Heuristic-Guided Counterexample Search in FLAVERS

Jianbin Tan, George Avrunin, Lori Clarke, Shlomo Zilberstein
University of Massachusetts, Amherst

Stefan Leue
University of Konstanz

Finite State Verification (FSV)

- FSV techniques verify whether a model of a system is consistent with a specified property
  - If the property is found to be violated, *counterexamples* are usually provided to demonstrate how the violation happened
  - Counterexamples help isolate the cause of the problem

Counterexample Search

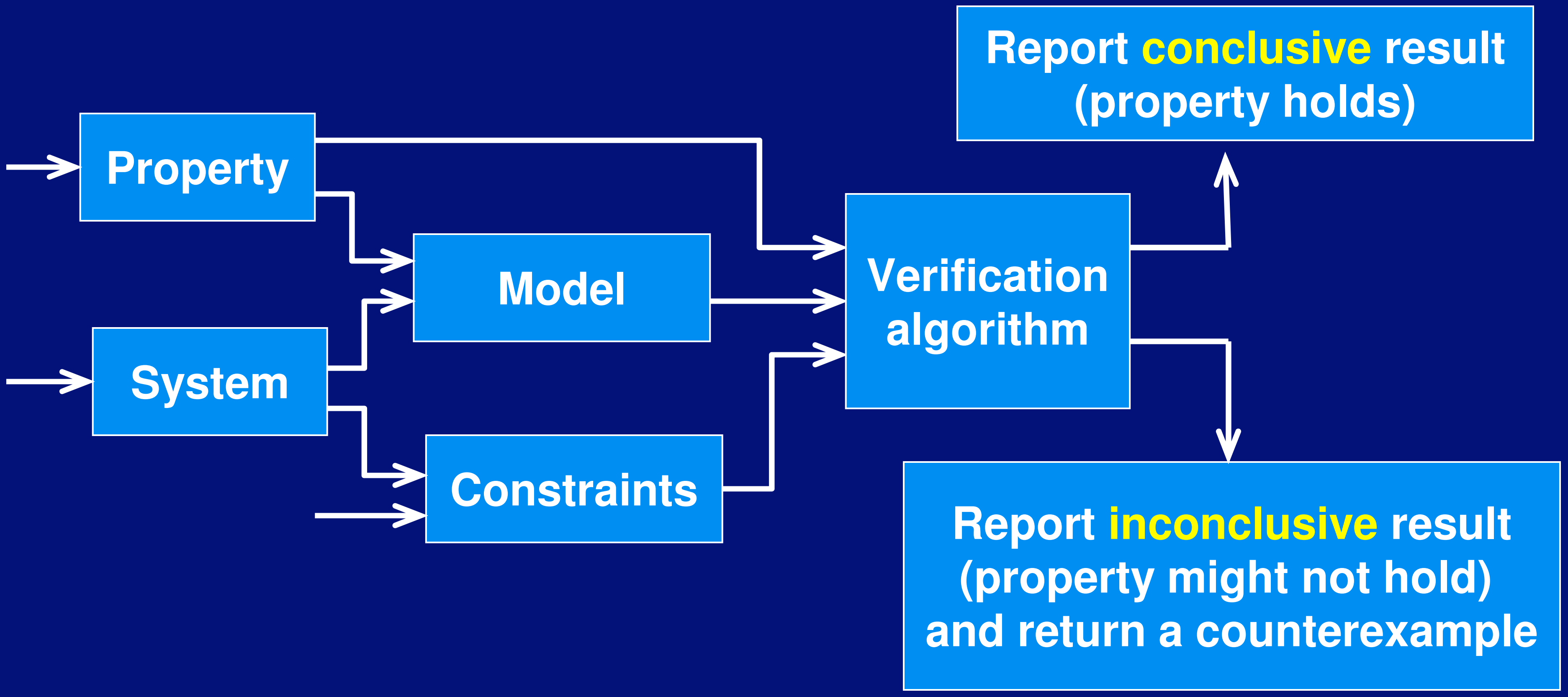
- Can represent the verification problem as a search for counterexamples
  - Two metrics: time and length
- Standard algorithms have drawbacks
  - BFS: finds the shortest counterexample but usually is slow
  - DFS: usually is fast, but tends to produce a long counterexample
- Want a heuristic search algorithm that usually finds short counterexamples fast

Outline

- FLAVERS overview
- Heuristic search algorithms considered
- Experimental results
- Related work
- Conclusions and future work

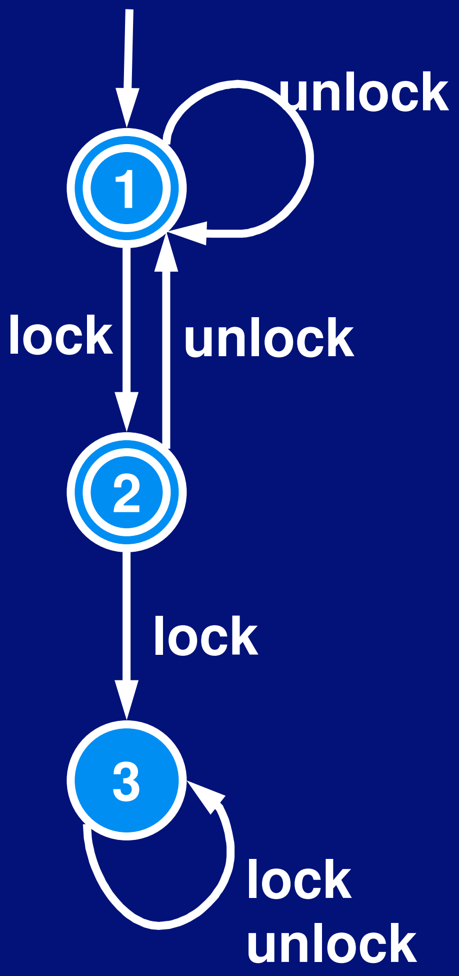
FLAVERS Architecture

FLow Analysis for VERification of Systems



Property

- Specifies sequences of events that should occur on all executions of the system
- Represented as a finite-state automaton (FSA)
- Example: “lock” can never occur consecutively



Model

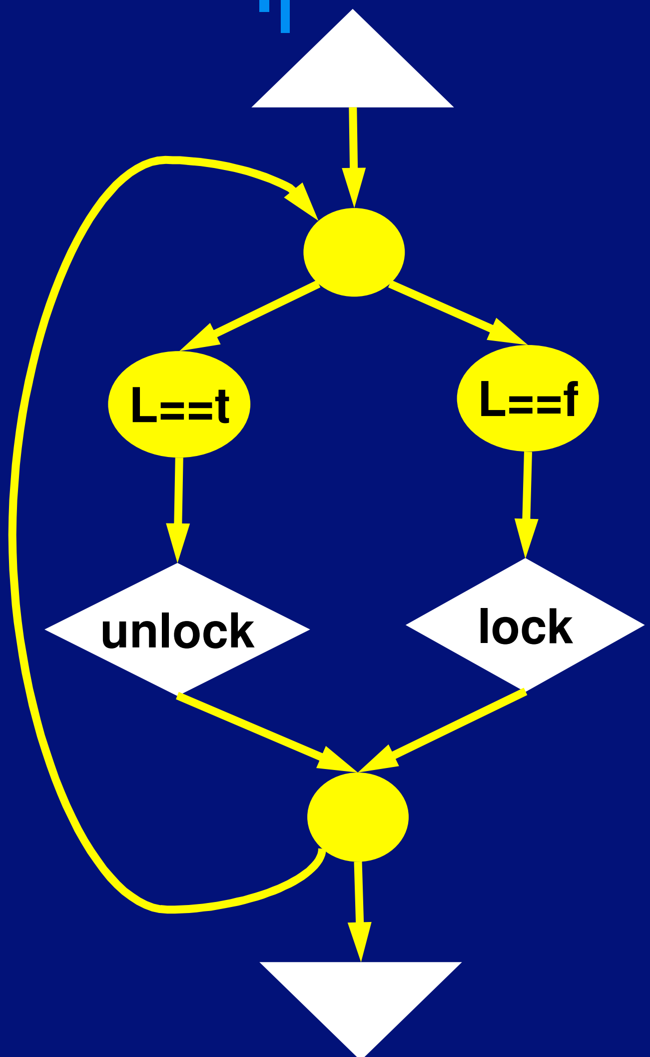
- A flow graph that models the event sequences of the system
  - Built from annotated control flow graphs for the threads
  - Each node may be labeled by one event
  - Each path in the model represents a sequence of events
  - Conservative but imprecise

Model: An Example

```
Task1
 loop
  if ( locked ) then
     call Task2.unlock
  else
     call Task2.lock
  end if
  exit when done
 end loop

Task2
 loop
    select
       accept lock
       locked:=true
    or
       accept unlock
       locked:=false
    end select
    exit when done
 end loop
```

Model: An Example

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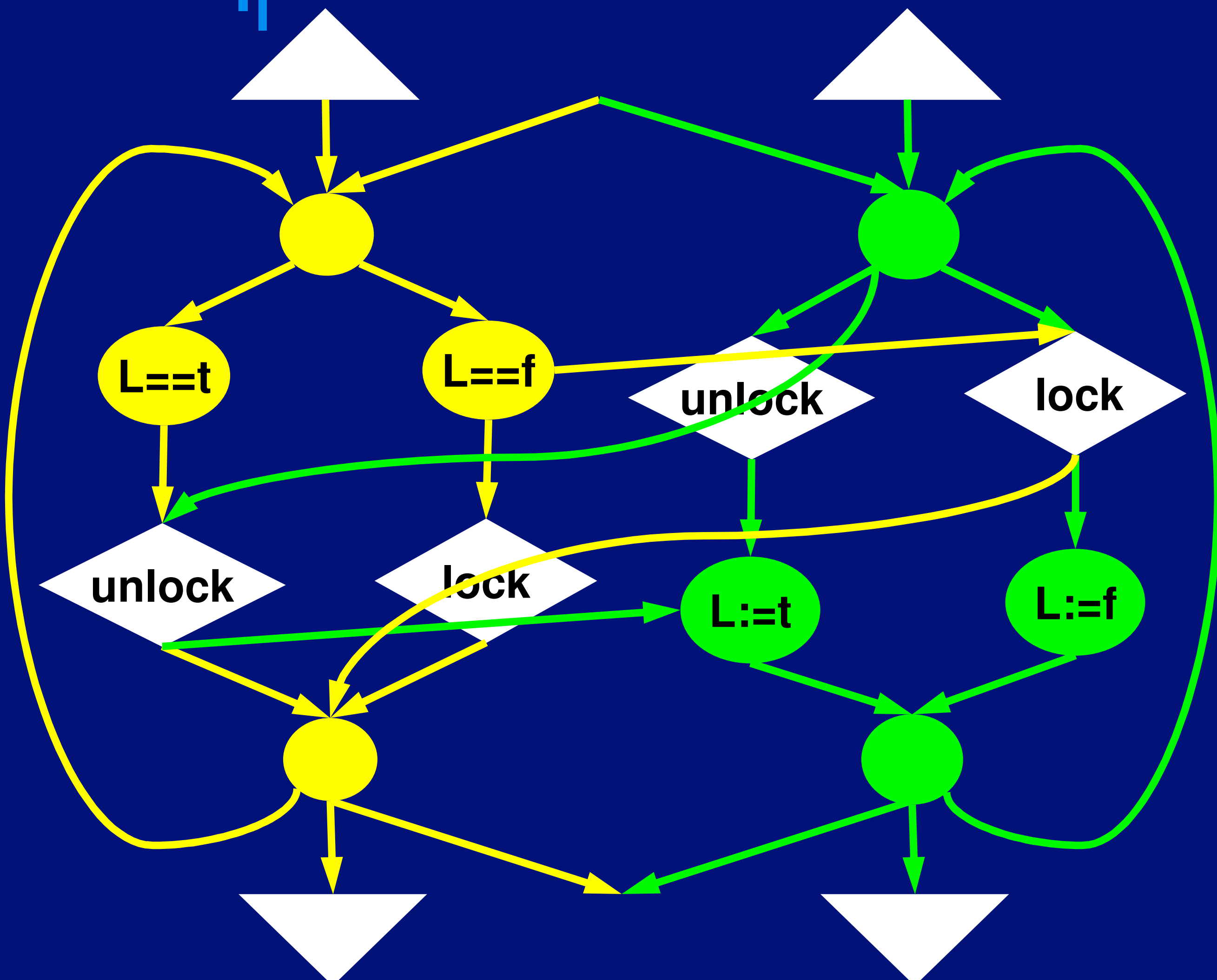


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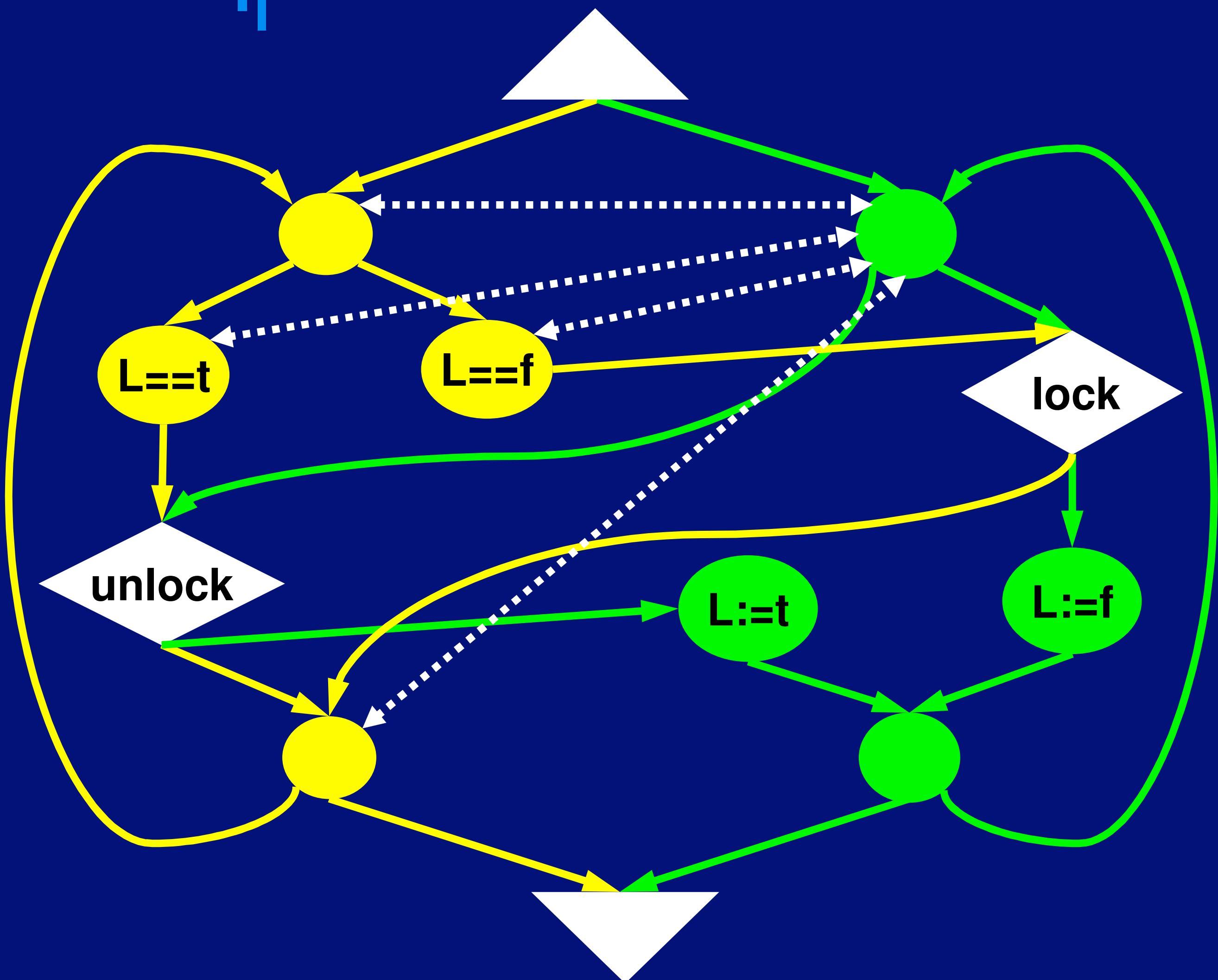


