Continuous Deductive Verification with Frama-C

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Continuous Verification

What problems we are trying to solve?

- Formal verification of a project (e.g., ACSL-By-Example)
    - Global logic definitions (lemmas, common predicates, …)
    - Changes in a toolchain

- Formal verification of a continuously developed project
    - Developers != Verifiers
    - Can’t be verified once and for all
    - Verified code sometimes differs from the original one
    - Need to maintain specifications to reflect code changes

Continuous Verification

What could we do?

- Continuous Integration (CI) + Verification == Continuous Verification (CV)
- Automation of proofs as much as possible
  - Auto-active verification
  - Special strategies for VCs transformations and solvers runs
  - Contradiction checking
    - Transformation (smoke detector in Why3)
    - //@ assert 0 == 1; //@ check \false;
- Frequent replays of proofs
- Tracking of differences between the original and verified code
  - In case verifiers can’t force developers to accept the verified code

Vessedia Project

- IoT Operating System (OS) Contiki
  - More than 1000 commits in 2018 by 43 authors
  - Changed more than a thousand files
  - Added 70 thousand lines of code and deleted approximately 16 thousand
- Formal verification of parts of the Contiki with Frama-C/WP
- Verified parts: AES-CCM modules, lists functions, memory allocation module
- Project: https://www.vessedia.eu/

- Towards Formal Verification of Contiki: Analysis of the AES–CCM* Modules with Frama-C. A. Peyrard, N. Kosmatov, S. Duquennoy, S. Raza
- Ghosts for Lists: A Critical Module of Contiki Verified in Frama-C. A. Blanchard, N. Kosmatov, F. Loulergue
- Formal Verification of a Memory Allocation Module of Contiki with Frama-C: a Case Study. F. Mangano, S. Duquennoy, N. Kosmatov

AstraVer Project

- Verification of a closed-source access control system
- Size of code < 10.000 SLOC
- Constant development of code
  - Started around 2014
  - Need to maintain ACSL specifications
  - Rewrote all specifications 3x times by now
- Project: http://www.ispras.ru/en/technologies/astraver_toolset/

- Deductive Verification of Unmodified Linux Kernel Library Functions. Efremov D., Mandrykin M., Khoroshilov A.

Our General Approach

- Store specifications next to the code
  - Developers could benefit from specifications
  - Store verification results of a previous run for Frama-C/WP
  - Store verification sessions for Frama-C/AstraVer(Jessie)

- For every modified function (or for all verified functions)
  1. **Extricate** it from the sources with all dependencies and specifications
  2. **Patch** the extracted code to obtain the version ready for verification
  3. **Replay** the verification
     - Compare results with existing sessions or previous results

Step 1. Extricate. Motivation (1)

Size of code

- Unsupported features of the toolset:
    - Blocks parsing: int128, asm goto, __builtin*, zero-size arrays, …
- Source code size:
    - Module size: < 10 KSLOC
    - Headers from the kernel: + 400 KSLOC (less than 100 KSLOC is relevant)
    - It takes ~20 minutes for the tools to start and generate proof obligations
- Different functions can use different settings for the verification, e.g. –wp-model ‘Typed+Cast’ instead of the default model

