μZ

Fix-point engine in 

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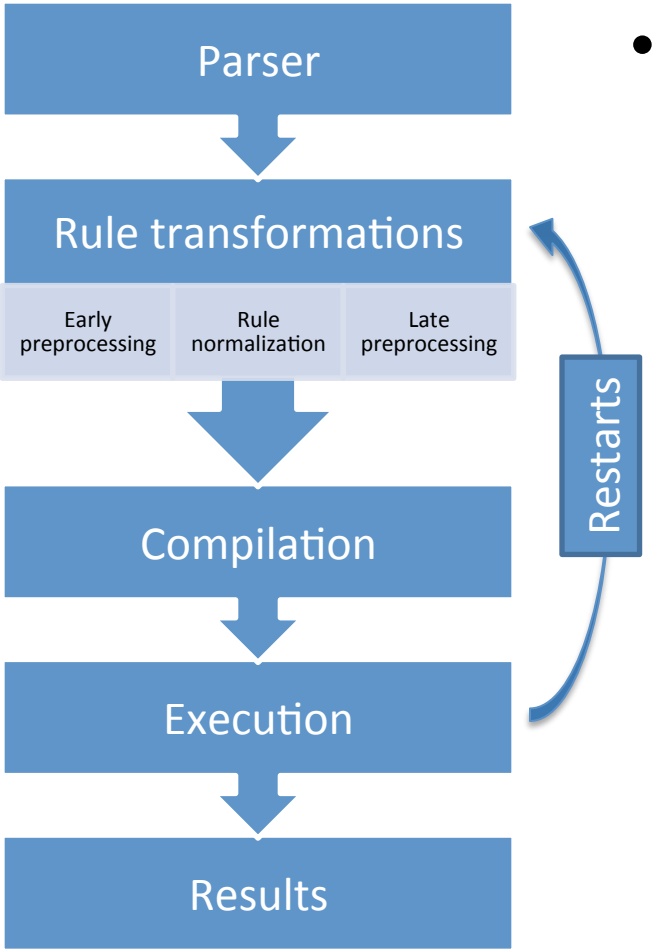
Motivation

- Horn EPR applications (Datalog)
  - Points-to analysis
  - Security analysis
  - Deductive data-bases and knowledge bases (Yago)
- Many areas of software analysis use fixed points
  - Model-checking
    - Set of reachable states is minimal fixed point
  - Abstract interpreters
    - Fixed points using approximations on infinite latices
  - Using first-order engines here requires an extra layer

μZ

- Efficient Datalog engine
- Encapsulates SMT solving using Z3
- Extensible

Architecture

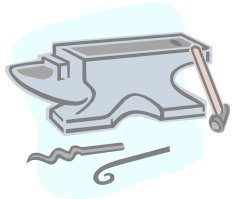


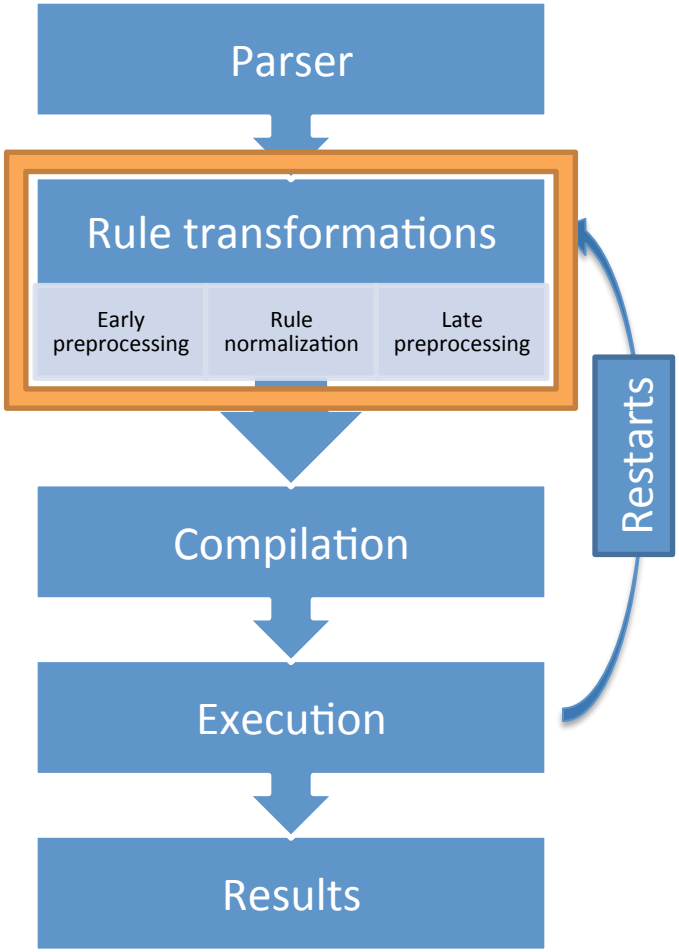
- Datalog

```
PointsTo(v2, h2) :-
        Load(v2, v1, f),
        PointsTo(v1, h1),
        HeapPointsTo(h1, f, h2).
Load("b", "global", "Function").
Prototype(”f2::N.js:33", h1) :- GlobalFunctionPrototype(h1).
Prototype(”f6::N.js:37", h1) :- GlobalFunctionPrototype(h1).
```

