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Verifying Data Constraint Equivalence in FinTech Systems

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FinTech Systems

- Offer financial services to consumers or businesses
  - Mobile Payment Apps
  - Peer-to-Peer Lending
  - Personal Finance Apps

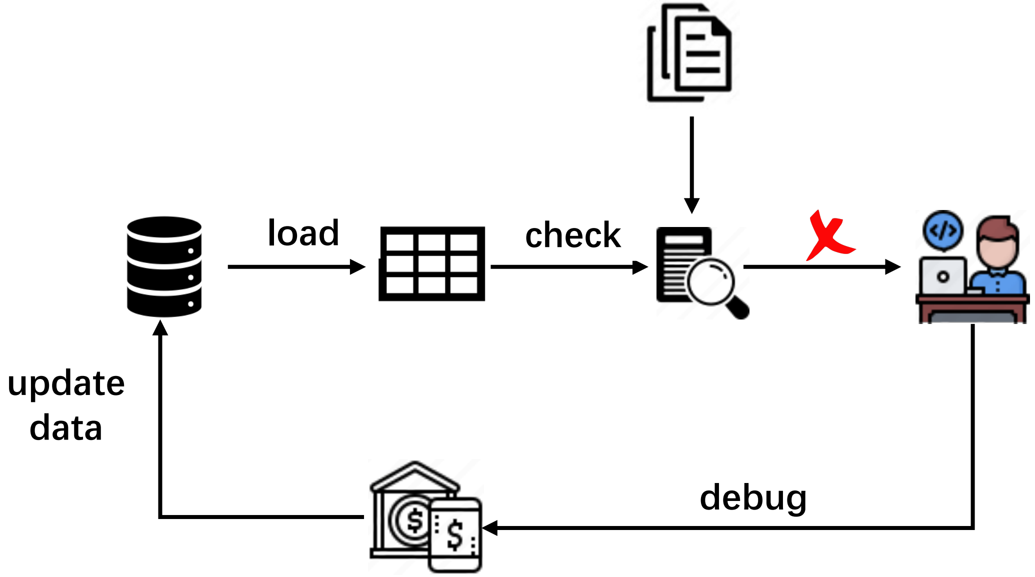
- Important to validate the correctness of financial data

Data Constraints in FinTech Systems

- A predicate over table attributes
  - Operation: numeric comparison/computation, substring matching
  - Control flow: sequencing, branch
- Examined upon huge relational tables per minute/hour

```
if(acc.type == 'IN'){
  amount = acc.in;
} else {
  amount = acc.out;
}
r1 = amount > 0;
r2 = acc.in_id != nil;
r3 = acc.out_id != nil;
assert(r1 && r2 && r3);
```

