Correctness, Compositionality, Concurrency
Facets of formal program analysis

Martin Steffen

Autumn 2017

Program analysis

"process of automatically analyzing the behavior of computer programs"

- all kinds of beneficial effects. . .

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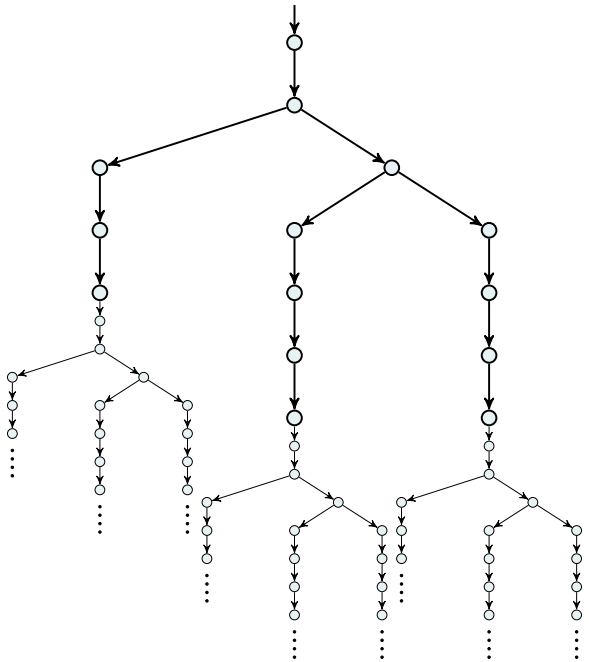
"process of automatically analyzing the behavior of computer programs"

- all kinds of beneficial effects. . .

Rice's theorem

All non-trivial, semantic properties of programs are undecidable.

The good, the bad, and the ones we can't figure out



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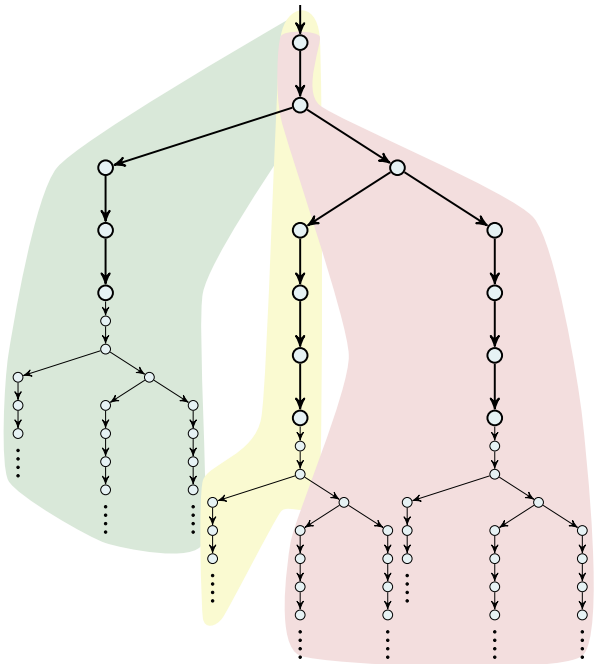
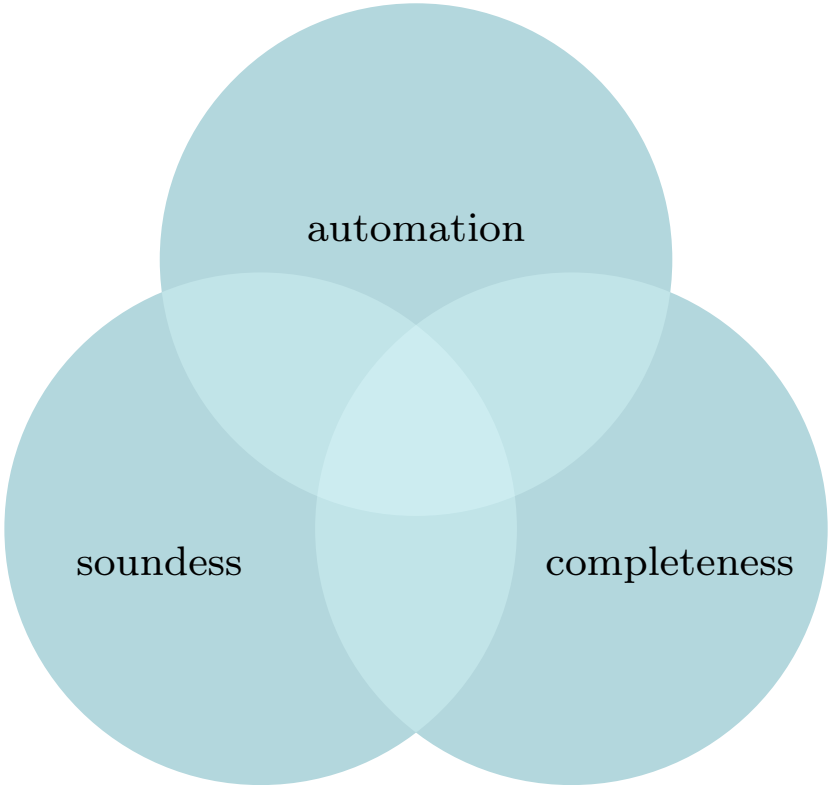
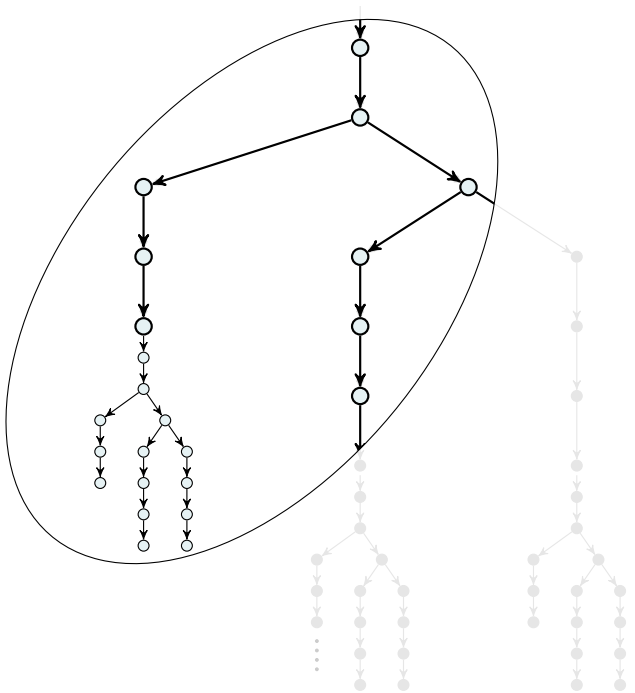
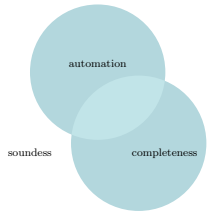


Two out of three ain't bad



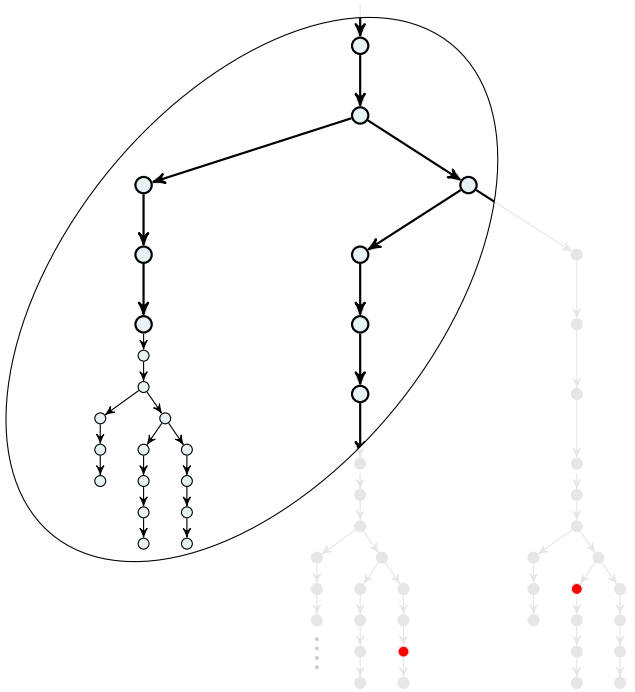
Sacrifice soundness / underapproximation

