# Configurable Software Model Checking

## CPAchecker

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CPA✓

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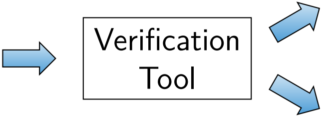
SoSy-Lab Software Systems

# Software Verification

C Program

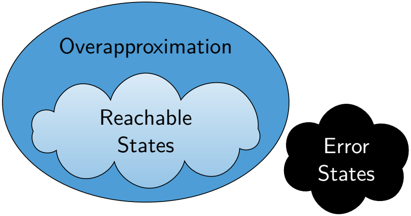
```
int main() {
   int a = foo();
   int b = bar(a);

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




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
- 2003: Multi-threading support
- 2004: Test-case generation, interpolation, spec. lang.
- 2005: Memory safety, predicated lattices
- 2006: Lazy shape analysis
- Maintenance and extensions became extremely difficult because of design choices that were not easy to revert
- 2007: Configurable program analysis,
  CPAchecker was started
  as complete reimplementation from scratch

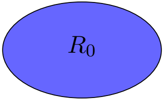
# CPAchecker History (2)

- 2009: Large-block encoding
- 2010: Adjustable-block encoding
- 2012: Conditional model checking, PredAbs vs. Impact
- 2013: Explicit-state MC, BDDs, precision reuse
- ...

# Software Verification by Model Checking

[Clarke/Emerson, Sifakis 1981]

Iterative fixpoint (forward) post computation



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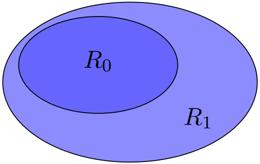

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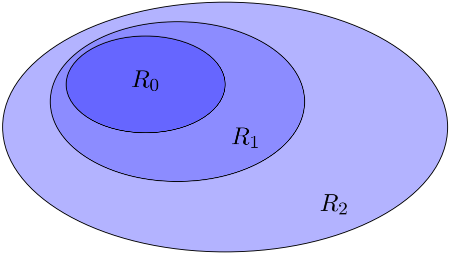

