Specification and Verification of High-Level Properties

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Frama-C

A verification *framework* for C programs

- A specification language: ACSL
- A kernel to parse C and ACSL
- A large collection of collaborative plugins

frama C

Software Analyzers

ACSL is a contract-oriented specification language.

Example: The contract of a function testing if an array `T` of with `size` elements contains `x`

```
/*@
  requires \valid_read(T + (0..(size - 1)));
  ensures \result == 0 <==> \forall integer j;
    0 <= j < size ==> T[j] != x;
  assigns \nothing \from size, x, *(T + 0 .. (size - 1));
*/
int is_member(int* T, unsigned size, int x) { ... }
```

Deductive Verification with WP

```
/*@ requires \valid_read(T + (0..(size - 1)));
    ensures \result == 0 <==> \forall integer j;
        0 <= j < size ==> T[j] != x;
    assigns \nothing;
*/
int is_member(int* T, unsigned size, int x) {
    int res = 0;
    /*@ loop invariant ... */
    for(unsigned i = 0 ; i < size ; ++i) {
        /*@ assert rte: mem_access: \valid_read(T + i); */
        if(T[i] == x)
            res = 1;
    }
    return res;
}
```

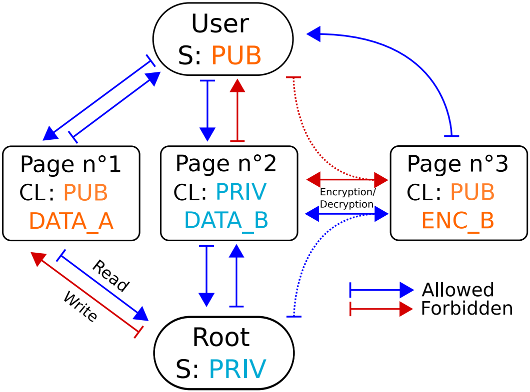
WP and deductive verification

- Brings formal guarantees when tests only increase trust
- Sound but incomplete

The Limits of ACSL: a Case Study

Confidentiality-oriented page management:

- Each page has a confidentiality level CL (PUBLIC or PRIVATE),
- Each process has a similar level,
- A process can read from (or write to) a page depending on their levels
- A process may encrypt/decrypt a page, thus changing its level



Function contracts are insufficient: need for more **global** properties

Solution: Meta-Properties

We introduce meta-properties, which are a combination of:

- **A classic property** P, expressed in ACSL.
- **A context:** The specific situation in which P must hold inside a function.
- **Target functions:** The set of functions for which P should hold in the given context.

```
meta \strong_invariant({foo,bar}), A < B;
```

"$A < B$" must hold everywhere in functions `foo` and `bar`

```
meta \writing(ALL), \written != &X;
```

No function can modify the global variable `X`

```
meta \writing(ALL), \written == &X ==> X == 0;
```

A function can only modify `X` if it was previously null

Available Contexts for Meta-Properties

- **Strong invariant:** Everywhere in the function
- **Weak invariant:** Before and after the function
- **Upon writing:** Whenever the memory is modified. The property P can use a special meta-variable `\written`, referencing the address being written to at a particular point.

```
meta \writing(ALL), \written != &X;
```

No function can modify the global variable `X`

- **Upon reading:** Similarly, when memory is read
- **Upon calling:** Similarly, when a function is called

Use of Labels in Meta-Properties

In Frama-C, predicates can refer to the value of locations at different points (labels): *Pre*, *Post*, *Here*, C labels, etc.

```
assert \at(x, Here) == \at(x, Pre);
```

`x` has the same value as when the function was called

Still true for meta-properties with two more labels: *Before* (resp. *After*), referring to state before (resp. after) any statement relevant to the context.

```
meta \writing(main), \written != &X ||
    \at(X, Before) == 0 || \at(X, After) != 0;
```

There is no statement changing `X` to 0 in `main`

Automatic Verification of Meta-properties (1/4)

Translation of meta-properties into native ACSL: leverage existing tools.

