Detecting Atomicity Violations via Integrated Dynamic and Static Analysis

FRACTAL

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Outline

- Introduction to atomicity
- Integrate dynamic and static analysis to detect atomicity violations
- Conflict-edge algorithm
- Experiments and conclusions

A Typical Concurrency Error: Atomicity Violation

Duplicate vector v1

Thread 1

lock(v1);
v2 = new Vector(v1.size());
unlock(v1);

lock(v1);
copy v1's elements to v2;
unlock(v1);

Thread 2

lock(v1);
Remove all elements in v1;
unlock(v1);

Error: space is allocated for v2,
but no elements are copied.

Informal Definition of Atomicity

- **Transaction**: an execution of a code block expected to be atomic.
- Given a program, a set of code blocks (includes transactions) is **atomic** if every concurrent execution of the program is **equivalent** to a serial execution (i.e., the transactions are executed without interruption by other threads).
- Two executions are **equivalent** if every two conflicting events (a read and a write to the same variable, or two writes to the same variable) appear in the same order.

Example: Atomicity Violation

- Transaction t1= $W_1(x)$ $W_2(x)$
- Transaction t2 = W(x).
- All feasible executions:

E1: $W_1(x)$ $W_2(x)$ $W(x)$ serial

E2: $W(x)$ $W_1(x)$ $W_2(x)$ serial

E3: $W_1(x)$ $W(x)$ $W_2(x)$ not serial

- E3 is not equivalent to E1 and E2,
- {t1, t2} has a potential atomicity violation.

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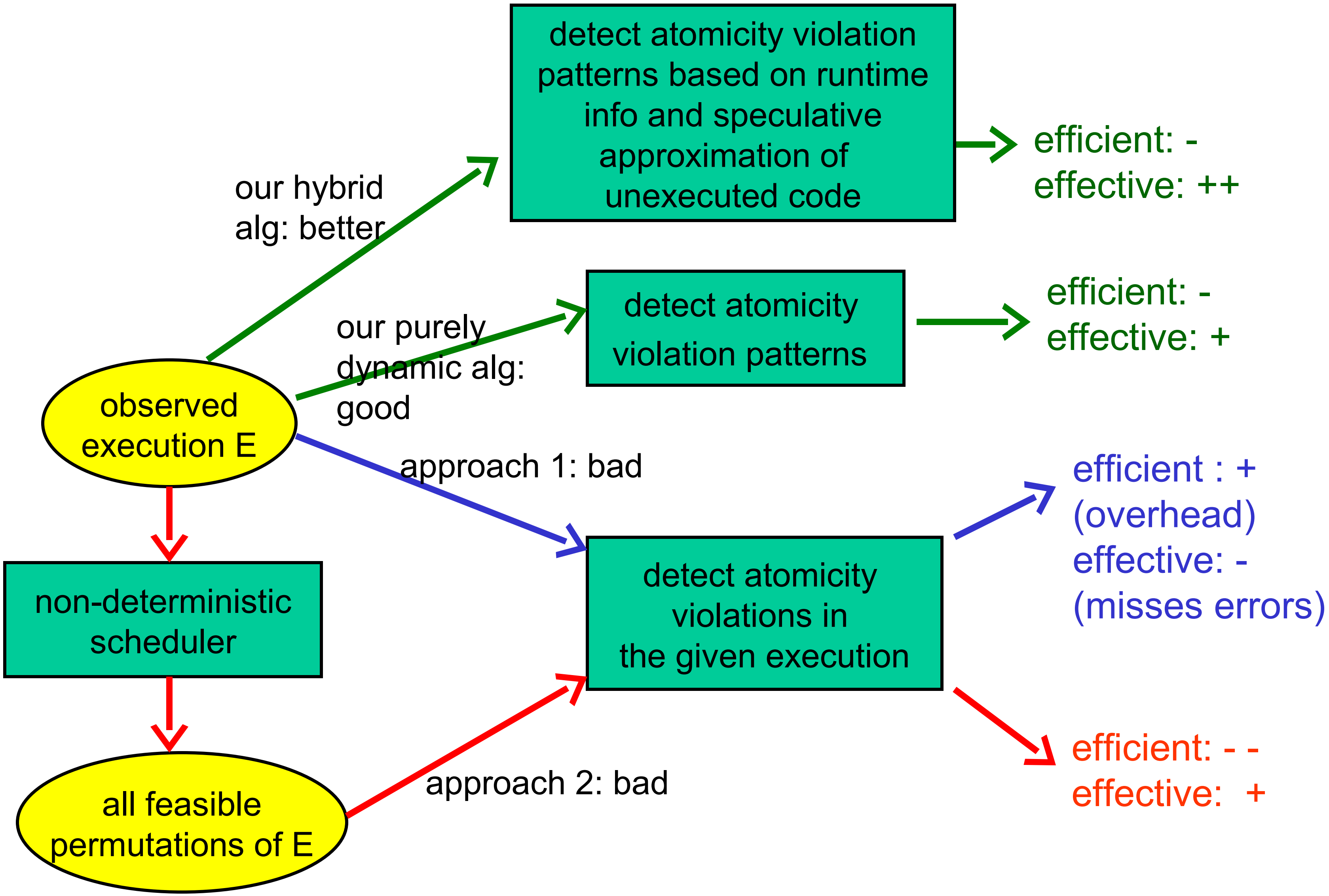
Approaches to Detect Atomicity Violations

- Purely static (Flanagan et al.)
  - Pros: all possible behaviors can be checked.
  - Cons: many false positives.
- Purely dynamic (Wang et al.; Flanagan et al.; Xu et al.; Lu et al.; Park et al.)
  - Pros: much fewer false positives.
  - Cons: cannot analyze unobserved behaviors.
- Integrated static and dynamic analysis (our approach)
  - Get some of the benefits of both approaches
  - Few false positives
  - Analyzes some unobserved behaviors

How to Detect Atomicity Violations?



