FSM Inference from Long Traces

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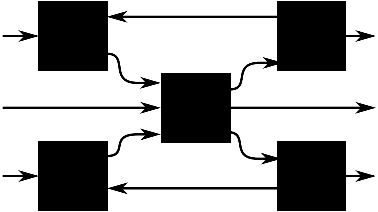
Context

Increasingly modular applications

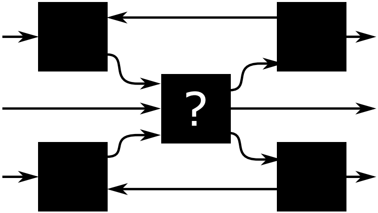


Context

Increasingly modular applications

$\Rightarrow$ no source code

$\Rightarrow$ no documentation



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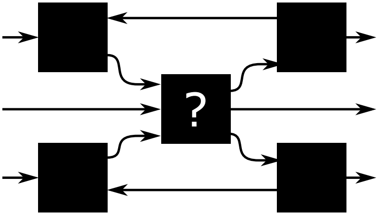
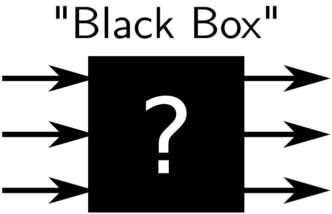


Can we trust these modules?

Problematic



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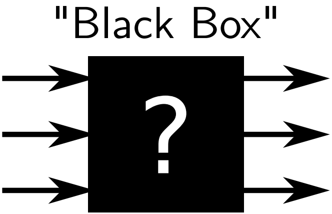
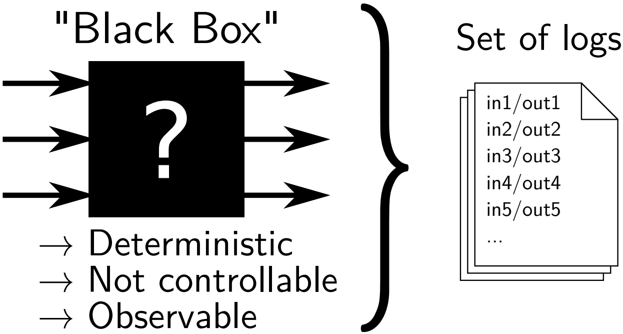


$\rightarrow$ Deterministic
$\rightarrow$ Not controllable
$\rightarrow$ Observable

Problematic



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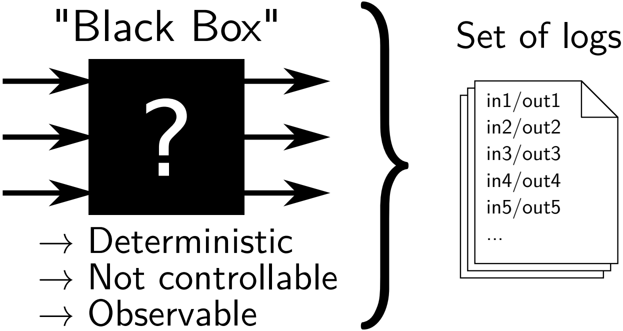

Question: How can we infer a model for the black box from long traces?

Overview

1. Introduction
2. Passive Inference
3. Incremental Inference
4. Conclusion

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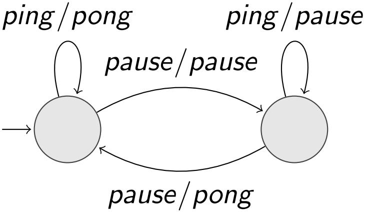
Model

Finite State Machine (FSM)

A FSM is a 5-tuple (S, s_0, I, O, T), where:

- S is a finite set of states with initial state s_0
- I and O are finite non-empty sets of inputs and outputs
- T is a transition relation $T \subseteq S \times I \times O \times S$



Law of parsimony: Among competing hypotheses, the one with the fewest assumptions should be selected

For FSM inference: Find a *minimal* FSM consistent with the set of traces

Formal statement of the problem

Let $\mathcal{T}$ be a set of traces and n be an integer. Find an FSM with at most n states consistent with $\mathcal{T}$

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CSP formulation (Biermann & Feldman 1972)

The set of states Q is represented by integer variables $q_0, q_1, \ldots, q_{|Q|-1}$ taking values from 0 to $n-1$ such that:

$$\forall q_i, q_j \in Q : \text{if } q_i \not\cong q_j \text{ then } q_i \neq q_j$$
$$\text{if } \exists a \in I : \lambda(q_i, a) = \lambda(q_j, a) \text{ then}$$
$$(q_i = q_j) \Rightarrow (\Delta(q_i, a) = \Delta(q_j, a))$$

