

Automata in Software Verification and Testing

Martin Hruška

supervisors: Tomáš Vojnar, Lukáš Holík

Brno University of Technology, Czech Republic

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Introduction

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 - ▶ Shape analysis (majority of the work).
 - ▶ Automated software testing (described later).

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 - ▶ Automated software testing (described later).
- **Shape analysis** — formal verification of programs with dynamic data structures.
- Goal of shape analysis: **Derive reachable shapes of dynamic data structures**.
 - ▶ Can be used to find bugs such as invalid memory dereferences, invalid frees, memory leaks.
- When an error is found, the method should provide a **counterexample**.
- Have to deal with **infinite state spaces**.

Application

- Proving correctness of critical software systems (e.g., operating system kernel).

Automata Theory in Shape Analysis

- Data structures can be viewed as graphs.
- Graphs can be accepted by automata.
- An automaton can represent a set of graphs.
- **Goal of analysis:** Derive an automaton for each program location representing all possible shapes of data structures at the location,
 - ▶ So called **shape invariant**.
- Applied in **Abstract Regular Tree Model Checking (ARTMC)**.

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- Existing **efficient algorithms** for handling finite automata.
- **Flexibility** to represent various kinds of data structures.

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Counterexample Validation and Abstraction Refinement for Shape Analysis based on Forest Automata

Holík, L., [Hruška, M.](#), Lengál, O., Rogalewicz, A., Vojnar, T.: Counterexample Validation and Interpolation-Based Refinement for Forest Automata. In *Proc. of VMCAI'17*, LNCS 10145, Springer, 2017.

Forest Automata Encoding of Heap

- A **Forest Automaton (FA)*** is a tuple of **tree automata (TA)**.

* P. Habermehl, L. Holik, J. Simacek, A. Rogalewicz, and T. Vojnar. *Forest Automata for Verification of Heap Manipulation*. *FMSD*, 41(1):83–106, Springer, 2012.

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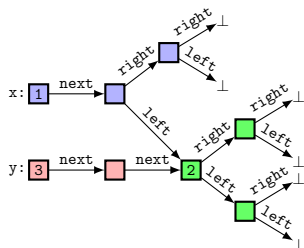
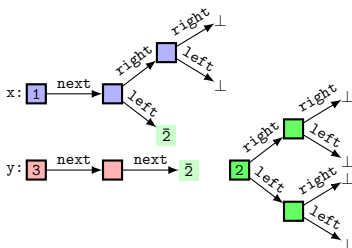
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- An FA $F = (TA_1, \dots, TA_n)$ represents **tree decompositions** (tuples of trees t_1, \dots, t_n) of heap graphs such that $\forall 1 \leq i \leq n : t_i \in L(TA_i)$.

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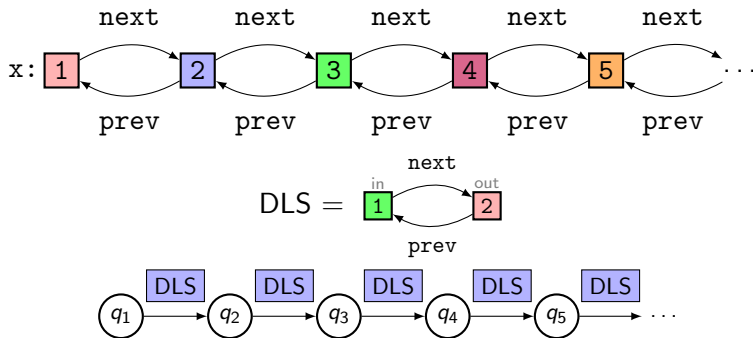
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- Encoded heap graphs obtained by connecting leaves with the referenced roots.



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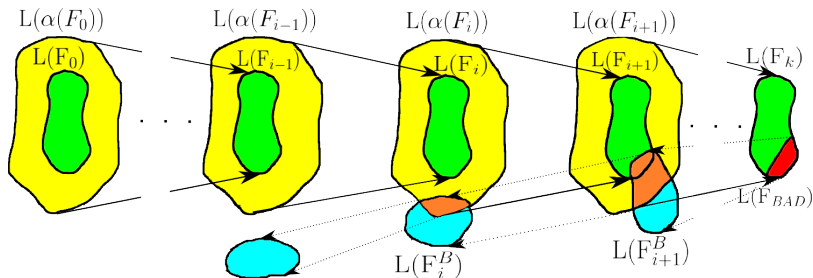
Boxes

- **Boxes** are used to extend the expressive power of FA.
- A box is an FA that can be used as a symbol of another FA.
- A box represents repeating subgraphs of a heap.
- FA having boxes in the alphabet are called **hierarchical**.



