Playing spy games in Iris

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Contents

A family of related algorithms for computing the *least solution* of a system of recursive equations:

- Le Charlier and Van Hentenryck (1992).
- Vergauwen and Lewi (1994).
- Fecht and Seidl (1999) coin the term "local generic solver".
- F. P. (2009) releases Fix and asks how to *verify* it.

API of a solver

A solver computes the *least fixed point* of a user-supplied monotone second-order function:

```
type valuation = variable -> property
val lfp: (valuation -> valuation) -> valuation
```

`lfp eqs` returns a function `phi` that purports to be the least fixed point.

We are interested in *on-demand, incremental, memoizing* solvers.

Nothing is computed until `phi` is applied to a variable `v`. *Minimal work* is then performed: the least fixed point is computed at `v` and at the variables that `v` *depends* upon. It is memoized to avoid recomputation. Dependencies are discovered at runtime via *spying*.

A challenge

F. P. (2009) offers the verification of a local generic solver as a *challenge*.

Why is it difficult?

A solver offers a pure API, yet uses mutable internal state:

- for memoization – use a lock and its invariant;

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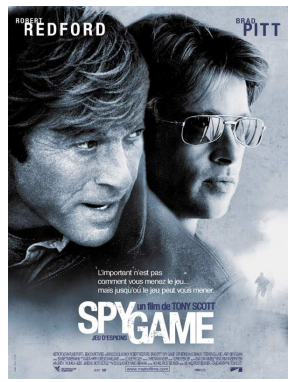

Why is it difficult?

A solver offers a pure API, yet uses mutable internal state:

- for memoization – use a lock and its invariant;
- for *spying* on the user-supplied function `eqs`.

In short, we want a *modular* specification in higher-order separation logic:

$$\mathcal{E} \text{ is monotone } \Rightarrow$$
$$\{\mathit{eqs}\ \mathit{implements}\ \mathit{flip}\,\mathcal{E}\}$$
$$\mathit{lfp}\ \mathit{eqs}$$
$$\{\mathit{get}.\ \mathit{get}\ \mathit{implements}\ \bar{\mu}\mathcal{E}\}$$

$\bar{\mu}\mathcal{E}$ is *the optimal least fixed point of* $\mathcal{E}$.

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The essence of spying can be distilled in a single combinator, `modulus`, so named by Longley (1999).

```
val modulus:
  (('a -> 'b) -> 'c              ) ->
  (('a -> 'b) -> 'c * ('a list))
```

The call "`modulus ff f`" returns a *pair* of

- the result of the call "`ff f`", and
- the list of arguments with which `ff` has queried `f` during this call.

This is a complete list of points on which `ff` *depends*.

Here is a simple-minded imperative implementation of `modulus`:

```
let modulus ff f =
  let xs = ref [] in
  let spy x =
    (* Record a dependency on x: *)
    xs := x :: !xs;
    (* Forward the call to f: *)
    f x
  in
  let c = ff spy in
  (c, !xs)
```

Longley (1999) gives this code and claims (without proof) that it has the desired denotational semantics in the setting of a pure λ-calculus.

Specification of modulus

What is a plausible specification of `modulus`?

$$\{f \textit{ implements } \phi * \textit{ff implements } \mathcal{F}\}$$
$$\textit{modulus ff f}$$
$$\{(c, ws).\ \lceil c = \mathcal{F}(\phi) \rceil\}$$

The postcondition means that c is the result of the call "`ff f`"...

"f *implements* ϕ" is sugar for the triple $\forall x.\ \{\textit{true}\}\ f\ x\ \{y.\ \lceil y = \phi(x) \rceil\}$.

"$\textit{ff implements } \mathcal{F}$" means $\forall f, \phi.\ \{f \textit{ implements } \phi\}\ \textit{ff}\ f\ \{c.\ \lceil c = \mathcal{F}(\phi) \rceil\}$.

What is a plausible specification of `modulus`?

$$\{f \textit{ implements } \phi * \mathit{ff} \textit{ implements } \mathcal{F}\}$$
$$\mathit{modulus}\ \mathit{ff}\ f$$
$$\{(c, ws).\ \lceil \forall \phi'.\ \phi' =_{ws} \phi \Rightarrow c = \mathcal{F}(\phi') \rceil\}$$

The postcondition means that c is the result of the call "`ff f`"... *and that `c` does not depend on the values taken by `f` outside of the list `ws`.*

"f *implements* ϕ" is sugar for the triple $\forall x.\ \{\mathit{true}\}\ f\ x\ \{y.\ \lceil y = \phi(x) \rceil\}$.