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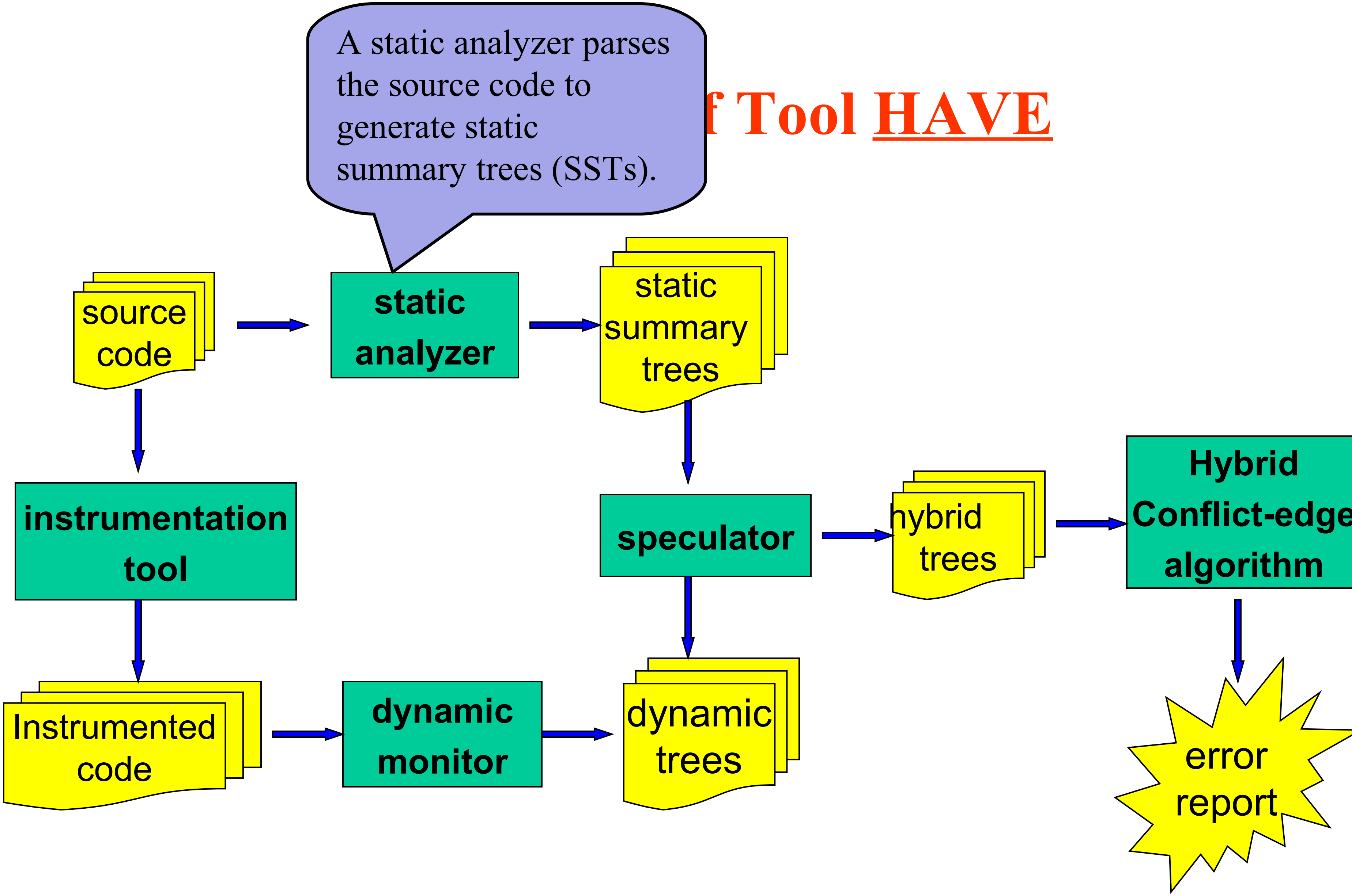
A static analyzer parses the source code to generate static summary trees (SSTs).
source code
static analyzer
static summary trees
instrumentation tool
speculator
hybrid trees
Hybrid Conflict-edge algorithm
Instrumented code
dynamic monitor
dynamic trees
error report