- Prolog without functions
- Finite domains
- Evaluation using relation algebra
  - join, project, select, union

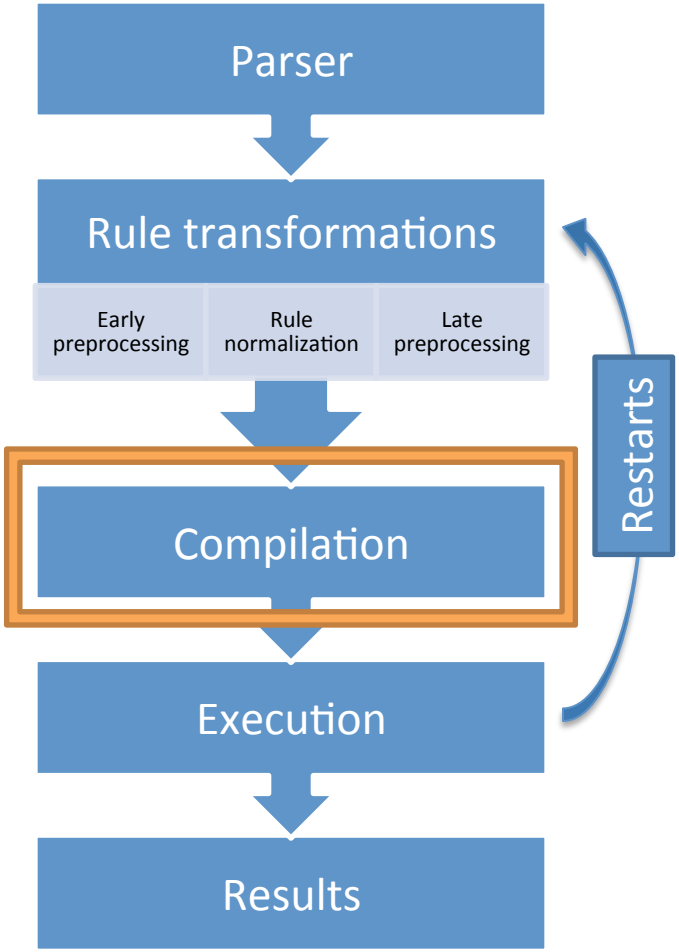
Architecture





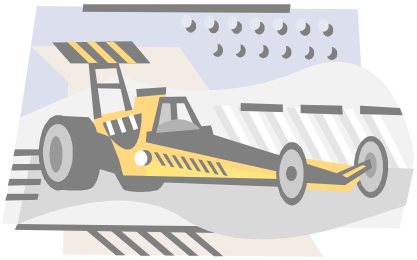
- Rule transformations
  - Normalization
    - Tail contains at most two predicates
    - Corresponds to join planning in databases
    - Identifies common subexpressions
  - Preprocessing
    - Add tracing columns if we want proofs
    - Magic Sets for goal orientation
    - Equivalent transformations of rules to improve performance
  - Restarts
    - There is often little information about the relations at the beginning
    - We may restart and redo the transformations when we know more
      - e.g. sizes of relations