"ff *implements* $\mathcal{F}$" means $\forall f, \phi.\ \{f \textit{ implements } \phi\}\ \mathit{ff}\ f\ \{c.\ \lceil c = \mathcal{F}(\phi) \rceil\}$.

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Why verifying modulus seems challenging

```
let modulus ff f =
  let xs = ref [] in
  let spy x =
    xs := x :: !xs; f x
  in let c = ff spy in
  (c, !xs)
```

$$\{f \textit{ implements } \phi * \textit{ff implements } \mathcal{F}\}$$
$$\textit{modulus ff f}$$
$$\{(c, ws).\ \lceil \forall \phi'.\ \phi' =_{ws} \phi \Rightarrow c = \mathcal{F}(\phi') \rceil\}$$

`ff` expects an *apparently pure* function as an argument, so we *must* prove "*spy implements* ϕ'" for *some* ϕ', and we will get $c = \mathcal{F}(\phi')$. However,

- Proving $c = \mathcal{F}(\phi')$ for *one* function ϕ' is not good enough. It seems as though as we need *spy* to implement *all* functions ϕ' *at once*.
- The set of functions ϕ' over which we would like to quantify is *not known in advance* — it depends on `ws`, a *result* of `modulus`.
- What invariant describes `xs`? *Only in the end* does it hold a *complete* list `ws` of dependencies.

Ingredients of a solution

- We need *spy* to implement all functions ϕ' at once...
- The list `ws` is not known in advance...
- What invariant describes `xs`?

Ingredients of a solution

- We need *spy* to implement all functions ϕ' at once...
  — Use a *conjunction rule* to focus on one function ϕ' at a time.
- The list `ws` is not known in advance...

- What invariant describes `xs`?

Ingredients of a solution

- We need *spy* to implement all functions ϕ' at once...
  — Use a *conjunction rule* to focus on one function ϕ' at a time.
- The list `ws` is not known in advance...
  — Use a *prophecy variable* to name this list ahead of time.
- What invariant describes `xs`?

Ingredients of a solution

- We need *spy* to implement all functions ϕ' at once...
  — Use a *conjunction rule* to focus on one function ϕ' at a time.
- The list `ws` is not known in advance...
  — Use a *prophecy variable* to name this list ahead of time.
- What invariant describes `xs`?
  — The elements *currently recorded* in `!xs`, concatenated with those that *will be recorded* in the future, form the list `ws`.

Past, present and future in Hoare Logic

In Hoare Logic and Separation Logic, assertions describe the *current* state.

- e.g., "at this point, `!xs` is the empty list `[]`"

The current state, possibly enriched with *ghost state*, reflects the *past*.

There is no way of talking about the *future!*

Past, present and future in Hoare Logic

In Hoare Logic and Separation Logic, assertions describe the *current* state.

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The current state, possibly enriched with *ghost state*, reflects the *past*.

There is no way of talking about the *future!*

Enter *prophecy variables* (Abadi and Lamport 1988; Jung et al. 2020).

A *ghost variable* with three operations: allocation, assignment, disposal.

The reasoning rules allow referring to the sequence *xs* of *future writes*.

Prophecy Allocation

$$\{\mathit{true}\}\ \mathit{newProph}()\ \{p.\ \exists \mathit{xs}.\ p \text{ will receive } \mathit{xs}\}$$

Prophecy Assignment

$$\{p \text{ will receive } \mathit{xs}\}\ \mathit{resolveProph}\ p\ x\ \left\{().\ \exists \mathit{xs}'.\ \begin{array}{l}\ulcorner \mathit{xs} = x :: \mathit{xs}' \urcorner \\ p \text{ will receive } \mathit{xs}'\end{array}\right\}$$

Prophecy Disposal

$$\{p \text{ will receive } \mathit{xs}\}\ \mathit{disposeProph}\ p\ \{().\ \ulcorner \mathit{xs} = [] \urcorner\}$$

