25: Distributed Systems & Hybrid Systems

15-424: Foundations of Cyber-Physical Systems

André Platzer

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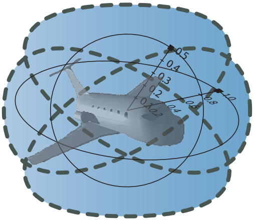


Outline

Complex Physical Systems:

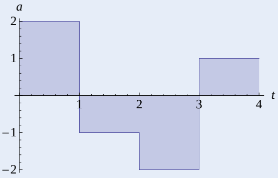
Q: I want to verify my car

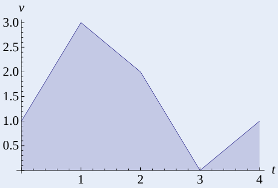
Challenge

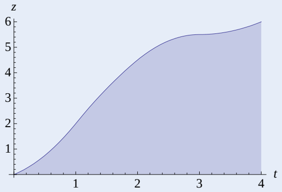
Q: I want to verify my car A: Hybrid systems

Challenge (Hybrid Systems)

- Continuous dynamics (differential equations)
- Discrete dynamics (control decisions)



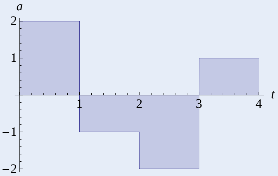


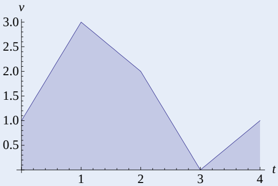


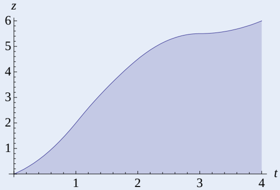
Q: I want to verify my car A: Hybrid systems Q: But there's a lot of cars!

Challenge (Hybrid Systems)

- Continuous dynamics (differential equations)
- Discrete dynamics (control decisions)



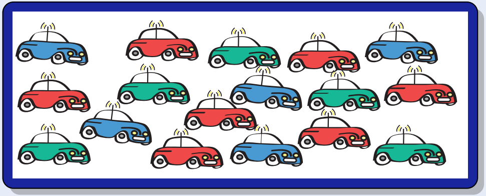




Complex Physical Systems:

Q: I want to verify a lot of cars

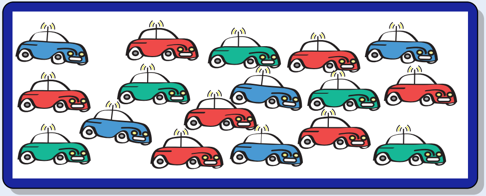
Challenge

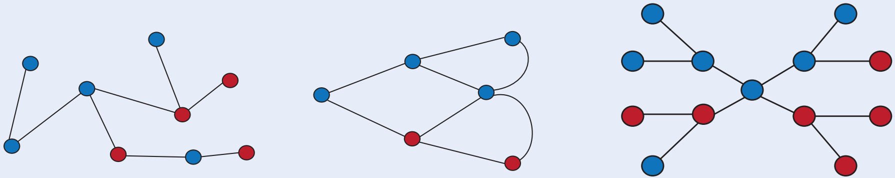


Q: I want to verify a lot of cars A: Distributed systems

Challenge (Distributed Systems)

- Local computation (finite state automaton)
- Remote communication (network graph)

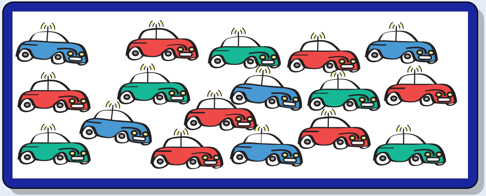


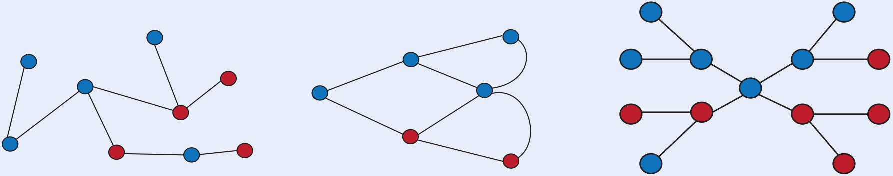


Q: I want to verify a lot of cars A: Distributed systems Q: But they move!

Challenge (Distributed Systems)

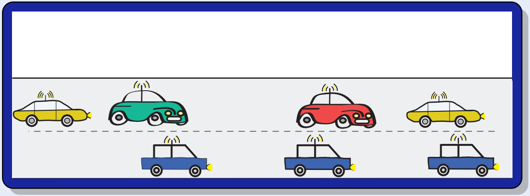
- Local computation
  (finite state automaton)
- Remote communication
  (network graph)





Q: I want to verify lots of moving cars

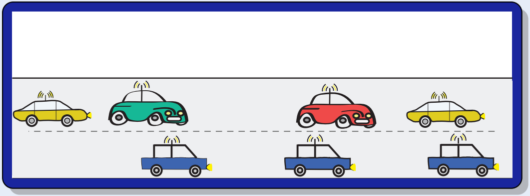
Challenge



Q: I want to verify lots of moving cars A: Distributed hybrid systems

Challenge (Distributed Hybrid Systems)

- Continuous dynamics (differential equations)
- Discrete dynamics (control decisions)
- Structural dynamics (remote communication)

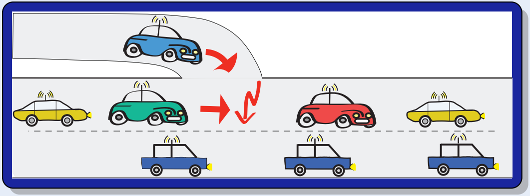


Complex Physical Systems: Distributed Hybrid Systems

Q: I want to verify lots of moving cars A: Distributed hybrid systems

Challenge (Distributed Hybrid Systems)

- Continuous dynamics (differential equations)
- Discrete dynamics (control decisions)
- Structural dynamics (remote communication)
- Dimensional dynamics (appearance)



Complex Physical Systems: Distributed Hybrid Systems

Q: I want to verify lots of moving cars A: Distributed hybrid systems Q: How?

Challenge (Distributed Hybrid Systems)

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- Structural dynamics (remote communication)
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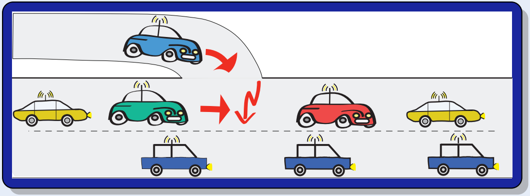

State of the Art: Modeling and Simulation

No formal verification of distributed hybrid systems

Shift [4] The Hybrid System Simulation Programming Language

R-Charon [5] Modeling Language for Reconfigurable Hybrid Systems

Hybrid CSP [6] Semantics in Extended Duration Calculus

Φ-calculus [9] Semantics in rich set theory

HyPA [7] Translate fragment into normal form.