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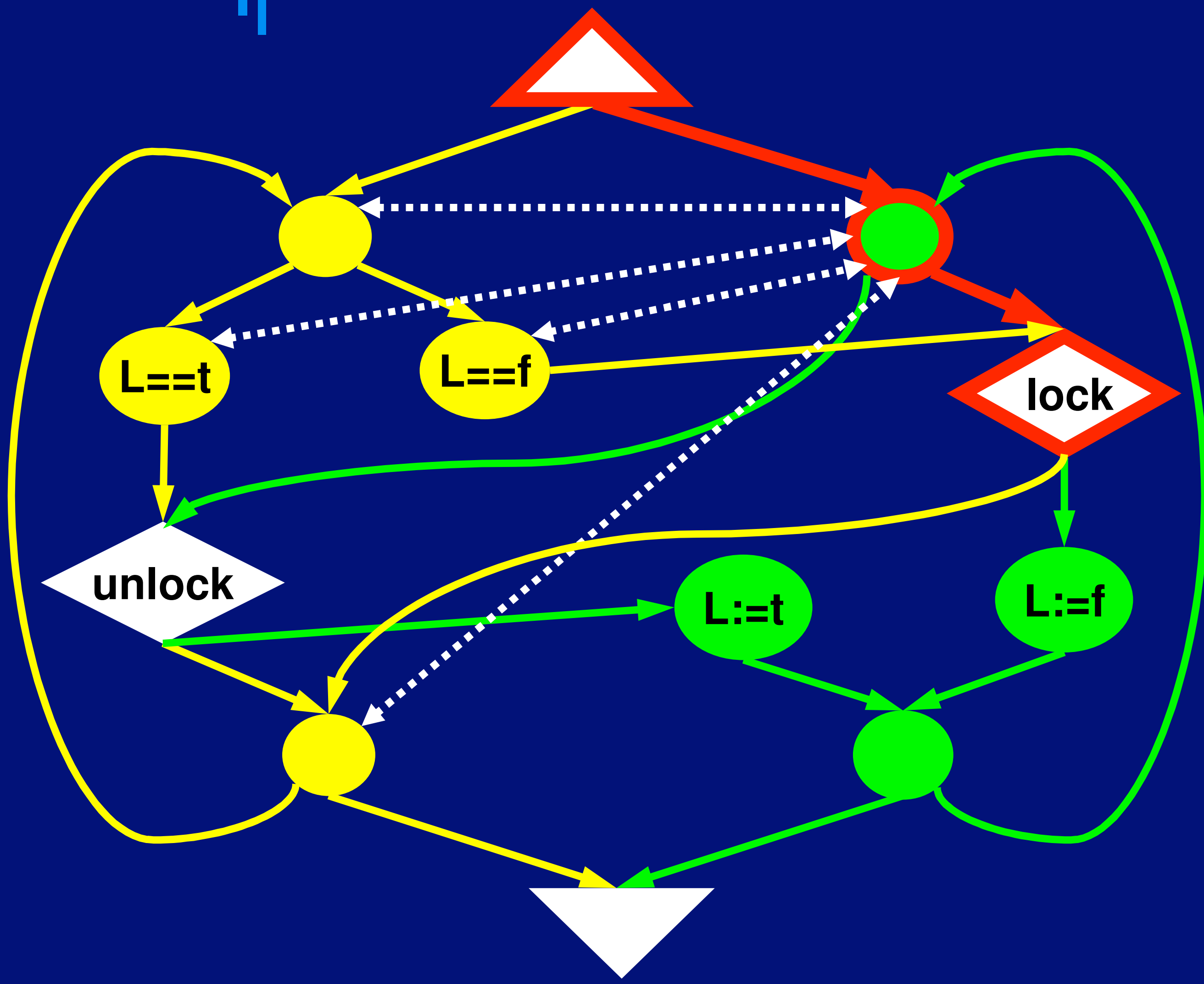
Model is Imprecise

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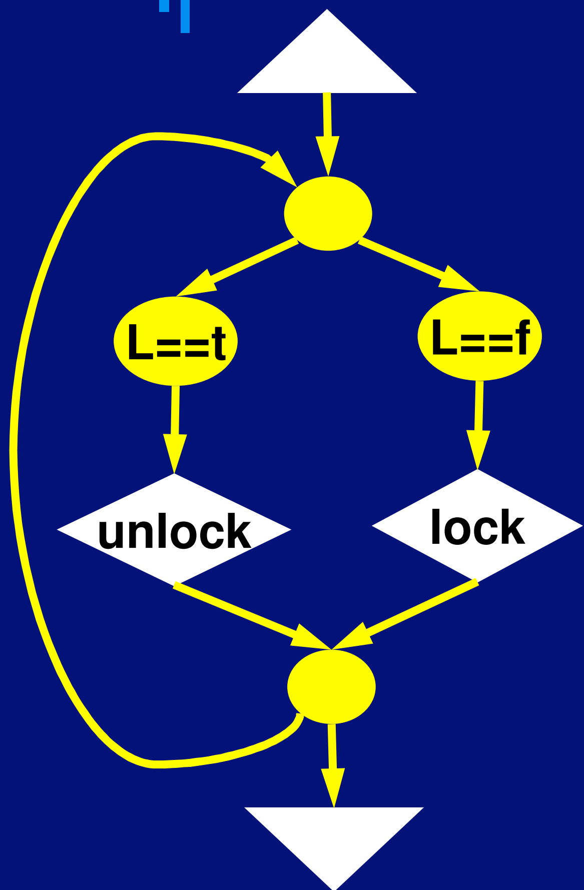
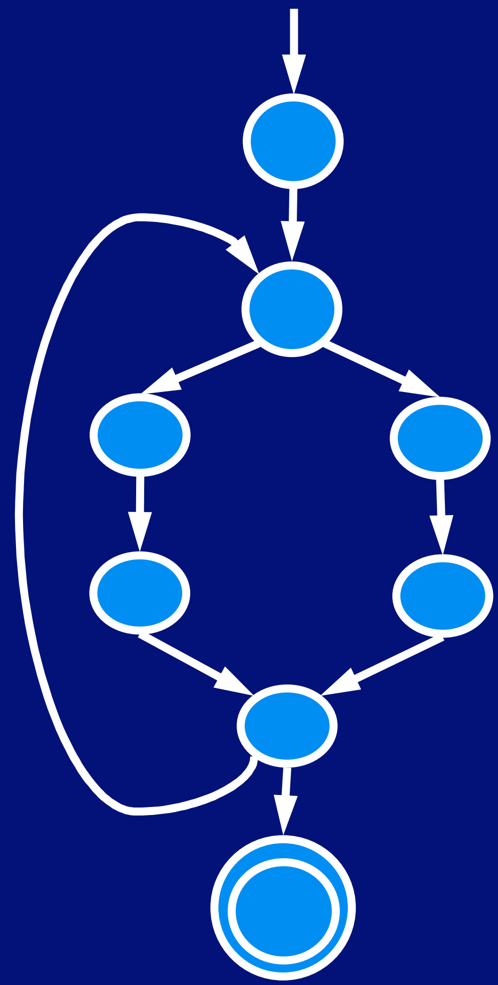
Constraints

- Introduced to refine the model
  - Specify valid sequences of events in the model
  - If a path is not accepted by a constraint, the path is rejected
- Represented as FSAs
- Several kinds of constraints
  - Many can be automatically created

Constraint: An Example

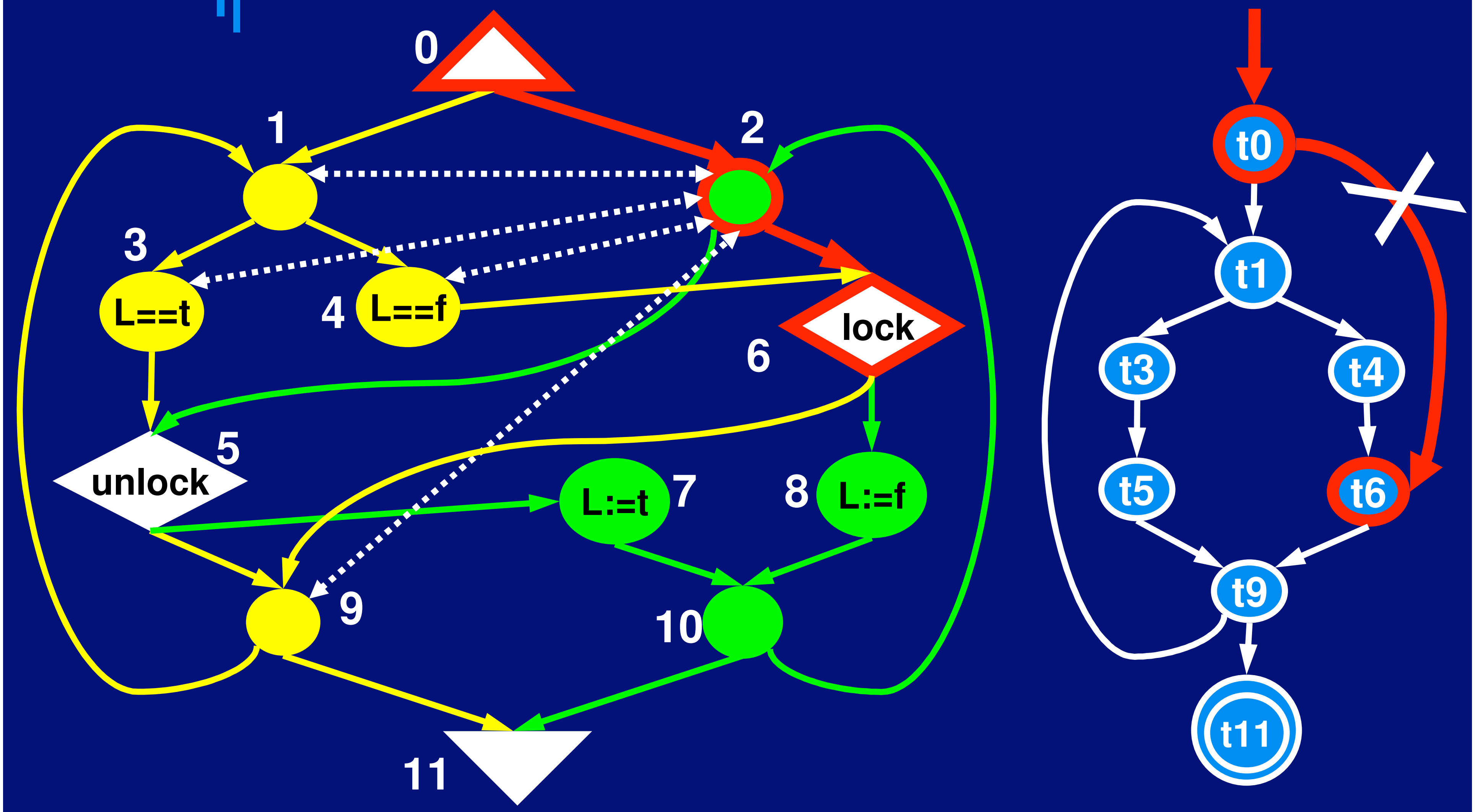


Control flow graph of Task1



Task Automaton (TA) of Task1

Constraints Make the Model More Precise



Verification Algorithms

- FLAVERS explores all paths in the model that do not violate any constraint
- There are several alternative algorithms that can be used
  - Data-flow analysis algorithms work well when the property turns out to hold
  - Search algorithms work well when there are counterexamples

