Evaluation of Temporal Queries

with Applications in Program Debugging

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with Applications in Program Debugging

1. **Debugging with Temporal Queries**
2. **Query Evaluation: Compilation Approach**
3. **Query Evaluation: Recursive Temporal Queries**

Debugging with Temporal Queries

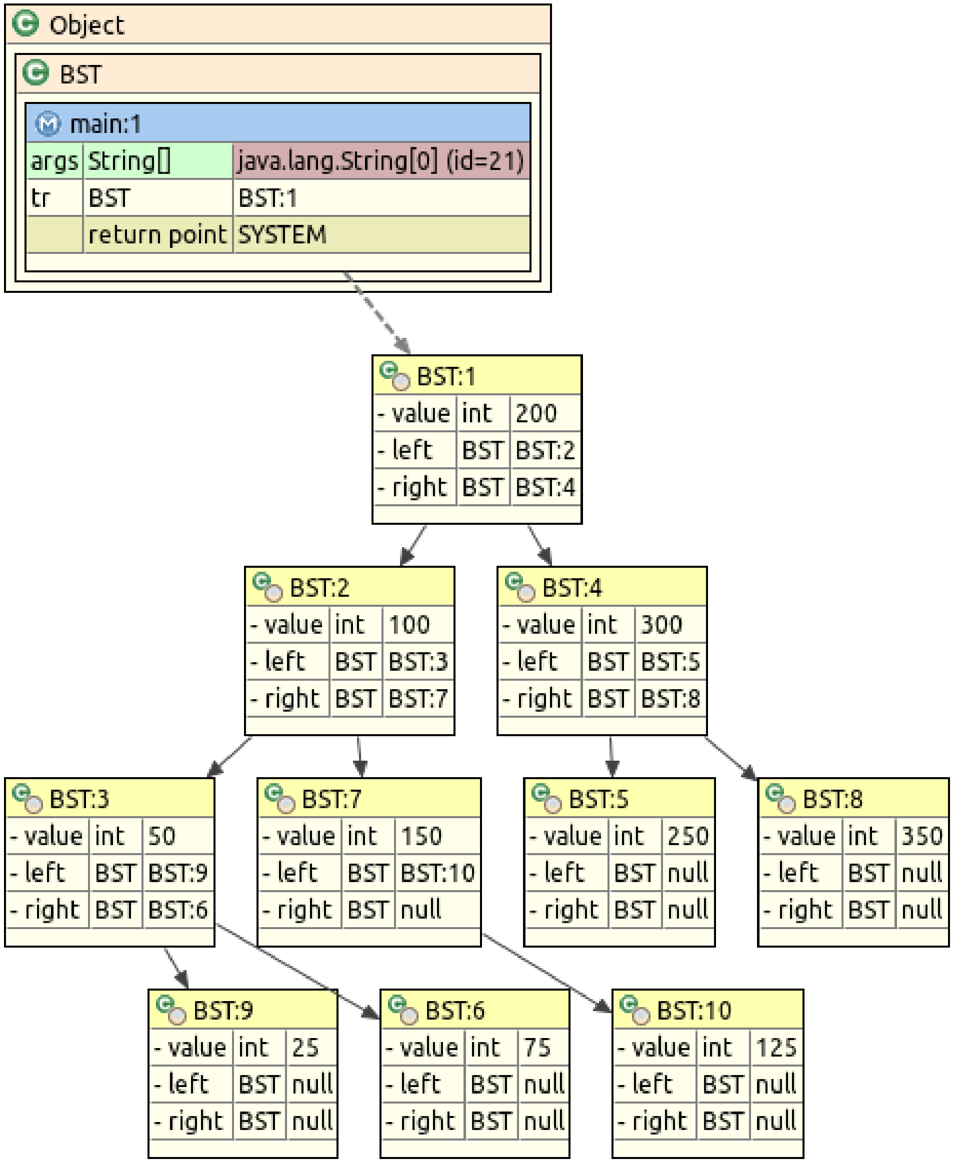
Example: Binary Search Tree

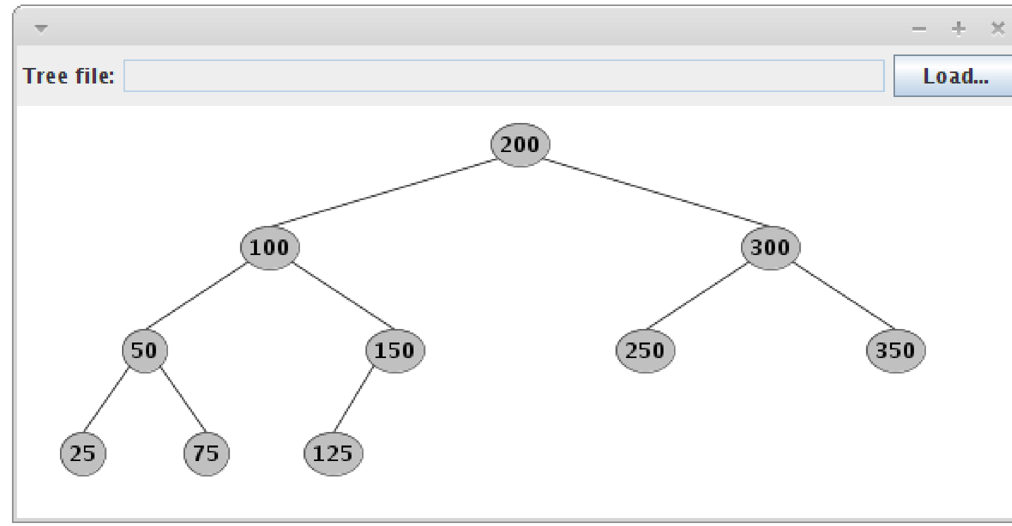
```
public class BST {

  private final int value;
  private BST left = null;
  private BST right = null;

  public BST(final int n) {
    value = n;
  }

  public void insert(final int n) {
    if (value == n) {
      return;
    }
    if (value < n) {
      if (right == null) {
        right = new BST(n);
      }
      else {
        right.insert(n);
      }
    }
    else if (left == null) {
      left = new BST(n);
    }
    else {
      left.insert(n);
    }
  }
}
```

- Sample debug questions
  - *was there ever* a path between...?
  - *when* was there a path between...?
  - *was there ever* an invariant violatation?