ACP^{srt}_{hs} [10] Modeling language proposal

χ process algebra [8] Simulation, translation of fragments to PHAVER, UPPAAL

OBSHS [11] Partial random simulation of objects

Contributions

1. System model and semantics for distributed hybrid systems: QHP
2. Specification and verification logic: Qd$\mathcal{L}$
3. Proof calculus for Qd$\mathcal{L}$
4. First verification approach for distributed hybrid systems
5. Sound and complete axiomatization relative to differential equations
6. Prove collision freedom in a (simple) distributed car control system, where new cars may appear dynamically on the road
7. Logical foundation for analysis of distributed hybrid systems
8. Fundamental extension: first-order $x(i)$ versus primitive x

CSL'10,LMCS'12

Outline

1. Motivation
2. Quantified Differential Dynamic Logic Qd$\mathcal{L}$
   - Design
   - Syntax
   - Semantics
3. Proof Calculus for Distributed Hybrid Systems
   - Compositional Verification Calculus
   - Deduction Modulo with Free Variables & Skolemization
   - Actual Existence and Creation
   - Soundness and Completeness
   - Quantified Differential Invariants
4. Applications
5. Conclusions

Outline (Conceptual Approach)

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Model for Distributed Hybrid Systems

Q: How to model distributed hybrid systems

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- Continuous dynamics (differential equations)
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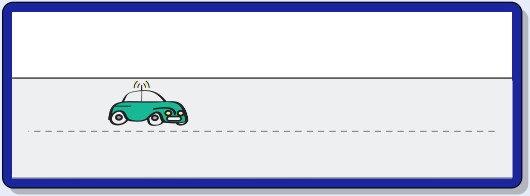

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  $$x'' = a$$
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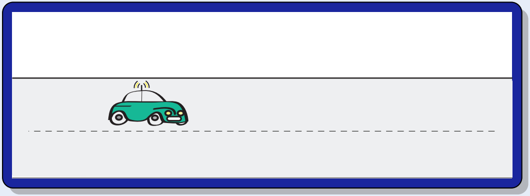

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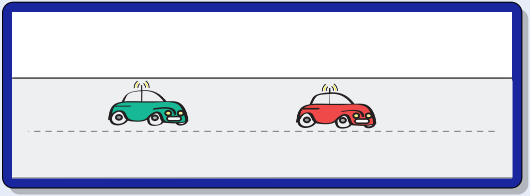
  $a := \texttt{if} .. \texttt{then}\, A\, \texttt{else} -b$

- Structural dynamics (communication/coupling)



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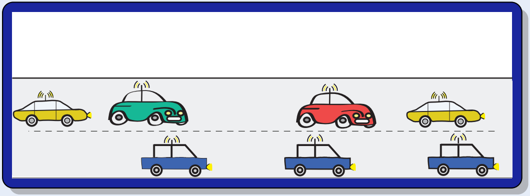

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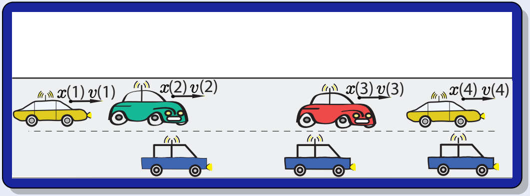

Q: How to model distributed hybrid systems

Model (Distributed Hybrid Systems)

- Continuous dynamics (differential equations)
  $$x(i)' = a(i)$$
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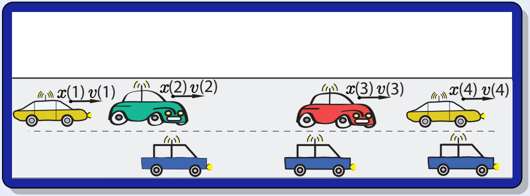

Model for Distributed Hybrid Systems

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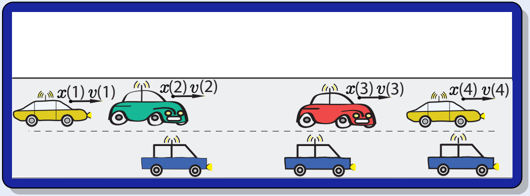

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  $\forall i\; a(i) := \texttt{if}\, ..\, \texttt{then}\, A\, \texttt{else}\, -b$
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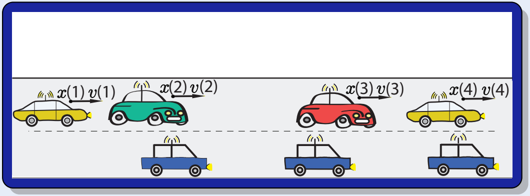
  $\ell(i) := carInFrontOf(i)$



Model for Distributed Hybrid Systems

Q: How to model distributed hybrid systems A: Quantified Hybrid Programs

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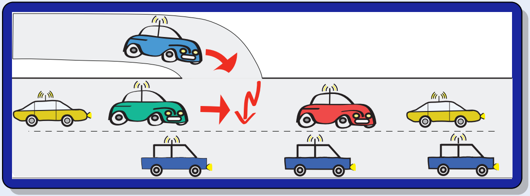
  $$\ell(i) := carInFrontOf(i)$$
- Dimensional dynamics (appearance)



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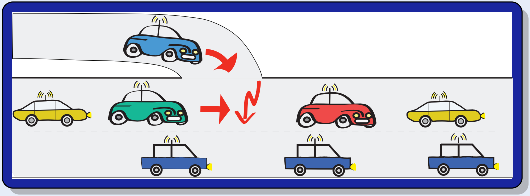
- Dimensional dynamics (appearance)
  $n := \texttt{new}\ Car$



Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Syntax

Definition (Quantified hybrid program α)

$\forall i : C\ x(i)' = \theta$	(quantified ODE)	
$\forall i : C\ x(i) := \theta$	(quantified assignment)	jump & test
$?Q$	(conditional execution)	
$\alpha; \beta$	(seq. composition)	Kleene algebra
$\alpha \cup \beta$	(nondet. choice)	
α^*	(nondet. repetition)	

Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Syntax

Definition (Quantified hybrid program α)

$$
\left.
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\alpha^* & \text{(nondet. repetition)}
\end{array}
\right.
$$

$\forall i : C\ x(s) := \theta$, $?Q$, $\alpha;\beta$: jump & test

$\alpha;\beta$, $\alpha \cup \beta$, α^*: Kleene algebra

Quantified Differential Dynamic Logic Q$d\mathcal{L}$: Syntax

Definition (Quantified hybrid program α)

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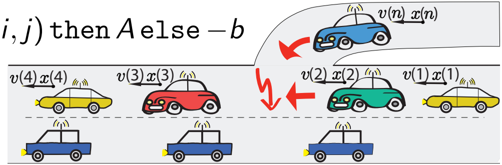
$$\left.\begin{array}{ll} \alpha; \beta & \text{(seq. composition)} \\ \alpha \cup \beta & \text{(nondet. choice)} \\ \alpha^* & \text{(nondet. repetition)} \end{array}\right\} \text{Kleene algebra}$$

$$DCCS \equiv (ctrl; drive)^*$$

$$ctrl \equiv \forall i : C\ a(i) := \texttt{if}\ \forall j : C\ far(i,j)\ \texttt{then}\ A\ \texttt{else}\ -b$$

$$drive \equiv \forall i : C\ x(i)'' = a(i)$$



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\alpha^* & \text{(nondet. repetition)}
\end{array}$$

- jump & test: quantified assignment, conditional execution
- Kleene algebra: seq. composition, nondet. choice, nondet. repetition

$$\begin{aligned}
DCCS &\equiv (appear ; ctrl ; drive)^* \\
appear &\equiv n := \mathtt{new}\ C ;\quad ?(\forall j : C\ far(j, n)) \\
ctrl &\equiv \forall i : C\ a(i) := \mathtt{if}\ \forall j : C\ far(i, j)\ \mathtt{then}\ A\ \mathtt{else}\ {-b} \\
drive &\equiv \forall i : C\ x(i)'' = a(i)
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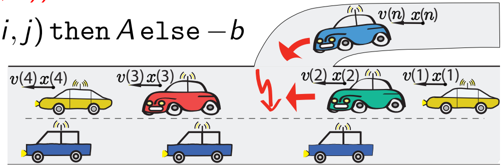

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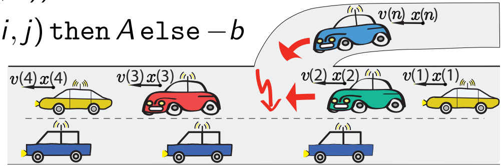
drive &\equiv \forall i : C \; x(i)'' = a(i)
\end{aligned}
$$

$\mathtt{new}\ C$ is definable!