- The amount is great than 0
- Two accounts are not null

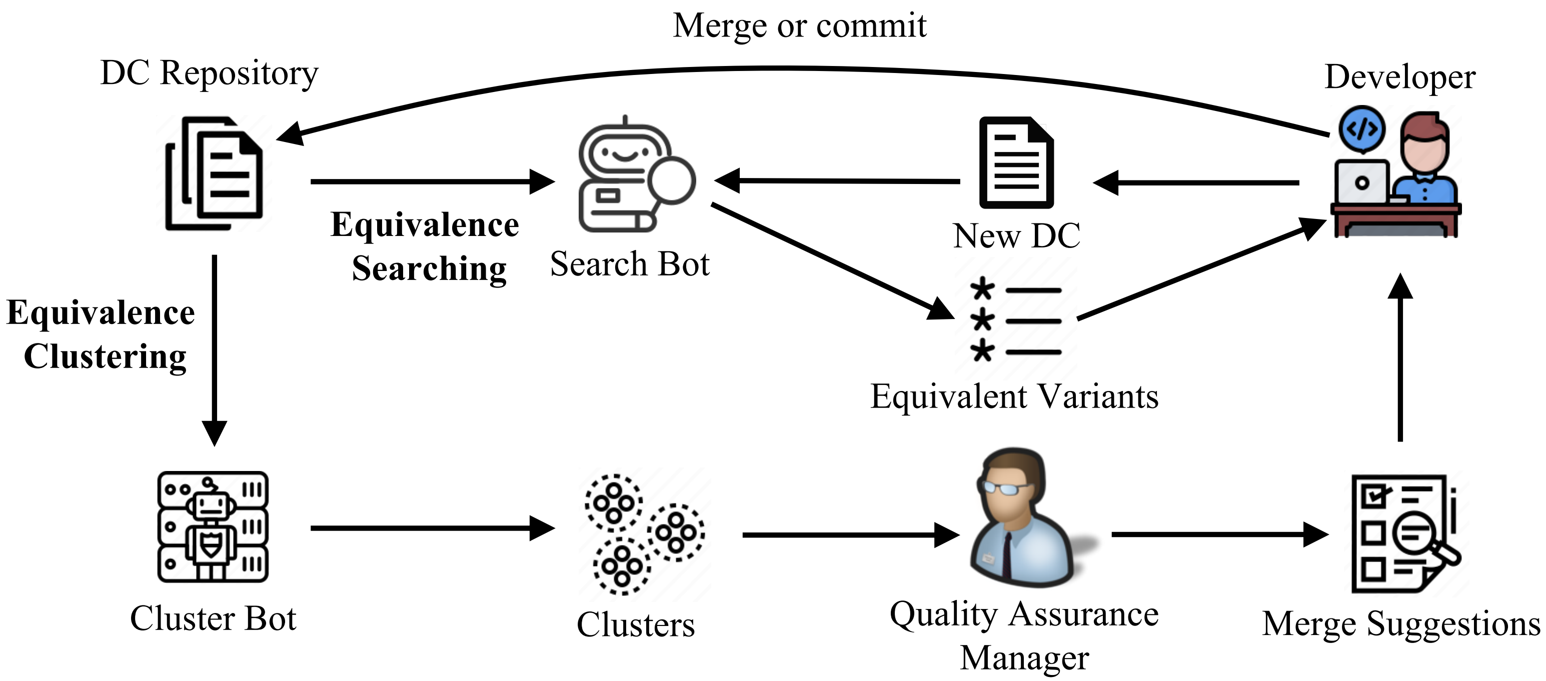


Equivalent Data Constraints

- Existence of equivalent data constraints
  - Over **20%** of data constraints are equivalent to others in Ant Group
- Root cause
  - Unaware of existing data constraints
- Consequence
  - Waste computation resources
  - Redundant error messages

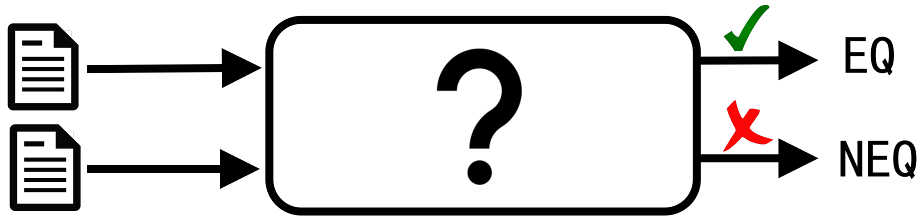
Resolving Equivalent Data Constraints

- Equivalence searching/clustering



Data Constraint Equivalence Verification

- Problem
  - Given two data constraints r1 and r2, determine whether r1 is semantically equivalent to r2.



- Challenge
  - Achieve high efficiency, soundness, and completeness simultaneously
    - Tens of thousands of data constraints can amplify the efficiency bottleneck.
    - An unsound decision procedure would result in financial loss.
    - An incomplete decision procedure would hide opportunities for optimization.

Existing Effort

- Term rewriting identifies equivalent variants
  - Ensure soundness
  - Discover restrictive forms of equivalent patterns
  - Search vast space when applying rewrite rules

- SMT-based symbolic reasoning verifies logical equivalence
  - Ensure soundness and completeness for decidable fragment
  - SMT solver targets satisfiability problem instead of logical equivalence checking
    - Invoked thousands of times, degrading the efficiency

Motivating Example

- Lexical differences in non-equivalent data constraints
  - Example: (a) and (c)
  - Pose constrain over different table attributes

- Isomorphic structures in equivalent data constraints
  - Example: (b) and (d)
  - Only differ in the order of commutative operands and assertions

```
s = 'IN';
if(contains(t.ty,s))
  assert(t.in > 0);
else
  assert(t.out > 0);
assert(t.amt > 0);
assert(t.oid != 0);
```

