QuickChecking Static Analysis Properties

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Abstract Interpretation Winter School

From forthcoming ICST'15 paper

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Who checks the checker?

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Many static analyses build on...

Theorem (Tarski 1955). Given

- a complete lattice $\langle L; \sqsubseteq \rangle$ and
- a monotone (order-preserving) function $f : L \to L$,

then the fixed points of f form a complete lattice.

In particular f has a least and a greatest fixed point.

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Software tools depend on these premises.

How do we ensure them?

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A range of approaches…

for ensuring static analysis properties:

- basic testing
- informal monotonicity arguments
- pen-and-paper monotonicity/soundness proofs
- …
- static monotonicity analysis (Murawski-Yi:VMCAI02)
- automated fixed point checking (Blazy-Laporte-Maroneze-Pichardie:SAS13)
- machine-formalized proofs (Cachera-Jensen-Pichardie-Rusu:TCS05)

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This work (read: cat out of the bag)

Check essential properties (lattice, monotonicity, . . .)

- □ with QuickCheck (Claessen-Hughes:ICFP’00) and
- □ an embedded DSL

for increased confidence in your static analysis code.

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Pro: lightweight,
effective in terms of coverage

Con: ***confidence***,
not proof

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A simple example (1/3)

A two-element lattice expressed as an OCaml module:

```
module L = struct
  let name = "example lattice"
  type elem = Top | Bot
  let leq a b = match a,b with
    | Bot, _ -> true
    | _, Top -> true
    | _, _   -> false
  let join e e' = if e = Bot then e' else Top
  let meet e e' = if e = Bot then Bot else e'
  (* ... *)

  let to_string e = if e = Bot then "Bot" else "Top"
end
```

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  let join e e' = if e = Bot then e' else Top
  let meet e e' = if e = Bot then Bot else e'
  (* ... *)
  let arb_elem = Arbitrary.among [Bot; Top]
  let to_string e = if e = Bot then "Bot" else "Top"
end
```

We extend the lattice with a **generator**
of arbitrary lattice elements.

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A simple example (2/3)

Using a reusable functor of lattice property tests

```
# let module LTests = GenericTests(L) in
  run_tests LTests.suite;;
```

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A simple example (2/3)

Using a reusable functor of lattice property tests

```
# let module LTests = GenericTests(L) in
  run_tests LTests.suite;;
  check 19 properties...
testing property leq reflexive in example lattice...
  [✓] passed 1000 tests (0 preconditions failed)
testing property leq transitive in example lattice...
  [✓] passed 1000 tests (0 preconditions failed)
testing property leq anti symmetric in example lattice...
  [✓] passed 1000 tests (0 preconditions failed)
testing property bot is lower bound in example lattice...
  [✓] passed 1000 tests (0 preconditions failed)
testing property join commutative in example lattice...
  [✓] passed 1000 tests (0 preconditions failed)

... (28 additional lines cut)...

tests run in 0.02s
[✓] Success! (passed 19 tests)
```

we can quickcheck `L` for a range of lattice properties!

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A simple example (3/3)

– and there's more!

Suppose we have a lattice operation:

```
(*  flip : L -> L  *)
let flip e = if e = L.Bot then L.Top else L.Bot
```

Note: This guy is **not** monotone.

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A simple example (3/3)

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Let's test it:

```
# let flip_desc = ("flip",flip) in
  run (testsig (module L) -<-> (module L) =:  flip_desc);;
```

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let flip e = if e = L.Bot then L.Top else L.Bot
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Note: This guy is **not** monotone.

Let's test it:

```
# let flip_desc = ("flip",flip) in
  run (testsig (module L) -<-> (module L) =:  flip_desc);;
  testing property 'flip monotone in 1. argument'...
  [✗] 270 failures over 1000 (print at most 1):
  (Bot, Top)
```

using our type-safe EDSL with mathmode-inspired arrow syntax $\texttt{flip} : L \xrightarrow{\sqsubseteq} L$

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The rest of this talk

- Introduction
- QuickCheck, briefly
- A more complex example: Lua type analysis
  - Lua (briefly)
  - A static analysis of Lua
  - Testing lattices
  - Testing lattice operations
  - Evaluation
- Conclusion

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QuickCheck, briefly (1/2)

Throughout we use OCaml with the ’qcheck’ library

E.g., monotonicity $\forall \mathtt{a}, \mathtt{b}.\ \mathtt{a} \sqsubseteq \mathtt{b} \Rightarrow \mathtt{flip\ a} \sqsubseteq \mathtt{flip\ b}$
translates into a function modeling the implication:

```
fun (a,b) -> Prop.assume (L.leq a b); L.leq (flip a) (flip b)
```

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```

Combinators for composing generators:

```
let arb_pair = Arbitrary.pair L.arb_elem L.arb_elem
```

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Combinators for composing generators:

```
let arb_pair = Arbitrary.pair L.arb_elem L.arb_elem
```

A monotonicity test written out:

```
# let mon_test = mk_test arb_pair
        (fun (a,b) -> Prop.assume (L.leq a b); L.leq (flip a) (flip b));;
  val mon_test : QCheck.test = <abstr>
```

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let arb_pair = Arbitrary.pair L.arb_elem L.arb_elem
```

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# let mon_test = mk_test arb_pair
        (fun (a,b) -> Prop.assume (L.leq a b); L.leq (flip a) (flip b));;
  val mon_test : QCheck.test = <abstr>
# run mon_test;;
testing property <anon prop>...
  [✗] 27 failures over 100
```

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QuickCheck, briefly (2/2)

To improve usability 'qcheck' supports more arguments:

```
mk_test ~n:1000 ~pp:pp_pair ~name:"flip monotone"
  arb_pair (fun (a,b) -> Prop.assume (L.leq a b); L.leq (flip a) (flip b))
```

which will

- name the property,
- run 1000 tests instead, and
- use the pretty printer `pp_pair` defined as

  ```
  let pp_pair = PP.pair L.to_string L.to_string
  ```

  to print counter examples

QuickCheck, briefly (2/2)

To improve usability 'qcheck' supports more arguments:

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mk_test ~n:1000 ~pp:pp_pair ~name:"flip monotone"
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  ```

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Compare above to