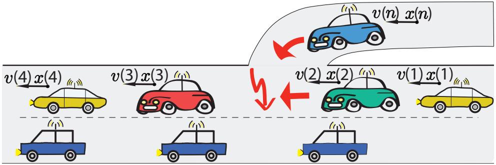
Quantified Differential Dynamic Logic $\mathsf{Qd}\mathcal{L}$: Syntax

Definition ($\mathsf{Qd}\mathcal{L}$ Formula ϕ)

$\neg, \wedge, \vee, \rightarrow, \ \forall x, \exists x, \ =, \geq, \ +, \cdot$ ($\mathbb{R}$-first-order part)

$[\alpha]\phi, \quad \langle\alpha\rangle\phi$ (dynamic part)

$$[(\mathit{appear}\,;\mathit{ctrl}\,;\mathit{drive})^*]\ \forall i{\neq}j : C\ x(i) \neq x(j)$$



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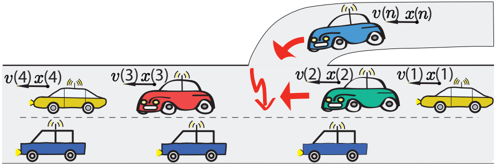
$[\alpha]\phi, \quad \langle\alpha\rangle\phi$ (dynamic part)

$$\forall i, j : C \ \mathit{far}(i, j) \rightarrow [(\mathit{appear}; \mathit{ctrl}; \mathit{drive})^*] \ \forall i{\neq}j : C \ x(i) \neq x(j)$$



Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Syntax

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$\neg, \wedge, \vee, \rightarrow,\ \forall x, \exists x,\ =, \geq,\ +, \cdot$ ($\mathbb{R}$-first-order part)

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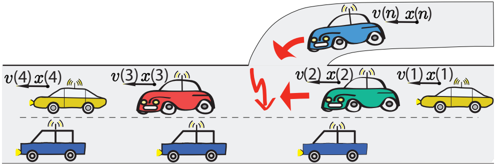
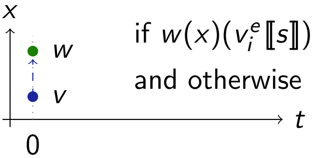
$$\begin{aligned} \mathit{far}(i,j) \ \equiv\ i \neq j \ \rightarrow\ & x(i) < x(j) \wedge v(i) \leq v(j) \wedge a(i) \leq a(j) \\ & \vee x(i) > x(j) \wedge v(i) \geq v(j) \wedge a(i) \geq a(j) \ldots \end{aligned}$$



Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Semantics

Definition (Quantified hybrid program α: transition semantics)

$$v \xrightarrow{\forall i : C \; x(s) := \theta} w$$

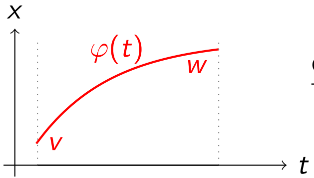


if $w(x)(v_i^e[\![s]\!]) = v_i^e[\![\theta]\!]$ (for all e)

and otherwise unchanged

Definition (Quantified hybrid program α: transition semantics)

$$v \xrightarrow{\forall i : C\ x(s)' = \theta} w$$



$\forall i\, x(s)' = \theta$

$$\frac{\mathrm{d}\, \varphi(t)_i^e [\![x(s)]\!]}{\mathrm{d}t}(\zeta) = \varphi(\zeta)_i^e [\![\theta]\!] \quad \text{(for all } e\text{)}$$

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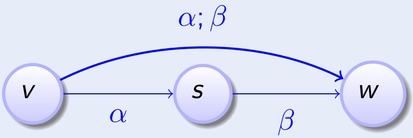

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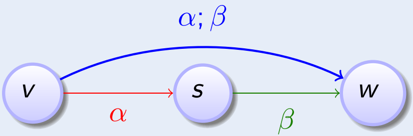

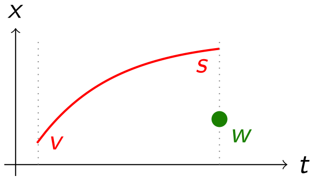

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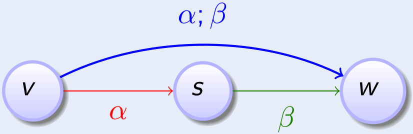
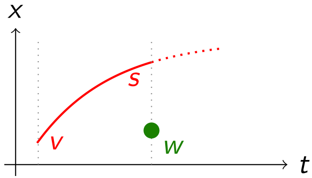
Definition (Quantified hybrid program α: transition semantics)



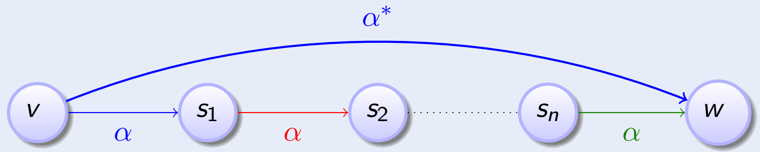


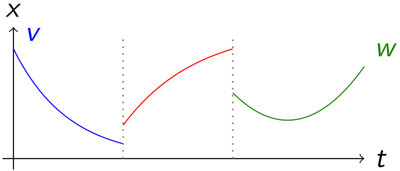
Definition (Quantified hybrid program α: transition semantics)

$$\begin{tikzcd} v \arrow[r, "\alpha"'] \arrow[rrrr, bend left, "\alpha^*"] & s_1 \arrow[r, "\alpha"'] & s_2 \arrow[r, dotted, no head] & s_n \arrow[r, "\alpha"'] & w \end{tikzcd}$$

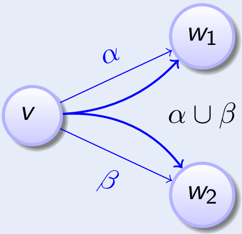
Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Semantics

Definition (Quantified hybrid program α: transition semantics)



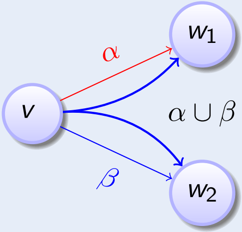


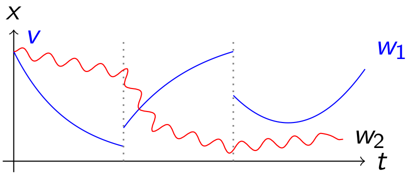
Definition (Quantified hybrid program α: transition semantics)



Quantified Differential Dynamic Logic $\mathsf{Qd}\mathcal{L}$: Semantics

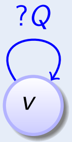
Definition (Quantified hybrid program α: transition semantics)



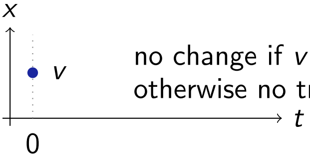


Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Semantics

Definition (Quantified hybrid program α: transition semantics)



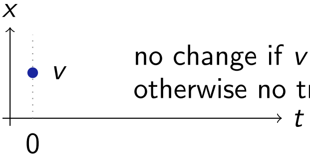
if $v \models Q$



no change if $v \models Q$
otherwise no transition

Definition (Quantified hybrid program α: transition semantics)

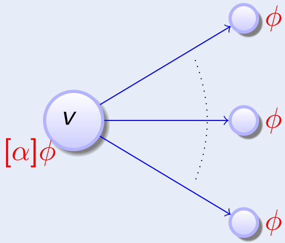
v if $v \not\models Q$



no change if $v \models Q$
otherwise no transition

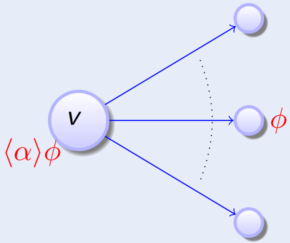
Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Semantics