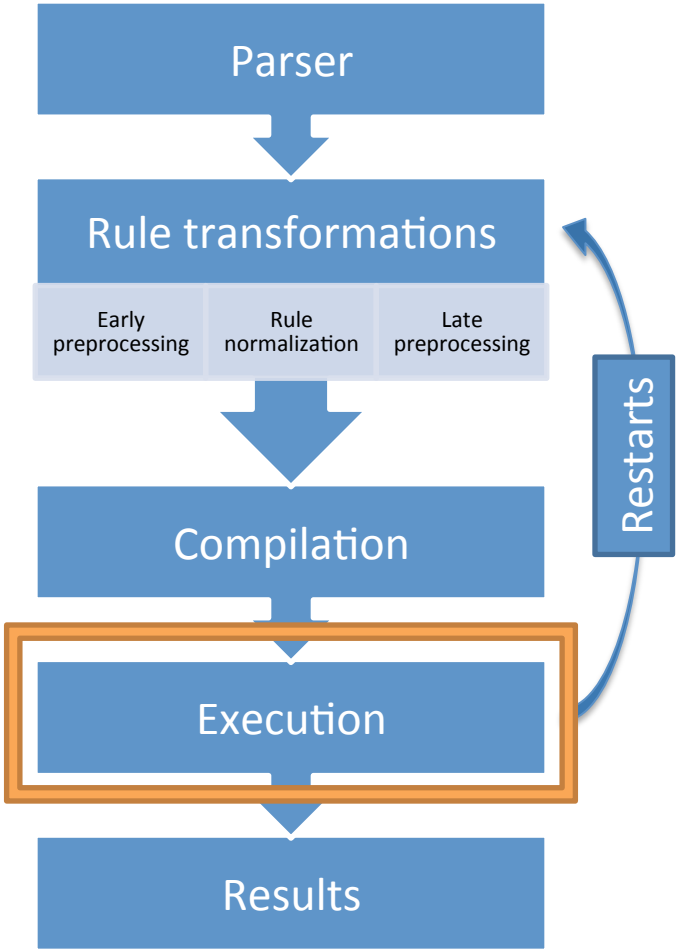
Architecture



- Compilation
  - Into register machine
  - Straightforward for non-recursive rules
  - Recursive rules stratified and compiled using delta relations
  - Compile each SCC separately
    - Split SCC into core and acyclic part
    - Deltas of the acyclic part are local inside the loop
      - Speeds up new fact propagation
      - Reduces amount of emptiness checks
      - In the loop condition we check only for core delta relations
  - Specialized compilation modes
    - Abstract interpretation
    - Bounded mode checking (not implemented yet)

