Counterexample-Guided Synthesis of Safety Contracts

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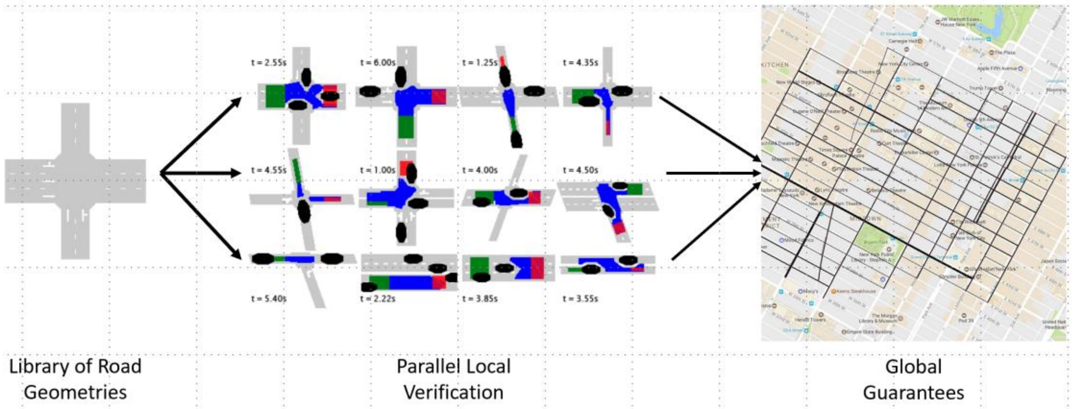
Overview

- Scalable verification and safety guarantees
- Scalability with respect to
  - Space: size of road network
  - Fleet: number of vehicles
  - Specification: rules of the roads
  - **Traffic: driving scenarios (NEW!)**
- Vision:
  “Provide long-term safety guarantees for autonomous vehicle deployment”

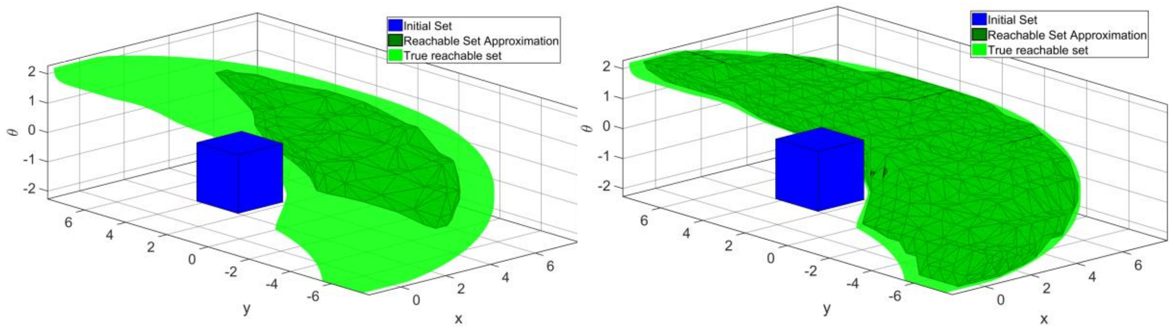
Prior Work

- Scalable verification through assume-guarantee contracts



[1] Liebenwein, Lucas et al. "Compositional and Contract-based Verification for Autonomous Driving on Road Networks." International Symposium on Robotics Research (ISRR), 2017, Puerto Varas, Chile

