Recent Advances in Causality Checking

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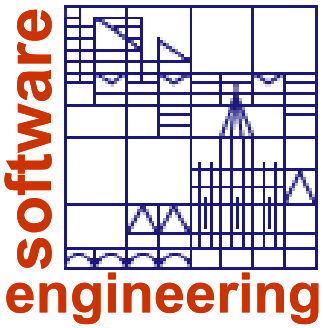

Joint work with

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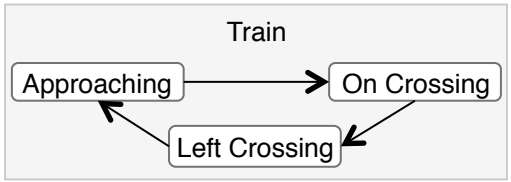
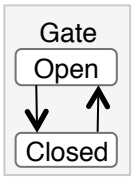
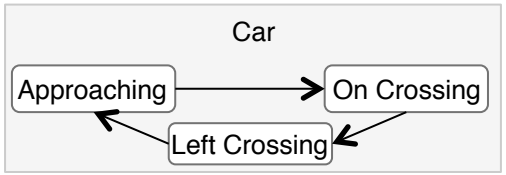
Analysis of Complex Systems

- **A Railroad Crossing**

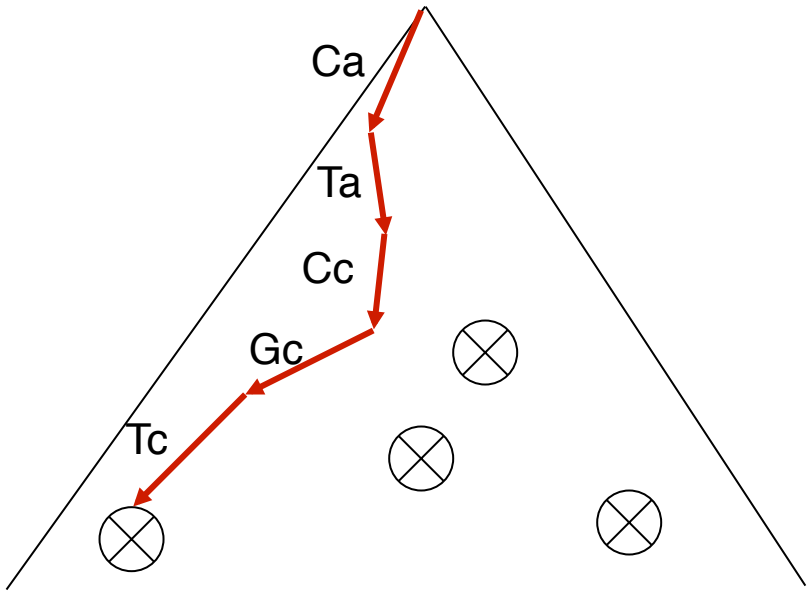
Model Checking

$M \models S$

model of the software (transition system, Kripke structure)	model checking algorithm	requirement specification (assertions, temporal logic, automata)
	state space search (depth-first or breadth-first search)	*there is never a train in the crossing at the same time when there is a car in the crossing* $\varphi = \Box\neg(Tc \wedge Cc)$
		
		