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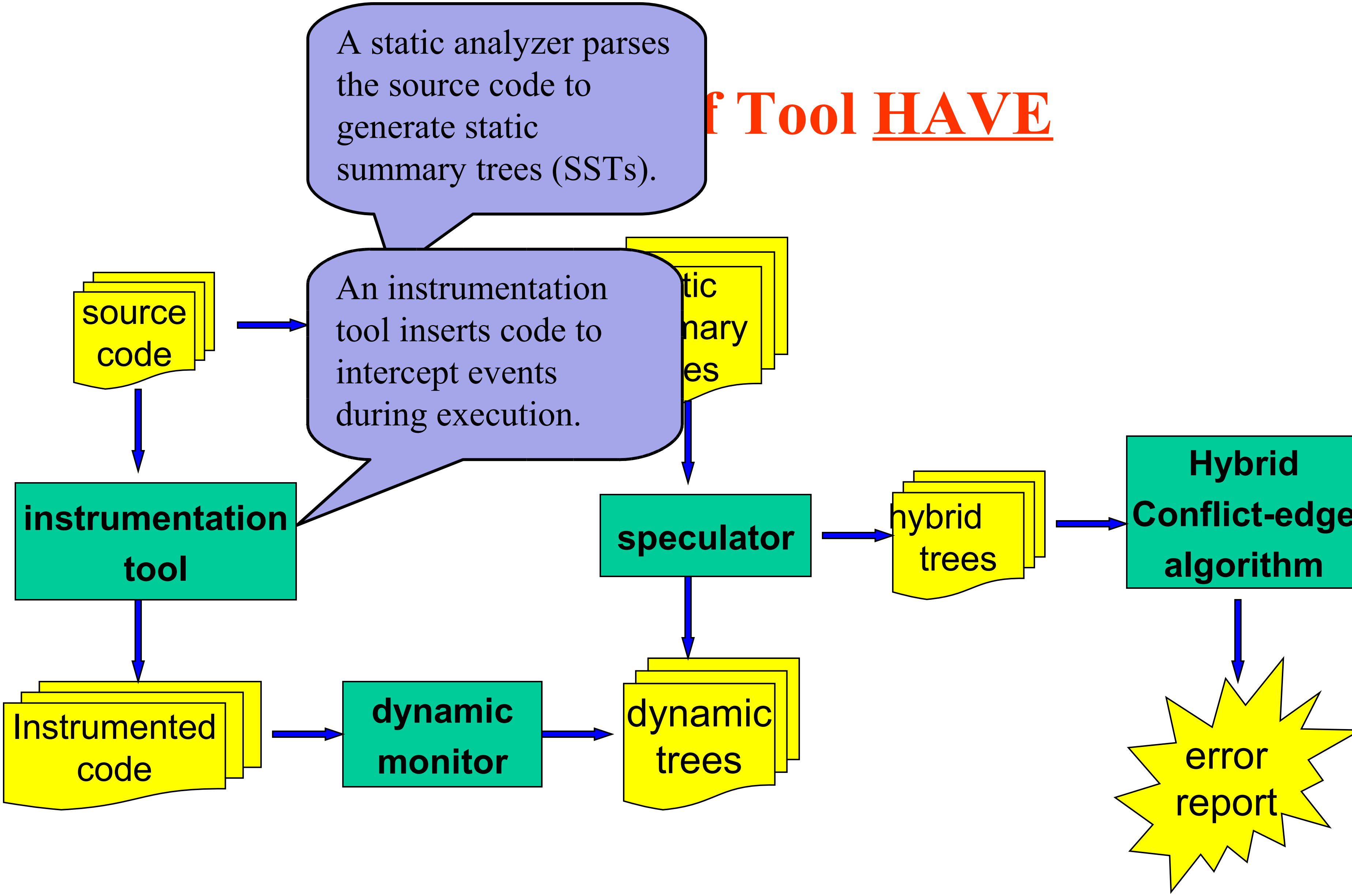
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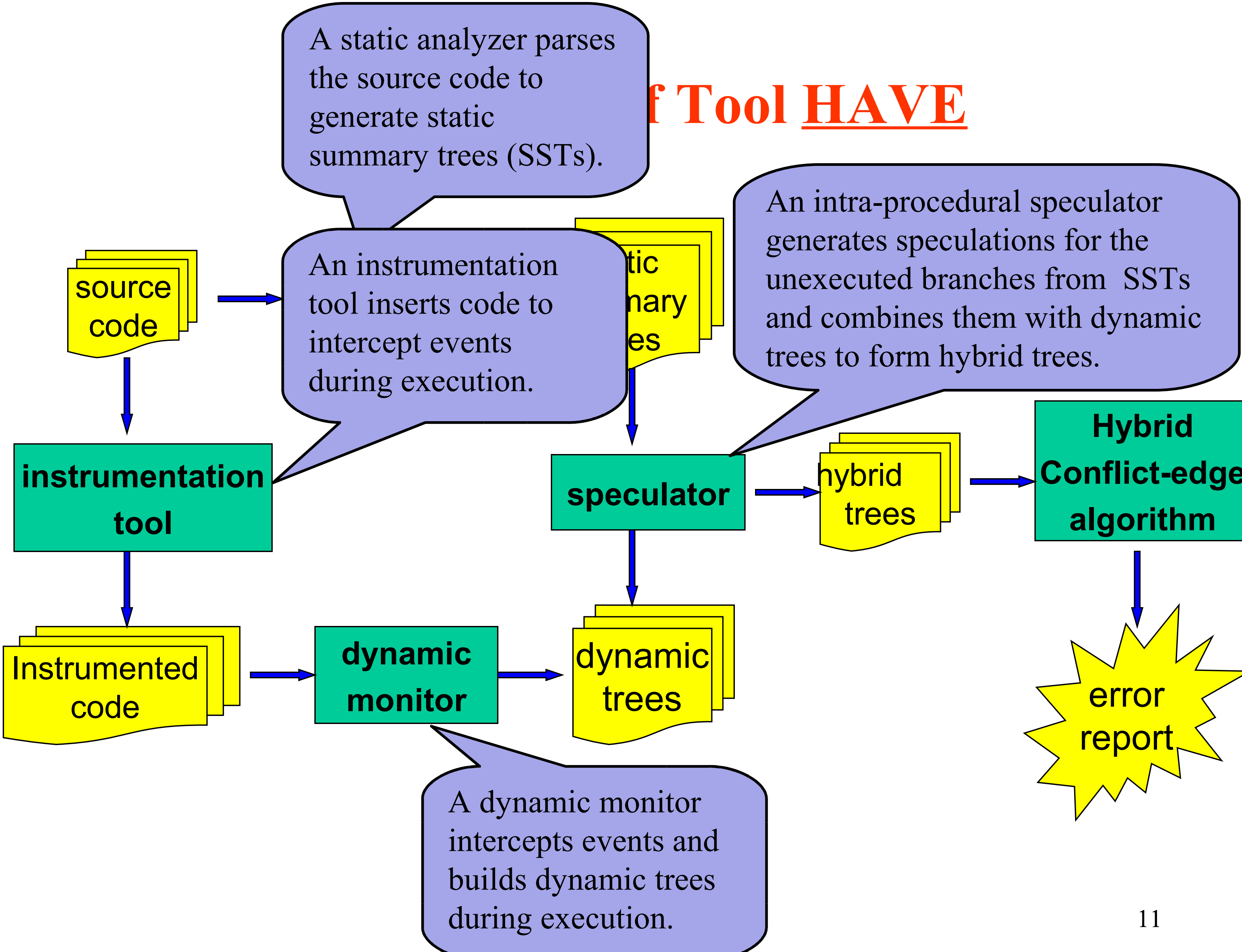
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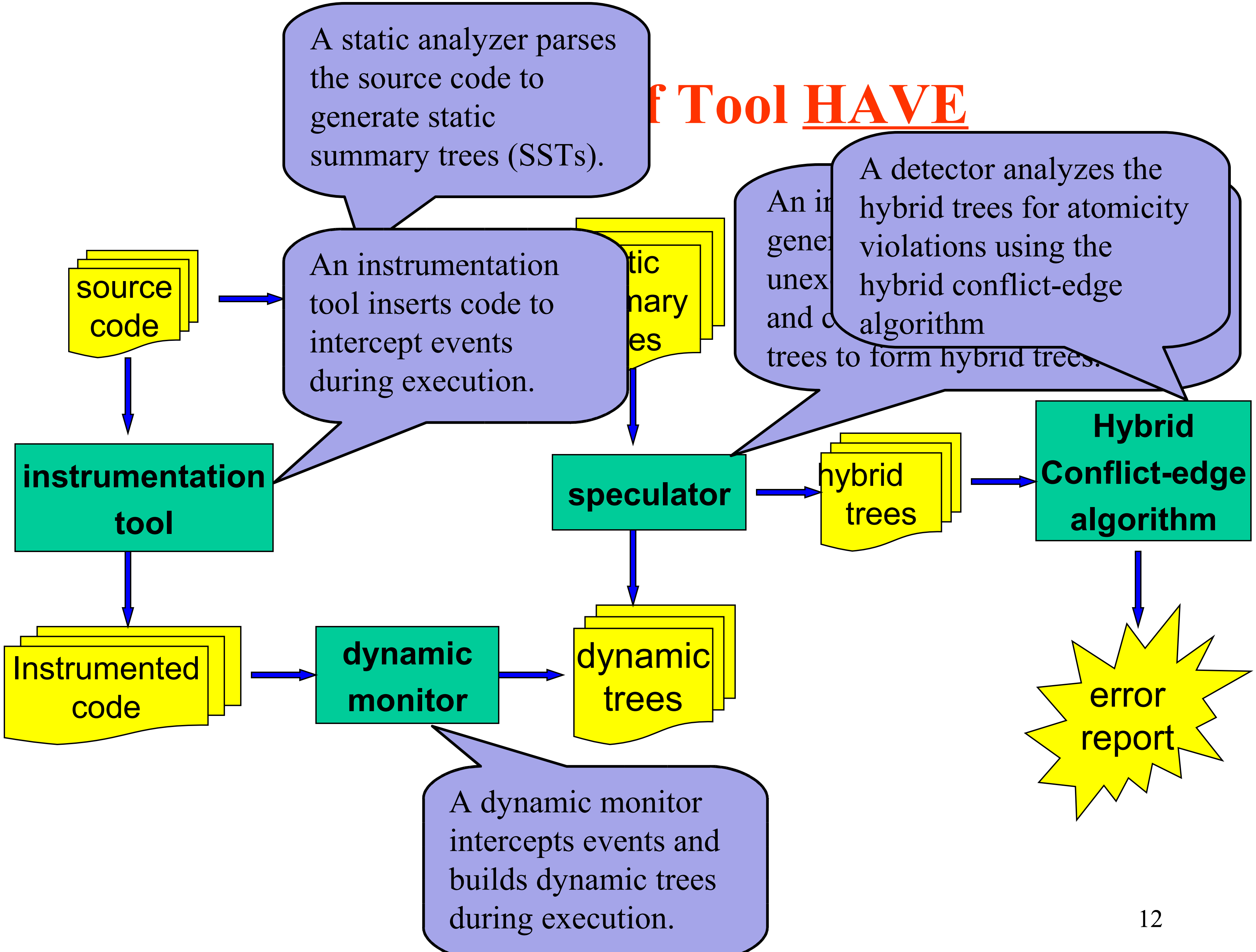
static summary trees
An instrumentation tool inserts code to intercept events during execution.
An intra-procedural speculator generates speculations for the unexecuted branches from SSTs and combines them with dynamic trees to form hybrid trees.
instrumentation tool
speculator
hybrid trees
Hybrid Conflict-edge algorithm
Instrumented code
dynamic monitor
dynamic trees
error report
A dynamic monitor intercepts events and builds dynamic trees during execution.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trees to form hybrid trees.
A detector analyzes the hybrid trees for atomicity violations using the hybrid conflict-edge algorithm
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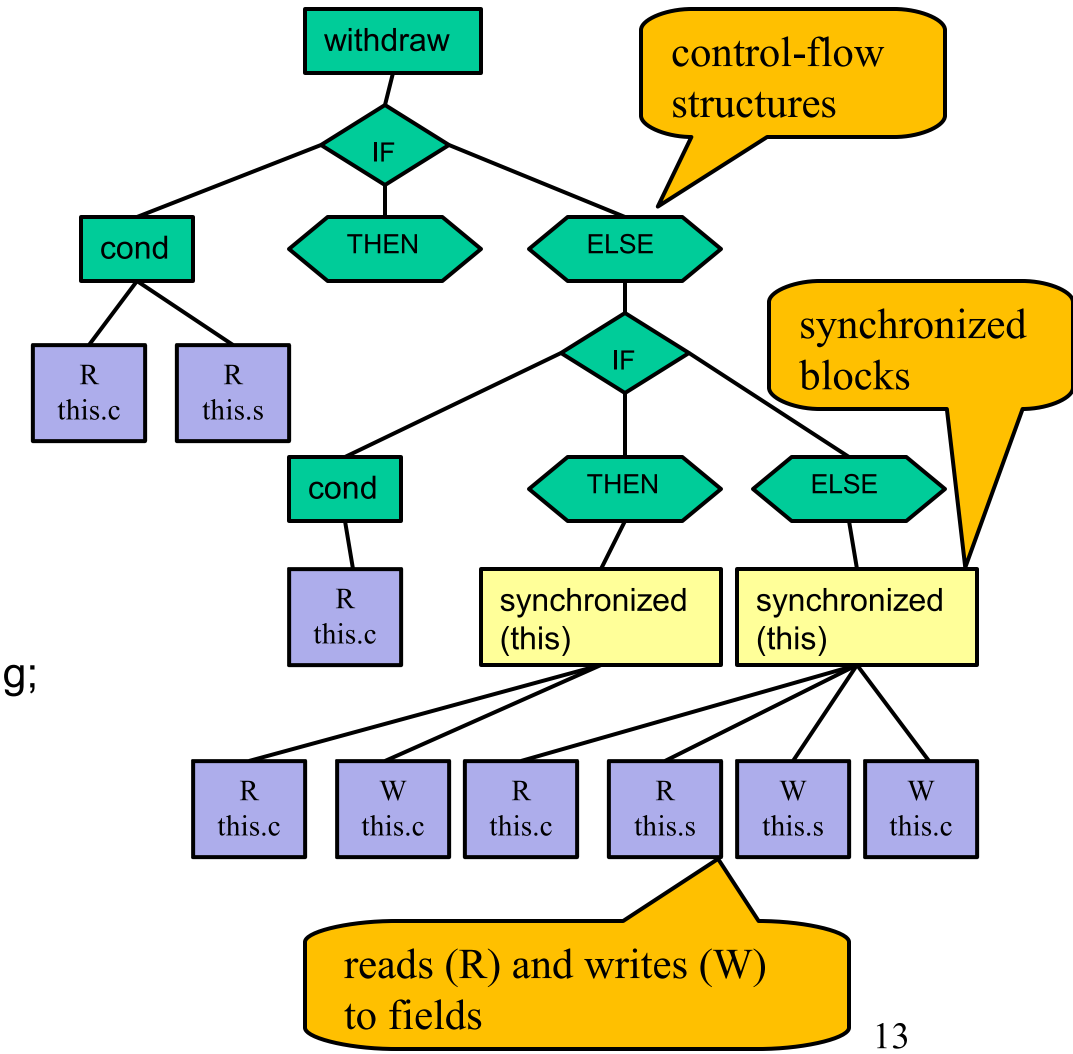
A dynamic monitor intercepts events and builds dynamic trees during execution.