(a)

```
if(contains(t.ty,'IN')){
  assert(t.old == t.new - t.in);
} else {
  assert(t.old == t.new + t.out);
}
assert(t.oid != 0);
assert(t.iid != 0);
```

(b)

```
s = 'IN';
if(not contains(t.ty,s))
  assert(t.out > 0);
else
  assert(t.new > 0);
assert(t.amt > 0);
assert(t.iid != 0);
```

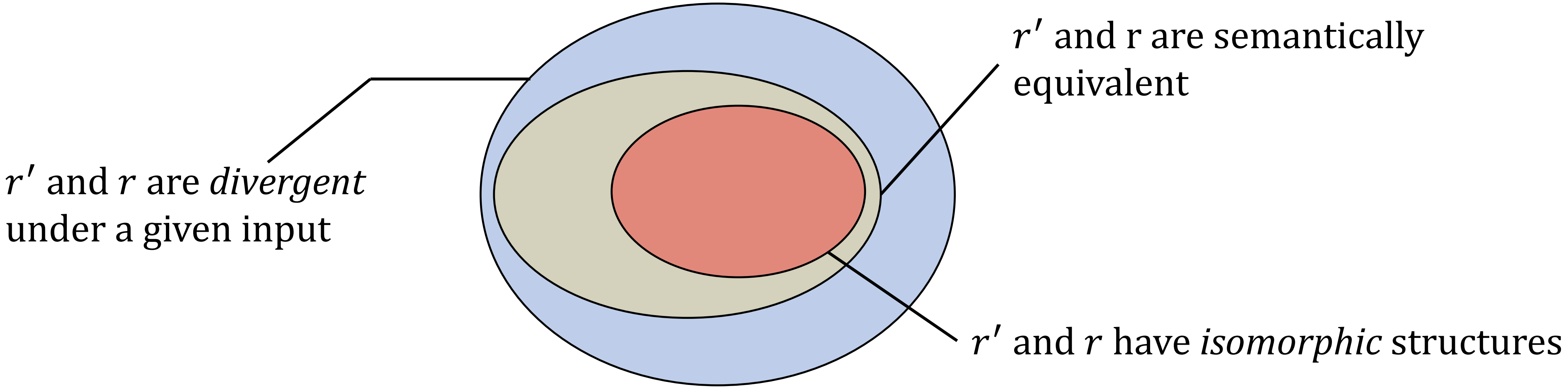
(c)

```
assert(t.iid != 0);
assert(t.oid != 0);
if(not contains(t.ty,'IN'))
  cash = t.out + t.new;
else
  cash = t.new - t.in;
assert(cash == t.old);
```

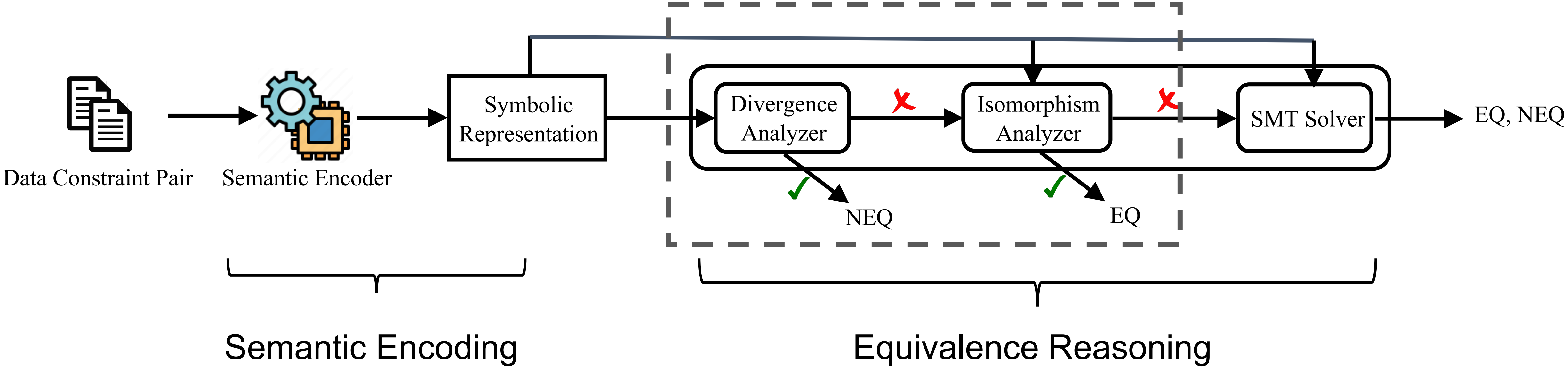
(d)