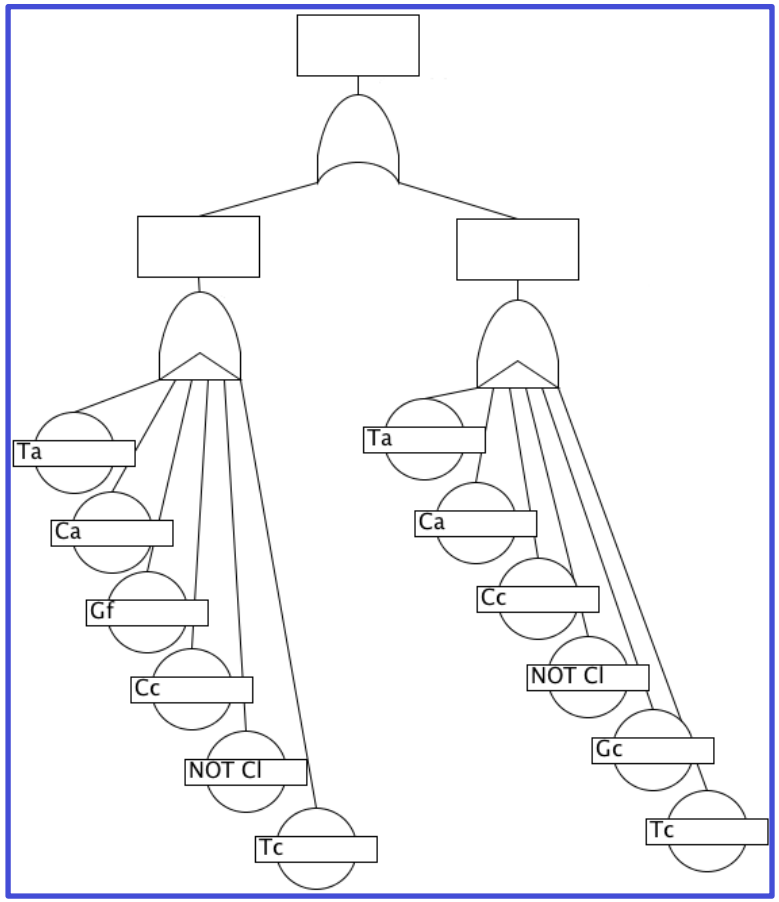
Model Checking

- **Model Checking Result**
  - the path into a property violating state
    - called an error path or counterexample



Interpreting Counterexamples

- **Railroad Crossing Example:**
  - 11 error-paths (only considering shortest paths)



- all lead into a property violating state (accident)
- for debugging
  - **what is the cause?**
- manual analysis
  - tedious
  - error prone
  - essentially impossible
- our goal:
  - **algorithmic causality computation**

- **Models of Causality**
- **Causality Computation**
- **Probability Computation for Causal Events**
- **Evaluation**
- **Conclusion**

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Causality

- **(Naive) Lewis Counterfactual Reasoning**

  c is causal for e (effect / hazard) if, had c not happened, then e would not have happened either

  - logical foundation of some software debugging techniques, e.g.,
    - delta debugging
    - nearest neighbor techniques
  - best suited for single cause failures

Halpern / Pearl Structural Equation Model (SEM)

- **Key Ideas**
  - events are represented by boolean variables
    - specified using structural equations
  - computes minimal boolean disjunction and conjunction of causal events
  - causal dependency of events represented by causal networks
  - reference

J. Halpern and J. Pearl, "Causes and explanations: A structural-model approach. Part I: Causes," *The British Journal for the Philosophy of Science*, 2005.

Halpern / Pearl Structural Equation Model (SEM)

- **Actual Causality Conditions**
  - AC1: ensures that there exists a world where the boolean combination of causal events **c** and the effect **e** occur
  - AC2:
    1. if at least one of the causal events does not happen, the effect **e** does not happen
    2. if the causal events occur, the occurrence of other events can not prevent the effect
  - AC3: no subset of the causal events satisfies AC1 and AC2 (minimality)

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Causality Computation

- **Main Goal:**
  Computation of Causal Events for a Property Violation
  - Consider event order as causal factor
  - Make Structural Equation Model applicable to transition systems

Florian Leitner-Fischer and Stefan Leue:
Probabilistic Fault Tree Synthesis using Causality Computation,
accepted for publication in International Journal of Critical Computer-Based Systems, 2013.

Event Order Logic

- **Boolean Event Occurrence Conditions**
  - $a \wedge b$, $a \vee b$, $\neg a$
- **Event Ordering Conditions**
  - $a \wedge\!\!\cdot\, b$
    - a and b occur, and a occurs before b
- **Interval Operators**
  - $a \wedge\!\!\cdot\, [\, b$
    - a occurs until eventually b will hold in every state
  - $a \wedge\!\!\cdot\,]\, b$
    - a always holds until eventually b occurs
  - $a \wedge\!\!\cdot_{<} b \wedge\!\!\cdot_{>} c$
    - in the interval delimited by a and c, b always holds
- **Model-theoretic Semantics**
  - Event Order Logic is an LTL

Event Order Logic

- **Representation of Traces**

$$\sigma = \text{“Ta, Ca, Gf, Cc, Tc”}$$

$$\psi = \mathrm{Ta} \barwedge \mathrm{Ca} \barwedge \mathrm{Gf} \barwedge \mathrm{Cc} \barwedge \mathrm{Tc}$$

- **Representation of Ordering Constraints**

$$(\mathrm{Ta} \wedge \mathrm{Ca}) \barwedge \mathrm{Gf}$$

$$\mathrm{Cc} \barwedge_{<} \neg\mathrm{Cl} \barwedge_{>} \mathrm{Tc}$$

Causality Computation

- **Probabilistic Causality Computation**
  - Probabilistic counterexample and good paths are computed
  - Causality computation performed as post-processing step
  - Benefit
    - Probability for combination of events causing a hazard
  - Disadvantage
    - Probability computation for each bad trace necessary

- **Causality Checking**
  - Integrated into the state space search algorithms used for model checking
  - Benefit
    - Enables on-the-fly causality computation
  - Disadvantage
    - No probabilities available