Debugging with Temporal Queries

Example: Binary Search Tree

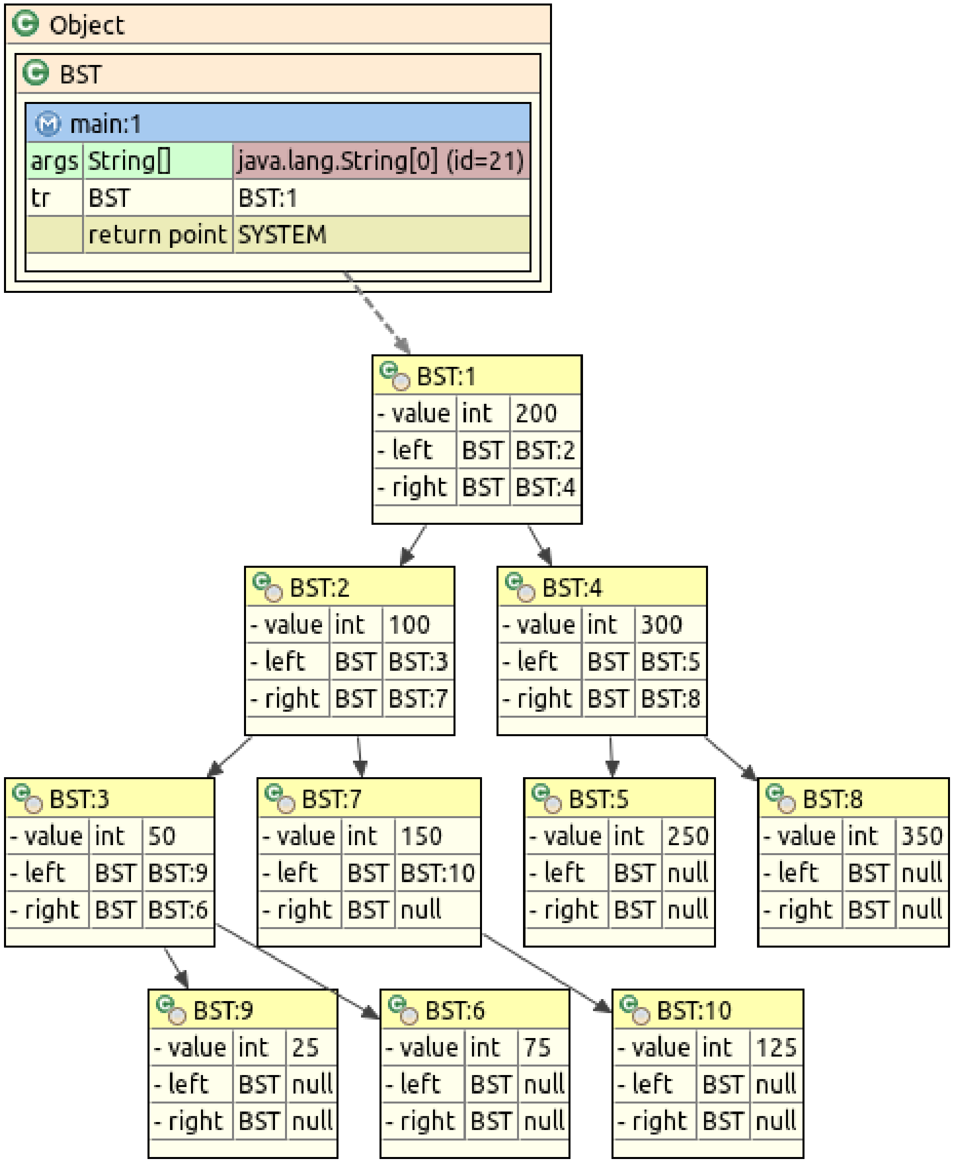




- JIVE's Object Diagram
  - run-time view of object heap
  - one diagram for each time in execution
  - supports visual debugging
  - supports back-in-time stepping
  - not scalable for large execution traces
  - solution: query-based debugging!

Debugging with Temporal Queries

Example: Binary Search Tree

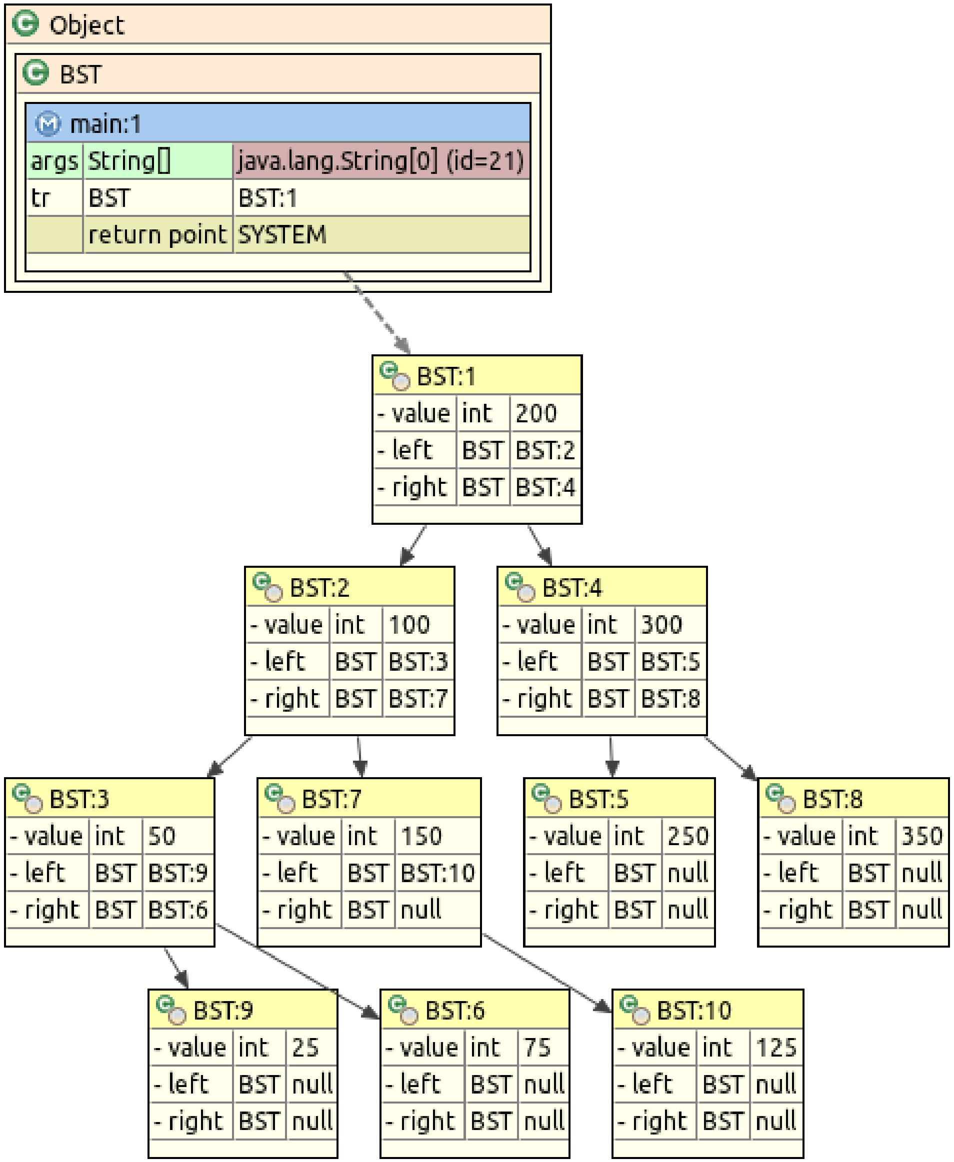


- Query-based debugging
  - schema: BST(id, key, lid, rid)
  - consider the given program state
  - recursive Datalog queries (non-temporal)

```
Q1: Is there a path 100 → K, K < 60?

Q1() :- Path(A,D),
        BST(A,100,_,_),
        BST(D,K,_,_), K < 60

% base cases: direct edges
Path(A,D) :- BST(A,_,D,_)
Path(A,D) :- BST(A,_,_,D)
% recursive cases
Path(A,D) :- Path(A,N), BST(N,_,D,_)
Path(A,D) :- Path(A,N), BST(N,_,_,D)
```