An Overview of Verification Method

- Based on **Abstract Regular Tree Model Checking (ARTMC)**[†] and **Counterexample-guided Abstraction Refinement (CEGAR)**[‡].
 - Sets of heap configurations are represented by automata.
 - Employs **abstraction** over automata to overapproximate the set of reachable configurations (allowing termination on ∞ state spaces).



[†] A. Bouajjani, P. Habermehl, A. Rogalewicz, and T. Vojnar. *Abstract Regular (Tree) Model Checking*. *STTT*, 14(2):167–191, Springer, 2012

[‡] E.M. Clarke, O. Grumberg, S. Jha, Y. Lu, H. Veith: *Counterexample-guided abstraction refinement for symbolic model checking*. *J. ACM* 50(5), 752–794 (2003)

Abstraction

- Overapproximates reachable configurations and accelerates analysis
- Collapses states in the same equivalence class of a relation \sim
- Height Abstraction
 - ▶ Equivalence \sim_H is defined as

$$q_1 \sim_H q_2 \stackrel{DEF}{\equiv} L^n(q_1) = L^n(q_2)$$

where $L^n(q)$ is the language of prefixes of trees accepted from $L(q)$ with height up to n

- ▶ Refinement: By increasing the height
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- Predicate Language Abstraction

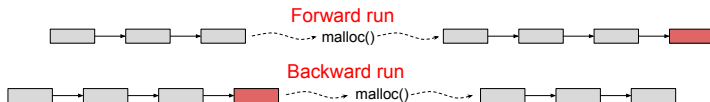
- ▶ Given a set of predicate languages $P = \{p_1, \dots, p_n\}$, equivalence \sim_P is defined as

$$q_1 \sim_P q_2 \stackrel{DEF}{\equiv} \forall p \in P : L(q_1) \cap p \neq \emptyset \Leftrightarrow L(q_2) \cap p \neq \emptyset$$

- ▶ **Refinement**: Interpolating languages from counterexamples
 - ▶ **Informed refinement**

Backward Run and Abstraction for Forest Automata

- Counterexample validation via backward run.
- Ingredients for backward run:
 - ▶ Reversion of abstract transformations.

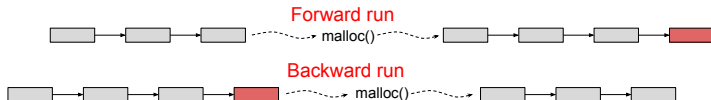


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- ▶ Reversion of abstraction \rightarrow intersection of FA.

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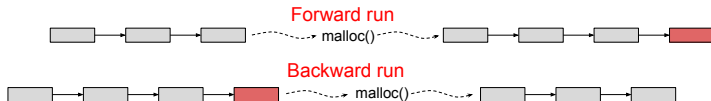
- ▶ Precise reversion of folding and unfolding of boxes \Rightarrow compatible form.

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- Ingredients for predicate language abstraction:

- ▶ Predicate languages represented by TA.
- ▶ New predicate TAs obtained by intersecting FAs from FW and BW run.

