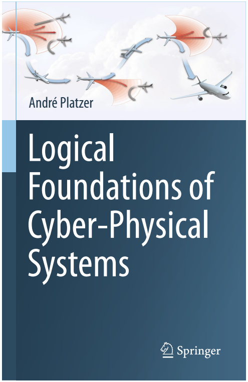
04: Safety & Contracts

Logical Foundations of Cyber-Physical Systems



André Platzer

Carnegie Mellon University
Computer Science Department

Outline

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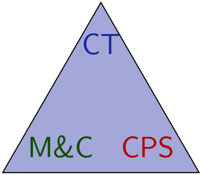
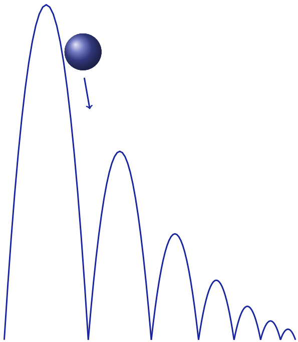
rigorous specification
contracts
preconditions
postconditions
differential dynamic logic



discrete+continuous
analytic specification

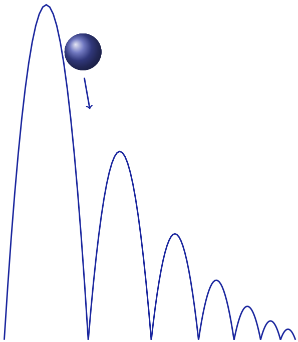
model semantics
reasoning principles

Outline



Example (Quantum the Bouncing Ball)

Quantum the Acrophobic Bouncing Ball



Example (Quantum the Bouncing Ball)

$$\{x' = v, v' = -g\}$$

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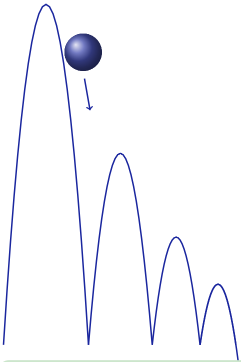

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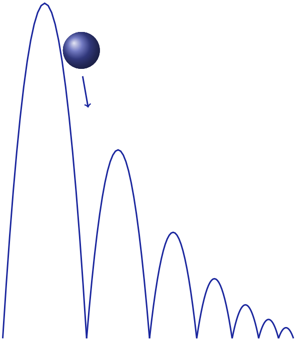
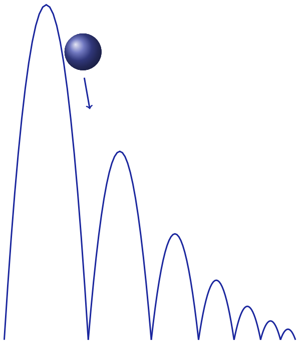


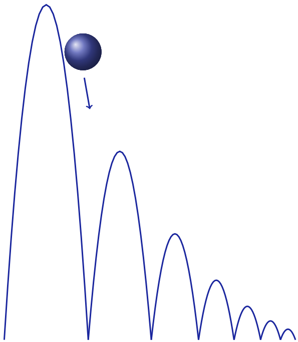
Example (Quantum the Bouncing Ball)

$$\{x' = v, v' = -g \,\&\, x \geq 0\}$$



Example (Quantum the Bouncing Ball)

$$\{x' = v, v' = -g \,\&\, x \geq 0\};$$
$$\text{if}(x = 0)\ \ v := -cv$$



Example (Quantum the Bouncing Ball)

$$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$$
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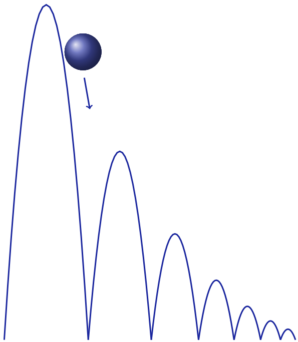
Quantum Discovered a Crack in the Fabric of Time



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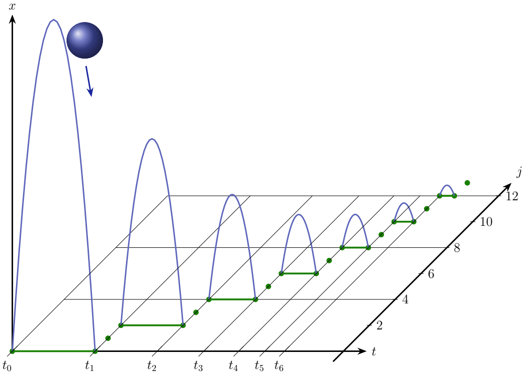