Debugging with Temporal Queries

Example: Binary Search Tree

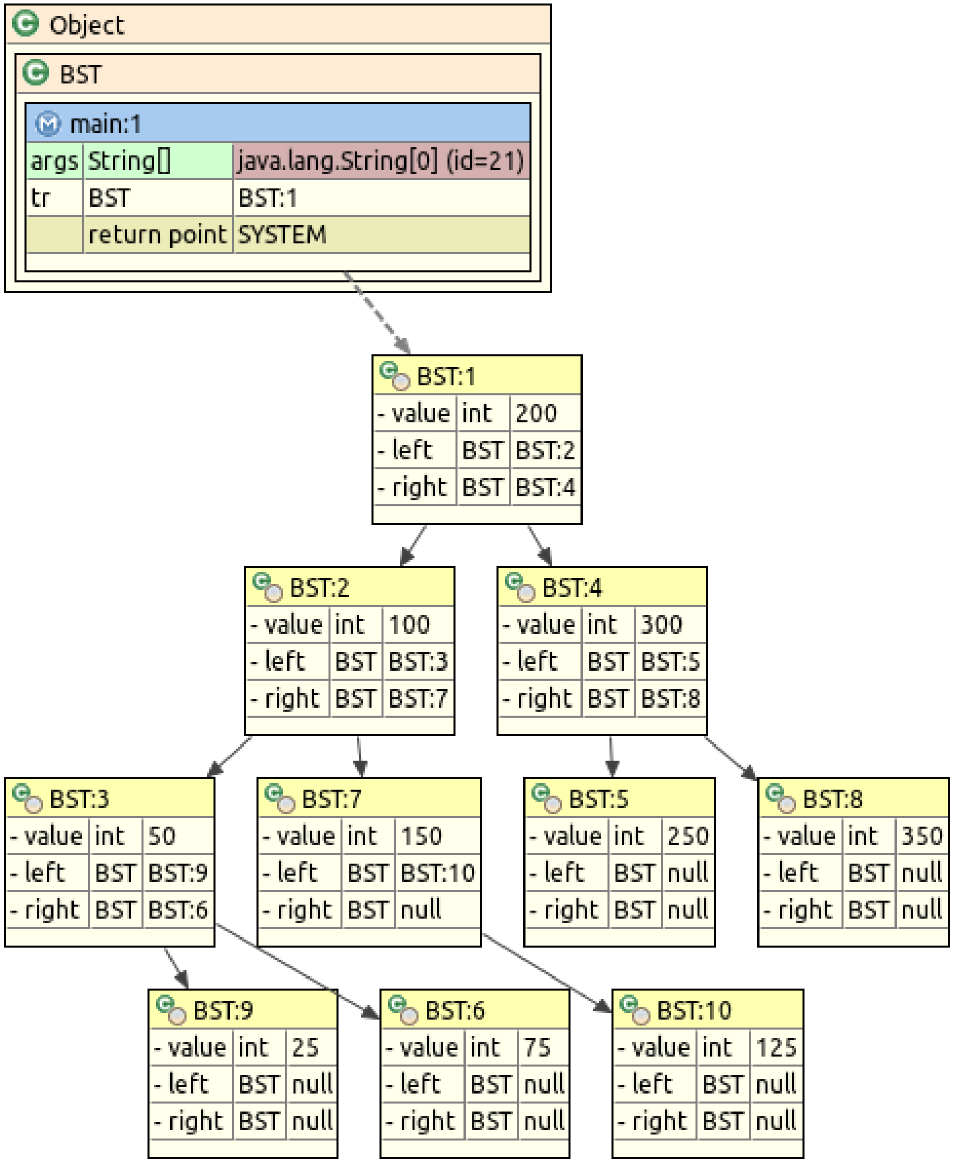


- BST Invariant: given a node N
  - left subtree keys are *smaller* than key(N)
  - right subtree keys are *larger* than key(N)
  - left and right subtrees are BSTs

```
Q2: Is the BST invariant violated?

Q2() :- Left(A,D), BST(A,KA,_,_),
        BST(D,KD,_,_), KA < KD
Q2() :- Right(A,D), BST(A,KA,_,_),
        BST(D,KD,_,_), KA > KD

% D is a node in A's left subtree
Left(A,D) :- BST(A,_,D,_)
Left(A,D) :- Left(A,N), Path(N,D)

% D is a node in A's right subtree
Right(A,D) :- BST(A,_,_,D)
Right(A,D) :- Right(A,N), Path(N,D)
```