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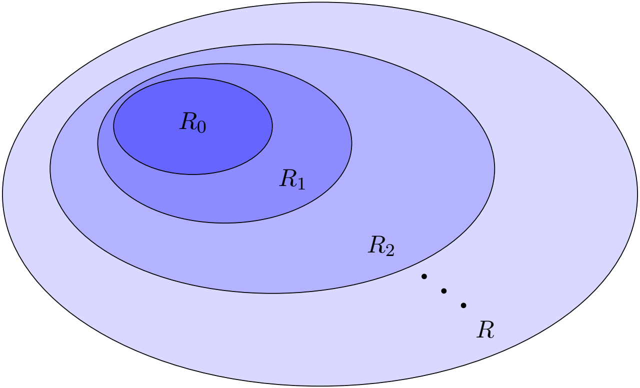


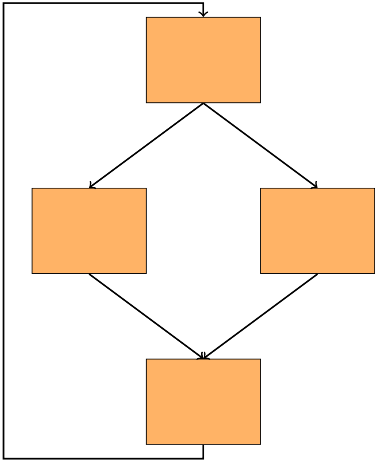
# Software Model Checking

*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

Fixpoint computation on the CFG



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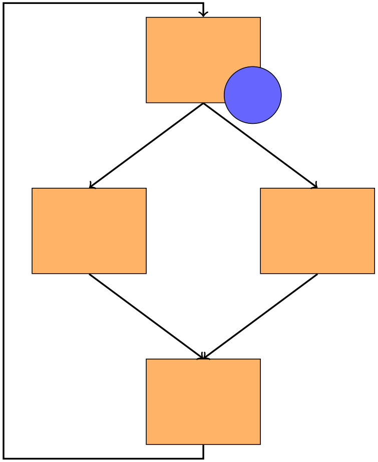

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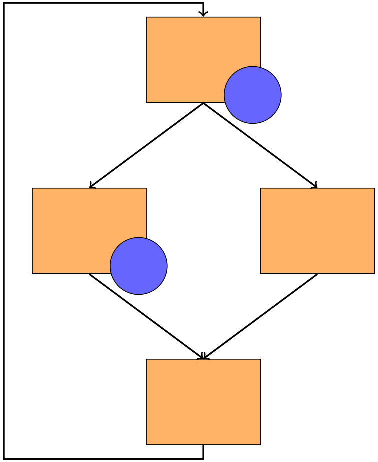

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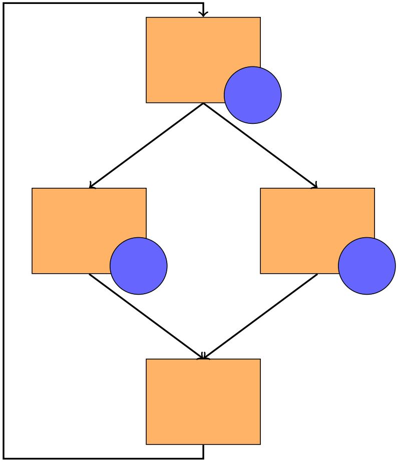
Fixpoint computation on the CFG



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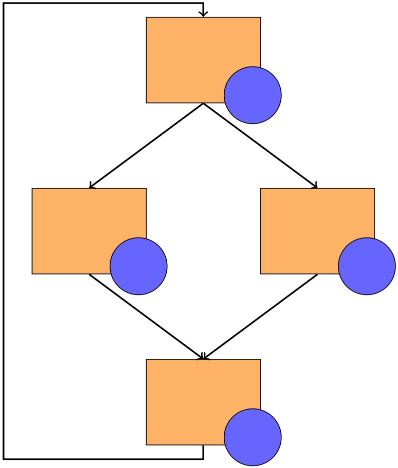

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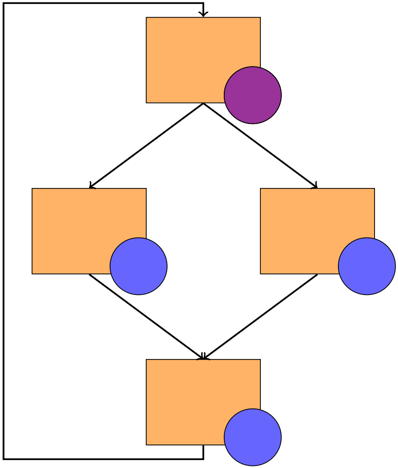

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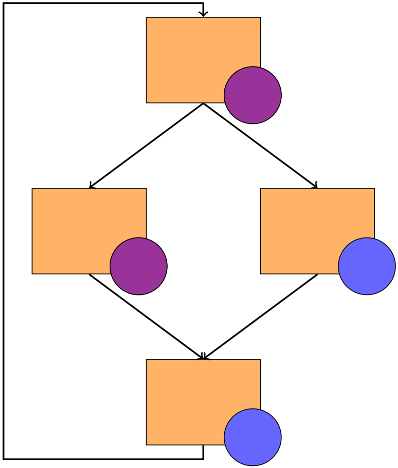

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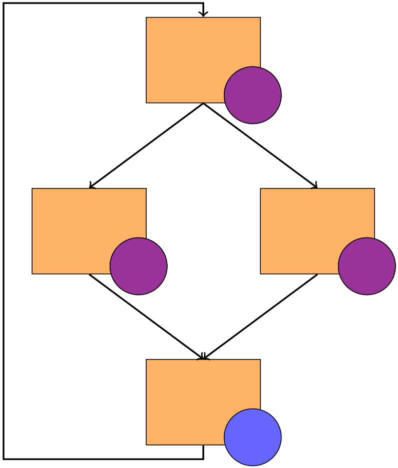

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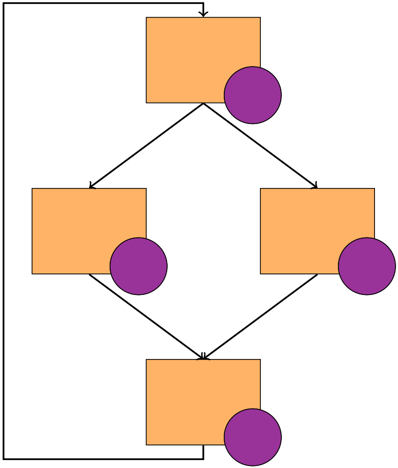

# Software Model Checking

*Reached*, *Frontier* $:= \{e_0\}$
**while** *Frontier* $\neq \emptyset$ **do**
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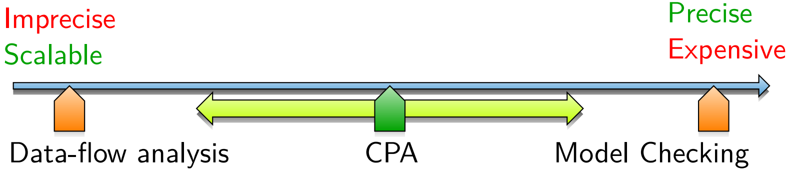
    **if** $\neg$**stop**$(e', \textit{Reached})$ **then**
      add $e'$ to *Reached*, *Frontier*