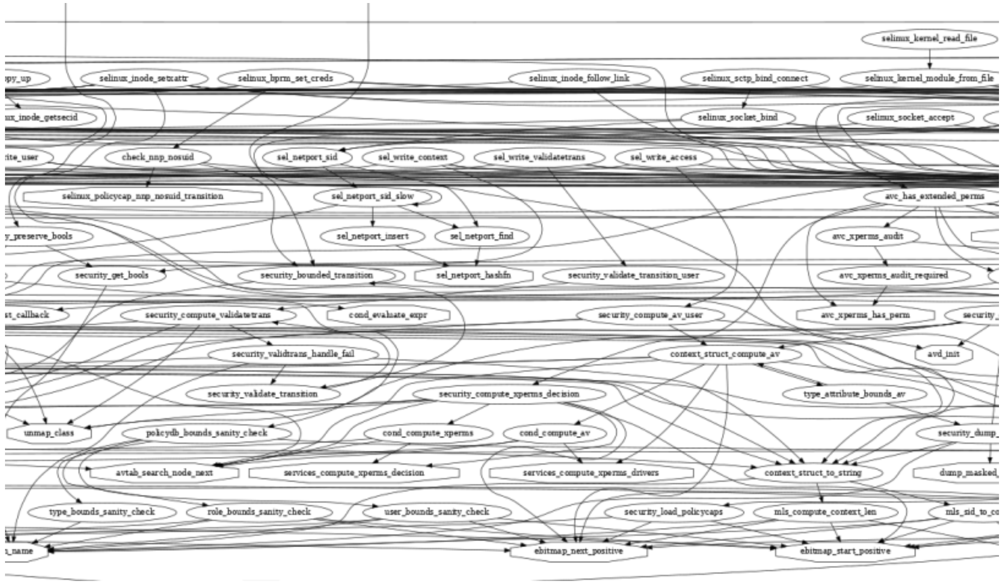
Step 1. Extricate. Motivation (2)

Size of a verification task

- Other functions may force the verification tools to include additional theories to verification tasks
  - A single bitwise operation from other function may lead to the inclusion of bitwise definitions to verification tasks
- “Unrelated” global definitions also extend verification tasks
- Sometimes it is possible to fully prove functions one by one, but it is hard to achieve the same for them together

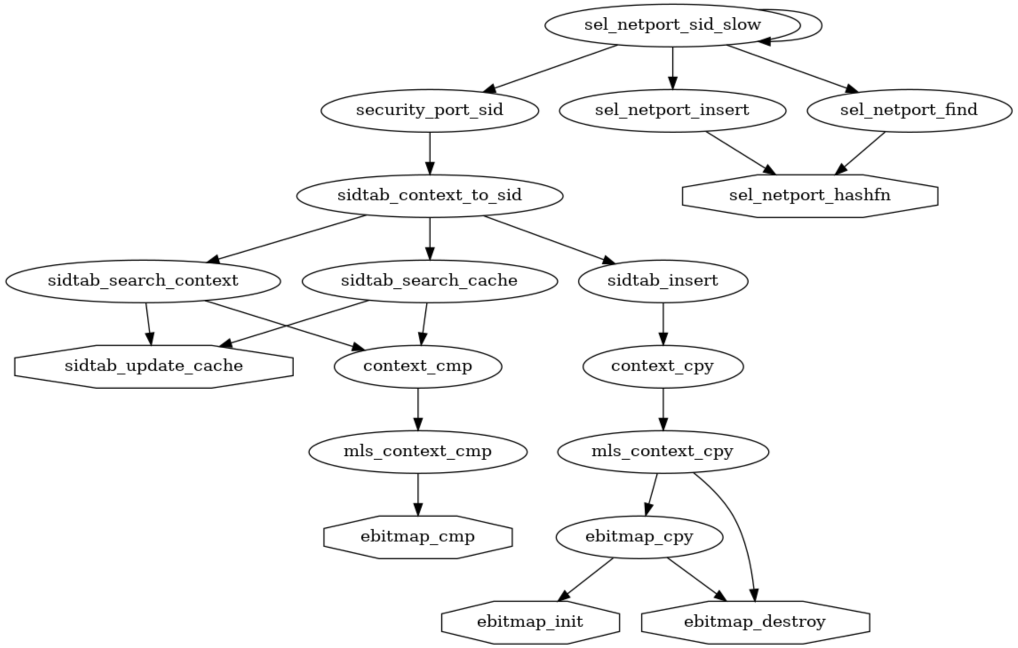
Step 1. Extricate. Implementation

SELinux Callgraph



Extricate

sel_netport_sid_slow function



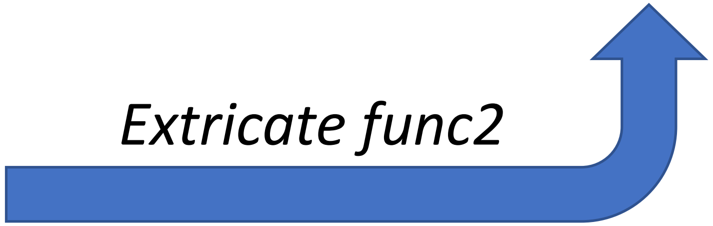
GitHub: https://github.com/evdenis/spec-utils