Definition (Qd$\mathcal{L}$ Formula ϕ)



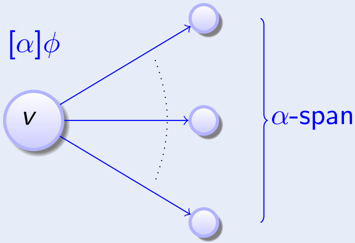
Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Semantics

Definition (Qd$\mathcal{L}$ Formula ϕ)



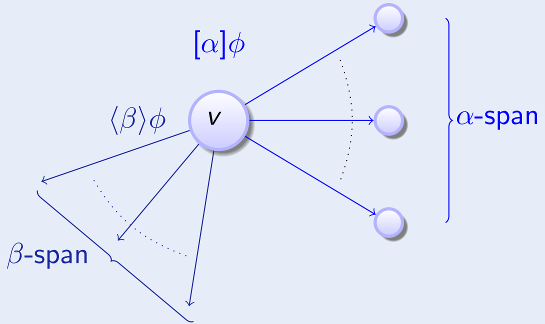
Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Semantics

Definition (Qd$\mathcal{L}$ Formula ϕ)

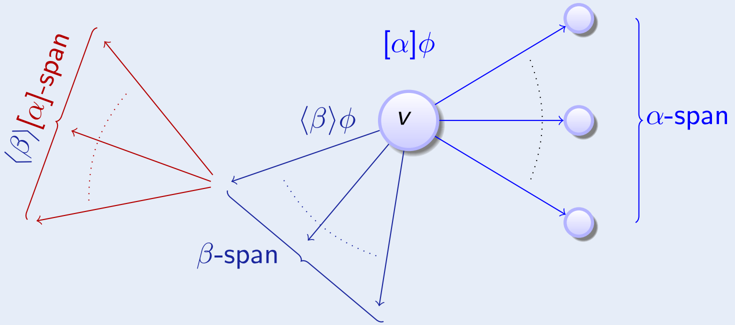


Quantified Differential Dynamic Logic Qd$\mathcal{L}$: Semantics

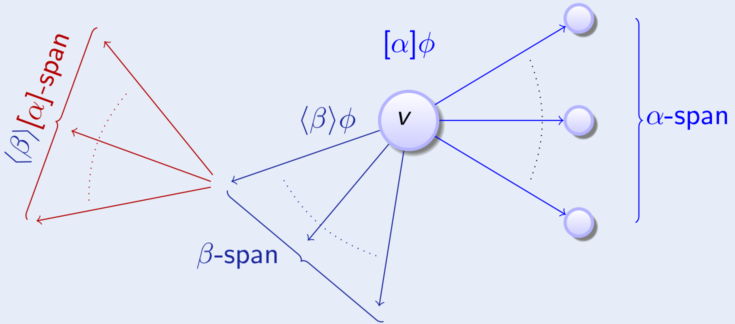
Definition (Qd$\mathcal{L}$ Formula ϕ)



Definition (Qd$\mathcal{L}$ Formula ϕ)



Definition (Qd$\mathcal{L}$ Formula ϕ)

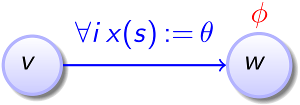


compositional semantics $\Rightarrow$ compositional calculus!

Outline (Verification Approach)

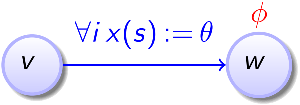
1. Motivation
2. Quantified Differential Dynamic Logic Qd$\mathcal{L}$
   - Design
   - Syntax
   - Semantics
3. Proof Calculus for Distributed Hybrid Systems
   - Compositional Verification Calculus
   - Deduction Modulo with Free Variables & Skolemization
   - Actual Existence and Creation
   - Soundness and Completeness
   - Quantified Differential Invariants
4. Applications
5. Conclusions

$$\frac{}{\phi([\forall i\, x(i) := \theta]x(u))}$$



Proof Calculus for Quantified Differential Dynamic Logic

$$\frac{\forall i\,(i = u \to \phi(\theta))}{\phi([\forall i\, x(i) := \theta]x(u))}$$



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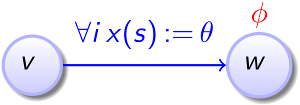

Proof Calculus for Quantified Differential Dynamic Logic

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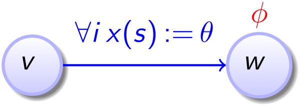
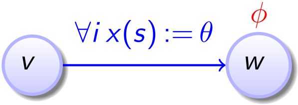


$$\frac{}{\phi([\underbrace{\forall i\, x(s) := \theta}]x(u))}$$

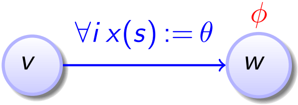
$$\frac{\forall i\,(i = [\forall i\, x(i) := \theta]u \to \phi(\theta))}{\phi([\forall i\, x(i) := \theta]x(u))}$$



$$\frac{\texttt{if}\ \exists i\, s = u\ \texttt{then}\ \forall i\,(s = u \to \phi(\theta))\ \texttt{else}\ \phi(x(u))}{\phi([\underbrace{\forall i\, x(s) := \theta}_{}]x(u))}$$

Proof Calculus for Quantified Differential Dynamic Logic

$$\frac{\forall i\,(i = [\forall i\, x(i) := \theta]u \rightarrow \phi(\theta))}{\phi([\forall i\, x(i) := \theta]x(u))}$$



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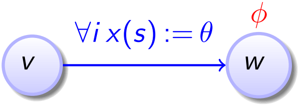

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Proof Calculus for Quantified Differential Dynamic Logic

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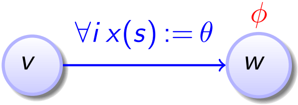

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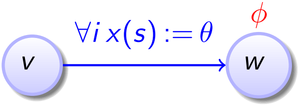
Proof Calculus for Quantified Differential Dynamic Logic

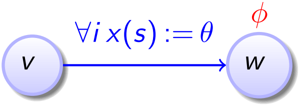
$$\frac{\forall i\,(i = [\forall i\, x(i) := \theta]u \to \phi(\theta))}{\phi([\forall i\, x(i) := \theta]x(u))}$$



$$\frac{\texttt{if}\ \exists i\, s = [\mathcal{A}]u\ \texttt{then}\ \forall i\,(s = [\mathcal{A}]u \to \phi(\theta))\ \texttt{else}\ \phi(x([\mathcal{A}]u))}{\phi([\underbrace{\forall i\, x(s) := \theta}_{\mathcal{A}}]x(u))}$$

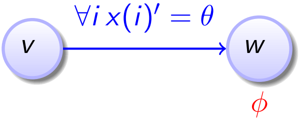
Proof Calculus for Quantified Differential Dynamic Logic

$$\frac{\forall i\,(i = [\forall i\, x(i) := \theta]u \to \phi(\theta))}{\phi([\forall i\, x(i) := \theta]x(u))}$$

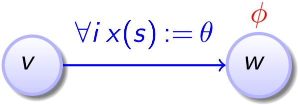


$$\frac{\texttt{if}\ \exists i\, s = [\mathcal{A}]u\ \texttt{then}\ \forall i\,(s = [\mathcal{A}]u \to \phi(\theta))\ \texttt{else}\ \phi(x([\mathcal{A}]u))}{\phi([\underbrace{\forall i\, x(s) := \theta}_{\mathcal{A}}]x(u))}$$

$$\frac{\forall t{\geq}0\, [\forall i\, x(i) := x_i(t)]\phi}{[\forall i\, x(i)' = \theta]\phi}$$

