Local Reasoning about the Presence of Bugs: **Incorrectness Separation Logic (ISL)**

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State of the Art: ***Correctness***

- Lots of work on ***local reasoning*** for proving ***correctness***
  - ➡ Prove the ***absence of bugs***
  - ➡ ***Over-approximate*** reasoning

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    in ***resources*** accessed ⇒ spatial locality

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    in ***resources*** accessed ⇒ spatial locality
- ➡ ***Scalability*** to large teams and codebases

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  - e.g. ***Infer***

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  - Using ***correctness***-based compositional analysis

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❖ Exce

➡ e.

➡ Us

Incorrectness Logic (O'Hearn)
Formal Foundations
for
Bug Catching

Incorrectness Logic (IL)

Hoare triples {p} C {q}

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For all states s *in* p
if running C *on* s *terminates in* s', *then* s' *is in* q

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Hoare triples {p} C {q} *iff* post(C)p ⊆ q

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Incorrectness triples [p] C [q] *iff* post(C)p ⊇ q

For all states s *in* q
s *can be reached by running* C *on some* s' *in* p

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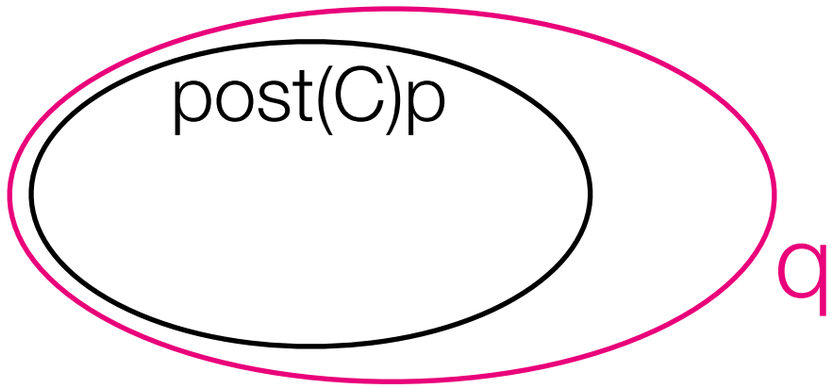

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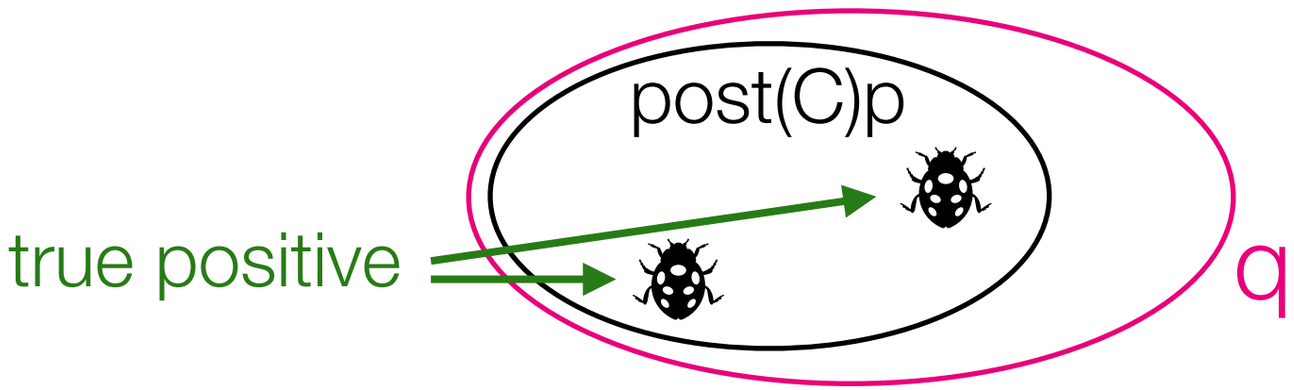

