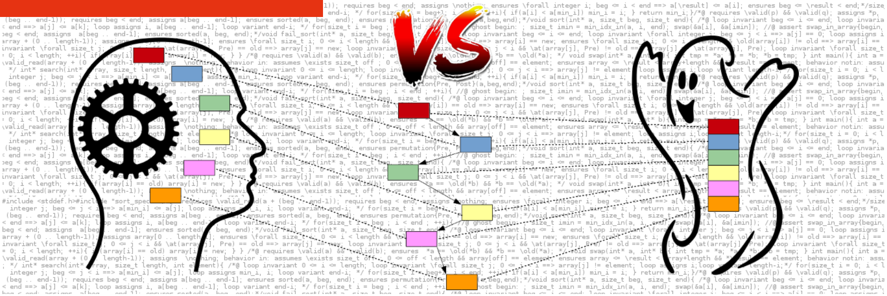
Logic Against Ghosts:

Comparison of two Proof Approaches for Linked Lists



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Formal verification of IoT Software

The VESSEDIA project

- make IoT software safer
- mainly by making formal verification more affordable for this field
- How? Make it easier to apply

Use case: the Contiki Operating System

- an operating system for (low power) IoT devices
- critical module: the linked-list module

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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Observers

Update list beginning

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Observers

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Update list end

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Observers

Update list beginning

Update list end

Update list anywhere

Frama-C at a glance

frama C

Software Analyzers

- a Framework for Modular Analysis of C code
- developed at CEA List
- 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]

Deductive verification with Frama-C

The WP plugin

- based on Dijkstra's weakest precondition calculus
- verify that:
  - every function ensures its postcondition,
  - each function call respects the precondition about the input,
  - no runtime error can happen
- input: program annotated with ACSL contracts
  - precondition, postcondition, loop invariant, ...
- output: a set of verification conditions (VCs)
  - that are then transmitted to automatic/interactive provers

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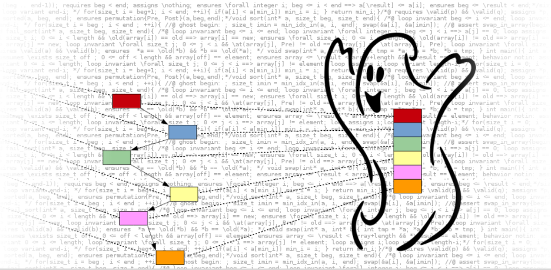
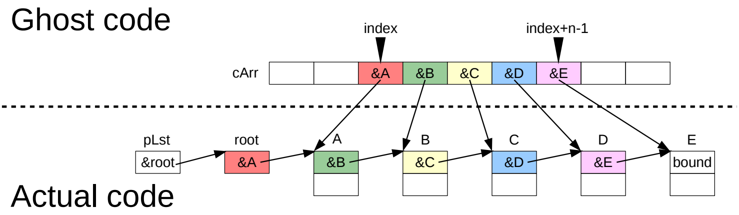
Ghosts for lists



Proof using ghost arrays [NFM 2018]



Example

```
list* list_pop(list_t pLst) /*@ ghost (list** array, int index, int size) */ {
  list* root = *pLst ;
  if(root){
    //@ ghost array_pop(pLst, array, index, size) ;
    *plst = root->next ;
  }
  return root ;
}
```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Limitations

Ghosts are still quite concrete

- we need to show that the array is **spatially separated** from the list elements
- which is **costly** for the verification process
  - about a third of the annotations are dedicated to this
  - it pollutes the proof context

Maintain equivalence

- each time we modify the list, we have to modify the content of the array
- $\Rightarrow$ **more functions to verify**

The `list_insert` function was not proved

- ... and we expected it to be **really hard** to prove because of memory separation