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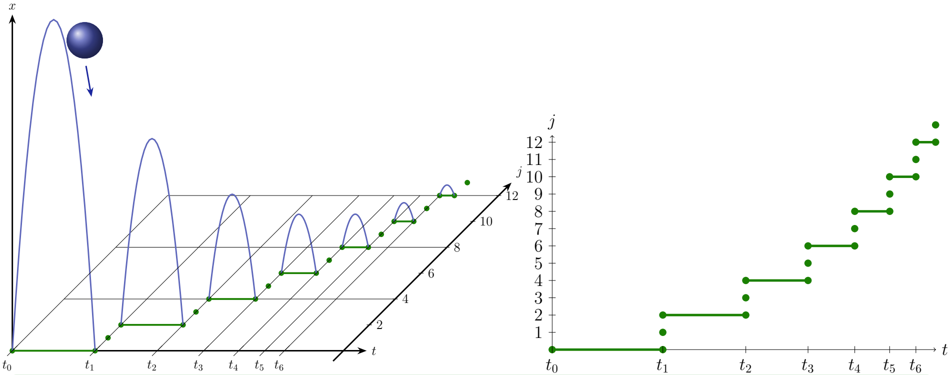

Example (Quantum the Bouncing Ball)

$$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$$
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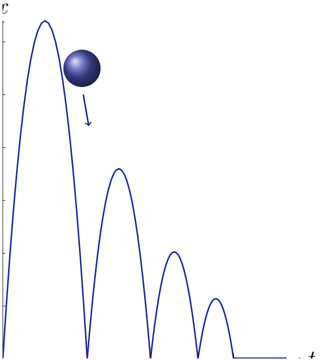
Quantum Learns to Deflate



Example (Quantum the Bouncing Ball)

$$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$$
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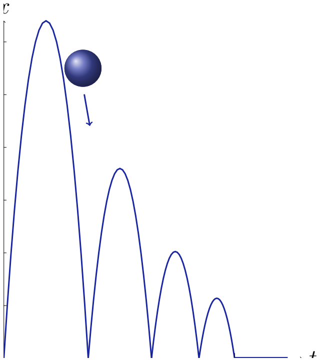
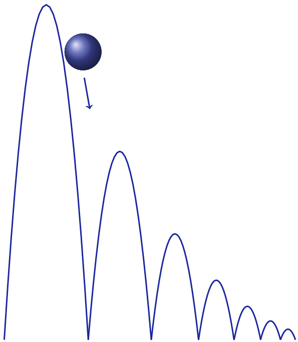


Example (Quantum the Bouncing Ball)

$$\left(\{x' = v, v' = -g \,\&\, x \geq 0\};\right.$$
$$\left.\text{if}(x = 0)\,(v := -cv \cup v := 0)\right)^*$$

Quantum the Acrophobic Bouncing Ball



Example (Quantum the Bouncing Ball)

$$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$$
$$\mathrm{if}(x = 0)\;\; v := -cv\big)^*$$

Outline

Safety of Robots

Safety of Robots

Three Laws of Robotics — Isaac Asimov 1942

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

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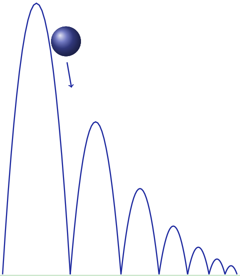
Three Laws of Robotics are not the answer.
They are the inspiration!



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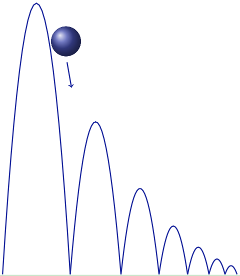
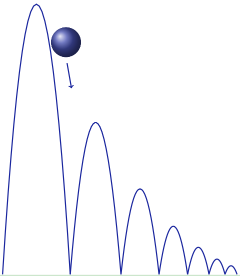


Example (Quantum the Bouncing Ball)

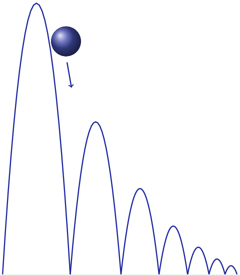
ensures$(0 \le x)$

$$\big(\{x' = v, v' = -g \,\&\, x \ge 0\};$$
$$\text{if}(x = 0)\; v := -cv\big)^*$$



Example (Quantum the Bouncing Ball)

$$\textbf{ensures}(0 \le x)$$
$$\textbf{ensures}(x \le H)$$
$$\big(\{x' = v, v' = -g \,\&\, x \ge 0\};$$
$$\text{if}(x = 0)\, v := -cv\big)^*$$



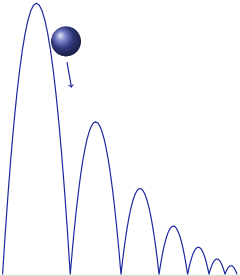
Example (Quantum the Bouncing Ball)

$\textbf{requires}(x = H)$

$\textbf{ensures}(0 \leq x)$

$\textbf{ensures}(x \leq H)$

$$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};\\ \quad \text{if}(x = 0)\, v := -cv\big)^*$$



Example (Quantum the Bouncing Ball)

$$\textbf{requires}(x = H)$$

$$\textbf{requires}(0 \leq H)$$

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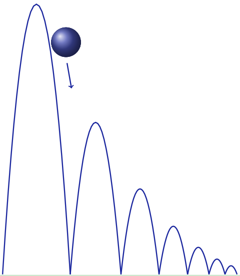