Debugging with Temporal Queries

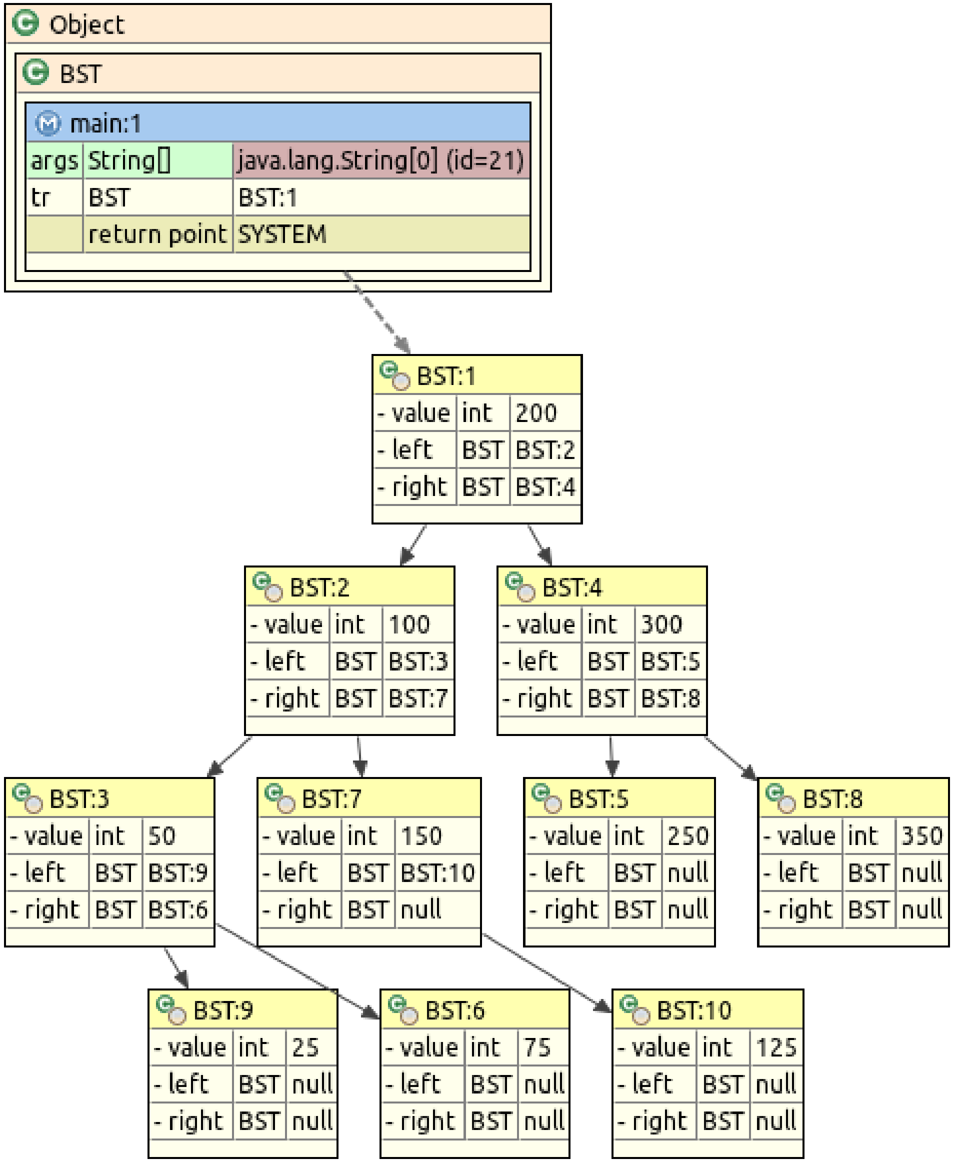
Example: Binary Search Tree



- Query-based debugging
  - Q1 and Q2 only work for a fixed state
  - solution-- temporal approach
- Challenges
  - how do we incorporate time?
  - data model-- points, intervals, or...?
  - representation of temporal data
  - query language syntax and semantics?
  - query language expressiveness?
    - set and bag operations?
    - grouping and aggregation?
    - recursion?

Debugging with Temporal Queries

Example: Binary Search Tree

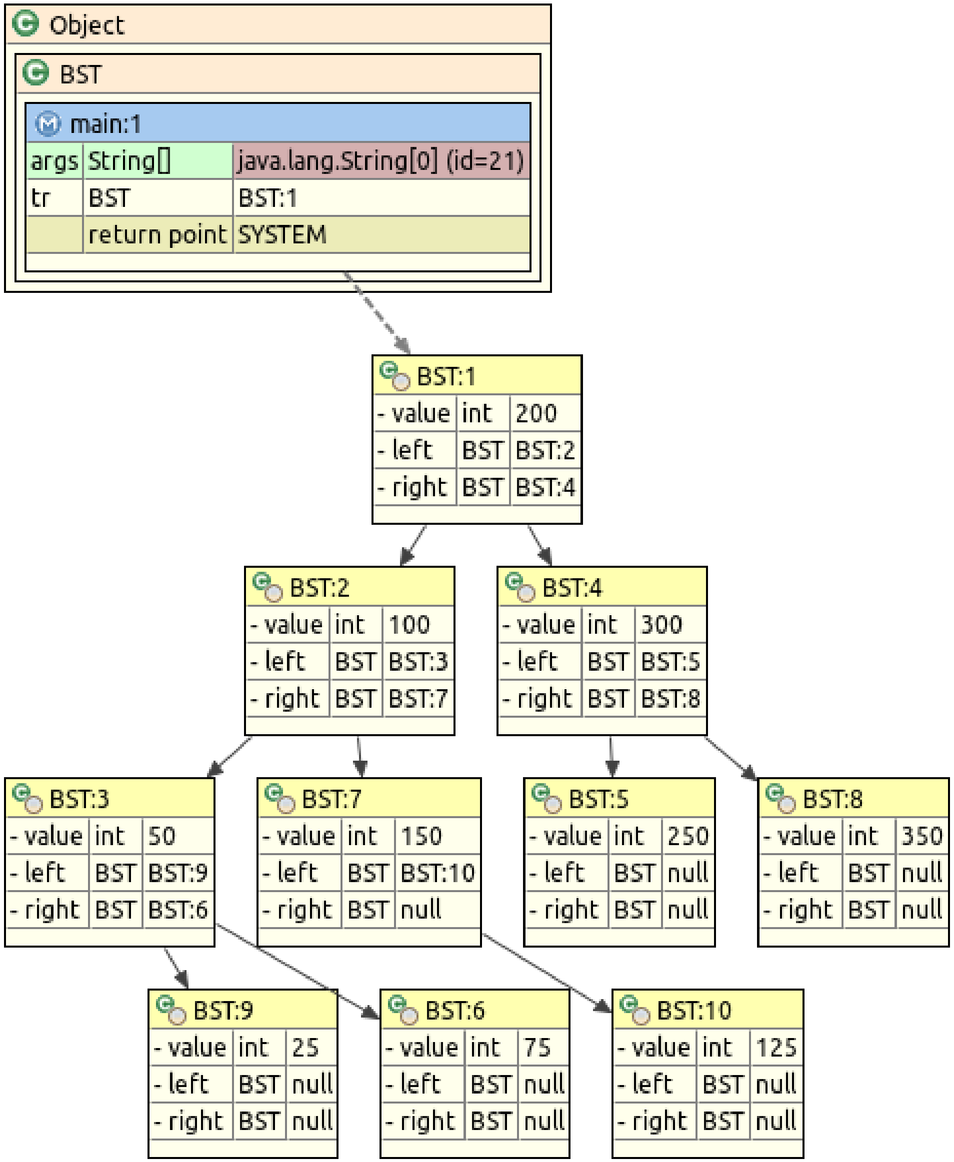


- Point-based temporal model
  - BST(id, key, lid, rid, time)
  - time is discrete and linearly ordered
  - conceptually simple
  - query formulation intuitive
  - *materializing BST is impractical*

```
Q1: When was there a path 100 → K, K < 60?

Q1(T) :- Path(A,D,T),
         BST(A,100,_,_,T),
         BST(D,K,_,_,T), K < 60

% base cases: direct edges
Path(A,D,T) :- BST(A,_,D,_,T)
Path(A,D,T) :- BST(A,_,_,D,T)
% recursive cases-- temporal equijoins!
Path(A,D,T) :- Path(A,N,T), BST(N,_,D,_,T)
Path(A,D,T) :- Path(A,N,T), BST(N,_,_,D,T)
```