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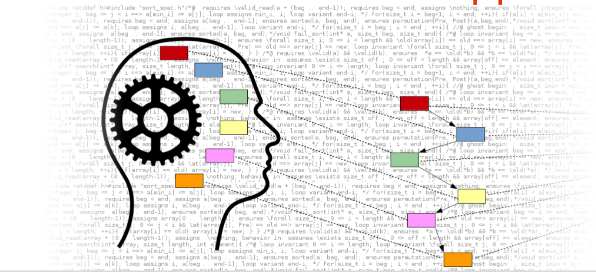
New approach: logic lists



ACSL logic lists

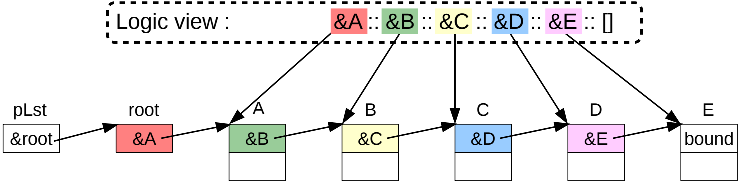
```
\let empty_list = \Nil ;
\let an_elem = \Cons(1, empty_list) ;
\let another_one = [| 2 |] ;
\let multi = [| 3, 4, 5 |] ;
\let concat = (an_elem ^ another_one ^ multi ^ [| 6, 7, 8 |]) ;
/* etc ... */
```

What is the difference with ghost arrays?

Purely logic type:

- easier to handle for SMT solvers,
  - natively handled type
  - no encoding of the C semantics (related to arrays)
- no separation property needed,
- leads to more concise specification.

Formalization I




```
/*@
  inductive linked_ll{L}(list *bl, list *el, \list<list*> ll) {
  case linked_ll_nil{L}: ∀ list *el;
    linked_ll{L}(el, el, \Nil);
  case linked_ll_cons{L}: ∀ list *bl, *el, \list<list*> tail;
    \separated(bl, el) ⇒ \valid(bl) ⇒
    linked_ll{L}(bl->next, el, tail) ⇒
    separated_from_list(bl, tail) ⇒
      linked_ll{L}(bl, el, \Cons(bl, tail));
  }
*/
```

An issue: no global \exists in contracts

A classic way to specify a list pop feature:

```
/*@ ∃ list* hd, \list<list*> l ;
  @
  @ ...
  @
  @ behavior not_empty:
  @   assumes *list ≠ NULL ;
  @   requires linked_ll(*list, NULL, \Cons(hd, l));
  @   assigns *list ;
  @   ensures \result == hd == \old(*list) ;
  @   ensures linked_ll(*list, NULL, l);
  @*/
list * list_pop(list_t list);
```

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  @   ensures linked_ll(*list, NULL, l);
  @*/
list * list_pop(list_t list);
```

ACSL does not allow to quantify variables over a contract

Formalization II

Solution: a logic function that provides the right value to solvers

```
/*@ axiomatic To_ll {
    logic \list<list*> to_ll{L}(list* bl, list* el)
      reads { e->next
            | list* e ; \valid(e) ∧ in_list(e, to_ll(bl, el)) } ;

    axiom to_ll_nil{L}: ∀ list *el ;
      to_ll{L}(el, el) == \Nil ;

    axiom to_ll_cons{L}: ∀ list *bl, *el ;
      \separated(bl, el) ⇒
      \valid(bl) ⇒
      ptr_separated_from_list(bl, to_ll{L}(bl->next, el)) ⇒
        to_ll{L}(bl, el) == (\Cons(bl, to_ll{L}(bl->next, el))) ;
  }
*/
```


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Example of contract

```
/*@ requires linked_ll(*list, NULL, to_ll(*list, NULL));
  @ assigns *list ;
  @
  @ ensures linked_ll(*list, NULL, to_ll(*list, NULL));
  @
  @ behavior empty:
  @   assumes *list == NULL ;
  @   ensures \result == NULL ;
  @
  @ behavior not_empty:
  @   assumes *list ≠ NULL ;
  @   ensures \result == \old(*list) ;
  @   ensures to_ll{Pre}(\at(*list, Pre), NULL) ==
  @           ([| \at(*list, Pre) |] ^ to_ll(*list, NULL));
  @
  @ complete behaviors; disjoint behaviors;
  @*/
list * list_pop(list_t list);
```


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Example of lemma (split a list)

