Configurable Software Model Checking

CPAchecker

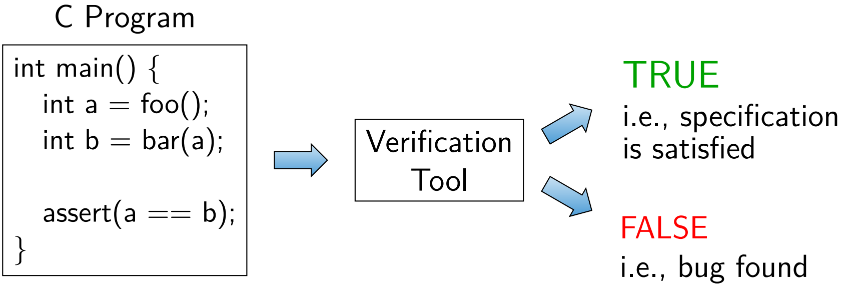
Dirk Beyer

CPA✓

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

SoSy-Lab Software Systems

Software Verification



C Program

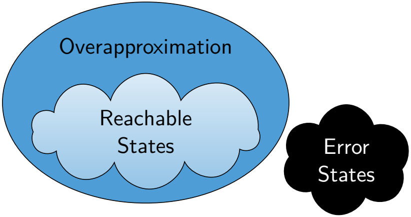
```
int main() {
   int a = foo();
   int b = bar(a);

   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, 27]
- 2003: Multi-threading support [25]
- 2004: Test-case generation, interpolation, spec. lang. [9, 1]
- 2005: Memory safety, predicated lattices [24, 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]

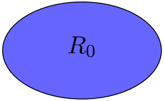
CPAchecker History (2)

- 2009: Large-block encoding [2, FMCAD '09]
- 2010: Adjustable-block encoding [15, FMCAD '10]
- 2012: Conditional model checking [10, FSE '12],
  PredAbs vs. Impact [20, FMCAD '12]
- 2013: Explicit-state MC [16, FASE '13],
  BDDs [19, STTT '14],
  precision reuse [17, FSE '13]
- ...

Software Verification by Model Checking

[23, 31, Clarke/Emerson, Queille/Sifakis 1981]

Iterative fixpoint (forward) post computation



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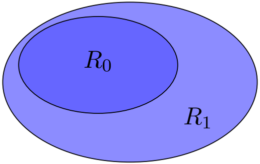

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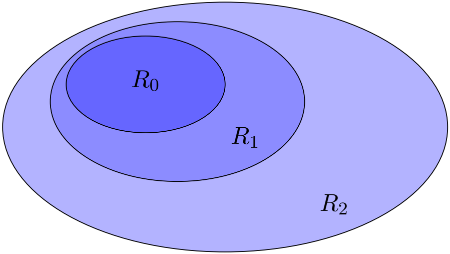