Example (Quantum the Bouncing Ball)

$\textbf{requires}(x = H)$

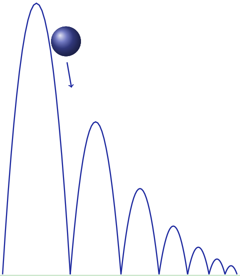
$\textbf{requires}(0 \leq H)$

$\textbf{ensures}(0 \leq x)$

$\textbf{ensures}(x \leq H)$

$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$

$\;\text{if}(x = 0)\, v := -cv\big)^* \textbf{@invariant}(x \geq 0)$



Example (Quantum the Bouncing Ball)

$$\textbf{requires}(x = H)$$
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$$\textbf{ensures}(x \leq H)$$
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$$\text{if}(x = 0)\ v := -cv\big)^* \textbf{@invariant}(x \geq 0)$$

Outline

1. Learning Objectives
2. Quantum the Acrophobic Bouncing Ball
3. Contracts for CPS
   - Safety of Robots
   - Safety of Bouncing Balls
4. Logical Formulas for Hybrid Programs
5. Differential Dynamic Logic
   - Syntax
   - Semantics
   - Notational Convention
6. Identifying Requirements of a CPS
7. Summary

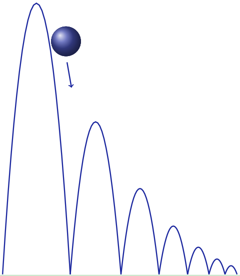
Contracts are Not Enough

CPS contracts are crucial for CPS safety.
We need to understand CPS programs and contracts and how we can convince ourselves that a CPS program respects its contract.

Contracts are at a disadvantage compared to full logic.

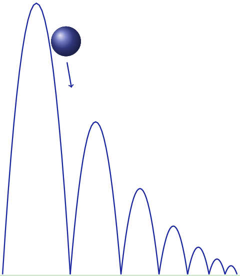
Logic is for Specification and Reasoning

1. Specification of a whole CPS program.
2. Analytic inspection of its parts.
3. Argumentative relations between contracts and program parts.
   "Yes, this CPS program meets its contract, and here's why ..."



Example (Quantum the Bouncing Ball)

$$\begin{aligned}
&\textbf{requires}(x = H)\\
&\textbf{requires}(0 \leq H)\\
&\textbf{ensures}(0 \leq x)\\
&\textbf{ensures}(x \leq H)\\
&\big(\{x' = v, v' = -g \,\&\, x \geq 0\};\\
&\quad \mathrm{if}(x = 0)\, v := -cv\big)^*
\end{aligned}$$



Example (Quantum the Bouncing Ball)

$\mathbf{requires}(x = H)$

$\mathbf{requires}(0 \leq H)$

$\mathbf{ensures}(0 \leq x)$

$\mathbf{ensures}(x \leq H)$

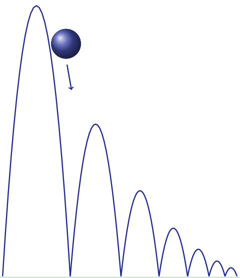
$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$

$\quad \mathrm{if}(x = 0)\, v := -cv\big)^*$

Precondition:

$x = H \land 0 \leq H$ in FOL

Contracts for Quantum the Acrophobic Bouncing Ball



Example (Quantum the Bouncing Ball)

requires$(x = H)$

requires$(0 \leq H)$

ensures$(0 \leq x)$

ensures$(x \leq H)$

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Precondition:

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Postcondition:

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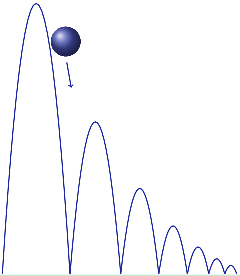

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$\text{if}(x = 0)\, v := -cv\big)^*$

Precondition:

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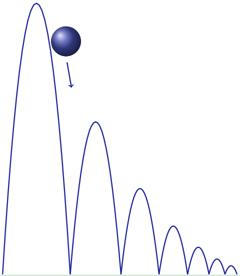
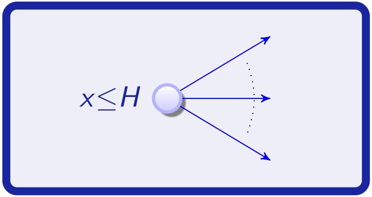
Postcondition:

$0 \le x \land x \le H$ in FOL

How to say post is true after all HP runs?