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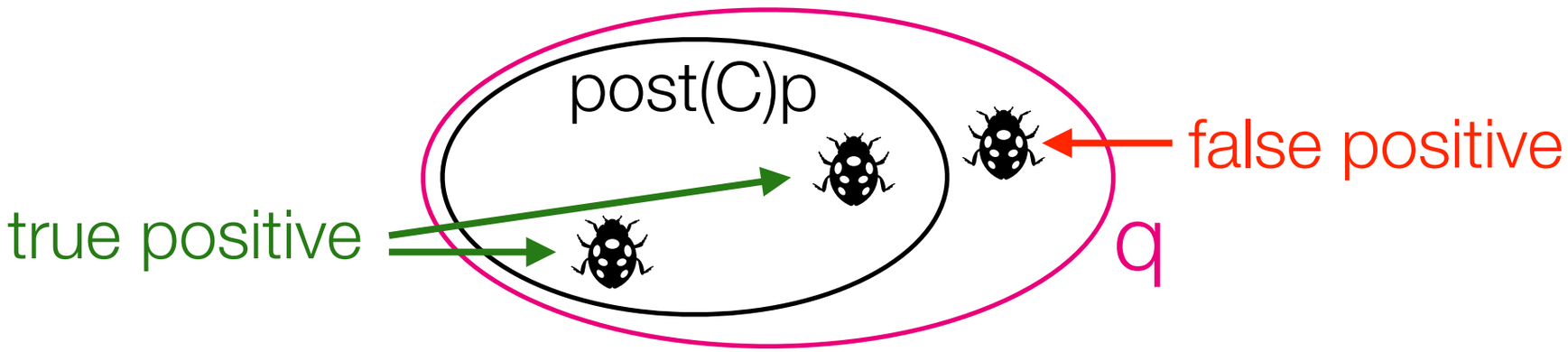

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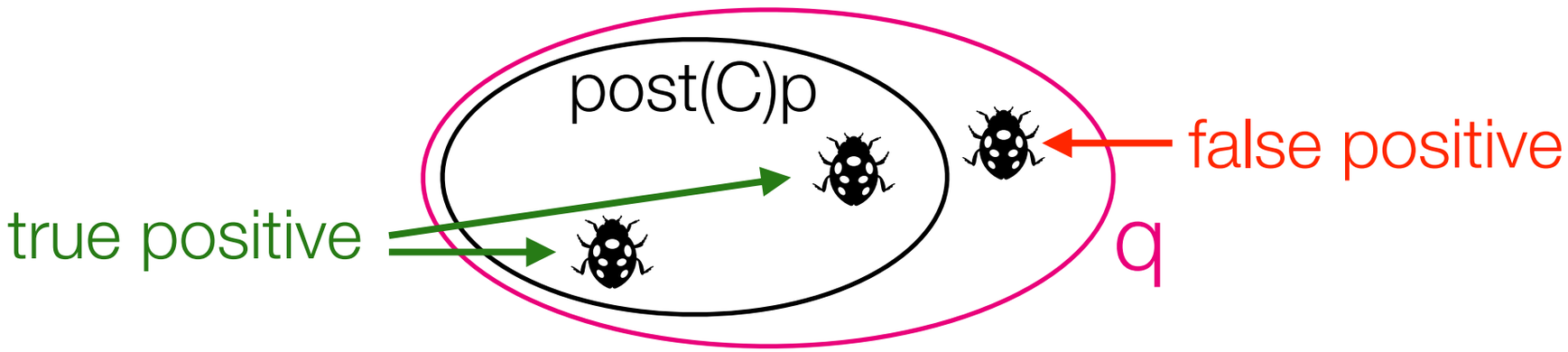

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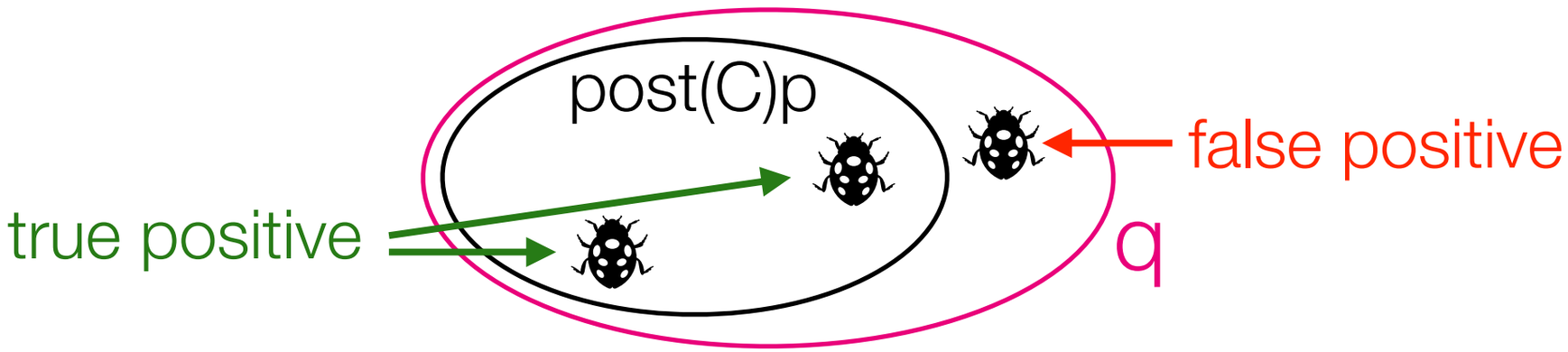

