Let's try to understand (part of) Iris

Willem Penninckx

The Paper

Iris: Monoids and Invariants as an Orthogonal Basis for Concurrent Reasoning

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DISCLAIMER

I'm not an expert

Concurrency is about shared state

Situation	**Shared state**	**Verify this**
Shared memory	Memory	No secret overwrites, Counter only increases
Message-passing	Network	Protocol
Input/output	Filesystems, Humans, ...	Protocol

How to verify when there's concurrency?

> “ ”
>
> Monoids and invariants are all you need
>
> – Iris

Invariant:
assertion about shared state

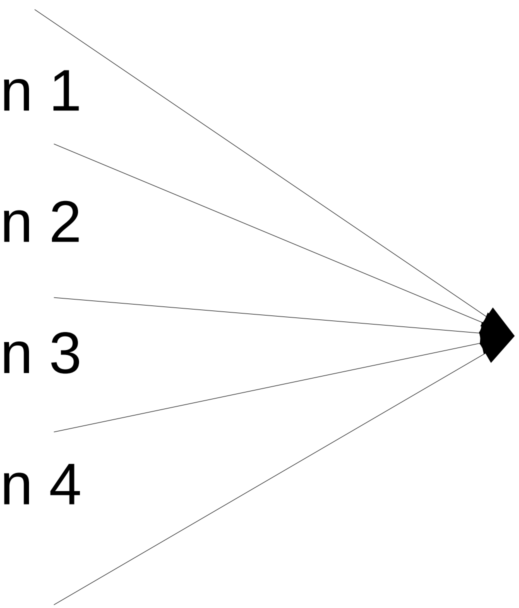
Thread 1:

Atomic operation 1

Atomic operation 2

Atomic operation 3

Atomic operation 4



Assertion holds

(Iris-style) Monoid

“error” element

Commutative binary operator

$$\mathrm{Nat} = (\mathbb{N} \cup \{\bot\}, \bot, 0, +_{\mathbb{N}})$$

Name of
the monoid

Set

$\mathrm{Neutral\ element}(n +_{\mathbb{N}} 0 = n)$

“Case study”: Verification + concurrency + heap

Proglang:
v = malloc()
v1 = !v2
v1 := v2
v1 = v2

Attempt #1

Invariant, e.g.: $\exists h \in \text{Heaps}. \lfloor h \rfloor$

GLOBAL physical state is h

$$M_{\text{h}} = (\text{Heaps} \cup \{\bot\}, \bot, \text{emptyheap}, \cdot_{\text{h}})$$

$$\{h : \text{Locations} \rightharpoonup \text{Values}\}$$

$$\{1 \mapsto 2\} \cdot_h \{7 \mapsto 8\} = \{1 \mapsto 2, 7 \mapsto 8\}$$

$$\{1 \mapsto 2\} \cdot_h \bot = \bot$$

$$\{1 \mapsto 2\} \cdot_h \{1 \mapsto 2\} = \bot$$

Thread 1:

v1 = malloc()

v1 := 7

$\exists h \in \mathrm{Heaps}. \lfloor h \rfloor$

"$\mathit{v1} \mapsto 7$" ?

“partial knowledge” in monoid

$M_a = ($

Set $|M_a|$

$, \perp, \ldots, \cdot_a)$

“partial knowledge” in monoid

Local partial knowledge

$$M_a = (\{\perp\} \cup \{(g, l) \mid \ldots$$

$$\ldots$$

$$\ldots$$

$$, \perp, \ldots, \cdot_a)$$

Global knowledge

“partial knowledge” in monoid

Local partial knowledge

$$M_a = (\{\bot\} \cup \{(g, l) \mid \begin{array}{l} g \in \mathrm{Heaps} \cup \{\epsilon_g\} \\ l \in \mathrm{Heaps} \\ \cdots \end{array}$$