Static Analyzer

- The static analyzer parses source code to construct static summary trees.

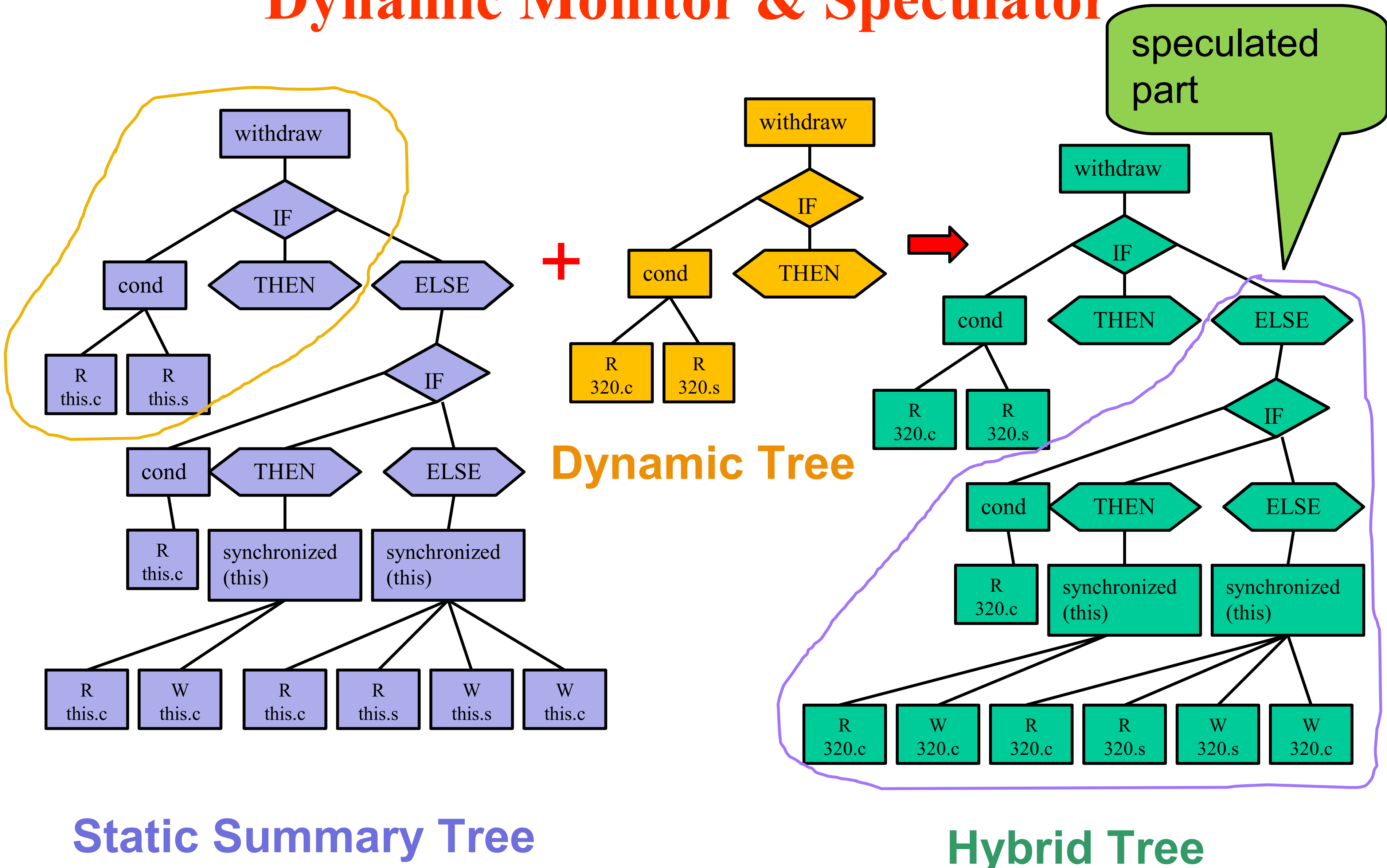
```
class Account {
   int checking, saving;

   public void withdraw(int w) {
      if ((this.checking + this.saving) < w)
         print("Insufficient balance");
      else if (this.checking >= w)
         synchronized(this)
            this.checking -= w;
      else
          synchronized(this) {
               this.saving -= w - this.checking;
               this.checking = 0;
          }
   }
}
```