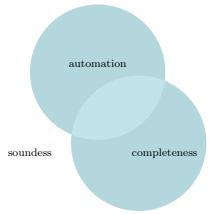




- testing (and “testing can be formal too”)
- run-time verification

Sacrifice soundness / underapproximation



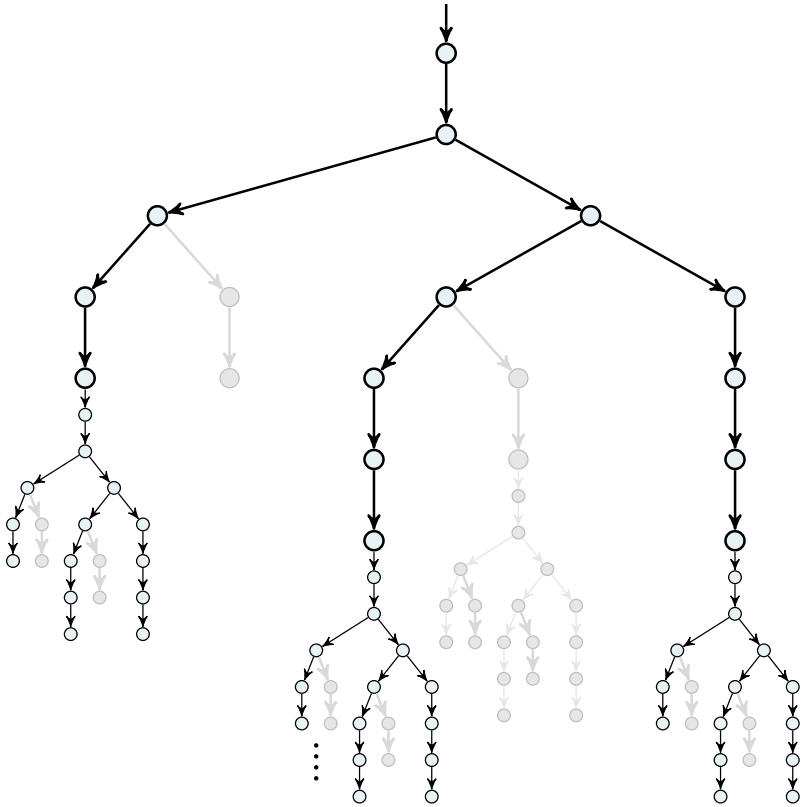


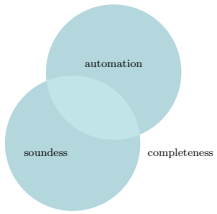
- testing (and “testing can be formal too”)
- run-time verification

Of course: one can do better than just that...

- avoiding redundant exploration (POR)
- prioritizing
  - preemption bounding
- symbolic execution
- combination with (other) static analysis

Giving up on completeness





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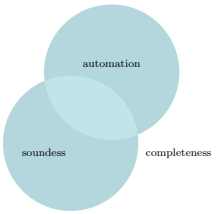
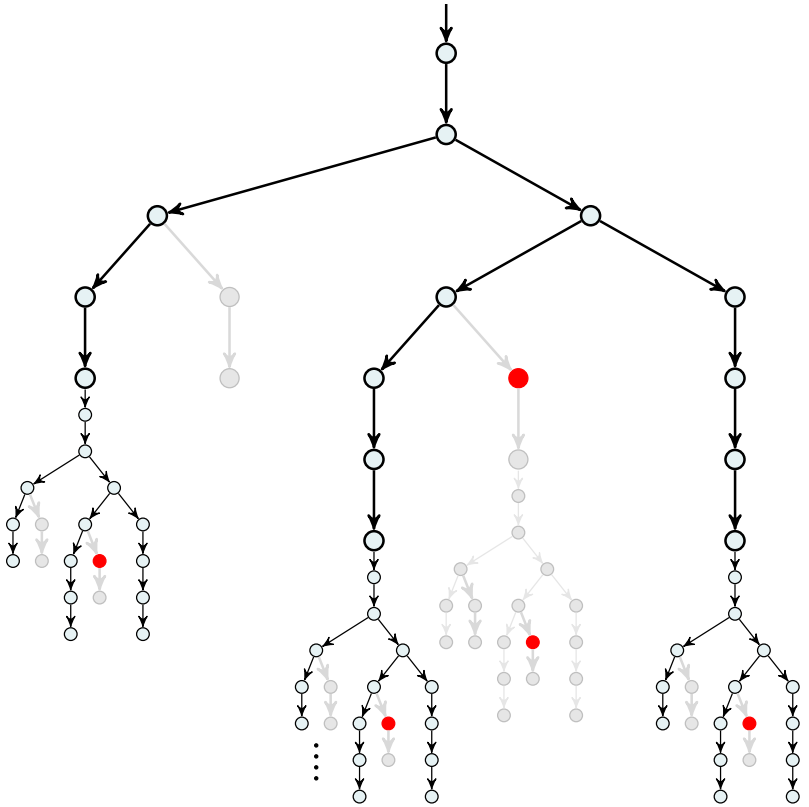


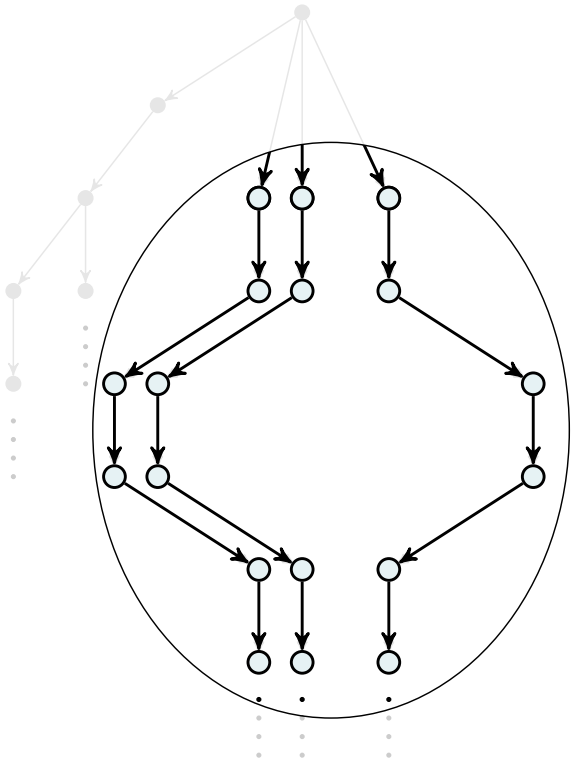


false positives

But how?

```
if x=y then skip else x:=x+1
```

Assume $(x, y) \in \{(0,0), (1,1), (0,1)\}$



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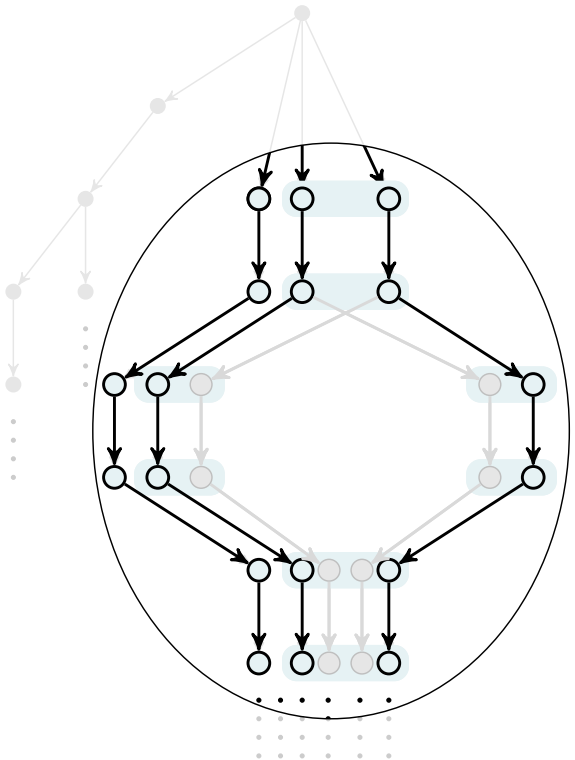
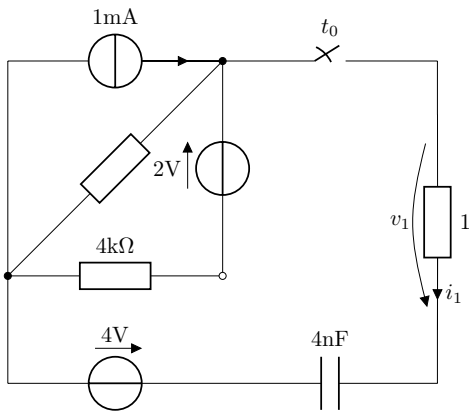
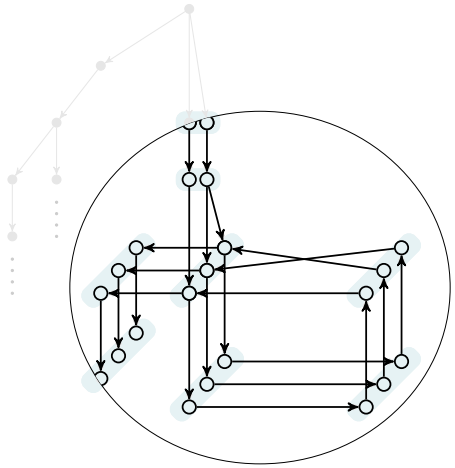