No global knowledge

$$, \bot, \ldots, \cdot_a)$$

Global knowledge

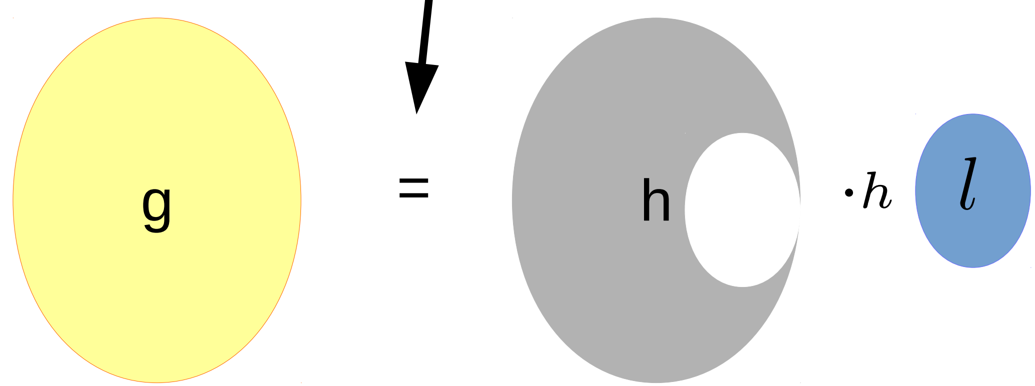
“partial knowledge” in monoid

Local partial knowledge

$$M_a = (\{\perp\} \cup \{(g, l) \mid g \in \text{Heaps} \cup \{\epsilon_g\}$$
$$l \in \text{Heaps}$$
$$g \neq \epsilon_g \rightarrow \exists h.\ g = h \cdot_h l\}$$
$$, \perp, \ldots, \cdot_a)$$

No global knowledge

Global knowledge



“partial knowledge” in monoid

$$M_a = (\{\bot\} \cup \{(g,l)|\; \begin{array}{l} g \in \mathrm{Heaps} \cup \{\epsilon_g\} \\ l \in \mathrm{Heaps} \\ g \neq \epsilon_g \to \exists h.\; g = h \cdot_h l\} \end{array}$$

$$, \bot, \ldots, \cdot_a)$$

Exercise: what does this mean?

$$(\epsilon_g, \mathrm{emptyheap})$$

$$(\epsilon_g, (1 \mapsto 2, 102 \mapsto 7))$$

$$((1 \mapsto 2, 102 \mapsto 7), (1 \mapsto 2, 102 \mapsto 7))$$

$$(\mathrm{emtyheap}, \mathrm{emtyheap})$$

$$M_a = (\{\bot\} \cup \{(g,l) |\; g \in \text{Heaps} \cup \{\epsilon_g\}$$
$$l \in \text{Heaps}$$
$$g \neq \epsilon_g \to \exists h.\; g = h \cdot_h l\}$$
$$, \bot, \ldots, \cdot_a)$$

$$(\epsilon_g, l_1) \cdot_a (g, l_2) = (g, l_1 \cdot_h l_2) \textbf{ if } (g, l_1 \cdot_h l_2) \in |M_a| \backslash \{\bot\}$$
$$m_1 \cdot_a m_2 = \bot \textbf{ other cases}$$

Note: in paper composition
Is just pointwise
(so (\eps, l1) . (\eps l2) is not always \bot)

Exercise: what is the neutral element?

Thread 1:

v1 = malloc()

$\exists h \in \mathrm{Heaps}. \lfloor h \rfloor$

v1 := 7

“$v1 \mapsto 7$” ?

Thread 1:

v1 = malloc()

v1 := 7

$\exists h \in \text{Heaps}. \boxed{(h, \text{emptyheap})} * \lfloor h \rfloor$

$\cancel{\exists h \in \text{Heaps}. \lfloor h \rfloor}$

$\boxed{(\epsilon_g, \{\mathit{v1} \mapsto 7\})}$

Link with physical?

Combined:

$$\boxed{(\epsilon_g, \{\mathit{v1} \mapsto 7\})} * \exists h \in \text{Heaps}. \boxed{(h, \text{emptyheap})} * \lfloor h \rfloor$$

$$= \exists h \in \text{Heaps}. \boxed{(\epsilon_g, \{\mathit{v1} \mapsto 7\}) \cdot_a (h, \text{emptyheap})} * \lfloor h \rfloor$$

$$= \exists h \in \text{Heaps}. \boxed{(h, \{\mathit{v1} \mapsto 7\})} * \lfloor h \rfloor$$

Know $\mathit{v1} \mapsto 7$ in physical state!

