State-merging DFA induction algorithms with mandatory merge constraints

From MSM to ASM

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Motivations

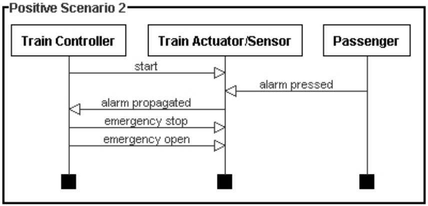
Requirements Engineering (RE)

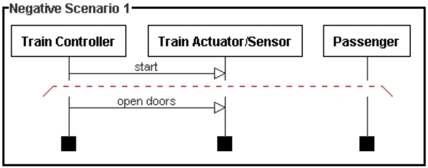
- It has been claimed that the hardest part in building a software system is deciding precisely what the system should do
- One can automate parts of this RE process by learning behavior models from scenarios
- Scenarios are strings of possible events which can be generalized to form a language of acceptable behaviors
- Such languages are conveniently represented by finite-state machines

Scenarios

A train system example

- Scenarios describe interactions between the software-to-be and its environment
- Scenarios are typical examples of system usage provided by an end-user involved in the requirements elicitation process





Synthesis of behavior models and DFA induction

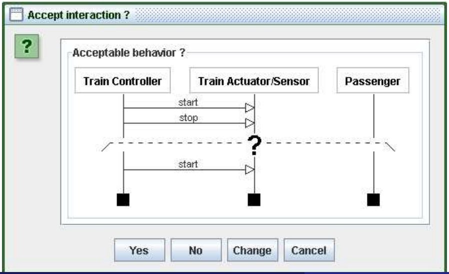
A win-win situation

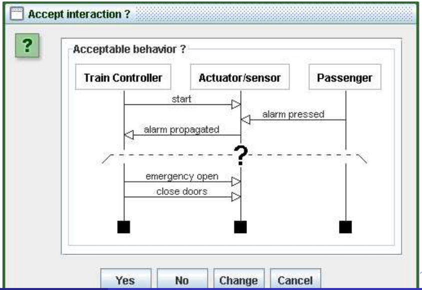
- Regular languages are considered to be powerful enough
- DFAs offer a convenient representation for model checking and code generation
- The typical size of such DFAs is about $20 \ldots 100$ states
  - $\Rightarrow$ hard to design exactly by a software analyst
  - $\Rightarrow$ not problematic for state-of-the-art DFA induction algorithm (RPNI, BlueFringe)
- Typical alphabet size $\approx 10 \ldots 20$
- The end-user can really be used as an oracle in practice

State-merging induction with membership queries

Our previous work: the QSM algorithm [Damas et al. 05], [Dupont et al. 08]

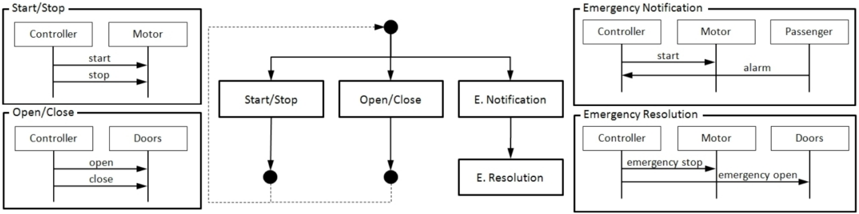
- An extension to RPNI or BlueFringe (also known as redBlue) with membership queries
- The limited amount of positive and negative scenarios provided initially by an end-user can be enriched by asking membership queries





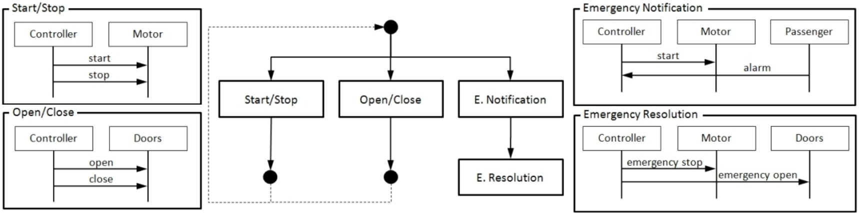
A high-level Message Sequence Chart

Flow-charting of various scenarios

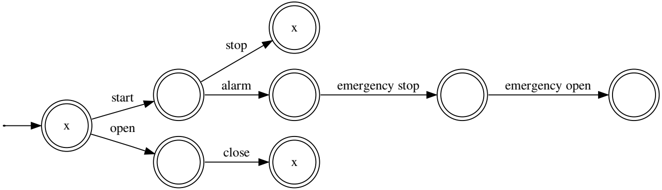


A high-level Message Sequence Chart

Flow-charting of various scenarios

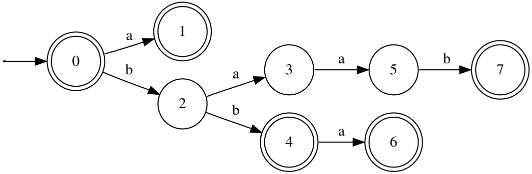


This information defines Mandatory Merge Constraints between some states of the prefix tree acceptor (PTA)