Not illustrated: assignments to reference variables.

Dynamic Monitor & Speculator



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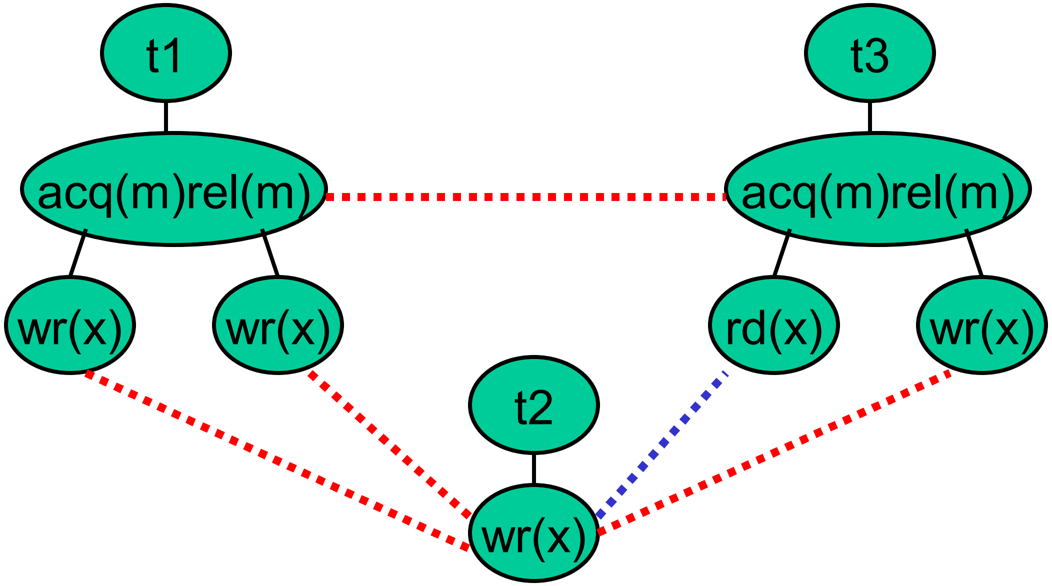
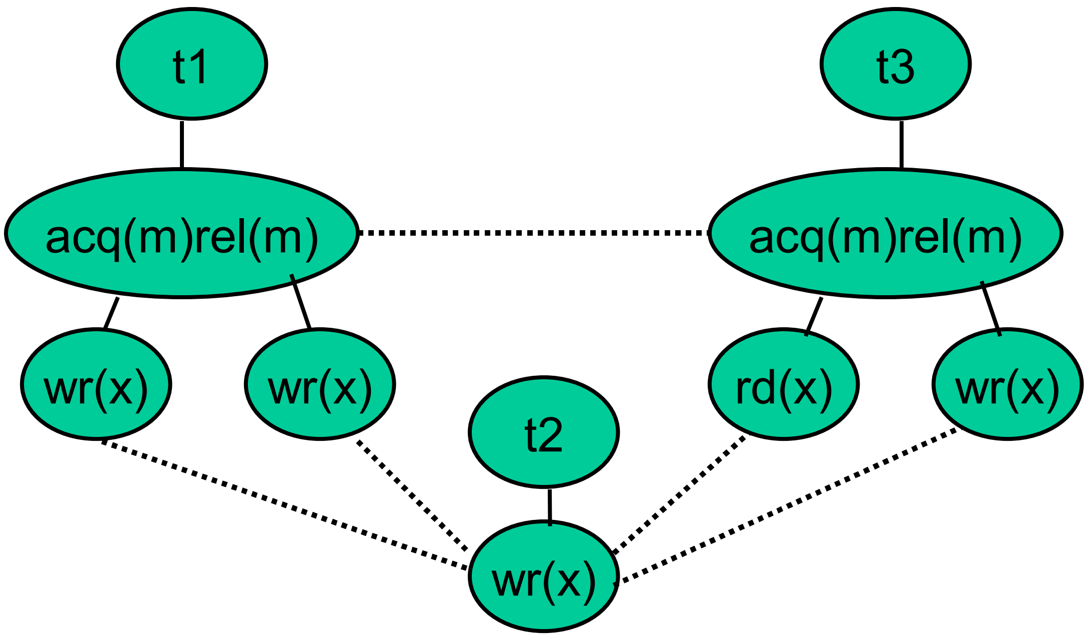
Add Inter-Edges Between Hybrid Trees

- Add **inter-edges** (also called **conflict edges**) between hybrid trees:
  - wr(x) – rd(x): the read event can read the value written by the write.
    - “can” means “in some feasible permutation of the execution”.
  - wr(x) – wr(x): both write to the same variable.
- If a common lock is held at both events, connect the lock nodes instead of the access nodes, because they cannot occur concurrently.