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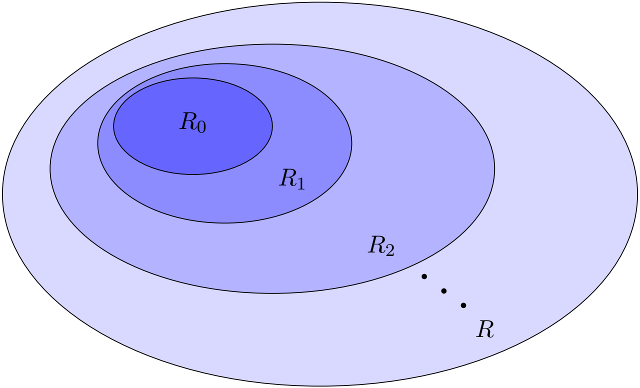


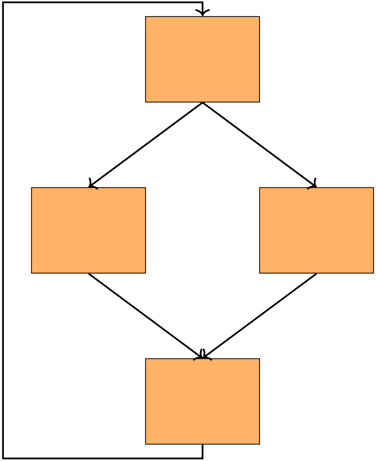
Software Model Checking

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




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

Software Verification by Data-Flow Analysis

[29, Kildall 1973]

Fixpoint computation on the CFG



Software Verification by Data-Flow Analysis

[29, Kildall 1973]

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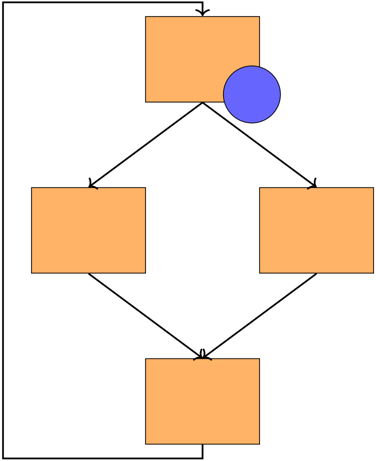

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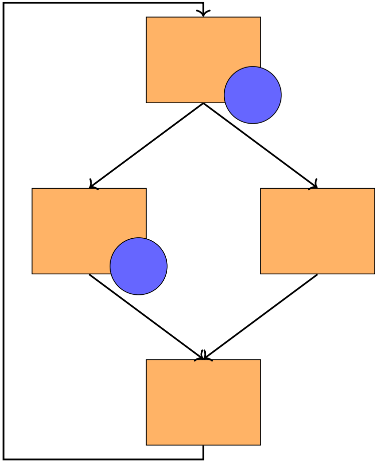

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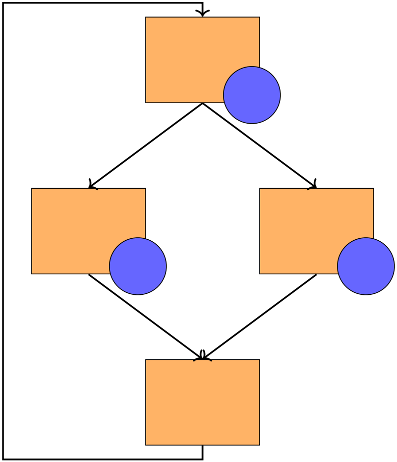

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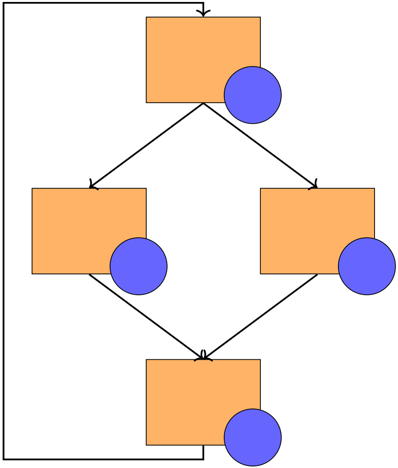

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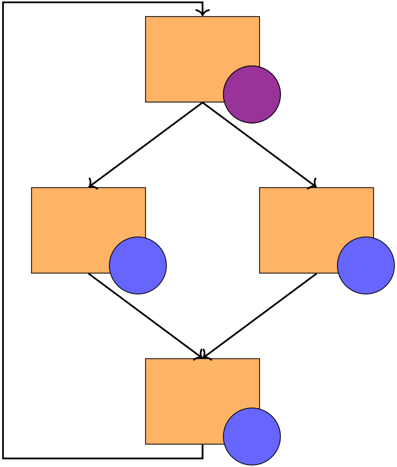

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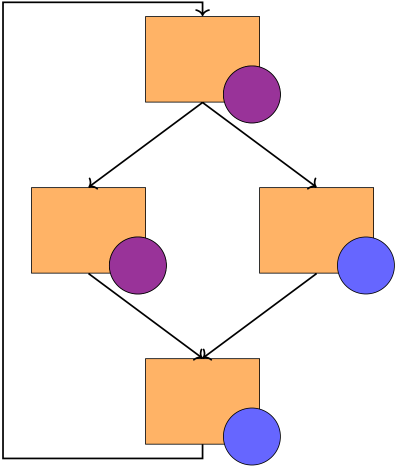

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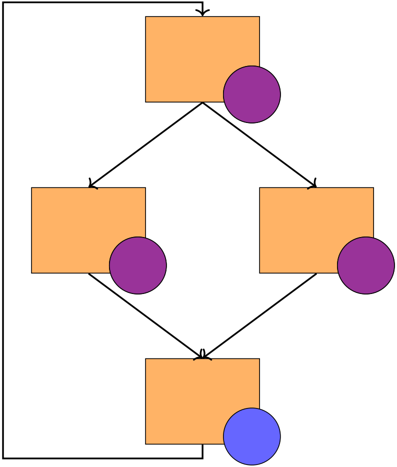

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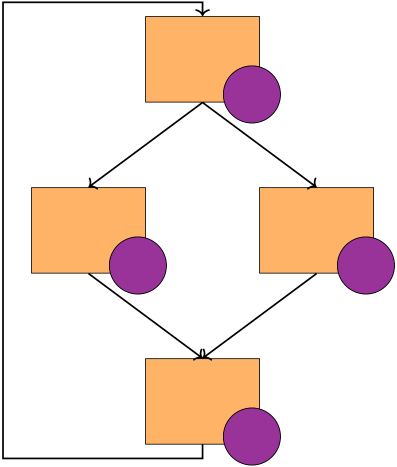

Software Model Checking