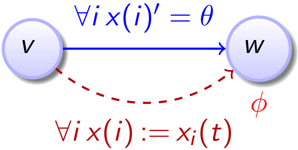


$$\frac{\forall i\, (i = [\forall i\, x(i) := \theta]u \to \phi(\theta))}{\phi([\forall i\, x(i) := \theta]x(u))}$$



$$\frac{\texttt{if}\ \exists i\, s = [\mathcal{A}]u\ \texttt{then}\ \forall i\, (s = [\mathcal{A}]u \to \phi(\theta))\ \texttt{else}\ \phi(x([\mathcal{A}]u))}{\phi(\underbrace{[\forall i\, x(s) := \theta]}_{\mathcal{A}}x(u))}$$

$$\frac{\forall t{\geq}0\, [\forall i\, x(i) := x_i(t)]\phi}{[\forall i\, x(i)' = \theta]\phi}$$

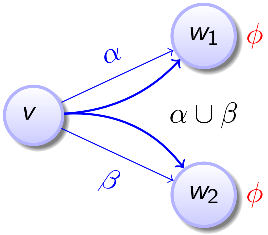


Proof Calculus for Quantified Differential Dynamic Logic

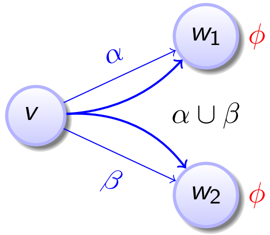
compositional semantics $\Rightarrow$ compositional rules!

Proof Calculus for Quantified Differential Dynamic Logic

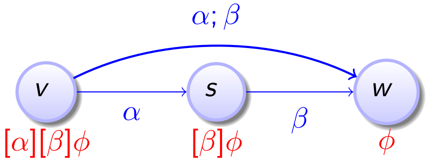
$$\frac{[\alpha]\phi \land [\beta]\phi}{[\alpha \cup \beta]\phi}$$



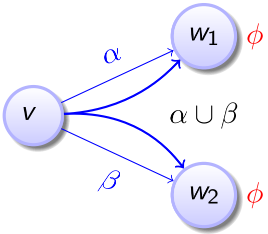
$$\frac{[\alpha]\phi \wedge [\beta]\phi}{[\alpha \cup \beta]\phi}$$



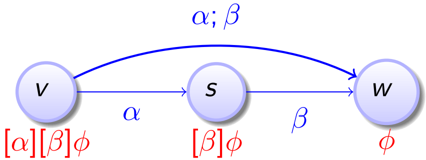
$$\frac{[\alpha][\beta]\phi}{[\alpha;\beta]\phi}$$



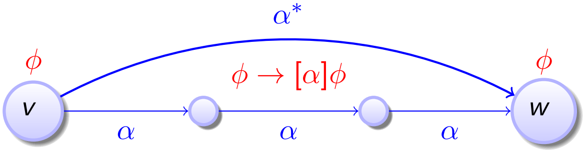
$$\frac{[\alpha]\phi \land [\beta]\phi}{[\alpha \cup \beta]\phi}$$



$$\frac{[\alpha][\beta]\phi}{[\alpha;\beta]\phi}$$

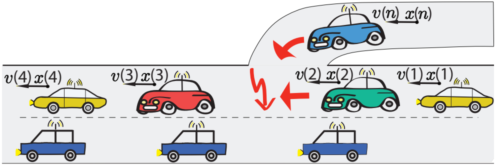


$$\frac{\phi \quad (\phi \rightarrow [\alpha]\phi)}{[\alpha^*]\phi}$$

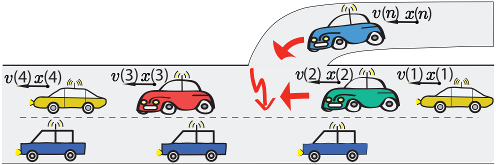


Deduction Modulo with Free Variables & Skolemization

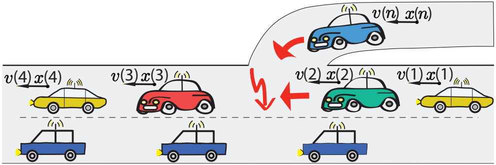
$$\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)'' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)$$



$$\frac{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)' = v(i), v(i)' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)}{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)'' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)}$$

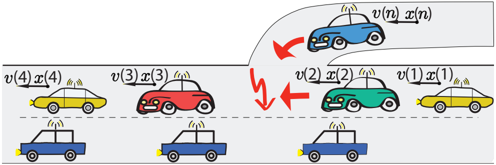


$$\frac{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow \forall t{\geq}0\, [\forall i\, x(i) := -\frac{b}{2}t^2 + v(i)t + x(i)] \forall j{\neq}k\, x(j){\neq}x(k)}{\frac{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)' = v(i), v(i)' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)}{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)'' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)}}$$



Deduction Modulo with Free Variables & Skolemization

$$\dfrac{\dfrac{\dfrac{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)'' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)}{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)' = v(i), v(i)' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)}}{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow \forall \color{red}{t{\geq}0}\, [\forall i\, x(i) := -\frac{b}{2}t^2 + v(i)t + x(i)]\forall j{\neq}k\, x(j){\neq}x(k)}}{\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow s{\geq}0 \rightarrow [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j{\neq}k\, x(j){\neq}x(k)}$$



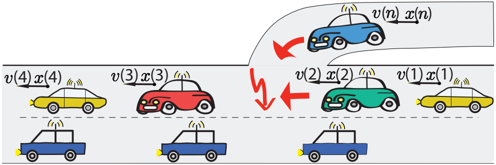
$$\forall i\neq j\, x(i)\neq x(j), s\geq 0 \rightarrow [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j\neq k\, x(j)\neq x(k)$$

$$\forall i\neq j\, x(i)\neq x(j) \rightarrow s\geq 0 \rightarrow [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j\neq k\, x(j)\neq x(k)$$

$$\forall i\neq j\, x(i)\neq x(j) \rightarrow \forall t\geq 0\, [\forall i\, x(i) := -\frac{b}{2}t^2 + v(i)t + x(i)]\forall j\neq k\, x(j)\neq x(k)$$

$$\forall i\neq j\, x(i)\neq x(j) \rightarrow [\forall i\, x(i)' = v(i), v(i)' = -b]\, \forall j\neq k\, x(j)\neq x(k)$$

$$\forall i\neq j\, x(i)\neq x(j) \rightarrow [\forall i\, x(i)'' = -b]\, \forall j\neq k\, x(j)\neq x(k)$$



$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \rightarrow \forall j{\neq}k\, \left(-\frac{b}{2}s^2 + v(j)s + x(j) \neq -\frac{b}{2}s^2 + v(k)s + x(k)\right)$$

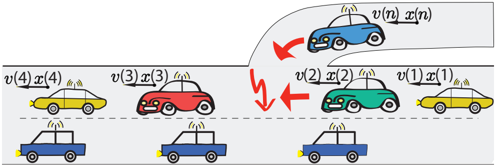
$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \rightarrow [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow s{\geq}0 \rightarrow [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow \forall t{\geq}0\, [\forall i\, x(i) := -\frac{b}{2}t^2 + v(i)t + x(i)] \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)' = v(i), v(i)' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow [\forall i\, x(i)'' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)$$



$$\forall i{\neq}j\, x(i){\neq}x(j) \to \forall j{\neq}k \quad \forall s{\geq}0\left(-\tfrac{b}{2}s^2+v(j)s+x(j) \neq -\tfrac{b}{2}s^2+v(k)s+x(k)\right)$$

$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \to \forall j{\neq}k\left(-\tfrac{b}{2}s^2 + v(j)s + x(j) \neq -\tfrac{b}{2}s^2 + v(k)s + x(k)\right)$$