Let's prove

$$\left\{\boxed{(\epsilon_g, \{v1 \mapsto 0\})}\right\} \text{ v1 := 7 } \left\{\boxed{(\epsilon_g, \{v1 \mapsto 7\})}\right\}_{\{\iota\}}$$

Our invariant holds

Strategy

- Open invariant
- Combine thread's ghost state with invar's
  - $\boxed{\mathrm{m}_1} * \boxed{\mathrm{m}_2} = \boxed{\mathrm{m}_1 . m_2}$ → Know $a \mapsto \_$ in physical state!
- Do physical update
  - $$\frac{}{\{\lfloor h[a \mapsto v_2] \rfloor\} \quad a := v_2 \; \{\lfloor h[a \mapsto v_2] \rfloor\}}$$
- Do ghost update
- Split thread's ghost state and invar's
- Close invariant

$$\left\{ \boxed{(\epsilon_g, \{\mathit{v1} \mapsto 0\})} \right\}$$

$$\left\{ \boxed{(\epsilon_g, \{\mathit{v1} \mapsto 0\})} * \exists h \in \mathrm{Heaps}. \boxed{(h, \mathrm{emptyheap})} * \lfloor h \rfloor \right\}$$

$$\left\{ \exists h \in \mathrm{Heaps}. \boxed{(\epsilon_g, \{\mathit{v1} \mapsto 0\}) \cdot_a (h, \mathrm{emptyheap})} * \lfloor h \rfloor \right\}$$

$$\left\{ \exists h \in \mathrm{Heaps}. \boxed{(h, \{\mathit{v1} \mapsto 0\})} * \lfloor h \rfloor \right\}$$

$$\left\{ \boxed{(h'[v1 \mapsto 0], \{\mathit{v1} \mapsto 0\})} * \lfloor h'[v1 \mapsto 0] \rfloor \right\}$$

frame

Phys. Upd

$$\left\{ \lfloor h'[v1 \mapsto 0] \rfloor \right\}$$

v1 := 7

$$\left\{ \lfloor h'[v1 \mapsto 7] \rfloor \right\}$$

$$\left\{ \boxed{(h'[v1 \mapsto 0], \{\mathit{v1} \mapsto 0\})} * \lfloor h'[v1 \mapsto 7] \rfloor \right\}$$

Need to update ghost state to close invar

$$\left\{\boxed{(\mathrm{h}'[v1 \mapsto 0], \{v1 \mapsto 0\})} * \lfloor h'[v1 \mapsto 7] \rfloor\right\}$$

???

$$\left\{\boxed{(\mathrm{h}'[v1 \mapsto 7], \{v1 \mapsto 7\})} * \lfloor h'[v1 \mapsto 7] \rfloor\right\}$$

$$\left\{\boxed{(\epsilon_g, \{v1 \mapsto 7\})} * \exists h \in \mathrm{Heaps}. \boxed{(h, \mathrm{emptyheap})} * \lfloor h \rfloor\right\}$$

$$\left\{\boxed{(\epsilon_g, \{v1 \mapsto 7\})}\right\}$$

Allowed if “does not harm other threads”

“Does not harm other threads”

$(\epsilon_g, \mathrm{emptyheap}) \rightsquigarrow \{(\epsilon_g, \{72 \mapsto 0\})\}$?

No: other thread might have e.g. $(\epsilon_g, \{72 \mapsto 123\})$

$$(\{72 \mapsto 12, 1 \mapsto 3\}, \{72 \mapsto 12\}) \rightsquigarrow \{(\{72 \mapsto 0, 1 \mapsto 3\}, \{72 \mapsto 0\})\}\ ?$$

Yes: cell update

$$a \rightsquigarrow \{b\} \iff \forall f : a.f \neq \bot \Rightarrow b.f \neq \bot$$

Increase-only counter

$$M_c = (\{\perp\} \cup \{(g,l) |\ \begin{array}{l} g \in \mathbb{N} \cup \{\epsilon_c\} \\ l \in \mathbb{N} \\ g \neq \epsilon_g \rightarrow l \leq g\} \end{array}$$

$$, \perp, \ldots, \cdot_c)$$

$$(\epsilon_c, l_1) \cdot_a (g, l_2) = (g, \min(l_1, l_2)) \textbf{ if } (g, \min(l_1, l_2)) \in |M_c| \backslash \{\perp\}$$

$$m_1 \cdot_c m_2 = \perp \textbf{ other cases}$$

Wrapping up

- Monoids
- Physical assertion
- Ghost assertion
- Invariants
- $\leadsto$

Teaser Episode 3

- Can I model I/O in Iris? (Willem)
- Logical Atomicity (Amin)