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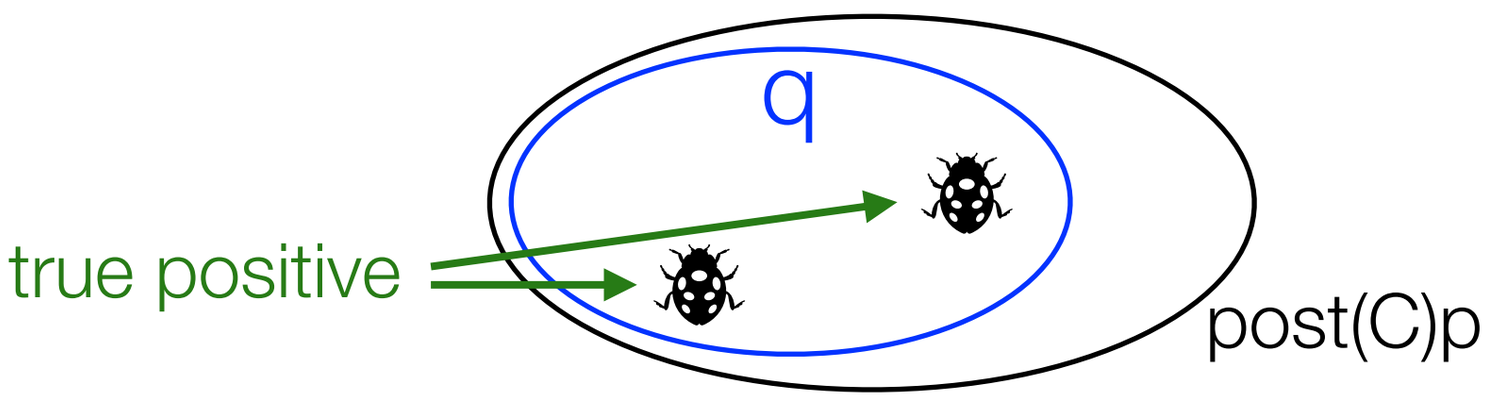

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Hoare triples $\{p\}\ C\ \{q\}$ *iff* $post(C)p \subseteq q$

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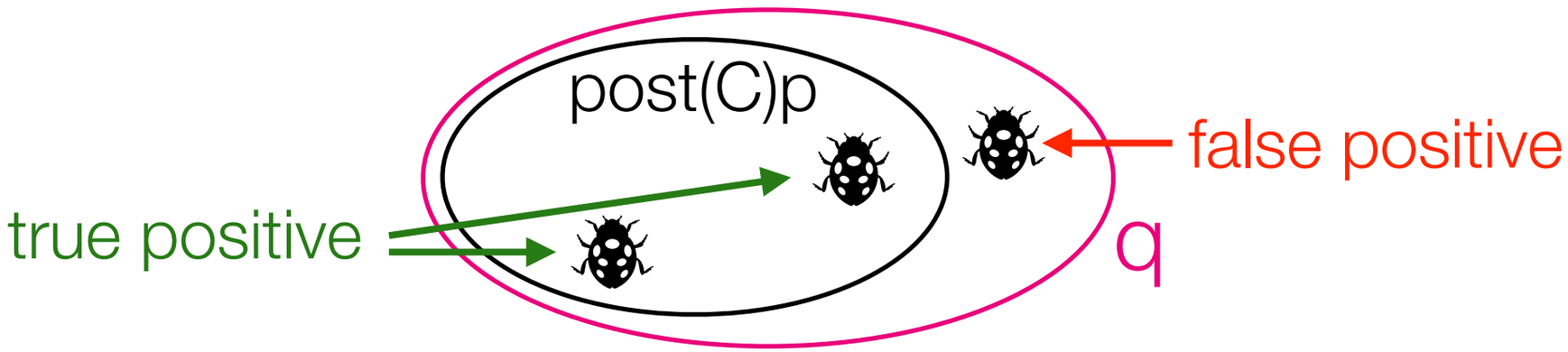