Abstraction

- abstraction ⇒ overapproximation ⇒ false positives
- lumping different “elements” together (values, program points . . .)
- *symbolic* representation
- abstract interpretation
- data flow analysis

Data flow analysis





- abstraction: “Ampere” . . .
- circuit laws (Kirchhoff)
- *stationary* solution

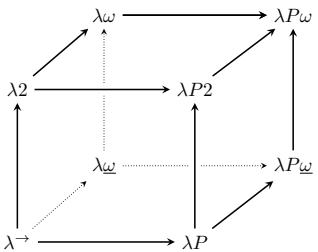
- abstraction: *sets* of values . . .
- *data flow constraints*, transfer functions
- fixpoint (μ or ν)

What's a type?

What's a type?

A **union** is a special data type available in C that allows to store different data types in the same memory location. You can define a union with many members, but only one member can contain a value at any given time. Unions provide an efficient way of using the same memory location for multiple-purpose.

What's a type?



- directive for memory allocation
- an object in a category? homotopy?
- an *abstraction?*
- formula in a HO constructive logic?

Types, flows, and effects

$$t : T$$

$$t : \texttt{Int}$$

What?

if t terminates, `Int`-value

Types, flows, and effects

$$t : T^{++}$$

What?	From where?
if t terminates, `Int`-value	data flow

Types, flows, and effects

$$t : T^{++} :: \varphi$$

What?	From where?	During?
if t terminates, `Int`-value	data flow	effects, *while* executing

- all of it: more or less approximative

Type systems & type checking

$$\Gamma \vdash t : T$$

- derivation systems

$$\dfrac{\dfrac{\dfrac{A, B \vdash A \qquad A, B \vdash B}{A, B \vdash A \wedge B}}{A \vdash B \to A \wedge B}}{\vdash A \to B \to A \wedge B}$$

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- derivation systems

$$\dfrac{\dfrac{\dfrac{x_1{:}T_1, x_2{:}T_2 \vdash x_1 : T_1 \qquad x_1{:}T_1, x_2{:}T_2 \vdash x_2 : T_2}{x_1{:}T_1, x_2{:}T_2 \vdash (x_1, x_2) : T_1 \times T_2}}{x_1{:}T_1 \vdash \lambda x_2{:}T_2.(x_1, x_2) : T_2 \to T_1 \times T_2}}{\vdash \lambda x_1{:}T_1.\lambda x_2{:}T_2.(x_1, x_2) : T_1 \to T_2 \to T_1 \times T_2}$$

Type checking

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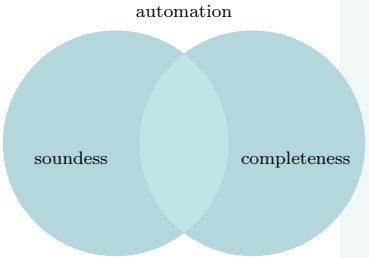
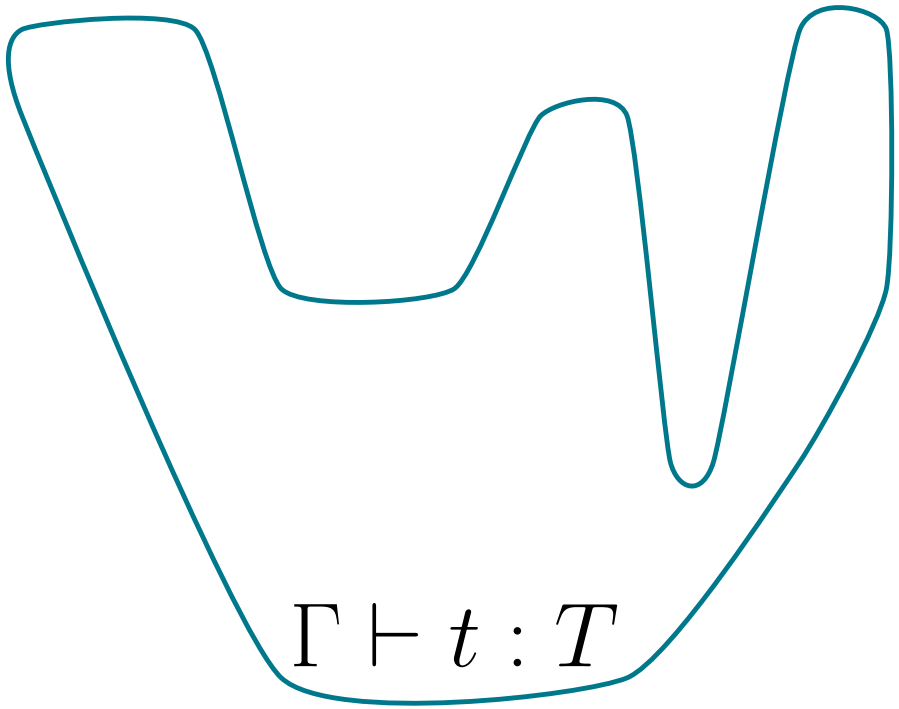
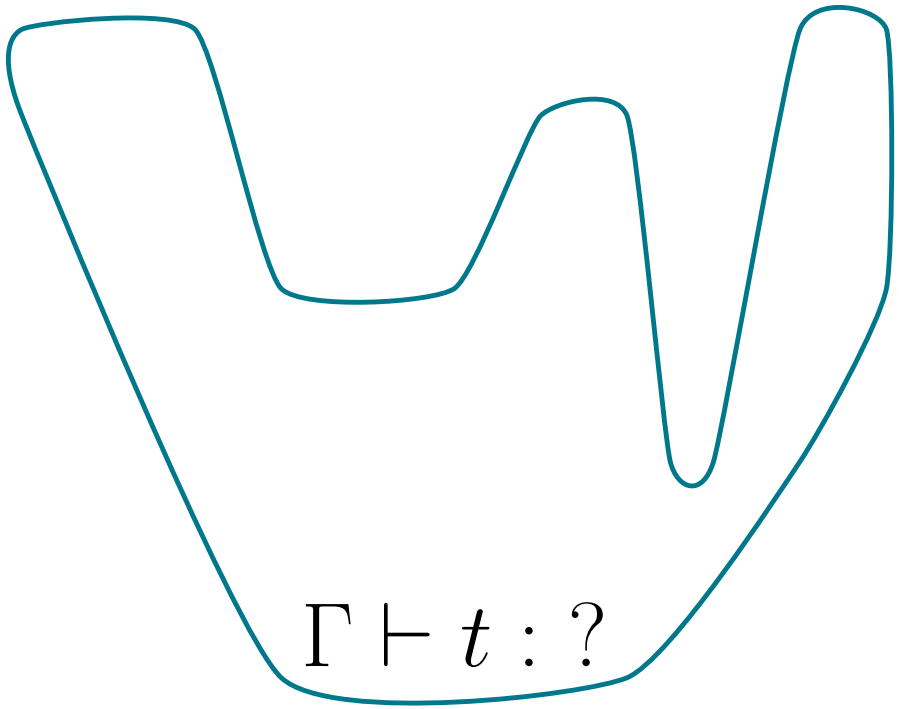




