Configurable Software Model Checking

CPAchecker

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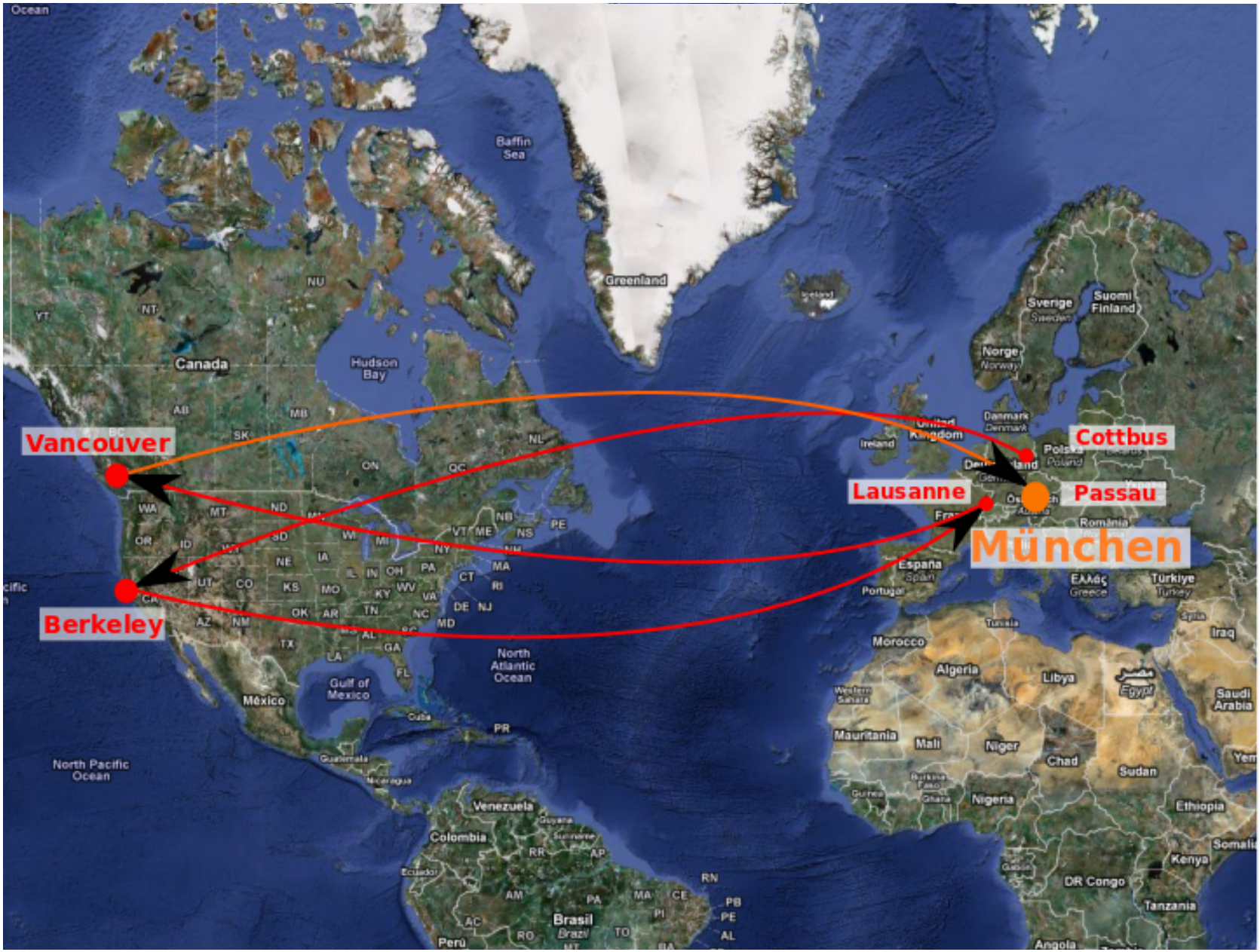
About the Speaker: Short CV

- 1998–2002 PhD on Verification of Hybrid Systems
- 2003 PostDoc at University of California, Berkeley
- 2004 PostDoc at EPFL Lausanne
- 2006 Assistant Professor at Simon Fraser University
- 2009 Professor at University of Passau
- 2016 Professor at LMU Munich

Trace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Sverige
Suomi Finland
Norge
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Portugal
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Greece
Türkiye
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Mauritania
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Niger
Chad
Sudan
Nigeria
Ethiopia
Kenya
DR Congo
Tanzania
Saudi Arabia
Iraq
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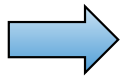
Software Verification

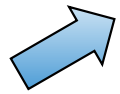
C Program

```
int main() {
    int a = foo();
    int b = bar(a);

    assert(a == b);
}
```



Verification Tool



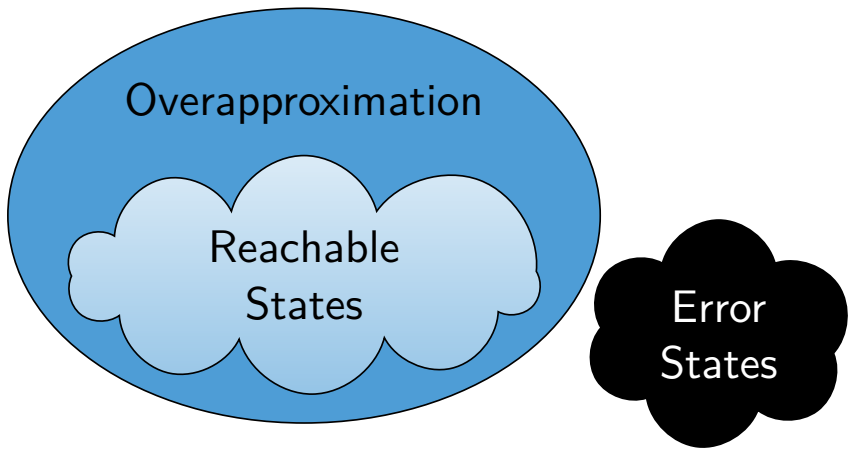
TRUE

i.e., specification is satisfied

FALSE

i.e., bug found

General method:
Create an overapproximation of the program states / compute program invariants



CPAchecker History

- 2002: BLAST with lazy abstraction refinement [9, 28]
- 2003: Multi-threading support [26]
- 2004: Test-case generation, interpolation, spec. lang. [9, 1]
- 2005: Memory safety, predicated lattices [25, 8]
- 2006: Lazy shape analysis [11]
- Maintenance and extensions became extremely difficult because of design choices that were not easy to revert
- 2007: Configurable program analysis [12, 13],
  CPAchecker was started
  as complete reimplementation from scratch [14]

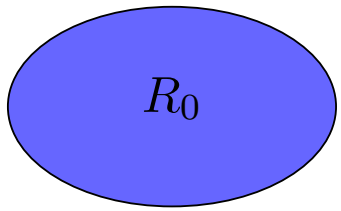
CPAchecker History (2)

- 2009: Large-block encoding [2, FMCAD '09]
- 2010: Adjustable-block encoding [15, FMCAD '10]
- 2012: Conditional model checking [10, FSE '12],
  PredAbs vs. Impact [21, FMCAD '12]
- 2013: Explicit-state MC [17, FASE '13],
  BDDs [20, STTT '14],
  precision reuse [18, FSE '13]
- ...

Software Verification by Model Checking

[24, 32, Clarke/Emerson, Queille/Sifakis 1981]

Iterative fixpoint (forward) post computation



Software Verification by Model Checking

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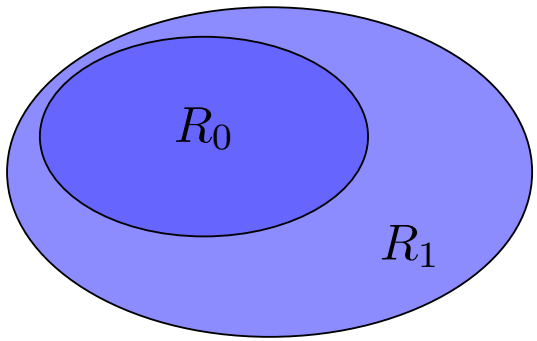