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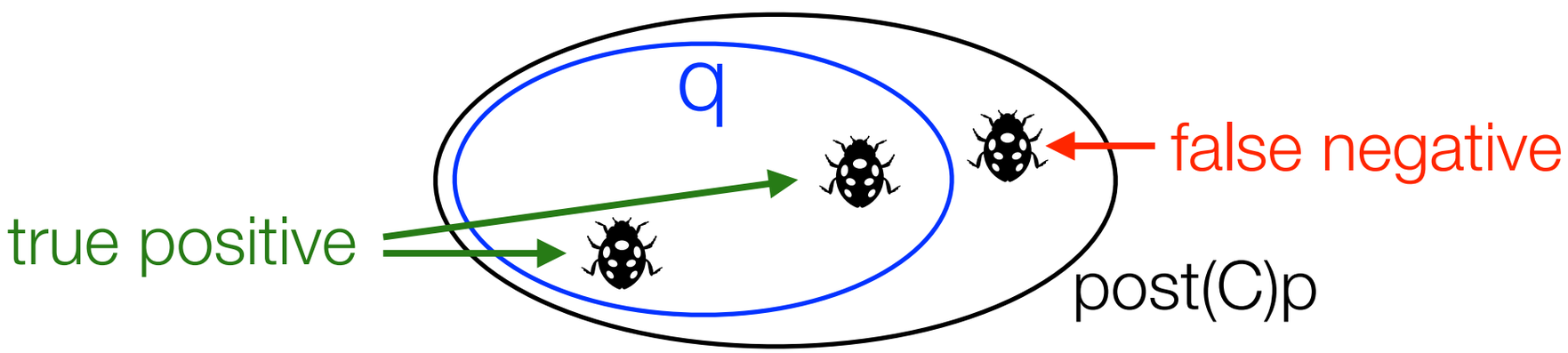

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[p] C [ε: q]

ε: exit condition

ok: normal execution

er : erroneous execution

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[y=v] x:=y [ok: x=y=v]

[p] error( ) [er: p]

Incorrectness Logic (IL)

$$[p]\ C\ [\varepsilon\colon q] \quad \textit{iff} \quad \mathrm{post}(C, \varepsilon)p \supseteq q$$

Equivalent Definition (reachability)

$$[p]\ C\ [\varepsilon\colon q] \quad \textit{iff} \quad \forall\, s \in q.\ \exists\, s' \in p.\ (s', s) \in [C]\varepsilon$$

Incorrectness Logic: Summary

+ ***Under-approximate*** analogue of Hoare Logic

+ Formal foundation for ***bug catching***

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+ ***Under-approximate*** analogue of Hoare Logic

+ Formal foundation for ***bug catching***

– Global reasoning: ***non-compositional*** (as in original Hoare Logic)

– Cannot target ***memory safety bugs*** (e.g. use-after-free)

Incorrectness Logic: Summary

+ ***Under-approximate*** analogue of Hoare Logic

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– Glob Logic)

– Can

Our Solution

Incorrectness Separation Logic

Contributions

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- Incorrectness ***Separation*** Logic (ISL)
  - ➡ IL + SL for ***compositional bug catching***

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  - ➡ ***invalid frame*** rule!

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- Recovering the ***footprint property*** for completeness

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- ISL-based ***analysis***
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    All bugs found are true bugs

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This talk

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post: {x = 1 ∧ y = 2 ∧ z = 3}

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pre: $\{x \neq y \wedge x \neq z \wedge y \neq z\}$

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n!/2 conjuncts !

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post: $\{ x \mapsto 1 * y \mapsto 2 * z \mapsto 3 \}$

$\forall x,v,v'.\ x \mapsto v * x \mapsto v' \Rightarrow \text{false}$

The Essence of Separation Logic (SL)

Frame Rule

$$\frac{\{p\}\ C\ \{q\}}{\{p * r\}\ C\ \{q * r\}}$$

$x \mapsto v * x \mapsto v' \Leftrightarrow \text{false}$ $\quad$ $x \mapsto v * \text{emp} \Leftrightarrow x \mapsto v$

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FREE $\{x \mapsto -\}\ \text{free}(x)\ \{\ \text{emp}\ \}$

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$$[p]\ C\ [\varepsilon : q]$$

SL

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ISL: Local Axioms (First Attempt)

WRITE

$[x \mapsto v']\ [x] := v\ [ok: x \mapsto v]$

ISL: Local Axioms (First Attempt)

WRITE

[x ↦ v’] [x]:= v [ok: x ↦ v]

[x=null] [x]:= v [er: x=null]

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null-pointer dereference error