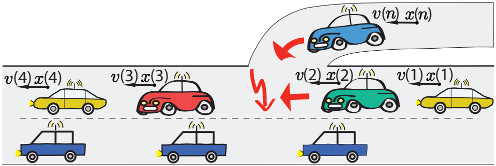
$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \to [\forall i\, x(i) := -\tfrac{b}{2}s^2 + v(i)s + x(i)]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \to s{\geq}0 \to [\forall i\, x(i) := -\tfrac{b}{2}s^2 + v(i)s + x(i)]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \to \forall t{\geq}0\, [\forall i\, x(i) := -\tfrac{b}{2}t^2 + v(i)t + x(i)] \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \to [\forall i\, x(i)' = v(i), v(i)' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

$$\forall i{\neq}j\, x(i){\neq}x(j) \to [\forall i\, x(i)'' = -b]\, \forall j{\neq}k\, x(j){\neq}x(k)$$



$$\forall i{\neq}j\, x(i){\neq}x(j) \rightarrow \forall j{\neq}k\ \mathrm{QE}\forall s{\geq}0\left(-\tfrac{b}{2}s^2+v(j)s+x(j) \neq -\tfrac{b}{2}s^2+v(k)s+x(k)\right)$$

$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \rightarrow \forall j{\neq}k\left(-\tfrac{b}{2}s^2 + v(j)s + x(j) \neq -\tfrac{b}{2}s^2 + v(k)s + x(k)\right)$$

$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \rightarrow [\forall i\, x(i) := -\tfrac{b}{2}s^2 + v(i)s + x(i)]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

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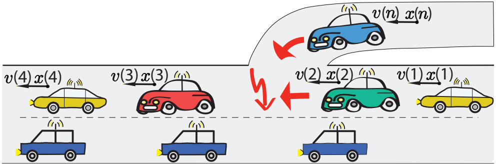

Deduction Modulo with Free Variables & Skolemization

$$\forall i{\neq}j\, x(i){\neq}x(j) \to \forall j{\neq}k\, (x(j){\leq}x(k) \land v(j){\leq}v(k) \lor x(j){\geq}x(k) \land v(j){\geq}v(k))$$

$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \to \forall j{\neq}k\, (-\frac{b}{2}s^2 + v(j)s + x(j) \neq -\frac{b}{2}s^2 + v(k)s + x(k))$$

$$\forall i{\neq}j\, x(i){\neq}x(j), s{\geq}0 \to [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j{\neq}k\, x(j){\neq}x(k)$$

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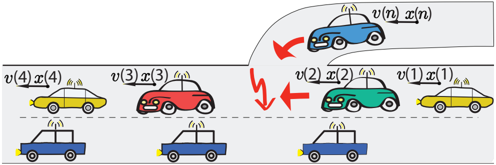
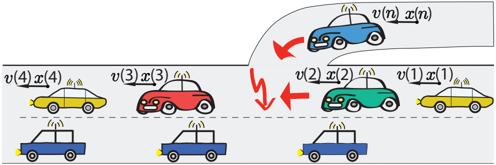


Deduction Modulo with Free Variables & Skolemization

$$\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\forall X, Y, V, W\, (X \neq Y \rightarrow X \leq Y \land V \leq W \lor X \geq Y \land V \geq W)}{\forall i \neq j\, x(i) \neq x(j) \rightarrow \forall j \neq k\, (x(j) \leq x(k) \land v(j) \leq v(k) \lor x(j) \geq x(k) \land v(j) \geq v(k))}}{\forall i \neq j\, x(i) \neq x(j), s \geq 0 \rightarrow \forall j \neq k\, (-\frac{b}{2}s^2 + v(j)s + x(j) \neq -\frac{b}{2}s^2 + v(k)s + x(k))}}{\forall i \neq j\, x(i) \neq x(j), s \geq 0 \rightarrow [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j \neq k\, x(j) \neq x(k)}}{\forall i \neq j\, x(i) \neq x(j) \rightarrow s \geq 0 \rightarrow [\forall i\, x(i) := -\frac{b}{2}s^2 + v(i)s + x(i)]\, \forall j \neq k\, x(j) \neq x(k)}}{\forall i \neq j\, x(i) \neq x(j) \rightarrow \forall t \geq 0\, [\forall i\, x(i) := -\frac{b}{2}t^2 + v(i)t + x(i)] \forall j \neq k\, x(j) \neq x(k)}}{\forall i \neq j\, x(i) \neq x(j) \rightarrow [\forall i\, x(i)' = v(i), v(i)' = -b]\, \forall j \neq k\, x(j) \neq x(k)}}{\forall i \neq j\, x(i) \neq x(j) \rightarrow [\forall i\, x(i)'' = -b]\, \forall j \neq k\, x(j) \neq x(k)}$$



Deduction Modulo with Free Variables & Skolemization

$$\forall X,Y,V,W\,(X\neq Y \to X\leq Y\land V\leq W \lor X\geq Y\land V\geq W)$$

$$\forall i\neq j\; x(i)\neq x(j) \to \forall j\neq k\,(x(j)\leq x(k)\land v(j)\leq v(k) \lor x(j)\geq x(k)\land v(j)\geq v(k))$$

$$\forall i\neq j\; x(i)\neq x(j), s\geq 0 \to \forall j\neq k\,(-\tfrac{b}{2}s^2 + v(j)s + x(j) \neq -\tfrac{b}{2}s^2 + v(k)s + x(k))$$

$$\forall i\neq j\; x(i)\neq x(j), s\geq 0 \to [\forall i\; x(i) := -\tfrac{b}{2}s^2 + v(i)s + x(i)]\,\forall j\neq k\; x(j)\neq x(k)$$

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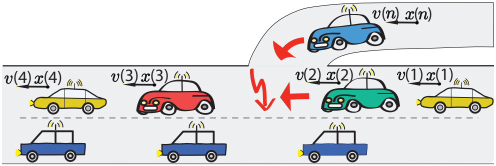
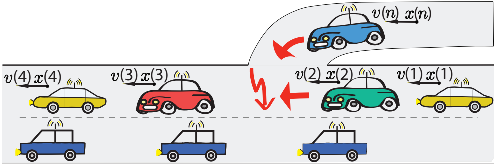


Actual Existence and Creation

Actual Existence Function $\mathrm{E}(\cdot)$

$$\mathrm{E}(i) = \begin{cases} 0 & \text{if } i \text{ denotes a possible object} \\ 1 & \text{if } i \text{ denotes an actively existing objects} \end{cases}$$



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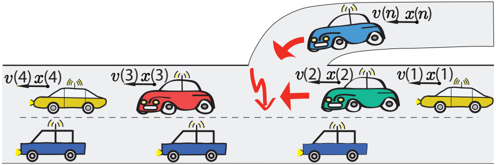
$$\frac{}{[n := \mathtt{new}\ C]\phi}$$



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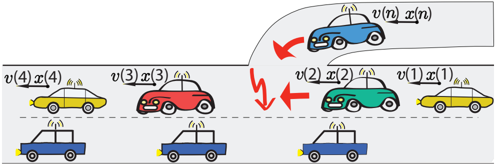

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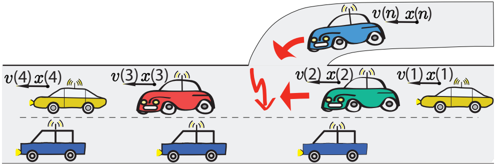
$$\frac{[(\forall j : C\ \ n := j);\ \ ?(\mathrm{E}(n) = 0);\qquad\qquad]\phi}{[n := \mathtt{new}\ C]\phi}$$



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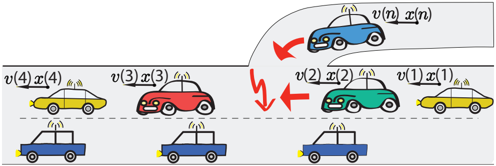