Debugging with Temporal Queries

Example: Binary Search Tree



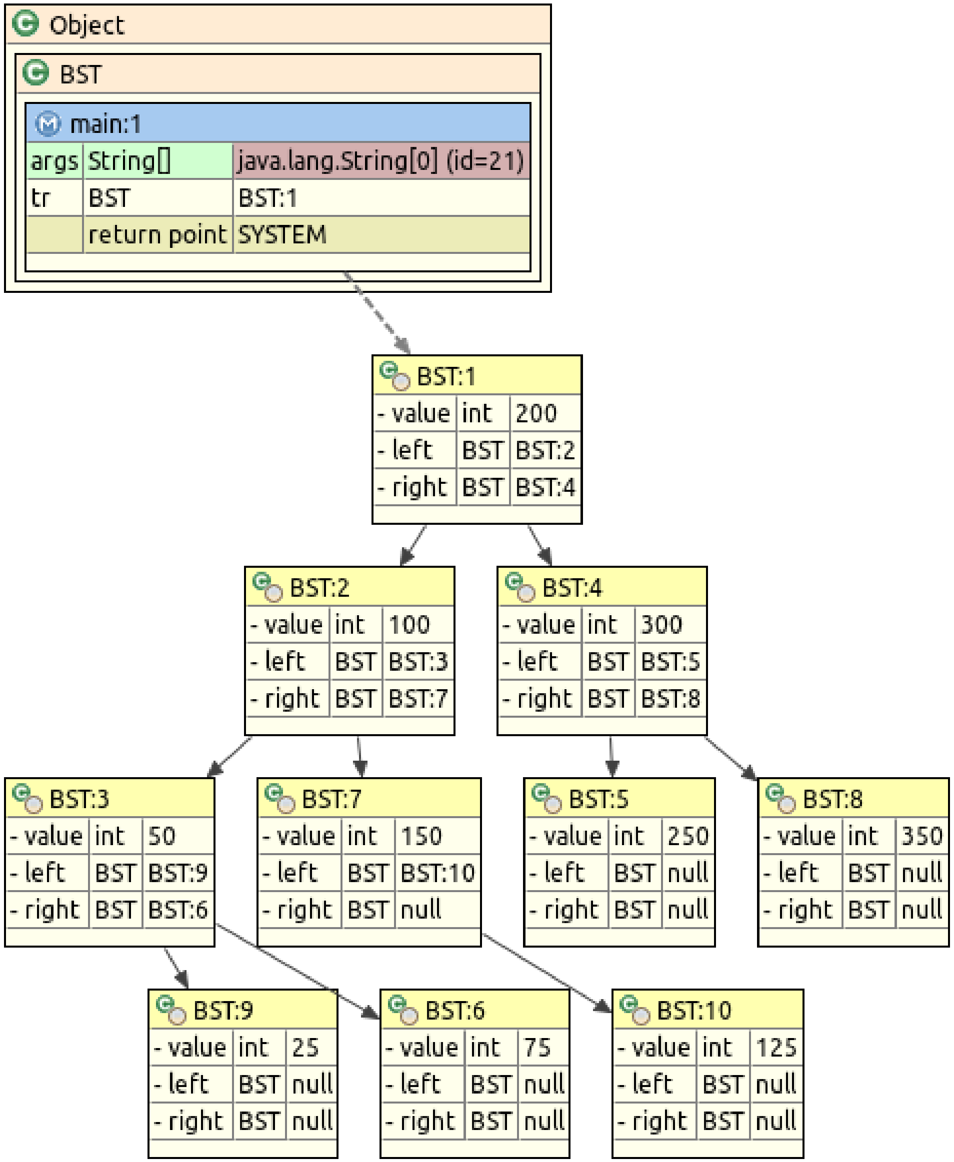
- Interval-based temporal model
  - BST(id, value, lid, rid, time_s, time_e)
  - time is discrete and linearly ordered
  - time_s < time_e
  - space-efficient representation
  - *query formulation much harder*

Q1: <u>When</u> was there a path 100 → K, K < 60?

```
% does not preserve set semantics! why?
Q1(TS,TE) :- Path(A,D,TSP,TEP),
             BST(A,100,_,_,TSA,TEA),
             BST(D, K,_ _,TSD,TED), K < 60,
% do intervals overlap? (not transitive!)
             TSP < TEA, TSA < TEP,
             TSP < TED, TSD < TEP,
             TSA < TED, TSD < TEA,
% interval construction
             TS = MAX(TSP,TSA,TSD),
             TE = MIN(TEP,TEA,TED)
```

Debugging with Temporal Queries

Example: Binary Search Tree



- Interval-based temporal model
  - BST(id, value, lid, rid, time_s, time_e)
  - time is discrete and linearly ordered
  - time_s < time_e
  - space-efficient representation
  - *query formulation much harder*

Q1: <u>When</u> was there a path 100 → K, K < 60?

```
% base cases: direct edges
Path(A,D,TS,TE) :- BST(A,_,D,_,TS,TE)
Path(A,D,TS,TE) :- BST(A,_,_,D,TS,TE)
% recursive cases-- temporal equijoins!
Path(A,D,TS,TE) :- Path(A,N,TSP,TEP),
  BST(N,_,D,_,TSN,TEN),
  TSP < TEN, TSN < TEP,
  TS = MAX(TSP, TSN), TE = MIN(TEP, TEN)
Path(A,D,TS,TE) :- Path(A,N,TSP,TEP),
  BST(N,_,_,D,TSN,TEN),
  TSP < TEN, TSN < TEP,
  TS = MAX(TSP, TSN), TE = MIN(TEP, TEN)
```