Type inference

$$\Gamma \vdash t : ?$$



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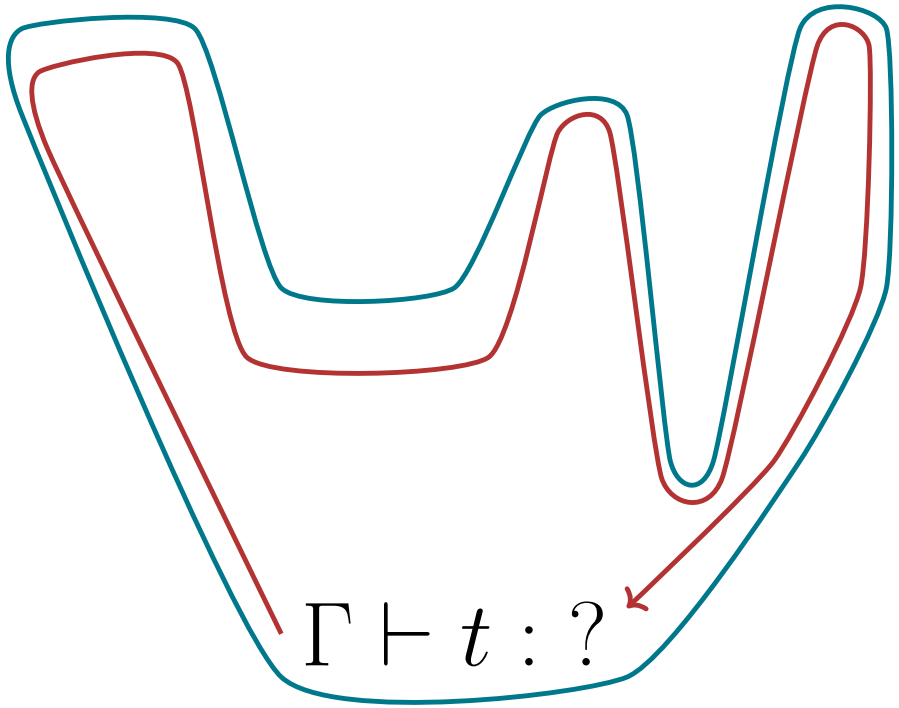

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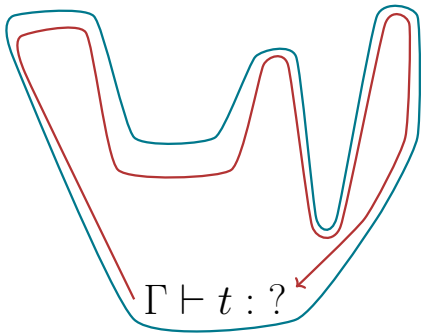
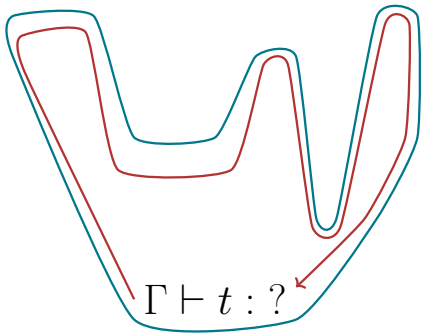


- *unification*
- decidability?
- cf. synthesized and inherited attributes

Type inference



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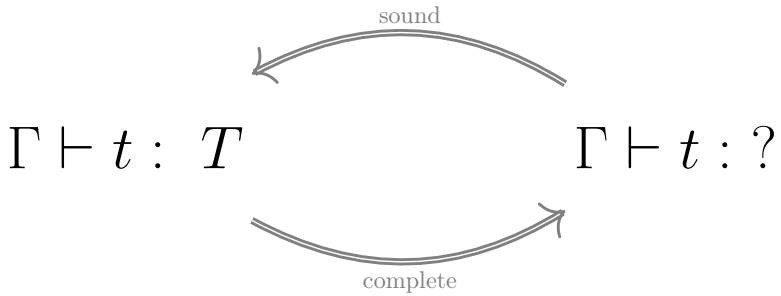

And for flows and effects?

$$\hat{\Gamma} \vdash t : \hat{T} :: \varphi$$

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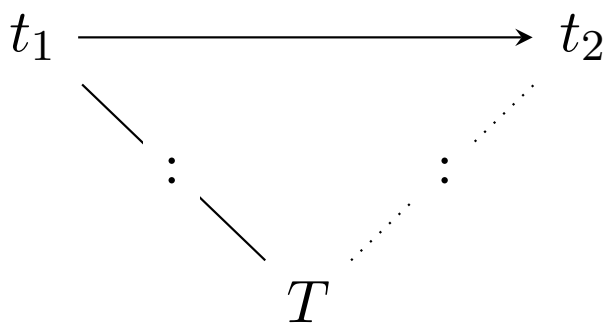
- adding constraints
- for flows: *simple* constraints

Correctness

Milner's dictum ("type safety" / "static typing")

Well-typed programs cannot go wrong!



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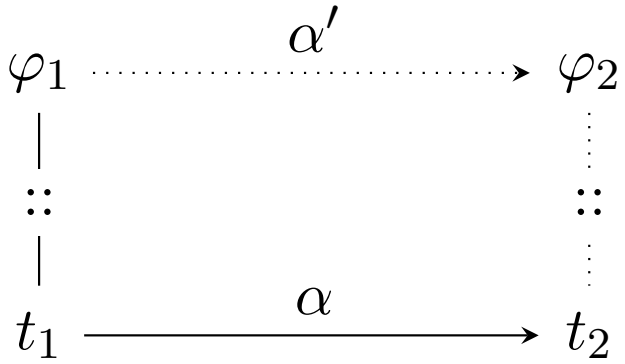

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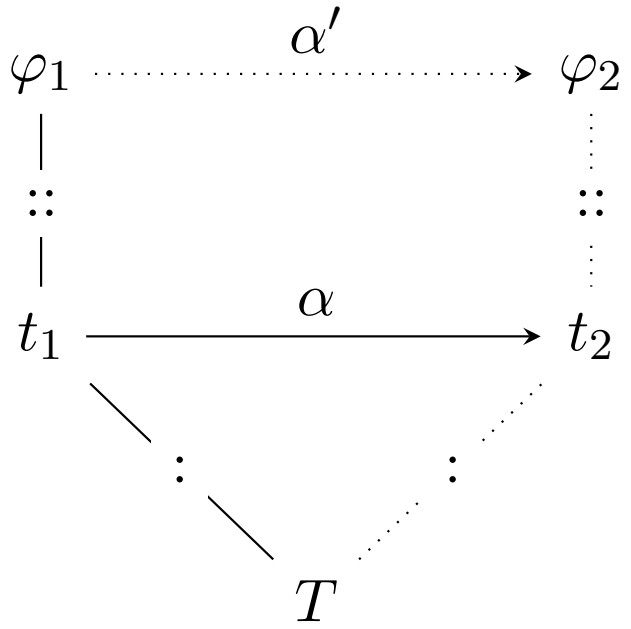
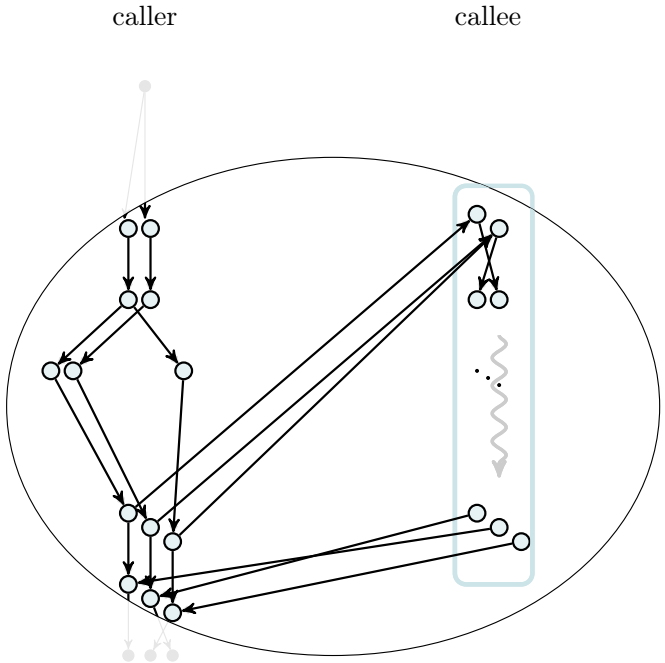


Context-sensitivity

- treat function calls “properly” (= dependent on call-site)