```
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while $\mathit{Frontier} \neq \emptyset$ do
    remove $e$ from $\mathit{Frontier}$
    for all $e' \in \underline{\textbf{post}}(e)$ do



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

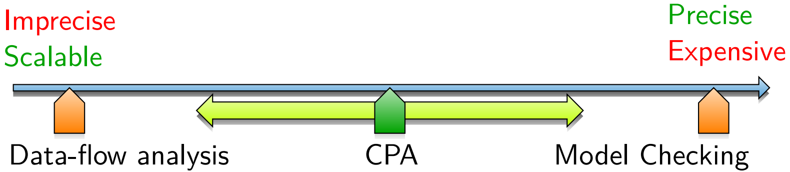
Configurable Program Analysis

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

Configurable Program Analysis

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

- Better combination of abstractions
  → Configurable Program Analysis



Imprecise
Scalable

Precise
Expensive

Data-flow analysis

CPA

Model Checking

Unified framework that enables intermediate algorithms

Dynamic Precision Adjustment

Lazy abstraction refinement: [26, Henzinger/Jhala/Majumdar/Sutre POPL '02]

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

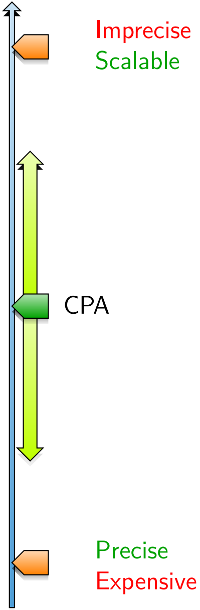
Dynamic Precision Adjustment

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

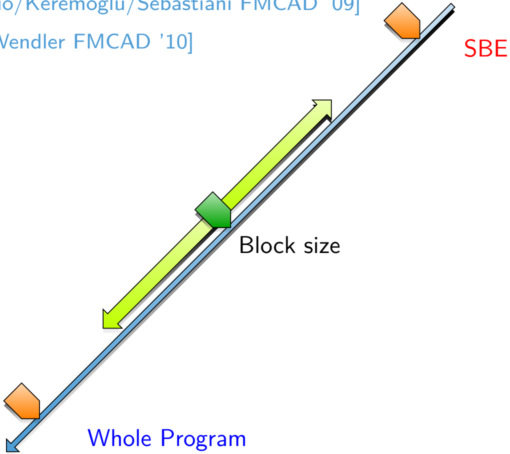


Adjustable Block-Encoding

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

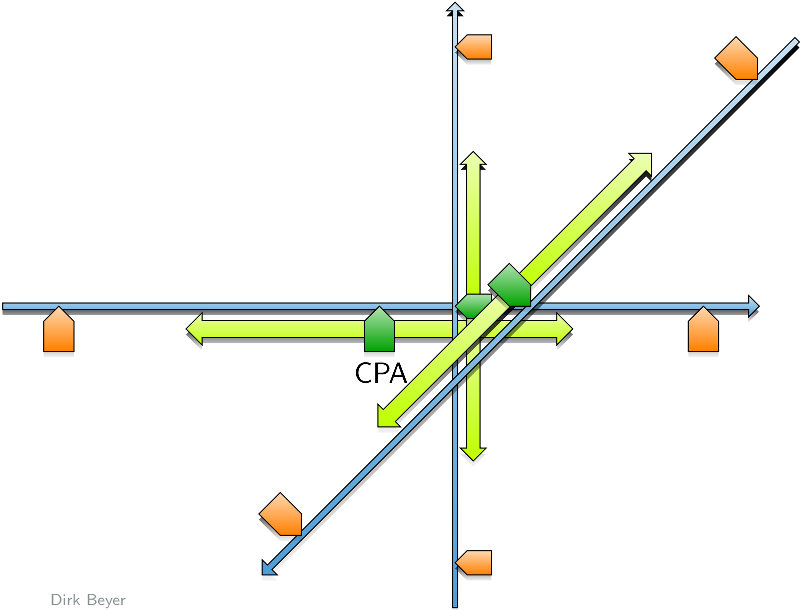