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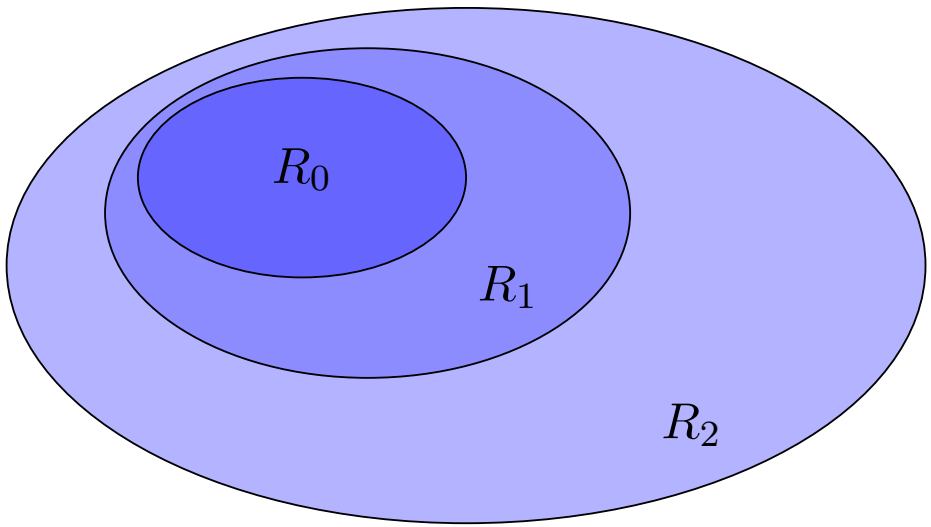

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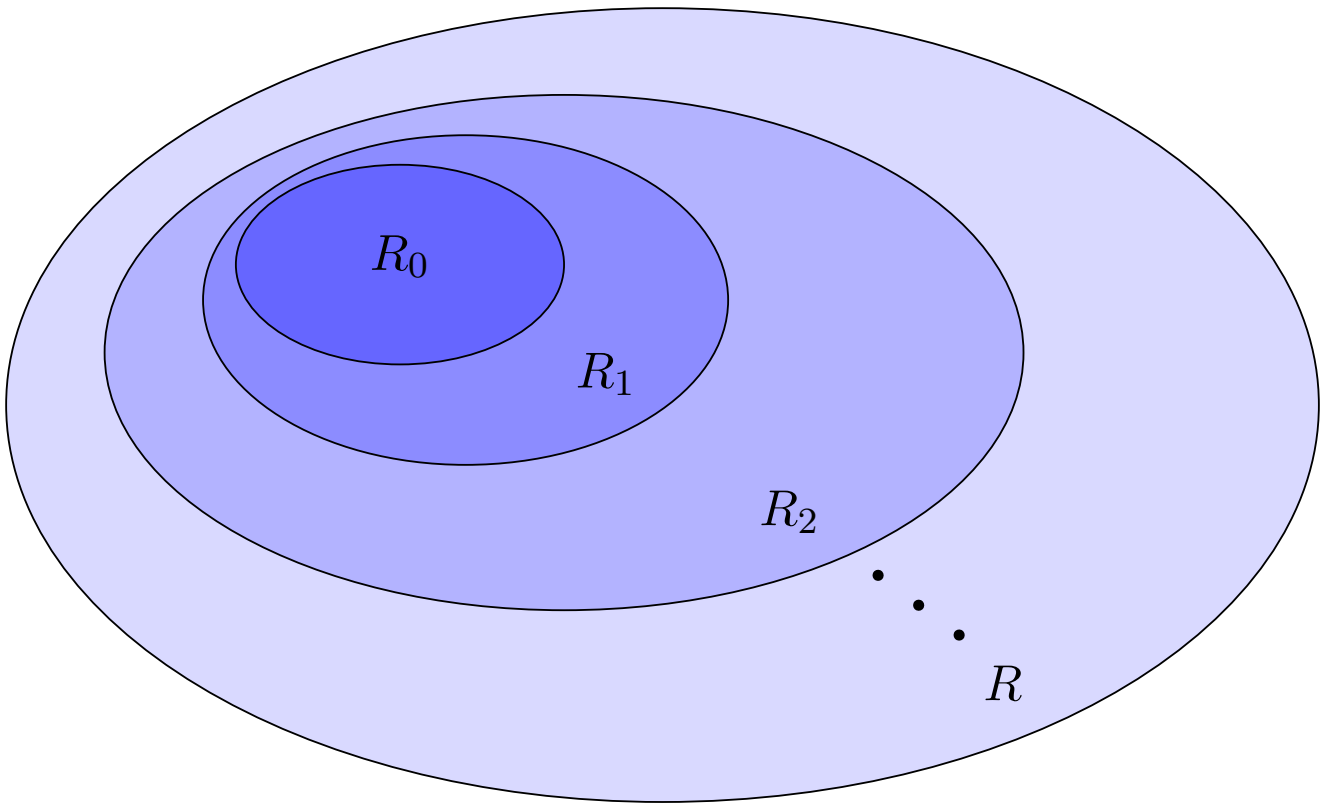


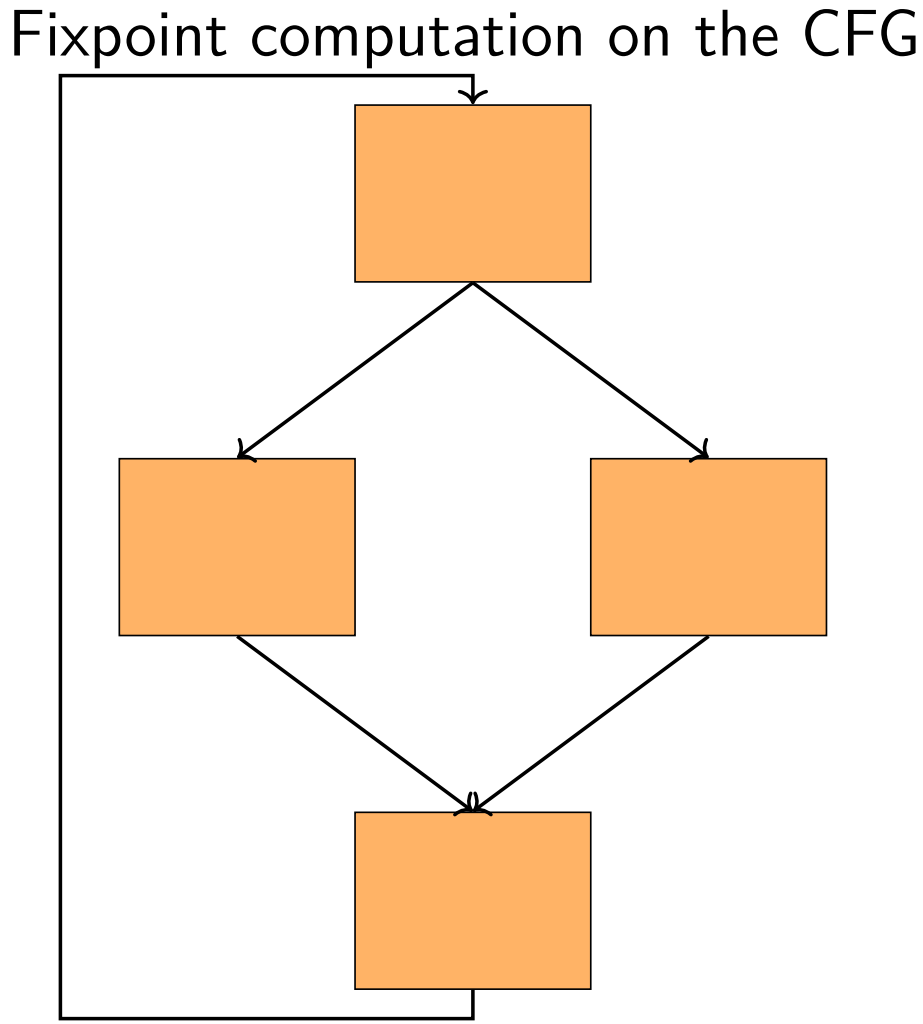
Software Model Checking

Reached, *Frontier* := $\{e_0\}$
while *Frontier* $\neq \emptyset$ **do**
  remove e from *Frontier*
  for all e' $\in$ **post**(e) **do**

    if $\neg$**stop**$(e', \mathit{Reached})$ **then**
      add e' to *Reached*, *Frontier*
return *Reached*

Software Verification by Data-Flow Analysis

[30, Kildall 1973]