State-merging DFA induction

Prefix-Tree Acceptor (PTA)



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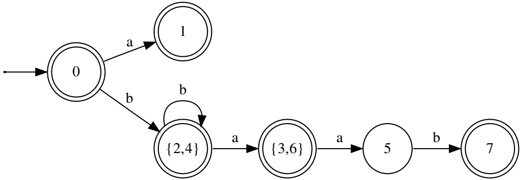
Quotient automaton

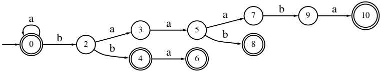


State-merging DFA induction algorithm

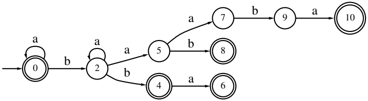
Algorithm STATE-MERGING DFA INDUCTION ALGORITHM
Input: A positive and negative sample (S_+, S_-)
Output: A DFA A consistent with (S_+, S_-)

```
// Compute a PTA, let N denote the number of its states
PTA ← Initialize(S+, S−); π ← {{0}, {1}, ..., {N − 1}}
// Main state-merging loop
while (Bi, Bj) ← ChoosePair(π) do
    πnew ← Merge(π, Bi, Bj)
    if Compatible(PTA/πnew, S−) then
        π ← πnew
return PTA/π
```

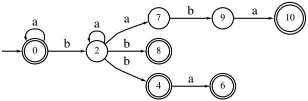
The `Merge` function also reduces non-determinism



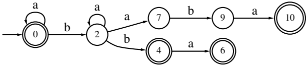
Merging 3 and 2



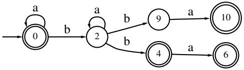
Merging 5 and 2 (for determinization)



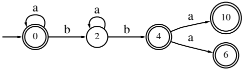
Merging 8 and 4



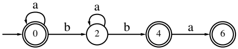
Merging 7 and 2



Merging 9 and 4



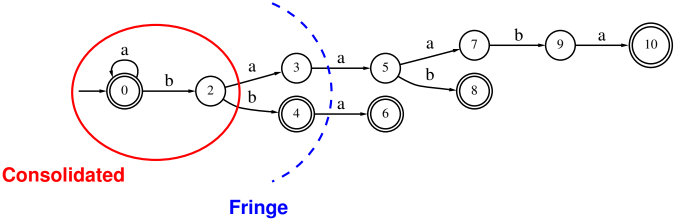
Merging 10 and 6



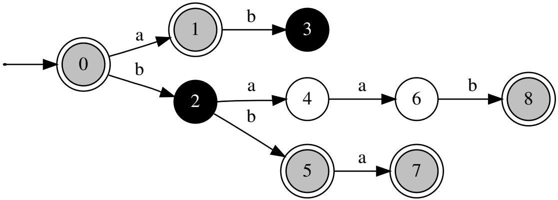
Tree invariant

Tree invariant property

- At least one of the 2 states implied in a merging operation is the root of a (sub)-tree
- True for RPNI, BlueFringe (= redBlue), *etc*
- Simplification of the actual implementation

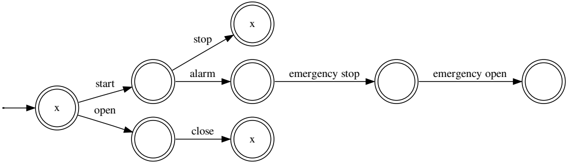


Incompatibility constraints



- Augmented PTA with positively accepting states (= grey) and negatively accepting states (= black)
- The `Merge` function reduces non-determinism and checks such coloring constraints
  - States having different colors may not be merged
  - States having the same color can be merged
- Coloring constraints define incompatibility between states from positive and negative information or additional domain knowledge [Coste et al. 04], [Dupont et al. 08]

Mandatory merge constraints



- Another kind of domain knowledge defines mandatory merge constraints between states sharing the same labels
- Labeling constraints are the logical counterpart to the coloring constraints
  - States with the same label must be merged
  - States with different labels can be merged
- A fully labeled PTA does not define a trivial induction problem
  - Without coloring constraints (such as those provided by the negative sample) all states will be merged

MSM algorithm

Algorithm MSM
Input: A non-empty initial positive and negative sample (S_+, S_-)
Input: Labeling and coloring constraints
Output: A DFA A consistent with (S_+, S_-) and all constraints

```
// Compute a PTA, let N denote the number of its states
PTA ← Initialize(S+, S−); π ← {{0}, {1}, ..., {N − 1}}

// Merge all states according to labeling constraints
while (Bi, Bj) ← FindSameBlocks(π) do
    π ← Merge(π, Bk, Bl)

// Main state-merging loop
while (Bi, Bj) ← ChoosePair(π) do
    try
        π ← Merge(π, Bi, Bj)
    catch avoid
        // inconsistency between coloring and labeling constraints

return PTA/π
```

MSM does not satisfy the tree invariant property

MSM is a straightforward extension to standard state-merging algorithms

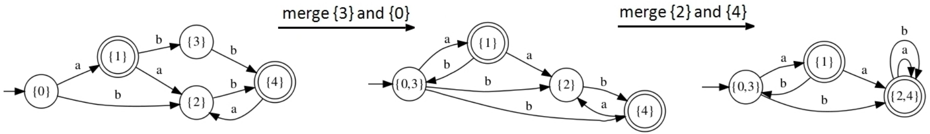
However...