Example (Quantum the Bouncing Ball)

requires$(x = H)$

requires$(0 \leq H)$

ensures$(0 \leq x)$

ensures$(x \leq H)$

$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$

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Precondition:

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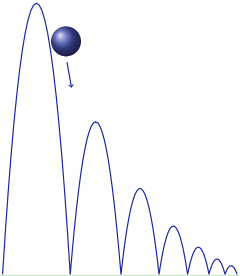
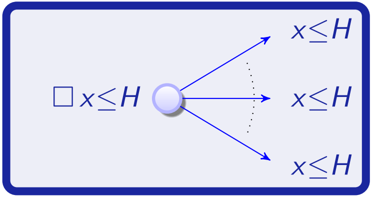
Postcondition:

$0 \leq x \land x \leq H$ in FOL





Example (Quantum the Bouncing Ball)

requires$(x = H)$	Precondition:
requires$(0 \le H)$	$x = H \land 0 \le H$ in FOL
ensures$(0 \le x)$	Postcondition:
ensures$(x \le H)$	$0 \le x \land x \le H$ in FOL

$$\big(\{x' = v, v' = -g \,\&\, x \ge 0\};$$
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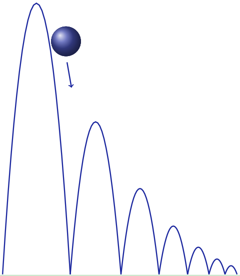
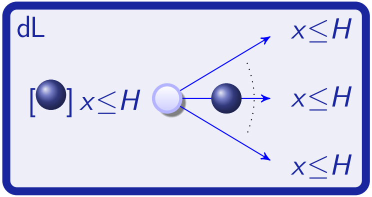
Contracts for Quantum the Acrophobic Bouncing Ball





Example (Quantum the Bouncing Ball)

$\mathbf{requires}(x = H)$

$\mathbf{requires}(0 \leq H)$

$\mathbf{ensures}(0 \leq x)$

$\mathbf{ensures}(x \leq H)$

$$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};\\ \;\mathrm{if}(x = 0)\, v := -cv\big)^*$$

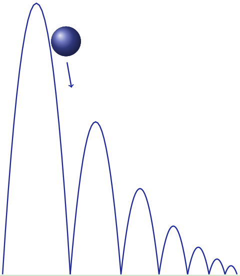
Precondition:

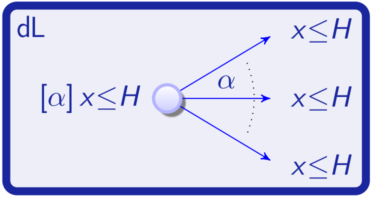
$x = H \wedge 0 \leq H$ in FOL

Postcondition:

$0 \leq x \wedge x \leq H$ in FOL

Contracts for Quantum the Acrophobic Bouncing Ball





Example (Quantum the Bouncing Ball)

requires$(x = H)$	Precondition:
requires$(0 \leq H)$	$x = H \land 0 \leq H$ in FOL
ensures$(0 \leq x)$	Postcondition:
ensures$(x \leq H)$	$0 \leq x \land x \leq H$ in FOL

$$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$$
$$\text{if}(x = 0)\, v := -cv\big)^*$$

$$[\big(\{x' = v, v' = -g \,\&\, x \geq 0\}; \mathrm{if}(x=0)\, v := -cv\big)^*]$$

Example (Quantum the Bouncing Ball)

requires$(x = H)$

requires$(0 \leq H)$

ensures$(0 \leq x)$

ensures$(x \leq H)$

$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$

$\mathrm{if}(x = 0)\, v := -cv\big)^*$

Precondition:

$x = H \wedge 0 \leq H$ in FOL

Postcondition:

$0 \leq x \wedge x \leq H$ in FOL

$$[(\{x' = v, v' = -g \,\&\, x \geq 0\}; \mathrm{if}(x=0)\, v := -cv)^*](x \leq H)$$

Example (Quantum the Bouncing Ball)

requires$(x = H)$
requires$(0 \leq H)$
ensures$(0 \leq x)$
ensures$(x \leq H)$
$(\{x' = v, v' = -g \,\&\, x \geq 0\};$
$\mathrm{if}(x = 0)\, v := -cv)^*$

Precondition:
$x = H \land 0 \leq H$ in FOL
Postcondition:
$0 \leq x \land x \leq H$ in FOL

$$[(\{x' = v, v' = -g \,\&\, x \geq 0\}; \mathrm{if}(x=0)\, v := -cv)^*](0 \leq x)$$
$$[(\{x' = v, v' = -g \,\&\, x \geq 0\}; \mathrm{if}(x=0)\, v := -cv)^*](x \leq H)$$

Example (Quantum the Bouncing Ball)

requires$(x = H)$

requires$(0 \leq H)$

ensures$(0 \leq x)$

ensures$(x \leq H)$

$(\{x' = v, v' = -g \,\&\, x \geq 0\};$

$\mathrm{if}(x = 0)\, v := -cv)^*$

Precondition:

$x = H \land 0 \leq H$ in FOL

Postcondition:

$0 \leq x \land x \leq H$ in FOL

$$[\big(\{x' = v, v' = -g \,\&\, x{\geq}0\}; \mathrm{if}(x{=}0)\, v := -cv\big)^*](0 \leq x)$$
$$[\big(\{x' = v, v' = -g \,\&\, x{\geq}0\}; \mathrm{if}(x{=}0)\, v := -cv\big)^*](x \leq H)$$
$$[\big(\{x' = v, v' = -g \,\&\, x{\geq}0\}; \mathrm{if}(x{=}0)\, v := -cv\big)^*](0{\leq}x \wedge x{\leq}H)$$