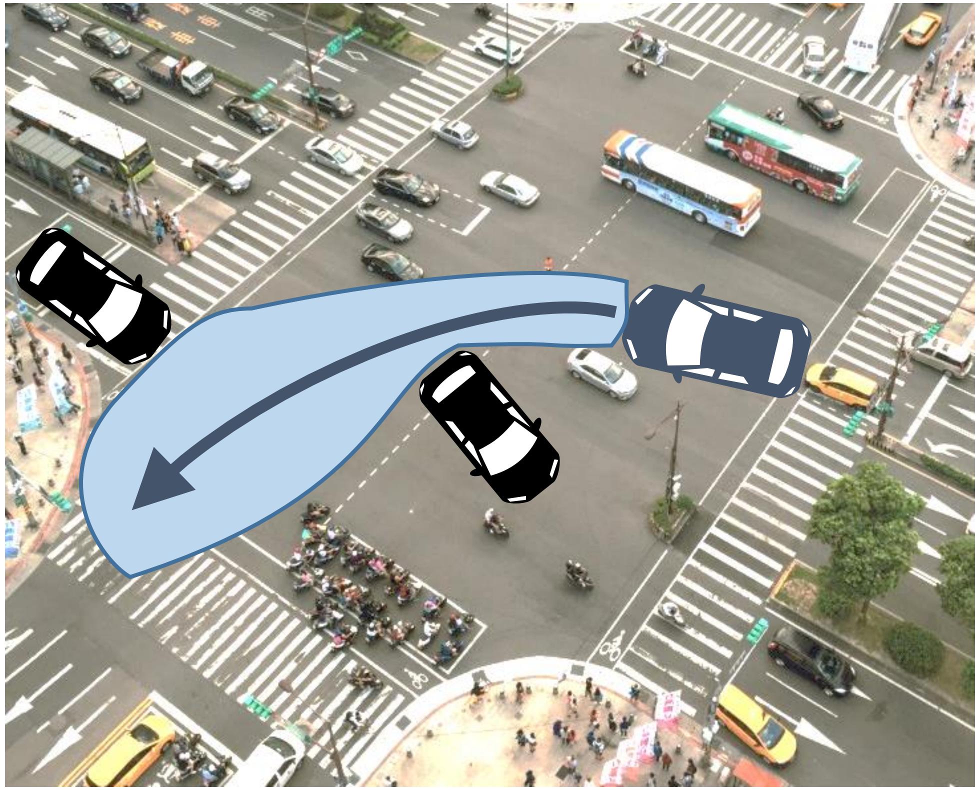
- Sampling-based reachability analysis



[2] Liebenwein*, Lucas, Cenk Baykal*, et al. "Sampling-Based Approximation Algorithms for Reachability Analysis with Provable Guarantees." Proceedings of Robotics: Science and Systems, 2018, Pittsburgh, Pennsylvania

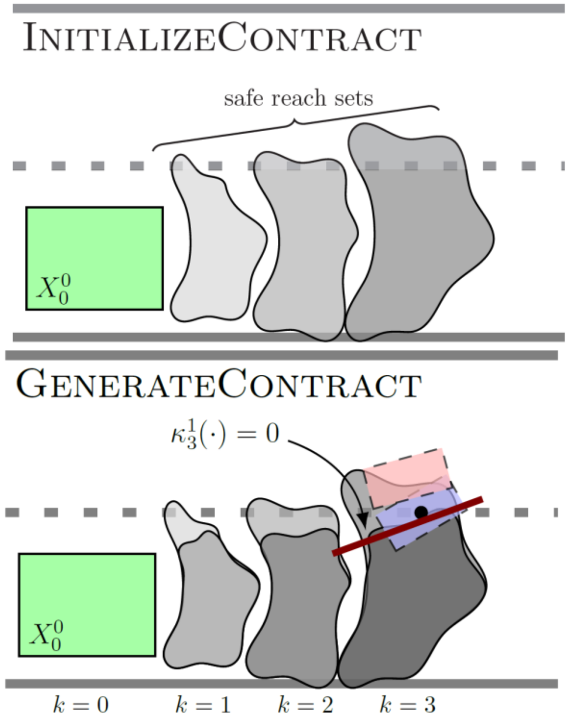
Safety Contracts

- Use easy-to-implement, explainable contracts
- Contract = set of state space constraints
- Contracts help to guard against other traffic participants