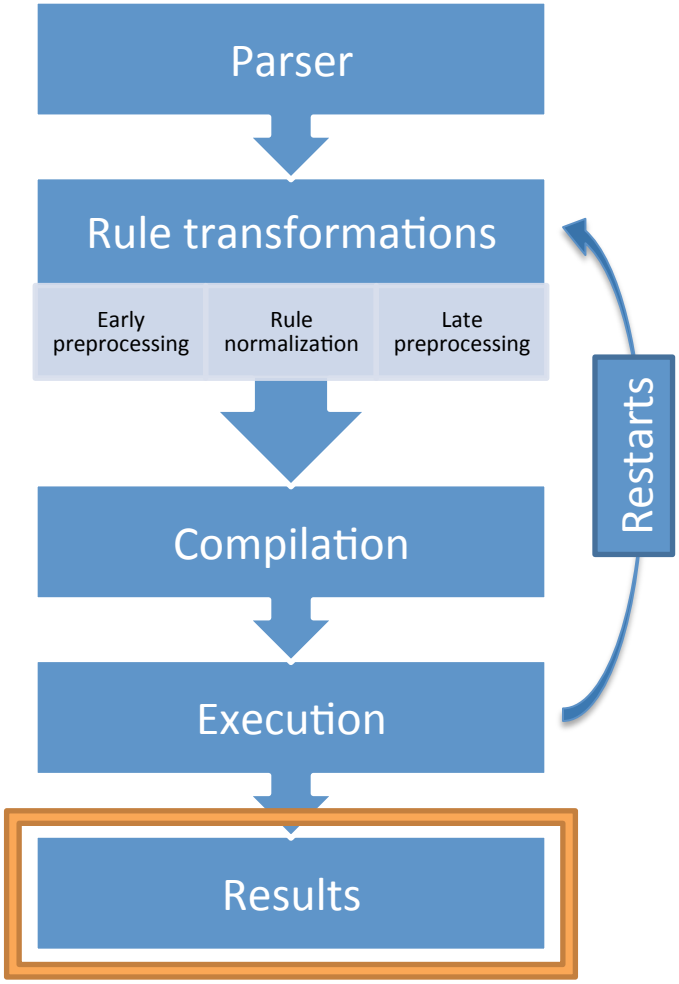
Architecture





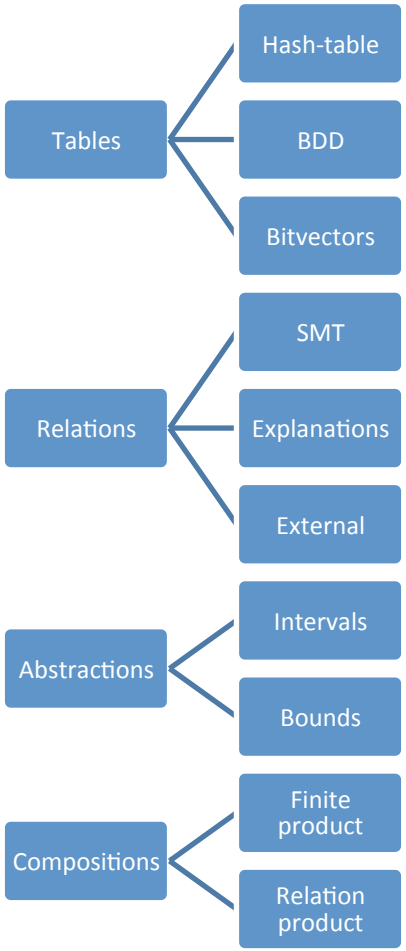
- Execution
  - Profiling data for each instruction and rule are collected
    - Profile guided rule transformations
    - Feedback to the user

Architecture



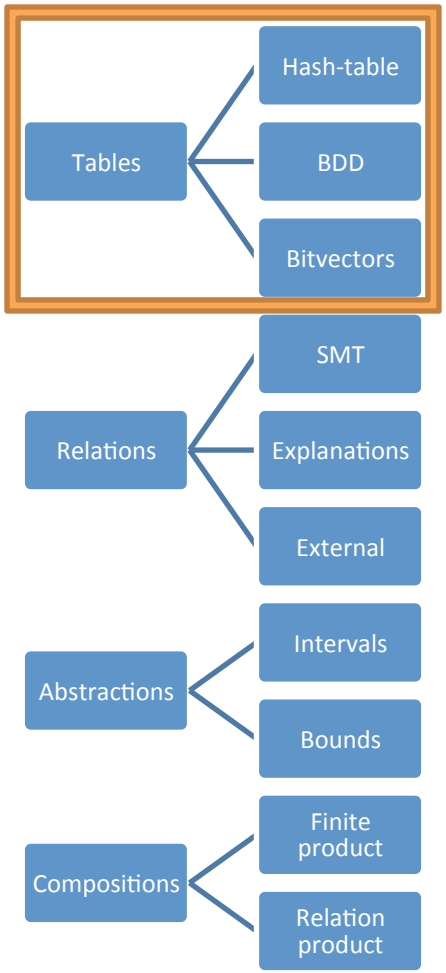
- Results of execution
  - Fixed point
  - Answers to a query
  - Possibly with an derivation tree
    - For each tuple in Finite Datalog
    - For each relation in Abstract Datalog