Efficient SAT formulation (Heule & Verwer 2013)

Translate a CSP formulation to SAT using unary coding for each integer variable, auxiliary variables and breaking symmetry formula

Problem: The time required to infer a model increases exponentially with the size of the logs

Overview

1 Introduction

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Idea: Do not consider the entire logs

First method: Use log prefixes and incrementally grow them

Algorithm 1 Infer an FSM from a set of traces

Input: A set of traces $\mathcal{T}$ and an integer n

Output: An FSM with at most n states and consistent with $\mathcal{T}$ if it exists

```
C := ∅
while C is satisfiable do
    Let M be an FSM of a solution of C
    if T ⊆ Tr_M then
        return M
    end if
    Let ω be the shortest trace in T \ Tr_M
    C := C ∧ C_ω, where C_ω has clauses encoding the fact that ω ∈ Tr_M
end while
return false
```

Example

$\mathcal{T} = \mathit{ping}/\mathit{pong}.\mathit{pause}/\mathit{pause}.\mathit{ping}/\mathit{pause}.\mathit{ping}/\mathit{pause}.\mathit{pause}/\mathit{pong}$
$.\mathit{pause}/\mathit{pause}.\mathit{ping}/\mathit{pause}.\mathit{pause}/\mathit{pong}.\mathit{ping}/\mathit{pause}.\mathit{ping}/\mathit{pause}.\mathit{pause}/\mathit{pause}$
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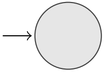
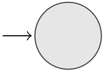


$\omega = \epsilon$

Example

$\mathcal{T} =$ *ping / pong.pause / pause.ping / pause.ping / pause.pause / pong .pause / pause.ping / pause.pause / pong.ping / pause.ping / pause.pause / pause .ping / pause.ping / pause.pause / ping.ping / pong.ping / pong ...*



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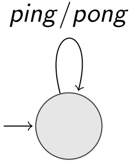

$\omega = ping/pong$

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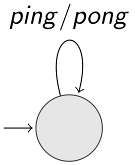

$\omega =$ *ping / pong*

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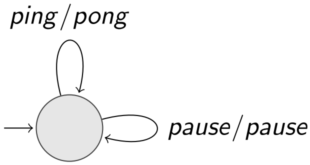

$\omega = ping/pong.pause/pause$

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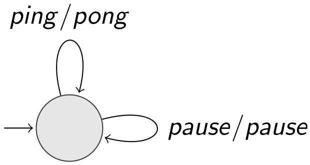

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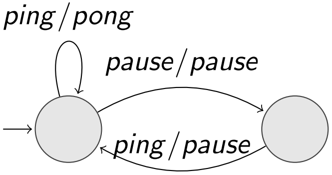

$\omega = ping/pong.pause/pause.ping/pause$

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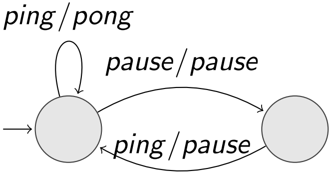

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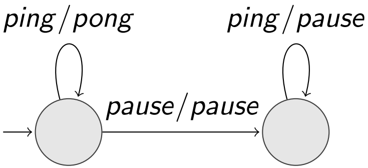

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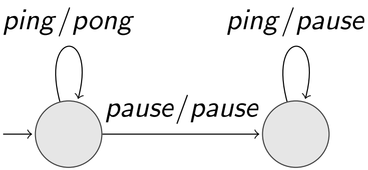

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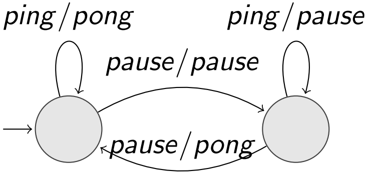
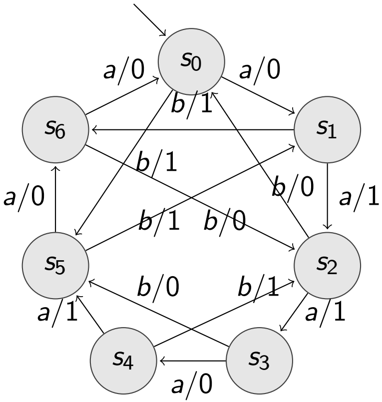


$\omega = ping/pong.pause/pause.ping/pause.ping/pause.pause/pong$

Benchmark

We calculate the average time over ten instances used to infer a random FSMs with seven states, two inputs *a* and *b*, and two outputs 0 and 1