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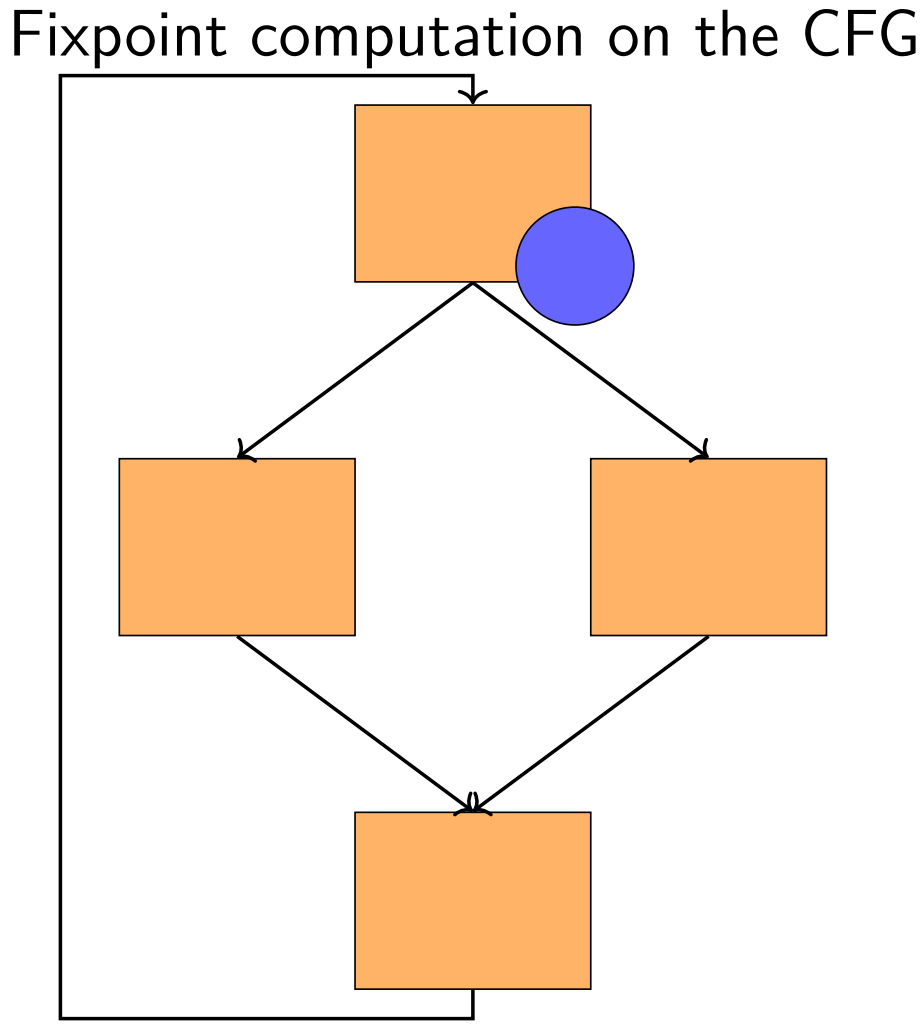

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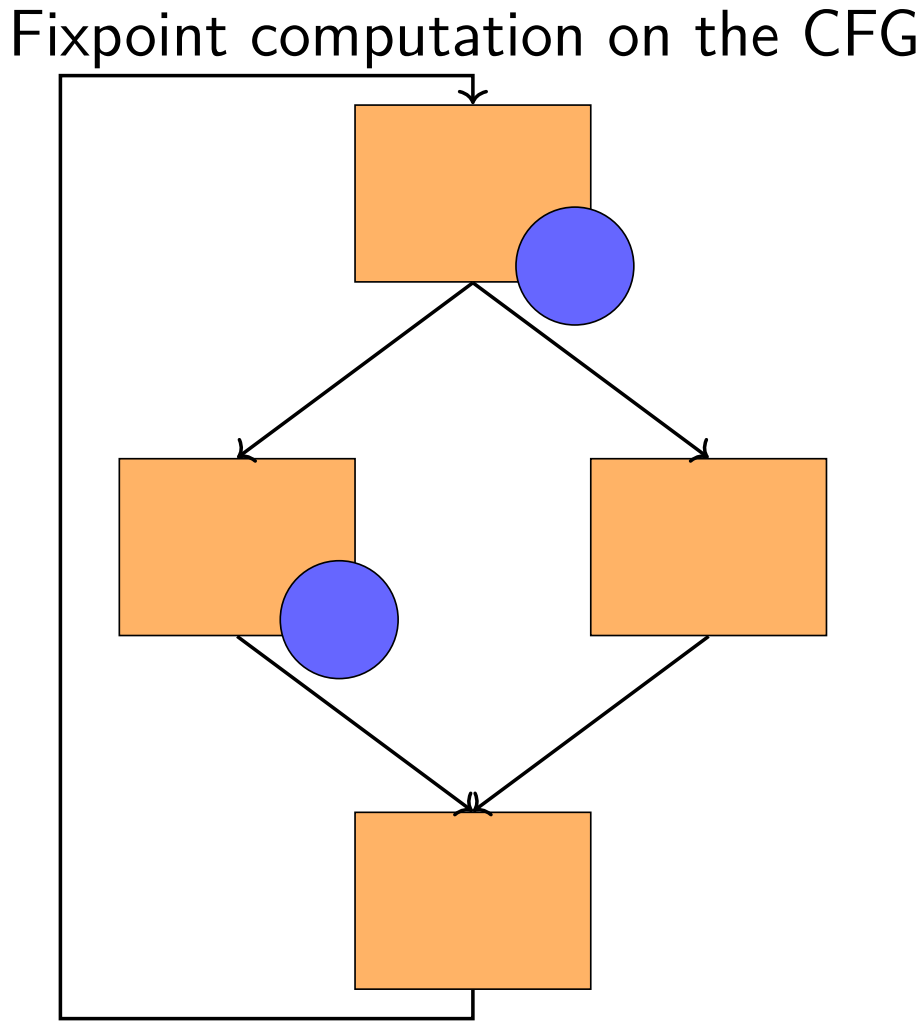

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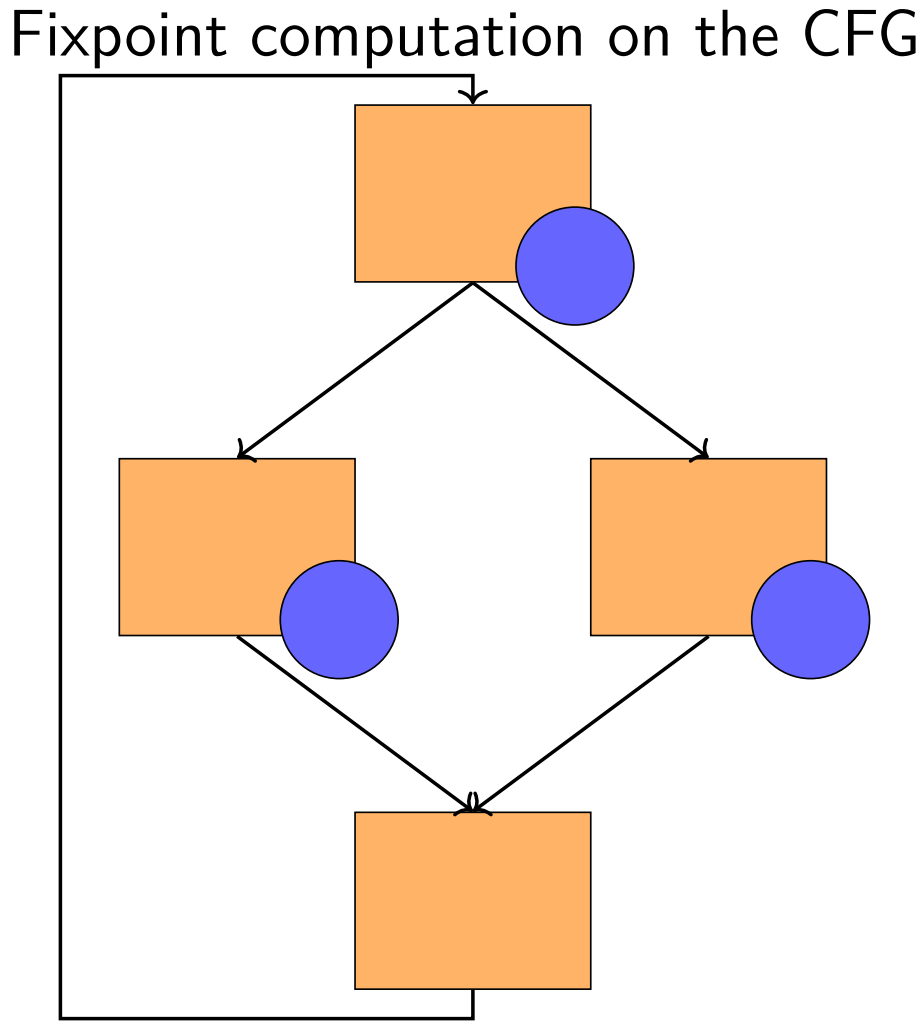