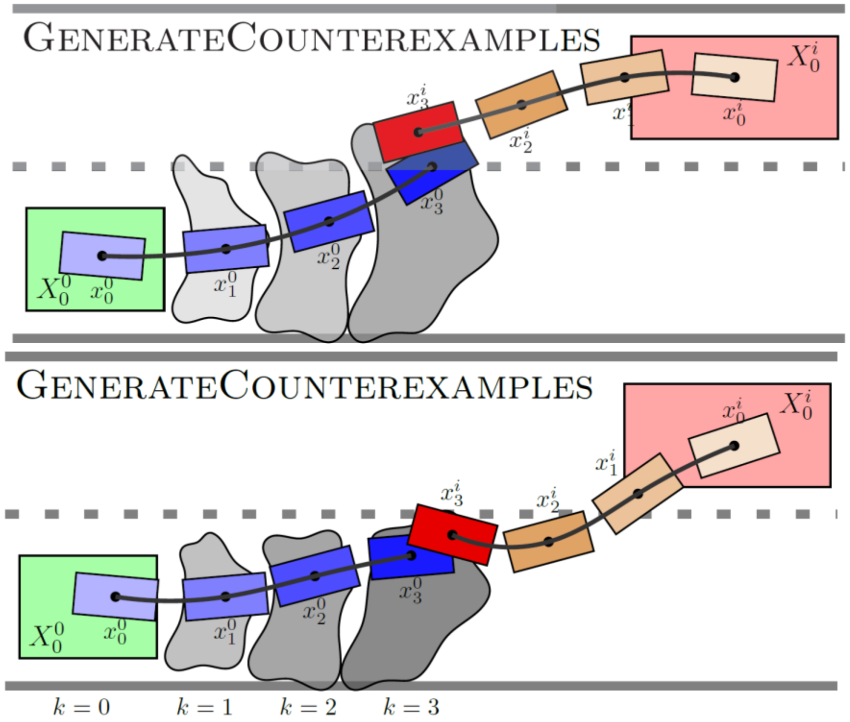


Overview

Candidate contracts with reachability analysis

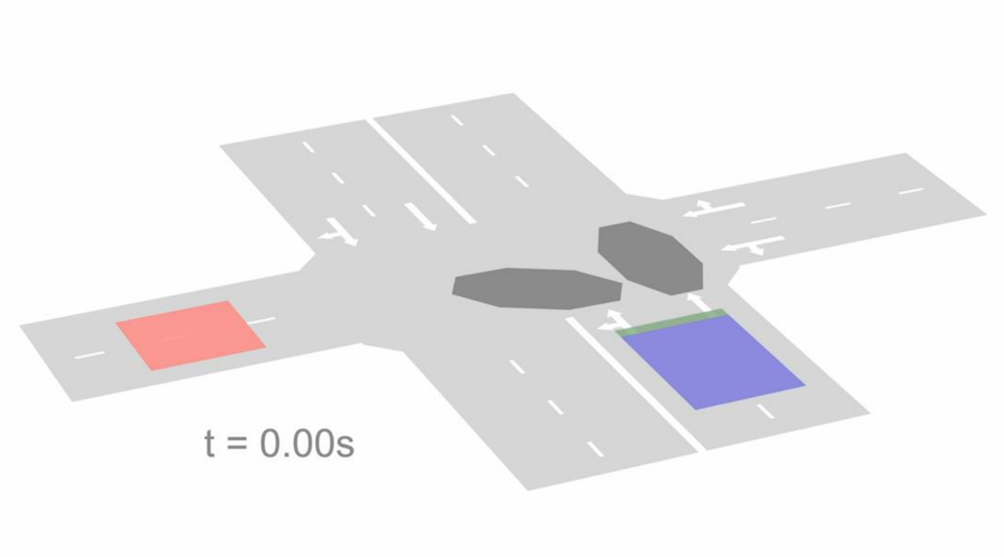


Refinement through falsification-based counterexamples



Generate Candidate Contracts

- Same principle as in ISRR’17
- Reachability analysis with
  - road segment
  - fixed traffic scenario
  - safety constraints
- Can leverage modular approach to verification



= Ego Car = Other Car = Entry Region = Exit Region

Generate Counterexamples

- Refinement of contract through falsification
- We try to find traffic trajectories such that
  - The behavior is “expectable”
  - The candidate contract cannot guard the ego-car
- Direct collocation **stochastic** quadratic program (SQP)

$$
\begin{aligned}
\max_{h,\bar{u},\bar{w},\bar{x}} \; & p(\bar{w}) \\
\text{s.t. } & x_{k+1} - x_k = h f_{collocation}, \quad \forall k = 0, \ldots, T-1 && \text{(dynamics)} \\
& x_k \in \mathcal{X}, \quad \forall k = 0, \ldots, T \\
& u_k \in \mathcal{U}, \quad \forall k = 0, \ldots, T-1 \\
& x_0 \in \mathcal{X}_0, \quad u_0 \in \mathcal{U} && \text{(initial conditions)} \\
& \psi(x_T) \leq 0 && \text{(safety specification)} \\
& \kappa_k^j(x_k) \leq 0, \quad \forall j = 1, \ldots, Q, \; \forall k = 0, \ldots, T && \text{(contracts)} \\
& p(\bar{w}) \geq \alpha T && \text{(chance constraint)}
\end{aligned}
$$

Rules of the Road and Behavior

- The safety contract of the ego-car consider rules of the roads

Table 1: Rules of the road for highway scenarios.