MSM does not satisfy the tree invariant property

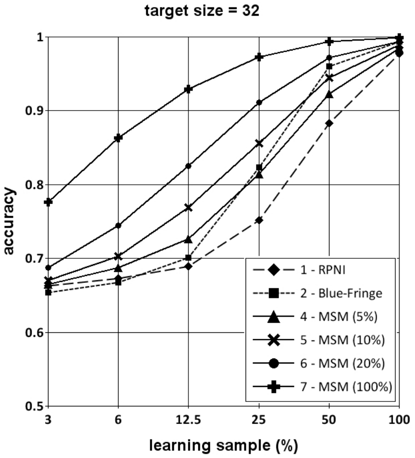
MSM is a straightforward extension to standard state-merging algorithms

However...

- Labeling constraints can force to merge states such that the resulting automaton has a general graph structure
- The **tree invariant property** is no longer satisfied
- Recursive merging to reduce non-determinism naturally stops even for general graphs

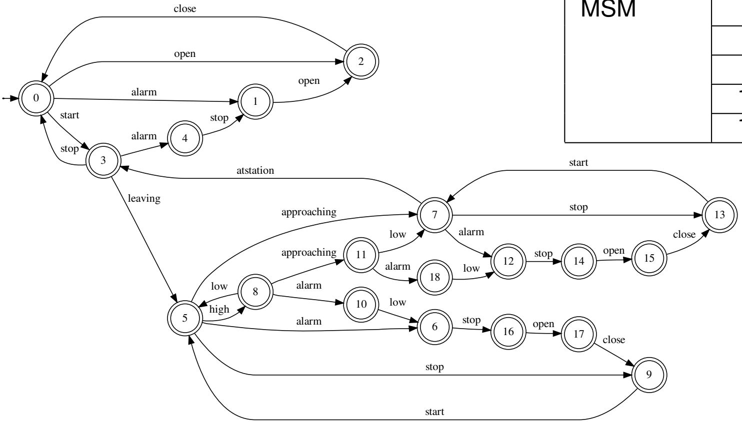


Experiments on synthetic data



Requirements engineering case study

Algorithm	|*lab*|	Accuracy
RPNI	-	0.55
BlueFringe	-	0.83
MSM	0	0.55
	3	0.71
	6	0.73
	10	0.88
	15	0.90



DFA induction from a positive DFA and a negative sample

Algorithm ASM
Input: A positive DFA A_+ and a negative sample S_-
Output: A DFA A consistent with (A_+, S_-)

$//$ Augment the automaton A_+ with states

$//$ marked/added from S_-

$M \leftarrow$ `Augment(`A_+`, `S_-`)`

$//$ Compute the natural order on M

$\pi \leftarrow$ `NatOrder(`M`)`

$//$ Main state-merging loop

$\pi \leftarrow$ `Generalize(`π`)`

return M/π

DFA induction from positive and negative DFAs

Algorithm ASM*
Input: A positive DFA A_+ and a negative DFA A_- such that $L(A_+) \cap L(A_-) = \emptyset$
Output: A DFA A consistent with (A_+, A_-)

// Augment the automaton A_+ with states

// marked/added from S_-

$M \leftarrow$ `Product(`A_+`, `A_-`)`

// Compute the natural order on M

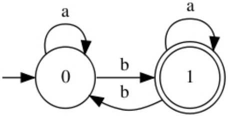
$\pi \leftarrow$ `NatOrder(`M`)`

// Main state-merging loop

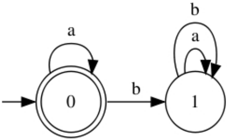
$\pi \leftarrow$ `Generalize(`π`)`

return M/π

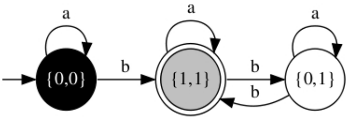
Product DFA



A_+



A_-



M

Take home message

- Mandatory merge constraints are introduced to model domain knowledge, for instance, from a Requirements Engineering perspective
- Mandatory merge constraints form the logical counterpart to incompatibility constraints
- The MSM algorithm deals with both types of constraints
- MSM is a straightforward extension to RPNI or BlueFringe but
  - without satisfying the tree-invariant property
  - using recursive merging extended to general graphs
- MSM gives rise to ASM* to induce DFAs from prior positive and negative DFAs
  - interesting from a practical viewpoint
  - may require a new theoretical framework

Future work

- MSM implementation with the BlueFringe search order (easy)
- MSM as an extension to QSM for active learning with queries (somewhat more challenging)
- Other applicative contexts where mandatory merge constraints are natural
- Further analyze ASM*
  - theoretically: characteristic samples?
  - practically: experimental protocol?