EqDAC: Key Idea

- Achieve an efficient decision procedure without “deep” semantic analysis
  - (Over-approximation) Lexical difference-guided input generation refutes data constraint equivalence
  - (Under-approximation) The isomorphic structure proves data constraint equivalence
  - **Polynomial time!**



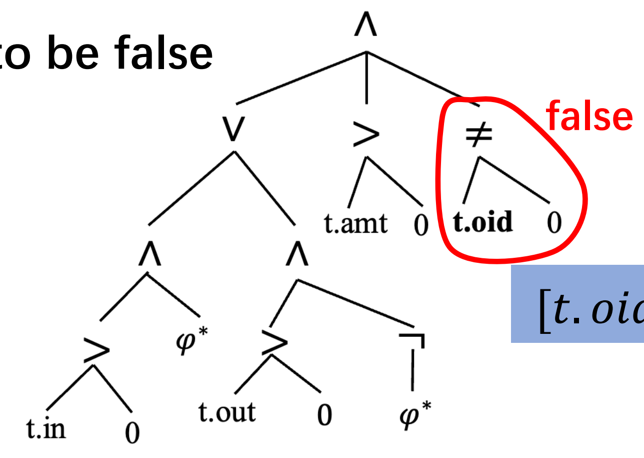
Workflow of EqDAC



Divergence Analysis

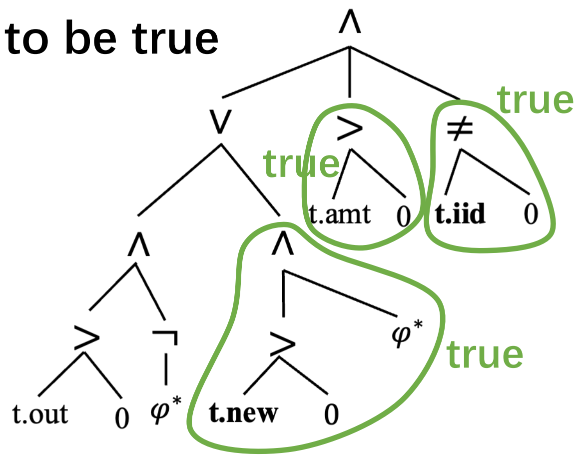
- Concretize data variables making two formulas evaluate differently, which refutes the equivalence

Enforce $\boldsymbol{\varphi_1}$ to be false



$[t.oid \rightarrow 0]$

Enforce $\boldsymbol{\varphi_2}$ to be true



$[t.oid \rightarrow 0,$
$t.iid \rightarrow 1,$
$t.amt \rightarrow 1,$
$t.new \rightarrow 2]$

$$\varphi_1 = ((t.in > 0 \wedge \phi_c) \vee (t.out > 0 \wedge \neg\phi_c)) \wedge \phi_a \wedge \phi_o$$