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ALLOC

$[emp]\ x:= alloc()\ [ok: \exists l.\ l \mapsto v \wedge x=l]$

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FREE

$[x \mapsto v]\ free(x)\ [ok: emp]$

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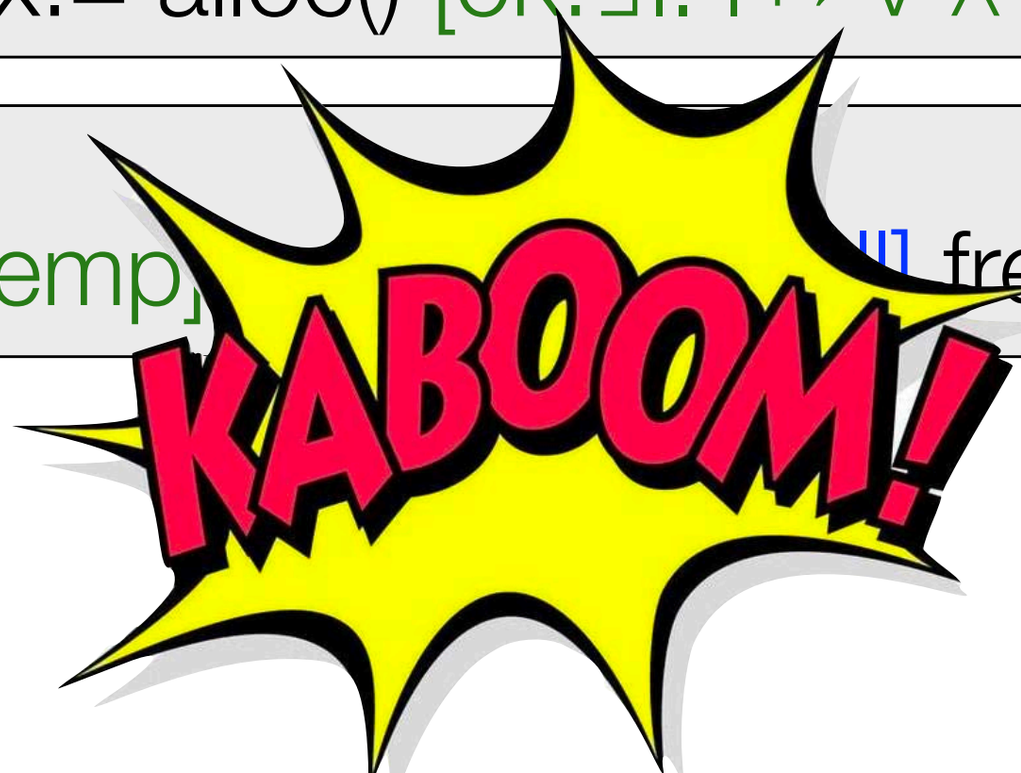

$[x=null]$ free(x) $[er: x=null]$

ISL: Local Axioms (First Attempt)

ISL

$$\frac{[p]\ C\ [\varepsilon: q]}{[p * r]\ C\ [\varepsilon: q * r]}$$

$x \mapsto v * x \mapsto v' \Leftrightarrow \text{false}$

$x \mapsto v * \text{emp} \Leftrightarrow x \mapsto v$

$[x \mapsto v]\ \text{free}(x)\ [\text{ok}: \text{emp}]$

$[p]\ C\ [\varepsilon: q]$ *iff* $\forall\, s \in q.\ \exists\, s' \in p.\ (s', s) \in [C]\varepsilon$

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$$\frac{[x \mapsto v]\ \text{free}(x)\ [\text{ok}: \text{emp}]}{[x \mapsto v * x \mapsto v]\ \text{free}(x)\ [\text{ok}: \text{emp} * x \mapsto v]}\ \text{(Frame)}$$

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$$\frac{[x \mapsto v]\ \text{free}(x)\ [\text{ok}\colon \text{emp}]}{[x \mapsto v * x \mapsto v]\ \text{free}(x)\ [\text{ok}\colon \text{emp} * x \mapsto v]}\ (\text{Frame})$$

$$\frac{}{[\text{false}]\ \text{free}(x)\ [\text{ok}\colon x \mapsto v]}\ (\text{Cons})$$

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$$\frac{[p]\ C\ [\varepsilon\colon q]}{[p * r]\ C\ [\varepsilon\colon q * r]}$$