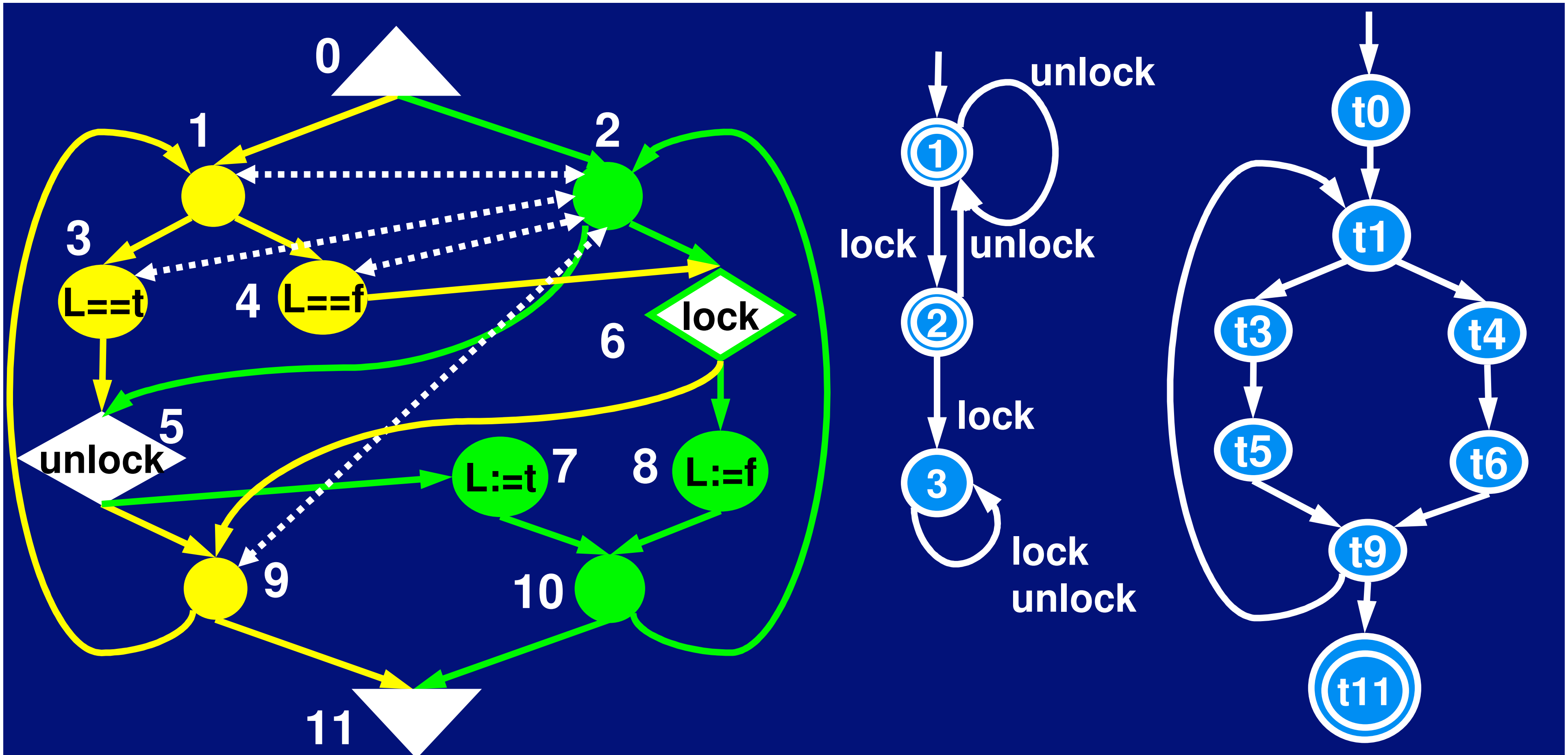
Search Framework

- Builds and checks a *node-tuple graph* on-the-fly

$$(x, \langle p_1, c_2, \ldots, c_m \rangle)$$

A node from the flow graph

A vector with states from the property FSA and each constraint FSA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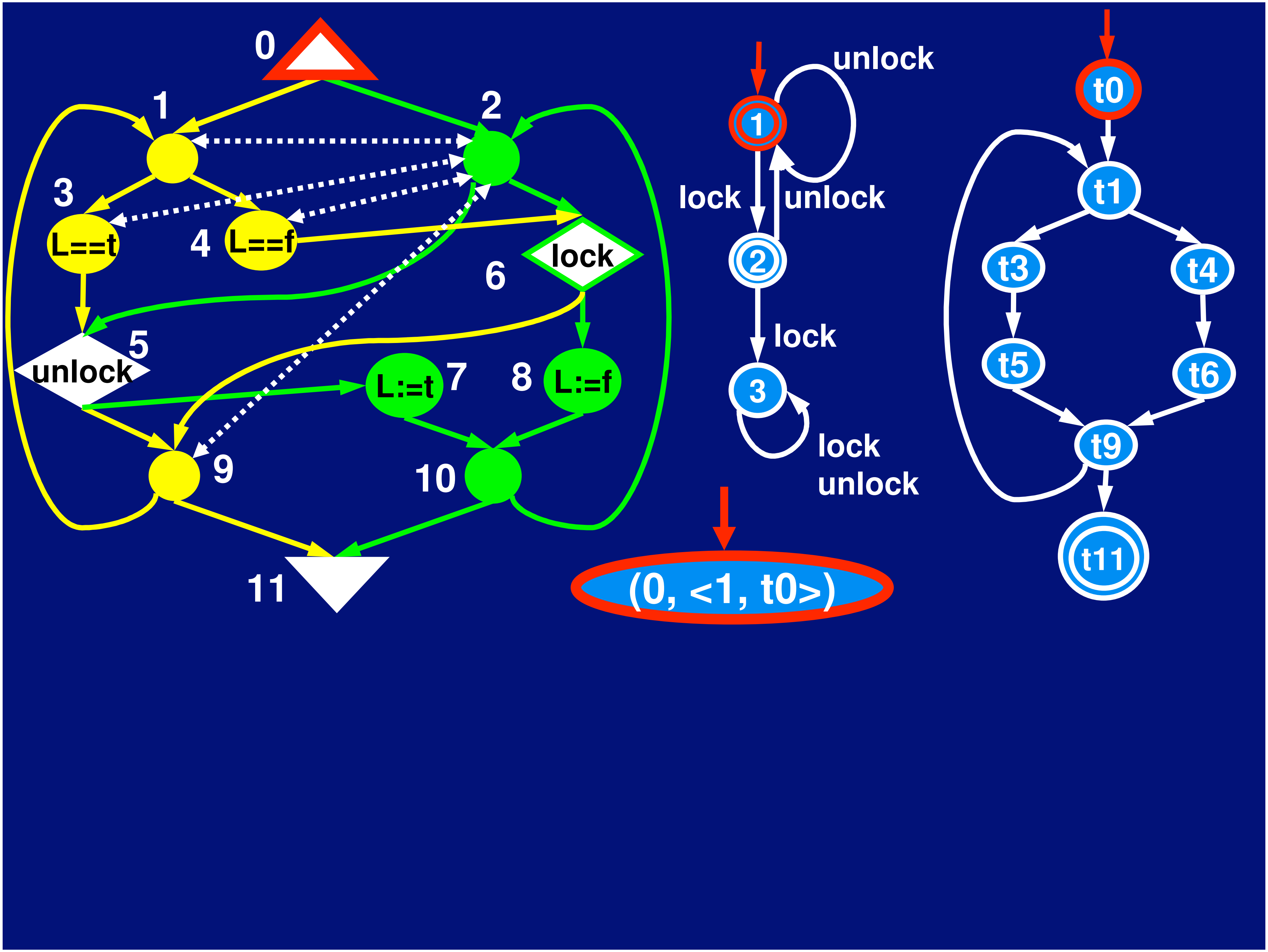
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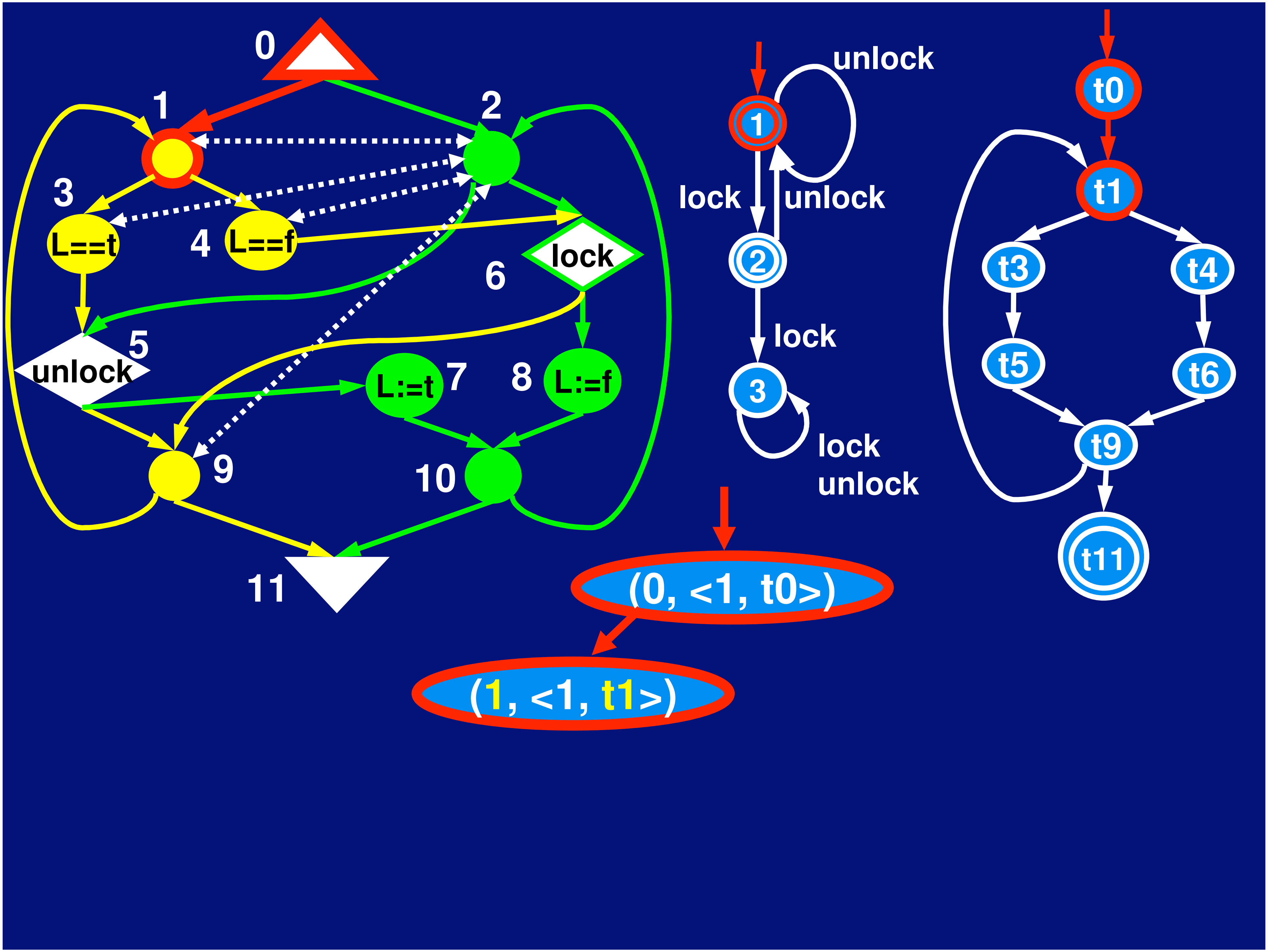
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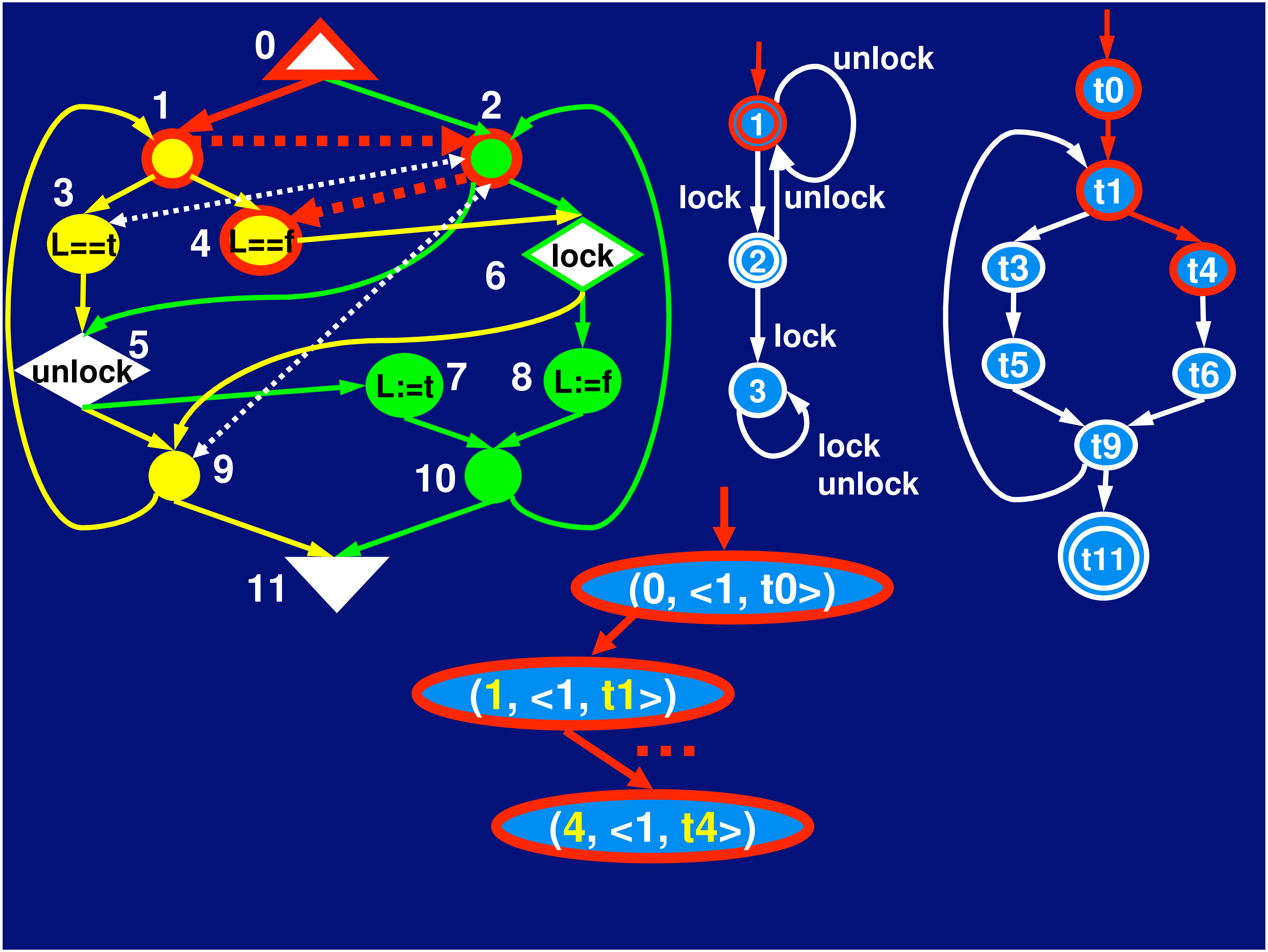