A weaker specification for modulus

Instead of establishing this *strong* specification for `modulus`...

$$\left(\begin{array}{c} \{f \ \mathit{implements}\ \phi * \mathit{ff}\ \mathit{implements}\ \mathcal{F}\} \\ \mathit{modulus}\ \mathit{ff}\ f \\ \{(c, ws).\ \lceil \forall \phi'.\ \phi' =_{ws} \phi \Rightarrow c = \mathcal{F}(\phi') \rceil\} \end{array}\right)$$

A weaker specification for modulus

$$\forall \phi'. \left(\begin{array}{c} \{f \ \mathit{implements}\ \phi * \mathit{ff}\ \mathit{implements}\ \mathcal{F}\} \\ \mathit{modulus}\ \mathit{ff}\ f \\ \{(c, ws).\ \lceil \quad \phi' =_{ws} \phi \Rightarrow c = \mathcal{F}(\phi') \rceil\} \end{array} \right)$$

...let us first establish a *weaker* specification.

Then (later), use an infinitary *conjunction rule* to argue (roughly) that the weaker spec implies the stronger one.

Assume ϕ' is given.

```
let modulus ff f =
  let xs, p, lk = ref [], newProph(), newLock() in
  let spy x =
    let y = f x in
    withLock lk (fun () ->
      xs := x :: !xs; resolveProph p x);
    y
  in
  let c = ff spy in
  acquireLock lk; disposeProph p; (c, !xs)
```

Step 1. Allocate a prophecy variable p.
Introduce the name *ws* to stand for the list of *future writes* to p.

Assume ϕ' is given.

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let modulus ff f =
  let xs, p, lk = ref [], newProph(), newLock() in
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  let c = ff spy in
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```

Step 2. Allocate a lock *lk*, which owns *xs* and *p*. Its invariant is that the list *ws* of *all writes* to *p* can be split into two parts:

- the *past writes*, the reverse of the current contents of *xs*;
- the remaining *future writes* to *p*.

Assume ϕ' is given.

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let modulus ff f =
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Step 2. Allocate a lock *lk*, which owns *xs* and *p*. Its invariant is that the list *ws* of *all writes* to *p* can be split into two parts:

- the *past writes*, the reverse of the current contents of *xs*;
- the remaining *future writes* to *p*.

Moving *x* from one part to the other preserves the invariant.

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  let c = ff spy in
  acquireLock lk; disposeProph p; (c, !xs)
```

Because *acquireLock* exhales the invariant and *disposeProph* guarantees there are no more future writes, !*xs* on the last line yields *ws* (reversed).

Thus, the name *ws* in the postcondition of *modulus* and the name *ws* introduced by *newProph* denote *the same set* of points.

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let modulus ff f =
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    y
  in
  let c = ff spy in
  acquireLock lk; disposeProph p; (c, !xs)
```

Step 3. Reason by cases:

- If $\phi' =_{ws} \phi$ does *not* hold, then the postcondition of *modulus* is *true*. Then, it suffices to prove that *modulus* is *safe*, which is not difficult.
- If $\phi' =_{ws} \phi$ does hold, continue on to the next slides...