```
let flip_desc = ("flip",flip) in
testsig (module L) -<-> (module L) =: flip_desc
```

A more complex example:
Lua and a static analysis for it

Lua?

Lua, in brief

- Developed in Brazil, +20 years ago
- Lightweight language (few, well-chosen features):
  - Dynamically typed
  - First-class functions
  - Builtin tables (associative arrays)
  - ...
- Multiparadigm (FP, OO, ...)
- Lightweight, cross-platform implementation
- Standalone and easily embeddable
- ...

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An example

This 5-line program:

```
1   function mktable(f)
2       return { x = f("x"), y = f("y") }
3   end
4
5   mktable(function (z) return z.." component" end)
```

illustrates Lua's records and first-class functions.

Lua type analysis keywords

We build a

- forward,
- flow-sensitive,
- *attribute-independent*,
- monomorphic

flow analysis over a suitable lattice structure.

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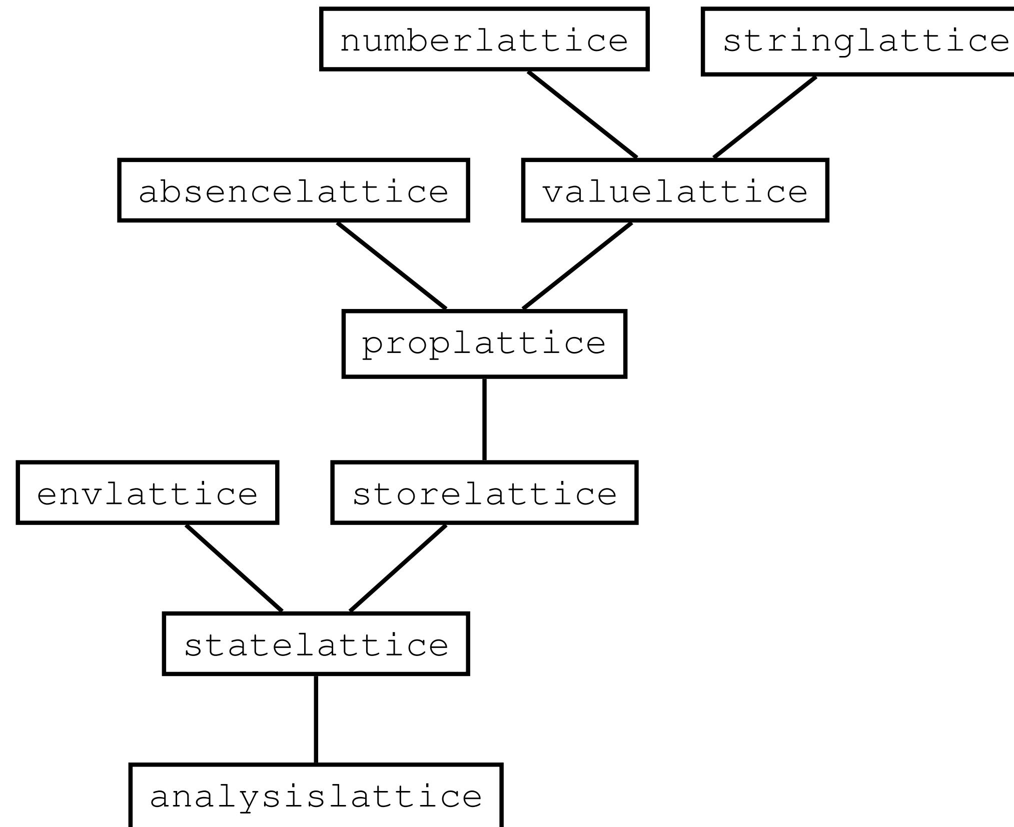
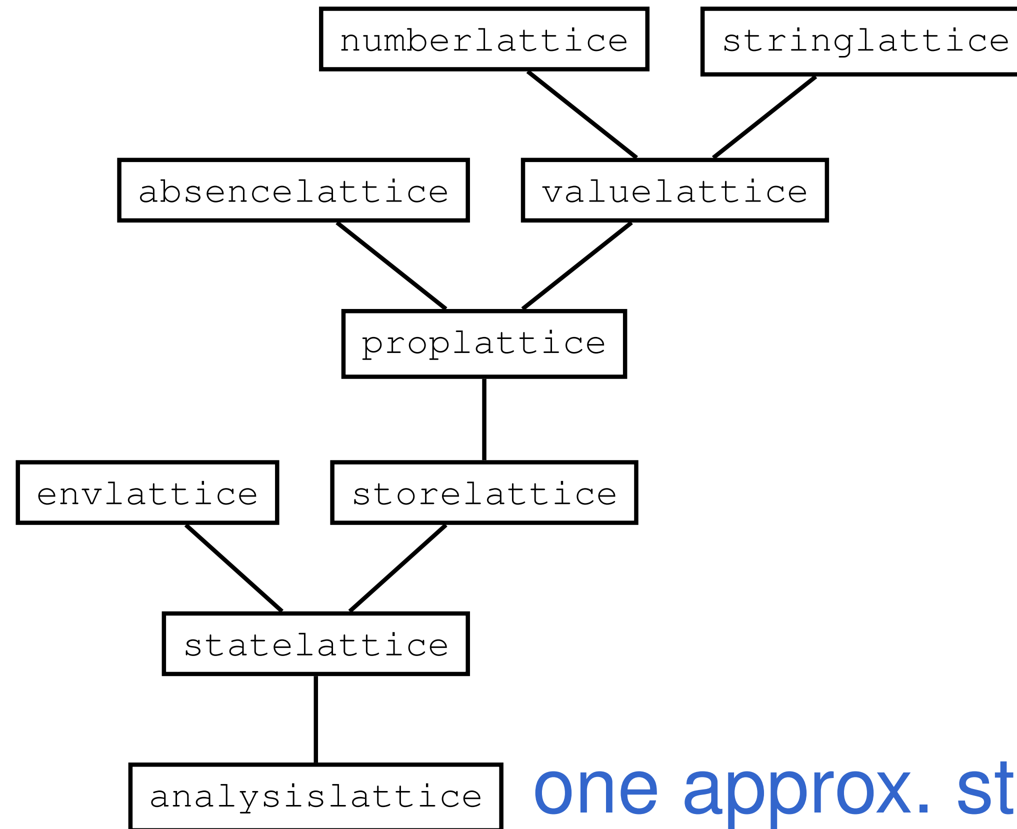
A lattice for Lua type analysis (1/2)



Akin to TAJS lattice for JavaScript (Jensen-al:SAS09)

A lattice for Lua type analysis (1/2)



one approx. state/program point