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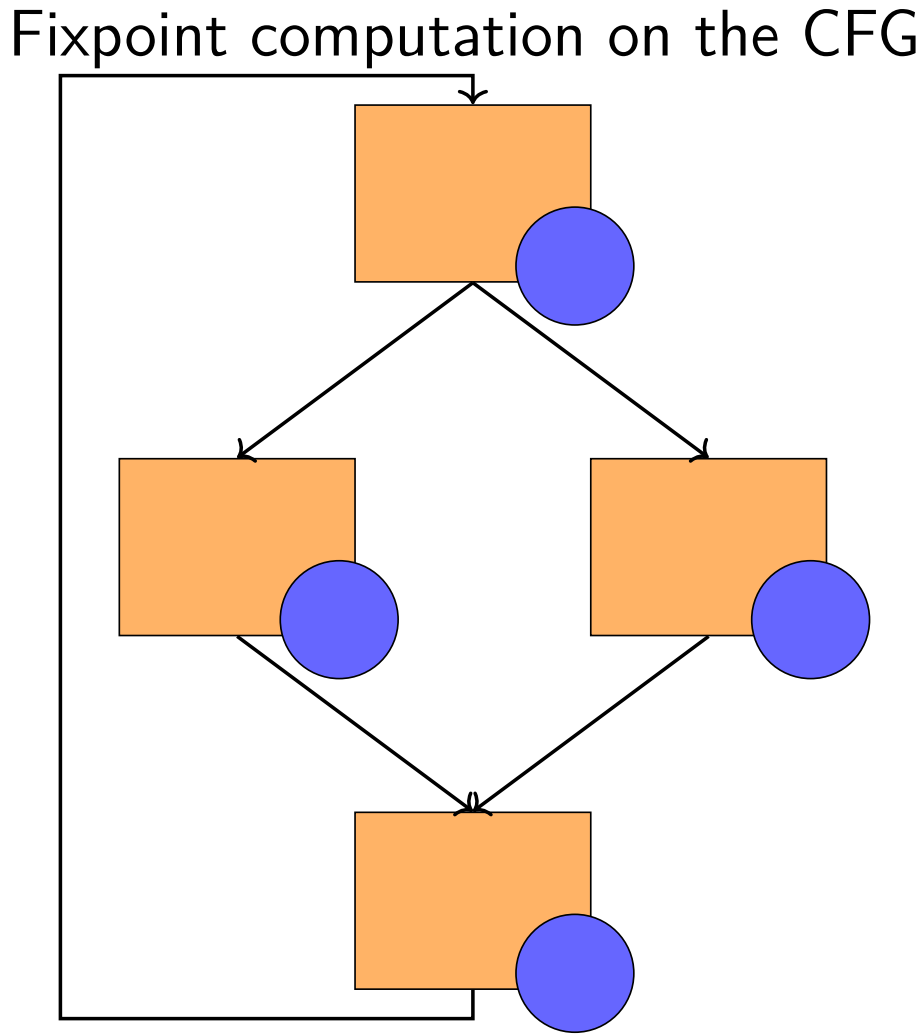

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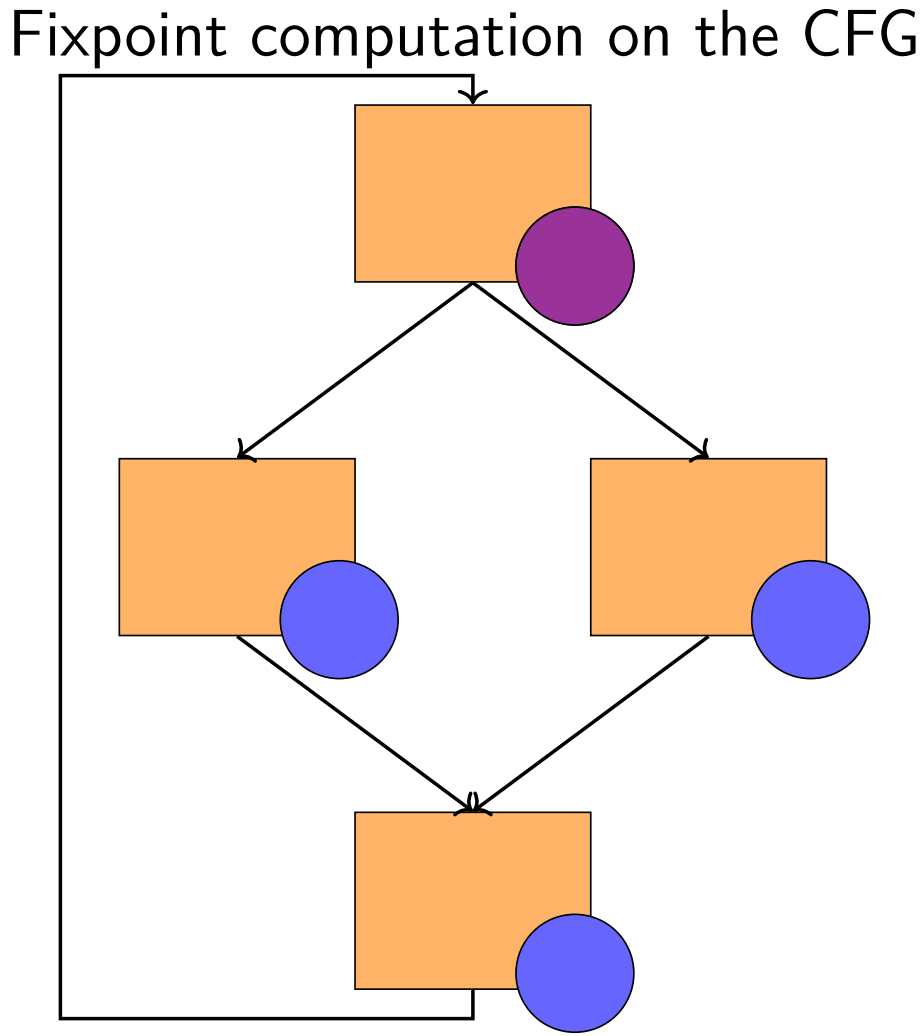

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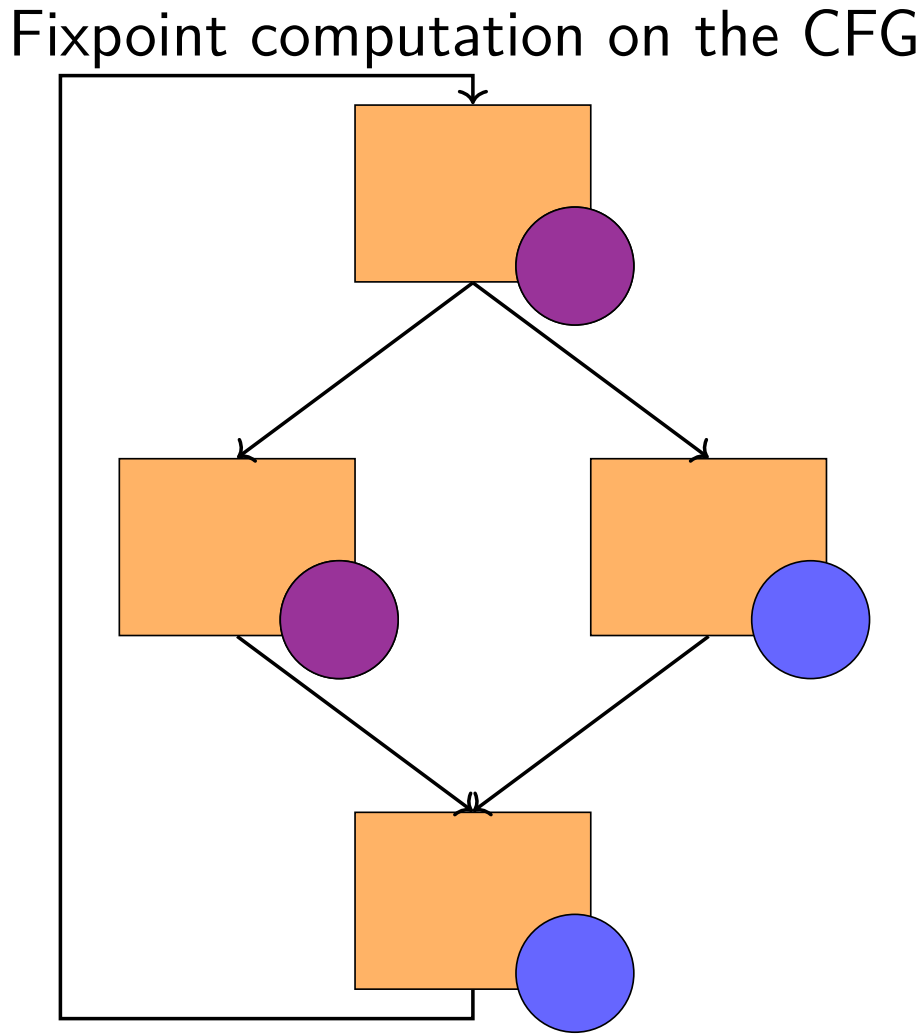