Relation representation



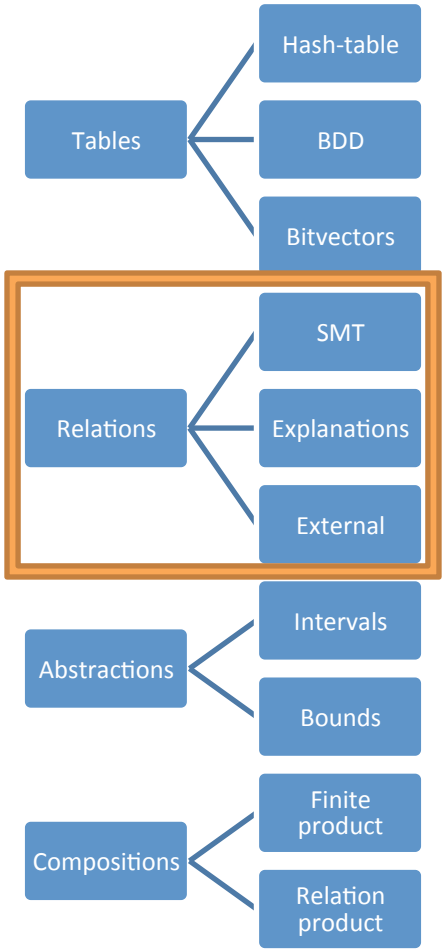
- Plugin architecture
- Plugins need to provide basic relation operations
  - Optional specialized operations for better performance
    - join-project, select-project, intersection,…

Relation representation



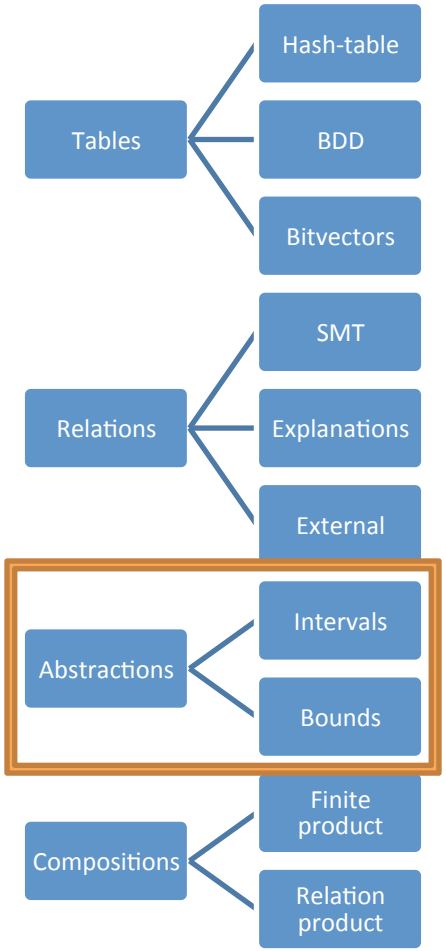
- Tables
  - Represent finite domains
  - Hash-tables
    - Indexes on subsets of columns (for joins, selections)
  - Bitvectors
    - Small domain relations
  - BDDs
    - Good for low entropy relations

Relation representation

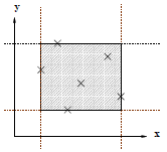


- Relations
  - Represent arbitrary domains
  - SMT relation
    - Relation operations implemented using SMT solver
    - union <-> disjunction
    - is_empty <-> is unsatisfiable
    - …
  - Explanations
    - Lightweight relation for building proof trees
  - External relations
    - User can provide their own relations using extended Z3 API