Example (Quantum the Bouncing Ball)

requires$(x = H)$

requires$(0 \leq H)$

ensures$(0 \leq x)$

ensures$(x \leq H)$

$\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$

$\mathrm{if}(x = 0)\, v := -cv\big)^*$

Precondition:

$x = H \wedge 0 \leq H$ in FOL

Postcondition:

$0 \leq x \wedge x \leq H$ in FOL

$$[(\{x' = v, v' = -g \,\&\, x{\geq}0\}; \text{if}(x{=}0)\, v := -cv)^*](0 \leq x)$$
$$\land\ [(\{x' = v, v' = -g \,\&\, x{\geq}0\}; \text{if}(x{=}0)\, v := -cv)^*](x \leq H)$$
$$\leftrightarrow\ [(\{x' = v, v' = -g \,\&\, x{\geq}0\}; \text{if}(x{=}0)\, v := -cv)^*](0{\leq}x \land x{\leq}H)$$

Example (Quantum the Bouncing Ball)

$\textbf{requires}(x = H)$

$\textbf{requires}(0 \leq H)$

$\textbf{ensures}(0 \leq x)$

$\textbf{ensures}(x \leq H)$

$(\{x' = v, v' = -g \,\&\, x \geq 0\};$

$\quad \text{if}(x = 0)\, v := -cv)^*$

Precondition:

$x = H \land 0 \leq H$ in FOL

Postcondition:

$0 \leq x \land x \leq H$ in FOL

$$[(\{x' = v, v' = -g \,\&\, x \geq 0\}; \mathrm{if}(x=0)\, v := -cv)^*](0 \leq x)$$

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requires$(x = H)$

requires$(0 \leq H)$

ensures$(0 \leq x)$

ensures$(x \leq H)$

$(\{x' = v, v' = -g \,\&\, x \geq 0\};$

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Precondition:

$x = H \land 0 \leq H$ in FOL

Postcondition:

$0 \leq x \land x \leq H$ in FOL

Contracts for Quantum the Acrophobic Bouncing Ball

$$x{=}H \rightarrow [(\{x' = v, v' = -g \,\&\, x{\geq}0\}; \mathrm{if}(x{=}0)\, v := -cv)^*](0 \leq x)$$

Example (Quantum the Bouncing Ball)

requires$(x = H)$
requires$(0 \leq H)$
ensures$(0 \leq x)$
ensures$(x \leq H)$
$(\{x' = v, v' = -g \,\&\, x \geq 0\};$
$\mathrm{if}(x = 0)\, v := -cv)^*$

Precondition:
$x = H \land 0 \leq H$ in FOL
Postcondition:
$0 \leq x \land x \leq H$ in FOL

Contracts for Quantum the Acrophobic Bouncing Ball

$$0\leq x \land x=H \rightarrow [(\{x' = v, v' = -g \,\&\, x\geq 0\}; \text{if}(x=0)\, v := -cv)^*](0 \leq x)$$

Example (Quantum the Bouncing Ball)

requires$(x = H)$

requires$(0 \leq H)$

ensures$(0 \leq x)$

ensures$(x \leq H)$

$(\{x' = v, v' = -g \,\&\, x \geq 0\};$

$\text{if}(x = 0)\, v := -cv)^*$

Precondition:

$x = H \land 0 \leq H$ in FOL

Postcondition:

$0 \leq x \land x \leq H$ in FOL

Outline

Differential Dynamic Logic: Syntax

Definition (Syntax of differential dynamic logic)

The *formulas* of *differential dynamic logic* are defined by the grammar:

$$P, Q ::= e \geq \tilde{e} \mid \neg P \mid P \wedge Q \mid P \vee Q \mid P \rightarrow Q \mid \forall x\, P \mid \exists x\, P \mid [\alpha]P \mid \langle\alpha\rangle P$$

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Not

And

Or

Imply

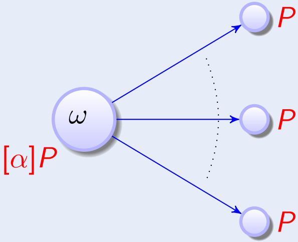
All reals

Some real

All runs

Some runs

Definition (dL Formulas)



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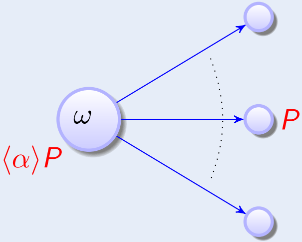
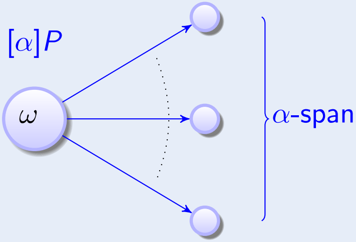
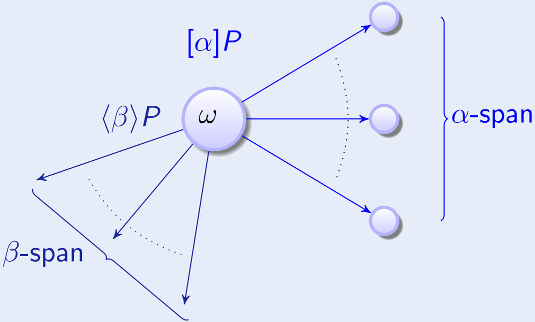


