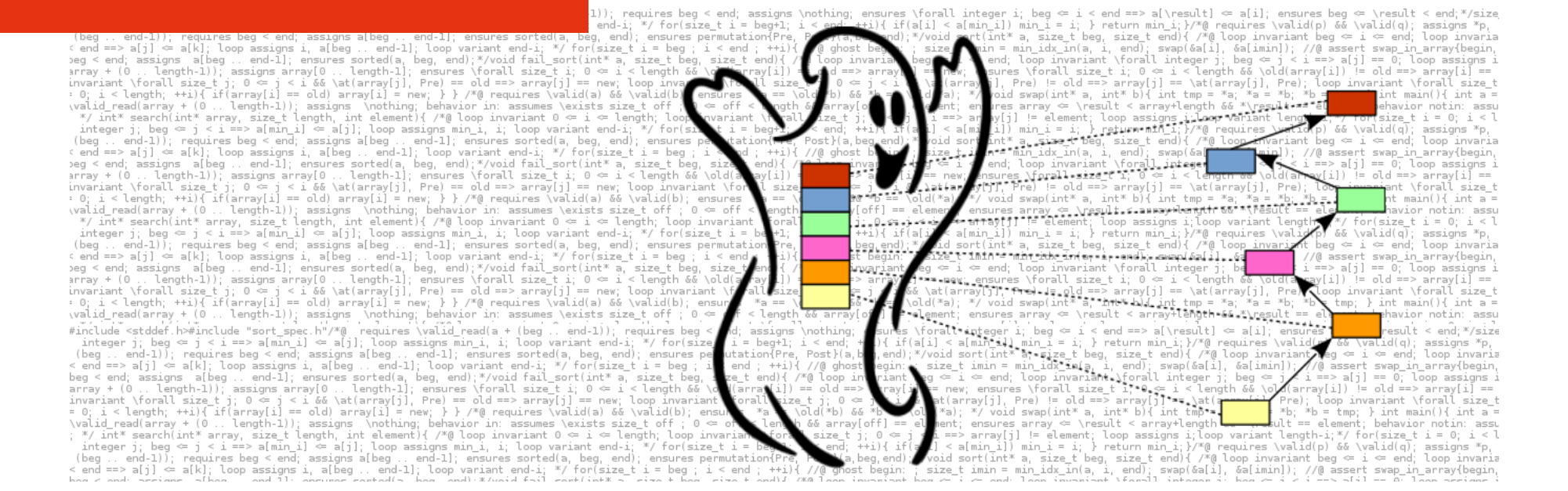
Ghosts for Lists: A Critical Module of Contiki Verified in Frama-C



Allan Blanchard Nikolai Kosmatov Frédéric Loulergue – 14/06/2018 @ AFADL 2018

01

Introduction

The Vessedia project

EU H2020 Vessedia project

- aims at making formal methods more usable in the context of the IoT
- comprises use-cases to evaluate the efficiency of the developed tools and methods
- `https://vessedia.eu`

Contiki-OS

- one of the use-cases targeted in Vessedia
- a lightweight OS for IoT

A lightweight OS for IoT

Contiki is a lightweight operating system for IoT

`https://github.com/contiki-ng/contiki-ng`

It provides a lot of features:

- (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, ...

Note for security: there is *no* memory protection unit.

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

Today's talk: the list module of Contiki

- a critical component of the core part of Contiki
- many client modules in the whole OS
- verification performed with Frama-C and its WP plugin

A. Blanchard, N. Kosmatov, and F. Loulergue.
Ghosts for lists: A critical module of contiki verified in Frama-C
NASA Formal Methods 2018

Frama-C at a glance

- A Framework for Modular Analysis of C code
- Developed at CEA List
- Released under LGPL license
- ACSL annotation language
- Extensible plugin oriented platform
  - > Collaboration of analyses over same code
  - > Inter plugin communication through ACSL formulas
  - > Adding specialized plugins is easy
- `http://frama-c.com/` [Kirchner et al. FAC 2015]