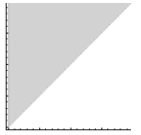
Relation representation



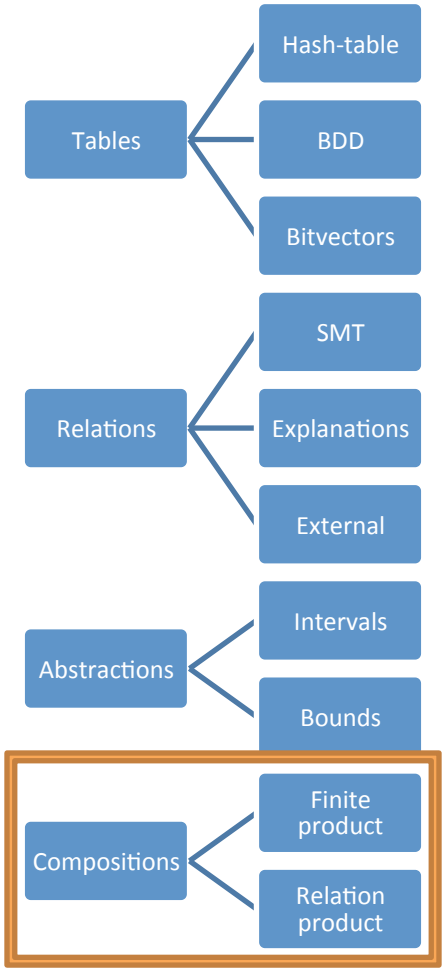
- Abstract domains
  - Relations do not need to be precise
  - Widening operations
    - Guarantee convergence of infinite domains
    - Specialized compilation mode to improve precision
  - Interval relation
    - upper and lower bound for each column



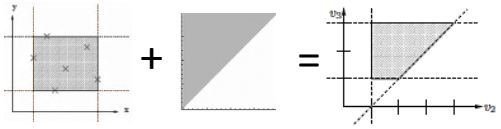
  - Bounds relation
    - inequalities between columns



Relation representation



- Compositions
  - Finite product: Table x Relation
    - Precise operations
    - Use
      - explanations for Finite Datalog
      - (possibly) context sensitivity in points-to analysis
  - Relation product: Relation x Relation
    - May be imprecise
      - relation implementations can be aware of each other to increase precision
    - Use
      - explanations for Abstract Datalog
      - combining abstract domains
      - intervals + bounds = pentagons



Rule preprocessing

Goal orientation

Removing unbound head variables

Coalescing similar rules

- Goal orientation
  - Magic Sets
    - 1980's Datalog optimization technique

```
1<2
2<3
…
99<100
x<z :- x<y, y<z
```

- Query:
  q(x) :- x<4
- We only need part of the '<' relation
- Introduce auxiliary 'r' (reachable) relation:

```
r(4).
r(x) :- r(y), x<y
x<z :- r(y), x<y, y<z
```

- Now evaluation of '<' is restricted only to tuples that may influence the result

Rule preprocessing

Goal orientation

Removing unbound head variables

Coalescing similar rules

- Removing unbound head variables

```
Load("vtmp1176", "vtmp1173", x).
Check(x) :- Load("vtmp1176", x, y).
=>
Load3("vtmp1176", "vtmp1173").
Check(x) :- Load("vtmp1176", x, y).
Check(x) :- Load3("vtmp1176", x).
```

– Unbound variables in head
  - Expensive for some table representations
  - Hash-table must store a tuple for each element in the domain
– Possible exponential increase of number of rules
  - Exponential with arity of relations

Benchmark	Size [statements/kb]	Untransformed	Transformed
alert_01.js	1827/390	90ms	90ms
settings.js	2636/515	130ms	100ms
prototype.js	25862/5460	2175ms	650ms

Rule preprocessing

- Coalescing similar rules

```
Prototype("f163::N.js:335", h1) :- GlobalFunctionPrototype(h1).
Prototype("f164::N.js:373", h1) :- GlobalFunctionPrototype(h1).
=>
Prototype(x, h1) :- GlobalFunctionPrototype(h1), Aux(x).
Aux("f163::N.js:335").
Aux("f164::N.js:373").
```