Trace length	**H&V method (sec.)**	**Prefix method (sec.)**
1k	2.5	0.2
2k	7.3	0.2
4k	20	0.2
8k	53	0.2
16k	190	0.3
32k	Out of Memory	0.5
64k	Out of Memory	1.5



Example of a random FSM

Infrequent Events

Algorithm 2 Example client

```
while true do
    if rand() mod 1/p == 0 then
        send("pause");
    else
        send("ping");
    end if
end while
```

$\mathcal{T} = ping/pong.ping/pong.ping/pong.ping/pong.ping/pong...$
$...ping/pong.$**pause/pause**$.ping/pause.ping/pause.ping/pause...$
$...ping/pause.$**pause/pong**$.ping/pong.ping/pong.ping/pong...$

Infrequent Events

We vary the chances that *b* will appear in a 64 000 length trace produced by a randomly generated FSM

Probability of ***b***	**Prefix-based (sec.)**
50 %	1.5
25 %	1.4
10 %	1.4
1 %	3.5
0.5 %	6.0
0.3 %	16
0.2 %	90
0.1 %	Out of Memory

Infrequent Events

Idea: Add less strong constraints that refute the conjectures

Method: Let M be a conjecture and ω be the shortest trace in $\mathcal{T} \setminus Tr_M$. If there exists a suffix ω' of ω such that $\forall s : \omega' \notin Tr(s)$ then it's sufficient to add the constraint that $\exists s : \omega' \in Tr(s)$ to refute M

Observations:

- The length of ω' can be much shorter than the length of ω
- The constraint $\exists s : \omega' \in Tr(s)$ is easy to write in SAT

Algorithm 3 Infer an FSM from a set of traces

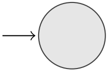
Input: A set of traces $\mathcal{T}$ and an integer n

Output: An FSM with at most n states consistent with $\mathcal{T}$ if it exists

$C := \emptyset$
while C is satisfiable **do**
    Let M be an FSM of a solution of C
    if $\mathcal{T} \subseteq Tr_M$ **then**
        return M
    end if
    Let ω be the shortest trace in $\mathcal{T} \setminus Tr_M$
    if $\exists \omega'$ the shortest suffix of ω such that $\forall s : \omega' \notin Tr(s)$ **then**
        $C := C \wedge C'_\omega$, where C'_ω has clauses encoding the fact that $\exists s : \omega' \in Tr(s)$
    else
        $C := C \wedge C_\omega$, where C_ω has clauses encoding the fact that $\omega \in Tr_M$
    end if
end while
return *false*

Example

$\mathcal{T}$ = *ping / pong.ping / pong.ping / pong.ping / pong.ping / pong...*
...ping / pong.**pause/pause**.*ping / pause.ping / pause.ping / pause...*
...ping / pause.**pause/pong**.*ping / pong.ping / pong.ping / pong...*



$\omega = \epsilon$

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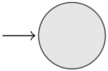

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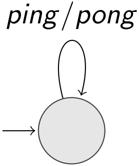

ω = *ping/pong*

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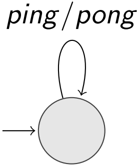

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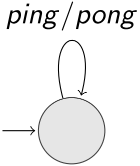

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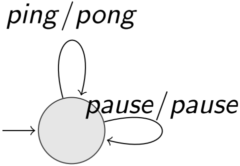

$$\boxed{\omega = ping/pong, \omega' = pause/pause}$$

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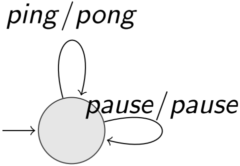

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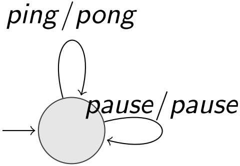

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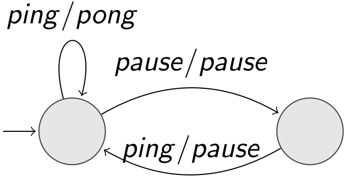

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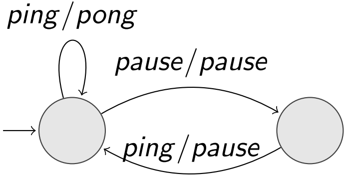

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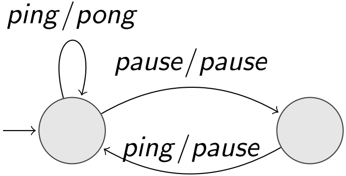