  [2, Beyer/Cimatti/Griggio/Keremoglu/Sebastiani FMCAD '09]

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



CPAchecker

[14, Beyer/Keremoglu CAV '11]



CPA – Summary

- Unification of several approaches
  → 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

CPA✓ 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 [28, 18]

CPACHECKER: Concepts

- Included Concepts:
  - CEGAR [21]
  - Interpolation [16, 7]
  - Adjustable-block encoding [15]
  - Conditional model checking [10]
  - Verification witnesses [5, 4]
- Further available analyses:
  - IMPACT algorithm [30, 20, 7]
  - Bounded model checking [22, 7]
  - k-Induction [6, 7]
  - Property-directed reachability [3]

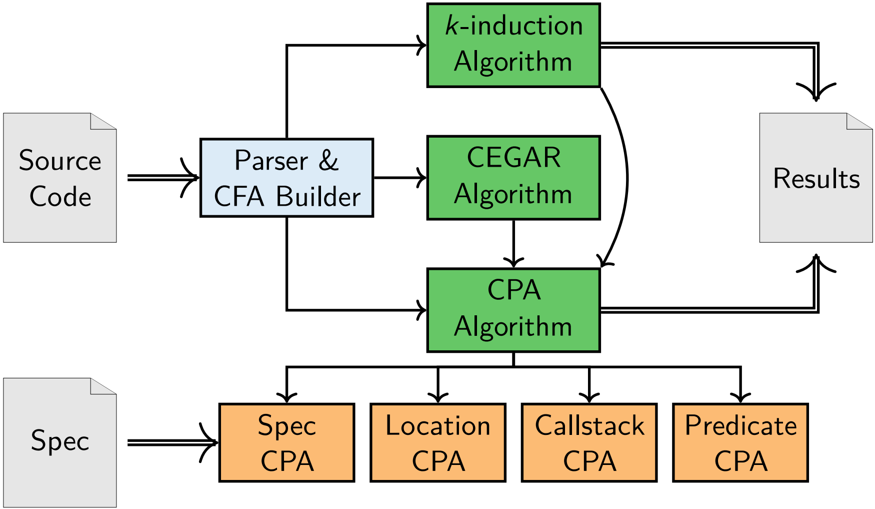
CPAchecker: Concepts

- 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



CPA✓ 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:
  - Calling function `__VERIFIER_error()` / `reach_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
  → 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

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