**return** *Reached*

# 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**($e'$, *Reached*) **then**
      add $e'$ to *Reached*, *Frontier*
**return** *Reached*

# Configurable Program Analysis

- Better combination of abstractions
  → Configurable Program Analysis [Beyer/Henzinger/Theoduloz CAV'07]




Unified framework that enables intermediate algorithms

# Dynamic Precision Adjustment

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

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

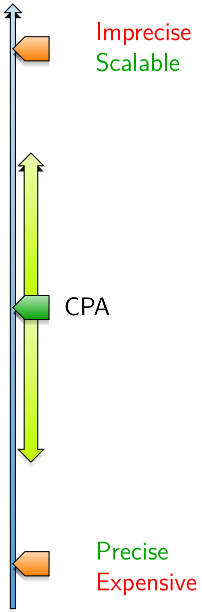
# Dynamic Precision Adjustment

Better fine tuning of the precision of abstractions
→ Adjustable Precision
[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**!

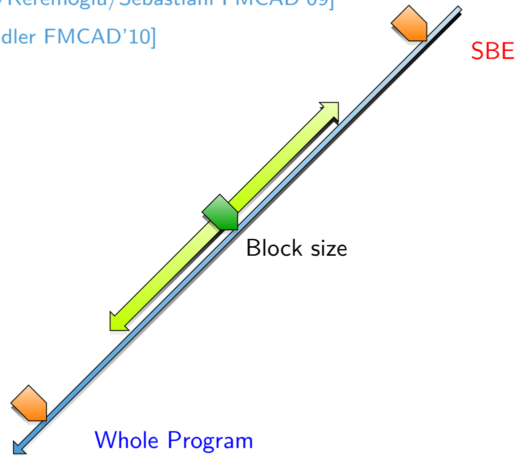


# Adjustable Block-Encoding

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

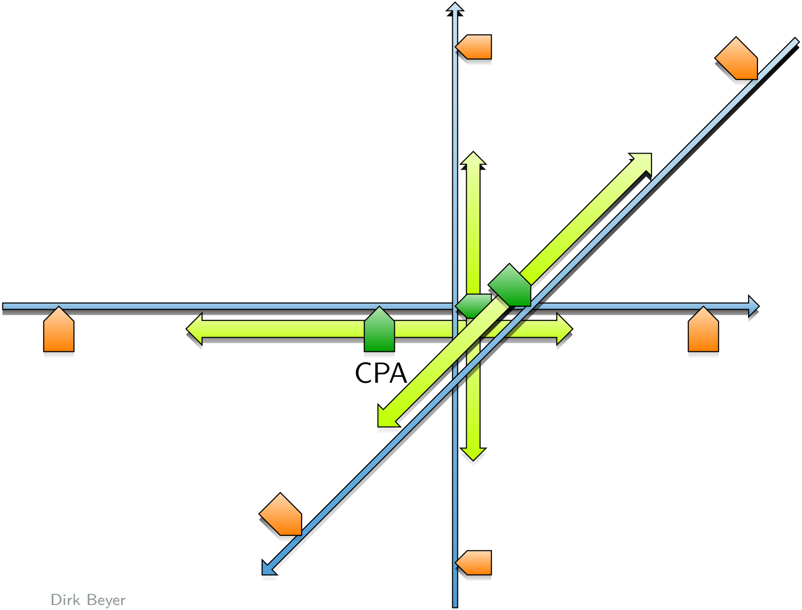
  [Beyer/Cimatti/Griggio/Keremoglu/Sebastiani FMCAD'09]

  [Beyer/Keremoglu/Wendler FMCAD'10]



# CPAchecker

[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
  - 430.000 lines of code
    (275.000 without blank lines and comments)
  - Started 2007

https://cpachecker.sosy-lab.org

# CPAchecker: Features

- Input language C (experimental: Java)
- Web frontend available:
  https://cpachecker.appspot.com
- 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/2018/results/
- Continuous success in competition since 2012
  (52 medals: 16x gold, 18x silver, 18x bronze)
- Awarded Gödel medal