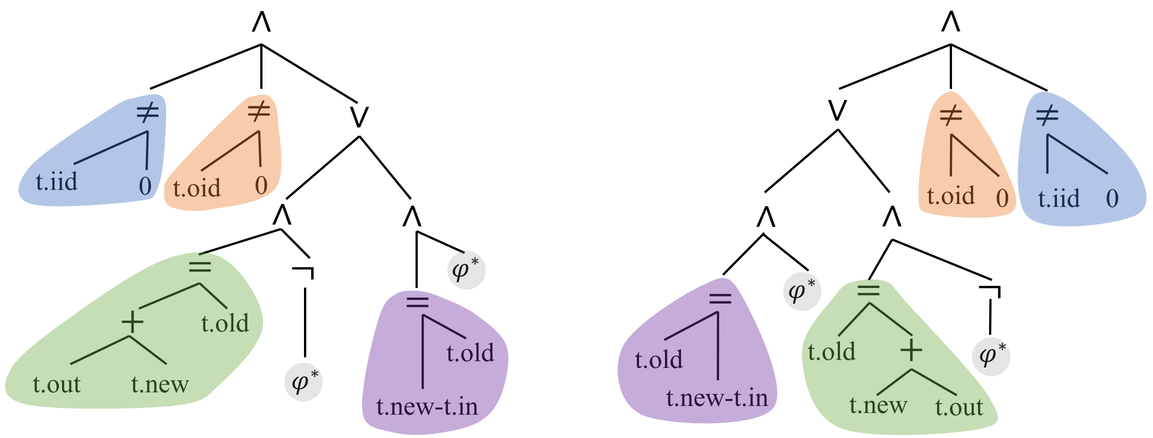
$$\varphi_2 = ((t.out > 0 \wedge \neg\phi_c) \vee (t.new > 0 \wedge \phi_c)) \wedge \phi_a \wedge \phi_i$$

Isomorphism Analysis

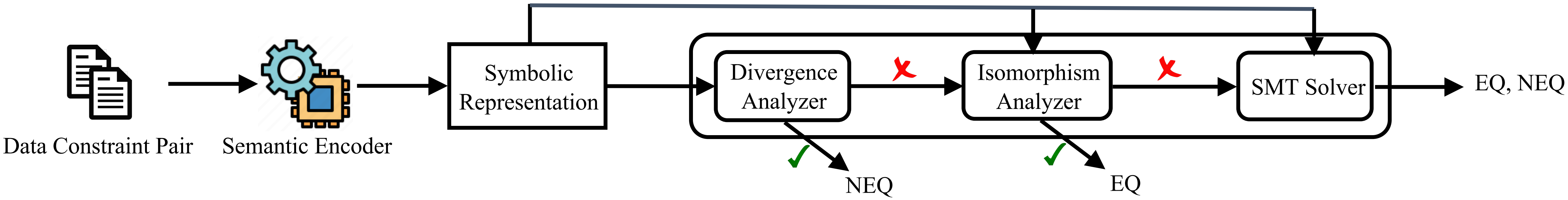
- Apply tree isomorphism algorithm to prove equivalence

```
if(contains(t.ty,'IN')){
  assert(t.old == t.new - t.in);
} else {
  assert(t.old == t.new + t.out);
}
assert(t.oid != 0);
assert(t.iid != 0);
```

```
assert(t.iid != 0);
assert(t.oid != 0);
if(not contains(t.ty,'IN'))
  cash = t.out + t.new;
else
  cash = t.new - t.in;
assert(cash == t.old);
```