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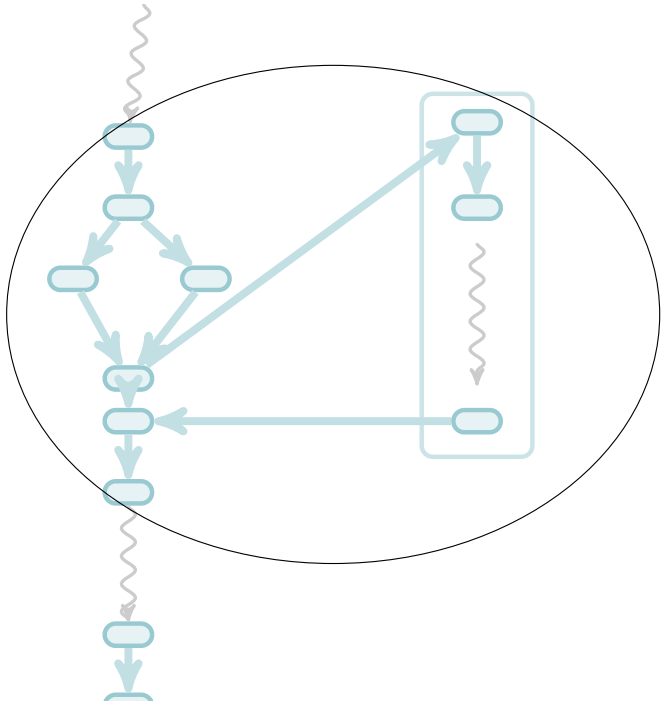

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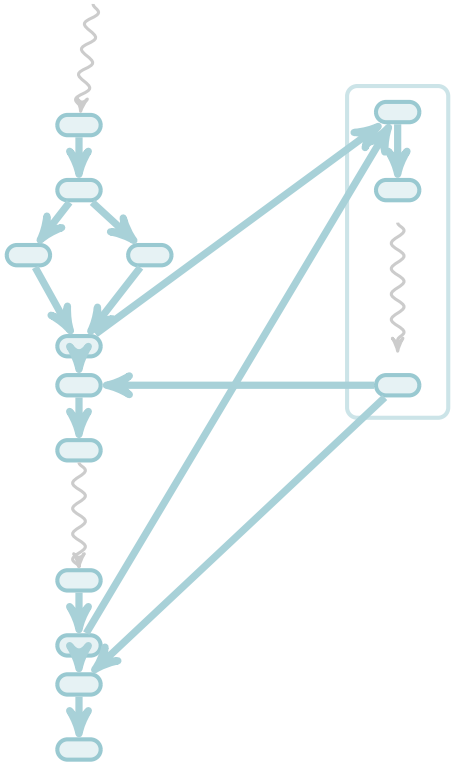

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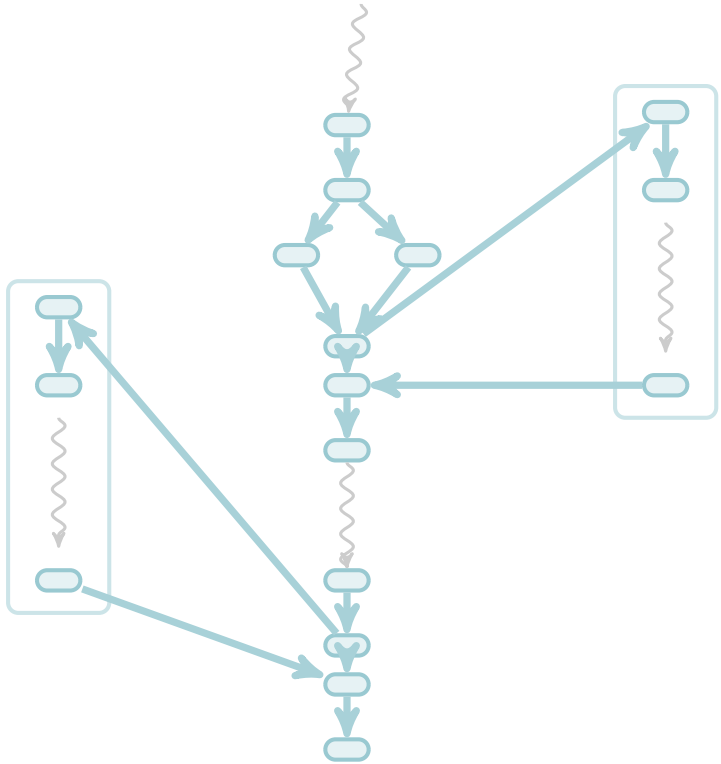

Compositional accounts and "polymophism"

- context-sensitive:function analysis distinguishing different call-sites

constrained universally quantified types

$$\forall Y \quad .\hat{T}$$

cf.

- *type schemes* in ML-polymorphmism and
- bounded quantification $\forall Y \leq T_1.T_2$ in $F_{\leq}$ ...

Compositional accounts and "polymophism"

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constrained universally quantified types

$$\forall Y : C.\hat{T}$$

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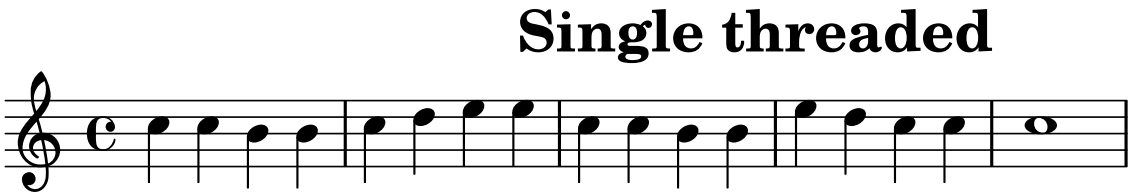
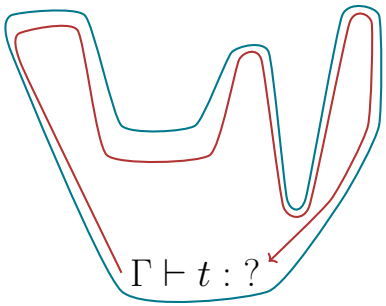
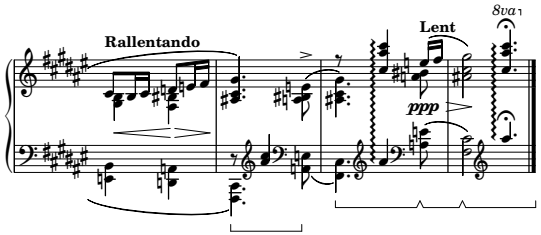
Program analysis





- types: basically *single threaded*
- structural analysis of *program code*

Concurrency and analysis



New kinds of errors

- races
- deadlocks
- starvation
- ...

Analyses get more hairy

- reproducability ("Heisenbugs")
- interference vs. isolation
- state space explosion problem

Illustration: Deadlock analysis

- given: multi-threaded calculus
- types and effects for lock interaction

$Y ::= \varrho \mid X$	type-level variables
$r ::= \varrho \mid \{\pi\} \mid r \sqcup r$	lock/label sets
$\hat{T} ::= B \mid \mathtt{L}^r \mid \hat{T} \xrightarrow{\varphi} \hat{T}$	types
$\hat{\sigma} ::= \forall \vec{Y}{:}C.\ \hat{T} \xrightarrow{\varphi} \hat{T} \mid \hat{T}$	type schemes
$C ::= \emptyset \mid \varrho \sqsupseteq r, C \mid \epsilon \sqsupseteq \varphi, C$	simple constraints

Deadlocks (2)

- two level approach

  local type and effect system

  global state exploration (à la model checking)