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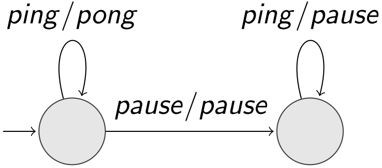

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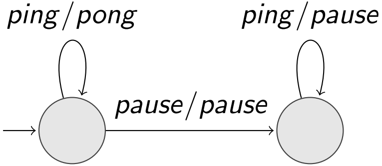

$\omega =$ *ping / pong*, $\omega' =$ *pause / pause*, $\omega' =$ *ping / pause.ping / pause*

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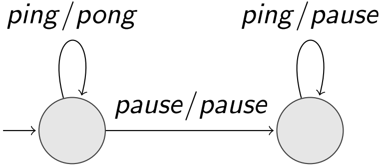

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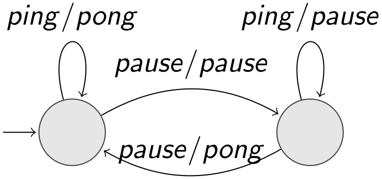
$\mathcal{T} = ping/pong.ping/pong.ping/pong.ping/pong.ping/pong...$
$...ping/pong.$**pause/pause**$.ping/pause.ping/pause.ping/pause...$
$...ping/pause.$**pause/pong**$.ping/pong.ping/pong.ping/pong...$



$\omega = ping/pong, \omega' = pause/pause, \omega' = ping/pause.ping/pause, \omega' = pause/pong$

Benchmark

We vary the chances that *b* will appear in a 64000 length trace produced by a randomly generated FSM

Probability of ***b***	**Prefix-based (sec.)**	**Suffix-based (sec.)**
50 %	1.5	2.4
25 %	1.4	1.4
10 %	1.4	1.4
1 %	3.5	1.4
0.5 %	6.0	1.5
0.3 %	16	1.4
0.2 %	90	1.5
0.1 %	Out of Memory	1.6

Overview

1 Introduction

2 Passive Inference

3 Incremental Inference

4 Conclusion

Conclusion

Our contributions include incremental algorithms for passive FSM inference

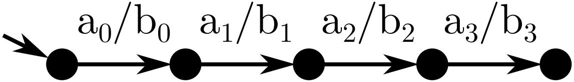
- Prefix-based algorithm
- Suffix-based algorithm

As future work, we want to investigate whether their combination will result in a more efficient method

Thank you

Table 1: Summary for encoding passive inference from ISFSM $W = (X, x_0, I, O, T)$ into SAT. n is the maximal number of states in an FSM to infer, $B = \{0, ..., n-1\}$

Clauses	**Range**
$v_{x_0,0}$	
$(v_{x,0} \vee v_{x,1} \vee ... \vee v_{x,n-1})$	$x \in X$
$(\neg v_{x,i} \vee \neg v_{x,j})$	$x \in X; 0 \leq i < j < n$
$(\neg v_{x,i} \vee \neg v_{x',i})$	$x \not\simeq x'; i \in B$
$(y_{a,i,j} \vee \neg v_{x,i} \vee \neg v_{x',j})$	$(x, a, o, x') \in T; i, j \in B$
$(\neg y_{a,i,h} \vee \neg y_{a,i,j})$	$a \in I; h, i, j \in B; h < j$
$(y_{a,i,0} \vee y_{a,i,1} \vee ... \vee y_{a,i,n-1})$	$a \in I; i \in B$
$(\neg y_{a,i,j} \vee \neg v_{x,i} \vee v_{x',j})$	$(x, a, o, x') \in T; i, j \in B$



$v_{0,0}$	$v_{1,0}$	$v_{2,0}$	$v_{3,0}$	$v_{4,0}$
$v_{0,1}$	$v_{1,1}$	$v_{2,1}$	$v_{3,1}$	$v_{4,1}$
$v_{0,2}$	$v_{1,2}$	$v_{2,2}$	$v_{3,2}$	$v_{4,2}$

Clauses	**Range**
$v_{x_0,0}$	
$(v_{x,0} \vee v_{x,1} \vee ... \vee v_{x,n-1})$	$x \in X$
$(\neg v_{x,i} \vee \neg v_{x,j})$	$x \in X; 0 \leq i < j < n$
$(\neg v_{x,i} \vee \neg v_{x',i})$	$x \not\cong x'; i \in B$
$(v_{x,i} \wedge v_{x',i}) \Rightarrow (v_{\Delta(x,a),j} \Rightarrow v_{\Delta(x',a),j})$	$x, x' \in X \mid \lambda(x,a) = \lambda(x',a); i, j \in B$