Experimental Evaluation

Program	Status	LoC	Time [s]	Refnm	Preds	Program	Status	LoC	Time [s]	Refnm	Preds
SLL (delete)	safe	33	0.02	0	0	DLL (rev)	safe	39	0.70	0	0
SLL (bubblesort)	safe	42	0.02	0	0	CDLL	safe	32	0.02	0	0
SLL (insertsort)	safe	36	0.04	0	0	DLL (insertsort)	safe	42	0.56	0	0
SLLOfCSLL	safe	47	0.02	0	0	DLLOfCDLL	safe	54	1.76	0	0
SLL01	safe	70	1.20	1	1	DLL01	safe	73	0.65	2	2
CircularSLL	safe	49	3.57	3	3	CircularDLL	safe	52	37.22	18	24
OptPtrSLL	safe	59	1.90	3	3	OptPtrDLL	safe	62	1.87	5	5
QueueSLL	safe	71	11.32	10	10	QueueDLL	safe	74	44.68	14	14
GBSLL	safe	64	0.84	3	3	GBDLL	safe	71	1.89	4	4
GBSLLSent	safe	68	0.85	3	3	GBDLLSent	safe	75	2.19	4	4
RGSLL	safe	72	14.41	22	38	RGDLL	safe	76	78.76	26	26
WBSLL	safe	62	0.84	5	5	WBDLL	safe	71	1.37	7	7
SortedSLL	safe	76	227.12	15	15	SortedDLL	safe	82	36.67	11	11
EndSLL	safe	45	0.07	2	2	EndDLL	safe	49	0.10	3	3
TreeRB	error	130	0.08	0	0	TreeWB	error	125	0.05	0	0
TreeCnstr	safe	52	0.31	0	0	TreeCnstr	error	52	0.03	0	0
TreeOfCSLL	safe	109	0.57	0	0	TreeOfCSLL	error	109	0.56	1	3
TreeStack	safe	58	0.20	0	0	TreeStack	error	58	0.01	0	0
TreeDSW	safe	72	1.87	0	0	TreeDSW	error	72	0.02	0	0
TreeRootPtr	safe	62	1.43	0	0	TreeRootPtr	error	62	0.17	2	6
SkipList	safe	84	3.36	0	0	SkipList	error	84	0.08	1	1

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 - ▶ Added support to run Forester using Benchexec.
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- **2017**
 - ▶ Generating correctness witness. In our case, printing forest automaton representing shape invariant for each line.
 - ▶ Counterexample analysis and abstraction analysis for hierarchical forest automata.
- Forester has never won any medal, but was able to verify difficult data structures (skip-lists, or trees) which were not solved by any other tool.

Towards Efficient Shape Analysis with Tree Automata

Holík, L., [Hruška, M.](#) NETYS'21.

Towards Efficient Shape Analysis with Tree Automata

- Forest Automata have their limits:
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- Forest Automata have their limits:
 - ▶ Can't represent data structures such as grid.
 - ▶ Are not closed under union (which complicates their manipulation during verification procedure, e.g., a fixpoint computing).
- We proposed a new automata capable of representing **graphs with bounded tree-width**.
- These automata also need **efficient algorithm for entailment** to be usable in shape analysis.

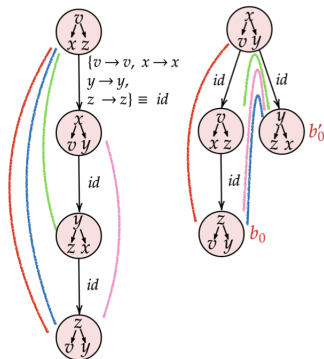
Towards Efficient Shape Analysis with Tree Automata

- A *tree decomposition* of a labeled graph g over a finite set of variables \mathbb{X} and alphabet Σ is a tree $d = (B, E)$. Nodes B of t are Σ -labeled graphs called *bags*. Nodes of a bag are variables from \mathbb{X} . Edges of d are labelled by partial mappings $\rho : \mathbb{X} \rightarrow \mathbb{X}$ called *parameter assignments*.

Graph of circular DLL

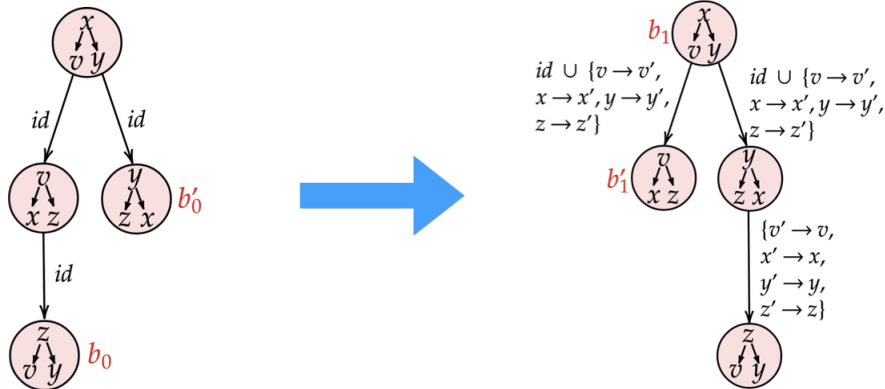


Tree decompositions:



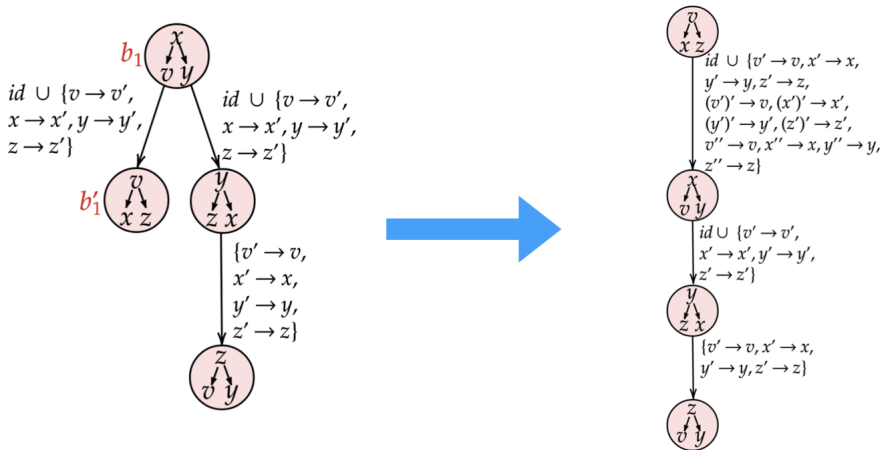
Automata over Graphs with Bounded Tree-width

- Reconnection - moving the bag b_0 under the bag b_1 .



Automata over Graphs with Bounded Tree-width

- Rotation - changing orientation of the edge between b_1 and b'_1



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- The implementation of a **tree automata phase at most doubles the number of variables** and leads to **an automaton that is of a polynomial size assuming a fixed tree-width** of the original automaton.
- Since automata inclusion is EXPTIME-complete, we have entailment which is **singly exponential** (assuming a fixed maximum tree width).

Shape Analysis based on SMT Solving in 2LS Framework

Malík, V., Hruška, M., Schrammel P., Vojnar T. FMCAD'18.

Shape Analysis based on SMT Solving in 2LS Framework

- Shape analysis using **SMT solving** to compute the points-to relation between pointers and memory dynamically allocated (represented by abstract objects).
- Domain designed for **representation of linked-lists** (therefore more straightforward than the automata-based approaches).
- Implemented within 2LS framework for program analysis.
 - ▶ Combination with other domains in this Framework, e.g., the numerical domain.
- Lacks generality of automata based approaches.

Shape Analysis based on SMT Solving in 2LS Framework

- Verification procedure takes:
 - ▶ A first order formula over combination of SMT theories that represents the program in SSA form.
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- We verify that there is no reachable counterexample violating the invariants.
- Technically, i.e., unsatisfiability of this formula:
 - ▶ $\exists \vec{x}, \vec{x}'. \neg(Init(\vec{x}) \implies \mathcal{T}(\vec{x}, \vec{d})) \vee \neg(\mathcal{T}(\vec{x}, \vec{d}) \wedge Trans(\vec{x}, \vec{x}') \implies \mathcal{T}(\vec{x}', \vec{d}))$
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 - ▶ where $\text{Init}(\vec{x})$ is an initial state of variables, \mathcal{T} represents program properties of interest and negation of their invariants, fmtrans formula representing program
- The template for shape analysis is: $\mathcal{T}^S \equiv \bigwedge_{p_i^{lb} \in \text{Ptr}^{lb}} \mathcal{T}_{p_i^{lb}}^S(d_{p_i^{lb}})$,
 - ▶ where $\mathcal{T}_{p_i^{lb}}^S(d_{p_i^{lb}}) \equiv (\bigvee_{a \in d_{p_i^{lb}}} p_i^{lb} = a)$.
 - ▶ Basically, it describes the points-to relation between a pointer (p_i^{lb}) and addresses (abstract value $d_{p_i^{lb}}$) that the pointer may point to.