ACSL: ANSI/ISO C Specification Language

Presentation

- Based on the notion of contract like in Eiffel, JML
- Allows users to specify functional properties of programs
  - > Correctness of the specification is crucial
  - > Attacks can exploit every single flaw ⇒ Complete proof is required!
- `http://frama-c.com/acsl`

Basic Components

- First-order logic
- Pure C expressions
- C types + $\mathbb{Z}$ (integer) and $\mathbb{R}$ (real)
- Built-in predicates and logic functions particularly over pointers: `\valid(p)`, `\valid(p+0..2)`, `\separated(p+0..2,q+0..5)`, `\block_length(p)`

Plugin Frama-C/WP

WP: A plugin for deductive verification

- Based on Weakest Precondition calculus [Dijkstra, 1976]
- Goal: Prove that a given program respects its specification
- Requires formal specification
- Capable to formally prove that
  - each program function always respects its contract
  - each function call respects the expected conditions on its inputs
  - each function call provides sufficient guarantees to ensure the caller's contract
  - common security related errors (e.g. buffer overflows) can never occur

02

Ghosts for lists

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
- maintain 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

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  struct list *next;
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Observers

Update list beginning

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```

Observers

Update list beginning

Update list end

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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

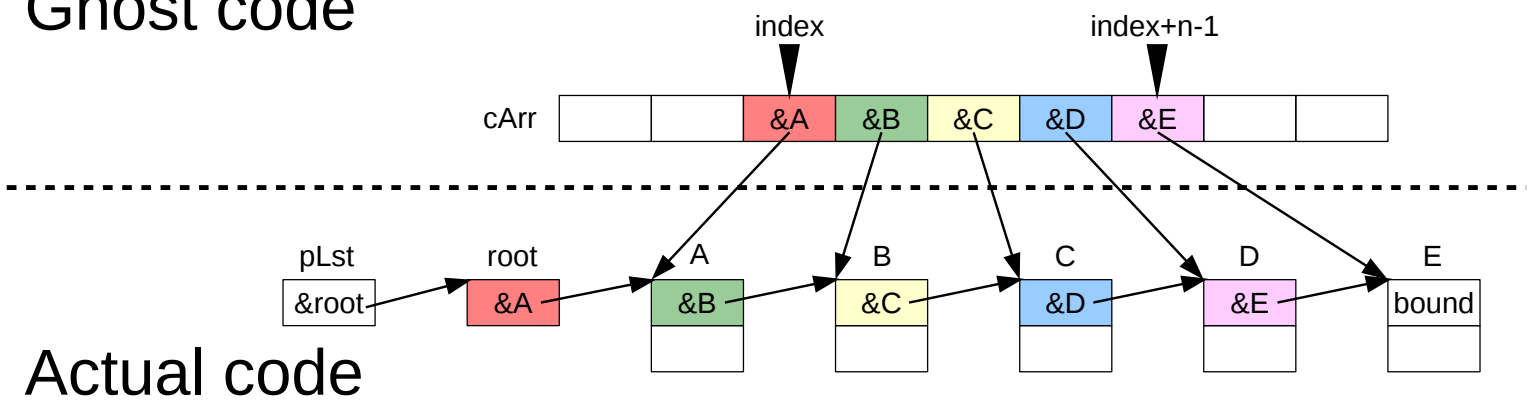
Update list end

Update list anywhere

Formalization approach - Overview

We maintain a ghost array that stores the addresses of the different list elements.