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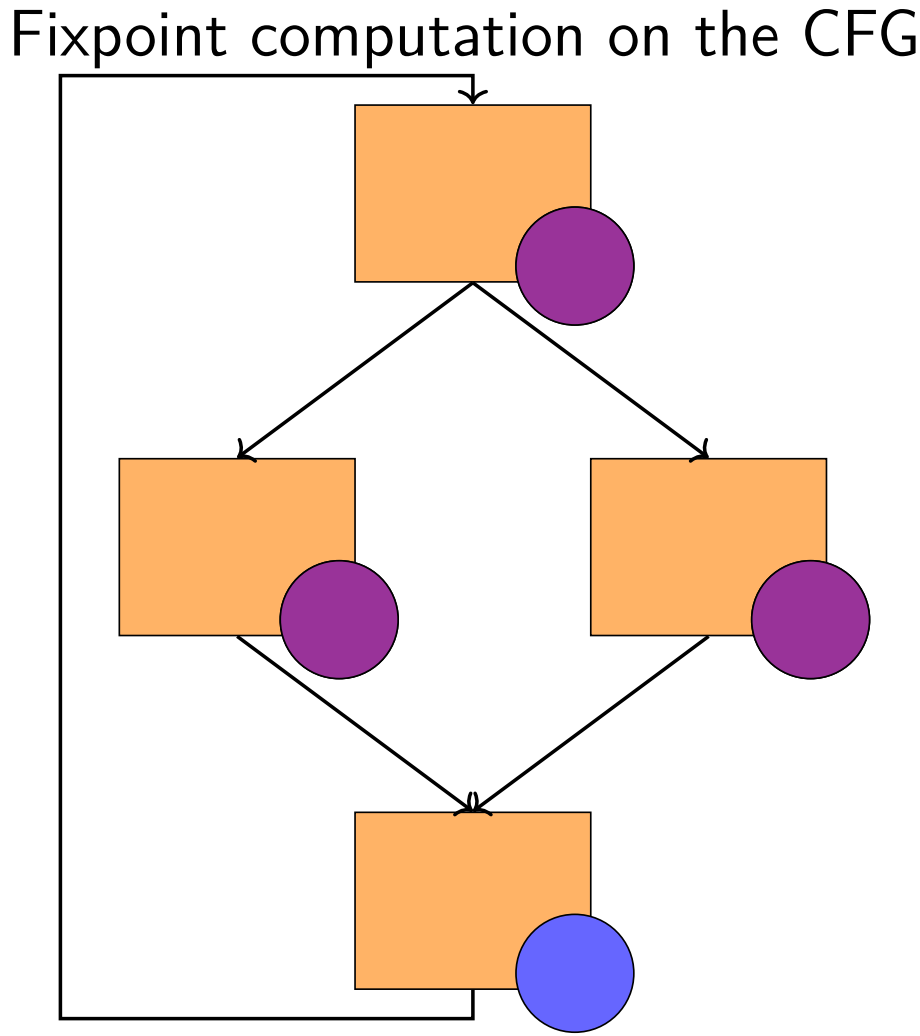

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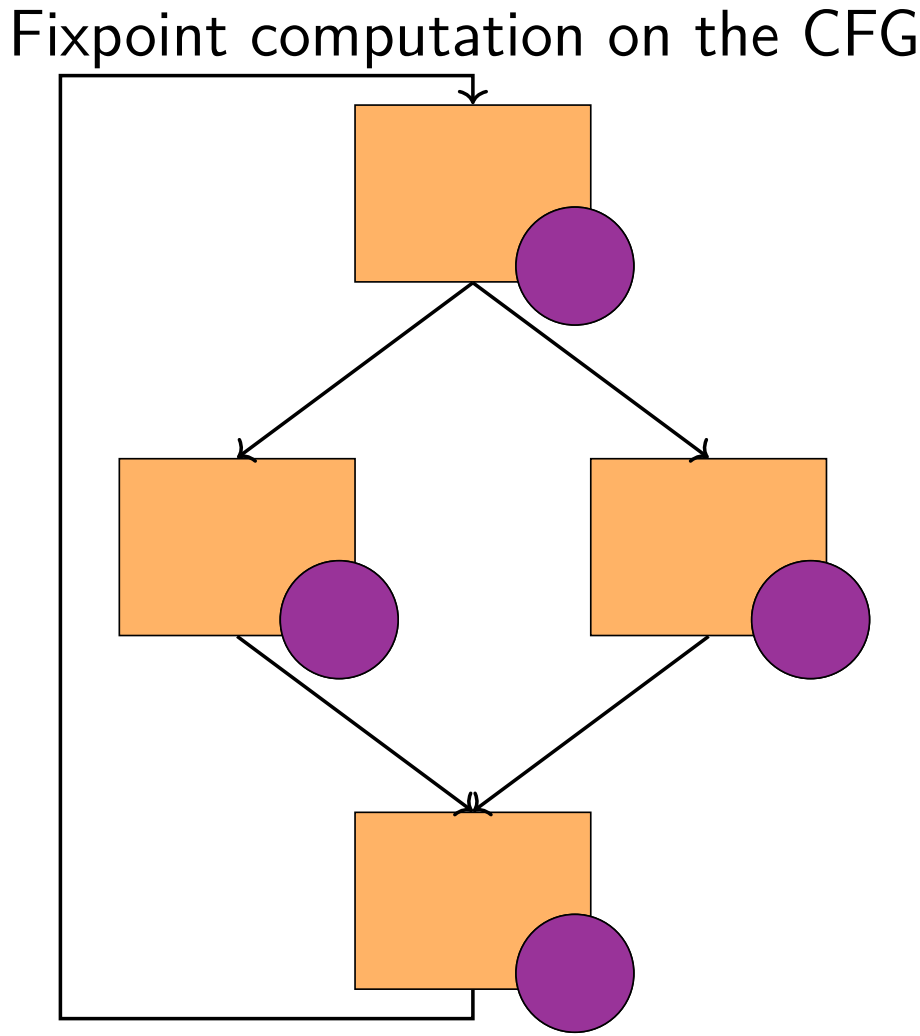


Software Model Checking

Reached, *Frontier* := $\{e_0\}$
while *Frontier* $\neq \emptyset$ **do**
  remove e from *Frontier*
  for all e' $\in$ **post**(e) **do**

    if $\neg$**stop**$(e', \mathit{Reached})$ **then**
      add e' to *Reached*, *Frontier*
return *Reached*

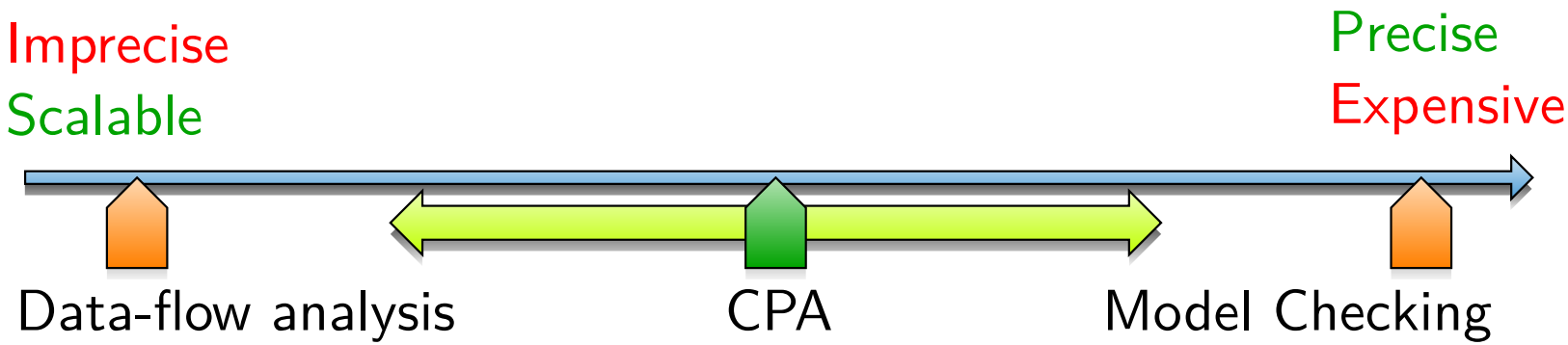
Configurable Program Analysis

Reached, *Frontier* := $\{e_0\}$
while *Frontier* $\neq \emptyset$ **do**
  remove e from *Frontier*
  for all e' $\in$ **post**(e) **do**
    for all e'' $\in$ *Reached* **do**
      e''_{new} := **merge**(e', e'')
      if $e''_{new} \neq e''$ **then**
        replace e'' in *Reached*, *Frontier* by e''_{new}
    if $\neg$**stop**$(e', \mathit{Reached})$ **then**
      add e' to *Reached*, *Frontier*
return *Reached*