No.	Rule	Constraint set
1	Don't drive in the left lanes.	$\{0 \leq x_c^0 \leq L, -n_{right} \cdot W \leq y_c^0 \leq 0\}$
2	If driving behind another car, keep a reasonable distance away to avoid collision if it suddenly stops.	$\{x_c^i - x_c^0 \geq \epsilon_x^{safe}\, v^0 \mid \forall i\ .\ x_c^i - x_c^0 \geq 0 \wedge \lvert y_c^i - y_c^0 \rvert < W\}$
3	If you want to slow down, give clear warning and do not inconvenience drivers behind you.	$\{x_c^0 - x_c^i \geq \epsilon_x^{safe}\, v^0 \mid \forall i\ .\ x_c^0 - x_c^i \geq 0 \wedge \lvert y_c^i - y_c^0 \rvert < W\}$
4	Don't cross solid lines.	$\{\xi_x^\ell \leq x_c^0 \leq \zeta_x^\ell \wedge - n_{right} \cdot W \leq y_c^0 \leq 0 \mid 1 \leq \ell \leq n_{solid}\}$
5	Overtake on the left when it is safe.	$\{y_c^0 - y_c^i > W \wedge v^0 > v^i \mid$ $\forall i\ .\ v^i > 0 \wedge \lvert x_c^0 - x_c^i \rvert \leq \epsilon_x^{overtake} \wedge$ $\nexists j\ .(\ \lvert x_c^j - x_c^i \rvert \leq \epsilon_x^{safe-overtake} \wedge y_c^0 - y_c^j \leq W)\}$
6	If another vehicle is trying to overtake you keep right and don't accelerate. If necessary, slow down and pull over.	$\{u_a^0 \leq 0 \wedge y_c^i - y_c^0 \geq W \wedge y_c^0 \leq 0 \mid$ $\forall i\ .\ y_c^i - y_c^0 \leq 1.5W \wedge v^i > 0 \wedge \lvert x_c^i - x_c^0 \rvert \leq \epsilon_x^{overtake}\}$
7	If passing oncoming traffic, leave sufficient lateral space to not get hit. If obstructed, slow down.	$\{y_c^i - y_c^0 \geq \epsilon_y^{safe} \mid y_c^i \geq 0 \wedge v^i \leq 0\}$
8	Don't drive abnormally slowly such that you impede the progress of other vehicles. Don't drive above the speed limit or abnormally fast.	$\{\lvert v^0 - \bar{v} \rvert \leq \epsilon_v, \lvert v^0 \rvert \leq \epsilon_v^{legal}\}$

- The traffic agents are modelled as **probabilistic** IDM agents

Table 2: Parameters used to model driver behaviors for the traffic cars.

	Description	Symbol	Driving Style Normal	Driving Style Aggressive
IDM	Reference speed (m/s)	v_{ref}	10	1.5
	Maximum acceleration (m/s^2)	a	1	4
	Comfortable deceleration (m/s^2)	b	3	6
	Minimum-desired net distance (m)	s_0	1	0.5
	Time headway to lead vehicle (s)	t_h	0.1	0.05
	Free-road exponent	δ	4	4
Pure-Pursuit	Lookahead distance (m)	s_{look}	15	10
Perception	Range (m)	$s_{perception}$	100	100
Disturbances	Steering angle variance (rad^2)	σ_δ	0.1	5
	Acceleration variance (m^2/s^4)	σ_a	0.1	2.5

Tuning of Behavior

Strict Rule Set

Relaxed Rule Set

Normal Driving Style

Aggressive Driving Style

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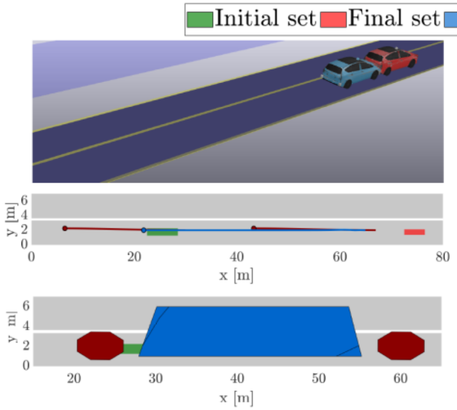
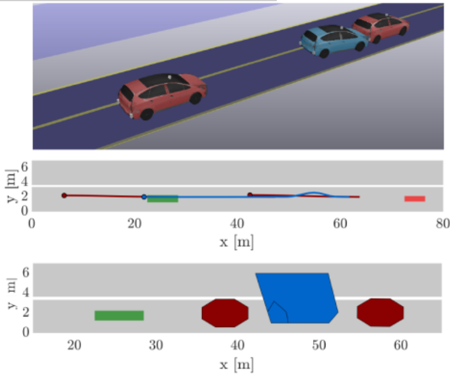
Results