Shape Analysis based on SMT Solving in 2LS Framework

Table: Comparison of 2LS with other tools on examples combining unbounded data structures and their stored data.

	2LS	CPA-Seq	PredatorHP	Forester	Symbiotic	UAutomizer
Calendar	2.88	timeout	false	unknown	timeout	timeout
Cart	23.70	timeout	false	unknown	timeout	timeout
Hash Function	3.65	8.51	unknown	unknown	unknown	timeout
MinMax	5.14	timeout	false	unknown	timeout	timeout
Packet Filter	431.00	timeout	timeout	unknown	unknown	timeout
Process Queue	6.62	7.68	timeout	unknown	timeout	timeout
Quick Sort	18.20	3.50	timeout	unknown	unknown	5.75
Running Example	1.24	timeout	timeout	unknown	timeout	unknown
SM1	0.53	timeout	0.31	false	timeout	timeout
SM2	0.55	5.41	false	false	timeout	14.50

Automated Software Testing (with Automata)

Fiedor, T., [Hruška, M.](#), [Smrčka, A.](#), Generating Scenarios for Digital Twins of Distributed Manufacturing Execution Systems. EUROCAST'22.

■ Manufacturing Execution System (MES)

- ▶ Software managing production in manufactory.
- ▶ MES tasks are:
 - Communication with Enterprise Resource Planning (ERP) systems such as SAP, e.g., checking quantity of material in stocks.
 - Scheduling production over the machines.
 - Controlling and communicating with machines during production.
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 - Processes inputs by human workers operating machines.
- ▶ Testing of MES is difficult because:
 - **Distributed nature of manufacturing**—different components (ERP, MES, Machines) run it own software and communicate asynchronously.
 - **Different communication protocols** between different components.
 - **Different formats structured data** in messages.
 - Nondeterministic factors—human workers and their interactions with machines, physical aspects of machines.

■ Digital twin

- ▶ Generally, digital copy of a cyber-physical system — simulation of reality on computer, often with graphical interface.
- ▶ Not everything needs to be simulated, some software may be used in digital twin natively.

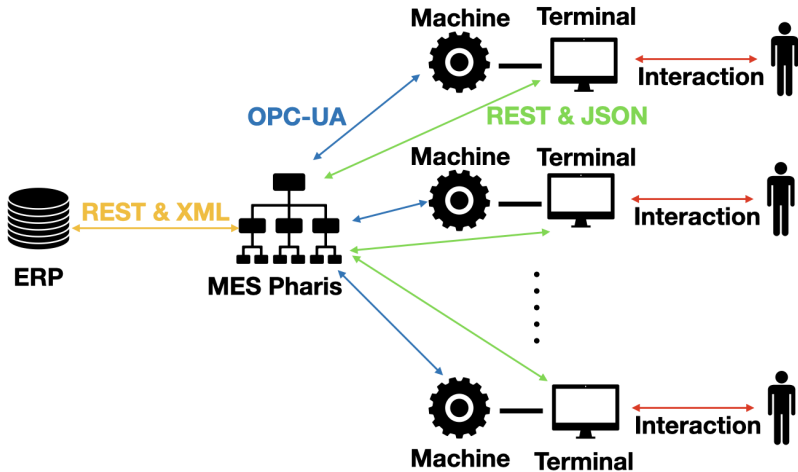
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- ▶ In our case, digital copy of a manufactory simulated in command line.
- ▶ Particularly, machines, ERP, or human workers are simulated, MES is executed natively.
- ▶ Can be orchestrated (deployed and controlled) by an input scenario (step by step).