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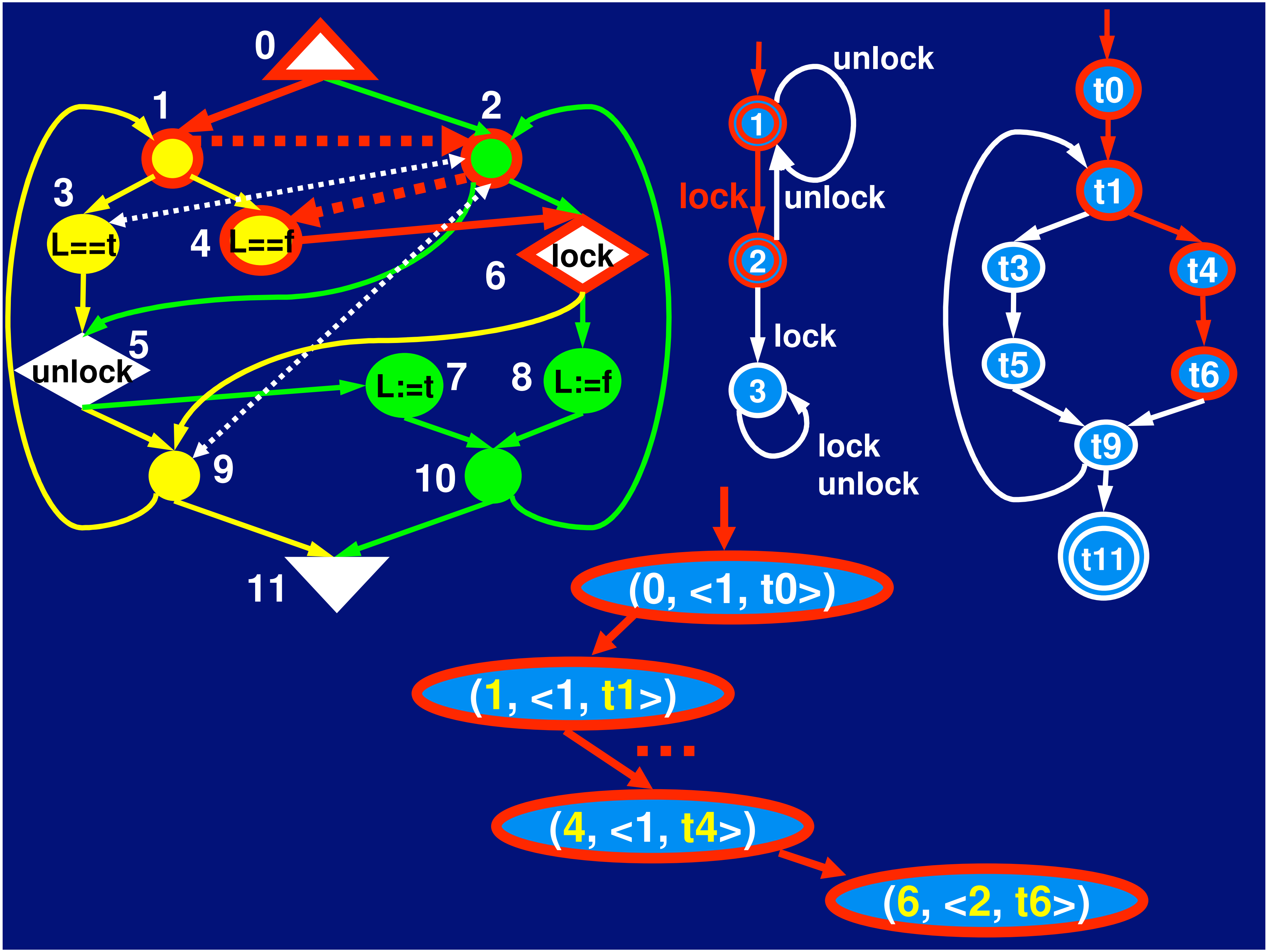
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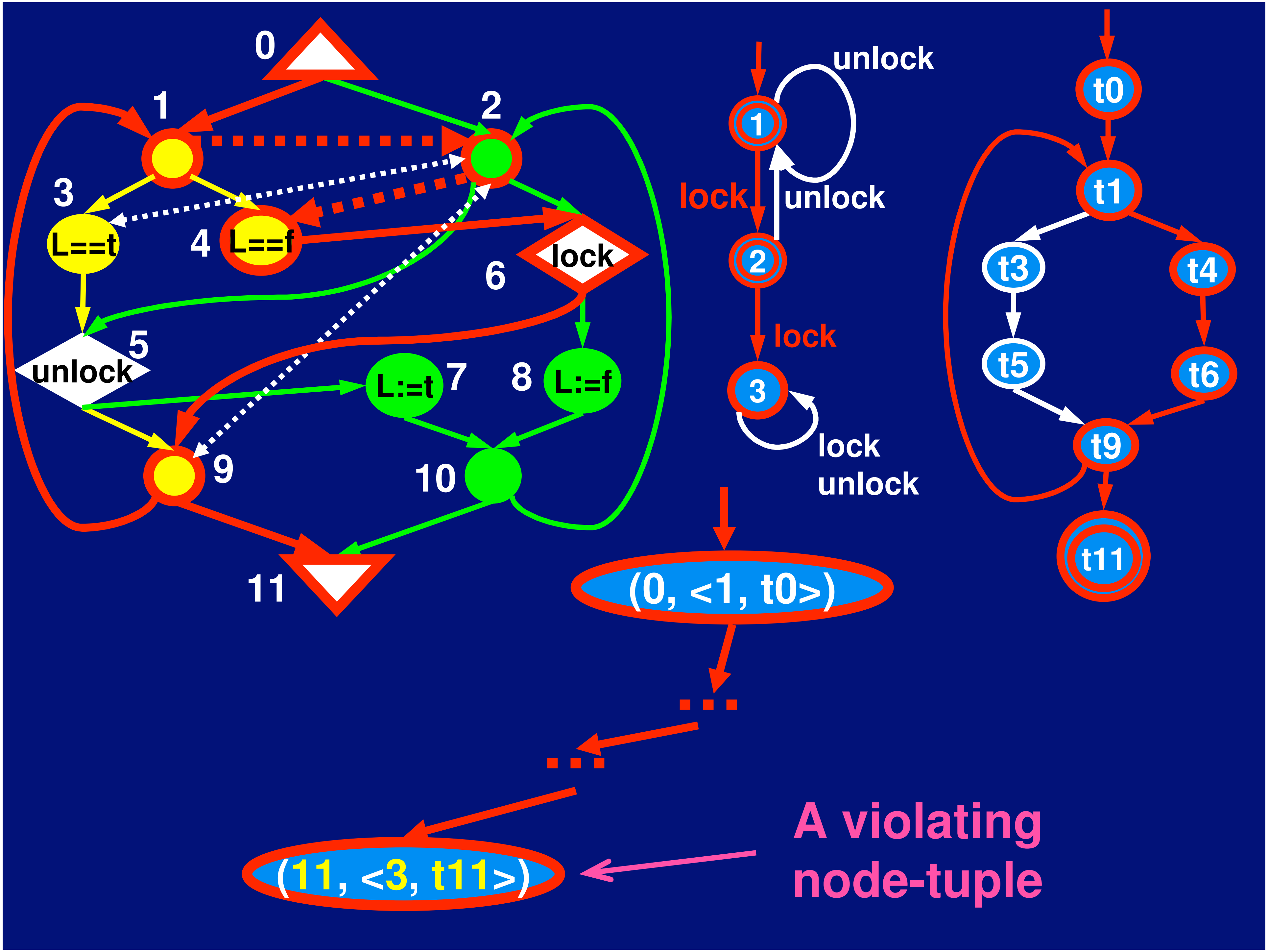
(6, <2, t6>)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t0
t1
t3
t4
t5
t6
t9
t11
(0, <1, t0>)
...
...
(11, <3, t11>)
A violating node-tuple

The Search Framework

Put the initial node-tuple in the worklist ***W***
While ***W*** is not Empty
    remove a node-tuple ***n*** from ***W***
    for each successor ***s*** of ***n***
        If ***s*** is a violating node-tuple
            Generate the counterexample
            Return INCONCLUSIVE
        Else if ***s*** has not been visited before
            Add ***s*** to ***W***
Return CONCLUSIVE

The Search Framework

Put the initial node-tuple in the worklist ***W***

While ***W*** is not Empty

  remove a node-tuple ***n*** from ***W***

  f… h successor ***s*** of ***n***

Consider different ways to remove elements from the worklist

- BFS: FILO
- DFS: FIFO
- Heuristic search: remove the node-tuple with the smallest value of an *evaluation function f(n)*

Considered Two Ways to Construct Evaluation Function *f*

- Best First (BF): $f(n) = h(n)$
- Weighted A* (WA*): $f(n) = g(n) + w^* h(n)$

Where:

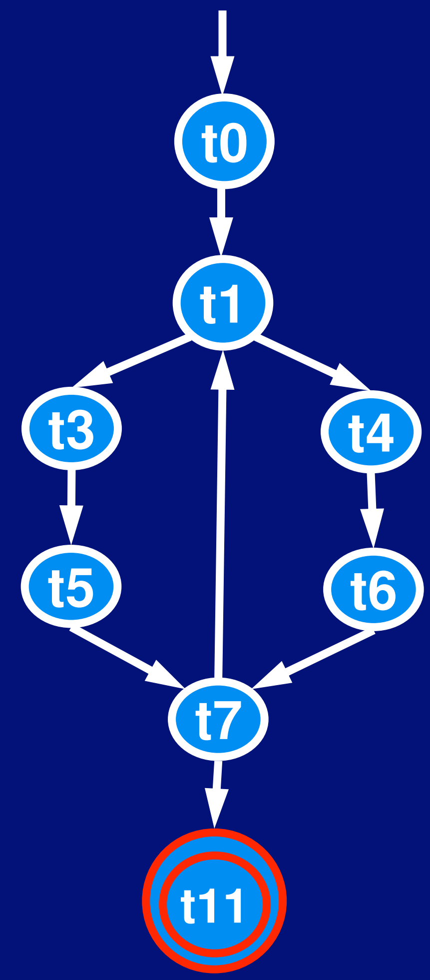
- $h(n)$: a heuristic function that estimates distance from current node n to a goal node
- $g(n)$: a function that gives a distance from the initial node to the current node
- w: a parameter that provides control over the trade-off between search time and the length of the path

Explore Heuristic Functions

- Usually based on aspects of the goal node
  - In FLAVERS, a goal node is a violating node-tuple
- Evaluated two heuristic functions that estimate distance to a goal node
  - TA heuristic: based on the TA states in a node-tuple
  - Trap heuristic: based on the property state in a node-tuple

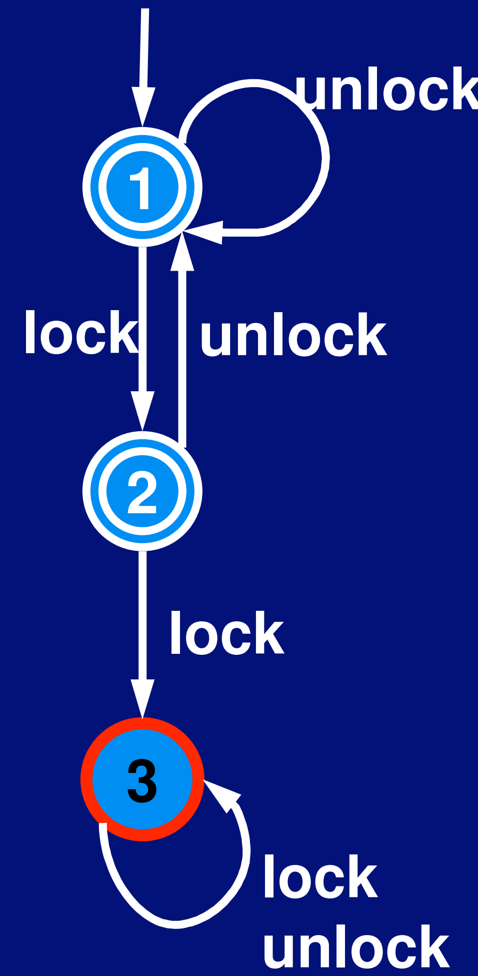
The TA Heuristic

- In a violating node-tuple, each TA must be in its final state
- Estimate the distance to a violating node-tuple
  - Sum over all TAs of the shortest distance *d* from the current state to the final state
  - E.g.: $d(t1) = 4$, $d(t5) = 2$



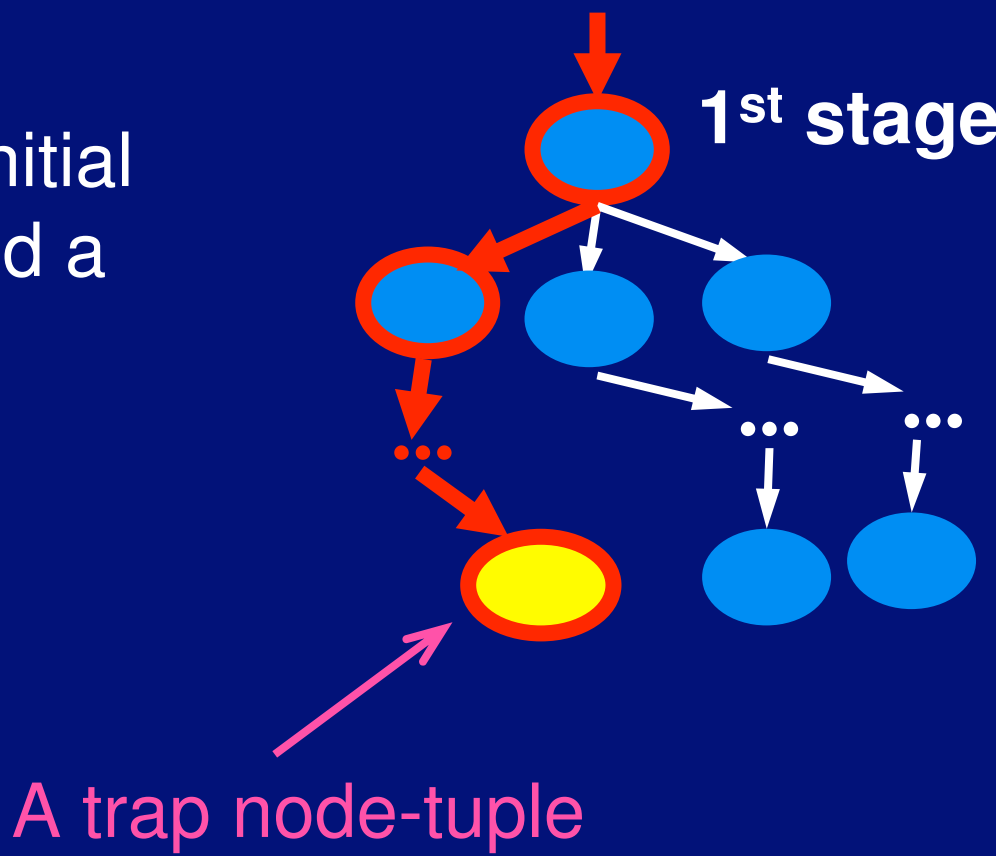
The Property Trap Heuristic

- A trap state is a non-accepting sink state
  - Multiple trap states can be merged
  - Once the property is in a trap state, it can never get into an accepting state
  - Fact: all safety properties can be represented by an FSA with a trap state
  - Trap node-tuple: a node-tuple with the property in the trap state