Algorithmics

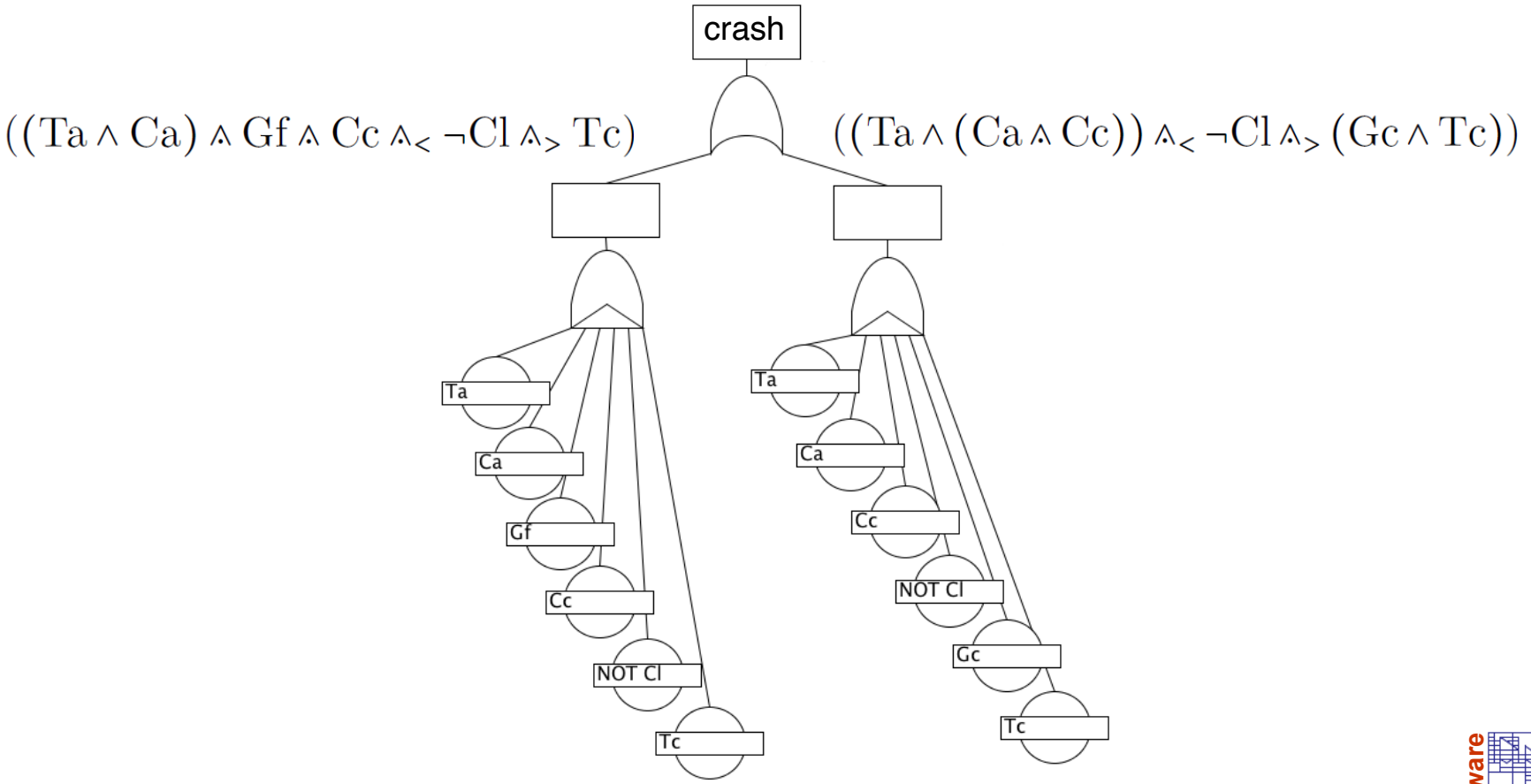
- **Sub-Executions**
  - reduce checks for AC1-AC3 and OC1 to sub-execution tests
    - ordered and unordered sub-execution operators
  - proofs in the paper

- **Implementation Variants**
  - Off-line Enumeration
    - enumerate traces
    - store counterexamples and good traces
    - perform sub-trace computations
  - On-the-fly
    - use DFS / BFS on the state space
      - store paths in an adequate data structure as you obtain them
        - subset graph

Florian Leitner-Fischer and Stefan Leue:
Causality Checking for Complex System Models,
In Proceedings of 14th International Conference on Verification, Model Checking, and Abstract Interpretation (VMCAI2013), LNCS, Volume 7737, Springer Verlag, 2013.