Strong invariant P: assert P when truth may change

Before and after transformation for

```
meta \strong_invariant(main), A == B;
```

A must remain equal to B at every point of main

```
void main() {
    C = 42;
    A = C;
    B = C;
}
```

```
/*@ requires A == B;
    ensures A == B;
*/
void main() {
    C = 42;
    A = C;
    //@ assert A == B; //Failure
    B = C;
    //@ assert A == B;
}
```

`lenient` delimiter:

- Combines strong and weak invarant
- Allows to break the invariant locally

Automatic Verification of Meta-properties (2/4)

Upon writing: detect modification sites by syntactic analysis

Before and after transformation for

`meta \writing(main), \written != &C;`

`main` cannot modify C

```
void main() {
    C = 42;
    A = C;
    B = C;
}
```

```
void main() {
    //@ assert &C != &C; //Failure
    C = 42;
    //@ assert &A != &C;
    A = C;
    //@ assert &B != &C;
    B = C;
}
```

Performance: discard any obvious assertion to avoid overloading the proof

Automatic Verification of Meta-properties (3/4)

After/Before labels: refer to local C labels

Before and after transformation for

```
meta \writing(main), \written != &X ||
    \at(X, Before) == 0 || \at(X, After) != 0;
```

There is no statement changing `X` to 0 in `main`

```
void main() {
    X = X;
    X = 4;
    X = 0;
}
```

```
void main() {
    _meta_1: X = X;
    /*@ assert \at(X, _meta_1) == 0
        || \at(X, Here) != 0; */
    _meta_2: X = 4;
    /*@ assert \at(X, _meta_2) == 0
        || \at(X, Here) != 0; */
    _meta_3: X = 0;
    /*@ assert \at(X, _meta_3) == 0
        || \at(X, Here) != 0; */
    //Failure
}
```

Automatic Verification of Meta-properties (4/4)

Specification-only functions: use *assigns* clause for *writing* context

```
/*@
    behavior BA:
      assumes PA(params);
      assigns XA1, XA2;
    behavior BB:
      assumes PB(params);
      assigns XB;
*/
extern void g(params);

void f() {
    g(act_params);
}

/*@ meta \writing(f),
    \written != &glob;
*/
```

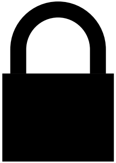
```
/*@
    behavior BA:
      assumes PA(params);
      assigns XA1, XA2;
    behavior BB:
      assumes PB(params);
      assigns XB;
*/
extern void g(params);

void f() {
    g(act_params);
    /*@ assert PA(act_parms)
          ⇒ &XA1 != &glob; */
    /*@ assert PA(act_parms)
          ⇒ &XA2 != &glob; */
    /*@ assert PB(act_parms)
          ⇒ &XB != &glob; */
}
```

Back to the Confidentiality Case Study

The confidentiality case study was:

- Implemented in C
- Partially specified with ACSL contracts
- Fully specified with meta-properties



Some of the meta-properties:

- Public allocated pages cannot be modified by private agents
- Confidentiality levels can only be modified by encryption/decryption
- Unallocated pages cannot be read from
- Only the allocation/deallocation functions can change the status of a page

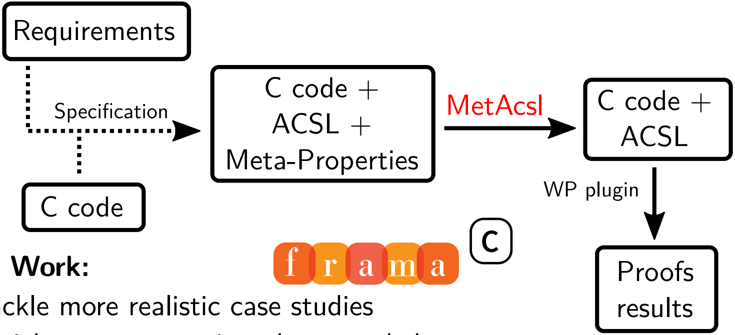
Verification results:

- Transformation time: < 5s
- 290 proof obligations
- Automatically proved in ≈ 1m with Alt-Ergo

Conclusion

Contributions:

- More expressive power: see case study
- High-level view of properties established on a software module
- Ease development: automatically check if a property is maintained after an update (of the code or of a function contract)



Future Work:

- Tackle more realistic case studies
- Enrich meta-properties where needed
- Prove soundness of transformation

Conclusion

Contributions:

- More expressive power: see case study
- High-level view of properties established on a software module
- Ease development: automatically check if a property is maintained after an update (of the code or of a function contract)

For more details, see:

- *MetAcsl: Specification and Verification of High-Level Properties*, (submitted for TACAS 2019, arXiv:1811.10509)
- `https://github.com/Firobe/metacsl_examples`