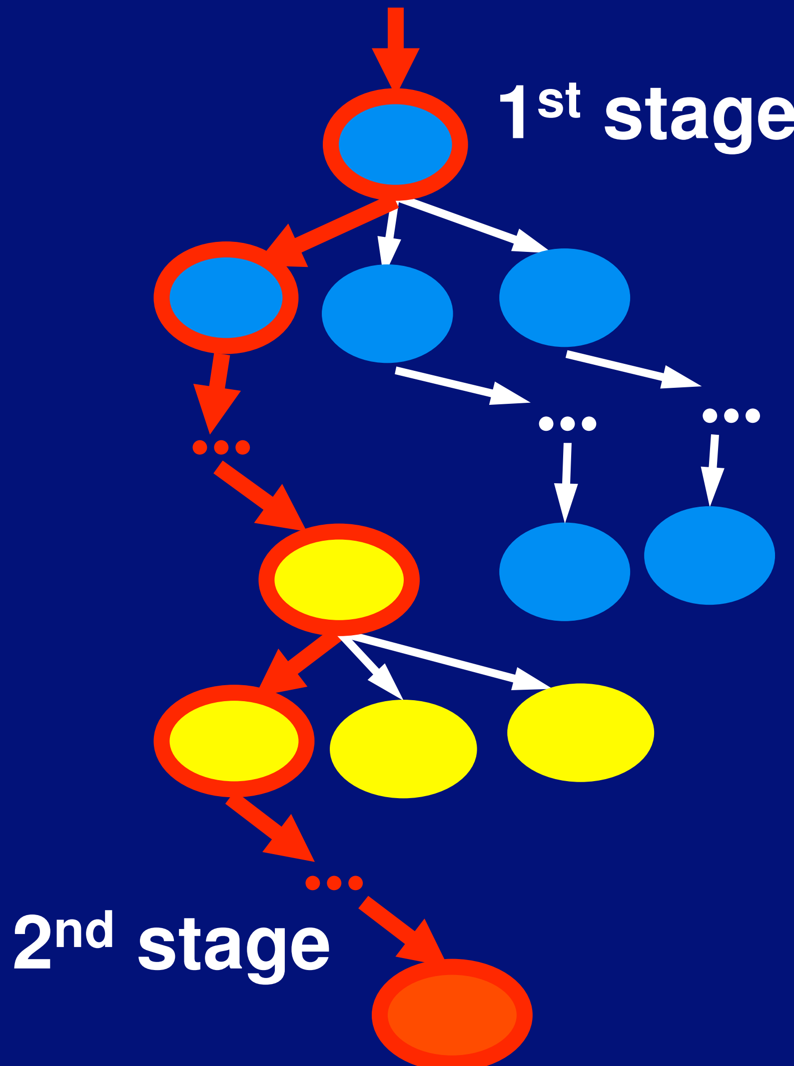
2-Stage Search Strategy

- 1st stage: from the initial node-tuple, try to find a short path to a trap node-tuple fast



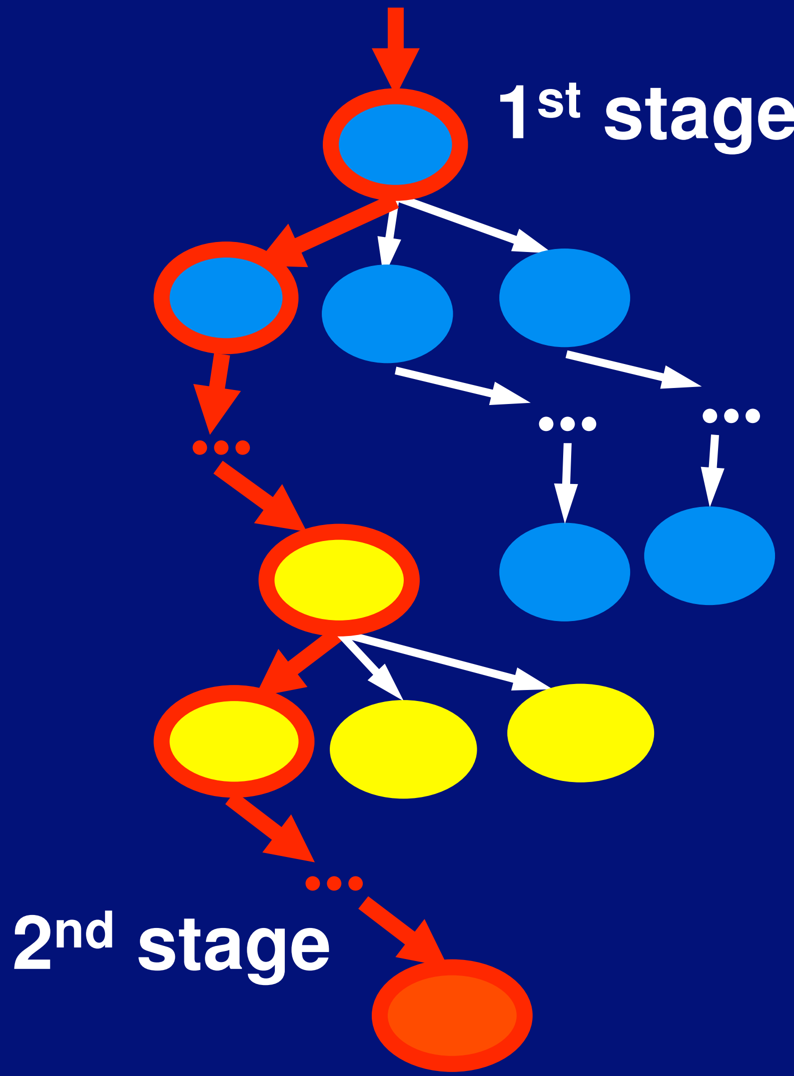
2-Stage Search Strategy

- 1st stage: from the initial node-tuple, try to find a short path to a trap node-tuple fast
- 2nd stage: from the trap node-tuple, try to find a path to a final node-tuple fast



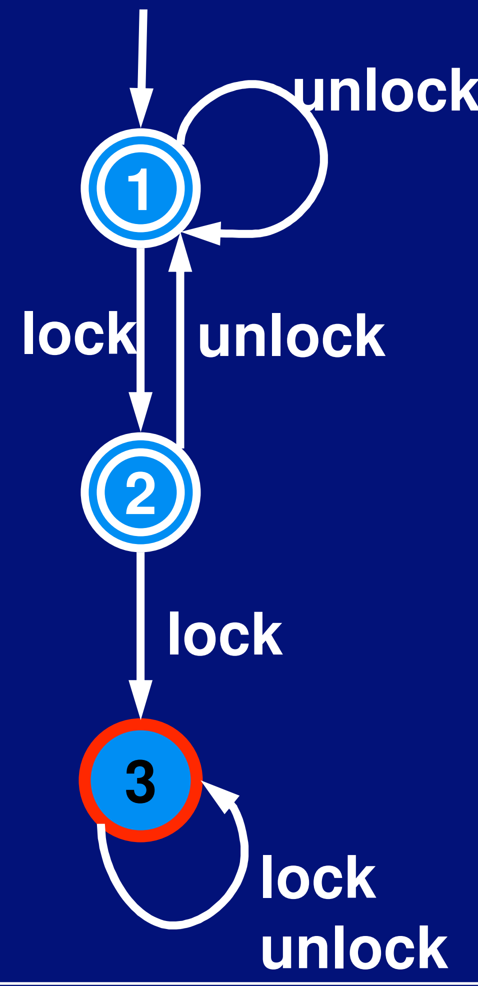
2-Stage Search Strategy

- Path found in the 1st stage is used to understand the cause of the violation
- Path found in the 2nd stage is needed to be sure the whole path is a counterexample



Trap Heuristic for the 1st Stage

- Estimate the distance to a trap node-tuple
  - Use the shortest distance *d* from the current property state to the trap state
  - E.g.: *d*(1)=2; *d*(2)=1; *d*(3)=0



Search Algorithms Evaluated

		BFS	DFS	WA_{ta} w=1, 2, 3, 5, 9	BF_{ta}	BF_{trap}	BF_{trap} +WA_{ta} w=1, 2, 3, 5, 9
1-Stage		√	√	√	√		
2-Stage	1st Stage	√		√		√	√
	2nd Stage		√		√		

- Trap heuristic, which is based on the property, can not be used in the WA* algorithm, which is based on the node-tuple graph

Search Algorithms Evaluated

		BFS	DFS	WA_{ta} w=1, 2, 3, 5, 9	BF_{ta}	BF_{trap}	$BF_{trap}+WA_{ta}$ w=1, 2, 3, 5, 9
1-Stage		√	√	√	√	X	X
2-Stage	1st Stage	√		√		√	√
	2nd Stage		√		√	X	X

- X: BF_{trap} is based on the property trap state, not the final node

Search Algorithms Evaluated

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1-Stage		√	√	√	√		
2-Stage	1st Stage	√	X	√	X	√	√
	2nd Stage		√		√		

- X: DFS and BF_{ta} tend to produce a long path

Search Algorithms Evaluated

		BFS	DFS	WA_{ta} w=1, 2, 3, 5, 9	BF_{ta}	BF_{trap}	BF_{trap} +WA_{ta} w=1, 2, 3, 5, 9
1-Stage		√	√	√	√		
2-Stage	1st Stage	√		√		√	√
	2nd Stage	X	√	X	√		

- X: BFS and WA_{ta} tend to be slow

Metrics

- Runtime ratio:

$$\frac{\textit{Runtime}}{\textit{BFS runtime}}$$

- Prefix length ratio:
  - Prefix length: length from the initial node-tuple to the first trap node-tuple

$$\frac{\textit{Prefix length}}{\textit{BFS prefix length}}$$

Subjects in the Experiment

- Widely studied concurrent systems

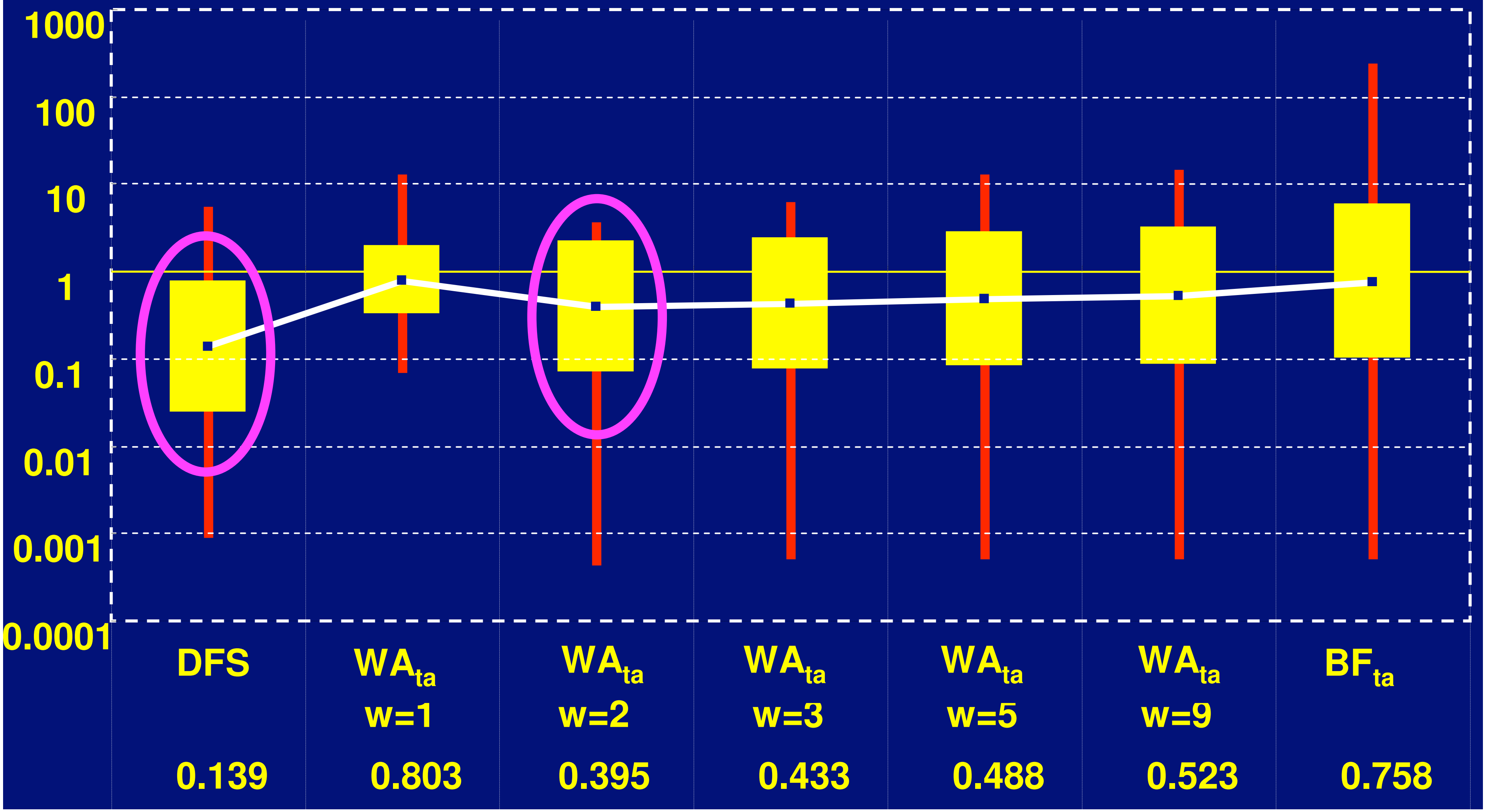
- Properties originally hold in the systems
  - For each property, find a minimal set of constraints that are necessary to prove the property
  - Remove one constraint from the minimal set to generate a subject for the experiment
    - *N* subjects will be generated if the set has *N* constraints