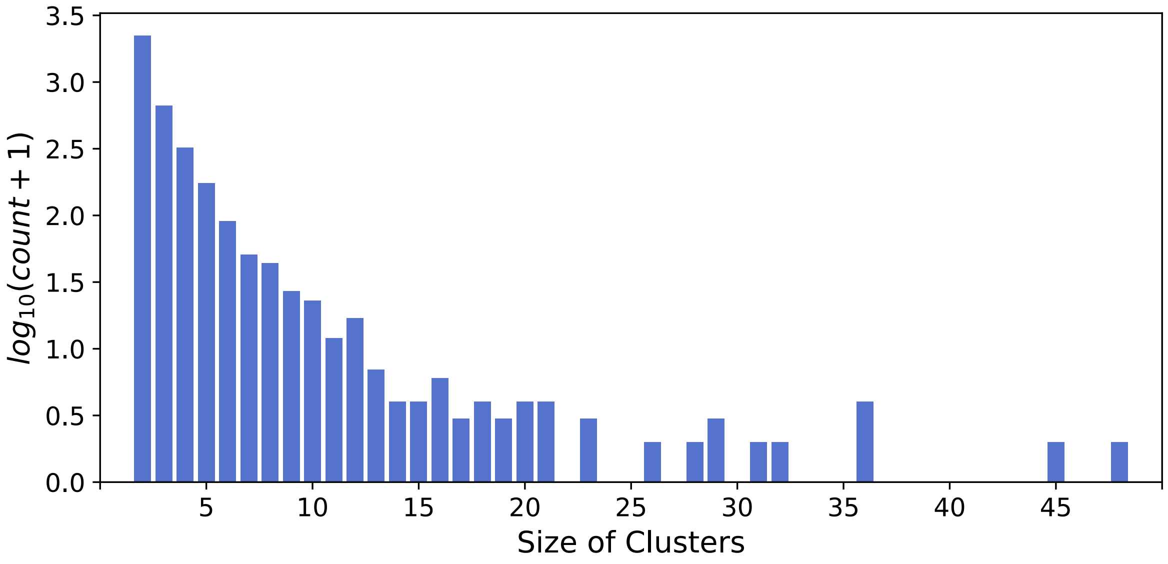
Theoretical Result



- Theorem 1: Except for SMT solving, other steps of EqDAC run in polynomial time to N, where N is the upper bound of the numbers of AST nodes for the two data constraints.
- Theorem 2: If the fragment of data constraints is decidable, EqDAC is sound and complete.

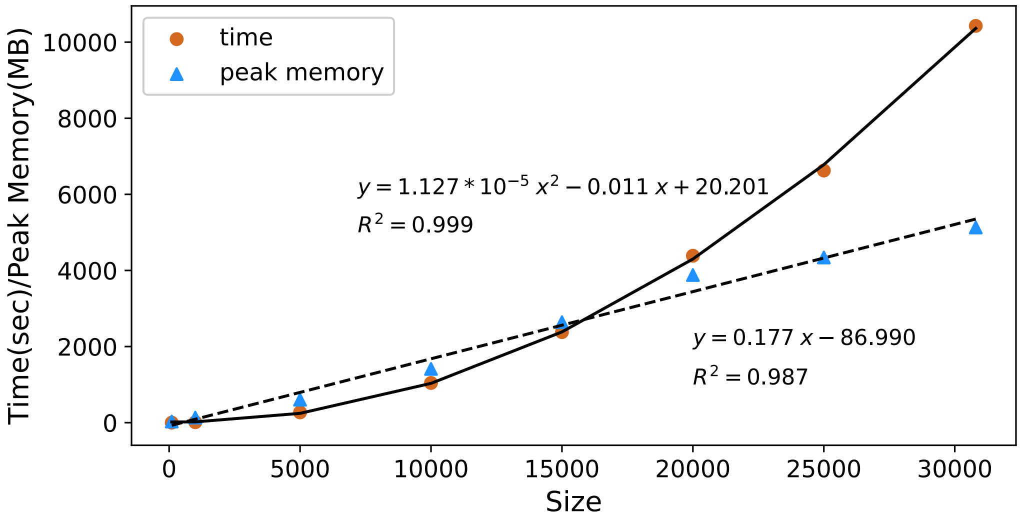
RQ1: Effectiveness

- Identify 26,789 equivalent pairs among 30,801 data constraints in Ant Group
  - 7,842 data constraints can be removed.
  - Error messages caused by data constraints in the same cluster can be merged
    - Extreme case: 48 equivalent data constraints in a cluster

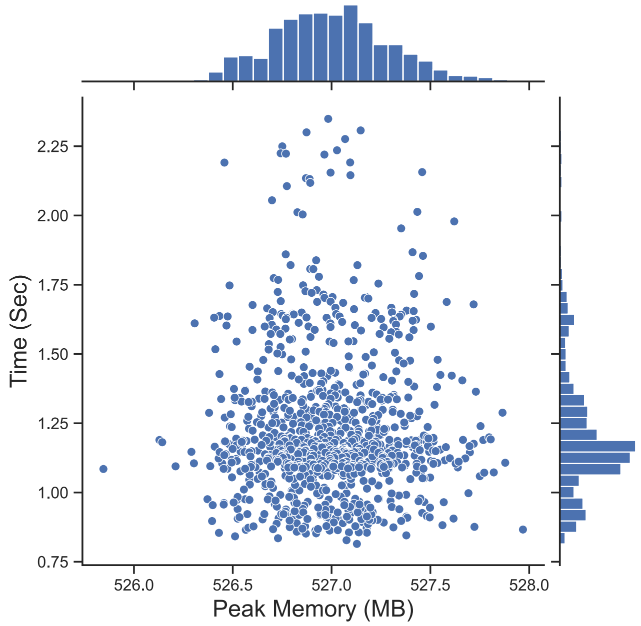


RQ2: Efficiency

- Equivalence clustering
  - Analyze 30,801 data constraints in 2.89 h
  - Peak memory: linear to #data constraints
  - Time cost: Quadratic to #data constraints