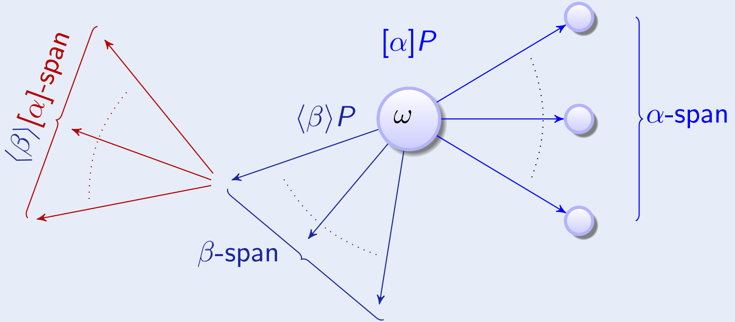
Definition (dL Formulas)



Definition (dL Formulas)



Definition (dL Formulas)



Differential Dynamic Logic: Syntax & Semantics

Definition (Syntax of differential dynamic logic)

The *formulas* of *differential dynamic logic* are defined by the grammar:

$$P, Q ::= e \geq \tilde{e} \mid \neg P \mid P \wedge Q \mid P \vee Q \mid P \rightarrow Q \mid \forall x\, P \mid \exists x\, P \mid [\alpha]P \mid \langle\alpha\rangle P$$

Definition (dL semantics) $([\![\cdot]\!] : \mathrm{Fml} \rightarrow \wp(\mathcal{S}))$

$$\begin{aligned}
[\![e \geq \tilde{e}]\!] &= \{\omega : \omega[\![e]\!] \geq \omega[\![\tilde{e}]\!]\} \\
[\![\neg P]\!] &= [\![P]\!]^\complement = \mathcal{S} \setminus [\![P]\!] \\
[\![P \wedge Q]\!] &= [\![P]\!] \cap [\![Q]\!] \\
[\![P \vee Q]\!] &= [\![P]\!] \cup [\![Q]\!] \\
[\![P \rightarrow Q]\!] &= [\![P]\!]^\complement \cup [\![Q]\!] \\
[\![\langle\alpha\rangle P]\!] &= [\![\alpha]\!] \circ [\![P]\!] = \{\omega : \nu \in [\![P]\!] \text{ for some } \nu :\ (\omega, \nu) \in [\![\alpha]\!]\} \\
[\![[\alpha]P]\!] &= [\![\neg\langle\alpha\rangle\neg P]\!] = \{\omega : \nu \in [\![P]\!] \text{ for all } \nu :\ (\omega, \nu) \in [\![\alpha]\!]\} \\
[\![\exists x\, P]\!] &= \{\omega : \omega_x^r \in [\![P]\!] \text{ for some } r \in \mathbb{R}\} \\
[\![\forall x\, P]\!] &= \{\omega : \omega_x^r \in [\![P]\!] \text{ for all } r \in \mathbb{R}\}
\end{aligned}$$

$$\omega_x^d(y) = \begin{cases} d & \text{if } y{=}x \\ \omega(y) & \text{if } y{\neq}x \end{cases}$$

$[\![P]\!]$	the set of states in which formula P is true
$\omega \in [\![P]\!]$	formula P is true in state ω, alias $\omega \models P$
$\models P$	formula P is valid, i.e., true in all states ω, i.e., $[\![P]\!] = \mathcal{S}$

Definition (dL semantics) ($[\![\cdot]\!] : \mathrm{Fml} \to \wp(\mathcal{S})$)

$$
\begin{aligned}
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Differential Dynamic Logic: Syntax & Semantics

$[\![P]\!]$	the set of states in which formula P is true
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$\exists d\,[x := 1; x'=d]x\geq 0$ and $[x := x+1; x'=d]x\geq 0$ and $\langle x'=d\rangle x\geq 0$

Definition (dL semantics) ($[\![\cdot]\!] : \mathrm{Fml} \to \wp(\mathcal{S})$)

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[\![e \geq \tilde{e}]\!] &= \{\omega : \omega[\![e]\!] \geq \omega[\![\tilde{e}]\!]\}\\
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$\models \exists d\, [x := 1; x' = d] x \geq 0$ and $\not\models [x := x+1; x' = d] x \geq 0$ and $\not\models \langle x' = d \rangle x \geq 0$

Definition (dL semantics) ($[\![\cdot]\!] : \mathrm{Fml} \to \wp(\mathcal{S})$)

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\end{aligned}
$$

Notational Conventions: Precedence

Convention (Operator Precedence)