Subjects in the Experiment

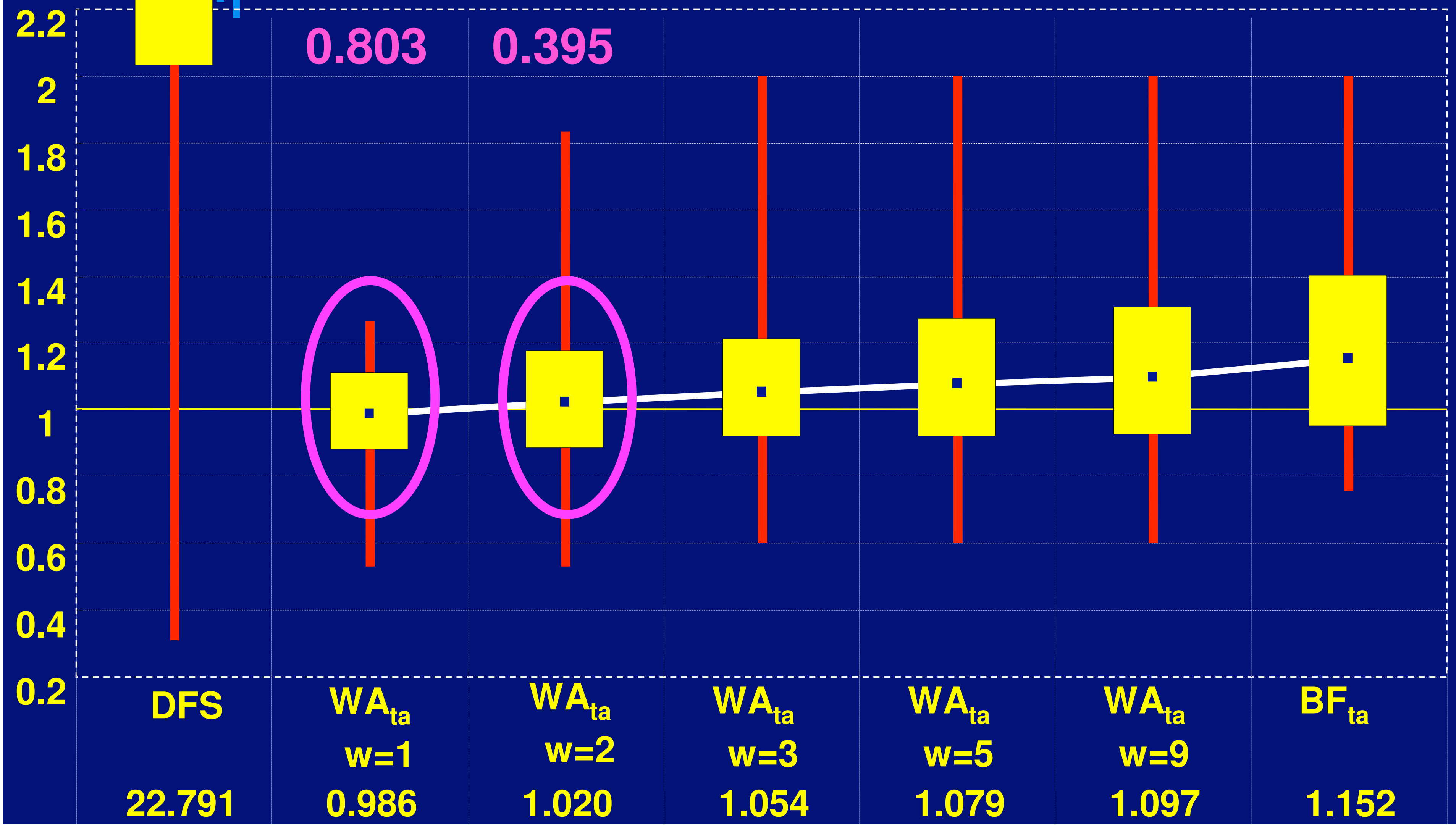
- Remove small subjects that do not differentiate the performance of algorithms

- Remove large subjects if not all algorithms can handle them

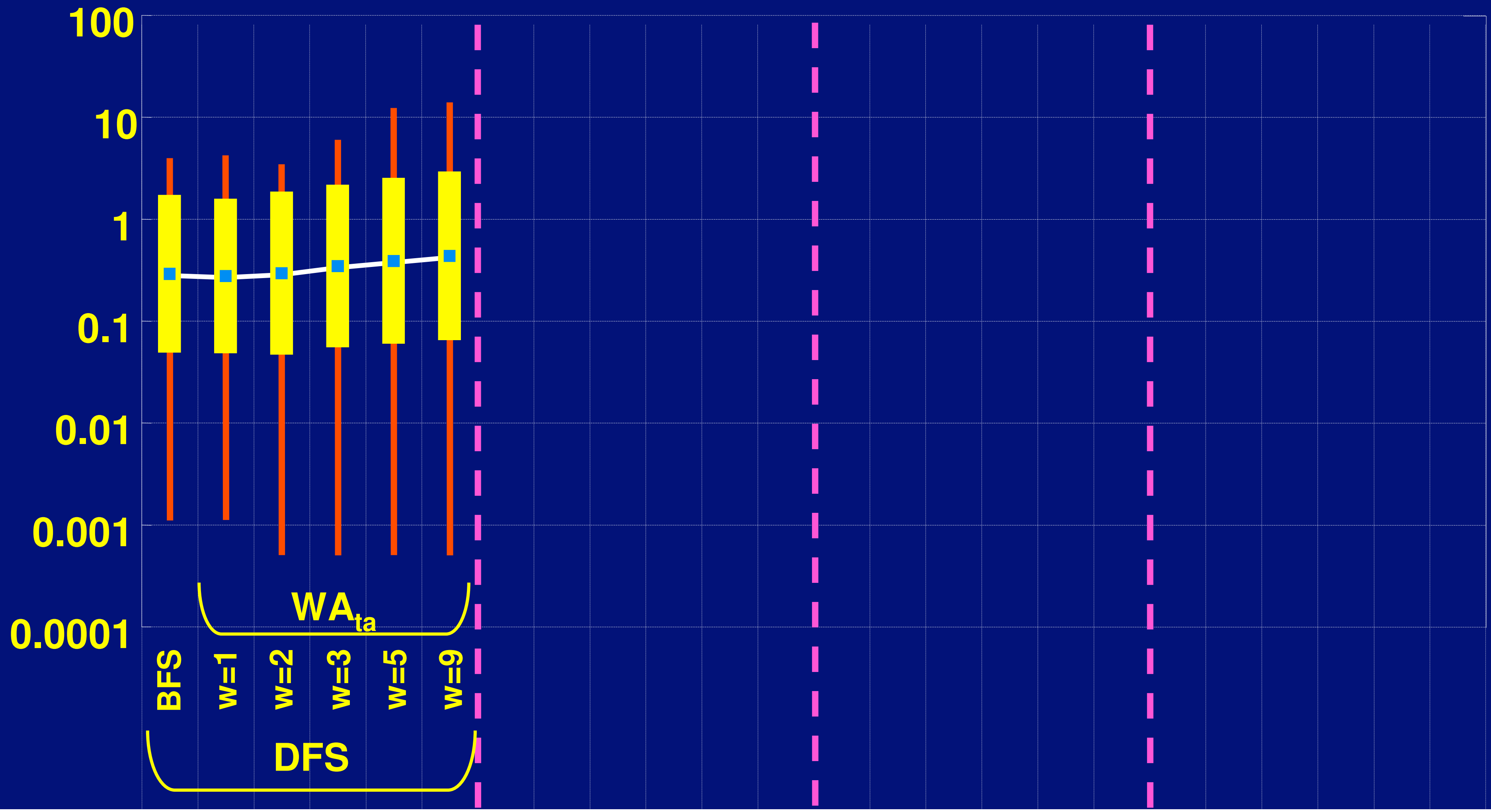
Runtime Ratios of 1-Stage Algorithms



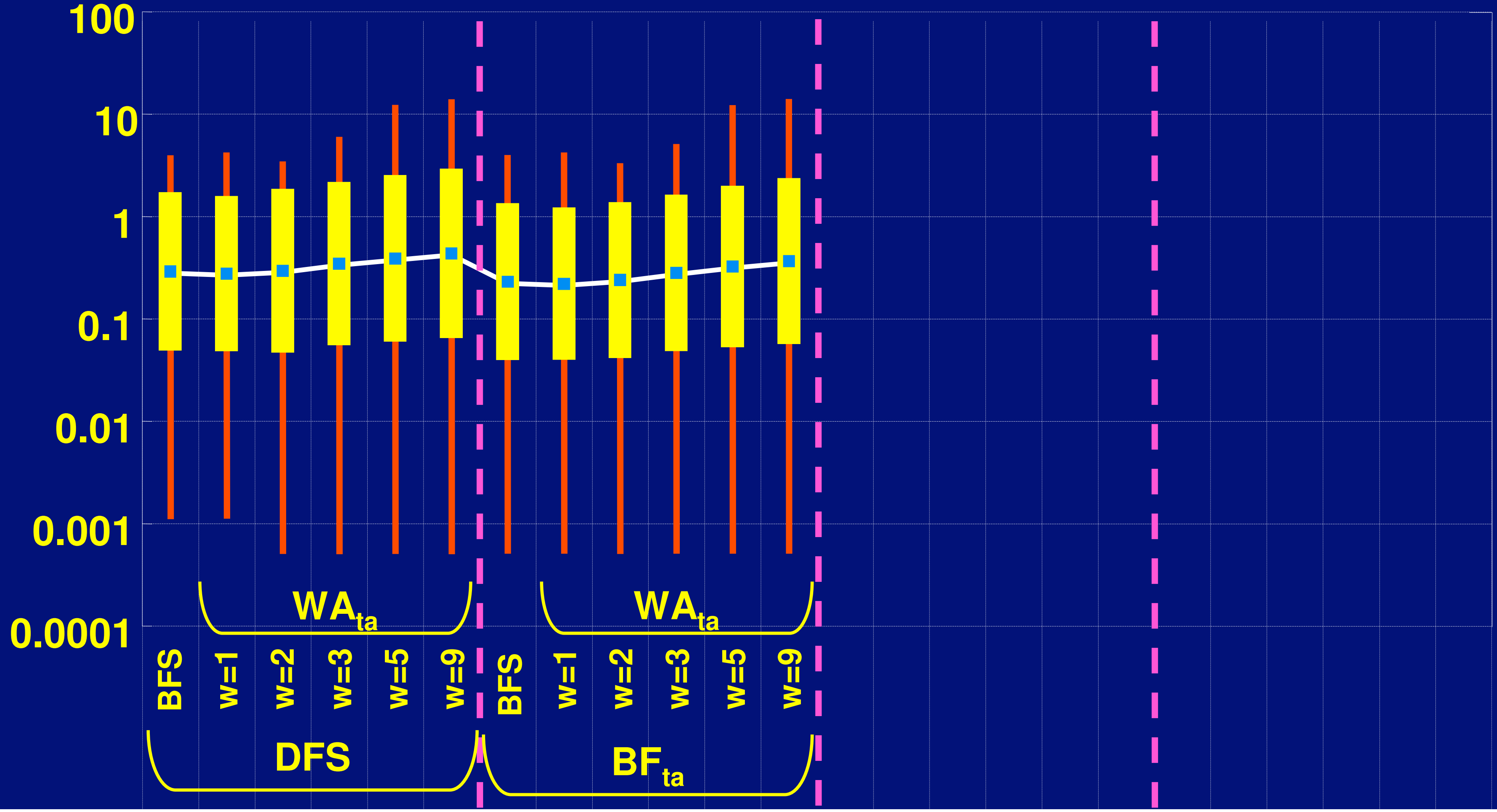
Prefix Length Ratios of 1-Stage Algorithms



Runtime Ratios of 2-Stage Algorithms



Runtime Ratios of 2-Stage Algorithms



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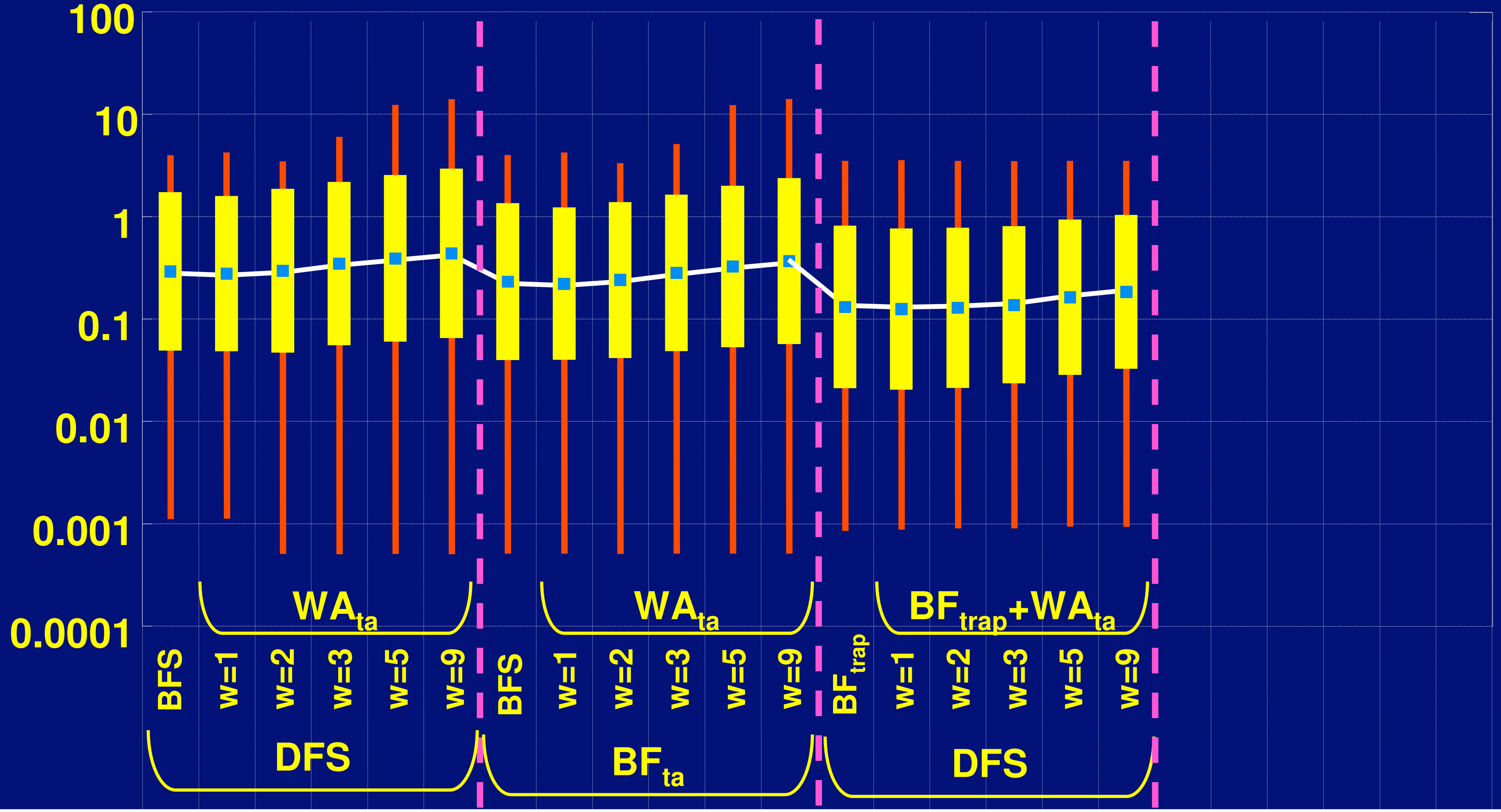