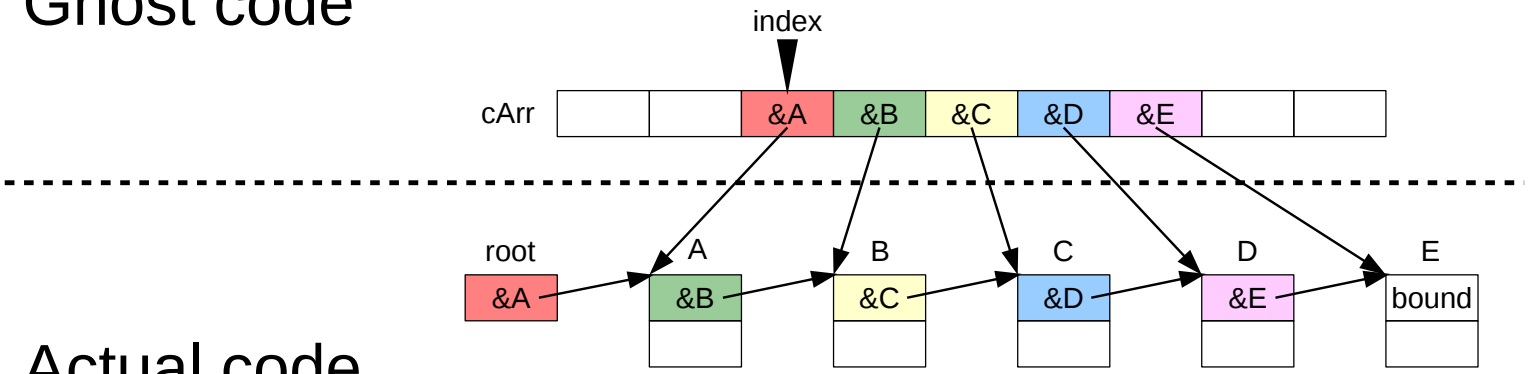
Ghost code



Actual code

Formalization approach - Induction

Ghost code



Actual code

```
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 - Induction

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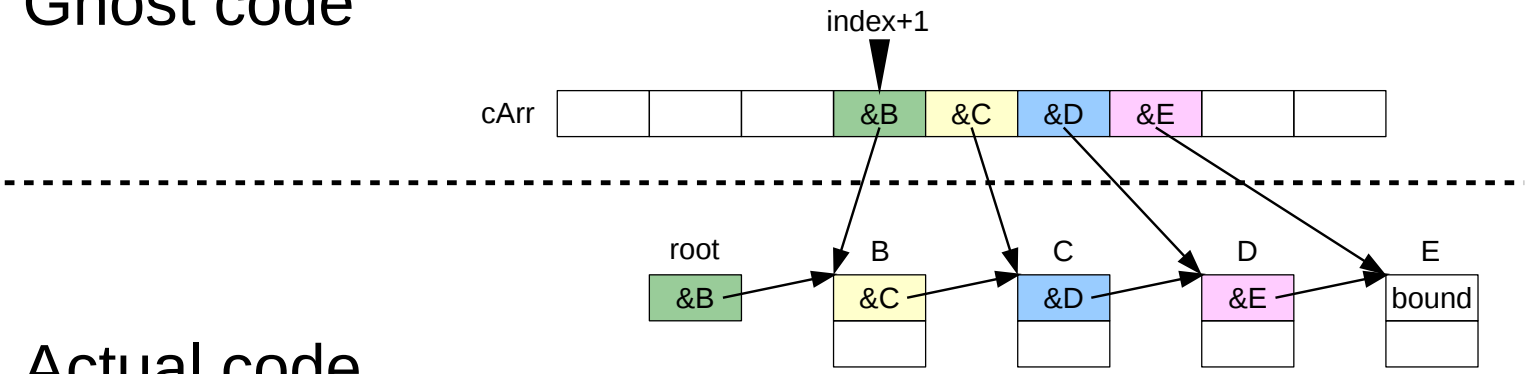

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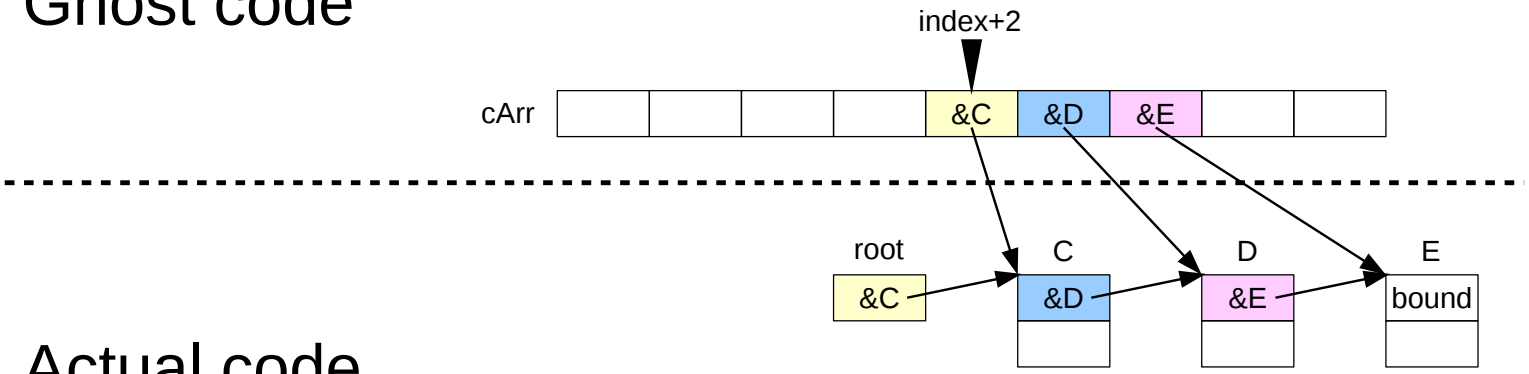

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}
