulergue, A. Blanchard, and N. Kosmatov. Ghosts for lists: from axiomatic to executable specifications (TAP 2018)
  - A. Blanchard, F. Loulergue and N. Kosmatov. Towards Full Proof Automation in Frama-C using Auto-Active Verification. (NFM 2019)
  - A. Blanchard, N. Kosmatov, and F. Loulergue. Logic against Ghosts: Comparison of two Proof Approaches for a List Module (SAC 2019)
    Best ACM Software Development paper award.