Our Previous Approach: Commit-Node Algorithm

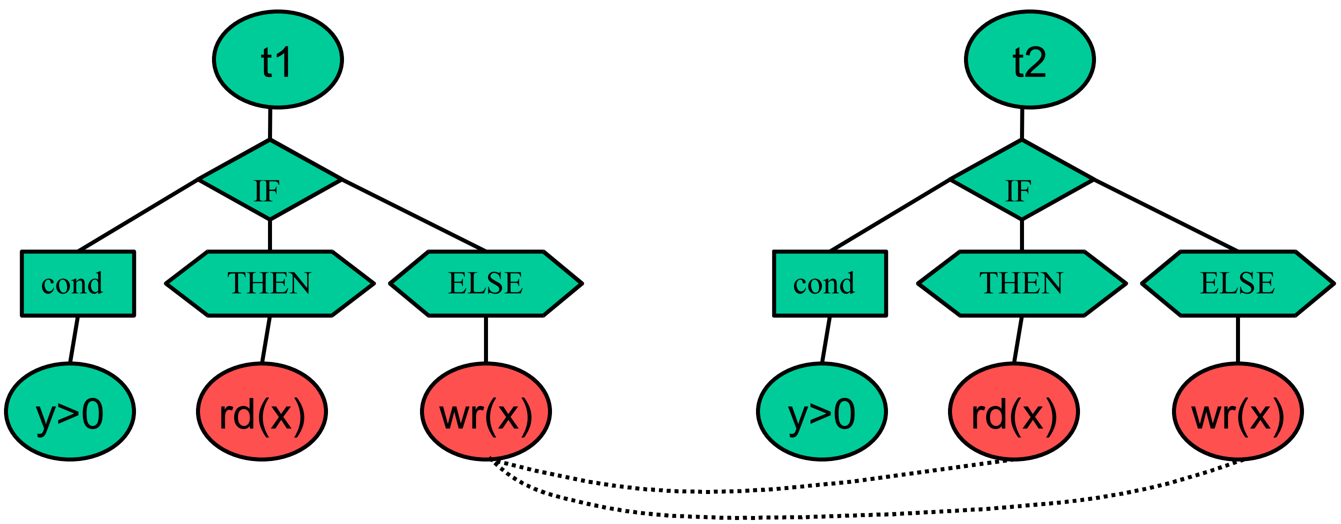
- **Communication node**: end-point of an inter-edge.
- **Commit node**: a communication node without communication node descendants.



The commit-node algorithm appeared in [Wang and Stoller, PPoPP 2006].

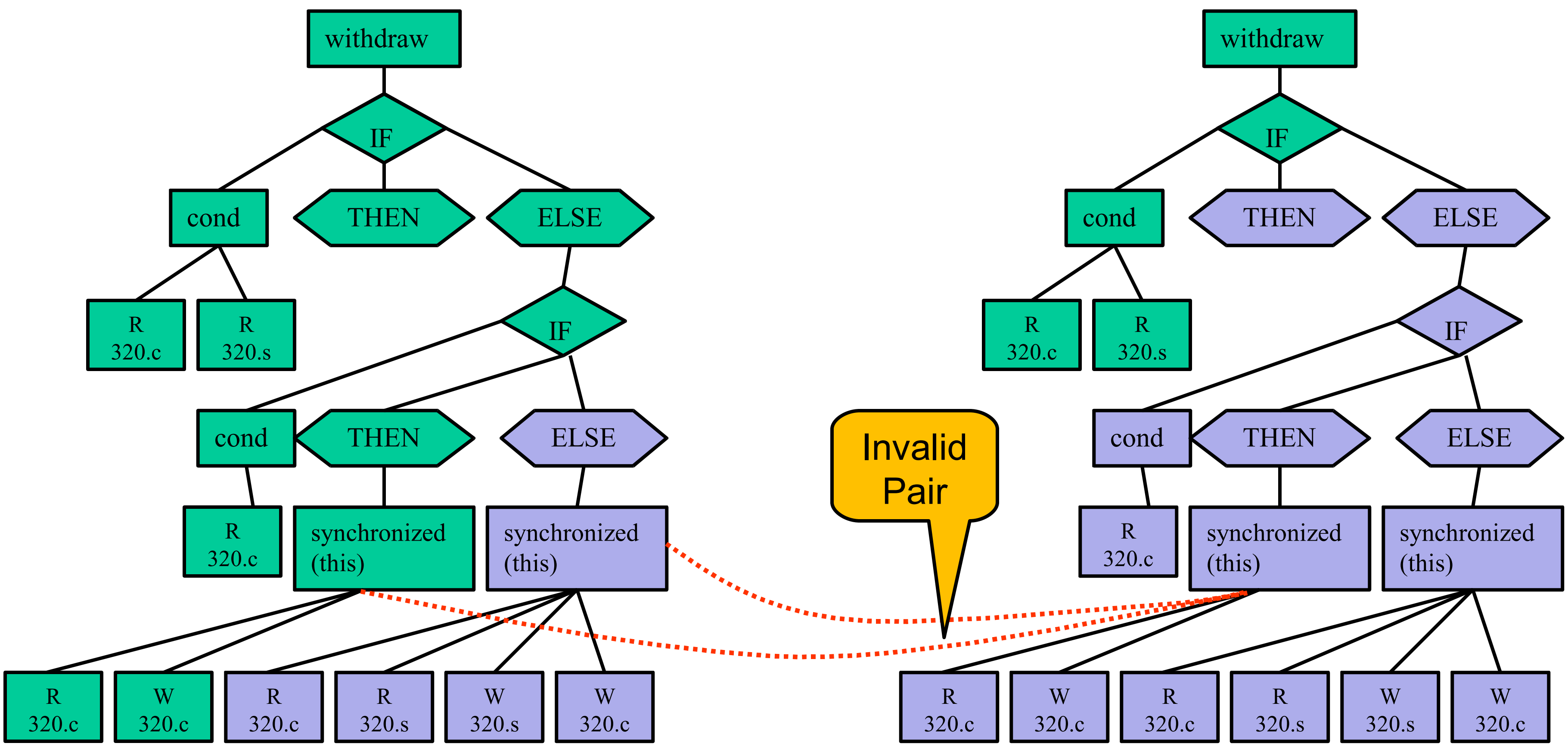
The Commit-Node Algorithm May Give False Alarms for Hybrid Trees.

- Motivation:
  - All inter-edges between dynamic trees (i.e., generated by purely dynamic analysis) can coexist in the same execution.
  - But this is not the case for inter-edges between hybrid trees.



Valid Inter-Edge Pair

- A pair (e, e') of inter-edges is valid for hybrid tree *t* if
  - e and e' are compatible, and
  - e is not an ancestor of e' in *t*, vice versa, and
  - e and e' are incident on different nodes of *t*