$x \mapsto v * x \mapsto v' \Leftrightarrow \text{false}$

$x \mapsto v * \text{emp} \Leftrightarrow x \mapsto v$

$$\frac{[x \mapsto v]\ \text{free}(x)\ [\text{ok}\colon \text{emp}]}{[x \mapsto v * x \mapsto v]\ \text{free}(x)\ [\text{ok}\colon \text{emp} * x \mapsto v]}\ (\text{Frame})$$

$$\frac{[x \mapsto v * x \mapsto v]\ \text{free}(x)\ [\text{ok}\colon \text{emp} * x \mapsto v]}{[\text{false}]\ \text{free}(x)\ [\text{ok}\colon x \mapsto v]}\ (\text{Cons})$$

$[p]\ C\ [\varepsilon\colon q]$ *iff* $\forall\ s \in q.\ \exists\ s' \in p.\ (s', s) \in [C]\varepsilon$

$[\text{false}]\ C\ [\varepsilon\colon q]$ ✗ (unless $q \Rightarrow \text{false}$)

ISL: Local Axioms (First Attempt)

ISL

$$\frac{[p]\ C\ [\varepsilon: q]}{[p * r]\ C\ [\varepsilon: q * r]}$$

$$x \mapsto v * x \mapsto v' \Leftrightarrow \text{false}$$

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Solution:

Track Deallocated Locations!

$$[x \mapsto v$$

(Frame)

$$\to v]$$

(Cons)

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$$[x \mapsto v]\ \mathrm{free}(x)\ [\mathrm{ok}: \mathrm{emp}]$$

Solution: Track Deallocated Locations!

$$[x \mapsto v]\ \mathsf{free}(x)\ [\mathsf{ok}:\ x \not\mapsto\ ]$$

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$[x \mapsto v]\ \text{free}(x)\ [\text{ok}: x \not\mapsto]$

x is ***deallocated***

$x \mapsto v * x \mapsto v' \Leftrightarrow \text{false}$

$x \mapsto v * \text{emp} \Leftrightarrow x \mapsto v$

Solution: Track Deallocated Locations!

$[x \mapsto v]$ free(x) $[ok: x \not\mapsto]$

x is ***deallocated***

$x \mapsto v * x \mapsto v' \Leftrightarrow$ false

$x \mapsto v * emp \Leftrightarrow x \mapsto v$

$x \mapsto v * x \not\mapsto \Leftrightarrow$ false

$x \not\mapsto * x \not\mapsto \Leftrightarrow$ false

Solution: Track Deallocated Locations!

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$$[\mathsf{false}]\ \mathsf{free}(x)\ [\mathsf{ok}: \mathsf{false}]$$ ✔

$$[p]\ C\ [\varepsilon: q] \quad \textit{iff} \quad \forall\, s \in q.\ \exists\, s' \in p.\ (s', s) \in [C]\varepsilon$$

$[p]\ C\ [\varepsilon: \mathsf{false}]$ ✔ (vacuous)

ISL: Local Axioms

$[x \mapsto v]$ free(x) [ok: $x \not\mapsto$] $[x=null]$ free(x) [er: x=null]

FREE

ISL: Local Axioms

$[x \mapsto v]$ free(x) $[ok: x \not\mapsto]$ **FREE**

$[x=null]$ free(x) $[er: x=null]$

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ISL: Local Axioms

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use-after-free error

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$[x \mapsto v']$ [x]:= v [ok: $x \mapsto v$]

WRITE

[x=null] [x]:= v [er: x=null]

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$[x \not\mapsto]$ y:= [x] [er: $x \not\mapsto$]

[emp] x:= alloc() [ok: $\exists l.\ l \mapsto v \wedge x=l$]

ALLOC

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[emp] x:= alloc() [ok:$\exists l.\ l \mapsto v \wedge x=l$]

ALLOC

$[y \not\mapsto]$ x:= alloc() [ok: $y \mapsto v \wedge x=y$]

Conclusions

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  - ➡ A unifying theory of testing and verification

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Thank You for Listening!

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Incorrectness Separation Logic

July 23rd @ 9:15

A. Raad J. Berdine H-H. Dang D. Dreyer P. O'Hearn J. Villard

Verification

Correctness

- Prove ***absence of bugs***
- ***Local*** reasoning
- ***Compositionality***
  - ➡ in code (incomplete code)
  - ➡ in resources accessed

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Incorrectness logic: global reasoning for ***bug catching***

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Incorrectness Separation Logic

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Incorrectness logic: global reasoning for ***bug catching***

+

Separation logic: correctness-based ***local*** reasoning

Formal foundation for ***local*** & ***compositional bug catching***