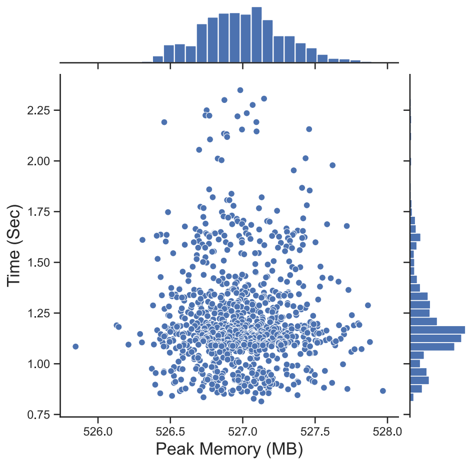


- Equivalence searching
  - #Data constraint = 30,801 – 1,000
  - Peak memory: 527.87 MB (max), 527.1 MB (avg)
  - Time cost: 2.50 sec (max), 1.22 sec (avg)



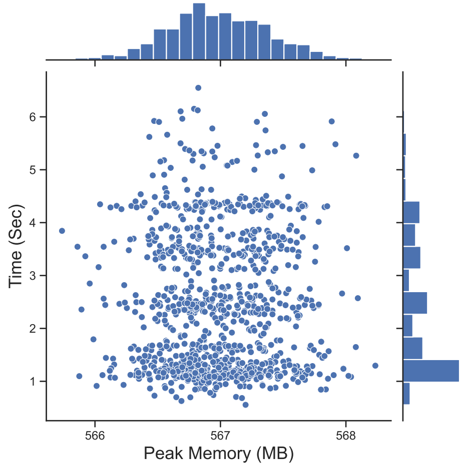
RQ3: Ablation Studies

- Equivalence searching



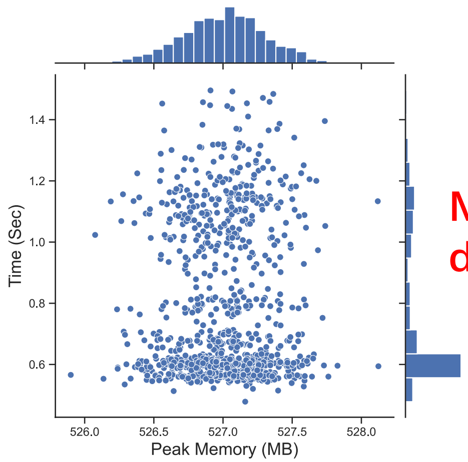
EqDAC

max: 2.50 sec, **avg:** 1.22 sec



EqDAC-NI

max: 6.56 sec, **avg:** 2.53 sec



EqDAC-NS

max: 1.48 sec, **avg:** 0.74 sec

Miss 37 equivalent data constraints

- Equivalence clustering

Variant	Time(h)	Mem(GB)	#Eq Pair	#Redundant
EqDAC-ND	OOT	7.27	141	53
EqDAC-NI	4.48	6.80	26,789	7,842
EqDAC-NS	2.13	3.94	25,952	7,296
EqDAC	2.89	5.01	26,789	7,842

EqDAC-ND: no divergence analysis
EqDAC-NI: no isomorphic analysis
EqDAC-NS: no SMT solving

Conclusion

- Formulate the problem of equivalence data constraint verification
  - Equivalence reasoning upon tens of thousands of programs, i.e., data constraints
- Propose an efficient, sound, and complete decision procedure
  - Leverage lexical difference and isomorphic structures for acceleration
- Provide a fundamental component of equivalence searching and clustering
  - Avoid the redundant checking of equivalent data constraints

Pre-print

Tool

Thank you for your listening!