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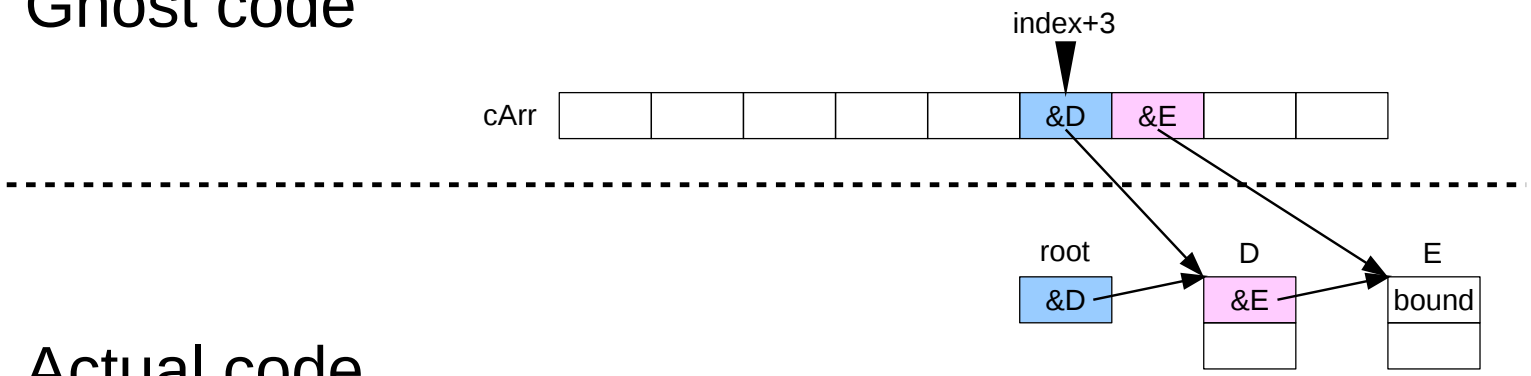
Formalization approach - Induction

Ghost code



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Formalization approach - Induction

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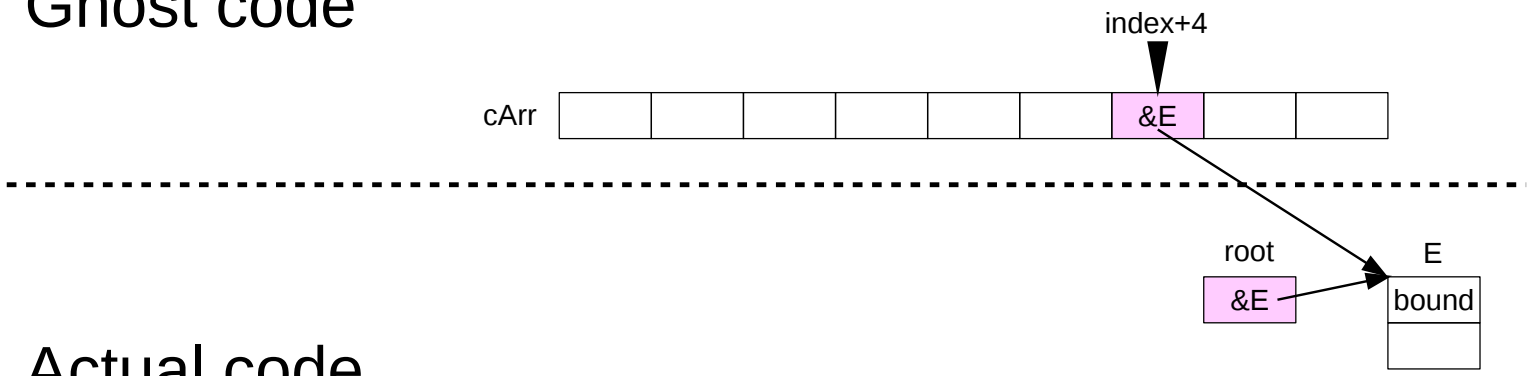

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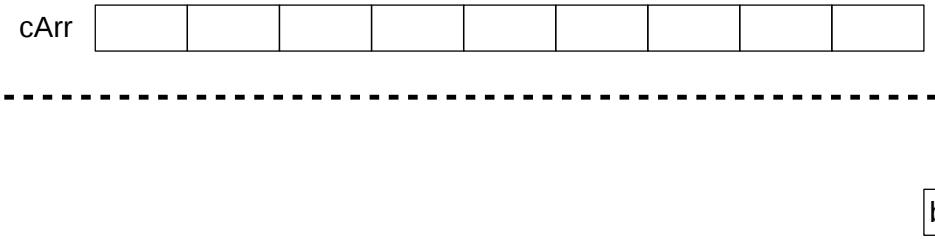
      linked_n(root, cArr, index, n, bound);
}
```