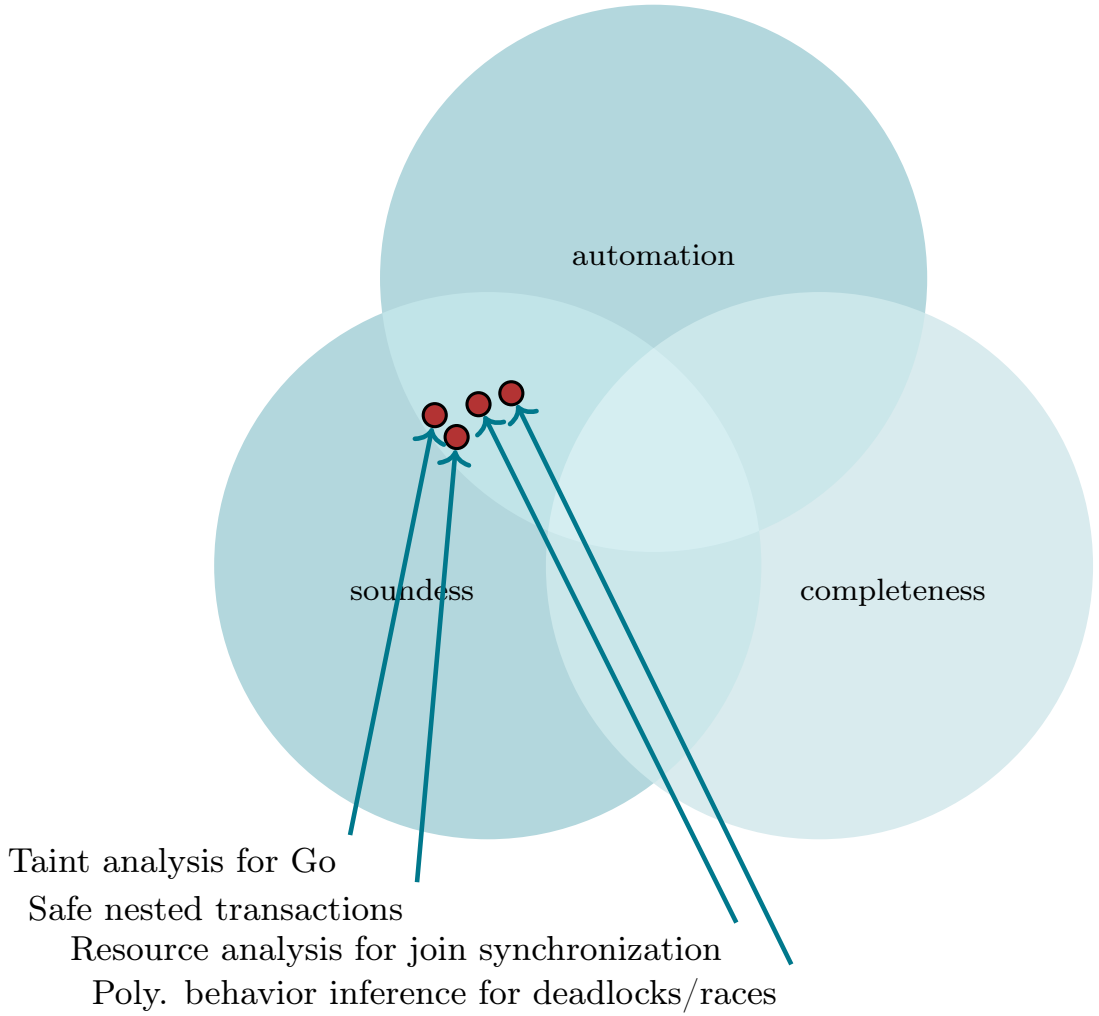
- flows: tracing lock instances (rudimentary *alias* analysis)

Processes as effects

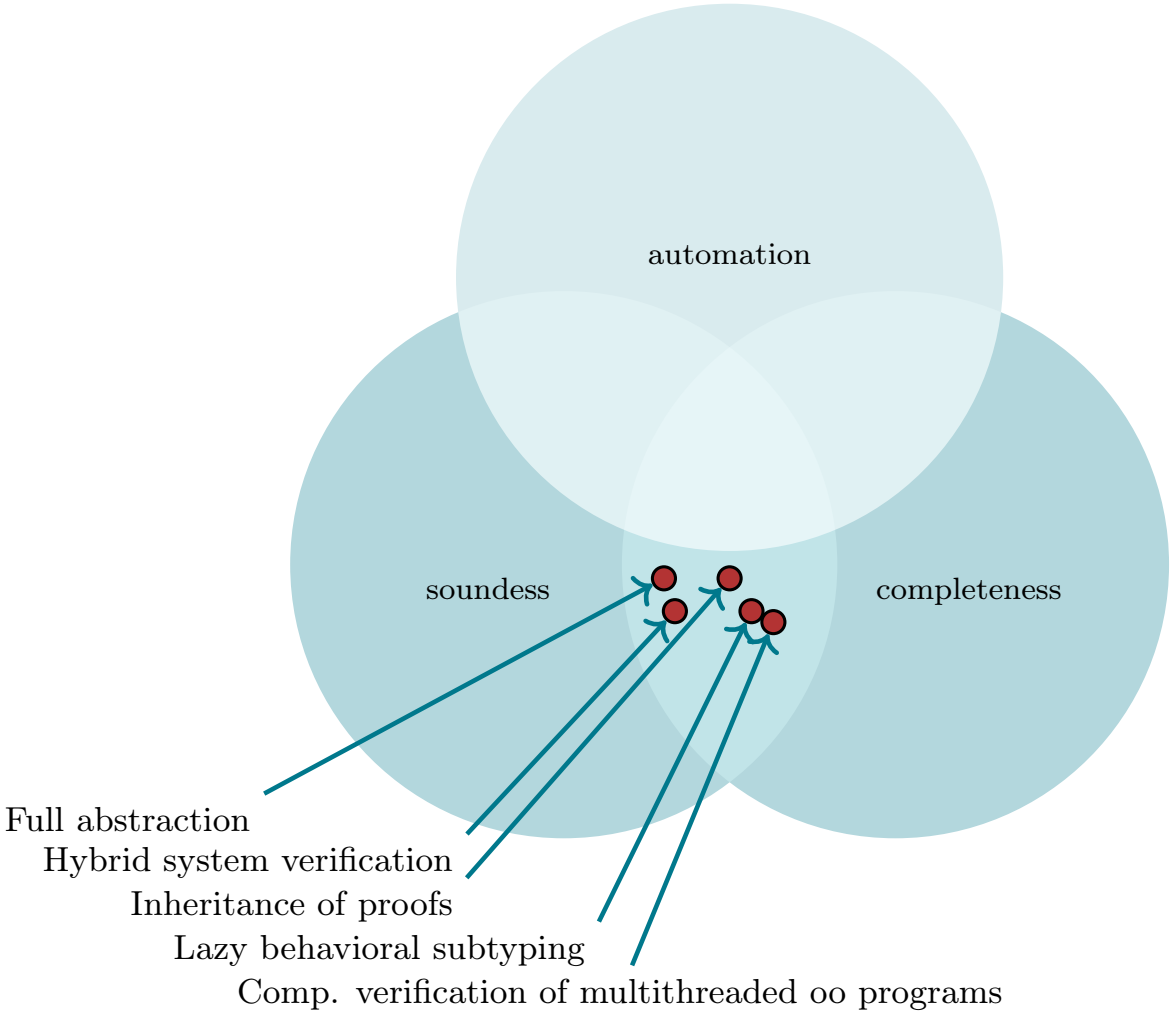
Abstracting approximative lock interaction of one thread into an"abstract process" (as in process algebra)

- correctness: deadlock-sensitive simulation
- further abstractions: bounded call stack