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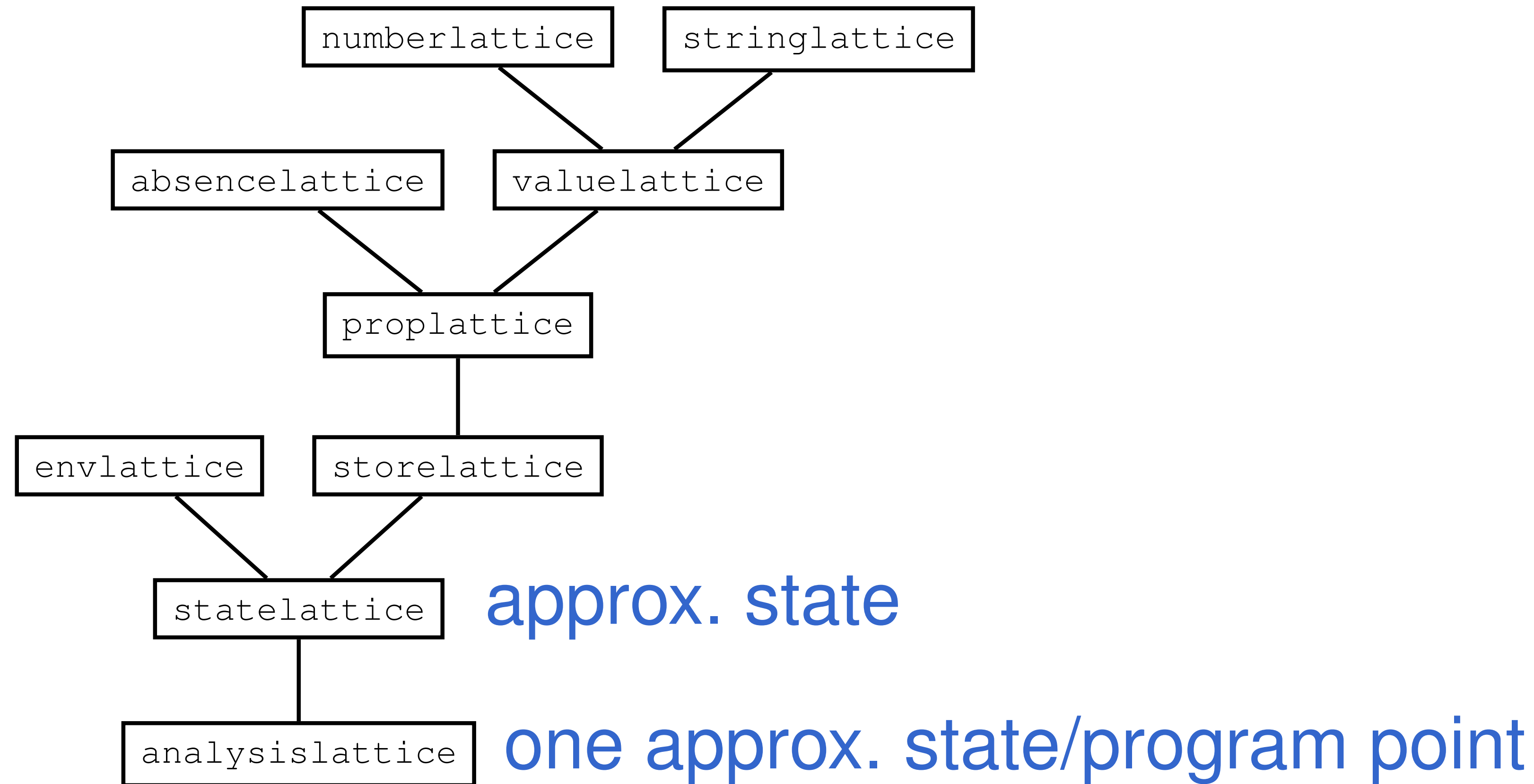

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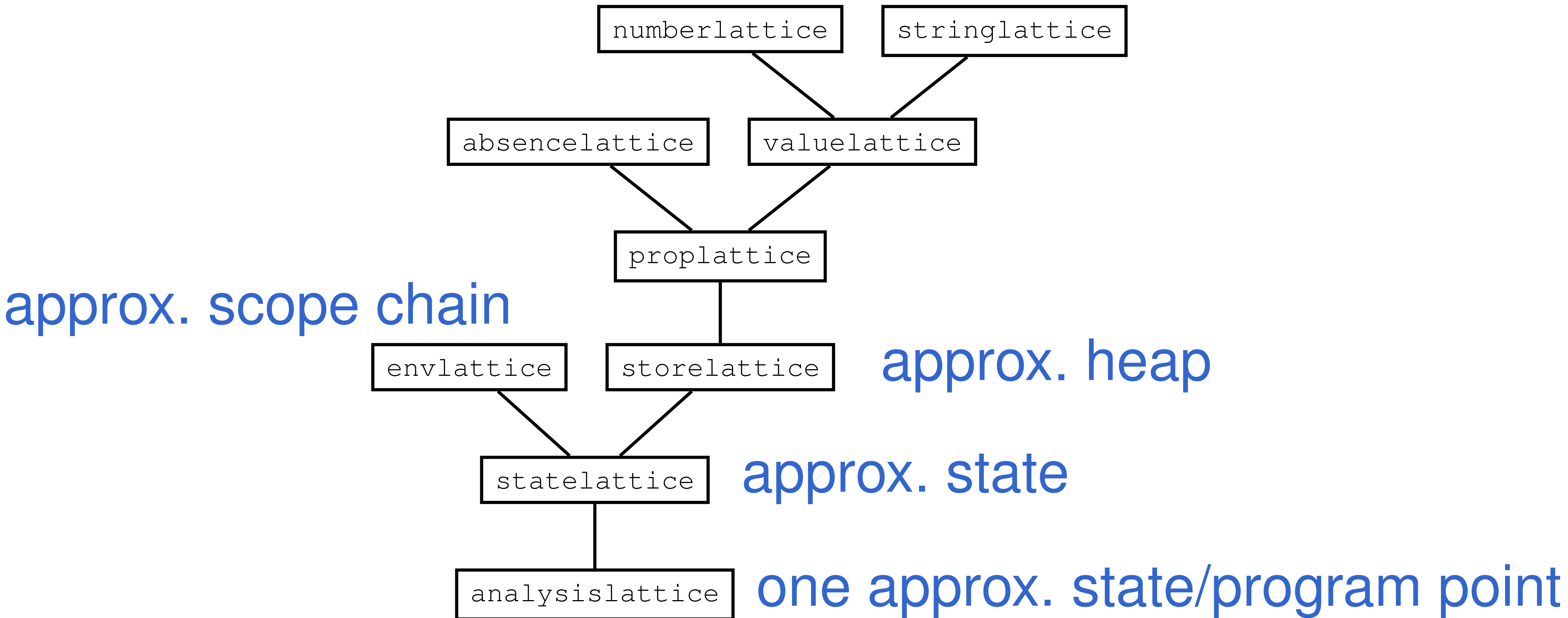

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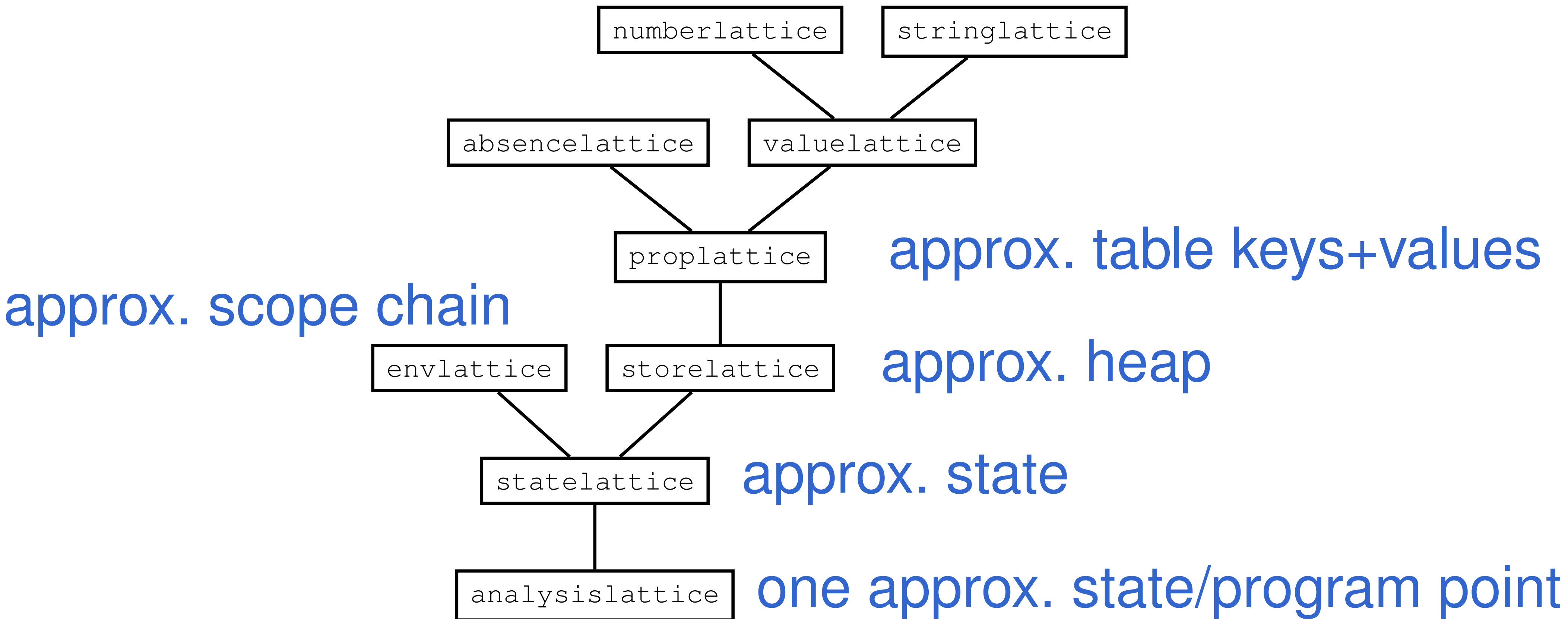

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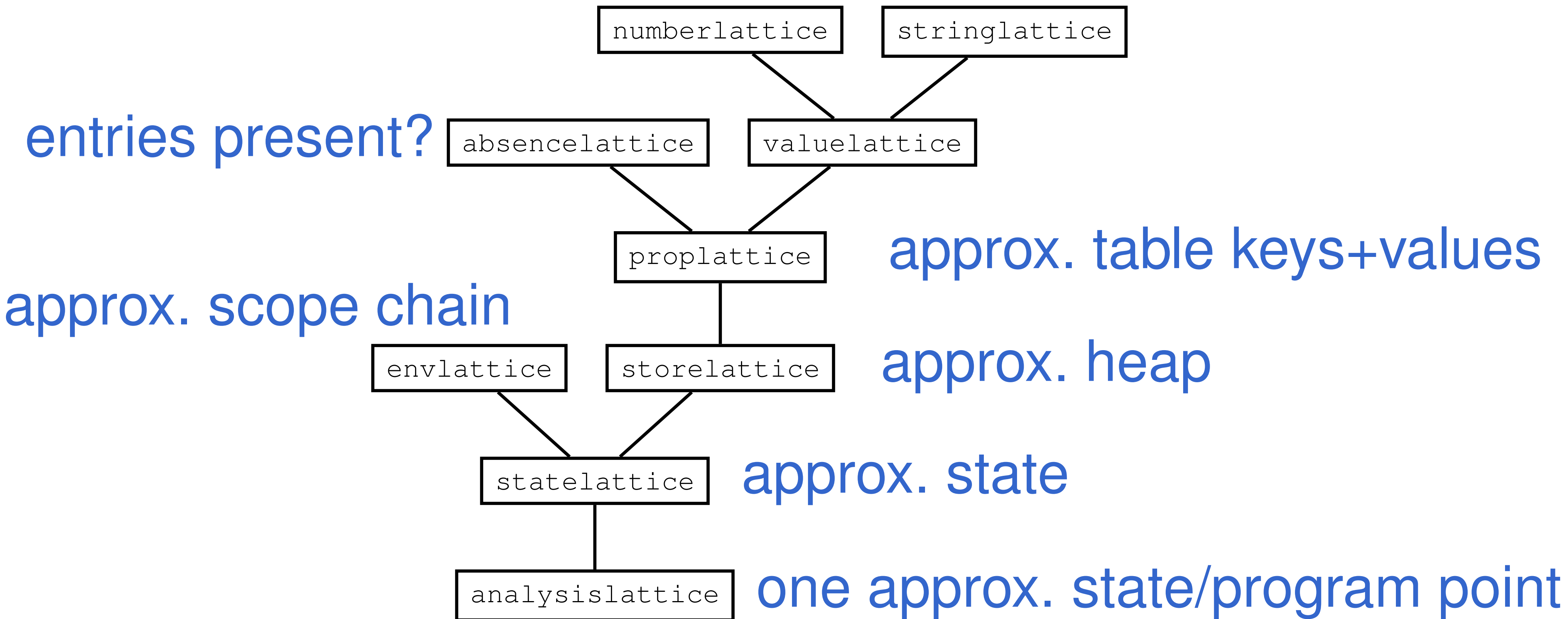

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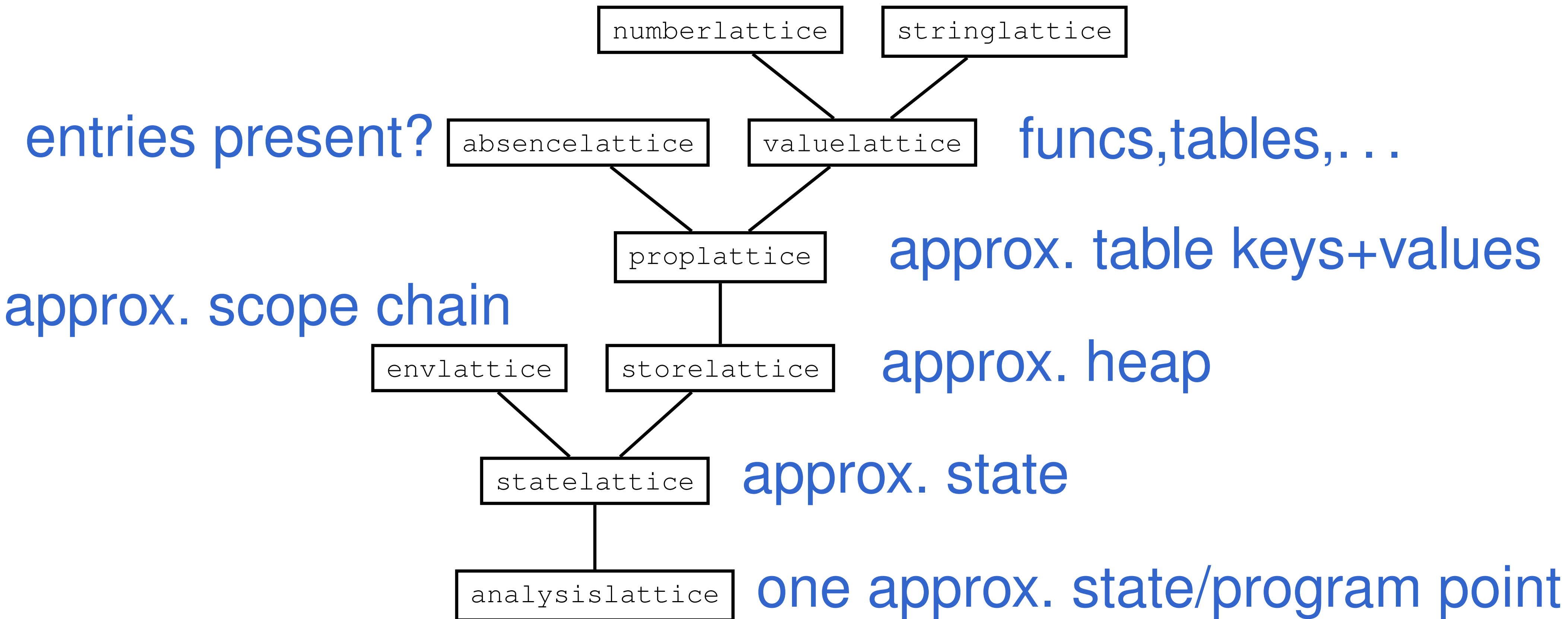

Akin to TAJS lattice for JavaScript (Jensen-al:SAS09)

A lattice for Lua type analysis (2/2)

The lattice modules have a consistent signature:

```
module type LATTICE_TOPLESS =
sig
  type elem
  val leq       : elem -> elem -> bool
  val bot       : elem
(* val top      : elem *)
  val join      : elem -> elem -> elem
  val meet      : elem -> elem -> elem
  val to_string : elem -> string
end
```

but not all have an explicit top element

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Testing the lattices

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Lattice properties

Lattices are partial orders:

$$\forall a \in L.\ a \sqsubseteq a \qquad \text{(reflexivity)}$$

$$\forall a, b, c \in L.\ a \sqsubseteq b \ \wedge\ b \sqsubseteq c \Rightarrow a \sqsubseteq c \qquad \text{(transitivity)}$$

$$\forall a, b \in L.\ a \sqsubseteq b \ \wedge\ b \sqsubseteq a \Rightarrow a = b \qquad \text{(anti-symmetry)}$$

with additional algebraic properties:

$$\forall a \in L.\ \bot \sqsubseteq a \ \wedge\ a \sqsubseteq \top \qquad \text{($\bot$ is lower bound, $\top$ is upper bound)}$$

$$\forall a, b \in L.\ a \sqcup b = b \sqcup a \ \wedge\ a \sqcap b = b \sqcap a \qquad \text{($\sqcup$,$\sqcap$ commutative)}$$

$$\forall a, b, c \in L.\ (a \sqcup b) \sqcup c = a \sqcup (b \sqcup c) \ \wedge\ (a \sqcap b) \sqcap c = a \sqcap (b \sqcap c) \qquad \text{($\sqcup$,$\sqcap$ associative)}$$

$$\forall a \in L.\ a \sqcup a = a \ \wedge\ a \sqcap a = a \qquad \text{($\sqcup$,$\sqcap$ idempotent)}$$

$$\forall a, b \in L.\ a \sqcup (a \sqcap b) = a \ \wedge\ a \sqcap (a \sqcup b) = a \qquad \text{($\sqcup$-$\sqcap$,$\sqcap$-$\sqcup$ absorption)}$$

$$\forall a, b \in L.\ a \sqsubseteq b \Leftrightarrow a \sqcup b = b \Leftrightarrow a \sqcap b = a \qquad \text{($\sqsubseteq - \sqcup - \sqcap$ compatible)}$$

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So we need `arb_elem` and equality operation in signature:

```
val arb_elem : elem Arbitrary.t
val eq       : elem -> elem -> bool
```

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Generating arbitrary lattice elements

Simple generators: (writing `Arb` for `Arbitrary`)

absencelattice: (two-elem lattice)

```
Arb.among [Bot; Top]
```

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Arb.(choose [return bot; lift const string; return top])
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labelsets: (set-based lattice) Using qcheck's fix combinator

```
Arb.(fix ~base:(return LabelSet.empty) (lift2 LabelSet.add arb_label))
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Composite generators:

pair lattices: `Arb.pair A.arb_elem B.arb_elem` for lattices `A` and `B`

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Composite generators:

pair lattices: `Arb.pair A.arb_elem B.arb_elem` for lattices `A` and `B`

map lattices: Using a helper function:

```
let build_map mt add ls =
  let rec build ls = match ls with
    | [] ->         Arb.return mt
    | (k,v)::ls -> Arb.(build ls >>= fun tbl -> return (add k v tbl)) in
  build ls
```

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Improving generators (1/2)

`arb_elem` isn't always sufficient:

```
let leq_trans = (* forall a,b,c. a <= b /\ b <= c  =>  a <= c *)
  mk_test ~n:1000 ~pp:pp_triple ~name:("leq transitive in " ^ L.name)
    arb_triple (fun (a,b,c) -> Prop.assume (L.leq a b);
                               Prop.assume (L.leq b c);
                               L.leq a c)
```

as it doesn't lead to very much checking:

```
testing property leq transitive in value lattice...
  [✓] passed 1000 tests (1000 preconditions failed)
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as it doesn't lead to very much checking:

```
testing property leq transitive in value lattice...
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```

Solution: extend signature further:

```
val arb_elem_le : elem -> elem Arbitrary.t
```

to generate elements less than a given argument

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Improving generators (2/2)

These are not much harder to write.

For example,

absencelattice:

```
let arb_elem_le e = if e = Top then arb_elem else Arb.return Bot
```

stringlattice:

```
let arb_elem_le e = match e with
  | Bot     -> Arb.return Bot
  | Const s -> Arb.among [Bot; Const s]
  | Top     -> arb_elem
```

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Improving generators (2/2)

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For example,

absencelattice:

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stringlattice:

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let arb_elem_le e = match e with
  | Bot     -> Arb.return Bot
  | Const s -> Arb.among [Bot; Const s]
  | Top     -> arb_elem
```

We can use `arb_elem_le` to generate ordered pairs (and triples):

```
let ord_pair =
  Arb.(L.arb_elem >>= fun e -> pair (L.arb_elem_le e) (return e))
```

e.g., to satisfy transitivity's precondition.

Testing the lattice operations

Operation tests under the hood (1/3)

Writing things out gets loooong, e.g., for `Str.concat`:

```
(* forall s. bot = s ^ bot *)
let concat_strict_snd =
  mk_test ~n:1000 ~pp:Str.to_string ~name:("Str.concat strict in 2. arg")
    Str.arb_elem (fun s -> Str.(eq bot (concat s bot)))

(* forall s,s',s''. s' <= s''  =>  (s ^ s') <= (s ^ s'')  *)
let concat_monotone_snd =
  mk_test ~n:1000 ~pp:(PP.pair Str.to_string pp_pair) ~name:("Str.concat monotone in 2. arg")
    (Arbitrary.pair Str.arb_elem ord_pair)
    (fun (s,(s',s'')) -> Prop.assume (Str.leq s' s''); Str.(leq (concat s s') (concat s s'')))

(* forall s,s',s''. s' ~ s''  =>  (s ^ s') ~ (s ^ s'') *)
let concat_invariant_snd =
  mk_test ~n:1000 ~pp:(PP.pair Str.to_string pp_pair) ~name:("Str.concat invariant in 2. arg")
    (Arbitrary.pair Str.arb_elem Str.equiv_pair)
    (fun (s,(s',s'')) -> Prop.assume (Str.eq s' s''); Str.(eq (concat s s') (concat s s'')))
```

Props $\sim$ functions, so let's build them with combinators!

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Operation tests under the hood (2/3)

We provide 3 combinators for typical properties:
`op_strict`, `op_monotone`, `op_invariant` (cf. Holdermans:PPDP13)

+ 2 for adding arguments: `pw_left`, `pw_right`

```
let str_concat = ("Str.concat",Str.concat) in
[ pw_left (module Str) op_strict    (module Str) (module Str) =:: str_concat;
  pw_left (module Str) op_monotone  (module Str) (module Str) =:: str_concat;
  pw_left (module Str) op_invariant (module Str) (module Str) =:: str_concat; ]
```

How?

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  pw_left (module Str) op_monotone  (module Str) (module Str) =:: str_concat;
  pw_left (module Str) op_invariant (module Str) (module Str) =:: str_concat; ]
```

How? `=::` is shorthand, infix syntax for `finalize`:

```
let finalize opsig (opname,op) =
  opsig (fun (pp,gen,prop,pname,leftargs) ->
          mk_test ~n:1000 ~pp:pp (* ... *)
            ~name:(Printf.sprintf "'%s %s in %i. argument'" opname pname leftargs)
            gen (prop op))
```

using CPS, with `finalize` supplying the initial continuation

DTU

Operation tests under the hood (3/3)