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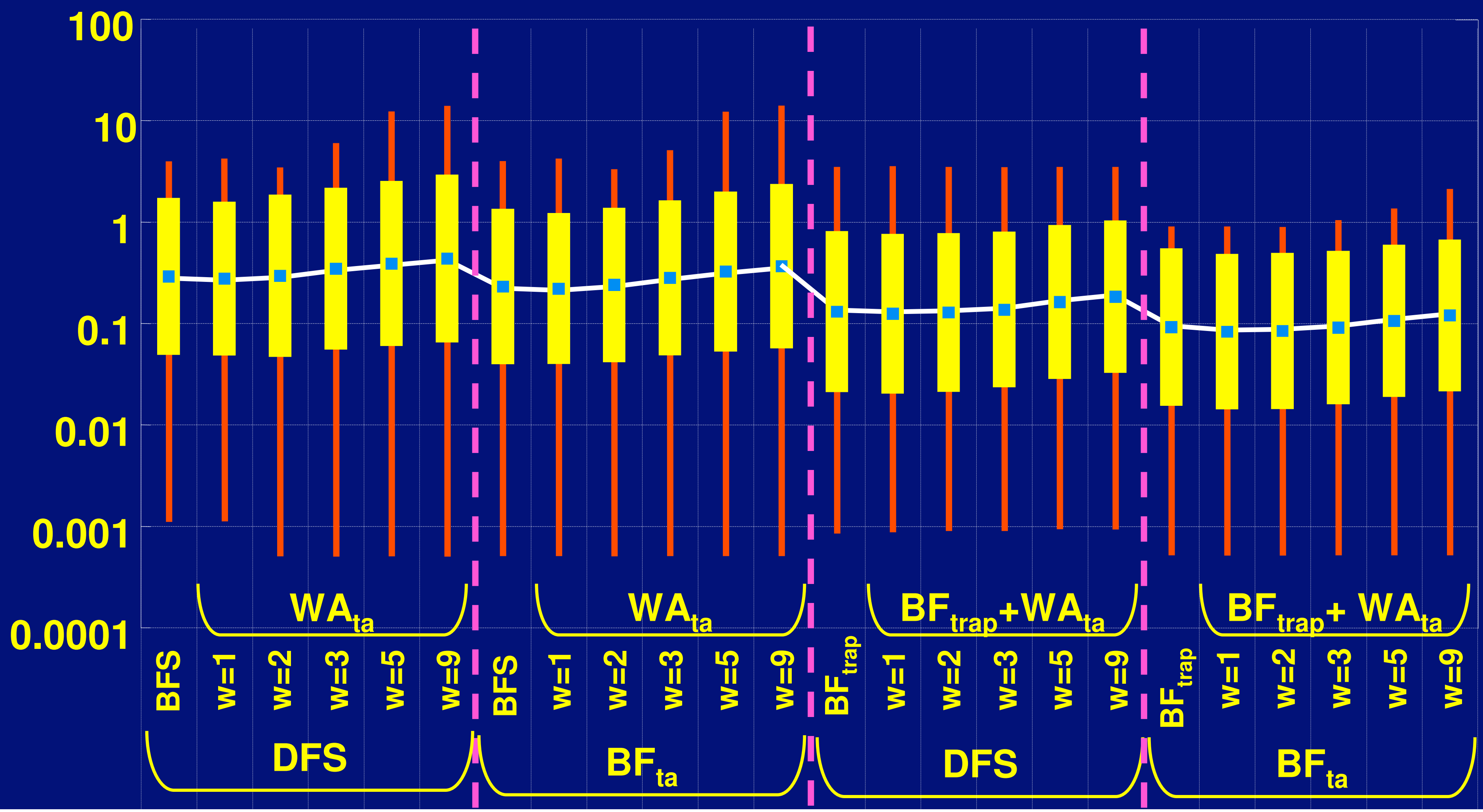
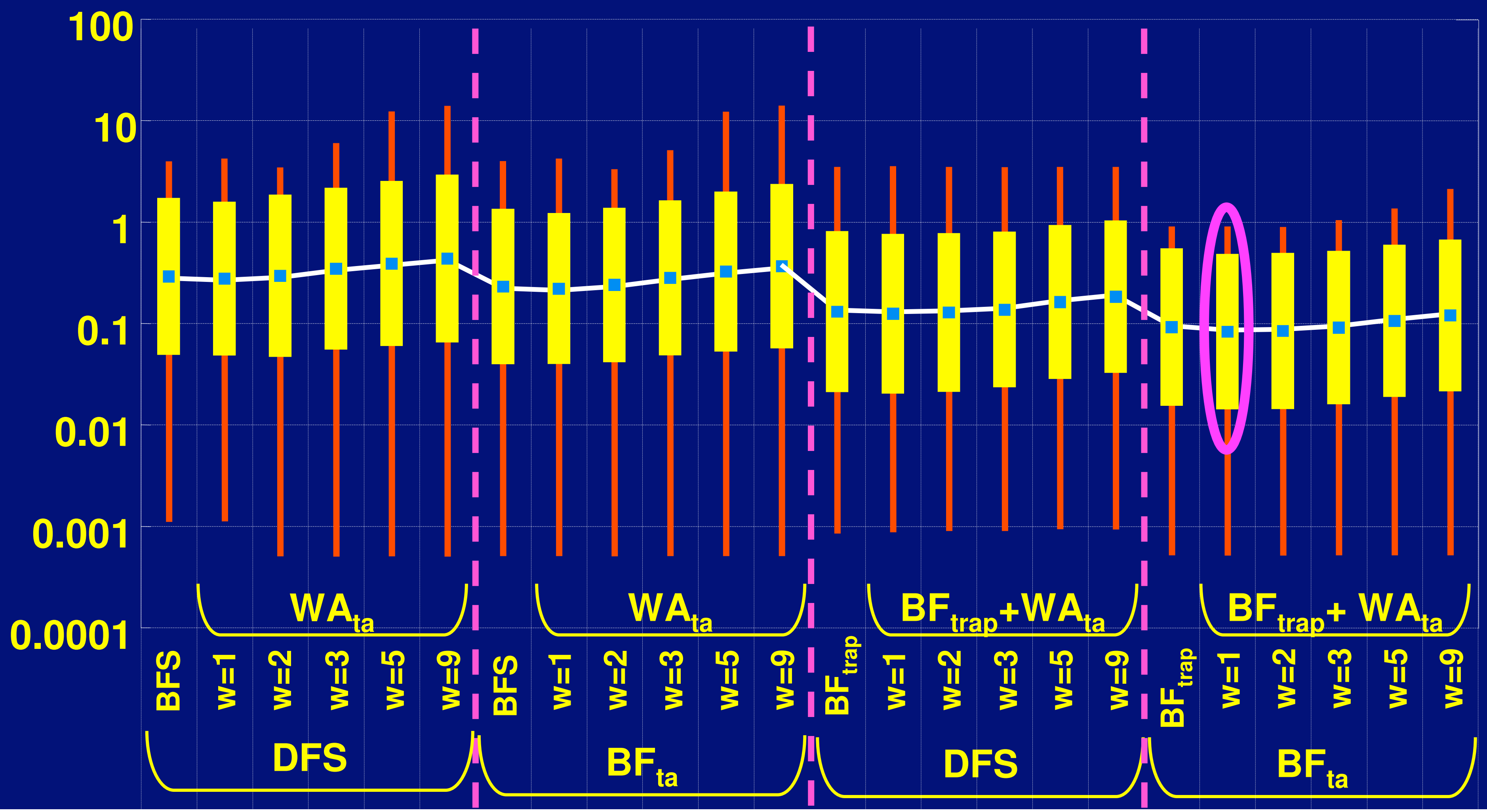
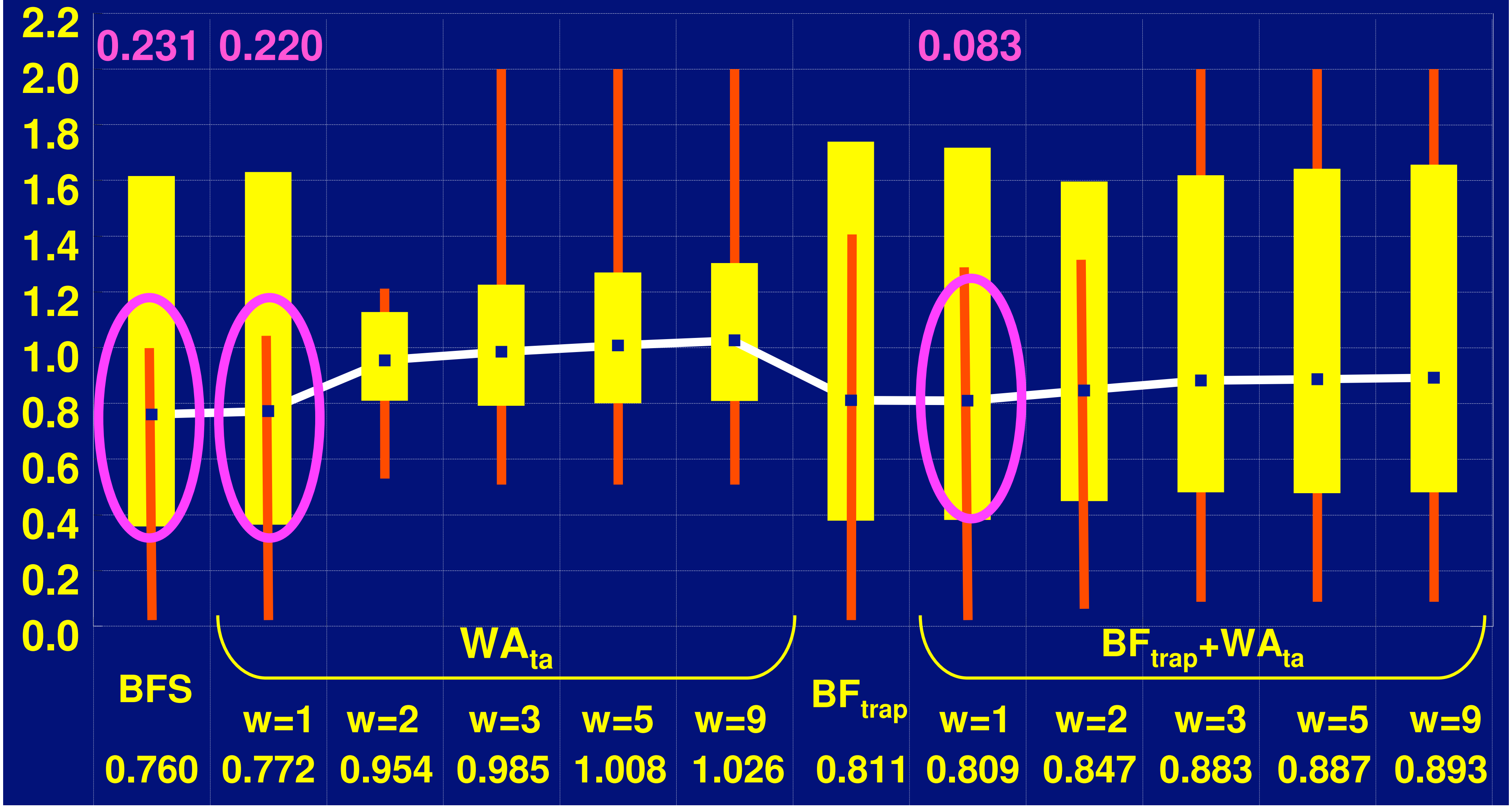