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 - Advantages

As long as we maintain the `linked_n` invariant,
we can easily reason about the content of the list:

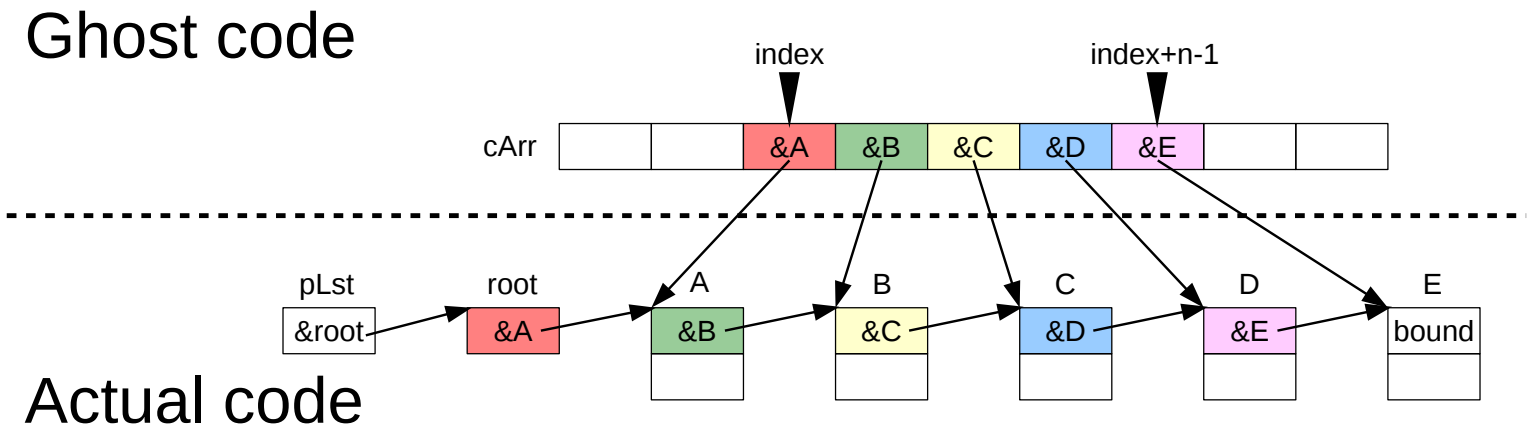
```
predicate unchanged{L1, L2}(struct list **array, int index, int size) =
  \forall integer i ; index <= i < index+size ==>
    \at(array[i]->next, L1) == \at(array[i]->next, L2);
```

While we have to update the array accordingly when the list is modified.