From combinators to arrow syntax:

```
let str_concat = ("Str.concat",Str.concat) in
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  (* ... and similar for the first argument ... *) ]
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DTU

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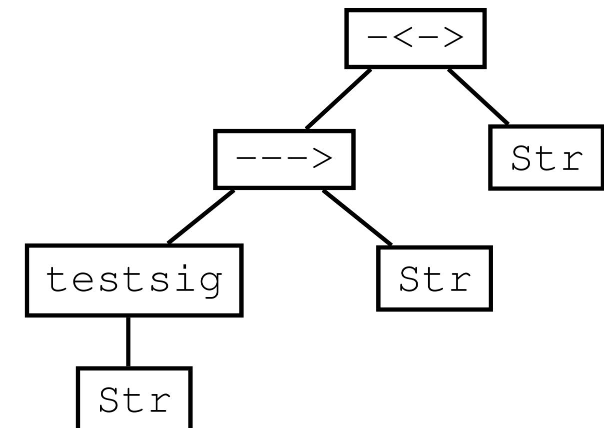
How? (Again arrows and `=:` are infix notation)



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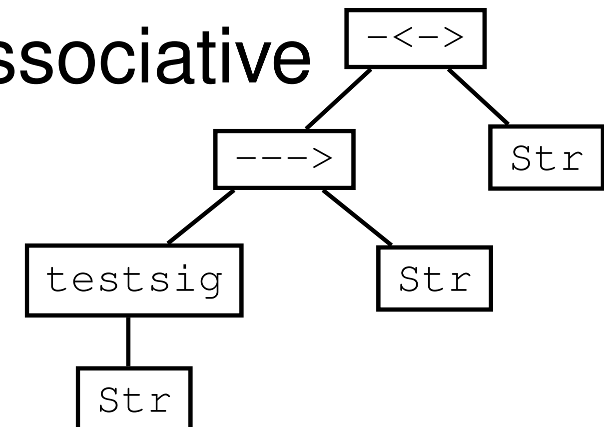
How? (Again arrows and `=:` are infix notation)

Function app. and infix arrows are left associative



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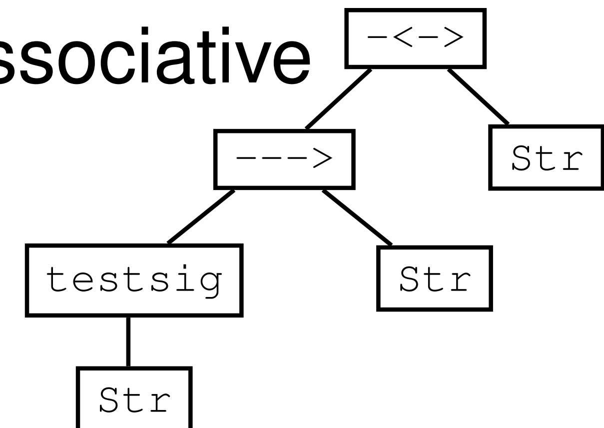

We program a DFS traversal through their definitions

Operation tests under the hood (3/3)

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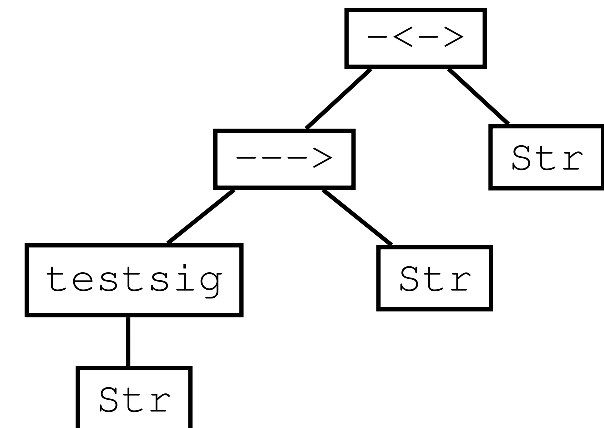
How? (Again arrows and `=:` are infix notation)

Statically typed embedding?



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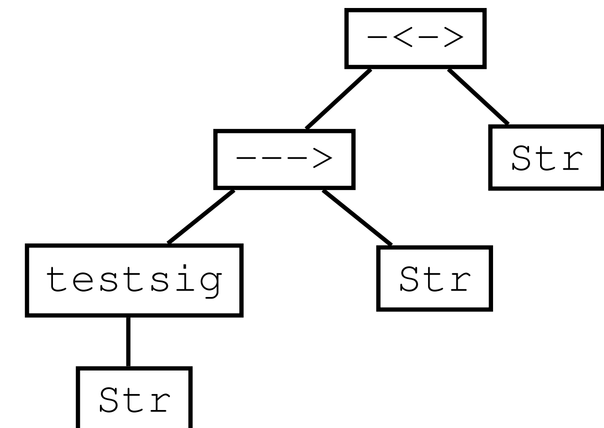
How? (Again arrows and `=:` are infix notation)

Statically typed embedding?
Utilize CPS's result-type polymorphism
(a'la Danvy:JFP98's printf)



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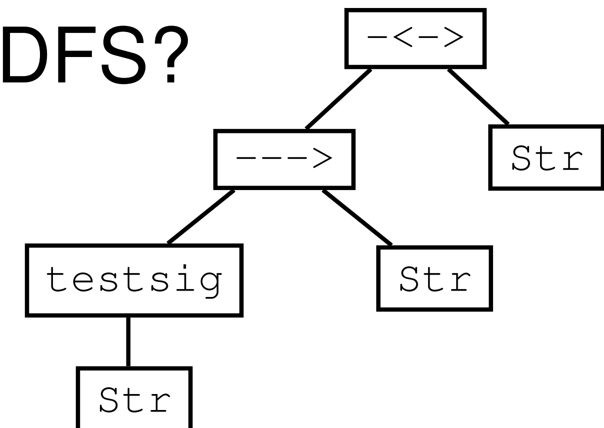
Q: Add args with `pw_left` or `pw_right` in the DFS?



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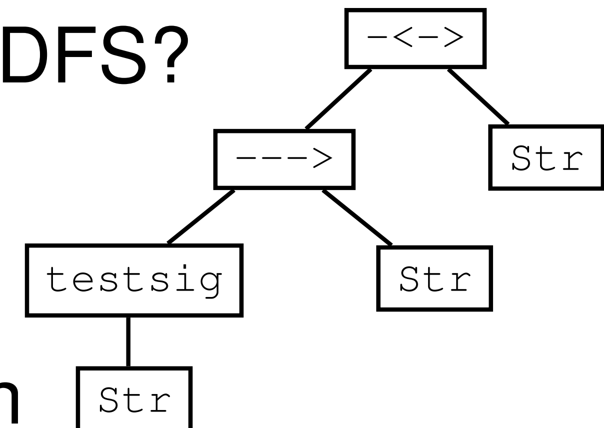
How? (Again arrows and `=:` are infix notation)

Q: Add args with `pw_left` or `pw_right` in the DFS?

A: a DFS state machine

- one register stores latest argument
- two other registers accumulates both as argument-adding transformers!