Type & effect systems



Proof systems for program verification



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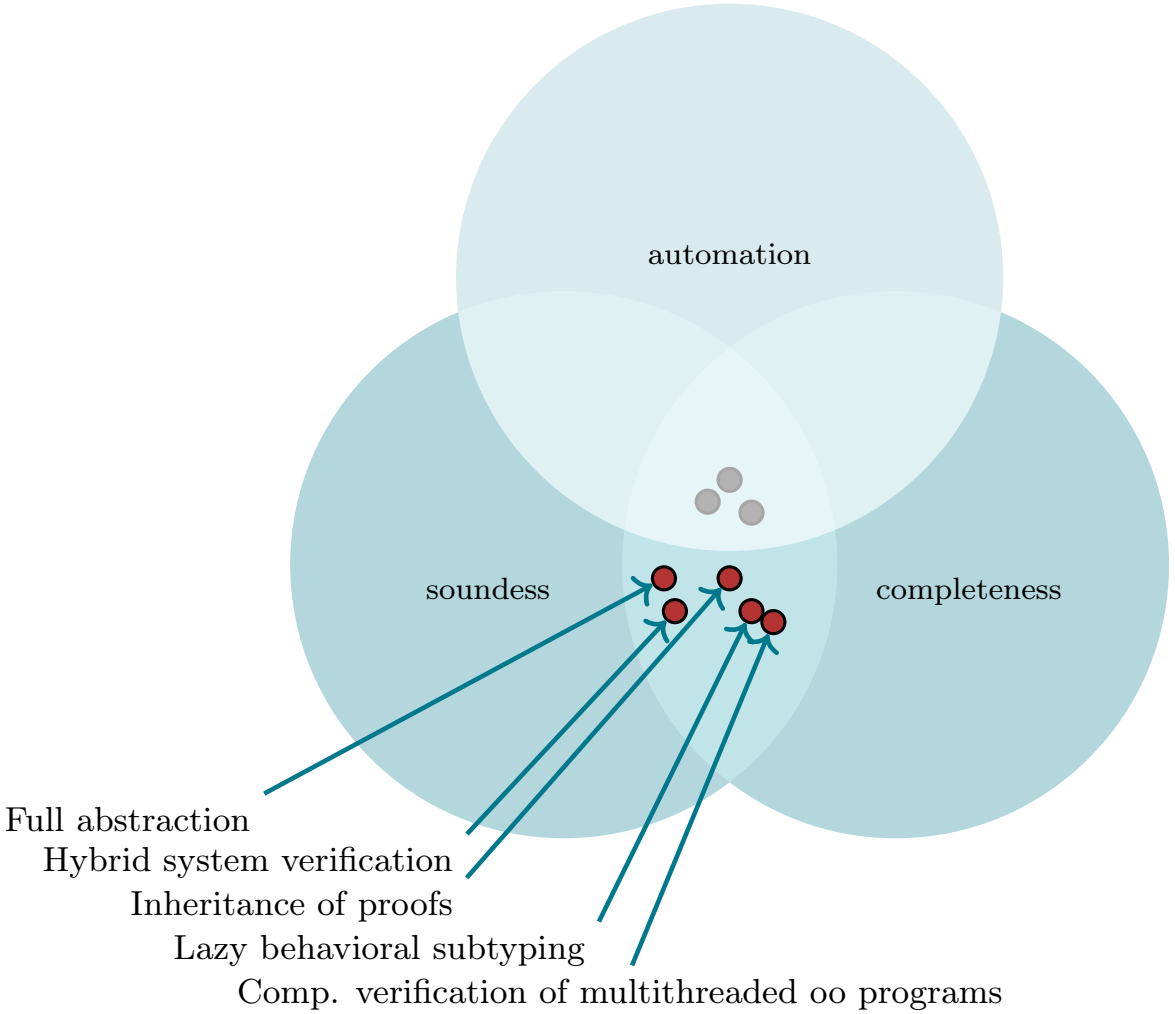
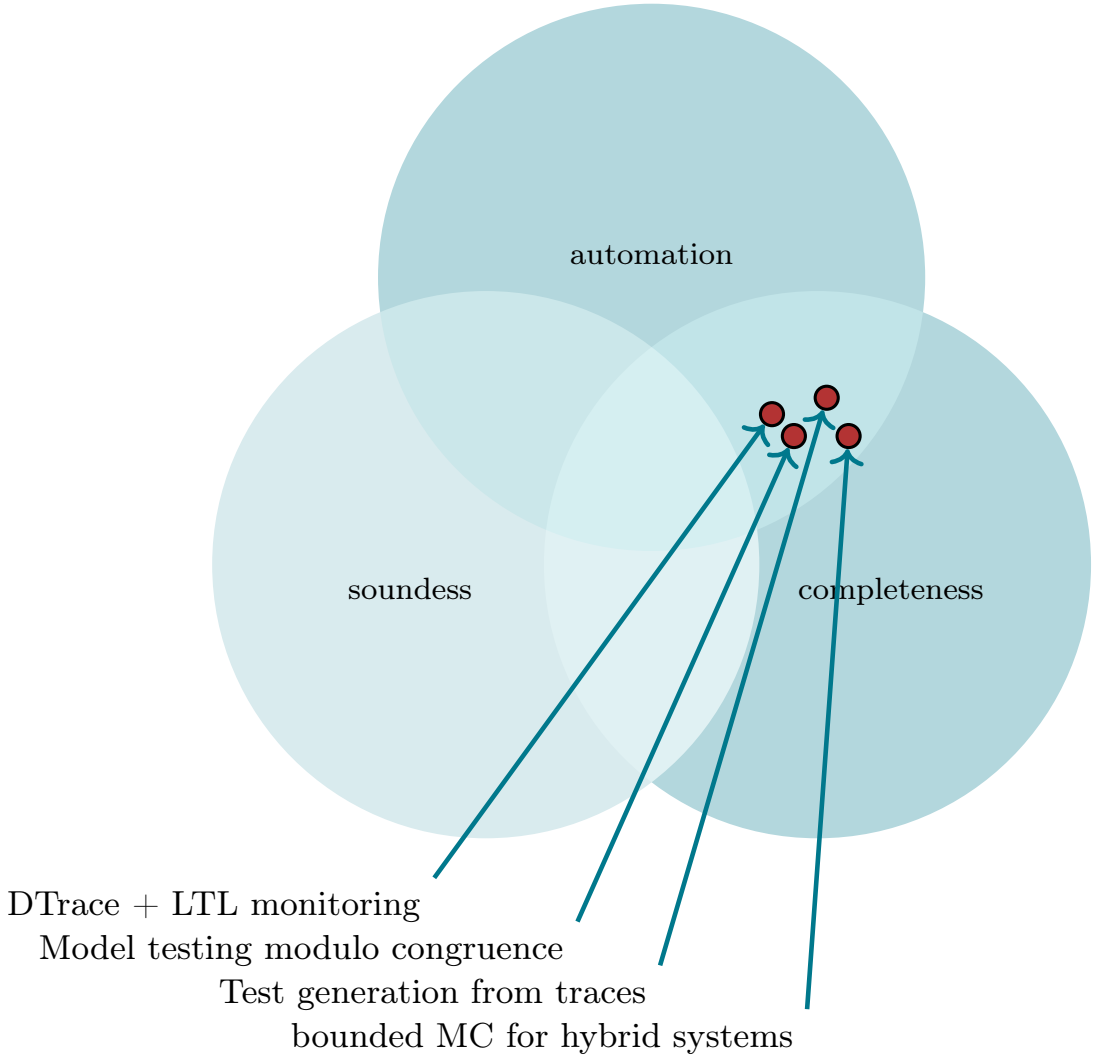


Run-time veryification, testing, BMC



Miscellaneous

- railway design verification (with datalog)
- full abstraction
- protocol verification (model checking, SDL) and engineering
- parametric model checking (rewriting theory, transducers)
- timed ambients & π-calculus (semantics, assumption-commitement type system for resources)
- semantics of weak memory models
- Petri-net semantics for concurrent actor language

Kudos

Slides were done with emacs *org-mode*, LaTeX, TikZ (and a bit Lilypond).

References I

Bibliography

[1] Ábrahám, E., de Boer, F. S., de Roever, W.-P., and Steffen, M. (2003). Inductive proof-outlines for monitors in Java. In Najm, E., Nestmann, U., and Stevens, P., editors, *FMOODS '03*, volume 2884 of *Lecture Notes in Computer Science*, pages 155–169 (15 pages). Springer Verlag. A longer version appeared as technical report TR-ST-03-1, April 2003.

[2] Ábrahám-Mumm, E., de Boer, F. S., de Roever, W.-P., and Steffen, M. (2002a). A tool-supported proof system for monitors in Java. In Bonsangue, M. M., de Boer, F. S., de Roever, W.-P., and Graf, S., editors, *FMCO 2002*, volume 2852 of *Lecture Notes in Computer Science*, pages 1–32 (33 pages). Springer Verlag.

[3] Ábrahám-Mumm, E., de Boer, F. S., de Roever, W.-P., and Steffen, M. (2002b). Verification for Java's reentrant multithreading concept. In Nielsen, M. and Engberg, U. H., editors, *Proceedings of FoSSaCS 2002*, volume 2303 of *Lecture Notes in Computer Science*, pages 4–20 (17 pages). Springer Verlag. A longer version, including the proofs for soundness and completeness, appeared as Technical Report TR-ST-02-1, March 2002.

[4] Bodden, E., Pun, K. I., Steffen, M., Stolz, V., and Wickert, A.-K. (2016). Information flow analysis for Go. In Margaria, T. and Steffen, B., editors, *7th International Symposium On Leveraging Applications of Formal Methods, Verification and Validation (ISOLA'16)*, volume 9952 of *Lecture Notes in Computer Science*, pages 431–445. Springer Verlag.