Example with `list_pop`

```
void simpl_list_pop(list_t pLst, struct list **cArr, int index, int n){
  if(*pLst != NULL) {
    //@ ghost array_pop(cArr, index, n, pLst, NULL);
    *pLst = (*pLst)->next;
  }
}
```

Current property:



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}
```
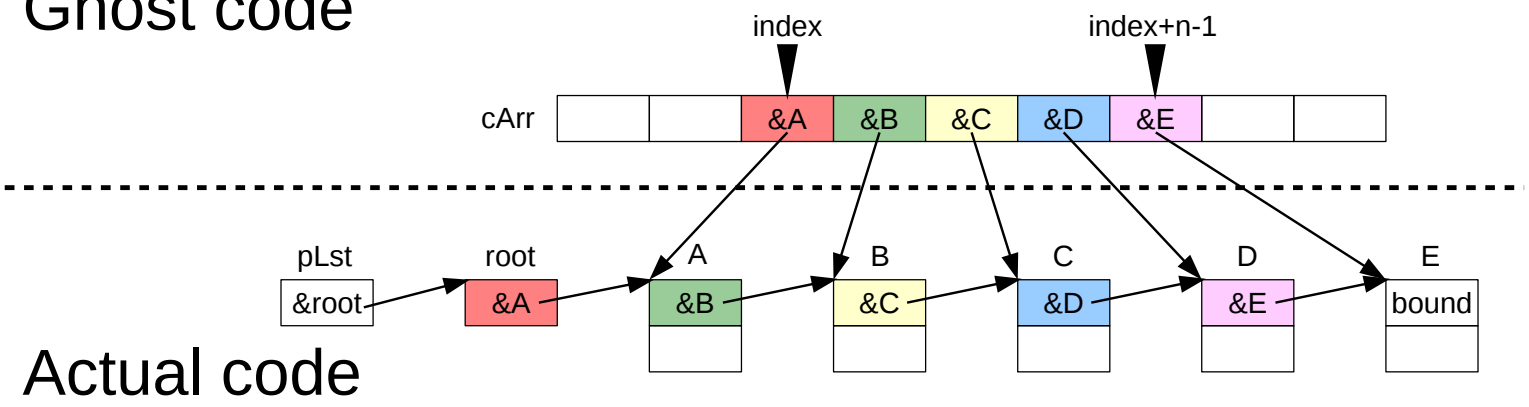

Current property:

```
linked_n(*pLst, cArr, index, n, NULL);
```

Ghost code



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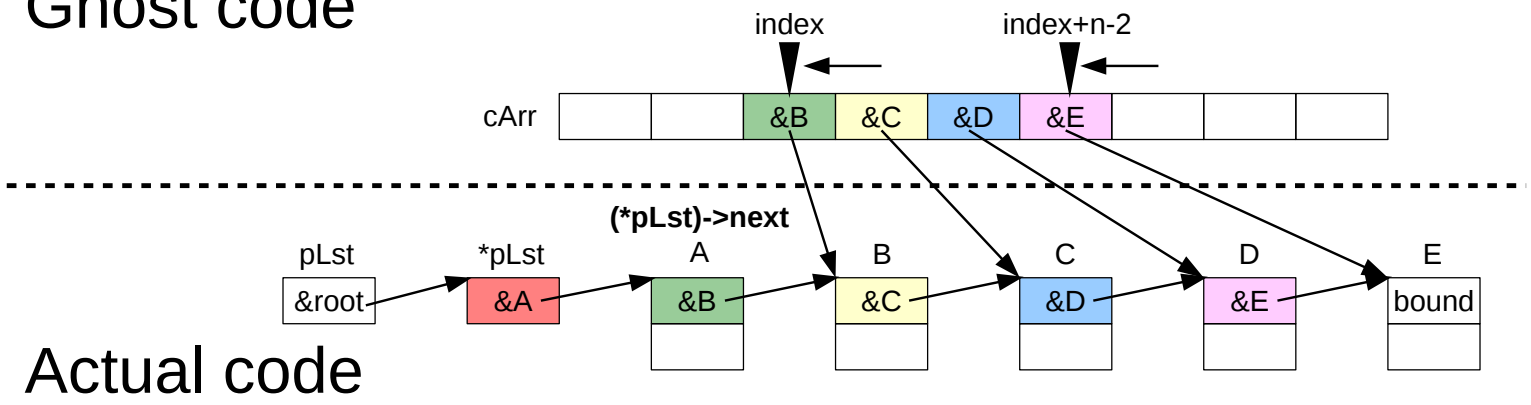
  }
}
```