1. Unary operators (e.g., *, $\neg$, $\forall x, \exists x$, $[\alpha], \langle\alpha\rangle$) bind stronger than binary
2. $\wedge$ binds stronger than $\vee$, which binds stronger than $\rightarrow, \leftrightarrow$
3. $;$ binds stronger than $\cup$
4. Arithmetic operators $+, -, \cdot$ associate to the left
5. Logical and program operators associate to the right

Example (Operator Precedence)

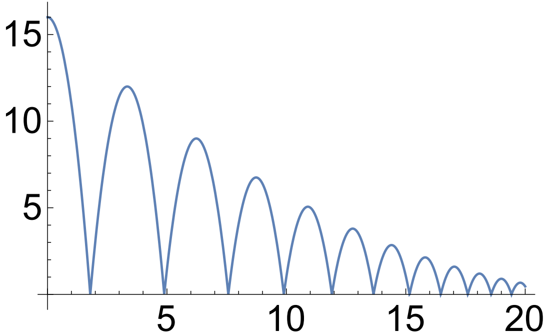
$[\alpha]P \wedge Q \equiv ([\alpha]P) \wedge Q \qquad \forall x\, P \wedge Q \equiv (\forall x\, P) \wedge Q \qquad \forall x\, P \rightarrow Q \equiv (\forall x\, P) \rightarrow Q$

$\alpha; \beta \cup \gamma \equiv (\alpha; \beta) \cup \gamma \qquad \alpha \cup \beta; \gamma \equiv \alpha \cup (\beta; \gamma) \qquad \alpha; \beta^* \equiv \alpha; (\beta^*)$

$P \rightarrow Q \rightarrow R \equiv P \rightarrow (Q \rightarrow R)$.

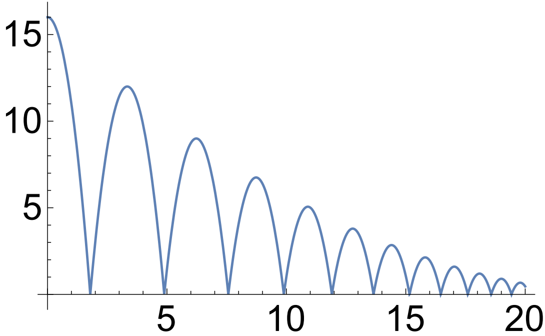
But $\rightarrow, \leftrightarrow$ expect explicit parentheses. Illegal: $P \rightarrow Q \leftrightarrow R \quad P \leftrightarrow Q \rightarrow R$

Outline



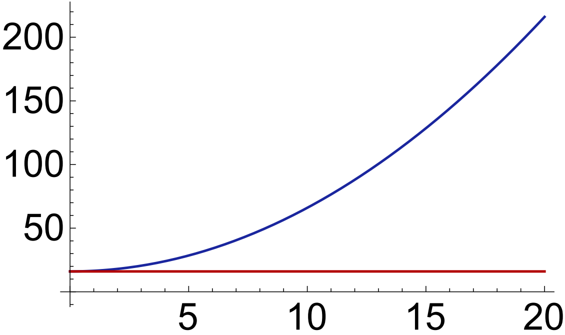
Example (Bouncing Ball)

$$\left(\{x' = v, v' = -g \,\&\, x \geq 0\};\ \text{if}(x = 0)\, v := -cv\right)^*$$



Example (Bouncing Ball)

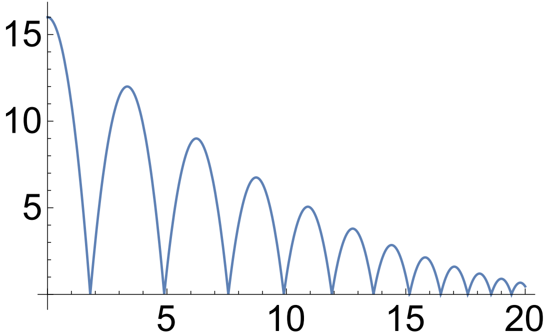
$$H{=}x{\geq}0 \quad \rightarrow \big[\big(\{x' = v, v' = -g \,\&\, x \geq 0\};\ \text{if}(x = 0)\, v := -cv\big)^*\big]\, 0{\leq}x{\leq}H$$



Not if $g < 0$ in anti-gravity

Example (Bouncing Ball)

$$H{=}x{\geq}0 \quad \rightarrow \big[\big(\{x' = v, v' = -g \,\&\, x \geq 0\};\ \text{if}(x = 0)\ v := -cv\big)^*\big]\ 0{\leq}x{\leq}H$$