- a `-<->` node switches their roles



[Demo]

DTU

Analysis prototype

We've built an analysis prototype

- Functional, written in OCaml
- One module per lattice (with associated operations)
- AST walker, written monadically
- In total: $\sim$ 5000 LOC

DTU

Quickcheck implementation effort

Quickcheck impl. is a 372 line module:

- functor w/19 reusable lattice property tests
- EDSL code
- reusable lattices (Booleans, pairs, . . .)

Case study: 1037 LOC on top.

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Hence approx. 2 LOC / checked property

So far: no quickchecking of tree walker

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Findings

- Copy-paste error in meet of `absencelattice`
- Two non-monotone operations found and fixed (labels in `valuelattice` didn't exist in `storelattice`, lookup failure)
- Several non-strict lattice operations (fix improves precision)
- Not all operations should be strict, e.g., `PL.add`

Quickchecking is a reason to (re)consider properties

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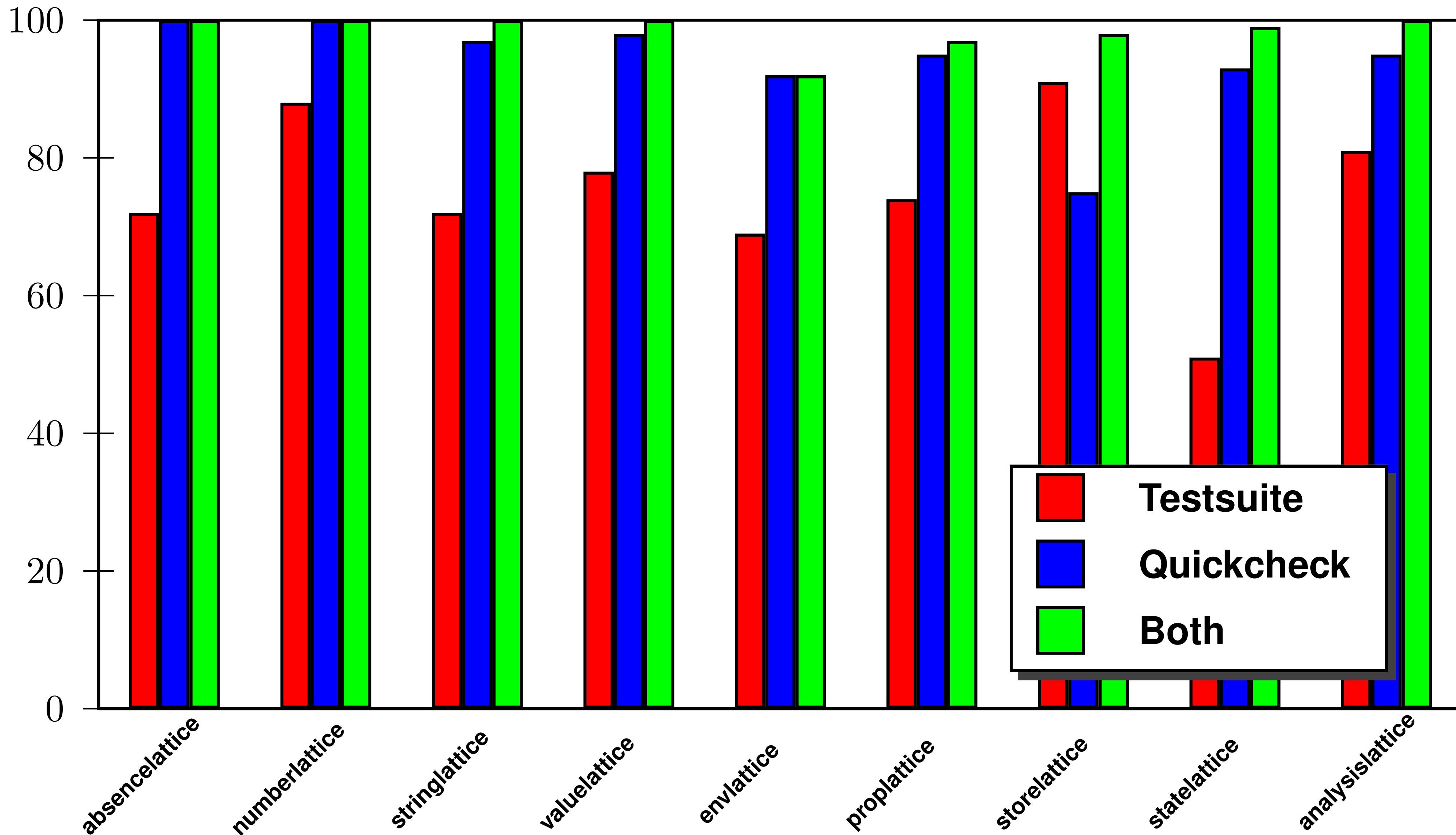
Experiment: coverage of lattice code (in %)



Excluding prettyprinters + tool frontend

Summary and conclusion

QuickCheck adds to the static analysis toolbox.

Using our approach we can check

essential static analysis properties

- which are beyond basic testing,
- in a lightweight, type-safe manner
- for increased confidence in an implementation.

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Have fun: `https://github.com/jmid/lcheck`

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Thanks