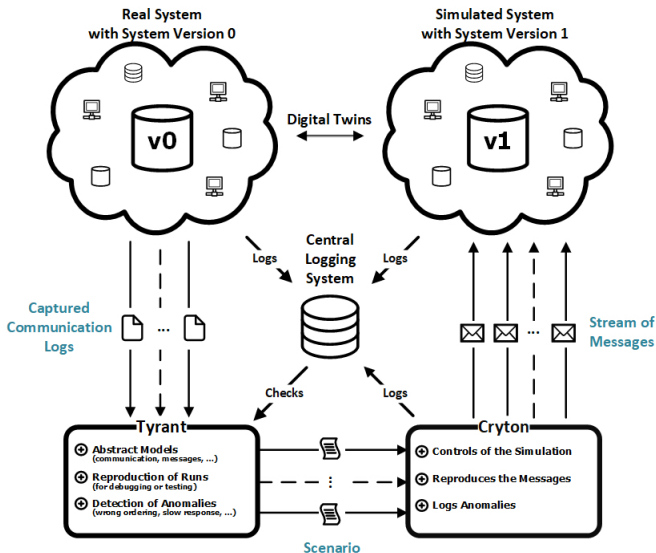
Context of project

- In collaboration with **Masaryk University** and **UNIS, a.s.** company
- The goal of project was to develop digital twin of systems controlled by MES **Pharis** developed by UNIS company
- The presented talk is about learning models of communication and generating scenarios for orchestrating digital twin
- Digital twin was implemented by Masaryk University

Real system



Our solution



Our solution

- Representing messages with structured data
 - ▶ Different formats of messages — JSON and XML
 - ▶ Generic representation and unified manipulation using Trie structure (prefix tree)
 - ▶ We classify messages based on structural similarity to different classes and create an abstract representation of each class.
 - ▶ Can automatically generate new messages from abstract representation.

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- Representing model of communication:
 - ▶ Representing communication in system using **event calendar**.
 - ▶ There is created an event in calendar for each message (containing sender, receiver, type of message, etc.).
 - ▶ Later serialized to a YAML scenario used for orchestrating digital twin.

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- Implemented in the **Tyrant** tool.

Automata abstraction to generate new tests cases

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- Runs of modeled system (which are basically series of events) are strings in language of automaton
- **Length abstraction of automaton** — merges states of automaton with the same prefix language w.r.t. a given length
- Abstraction overapproximates language of automaton \rightarrow language of abstracted automaton may contain strings which are not in the original one
- Such new strings could be converted back to **series of events** \rightarrow **new scenario** \rightarrow **new test case**

- We test and run our tools in UNIS company.
- We **automatically** generated a valid scenario for Cryton (so far, the scenarios were created **manually** by a human tester only).
- We made experiments with automatic new scenarios generation:
 - ▶ Abstraction only in certain types of communication (Primarily, between MES and machines).
 - ▶ Communication between terminals and MES is not suitable for abstraction (need to preserve sequences of messages).

- We test and run our tools in UNIS company.
- We **automatically** generated a valid scenario for Cryton (so far, the scenarios were created **manually** by a human tester only).
- We made experiments with automatic new scenarios generation:
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 - ▶ Communication between terminals and MES is not suitable for abstraction (need to preserve sequences of messages).
- **Future Work**
 - ▶ Deploy our tools in industry settings of UNIS company.
 - ▶ Tune automata abstraction and new messages generation for Pharis.

Conclusion

- Work presented in the thesis:
 - ▶ Counterexample analysis and abstraction refinement for Forest automata.
 - ▶ Competing in SV-COMP, edition 2015-2018.
 - ▶ Automata over graphs with bounded tree-width.
 - ▶ Shape analysis based on SMT solving.
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- Work not presented (or only mildly mentioned) in the thesis:
 - ▶ Connection of Predator and Symbiotic participating in SV-COMP'20.
 - ▶ The design and implementation of efficient automata library (MATA'24).

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The Definition of Graph Tree Width

- A tree decomposition of a graph $G = (V_G, E_G)$ is a tree $T = (V_T, E_T)$, such that:
 - ▶ $V_T \subseteq 2^{V_G}$
 - ▶ $\forall v_G \in V_G \exists v_T \in V_T : v_G \in v_T$
 - ▶ $\forall (u, v) \in E_G \exists v_T \in V_T : u, v \in v_T$
 - ▶ $\forall v_G \in V_G : \text{The set } \{v_t \in V_T \mid v_G \in v_t\} \text{ induces connected subtree}$
- A width of the given decomposition is the maximal cardinality of the nodes of the decomposition minus one.
- A tree width of the given graph is a minimal width of all possible tree decompositions of the given graph.