Current property:

```
linked_n((*pLst)->next, cArr, index, n-1, NULL);
```

Ghost code



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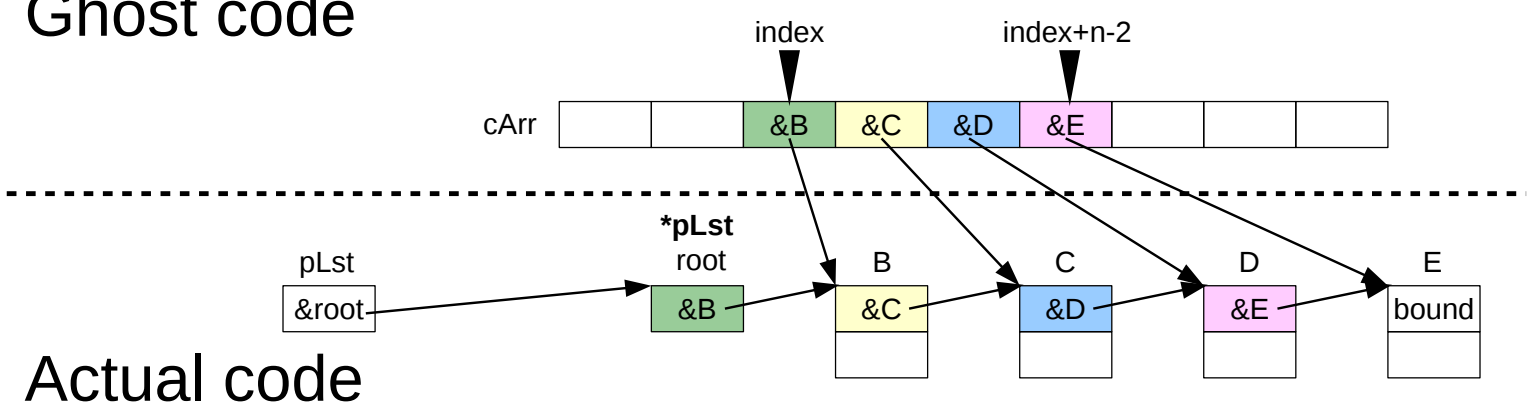