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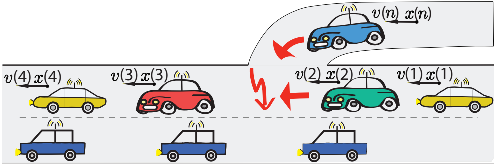
$$\forall i : C!\ \phi \;\equiv$$

$$\forall i : C!\ f(s) := \theta \;\equiv$$

$$\forall i : C!\ f(s)' = \theta \;\equiv$$



Actual Existence and Creation

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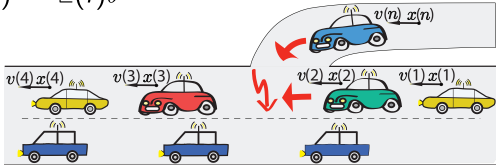
$$\frac{[(\forall j : C \;\; n := j);\;\; ?(\mathrm{E}(n) = 0);\;\; \mathrm{E}(n) := 1]\phi}{[n := \mathtt{new}\; C]\phi}$$

$$\begin{aligned} \forall i : C!\; \phi \;&\equiv\; \forall i : C \;\; (\mathrm{E}(i) = 1 \rightarrow \phi) \\ \forall i : C!\; f(s) := \theta \;&\equiv\; \forall i : C \;\; f(s) := (\mathtt{if}\, \mathrm{E}(i) = 1\, \mathtt{then}\, \theta\, \mathtt{else}\, f(s)) \\ \forall i : C!\; f(s)' = \theta \;&\equiv\; \forall i : C \;\; f(s)' = \mathrm{E}(i)\theta \end{aligned}$$



Soundness and Completeness

Theorem (Relative Completeness)

Qd$\mathcal{L}$ calculus is a sound & complete axiomatisation of distributed hybrid systems relative to quantified differential equations.

Proof 16p.

Soundness and Completeness

Theorem (Relative Completeness)

Qd$\mathcal{L}$ calculus is a sound & complete axiomatisation of distributed hybrid systems relative to quantified differential equations.

Proof 16p.

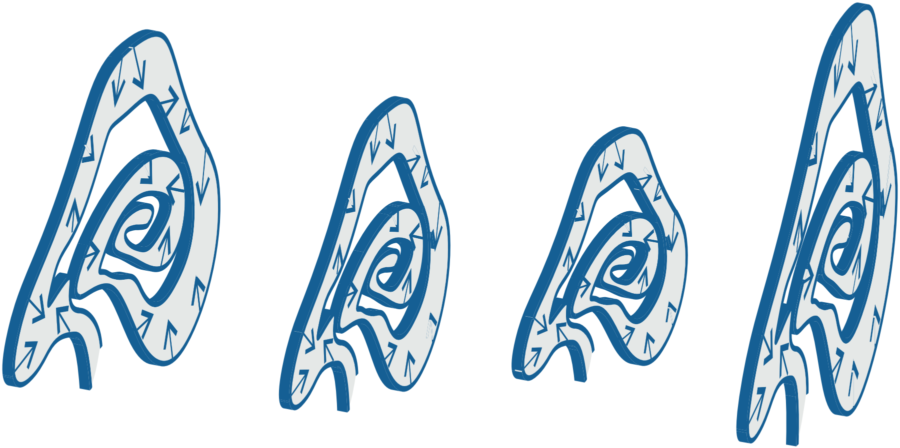
Corollary (Proof-theoretical Alignment)

proving distributed hybrid systems = proving dynamical systems!

Quantified Differential Invariants

Theorem (Quantified Differential Invariant) (HSCC'11)

$$\text{(QdI)} \quad \frac{Q \rightarrow [\forall i : C\ f(i)' := \theta] F'}{F \rightarrow [\forall i : C\ f(i)' = \theta \& Q] F} \quad \textit{is sound}$$



A Simple Proof with Quantified Differential Invariants

$$\frac{}{\forall i : C\ 2x(i)^3 \geq 1 \rightarrow [\forall i : C\ x(i)' = x(i)^2 + x(i)^4 + 2]\forall i : C\ 2x(i)^3 \geq 1}$$

A Simple Proof with Quantified Differential Invariants

$$\dfrac{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2](\forall i : C\ 2x(i)^3 \geq 0)'}{\forall i : C\ 2x(i)^3 \geq 1 \rightarrow [\forall i : C\ x(i)' = x(i)^2 + x(i)^4 + 2]\forall i : C\ 2x(i)^3 \geq 1}$$

A Simple Proof with Quantified Differential Invariants

$$\dfrac{\dfrac{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2]\forall i : C\ (2x(i)^3)' \geq 0}{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2](\forall i : C\ 2x(i)^3 \geq 0)'}}{\forall i : C\ 2x(i)^3 \geq 1 \rightarrow [\forall i : C\ x(i)' = x(i)^2 + x(i)^4 + 2]\forall i : C\ 2x(i)^3 \geq 1}$$

A Simple Proof with Quantified Differential Invariants

$$\dfrac{\dfrac{\dfrac{\overline{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2]\forall i : C\ 6x(i)^2 x(i)' \geq 0}}{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2]\forall i : C\ (2x(i)^3)' \geq 0}}{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2](\forall i : C\ 2x(i)^3 \geq 0)'}}{\forall i : C\ 2x(i)^3 \geq 1 \rightarrow [\forall i : C\ x(i)' = x(i)^2 + x(i)^4 + 2]\forall i : C\ 2x(i)^3 \geq 1}$$

A Simple Proof with Quantified Differential Invariants

$$
\cfrac{\cfrac{\cfrac{\cfrac{\forall i{:}C\ 6x(i)^2(x(i)^2+x(i)^4+2)\geq 0}{[\forall i{:}C\ x(i)':=x(i)^2+x(i)^4+2]\forall i{:}C\ 6x(i)^2x(i)'\geq 0}}{[\forall i{:}C\ x(i)':=x(i)^2+x(i)^4+2]\forall i{:}C\ (2x(i)^3)'\geq 0}}{[\forall i{:}C\ x(i)':=x(i)^2+x(i)^4+2](\forall i{:}C\ 2x(i)^3\geq 0)'}}{\forall i{:}C\ 2x(i)^3\geq 1\rightarrow[\forall i{:}C\ x(i)'=x(i)^2+x(i)^4+2]\forall i{:}C\ 2x(i)^3\geq 1}
$$

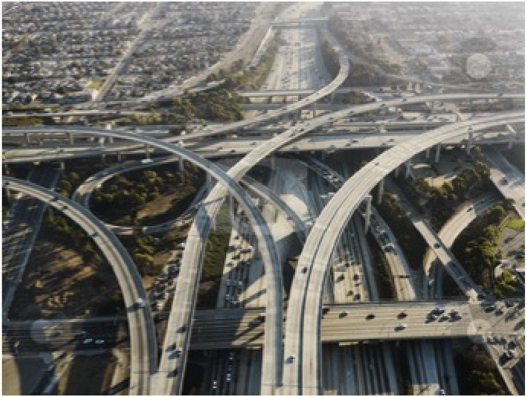
A Simple Proof with Quantified Differential Invariants

$$\dfrac{\dfrac{\dfrac{\dfrac{\textit{true}}{\forall i : C\ 6x(i)^2(x(i)^2 + x(i)^4 + 2) \geq 0}}{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2]\forall i : C\ 6x(i)^2 x(i)' \geq 0}}{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2]\forall i : C\ (2x(i)^3)' \geq 0}}{\dfrac{[\forall i : C\ x(i)' := x(i)^2 + x(i)^4 + 2](\forall i : C\ 2x(i)^3 \geq 0)'}{\forall i : C\ 2x(i)^3 \geq 1 \rightarrow [\forall i : C\ x(i)' = x(i)^2 + x(i)^4 + 2]\forall i : C\ 2x(i)^3 \geq 1}}$$

Outline

1. Motivation
2. Quantified Differential Dynamic Logic Qd$\mathcal{L}$
   - Design
   - Syntax
   - Semantics
3. Proof Calculus for Distributed Hybrid Systems
   - Compositional Verification Calculus
   - Deduction Modulo with Free Variables & Skolemization
   - Actual Existence and Creation
   - Soundness and Completeness
   - Quantified Differential Invariants
4. **Applications**
5. Conclusions

Driver's License Test for Robotic Cars?