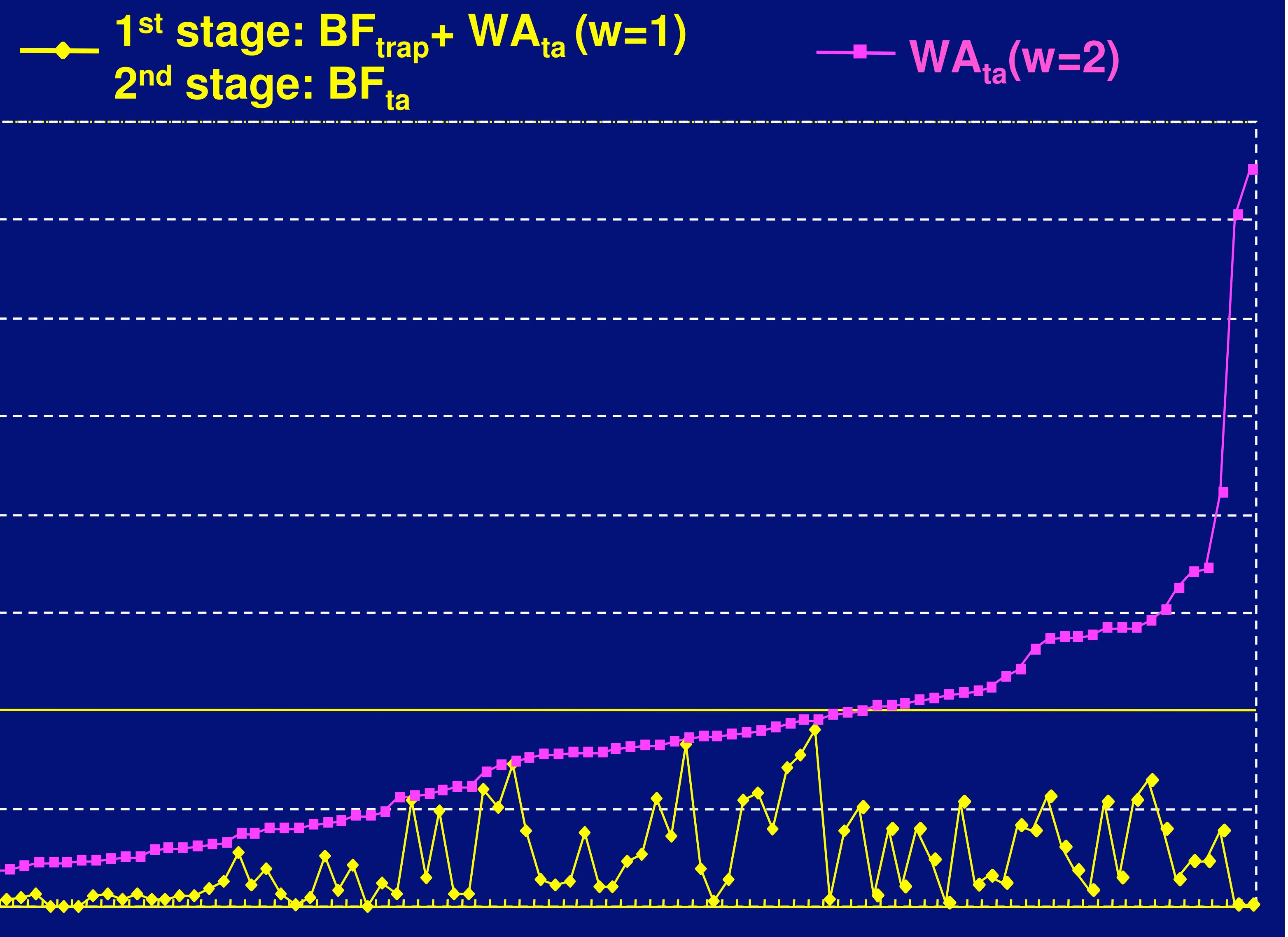
Runtime Ratios of 2-Stage Algorithms



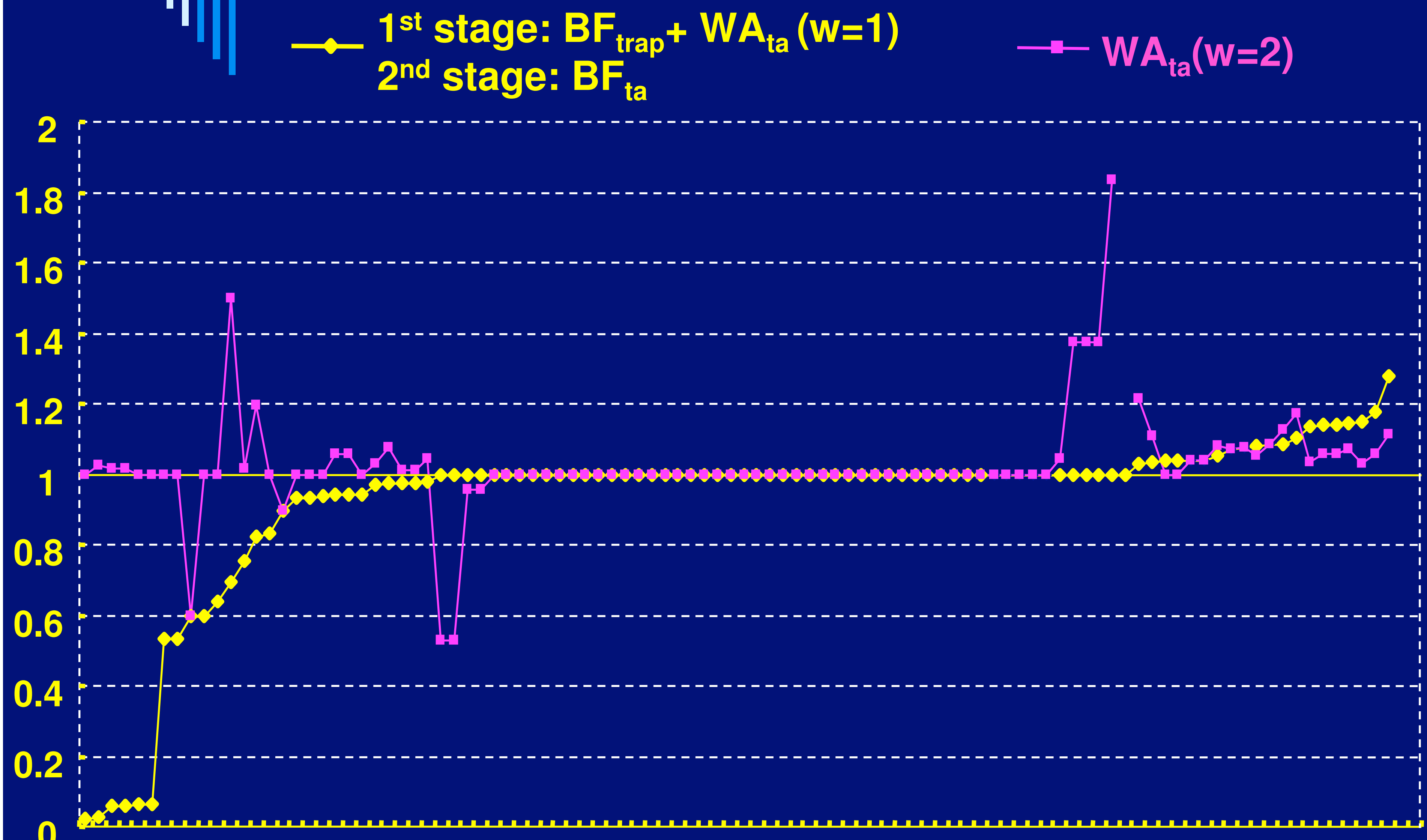
Prefix Length Ratios of 2-Stage Algorithms



Runtime Ratios Comparison



Prefix Length Ratios Comparison



Summary

- The 2-stage algorithm with
  $BF_{trap}+WA_{ta}$ (w=1) and BF_{ta}
  is surprisingly good
  - Runtime ratio:
    - Range from 0.001 to 0.903
    - Average 0.083
    - On average, faster than DFS (0.139)
  - Prefix length ratio:
    - Range from 0.021 to 1.278
    - Average 0.809
  - Works consistently well for these systems

Threats to Validity

- Systems used in the experiment might not be representative
- The inconclusive subjects are created by removing a constraint from the originally conclusive subjects
- Did not evaluate the performance of these algorithms in cases where the property FSAs do not have a trap state
  - 2-stage algorithm is not applicable in these cases

Related Work

- TA heuristic was first described by Cobleigh, etc.
  - Focused on comparing different algorithms used in different situations
- Our work developed the trap heuristic and the 2-stage search algorithm and focused on counterexamples

Related Work

- Apply heuristic search to guide the counterexample search in other FSV tools
  - HSF-SPIN: heuristics based on the property and the structure of the model
  - Java PathFinder: heuristics based on the structure of the model
  - MurØ: Hamming Distance based heuristic
  - VeriSoft: genetic algorithm
- Multi-stage search used in AI

Future Work

- Use heuristic algorithms on a broader range of systems and properties
  - Apply them to Java programs

- Explore the use of heuristic search to find counterexamples that are useful to refine the model

Conclusions

- Explored heuristic search algorithms to find short counterexample fast
- The best algorithm used property and model information
  - Always finds short, but not necessarily shortest, prefix faster than BFS and on average faster than DFS
- Other FSV approaches could also consider property and model based 2-stage heuristic search algorithms

Thank You

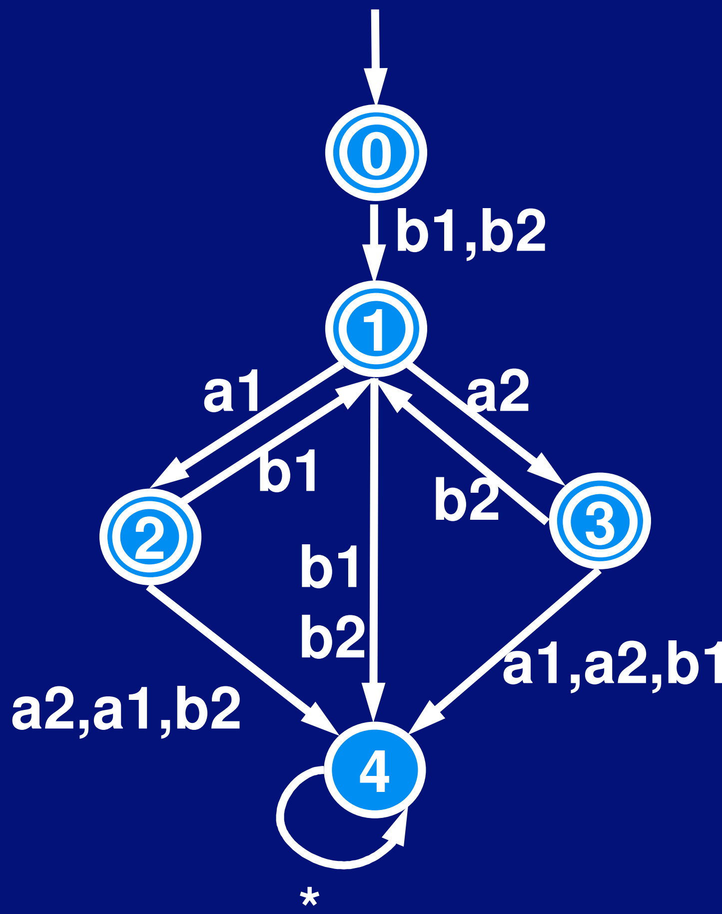
Questions?

Observation

- Trap node-tuple: a node-tuple with the property in the trap state
  - Use the trap state to guide the search to a trap node-tuple ("first part")
  - Once at a trap node-tuple, start a new search for a violating node-tuple that examines the successors of the trap node-tuple only ("second part")
  - Need second part to be sure it is a counterexample, but usually only need first part to understand the cause

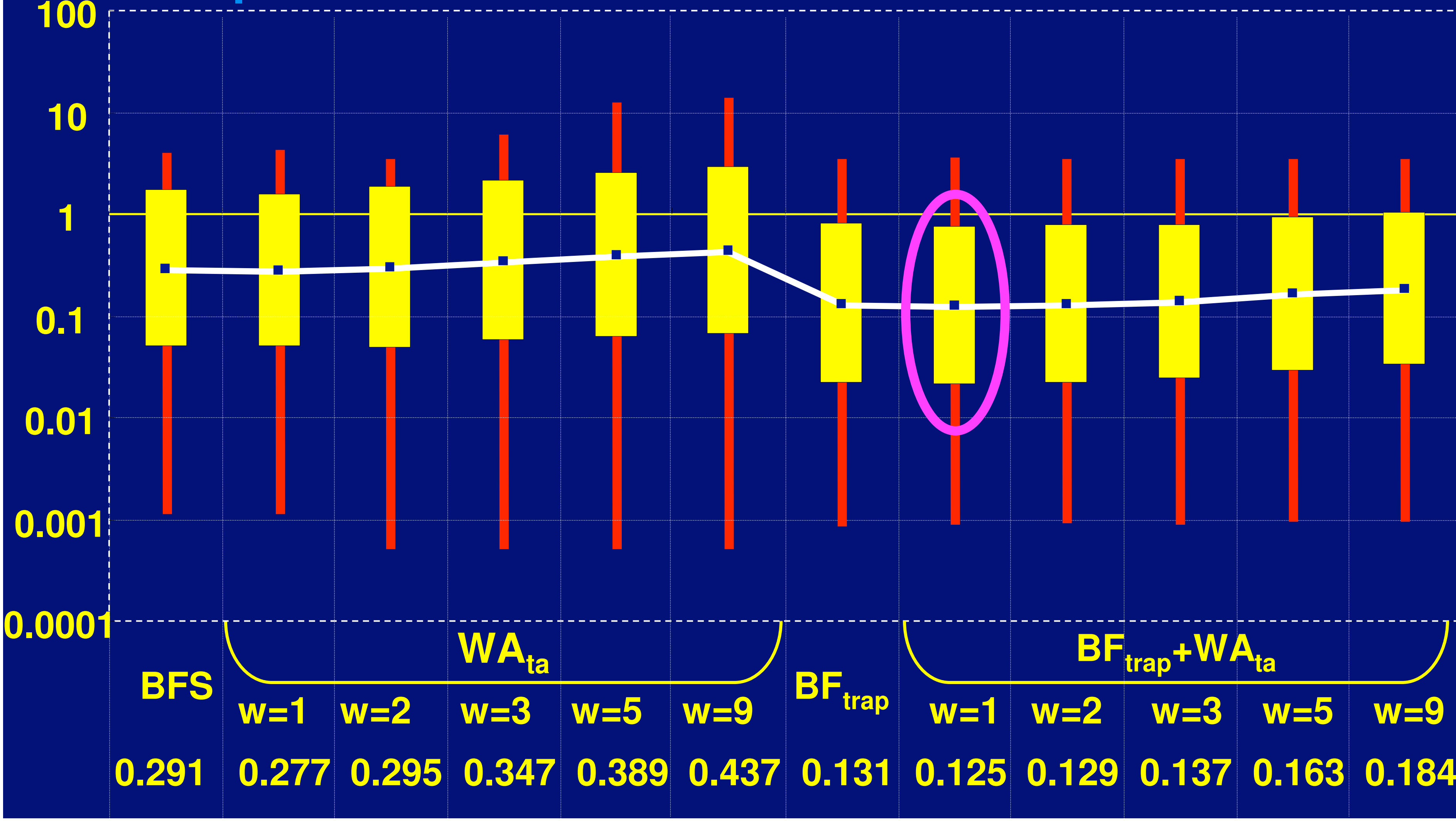
Refined Trap Heuristic

- Use the number of transitions to the trap state to reduce the tie
  - For a property state that has $k>1$ transitions to the trap state: $d = 1 + 1/k$
    - More transitions mean more possibilities to enter the trap state
    - Small estimated value is preferred



d(0)=2 *d*(1)=1.5
d(2)=h(3)=1.333 *d*(4) = 0

Runtime Ratios of 2-Stage Algorithms (2nd Stage uses DFS)



Runtime Ratios of 2-Stage Algorithms (2^{nd} Stage uses BF_{ta})