Configurable Program Analysis

[12, Beyer/Henzinger/Theoduloz CAV '07]

- Better combination of abstractions
  $\rightarrow$ Configurable Program Analysis



Unified framework that enables intermediate algorithms

Dynamic Precision Adjustment

Lazy abstraction refinement: [27, Henzinger/Jhala/Majumdar/Sutre POPL '02]

- Different predicates per location and per path
- Incremental analysis instead of restart from scratch after refinement

Dynamic Precision Adjustment

Better fine tuning of the precision of abstractions

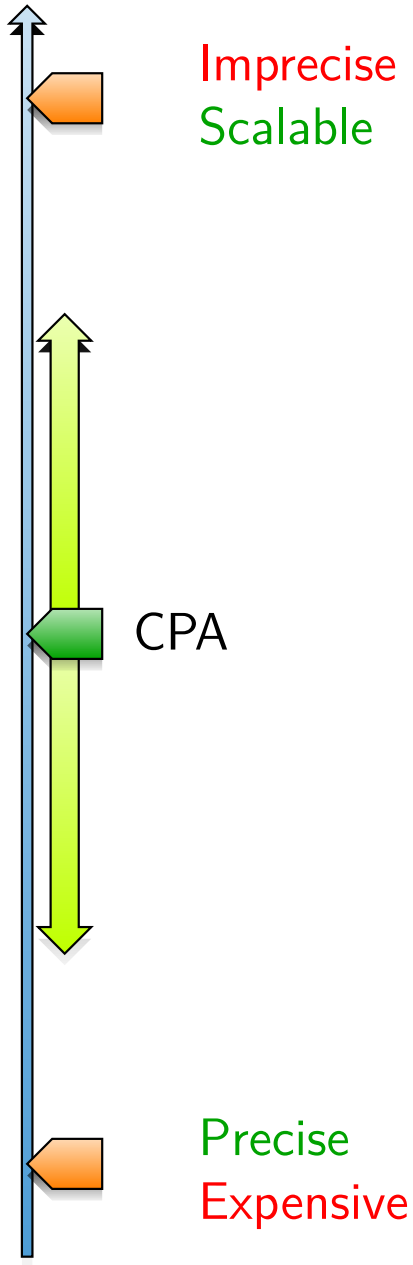
$\rightarrow$ Adjustable Precision

[13, Beyer/Henzinger/Theoduloz ASE'08]

Unified framework enables:

- switch on and off different analysis, and can
- adjust each analysis separately

- Not only **refine**, also **abstract**!

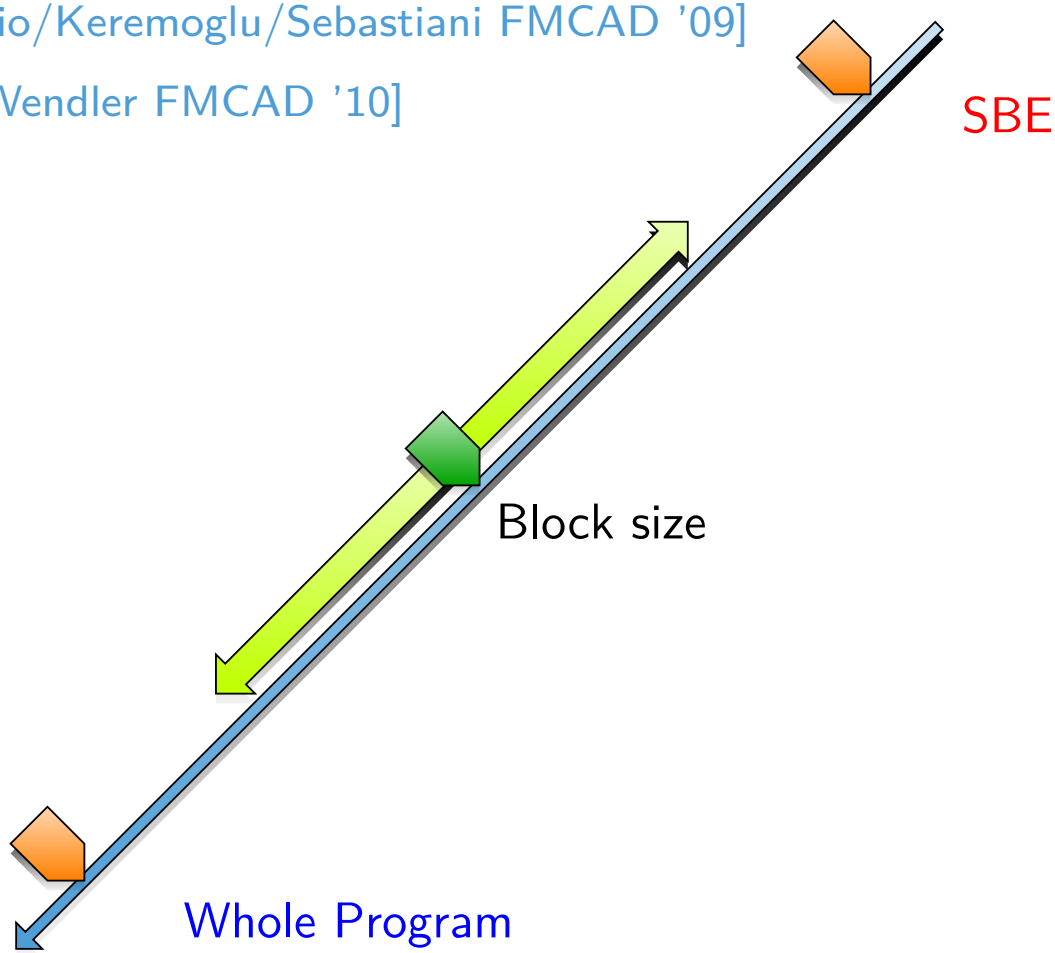


Adjustable Block-Encoding

- Handle loop-free blocks of statements at once
- Abstract only between blocks
  (less abstractions, less refinements)

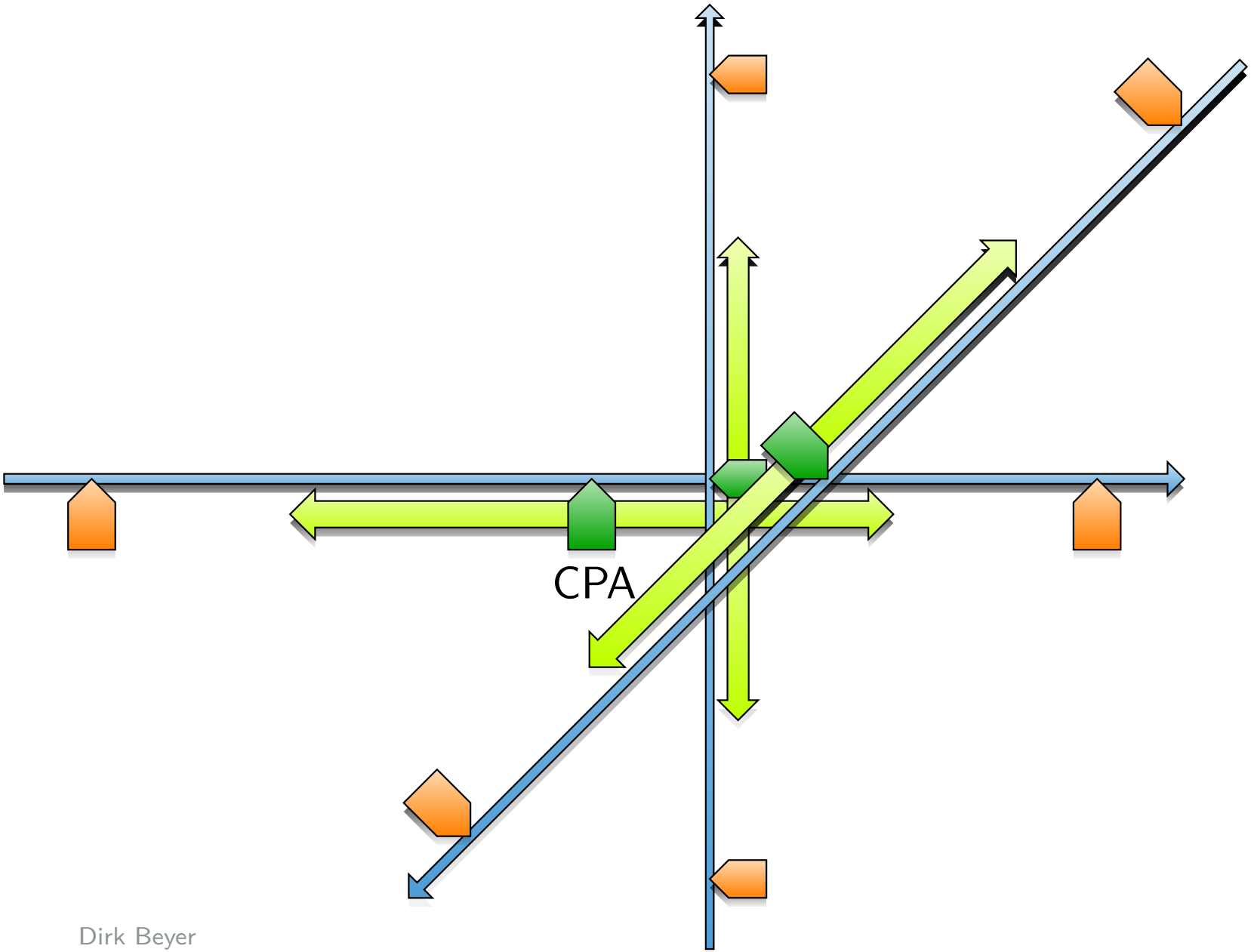
  [2, Beyer/Cimatti/Griggio/Keremoglu/Sebastiani FMCAD '09]