[5] de Boer, F. S., Bonsangue, M. M., Grüner, A., and Steffen, M. (2008). Automated test driver generation for Java components. In *Netherland's Testing Day "TestDag'08", Delft*. White Paper.

[6] de Boer, F. S., Bonsangue, M. M., Grüner, A., and Steffen, M. (2009). Java test driver generation from object-oriented interaction traces. *Electronic Notes in Theoretical Computer Science*, 243:33–47 (15 pages). Special issue for the Proceedings of the 2nd International Workshop on Harnessing Theories for Tool Support in Software TTSS'08, ICTAC 2008 satellite workshop, 30. August 2008, Istambul, Turkey.

[7] Dovland, J., Johnsen, E. B., Owe, O., and Steffen, M. (2008). Lazy behavioral subtyping. In Cuellar, J., Maibaum, T., and Sere, K., editors, *Proceedings of the 15th International Symposium on Formal Methods (FM'08)*, volume 5014 of *Lecture Notes in Computer Science*, pages 52–67 (16 pages). Springer Verlag.

References II

[8] Dovland, J., Johnsen, E. B., Owe, O., and Steffen, M. (2009). Incremental reasoning for multiple inheritance. In *Proceedings of the 7th International Conference on integrated Formal Methods (iFM'09), Düsseldorf, Germany, 16 – 19 February, 2009*, volume 5423 of *Lecture Notes in Computer Science*, pages 215–230. Springer Verlag.

[9] Dovland, J., Johnsen, E. B., Owe, O., and Steffen, M. (2010). Lazy behavioral subtyping. *Journal of Logic and Algebraic Programming*, 79(7):578–607. 30 pages. Article in Press, Preprint available at doi:10.1016/j.jlap.2010.07.008. Presented at the 20th Nordic Workshop on Programming Theory, NWPT '08, Tallinn. A shorter conference version appeared in the Proceedings of the 15th International Symposium on Formal Methods (FM'08), LNCS 5014.

[10] Dovland, J., Johnsen, E. B., Owe, O., and Steffen, M. (2011). Incremental reasoning with lazy behavioral subtyping for multiple inheritance. *Science of Computer Programming*, 76:915–941.

[11] Gaudel, M.-C. (1995). Testing can be formal, too. In Mosses, P. D., Nielsen, M., and Schwarzbach, M. I., editors, *Proceedings of TAPSOFT '95*, volume 915 of *Lecture Notes in Computer Science*, pages 82–96. Springer Verlag.

[12] Hofmann, M., Naraschewski, W., Steffen, M., and Stroup, T. (1998). Inheritance of proofs. *Theory and Practice of Object Systems (Tapos), Special Issue on the Third Workshop on Foundations of Object-Oriented Languages (FOOL 3, LICS and Federated Logic Conferences Workshop), July 1996*, 4(1):51–69 (19 pages). An extended version appeared as Interner Bericht, Universität Erlangen-Nürnberg, IMMDVII-5/96.

[13] Johnsen, E. B., Mai Thuong Tran, T., Owe, O., and Steffen, M. (2012a). Safe locking for multi-threaded Java. In *Proceedings of the International Conference on Foundations of Software Engineering (Theory and Practice) (FSEN'11)*, volume 7141 of *Lecture Notes in Computer Science*, pages 158–173. Springer Verlag.

[14] Johnsen, E. B., Mai Thuong Tran, T., Owe, O., and Steffen, M. (2012b). Safe locking for multi-threaded Java with exceptions. *Journal of Logic and Algebraic Programming, special issue of selected contributions to NWPT'10*. Available online 3. March 2012.

[15] Mai Thuong Tran, T., Owe, O., and Steffen, M. (2010). Safe typing for transactional vs. lock-based concurrency in multi-threaded Java. In Pham, S. B., Hoang, T.-H., McKay, B., and Hirota, K., editors, *Proceedings of the Second International Conference on Knowledge and Systems Engineering, KSE 2010*, pages 188 – 193. IEEE Computer Society.

References III

[16] Mai Thuong Tran, T. and Steffen, M. (2010). Safe commits for Transactional Featherweight Java. In Méry, D. and Merz, S., editors, *Proceedings of the 8th International Conference on Integrated Formal Methods (iFM 2010)*, volume 6396 of *Lecture Notes in Computer Science*, pages 290–304. Springer Verlag. An earlier and longer version has appeared as UiO, Dept. of Informatics Technical Report 392, Oct. 2009.

[17] Mai Thuong Tran, T., Steffen, M., and Truong, H. (2013). Compositional static analysis for implicit join synchronization in a transactional setting. In Eleftherakis, G., Hinchey, M., and Holcombe, M., editors, *Proceedings of SEFM'13*, volume 8137 of *Lecture Notes in Computer Science*, pages 212–228. Springer Verlag.

[18] Owe, O., Steffen, M., and Torjusen, A. (2010). Model testing asynchronously communicating objects using modulo AC rewriting. In *Proceedings of the 6th Workshop on Model-Based Testing MBT'10 (ETAPS Satellite Workshop)*, pages 68–84. Elsevier Science Publishers. Electronic Notes in Theoretical Computer Science ENTCS, Volume 264, Issue 3.

[19] Pun, K. I., Steffen, M., and Stolz, V. (2012). Deadlock checking by a behavioral effect system for lock handling. *Journal of Logic and Algebraic Programming*, 81(3):331–354. A preliminary version was published as University of Oslo, Dept. of Computer Science Technical Report 404, March 2011.

[20] Pun, K. I., Steffen, M., and Stolz, V. (2013). Deadlock checking by data race detection. In *Proceedings of the 5th IPM International Conference on Fundamentals of Software Engineering (FSEN'13)*, volume 8161 of *Lecture Notes in Computer Science*, pages 34–50. Springer Verlag.

[21] Pun, K. I., Steffen, M., and Stolz, V. (2014a). Behaviour inference for deadlock checking. In *Proceeding of the 8th International Symposium on Theoretical Aspects of Software Engineering (TASE'14)*, pages 106–113. IEEE.

[22] Pun, K. I., Steffen, M., and Stolz, V. (2014b). Deadlock checking by data race detection. *Journal of Logic and Algebraic Methods in Programming*. Available online 13 August 2014, http://dx.doi.org/10.1016/j.jlamp.2014.07.003. A preliminary version was published as University of Oslo, Dept. of Computer Science Technical Report 421, October 2012, and a shorter version in the proceedings of FSEN'13.

References IV

[23] Pun, K. I., Steffen, M., and Stolz, V. (2014c). Effect-polymorphic behaviour inference for deadlock checking. In Giannakopoulou, D. and Salaün, G., editors, *Proceedings of SEFM'14*, volume 8702 of *Lecture Notes in Computer Science*, pages 50–64. Springer Verlag. A longer version is available (under the title "Lock-Polymorphic Behaviour Inference for Deadlock Checking") as UiO, Dept. of Informatics Technical Report 436, Sep. 2013.

[24] Pun, K. I., Steffen, M., and Stolz, V. (2016a). Effect-polymorphic behaviour inference for deadlock checking. *Journal of Logic and Algebraic Methods in Programming*, 85(6). A longer version is available (under the title "Lock-Polymorphic Behaviour Inference for Deadlock Checking") as UiO, Dept. of Informatics Technical Report 436, Sep. 2013.

[25] Pun, K. I., Steffen, M., Stolz, V., Wickert, A.-K., Bodden, E., and Eichberg, M. (2016b). Don't let data Go astray: A context-sensitive taint analysis for concurrent programs in Go (extended abstract). In *Proceedings of the 24nd Nordic Workshop on Programming Theory (NWPT'16)*.

[26] Pun, K. I., Steffen, M., Stolz, V., Wickert, A.-K., Bodden, E., and Eichberg, M. (2017). Gotcha: Static taint analysis for Go. *Journal of Logic and Algebraic Methods in Programming*. Under Review for a special issue with selected papers from NWPT'16.

[27] Rice, H. G. (1953). Classes of recursively enumerable sets and their decision problems. *American Mathematical Society*, 74:358–366.

[28] Rosenberg, C. M., Steffen, M., and Stolz, V. (2016). Leveraging DTrace for runtime verification. In Sánchez, C., editor, *Proceedings of the 16th International Conference on Runtime Verification, RV 2016, Madrid, Spain, September 23-30, 2016*, volume 10012 of *Lecture Notes in Computer Science*, pages 318–332. Springer Verlag.