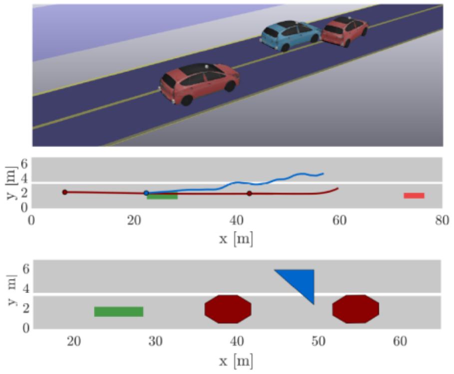
- Multiple iterations, same rules



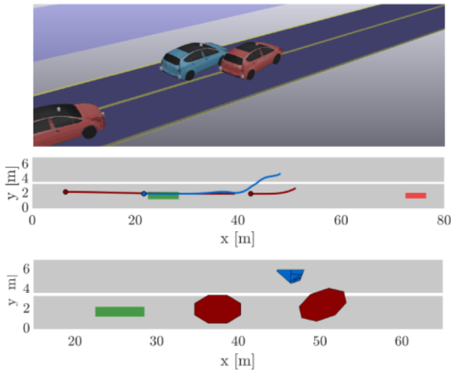
(a) Iteration 2



(b) Iteration 3

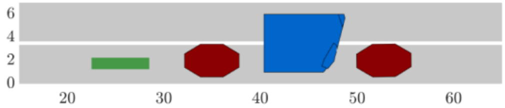


(c) Iteration 7

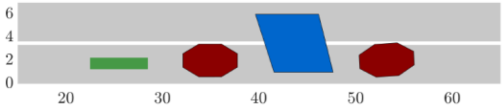


(d) Iteration 14

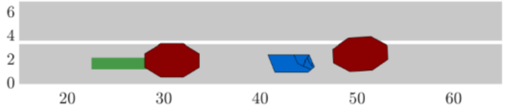
- Same iterations, different rules



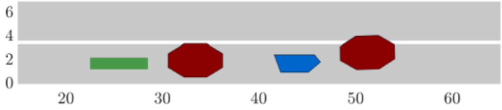
(a) Relaxed rules, normal driving



(b) Relaxed rules, aggressive driving



(c) Strict rules, normal driving



(d) Strict rules, aggressive driving

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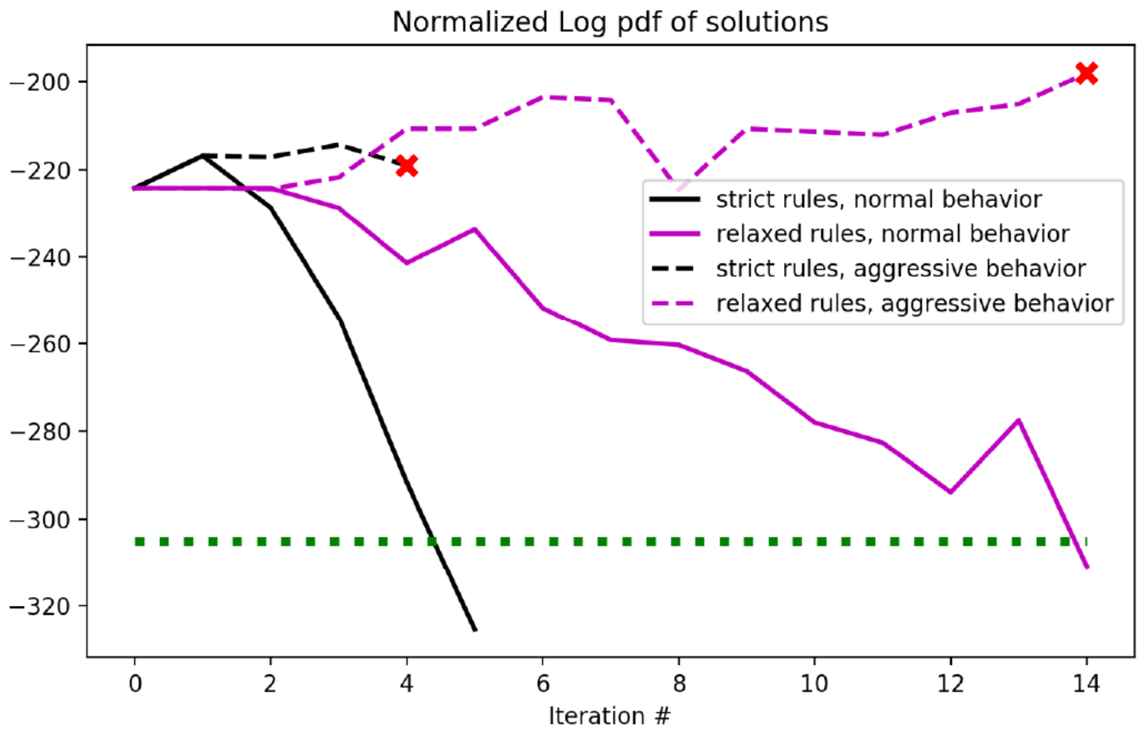
Explainability