  [15, Beyer/Keremoglu/Wendler FMCAD '10]



CPAchecker

[14, Beyer/Keremoglu CAV '11]



CPA – Summary

- Unification of several approaches
  $\rightarrow$ reduced to their essential properties
- Allow experimentation with new configurations
  that we could never think of
- Flexible implementation CPAchecker

CPAchecker

- Framework for Software Verification — current status
  - Written in Java
  - Open Source: Apache 2.0 License
  - ~80 contributors so far from 15 universities/institutions
  - 470.000 lines of code
    (300.000 without blank lines and comments)
  - Started 2007

https://cpachecker.sosy-lab.org

CPAchecker: Features

- Input language C (experimental: Java)
- Web frontend available:
  https://vcloud.sosy-lab.org/cpachecker/webclient/run
- Counterexample output with graphs
- Benchmarking infrastructure available
  (with large cluster of machines)
- Cross-platform: Linux, Mac, Windows

CPAchecker: Achievements

- Among world's best software verifiers:
  https://sv-comp.sosy-lab.org/2021/results/
- Continuous success in competition since 2012
  (66 medals: 19x gold, 22x silver, 25x bronze)
- Awarded Gödel medal
  by Kurt Gödel Society

- Used for Linux driver verification
  with dozens of real bugs found and fixed in Linux [29, 19]

CPAchecker: Concepts

- Included Concepts:
  - CEGAR [22] Interpolation [17, 7]
  - Configurable Program Analysis [12, 13]
  - Adjustable-block encoding [15]
  - Conditional model checking [10]
  - Verification witnesses [5, 4]
  - Various abstract domains: predicates, intervals, BDDs, octagons, explicit values
- Available analyses approaches:
  - Predicate abstraction [2, 15, 13, 18]
  - Impact algorithm [31, 21, 7]
  - Bounded model checking [23, 7]
  - k-Induction [6, 7]
  - IC3/Property-directed reachability [3]
  - Explicit-state model checking [17]
  - Interpolation-based model checking [16]

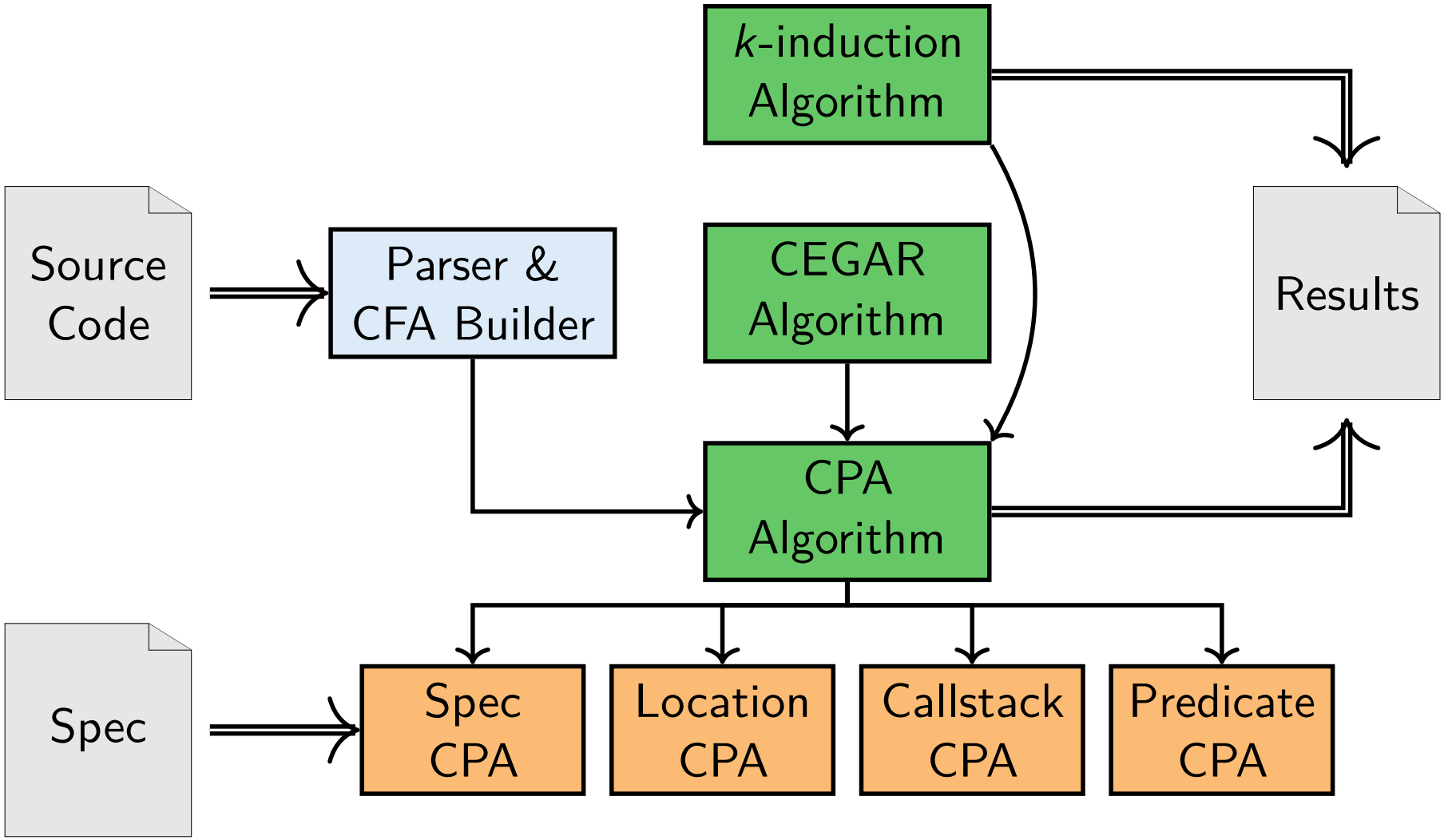
CPAchecker: Concepts

- Completely modular, and thus flexible and easily extensible
- Every abstract domain is implemented as a "Configurable Program Analysis" (CPA)
- E.g., predicate abstraction, explicit-value analysis, intervals, octagon, BDDs, memory graphs, and more
- Algorithms are central and implemented only once
- Separation of concerns
- Combined with Composite pattern

CPAchecker: Algorithms

- CPAAlgorithm is the core algorithm
  for reachability analysis / fixpoint iteration
- Other algorithms can be added if desired, e.g.,
  - CEGAR
  - Double-checking counterexamples
  - Sequential combination of analyses

CPAchecker: Architecture



Try CPAchecker

- Online at SoSy-Lab VerifierCloud:
  https://vcloud.sosy-lab.org/cpachecker/webclient/run
- Download for Linux/Windows:
  https://cpachecker.sosy-lab.org
  - Run `scripts/cpa.sh` | `scripts\cpa.bat`
  - `-default <FILE>`
  - Windows/Mac need to disable bitprecise analysis:
    ```
    -predicateAnalysis-linear
    -setprop solver.solver=smtinterpol
    -setprop analysis.checkCounterexamples=false
    ```
- Open graphical report in browser: `output/*.html`
- Open `.dot` files with dotty / xdot (www.graphviz.org/)

CPAchecker: Specification

- Model Checkers check only what you specified
- CPAchecker's default:
  - Label `ERROR`
  - Calling function `_assert_fail()`
  - `assert(pred)` needs to be pre-processed
- SV-COMP: LTL-based formulas
  (e.g., reachability of call to `reach_error()`)
- General: Monitor automata

CPAchecker for Developers

Want to implement your own analysis?