  by Kurt Gödel Society

- Used for Linux driver verification
  with dozens of real bugs found and fixed in Linux

# CPAchecker: Concepts

- Included Concepts:
  - CEGAR
  - Interpolation
  - Adjustable-block encoding
  - Conditional model checking
  - Verification witnesses
- Further available analyses:
  - Impact algorithm
  - Bounded model checking
  - k-Induction
  - Property-directed reachability

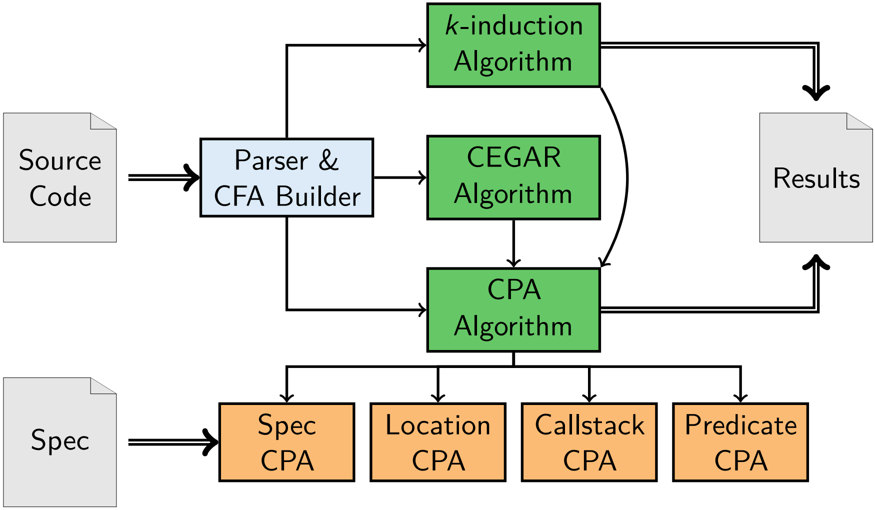
# CPAchecker: Concepts

- 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 Google AppEngine:
  https://cpachecker.appspot.com/
- Download for Linux/Windows:
  https://cpachecker.sosy-lab.org
  - Run `scripts/cpa.sh` | `scripts\cpa.bat`
  - `-predicateAnalysis <FILE>`
  - Windows/Mac need to disable bitprecise analysis:
    `-predicateAnalysis-linear`
    `-setprop solver.solver=smtinterpol`
    `-setprop analysis.checkCounterexamples=false`
- Look at `output/CPALog.txt` for problems
- Open `.dot` files with dotty / xdot (www.graphviz.org/)
- Open graphical report in browser: `output/*.html`

# 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:
  - Calling function `__VERIFIER_error()`
  - `-spec sv-comp-reachability`

# 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
  $\rightarrow$ Minimal configuration:
  abstract state and
  abstract post operator

# CPAchecker for Developers

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