- Probabilistic Modelling of Agents
- Falsification is used to capture a wide array of likely counterexamples
- Probabilities help to assess the usefulness of contracts
- Rules allow to tune behaviors



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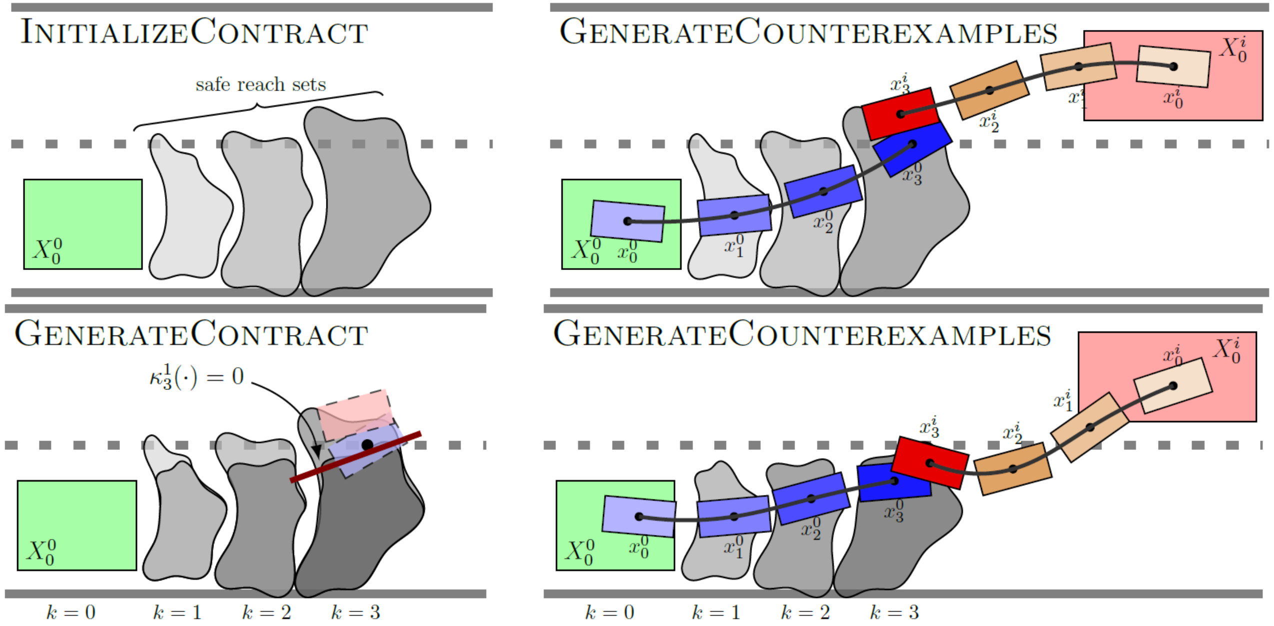
Conclusion

- Probabilistic safety contracts through **verification** and **falsification**
- Scalability and explainability
- **Outlook:**
  - More scenarios
  - Advanced rules of the roads
  - Intuitive contracts → use logical predicates?



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