- Easy, just write a CPA in Java
- Implementations for 10 interfaces needed
- But for 8, we have default implementations
  → Minimal configuration:
  abstract state and
  abstract post operator

The CPA framework is flexible:

- Many components are provided as CPAs:
  - Location / program counter tracking
  - Callstack tracking
  - Specification input (as automata)
  - Pointer-aliasing information
- CPAs can be combined,
  so your analysis doesn't need to care about these things

Conclusions

- Flexible framework
- Open source; large group of contributors
- Most state-of-the-art approaches integrated
- Decent performance (see competitions)
- Many papers decribing its concepts

References I

[1] Beyer, D., Chlipala, A.J., Henzinger, T.A., Jhala, R., Majumdar, R.: Generating tests from counterexamples. In: Proc. ICSE. pp. 326–335. IEEE (2004). https://doi.org/10.1109/ICSE.2004.1317455

[2] Beyer, D., Cimatti, A., Griggio, A., Keremoglu, M.E., Sebastiani, R.: Software model checking via large-block encoding. In: Proc. FMCAD. pp. 25–32. IEEE (2009). https://doi.org/10.1109/FMCAD.2009.5351147

[3] Beyer, D., Dangl, M.: Software verification with PDR: An implementation of the state of the art. In: Proc. TACAS (1). pp. 3–21. LNCS 12078, Springer (2020). https://doi.org/10.1007/978-3-030-45190-5_1

[4] Beyer, D., Dangl, M., Dietsch, D., Heizmann, M.: Correctness witnesses: Exchanging verification results between verifiers. In: Proc. FSE. pp. 326–337. ACM (2016). https://doi.org/10.1145/2950290.2950351

[5] Beyer, D., Dangl, M., Dietsch, D., Heizmann, M., Stahlbauer, A.: Witness validation and stepwise testification across software verifiers. In: Proc. FSE. pp. 721–733. ACM (2015). https://doi.org/10.1145/2786805.2786867

[6] Beyer, D., Dangl, M., Wendler, P.: Boosting k-induction with continuously-refined invariants. In: Proc. CAV. pp. 622–640. LNCS 9206, Springer (2015). https://doi.org/10.1007/978-3-319-21690-4_42

References II

[7] Beyer, D., Dangl, M., Wendler, P.: A unifying view on SMT-based software verification. J. Autom. Reasoning **60**(3), 299–335 (2018). https://doi.org/10.1007/s10817-017-9432-6

[8] Beyer, D., Henzinger, T.A., Jhala, R., Majumdar, R.: Checking memory safety with Blast. In: Proc. FASE. pp. 2–18. LNCS 3442, Springer (2005). https://doi.org/10.1007/978-3-540-31984-9_2

[9] Beyer, D., Henzinger, T.A., Jhala, R., Majumdar, R.: The software model checker Blast. Int. J. Softw. Tools Technol. Transfer **9**(5-6), 505–525 (2007). https://doi.org/10.1007/s10009-007-0044-z

[10] Beyer, D., Henzinger, T.A., Keremoglu, M.E., Wendler, P.: Conditional model checking: A technique to pass information between verifiers. In: Proc. FSE. ACM (2012). https://doi.org/10.1145/2393596.2393664

[11] Beyer, D., Henzinger, T.A., Théoduloz, G.: Lazy shape analysis. In: Proc. CAV. pp. 532–546. LNCS 4144, Springer (2006). https://doi.org/10.1007/11817963_48

[12] Beyer, D., Henzinger, T.A., Théoduloz, G.: Configurable software verification: Concretizing the convergence of model checking and program analysis. In: Proc. CAV. pp. 504–518. LNCS 4590, Springer (2007). https://doi.org/10.1007/978-3-540-73368-3_51

References III

[13] Beyer, D., Henzinger, T.A., Théoduloz, G.: Program analysis with dynamic precision adjustment. In: Proc. ASE. pp. 29–38. IEEE (2008). https://doi.org/10.1109/ASE.2008.13

[14] Beyer, D., Keremoglu, M.E.: CPAchecker: A tool for configurable software verification. In: Proc. CAV. pp. 184–190. LNCS 6806, Springer (2011). https://doi.org/10.1007/978-3-642-22110-1_16

[15] Beyer, D., Keremoglu, M.E., Wendler, P.: Predicate abstraction with adjustable-block encoding. In: Proc. FMCAD. pp. 189–197. FMCAD (2010), https://www.sosy-lab.org/research/pub/2010-FMCAD.Predicate_Abstraction_with_Adjustable-Block_Encoding.pdf

[16] Beyer, D., Lee, N.Z., Wendler, P.: Interpolation and SAT-based model checking revisited: Adoption to software verification. arXiv/CoRR **2208**(05046) (July 2022). https://doi.org/10.48550/arXiv.2208.05046

[17] Beyer, D., Löwe, S.: Explicit-state software model checking based on CEGAR and interpolation. In: Proc. FASE. pp. 146–162. LNCS 7793, Springer (2013). https://doi.org/10.1007/978-3-642-37057-1_11

[18] Beyer, D., Löwe, S., Novikov, E., Stahlbauer, A., Wendler, P.: Precision reuse for efficient regression verification. In: Proc. FSE. pp. 389–399. ACM (2013). https://doi.org/10.1145/2491411.2491429

References IV

[19] Beyer, D., Petrenko, A.K.: Linux driver verification. In: Proc. ISoLA. pp. 1–6. LNCS 7610, Springer (2012). https://doi.org/10.1007/978-3-642-34032-1_1

[20] Beyer, D., Stahlbauer, A.: BDD-based software verification: Applications to event-condition-action systems. Int. J. Softw. Tools Technol. Transfer **16**(5), 507–518 (2014). https://doi.org/10.1007/s10009-014-0334-1

[21] Beyer, D., Wendler, P.: Algorithms for software model checking: Predicate abstraction vs. IMPACT. In: Proc. FMCAD. pp. 106–113. FMCAD (2012)

[22] Clarke, E.M., Grumberg, O., Jha, S., Lu, Y., Veith, H.: Counterexample-guided abstraction refinement for symbolic model checking. J. ACM **50**(5), 752–794 (2003). https://doi.org/10.1145/876638.876643

[23] Clarke, E.M., Kröning, D., Lerda, F.: A tool for checking ANSI-C programs. In: Proc. TACAS. pp. 168–176. LNCS 2988, Springer (2004). https://doi.org/10.1007/978-3-540-24730-2_15

[24] Clarke, E.M., Emerson, E.A.: Design and synthesis of synchronization skeletons using branching-time temporal logic. In: Proc. Logic of Programs 1981. pp. 52–71. LNCS 131, Springer (1982). https://doi.org/10.1007/BFb0025774

[25] Fischer, J., Jhala, R., Majumdar, R.: Joining data flow with predicates. In: Proc. FSE. pp. 227–236. ACM (2005). https://doi.org/10.1145/1081706.1081742

References V

[26] Henzinger, T.A., Jhala, R., Majumdar, R., Qadeer, S.: Thread-modular abstraction refinement. In: Proc. CAV. pp. 262–274. LNCS 2725, Springer (2003). https://doi.org/10.1007/978-3-540-45069-6_27

[27] Henzinger, T.A., Jhala, R., Majumdar, R., Sutre, G.: Lazy abstraction. In: Proc. POPL. pp. 58–70. ACM (2002). https://doi.org/10.1145/503272.503279

[28] Henzinger, T.A., Jhala, R., Majumdar, R., Sutre, G.: Software verification with Blast. In: Proc. SPIN, pp. 235–239. LNCS 2648, Springer (2003). https://doi.org/10.1007/3-540-44829-2_17

[29] Khoroshilov, A.V., Mutilin, V.S., Petrenko, A.K., Zakharov, V.: Establishing Linux driver verification process. In: Proc. Ershov Memorial Conference. pp. 165–176. LNCS 5947, Springer (2009). https://doi.org/10.1007/978-3-642-11486-1_14

[30] Kildall, G.A.: A unified approach to global program optimization. In: Proc. POPL. pp. 194–206. ACM (1973). https://doi.org/10.1145/512927.512945

[31] McMillan, K.L.: Lazy abstraction with interpolants. In: Proc. CAV. pp. 123–136. LNCS 4144, Springer (2006). https://doi.org/10.1007/11817963_14

[32] Queille, J.P., Sifakis, J.: Specification and verification of concurrent systems in CESAR. In: Proc. Symposium on Programming. pp. 337–351. LNCS 137, Springer (1982). https://doi.org/10.1007/3-540-11494-7_22