Assume ϕ' is given. Assume $\phi' =_{ws} \phi$ holds.

```
  let modulus ff f =
    let xs, p, lk = ref [], newProph(), newLock() in
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      let y = f x in
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```

Step 4. Prove that *spy implements* ϕ'.

- We have $y = \phi(x)$. We wish to prove $y = \phi'(x)$.

Assume ϕ' is given. Assume $\phi' =_{ws} \phi$ holds.

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```

Step 4. Prove that *spy implements* ϕ'.

- We have $y = \phi(x)$. We wish to prove $y = \phi'(x)$.
- Because ϕ and ϕ' coincide on *ws*, the goal boils down to $x \in ws$.

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```

Step 4. Prove that *spy implements* ϕ'.

- We have $y = \phi(x)$. We wish to prove $y = \phi'(x)$.
- Because ϕ and ϕ' coincide on *ws*, the goal boils down to $x \in ws$.
- $x \in ws$ holds *because we make it hold* by writing x to p.
  — "there, let me bend reality for you"

Assume ϕ' is given. Assume $\phi' =_{ws} \phi$ holds.

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→ let c = ff spy in
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```

Step 5. From "*ff implements* $\mathcal{F}$" and "*spy implements* ϕ'", deduce that the call "*ff spy*" is permitted and that $c = \mathcal{F}(\phi')$ holds.

$c = \mathcal{F}(\phi')$ is the postcondition of *modulus*. We are done!

Contents

Recall that, from this *weak* specification of *modulus*...

$$\forall \phi'. \left(\begin{array}{c} \{f \ \mathit{implements}\ \phi * \mathit{ff}\ \mathit{implements}\ \mathcal{F}\} \\ \mathit{modulus}\ \mathit{ff}\ f \\ \{(c, ws).\ \lceil \quad \phi' =_{ws} \phi \Rightarrow c = \mathcal{F}(\phi') \rceil\} \end{array} \right)$$

$$\left(\begin{array}{c} \{f \ \mathit{implements}\ \phi * \mathit{ff} \ \mathit{implements}\ \mathcal{F}\} \\ \mathit{modulus}\ \mathit{ff}\ f \\ \{(c, ws).\ \lceil \forall \phi'.\ \phi' =_{ws} \phi \Rightarrow c = \mathcal{F}(\phi') \rceil\} \end{array}\right)$$

...we need to deduce this *stronger* specification.

This is where an infinitary *conjunction rule* is needed.

An array of conjunction rules

Binary, Non-Dependent

$$\frac{\{P\}\ e\ \{\_.\ \lceil Q_1 \rceil\} \qquad \{P\}\ e\ \{\_.\ \lceil Q_2 \rceil\}}{\{P\}\ e\ \{\_.\ \lceil Q_1 \wedge Q_2 \rceil\}}$$

Binary, Dependent

$$\frac{\{P\}\ e\ \{y.\ \lceil Q_1\ y \rceil\} \qquad \{P\}\ e\ \{y.\ \lceil Q_2\ y \rceil\}}{\{P\}\ e\ \{y.\ \lceil Q_1\ y \wedge Q_2\ y \rceil\}}$$

Infinitary, Non-Dependent

$$\frac{\forall x.\ \{P\}\ e\ \{\_.\ \lceil Q\ x \rceil\}}{\{P\}\ e\ \{\_.\ \lceil \forall x. Q\ x \rceil\}}$$

Infinitary, Dependent

$$\frac{\forall x.\ \{P\}\ e\ \{y.\ \lceil Q\ x\ y \rceil\}}{\{P\}\ e\ \{y.\ \lceil \forall x. Q\ x\ y \rceil\}}$$

The non-dependent variants are *sound*.

The dependent variants may be sound (*open question!*).
We can derive an approximation that's good enough for our purposes.

An unsound conjunction rule

All of the previous rules are restricted to *pure* postconditions.

An unrestricted conjunction rule is *unsound* in the presence of ghost state.

$$\textsc{Impure (Unsound!)}\quad \frac{\{P\}\ e\ \{\_.\ Q_1\} \qquad \{P\}\ e\ \{\_.\ Q_2\}}{\{P\}\ e\ \{\_.\ Q_1 \wedge Q_2\}}$$

Open question!

Would this rule be sound if every ghost update was apparent in the code?

Proof outline — infinitary, non-dependent case

Hypothesis: $\forall x.\ \{P\}\ e\ \{\_.\ \lceil Q\,x \rceil\}$
Goal: $\{P\}\ e\ \{\_.\ \lceil \forall x.\ Q\,x \rceil\}$