Evaluation of Temporal Queries

with Applications in Program Debugging

1 **Debugging with Temporal Queries**

2 **Query Evaluation: Compilation Approach**

3 **Query Evaluation: Recursive Temporal Queries**

Query Evaluation

Compilation Approach

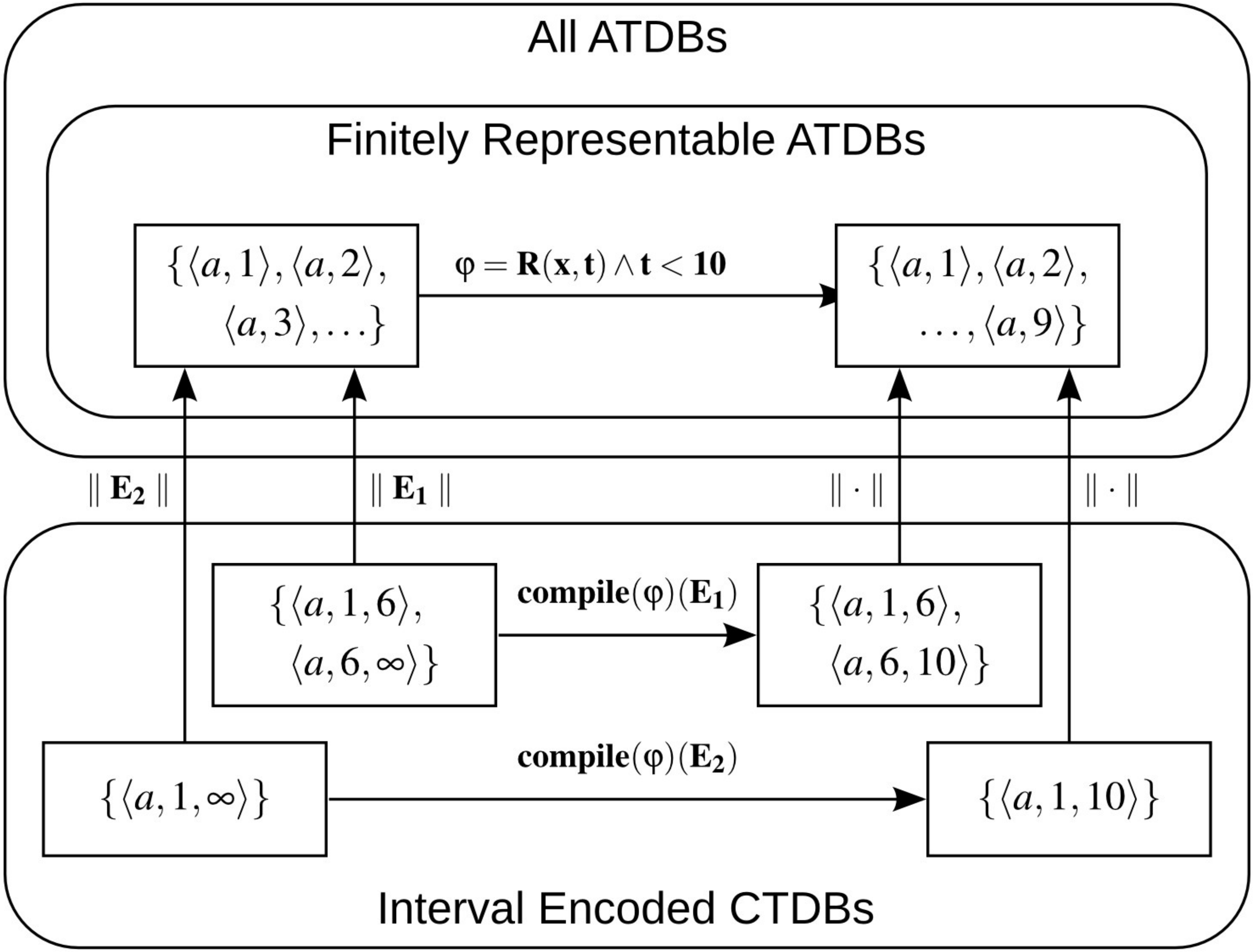
- Temporal Model
  - Abstract Temporal Database (ATDB)
  - Concrete Temporal Database (CTDB)
- ATDB
  - point-based, representation independent
  - possibly infinite, but finitely representable
  - only part of the temporal database exposed to users
- CTDB
  - interval-based encoding of the ATDB
  - used internally, transparent to users
  - an actual SQL/99 RDBMS, so we can leverage existing technology
- Challenge
  - how do we execute point-based queries against the CTDB?
  - through a query compilation technique

Query Evaluation

Compilation Approach

- Semantic mapping, || ||
  - maps CTDB elements to respecitve ATDB elements
- Compilation procedure
  - input: point-based temporal query Q
  - output: interval-based temporal query *compile*(Q)
- Query evaluation
  - compile(Q) is evaluated against the CTDB
  - *concrete tuples* are returned to user