Actual code

Example of required lemma

```
/*@
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) &&
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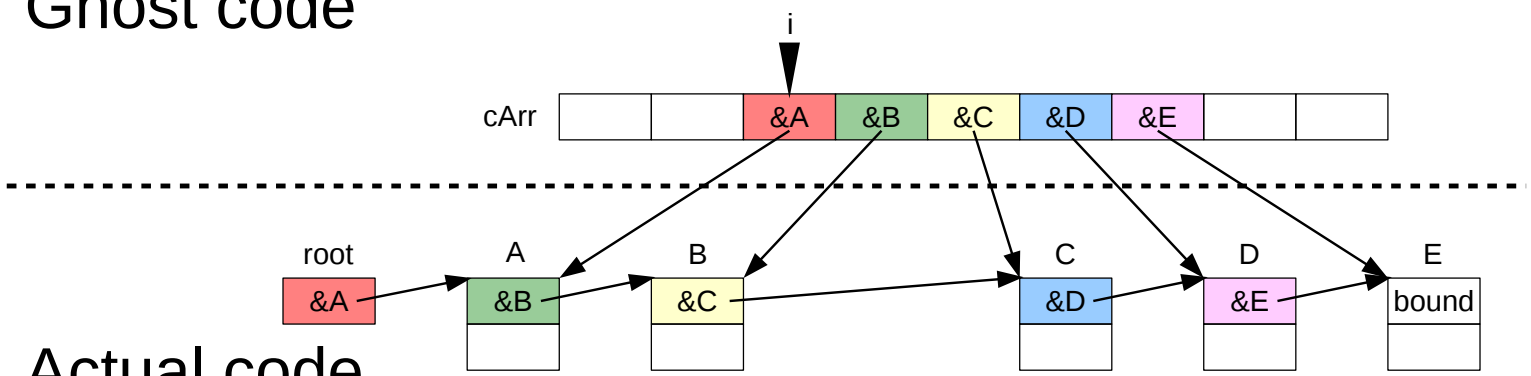

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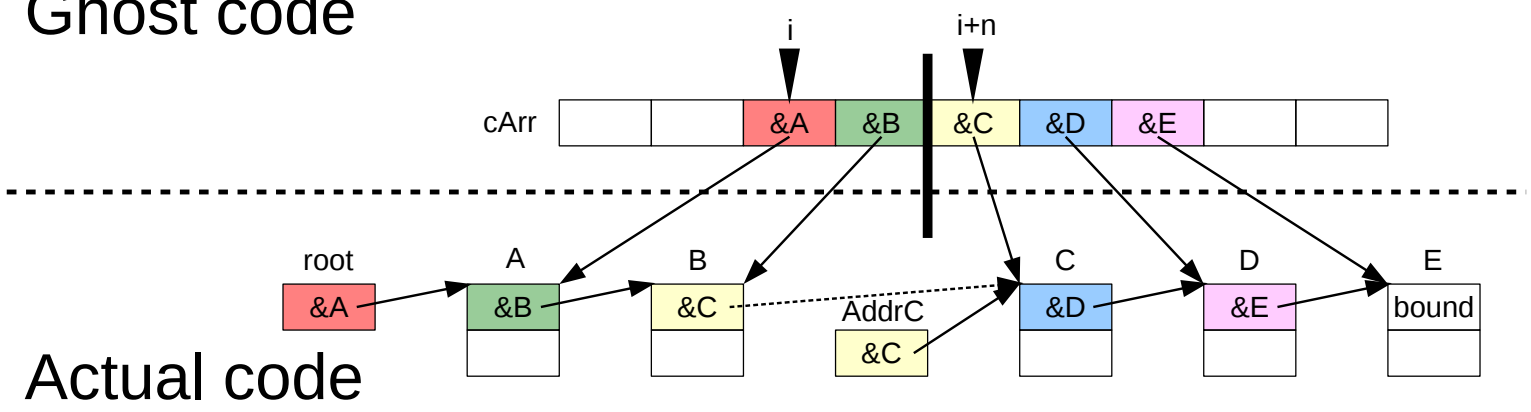

Actual code

Results

- Written specification and ghost code
  - 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 (96.7%) 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.
- We have built some tests to check the specification
  - some bugs in the specification were discovered and fixed
  - the handling of assigns could be improved

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Bug found in `list_insert`

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)

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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.

03

Conclusion & Future work

Let's sum up!

We presented the verification of the list module of Contiki

Verification

- based on a companion ghost array that tracks the status of the list
- comprises a set of lemmas that reduces the need for interactive proof
- still needs quite a lot of auxiliary annotations
- allowed us to find and fix a bug in the module

Ongoing & Future work

The verification of the list module can be improved

- while based on arrays, the specification is not executable
  - > Provably equivalent executable proof-of-concept version (TAP 2018)
- separation was really hard to handle
  - > (Ongoing) we should not have to deal with ghost separation
- one would prefer a more abstract specification
  - > (Ongoing) using ACSL logic lists
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  - > (Ongoing) we should not have to deal with ghost separation
- one would prefer a more abstract specification
  - > (Ongoing) using ACSL logic lists
  - > (Ongoing) using contiguous partial functions

Tutorial @HPCS 2018 (Orléans) in July

Secure Your Things: Verification of IoT Software with Frama-C

Thank you!

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