Result of Causality Checking

- **Railroad Crossing**
  - represented as Dynamic Fault Tree



- Models of Causality
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- **Probability Computation for Causal Events**
- Evaluation
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Causality Classes

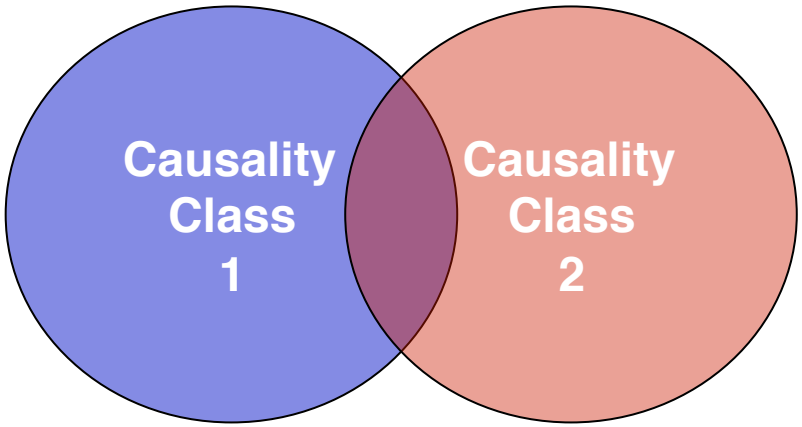
- **Disjuncts of the EOL formula represent „causality classes“**
  - Causality Classes: Represent a class of execution paths where the same events in the same order cause an effect or hazard

$$((\mathrm{Ta} \wedge \mathrm{Ca}) \mathbin{\mathbb{A}} \mathrm{Gf} \mathbin{\mathbb{A}} \mathrm{Cc} \mathbin{\mathbb{A}}_{<} \neg\mathrm{Cl} \mathbin{\mathbb{A}}_{>} \mathrm{Tc})$$

Ta, Ca, Gf, Cc, Tc
Ca, Ta, Gf, Cc, Tc
…

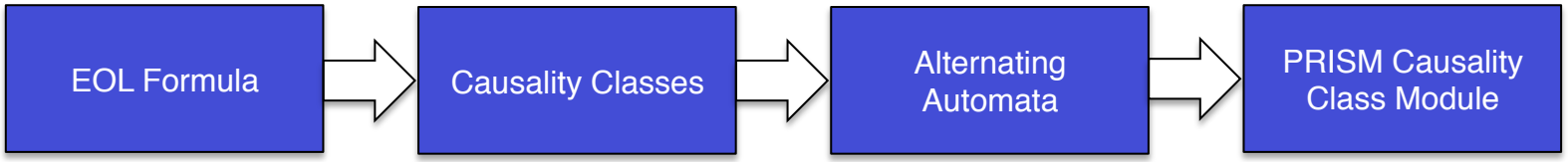
$$((\mathrm{Ta} \wedge (\mathrm{Ca} \mathbin{\mathbb{A}} \mathrm{Cc})) \mathbin{\mathbb{A}}_{<} \neg\mathrm{Cl} \mathbin{\mathbb{A}}_{>} (\mathrm{Gc} \wedge \mathrm{Tc}))$$

Ta, Ca, Gc, Gc, Tc
Ca, Ta, Cc, Gc, Tc
…



Probability Computation for Causality Classes

- **Key Idea:**
  1. Compute causal events using causality checking
  2. Compute probabilities of the paths represented by a causality class



- Causality classes are represented by alternating automata
- Alternating automata are translated to PRISM Causality Class Modules
- PRISM Causality Class Modules are synchronized with the PRISM model

Florian Leitner-Fischer and Stefan Leue:
On the Synergy of Probabilistic Causality Computation and Causality Checking,
In Proceedings of International SPIN Symposium on Model Checking of Software, Stony Brook, NY, USA, 2013 (to appear).

- Models of Causality
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- Probability Computation for Causal Events
- **Evaluation**
- Conclusion

Experimental Evaluation

	Combined Approach		Probabilistic Causality Comp.	
	Run time (sec.)	Memory (MB)	Run time (sec.)	Memory (MB)
Embedded: States: 6,013 Transitions: 25,340				
T=10	3.06	19.27	2,003.00	409
T=3600	4.79	19.29	2,102.00	409
Airbag: States: 2,952 Transitions: 14,049				
T=10	10.88	52.44	682.00	154
T=1000	33.63	52.44	874.00	154
Train Odometer Controller: States: 117,222 Transitions: 66,262				
T=10	91.37	195.29	16,191.00	1,886
T=1000	2,572.74	195.29	44,356.00	1,886

- **Combined Approach:**
  - Causality Checking + Probability Computation for Causality Classes
- **Combined Apporach outperforms Probabilistic Causality Computation**

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Conclusion

- **Causality Checking**
  - technique complementing model checking
    - aim: algorithmic support for the debugging of models
  - defined / adopted causality model
  - proposed implementation
  - probability computation for causality classes
  - applicable to non-trivial case studies

- **Future Work**
  - causality checking at the limits of scalability
    - dealing with incomplete information
  - causality checking in a symbolic environment
  - specific adaptions to functional safety analysis
    - minimal cut sets
    - root, common and cascading causes