Driver's License Test for Robotic Cars?

Driver's License Test for Robotic Cars? Proof!

Car Control: Local Lane Control Challenge

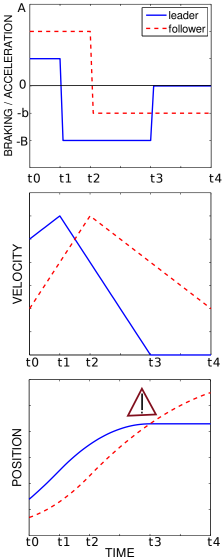
Challenge: Local lane dynamics

- A car controller for a differential equation respects separation of local lane.

Car Control: Local Lane Control Challenge

Challenge: Local lane dynamics

- A car controller for a differential equation respects separation of local lane.
- Follower car maintains safe distance to leader:

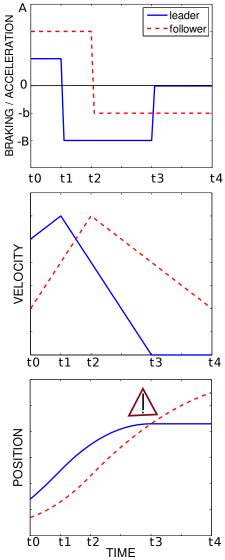


Car Control: Local Lane Control Challenge

Challenge: Local lane dynamics

- A car controller for a differential equation respects separation of local lane.
- Follower car maintains safe distance to leader:

$$f \ll \ell \rightarrow [(a_i := ctrl;\ x_i'' = a_i)^*]\, f \ll \ell$$



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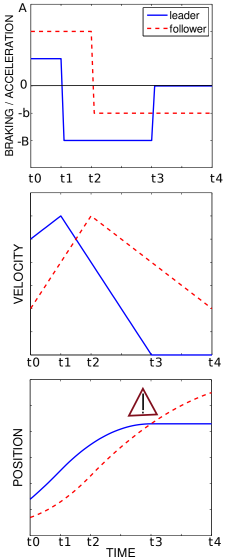

$$f \ll \ell \equiv \; (x_f \le x_\ell) \land (f \ne \ell) \to (x_\ell > x_f + \frac{v_f^2}{2b} - \frac{v_\ell^2}{2B} \land x_\ell > x_f \land v_f \ge 0 \land v_\ell \ge 0)$$

Car Control: Global Lane Control Challenge

Challenge: Global lane dynamics

- All controllers for arbitrarily many differential equations respect separation globally on lane.

Challenge: Global lane dynamics

- All controllers for arbitrarily many differential equations respect separation globally on lane.
- Each car safe behind all others

Car Control: Global Lane Control Challenge

Challenge: Global lane dynamics

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$$[(\forall i\, a(i) := ctrl;\ \forall i\, x(i)'' = a(i))^*]\,\forall i,j\, i \ll j$$

Car Control: Local Highway Control Challenge

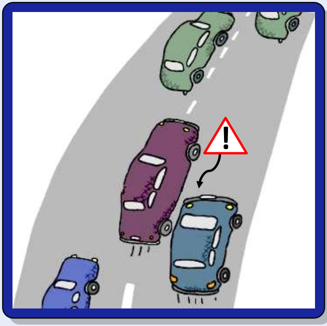
Challenge: Local highway dynamics

- All controllers for arbitrarily many differential equations respect separation locally on highway.

Car Control: Local Highway Control Challenge

Challenge: Local highway dynamics

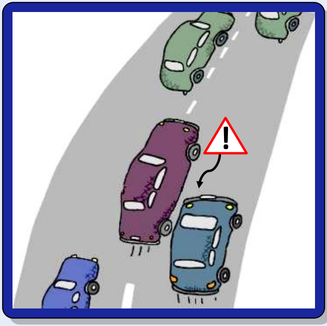
- All controllers for arbitrarily many differential equations respect separation locally on highway.
- For each lane: all controllers for the differential equations respect separation even if cars appear or disappear.



Car Control: Local Highway Control Challenge

Challenge: Local highway dynamics

- All controllers for arbitrarily many differential equations respect separation locally on highway.
- For each lane: all controllers for the differential equations respect separation even if cars appear or disappear.
- Each car safe behind all others, even if new cars appear or disappear.



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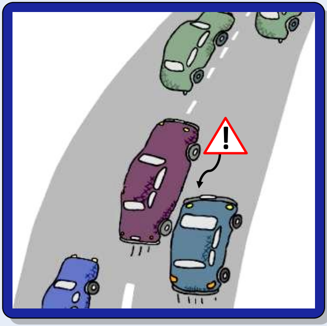

$$[(n := \mathtt{new}\ C;\ \forall i\, a(i) := ctrl;\ \forall i\, x(i)'' = a(i))^*]\, \forall i, j\; i \ll j$$

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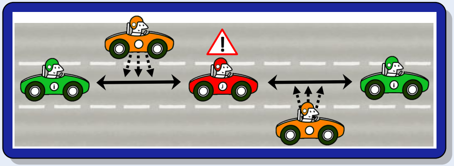
Challenge: Global highway dynamics

- All controllers for arbitrarily many differential equations respect separation globally on highway.

Car Control: Global Highway Control Challenge

Challenge: Global highway dynamics

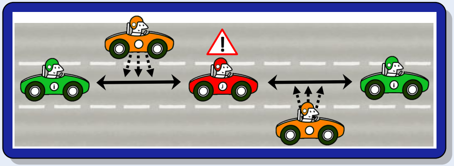
- All controllers for arbitrarily many differential equations respect separation globally on highway.
- All controllers for the differential equations respect separation even if cars switch lanes.



Car Control: Global Highway Control Challenge

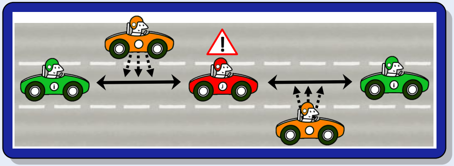
Challenge: Global highway dynamics

- All controllers for arbitrarily many differential equations respect separation globally on highway.
- All controllers for the differential equations respect separation even if cars switch lanes.
- On all lanes, all car safe behind all others on their lanes, even if cars switch lanes.



Car Control: Global Highway Control Challenge

Challenge: Global highway dynamics



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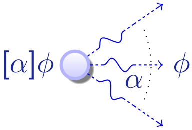
$$[\forall l\, (n := \mathtt{new}\ C;\ \forall i\, a(i) := ctrl;\ \forall i\, x(i)'' = a(i))^*]\, \forall l\, \forall i, j\ i \ll j$$

Outline

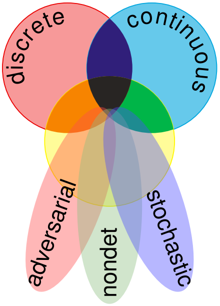
Conclusions

quantified differential dynamic logic

$$\mathsf{Qd}\mathcal{L} = \mathsf{FOL} + \mathsf{DL} + \mathsf{QHP}$$



- Distributed hybrid systems everywhere
- System model and semantics
- Logic for distributed hybrid systems
- Compositional proof calculus
- First verification approach
- Sound & complete / diff. eqn.
- Quantified differential invariants
- Distributed car control verified
- Distributed aircraft control verified



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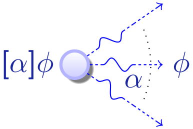

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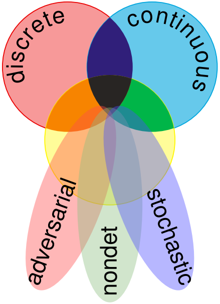

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