build passing coverage 64%

Step 1. Extricate. The example

```c
struct S1 { int a; int b; }
struct S2 { struct S1 *s; ... }

int func1(int a, int b) {
  ...
}

int func2(struct S1 *s) {
  func1(s->a, s->b);
}

int func3(struct S2 *s) {
  func1(...);
  func2(...);
}
```

```c
struct S1 { int a; int b; }


int func1(int a, int *b);



int func2(struct S1 *s) {
  func1(s->a, s->b);
}
```



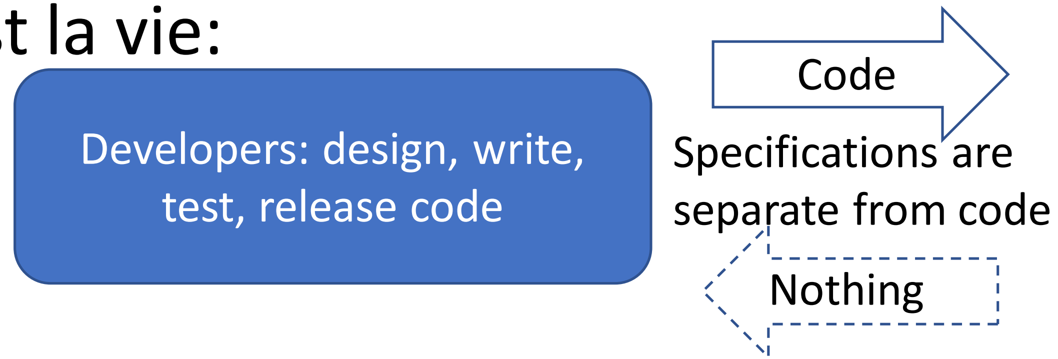
Step 2. Patch. Motivation (1)

- Not a mandatory step
- Verified Code != Original Code && Verifiers != Developers
  - verification toolset is not able to handle a code pattern
  - verification toolset does not support some verification features for now
  - verification driven refactoring
  - …
- Need to track the differences between a verified version and the original one
- **Temporary** step before either developers will accept the changes or verification toolchain will be improved
- A set of patches allows one to precisely track the issues and keep the same sources for the development and the verification
  - Don’t need to resolve merge conflicts with specifications (prevents automation) or backport the patches

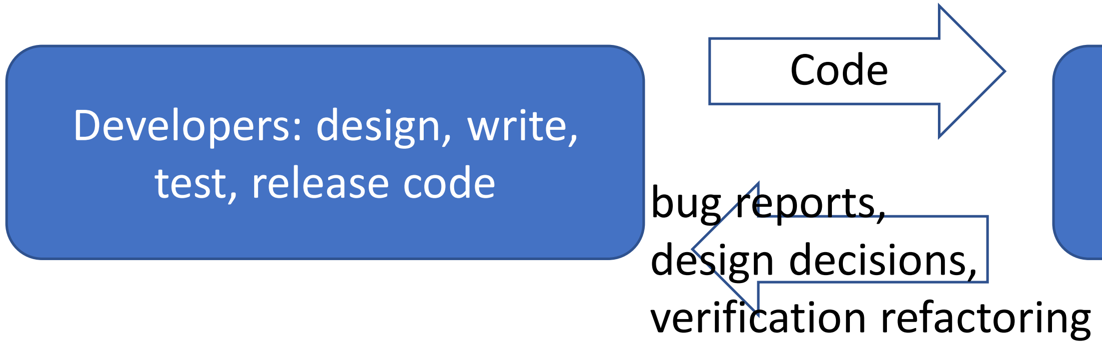
Step 2. Patch. Motivation (2)

Developers <-> Verification Engineers

C'est la vie:



Dreams for the future:



The idea of the slide was borrowed from David R. Cok presentation

Step 2. Patch. Implementation

- ACSL specifications from a verified version
  - Committed to the repository to the mainline development branch
  - Without modifications of the code
- In case the verified version of code differs
  - The modifications are local enough
  - Semantic patching. Coccinelle tool - http://coccinelle.lip6.fr/
  - Stable enough against development updates

Step 2. Patch. The example (1)

```
static void set_key(...) {
<...

-
memcpy(round_keys[0],key,AES_128_KEY_LEN
GTH);
+  for(i = 0; i < AES_128_KEY_LENGTH;
i++) {
+    round_keys[0][i] = key[i];
+  }

...>
}
```

- The set_key function from Contiki-NG os/lib/ccm-star.c
- Verified version differs from original one by “inlining” the memcpy function
- Frama-C fails to reason about non-modified version
- Developers will not accept this change

Step 2. Patch. The example (2)

```
@@
expression E;
@@

- E << 2
+ E * 4
```

- Simple patch for replacing bitwise shift
- Not easy to convince the developers to get rid of it
  - They tend to think this code looks smarter when they use it
- Makes Frama-C/WP cry

```
@set_key@
@@

- AES_128.set_key
+ set_key
```

- Function pointer
- Doesn’t supported by Frama-C for now
- Can be replaced by the direct call

Step 2. Patch. The example (3)

```
- void * list_tail(list_t list)
+ struct list * list_tail(list_t list)
{
+ int n;
  ...
- for(l = *list; l->next != NULL; l = l->next);
+ for(l = *list; l->next != NULL; l = l->next) {
+     //@ assert \valid(l);
+     //@ assert 0 <= n < \length(to_ll(*list, NULL))-1;
+     ++n;
+ }
  ...
}
```

- The list_tail function from Contiki-NG os/lib/list.c
- Replace “void *” with a concrete type
- Introduce additional local variable “n”
- Add body for the “for” loop
- Ghost expression for a loop body is not currently supported by Frama-C

Step 2. Patch. The example (4). Fail

The Original Code

```c
void list_remove(list_t list, void *item) {

  struct list *l, *r;

  if(*list == NULL) { return; }

  r = NULL;
  for(l = *list; l != NULL; l = l->next) {
    if(l == item) {
      if(r == NULL) {
        *list = l->next;
      } else {
        r->next = l->next;
      }
      l->next = NULL;
      return;
    }
    r = l;
  }
}
```

The Verified Code

```c
void list_remove(list_t list, struct list
*item) {
  if(*list == NULL) { return; }
  if(*list == item) {
    *list = (*list)->next ;
    return;
  }

  struct list *l = *list;
  int n = 0;
  while(l->next != item && l->next != NULL){
    l = l->next ;
    ++n;
  }

  if(l->next == item){
    l->next = l->next->next ;
  } else {
  }
}
```

Step 3. Replay. Implementation

- Frama-C/WP doesn’t support sessions for now
  - One needs to store the results of a previous run

- Check for results downgrade
  - Could be due to a code change by developers
  - Could be due to a global logical definitions change
  - Could be due to a verification toolchain update
  - Could be due to a server heavy load with other tasks (flickering)

- Frama-C/Jessie/Why3 replay
- Frama-C/WP run

Results

- Contiki-NG - https://github.com/evdenis/Contiki-NG
  - Extrication + Semantic patches, 50 functions
  - Replay based on a previous run
- AstraVer
  - Extrication
  - Tens of thousands verification conditions, replay takes about 6-7 hours
  - Replay based on sessions and why3 strategies
- ACSL-By-Example - https://github.com/fraunhoferfokus/acsl-by-example
  - Replay based on a previous run
- VerKer - https://github.com/evdenis/verker
  - Replay based on sessions

Questions?

How do we manage specifications

- We store specifications next to the code
  - Separate header files for axiomatizations (e.g., predicates, lemmas, logic functions)
  - Contracts for functions in headers files
  - Assertions and invariants in a body of a function
  - Approximately 2.6 lines of specification for a single line of code

- We believe that a developer could benefit from specifications
  - Even write a simple precondition
  - At least he can update a code without touching specifications