Valid Inter-Edge Pair

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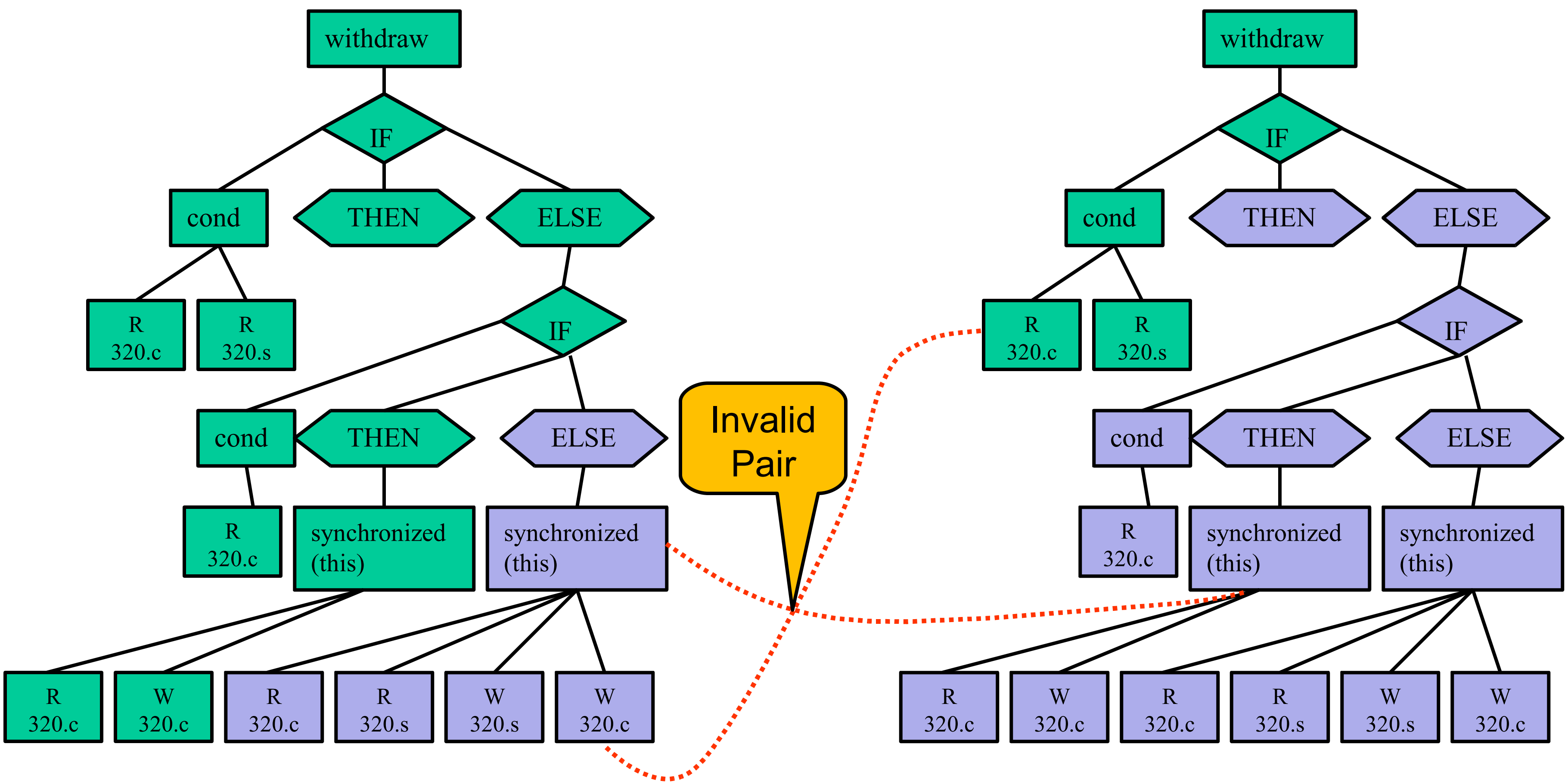
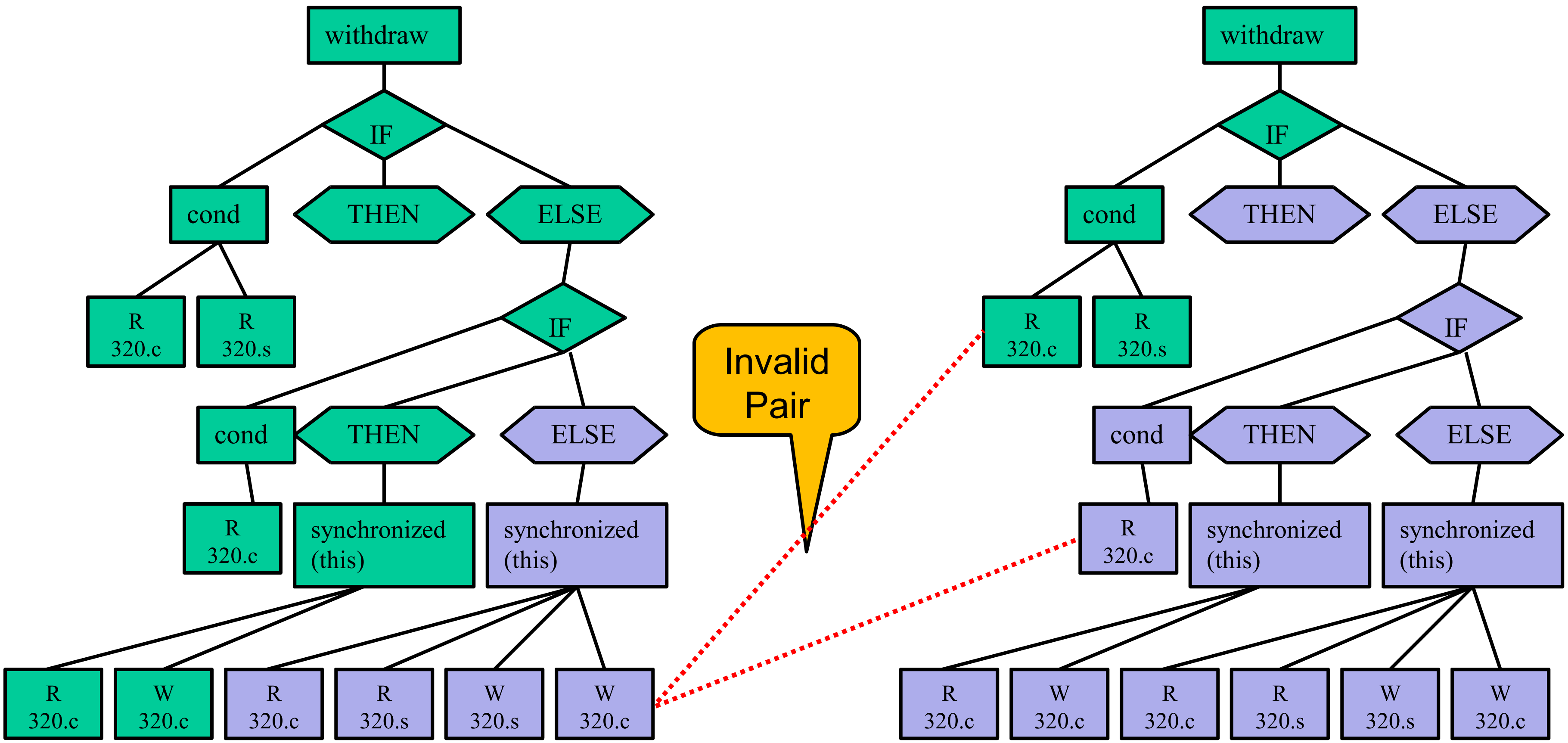