```
/*@
  lemma linked_ll_split{L}:
    ∀ struct list *bl, *el, \list<struct list*> l1, l2;
      linked_ll(bl, el, l1 ^ l2) ⇒ l1 ≠ \Nil ⇒
        \let bound = \nth(l1, \length(l1) - 1)->next ;
        linked_ll(bl, bound, l1) ∧ linked_ll(bound, el, l2) ;
*/

/*@
  lemma to_logic_list_split{L}:
    ∀ struct list *bl, *el, *sep, \list<struct list*> ll;
      ll ≠ \Nil ⇒ linked_ll(bl, el, ll) ⇒
      ll == to_logic_list(bl, el) ⇒
      in_list(sep, ll) ⇒
        ll == (to_logic_list(bl, sep) ^ to_logic_list(sep, el));
*/
```

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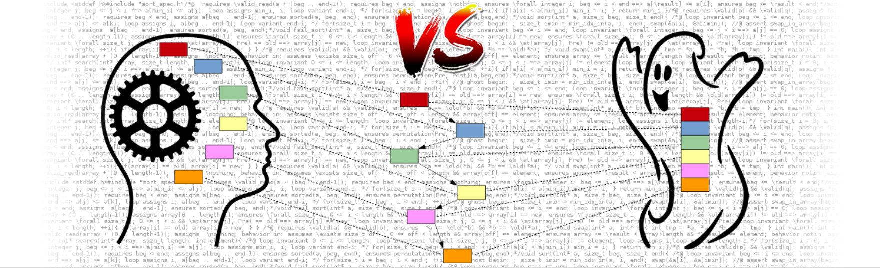
Results



The module is now entirely proved

Including the previously unproved `list_insert` function

- that we also optimized

Written annotations

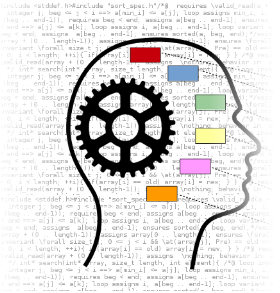
- Total: 1700 LoA (Lines of Annotations)
- 410 LoA for contracts
- 270 LoA for logic definitions and lemmas
- 1020 LoA for guiding annotations

Verification conditions (VCs)

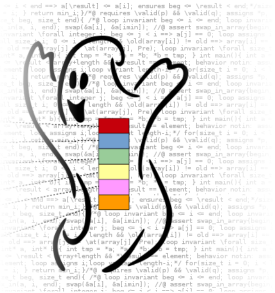
- Total: 757
- 33 for lemmas, proved using Coq
- 2 assertions needed to be proved with Coq
- all other VCs are proved automatically

Comparison of approaches

Generated verification conditions:



83	ensures	134
53	assigns	71
16	requires	69
264	guiding	399
54	RTE	108
33	Lemmas	24
503	Total	805
0.7s	Time/VC (automatic)	1.64s



(Excluding `list_insert`, not proved with the ghost approach)

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Let’s sum up!

Logic lists lead to efficient proof

The results show that with logic lists

- we are able to prove a previously unproven function (`list_insert`)
- the proof of the functions is easier
  - it requires less guiding annotations
  - VCs are discharged faster by SMT solvers
- the approach requires more lemmas
  - due to the generation of the witness for the logic list
  - these proofs are harder to write for non-experts
  - however we do not expect it to be a major problem
- it is not clear whether this approach can be made executable

Ongoing and Future work

Most recent work

- New proof (based on the ghost version) using auto-active verification [NFM 2019]

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- the difficulties with ghosts were due to memory separation
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Here comes a new challenger?

- another approach: pure observational function
- could lead to the same level of abstraction (no memory separation problem)
- while being directly executable

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Thank you for your attention!

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