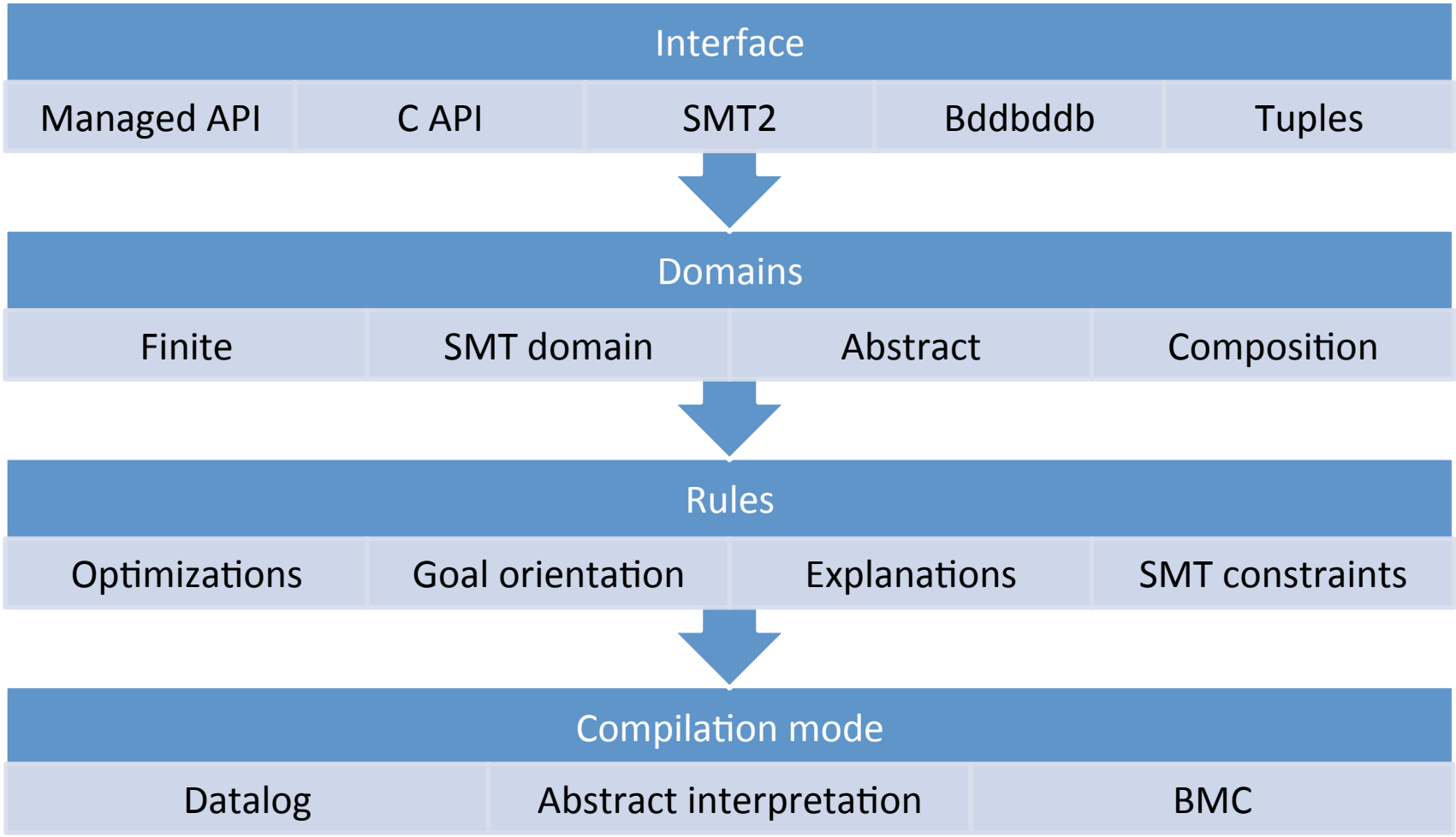
  - Replace several simpler rules with one more complex

Goal orientation

Removing unbound head variables

Coalescing similar rules

Conclusion


Interface
Managed API
C API
SMT2
Bddbddb
Tuples
Domains
Finite
SMT domain
Abstract
Composition
Rules
Optimizations
Goal orientation
Explanations
SMT constraints
Compilation mode
Datalog
Abstract interpretation
BMC