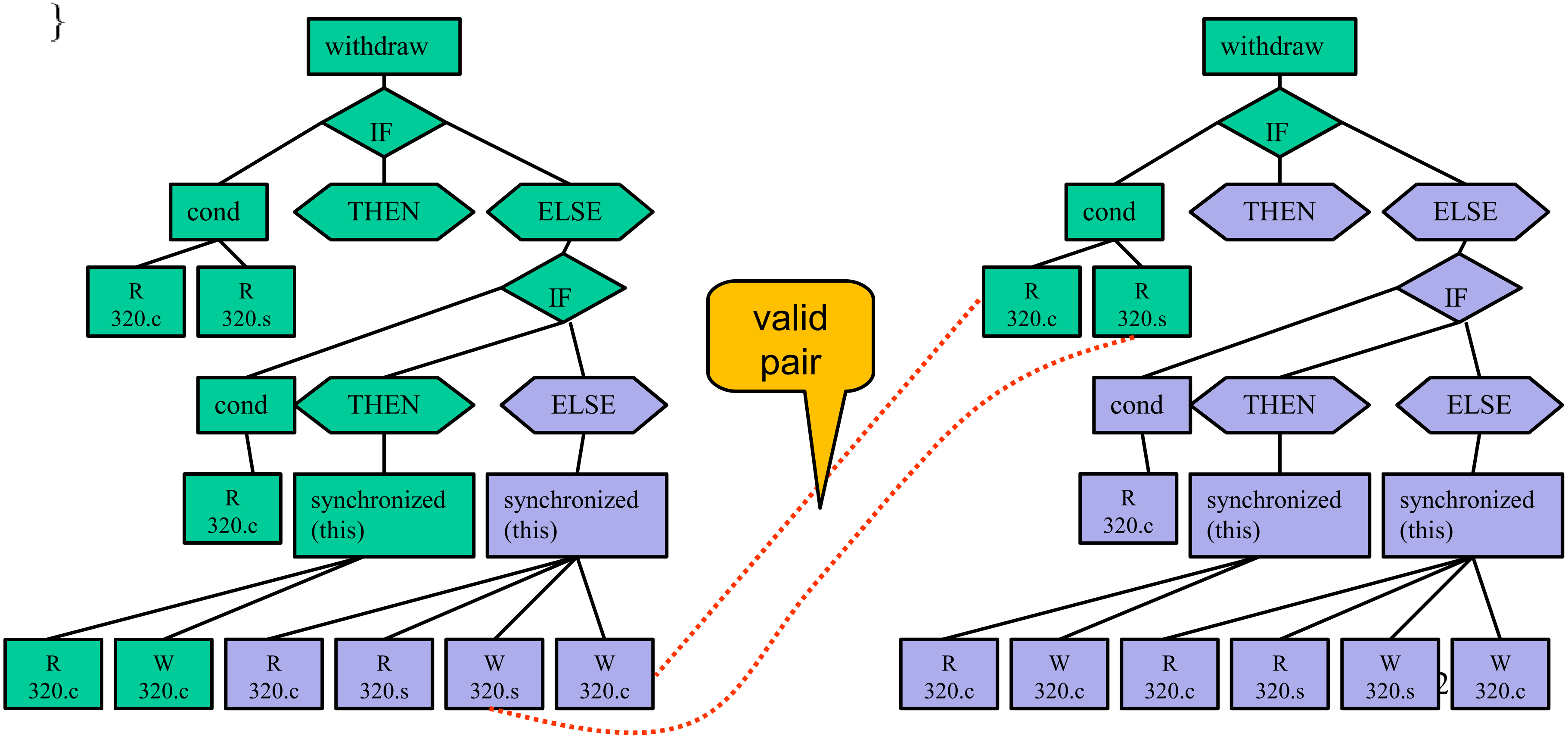
Valid Inter-Edge Pair

- A pair (e, e’) of inter-edges is valid for hybrid tree *t* if
  - e and e’ are compatible, and
  - e is not an ancestor of e’ in *t,* vice versa, and
  - e and e’ are incident on different nodes of *t*



Conflict-Edge Algorithm

CheckAtomicityViolations() {
  for each transactional hybrid tree t **do**
    for each valid inter-edge pair (e, e') of t **do**
      if only two hybrid trees including t are connected by e and e' **then**
        report a potential atomicity violation involving e and e'.
      else
        if $\exists$ a valid cycle c of inter-edges containing e and e' **then**
          report a potential atomicity violation involving c.
}



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Summary of Experiments

- Evaluated on 9 benchmarks totaling 284 KLOC
  - Includes Apache Tomcat and Jigsaw (web server from W3C)
- **Heuristic:** public or synchronized methods are expected to be atomic.

	Purely dynamic approach [Wang & Stoller, PPoPP 2006]	Hybrid approach
Accuracy	11 bugs (non-atomic transaction) involving 90 locations in source code 16 benign alarms 0 false alarms	13 bugs (non-atomic transaction) involving 145 locations in source code 16 benign alarms 0 false alarms
Performance (overhead)	Average 3.6x slowdown (except for the program TSP, with 35x slowdown)	Average 16.5x slowdown (except for the program TSP, with 167x slowdown)

A Possible Bug Found in TSP (parallel traveling salesman algorithm)

Thread: 11

```
static void set_best(int best, int[] path) {
        ....
        synchronized (TspSolver.MinLock) {
                if (best < TspSolver.MinTourLen) {
                        ...
                        TspSolver.MinTourLen = best;
                        ...
                }
        }
}
```

executed

```
static void set_best(int best, int[] path) {
        ....
        synchronized (TspSolver.MinLock) {
                if (best < TspSolver.MinTourLen) {
                        ...
                        TspSolver.MinTourLen = best;
                        ...
                }
        }
}
```

executed

```
[TspSolver.set_best(TspSolver.java)
synchronized@6658066@line:path=n/a@object:TspSolver.MinLock
TspSolver.set_best(TspSolver.java:1745)
TspSolver.visit_nodes(TspSolver.java:2674)
TspSolver.visit_nodes(TspSolver.java:2739)
TspSolver.visit_nodes(TspSolver.java:2739)
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TspSolver.visit_nodes(TspSolver.java:2739)
TspSolver.visit_nodes(TspSolver.java:2739)
TspSolver.recursive_solve(TspSolver.java:2504)
TspSolver.Worker(TspSolver.java:2791)
TspSolver.run(TspSolver.java:2518)]
```

Thread: 10

speculation

```
static void split_tour(int curr_ind) {
        ...
        synchronized (TspSolver.TourLock) {
                ...
                if (curr.last != Tsp.TspSize - 1) {
                        ...
                        for (i = 0; i < Tsp.TspSize; i++) {
                                ...
                                t3 = curr.lower_bound + wt <=
TspSolver.MinTourLen;
                                        ...
                        }
                }
        }
}
```

```
[TspSolver.split_tour(TspSolver.java:2224)
TspSolver.find_solvable_tour(TspSolver.java:1135)
TspSolver.get_tour(TspSolver.java)
synchronized@10736847@line:path=n/a@object:TspSolver.TourLock
TspSolver.get_tour(TspSolver.java:1287)
TspSolver.Worker(TspSolver.java:2784)
TspSolver.run(TspSolver.java:2518)]
```

Bugs Found in Jigsaw and Tomcat

- Jigsaw
  - The method `perform` in `httpd.java` has multiple atomicity violations regarding several fields, such as `LRUNode.next` and `ResourceStoreImpl.resources`.
- Tomcat
  - Potential atomicity violations are found on the fields *`StringCache.accessCount`* and *`StringCache.hitCount`* in the method *`toString(ByteChunk bc)`* of *`StringCache.java`*.
  - We classify this atomicity violation as a bug, because it may cause the statistics to be inaccurate, even though this inaccuracy does not cause other incorrect behavior.
- These bugs are not detected by the purely dynamic approach, because some of the field accesses are in speculatively executed branches.

Conclusions and Future Work

- Conclusions
  - We developed a new approach to enhance dynamic analysis with results from static analysis.
  - It improves code coverage and hence effectiveness at finding errors (atomicity violations).
    - Care is needed to avoid false alarms due to incompatible speculative branches.
  - In experiments, our new algorithm scales almost as well as our purely dynamic algorithm.
- Future work
  - Extend the static analysis to be inter-procedural.
  - Design more optimizations to reduce overhead.