Query Evaluation
Compilation Approach



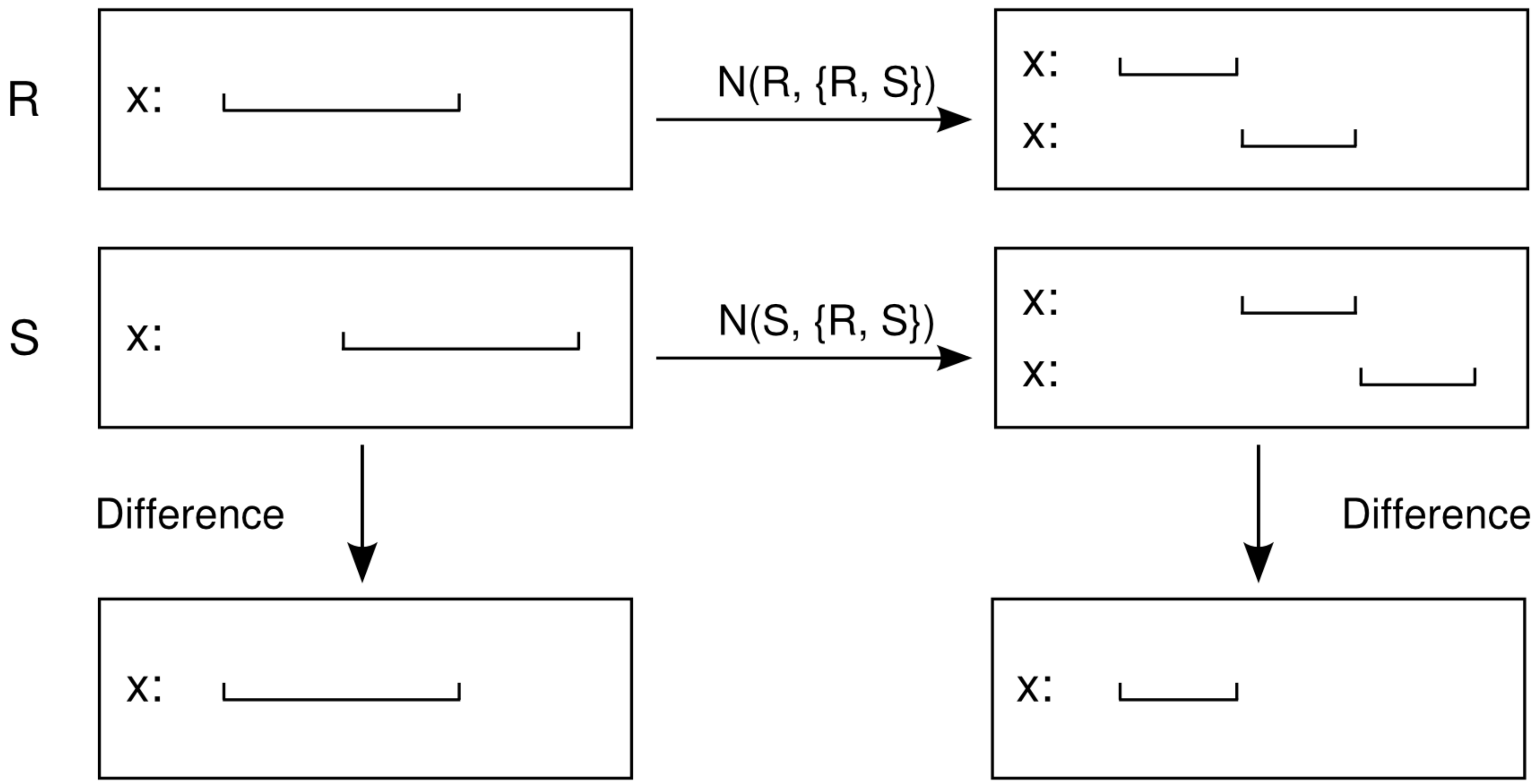
Query Evaluation

Compilation Approach

- Guarantee: compilation preserves semantics w.r.t. ATDBs
  - for every CTDB D, || *compile*(Q)(D) || = Q(|| D ||)
  - non-trivial!
- Challenges
  - mapping points to intervals: quantifier elimination, well studied
  - however, not sufficient to guarantee preservation of semantics w.r.t. ATDBs
- What is the problem?
  - under set semantics, concrete queries must return disjoint intervals
  - otherwise, we will observe several undesirable consequences...
  - set/bag operations:
    - e.g., expected empty set but tuples are returned
  - duplicate elimination:
    - e.g., [5, 10) is a duplicate if [1, 100) is in the result!
  - aggregation:
    - e.g., inconsistent sums/counts
  - recursion:
    - e.g., blowu-up in space/time complexity of the bottom-up evaluation

Query Evaluation
Compilation Approach

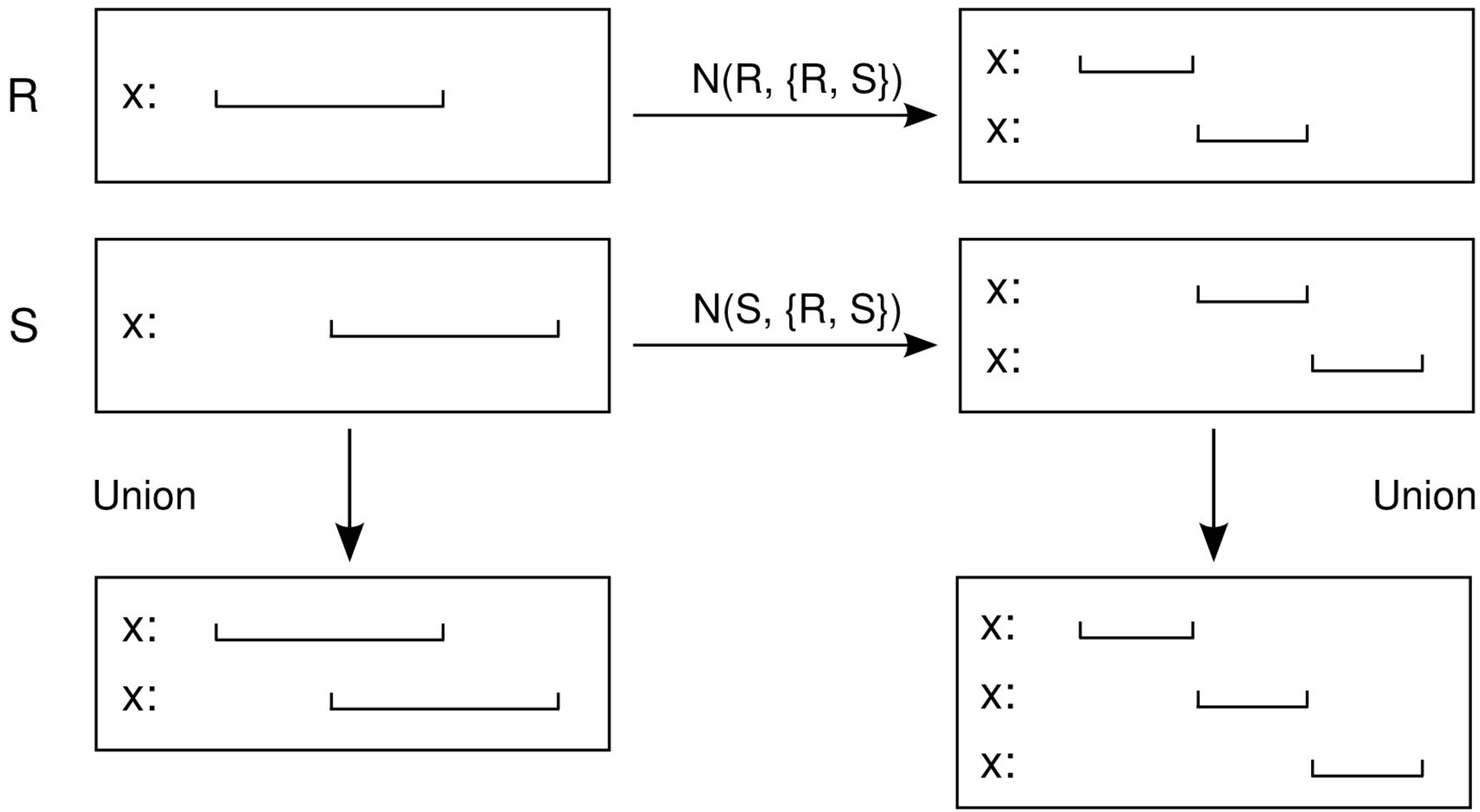
- Time compatibility using the N operator: set difference example



Query Evaluation

Compilation Approach

- Time compatibility using the N operator: set union example



Query Evaluation

Compilation Approach

- Use of N in the compilation of non-recursive queries
  - set/bag operations, grouping, aggregation, duplicate elimination, joins
  - → SQL/TP
- However, recursive queries are not supported...
- N Operator (intuition)
  - collects left (L) and right (R) interval endpoints of input relations
  - splits output relation intervals according to minimal intervals obtained from L and R
  - → must reference each input relation at least once to build L and R
  - → must introduce negation to guarantee minimality
- What is the problem?
  - syntactically, a recursive query is formulated as a union
  - compiling a recursive query introduces the N operator
  - the compiled recursive query is non-linear and has non-stratified negation!
  - SQL/99 and later engines cannot evaluate such queries
  - a more general solution to the bottom-up evaluation is required

Evaluation of Temporal Queries
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Query Evaluation

Recursive Temporal Queries

- Dilemma
  - using N: semantics w.r.t. ATDBs is preserved but cannot evaluate queries
  - not using N: can evaluate queries but semantics w.r.t. ATDBs is lost
  - our approach:
    - modified compilation to drop the use of N for recursive predicates
    - modified bottom-up evaluation to guarantee preservation of semantics w.r.t. ATDBs
- Modified Compilation
  - do not use N for recursive predicates
  - modified bottom-up evaluation code is incorporated in the compiled query
  - cannot be done in plain SQL-- produce a (database) function instead
  - introduce optimizations, e.g., magic sets, index creation, etc
- Modified Bottom-Up Evaluation
  - semantics w.r.t. ATDBs is preserved at every stage
  - evaluation terminates in finitely many steps
  - no redundant computation, i.e., new temporal facts are generated at every stage