$$\{P\}$$

Proof outline — infinitary, non-dependent case

Hypothesis: $\forall x.\ \{P\}\ e\ \{\_.\ \lceil Q\,x\rceil\}$
Goal: $\{P\}\ e\ \{\_.\ \lceil \forall x.\ Q\,x\rceil\}$

$$\{P\}$$

Case split: $(\forall x.\ Q\ x) \quad \vee \quad (\exists x.\ \neg\ Q\ x)$

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$$\{P\}$$

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$$\{P * \lceil\forall x.\ Q\ x\rceil\}$$
$$e$$
$$\{\lceil\forall x.\ Q\ x\rceil\}$$

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$$\{P\}$$

Case split: $(\forall x.\ Q\ x) \quad \vee \quad (\exists x.\ \neg\ Q\ x)$

$$\{P * \lceil\forall x.\ Q\ x\rceil\}$$
$$e$$
$$\{\lceil\forall x.\ Q\ x\rceil\}$$

$$\{P * \lceil\exists x.\ \neg\ Q\ x\rceil\}$$
$$\{\exists x.\ P * \lceil\neg\ Q\ x\rceil\}$$
$$e$$
$$\{\exists x.\ \lceil Q\ x\rceil * \lceil\neg\ Q\ x\rceil\}$$

Proof outline — infinitary, non-dependent case

Hypothesis: $\forall x.\ \{P\}\ e\ \{\_.\ \lceil Q\,x\rceil\}$
Goal: $\{P\}\ e\ \{\_.\ \lceil\forall x.\ Q\,x\rceil\}$

$$\{P\}$$

Case split: $(\forall x.\ Q\ x) \quad \vee \quad (\exists x.\ \neg\ Q\ x)$

$$\{P * \lceil\forall x.\ Q\ x\rceil\}$$
$$e$$
$$\{\lceil\forall x.\ Q\ x\rceil\}$$

$$\{P * \lceil\exists x.\ \neg\ Q\ x\rceil\}$$
$$\{\exists x.\ P * \lceil\neg\ Q\ x\rceil\}$$
$$e$$
$$\{\exists x.\ \lceil Q\ x\rceil * \lceil\neg\ Q\ x\rceil\}$$
$$\{\ \mathit{false}\ \}$$

Proof outline — infinitary, non-dependent case

Hypothesis: $\forall x.\ \{P\}\ e\ \{\_.\ \lceil Q\,x\rceil\}$
Goal: $\{P\}\ e\ \{\_.\ \lceil\forall x.\ Q\,x\rceil\}$

$$\{P\}$$

Case split: $(\forall x.\ Q\ x) \quad \vee \quad (\exists x.\ \neg\ Q\ x)$

$$\{P * \lceil\forall x.\ Q\ x\rceil\}$$
$$e$$
$$\{\lceil\forall x.\ Q\ x\rceil\}$$

$$\{P * \lceil\exists x.\ \neg\ Q\ x\rceil\}$$
$$\{\exists x.\ P * \lceil\neg\ Q\ x\rceil\}$$
$$e$$
$$\{\exists x.\ \lceil Q\ x\rceil * \lceil\neg\ Q\ x\rceil\}$$
$$\{\ \mathit{false}\ \}$$
$$\{\ \lceil\forall x.\ Q\ x\rceil\ \}$$

Same idea, but a *prophecy variable* must be used to name y ahead of time and allow the case split $(\forall x.\, Q\, x\, y) \vee \neg(\forall x.\, Q\, x\, y)$.

$$\textsc{Infinitary, Dependent}\quad \frac{\forall x.\, \{P\}\ e\ \{y.\, \lceil Q\, x\, y \rceil\}}{\{P\}\ e'\ \{y.\, \lceil \forall x. Q\, x\, y \rceil\}}$$

Because of this, e' in the conclusion is a copy of e instrumented with *newProph* and *resolveProph* instructions. (Ouch.)

Contents

- Extension of Iris's prophecy API: *disposeProph*; typed prophecies.
- Proof of the conjunction rule.
- Specification and proof of *modulus*.
- Specification and proof of a slightly simplified version of Fix:

$$\begin{array}{c} \mathcal{E} \text{ is monotone } \Rightarrow \\ \{\mathit{eqs}\ \mathit{implements}\ \mathit{flip}\,\mathcal{E}\} \\ \mathit{lfp}\,\mathit{eqs} \\ \{\mathit{get}.\ \mathit{get}\ \mathit{implements}\ \bar{\mu}\mathcal{E}\} \end{array}$$

where $\bar{\mu}\mathcal{E}$ is *the optimal least fixed point of* $\mathcal{E}$.

Limitations

A few optimizations are missing, e.g.,

- Fix uses a more efficient representation of the dependency graph.

Caveats:

- Termination is not proved.
- Deadlock-freedom is not proved.

Wishes:

- Is there any way of *not* polluting the code with operations on prophecy variables?

Take-home messages

Spying is another archetypical use of hidden state.

Prophecy variables are fun,
and they can be useful not just in concurrent code,
but also in *sequential code*.

Contents

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