BACKUP

Syntax

- Data constraint syntax

$$
\begin{aligned}
&\mathcal{V} := v_d \mid x \\
&\mathcal{L} := \{l_i \mid i \geq 1\} \\
&\mathcal{A} := l \mid v_d \mid a_1 \oplus a_2 \\
&\mathcal{C} := a_1 \odot a_2 \mid x_1 \odot x_2 \mid a \odot x \mid x \odot a \mid p(v, l) \mid p(v_1, v_2) \\
&\mathcal{B} := c \mid b_1 \textbf{ and } b_2 \mid b_1 \textbf{ or } b_2 \mid \textbf{not } b \mid \textbf{ite}_b(c_0, b_1, b_2) \\
&\mathcal{S} := x = a \mid \textbf{assert}(b) \mid s_1; s_2 \mid \textbf{ite}_s(c_0, s_1, s_2) \\
&\mathcal{R} := s+ \\
&\oplus := \ + \mid - \mid \times \mid \div \\
&\odot := \ > \mid < \mid \geq \mid \leq \mid == \mid \neq \\
&\mathcal{P} := \{\text{prefixOf},\ \text{suffixOf},\ \text{contains},\ \text{equals}\}
\end{aligned}
$$

Semantics

- An *interpretation* I is a mapping which maps each data variable v_d to a value in its domain.

$$I = \{\text{acc.type} \mapsto \text{'IN'},\ \text{acc.in} \mapsto 10,\ \text{acc.out} \mapsto 0,\ \text{acc.in\_id} \mapsto 1,\ \text{acc.out\_id} \mapsto 2\}$$

- Given a data constraint r, we say $I \vDash r$, i.e., I is a model of r, if and only if all the assertions in r hold under the interpretation I.

```
if(acc.type == 'IN'){
  amount = acc.in;
} else {
  amount = acc.out;
}
r1 = amount > 0;
r2 = acc.in_id != nil;
r3 = acc.out_id != nil;
assert(r1 && r2 && r3);
```

Data Constraint Equivalence

- The data constraints r_1 and r_2 are semantically equivalent, denoted by $r_1 \simeq r_2$, if and only if for any interpretation I, we have

$$I \vDash r_1 \Leftrightarrow I \vDash r_2$$

```
if(acc.type == 'IN'){
  amount = acc.in;
} else {
  amount = acc.out;
}
r1 = amount > 0;
r2 = acc.in_id != nil;
r3 = acc.out_id != nil;
assert(r1 && r2 && r3);
```

(a)

```
type = 'IN';
assert(acc.in_id != nil);
assert(acc.out_id != nil);
if(acc.type == type){
  amount = acc.in;
} else {
  amount = acc.out;
}
assert(amount > 0);
```

(b)

Semantic Encoding

- Evaluate user-defined variables

```
s = 'IN';
if(contains(t.ty,s))
  assert(t.in > 0);
else
  assert(t.out > 0);
assert(t.amt > 0);
assert(t.oid != 0);
```

$$\varphi_1 = ((t.in > 0 \land \phi_c) \lor (t.out > 0 \land \neg\phi_c)) \land \phi_a \land \phi_o$$

```
s = 'IN';
if(not contains(t.ty,s))
  assert(t.out > 0);
else
  assert(t.new > 0);
assert(t.amt > 0);
assert(t.iid != 0);
```

$$\varphi_2 = ((t.out > 0 \land \neg\phi_c) \lor (t.new > 0 \land \phi_c)) \land \phi_a \land \phi_i$$

$\phi_a = (t.amt > 0)$

$\phi_o = (t.oid \neq 0)$

$\phi_i = (t.iid \neq 0)$

$\phi_c = \texttt{contains}(t.ty,\ \text{'IN'})$

Equivalence Relation Verified by SMT Solver

- Case Study

```
   /* Data contraint 1 */
1  assert(t.id != t.pid);
1  assert(ut.oid != ut.iid);
   if(t.id == ut.oid){
     assert(t.pid == ut.iid);
1  } else {
     assert(t.id == ut.iid);
     assert(t.pid == ut.oid);}
```

```
/* Data contraint 2 */
if(t.id == ut.iid){
  assert(ut.oid == t.pid);
} else {                          2
  assert(t.id == ut.oid);
  assert(t.pid == ut.iid);}
assert(ut.iid != ut.oid); 2
assert(t.pid != t.id); 2
```

- 1 and 2 are equivalent
- 1 and 2 are equivalent
- 1 and 2 are not equivalent
- 1 ∧ 1 and 2 ∧ 2 are equivalent

END