Query Evaluation

Recursive Temporal Queries

- Traditional Bottom-Up Evaluation
  - `I, J = ∅`
  - **`repeat`**
  - `  J = I`
  - `  I =` T_P`(I)`
  - **`until`** `I = J`
  - **`return`** `I;`
- Details
  - fixpoint computation
  - based on the immediate consequence operator, T_P
  - T_P derives new ground facts from existing ground facts
  - termination: DB has finitely many symbols, no new symbols are introduced

Query Evaluation

Recursive Temporal Queries

- Normalizing Bottom-Up Evaluation
  - `I, J = ∅`
  - **`repeat`**
  - `  J = I`
  - `  I = ` T_{NP}`(I)`
  - **`until`** `|| I || = || J ||`
  - **`return`** `I;`
- Details
  - fixpoint computation
  - based on the normalizing immediate consequence operator, T_{NP}
  - T_{NP} derives new temporal ground facts from existing temporal ground facts
    - guarantees that set unions preserve semantics w.r.t. ATDBs
  - T_{NP} is not sufficient to guarantee termination or non-redundant computation
    - in general, $J \not\subseteq I$ due to representation differences at consecutive stages
    - however, $|| J || \subseteq || I ||$ holds at every stage, based on the correctness of T_{NP}
  - termination: based on the termination of constraint Datalog programs

Query Evaluation

Recursive Temporal Queries

- Abstract relation Refs(O, R, T) keeps track of the instants in which object O references object R at run-time. $\overline{\text{Refs}}$(O, R, Ts, Te) is its concrete counterpart.
- Now, consider the following *temporal transitive closure* query:

```
% X → Y at time T
TTC(X,Y,T) :- Refs(X,Y,T)
% X → Z at time T1 and Z → Y at a later time T
TTC(X,Y,T) :- TTC(X,Z,T1), Refs(Z,Y,T), T > T1
```

- The point-to-interval translation performed by the compiler yields:

```
% X → Y during [Ts,Te)
TTC(X,Y,Ts,Te) :- Refs(X,Y,Ts,Te)
% X → Z during [T1s,T1e) and Z → Y during [T2s,Te)
TTC(X,Y,Ts,Te) :- TTC(X,Z,T1s,T1e), Refs(Z,Y,T2s,Te),
                  Te > T1s+1, Ts = MAX(T2s,T1s+1)

% Te > T1s+1 implies that there exists T ∈ [T2s,Te) s.t. T > T1s
% Ts = MAX(T2s,T1s+1) is the smallest left endpoint contained in [T2s,Te)
```

Query Evaluation

Recursive Temporal Queries

```
% X → Y during [Ts,Te)
TTC(X,Y,Ts,Te) :- Refs(X,Y,Ts,Te)
% X → Z during [T1s,T1e) and Z → Y during [T2s,Te)
TTC(X,Y,Ts,Te) :- TTC(X,Z,T1s,T1e), Refs(Z,Y,T2s,Te),
                  Te > T1s+1, Ts = MAX(T2s,T1s+1)
```

- Now assume that $\overline{\text{Refs}}$ contains a single tuple, <1, 1, 1, 2^k+1>, for k > 0.
- Our modified evaluation of the concrete query produces:

$T_{NP} \uparrow 1 = \{<1,1,\mathbf{1},\mathbf{2^k+1}>\}$ % stage #1, base case

$T_{NP} \uparrow 2 = \{<1,1,\mathbf{1},\mathbf{2}>,<1,1,\mathbf{2},\mathbf{2^k+1}>\}$ % stage #2, recursive case

% $|| T_{NP} \uparrow 1 || = || T_{NP} \uparrow 2 ||$, i.e., both represent the same ATDB

Query Evaluation

Recursive Temporal Queries

- Using T_{NP} alone...
  - does not guarantee termination for infinite ATDBs, e.g., <1,1,1,+∞>
  - causes blowup, e.g., || J || = || I || may hold early on even though J ≠ I
  - re-evaluating the previous example...

T_{NP} ↑ 1 = {<1,1,**1,2^k+1**>} % stage #1, base case

T_{NP} ↑ 2 = {<1,1,**1,2**>,<1,1,**2,2^k+1**>} % stage #2

...

T_{NP} ↑ 2^k = {<1,1,**1,2**>,<1,1,**2,3**>,...,<1<1,1,**2^k,2^k+1**>} % stage #2^k

T_{NP} ↑ 2^k+1 = {<1,1,**1,2**>,<1,1,**2,3**>,...,<1<1,1,**2^k,2^k+1**>} % stage #2^k+1

Query Evaluation

Recursive Temporal Queries

- Using the modified termination condition alone…
  - causes space blowup, e.g., at every stage, I and J may contain temporal duplicates
  - re-evaluating the previous example…

$T_{NP} \uparrow 1 = \{\langle 1,1,\mathbf{1},\mathbf{2^k+1}\rangle\}$ % stage #1, base case

$T_{NP} \uparrow 2 = \{\langle 1,1,\mathbf{1},\mathbf{2^k+1}\rangle,\langle 1,1,\mathbf{2},\mathbf{2^k+1}\rangle\}$ % stage #2

...

$T_{NP} \uparrow 2^k = \{\langle 1,1,\mathbf{1},\mathbf{2^k+1}\rangle,\langle 1,1,\mathbf{2},\mathbf{2^k+1}\rangle,...,\langle 1\langle 1,1,\mathbf{2^k},\mathbf{2^k+1}\rangle\}$ % stage $\#2^k$

$T_{NP} \uparrow 2^k+1 = \{\langle 1,1,\mathbf{1},\mathbf{2^k+1}\rangle,\langle 1,1,\mathbf{2},\mathbf{2^k+1}\rangle,...,\langle 1\langle 1,1,\mathbf{2^k},\mathbf{2^k+1}\rangle\}$ % stage $\#2^k+1$

Query Evaluation

Recursive Temporal Queries

- Applications in debugging and program comprehension.
  - questions about temporal state of recursive data structures (Q1, Q2)
  - general questions about object relationships (TTC)
  - our main focus: query-based dynamic analysis!
- Dynamic Analysis
  - analysis of the properties of running programs
  - characteristics: precision, input dependence
  - e.g., dynamic slicing
    - given a variable V and program location L
    - determine the program statements that affected the value of V at L
  - can be implemented as a temporal recursive query
  - further applications
    - scaling our tool's visualizations by removing regions unrelated to the slice(s)
    - enhancing our tool's visual debugging capabilities

Thank You!