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$$H{=}x{\geq}0 \land g{>}0 \rightarrow \left[\left(\{x' = v, v' = -g \,\&\, x \geq 0\};\right.\right.$$
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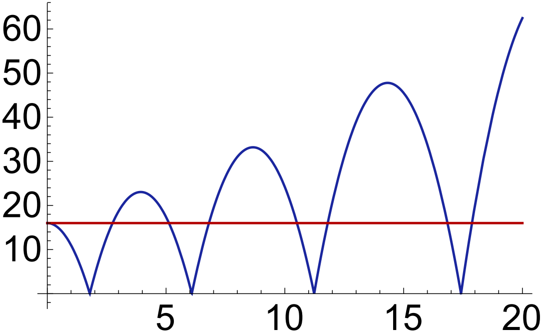
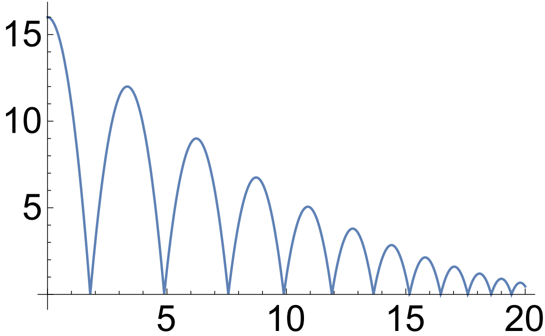


Not if $c > 1$ for anti-damping

Example (Bouncing Ball)

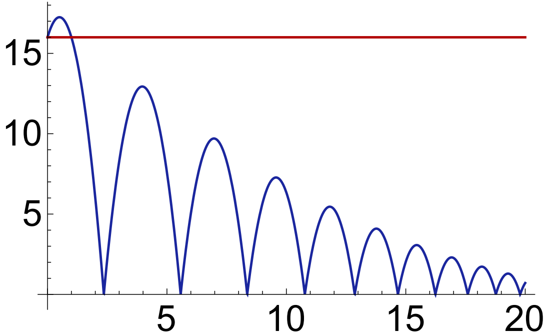
$$H{=}x{\geq}0 \land g{>}0 \rightarrow [(\{x' = v, v' = -g \,\&\, x \geq 0\};$$
$$\text{if}(x = 0)\; v := -cv)^*]\; 0{\leq}x{\leq}H$$



Example (Bouncing Ball)

$$1 \geq c \geq 0 \land H = x \geq 0 \land g > 0 \rightarrow \big[\big(\{x' = v, v' = -g \,\&\, x \geq 0\};\ \mathrm{if}(x = 0)\ v := -cv\big)^*\big]\, 0 \leq x \leq H$$

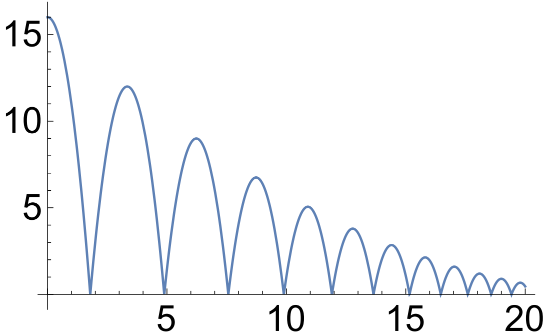
Quantum the Acrophobic Bouncing Ball



Not if $v > 0$ initial climbing

Example (Bouncing Ball)

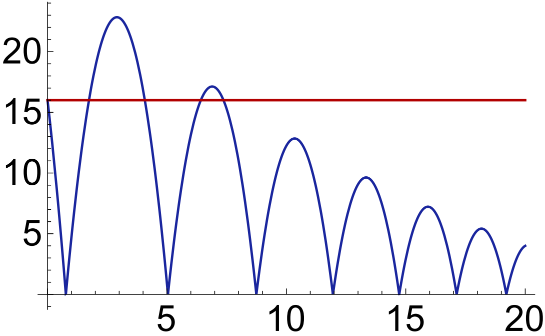
$$1\geq c\geq 0 \land H=x\geq 0 \land g>0 \to \big[\big(\{x' = v, v' = -g \,\&\, x \geq 0\};\ \text{if}(x = 0)\ v := -cv\big)^*\big]\, 0\leq x\leq H$$



Example (Bouncing Ball)

$$v\leq 0 \land 1\geq c\geq 0 \land H=x\geq 0 \land g>0 \rightarrow \left[\left(\{x' = v, v' = -g \,\&\, x \geq 0\};\ \text{if}(x = 0)\ v := -cv\right)^*\right] 0\leq x\leq H$$

Quantum the Acrophobic Bouncing Ball

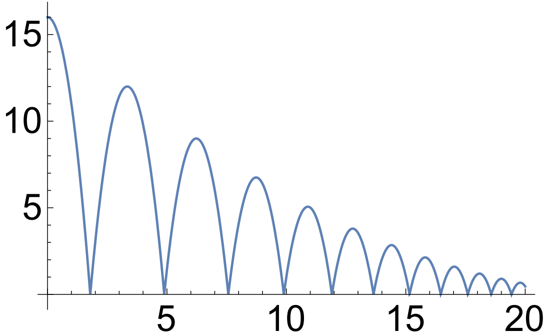


Not if $v \ll 0$ initial dribbling

Example (Bouncing Ball)

$$v\le 0 \land 1\ge c\ge 0 \land H=x\ge 0 \land g>0 \to [(\{x'=v, v'=-g \,\&\, x\ge 0\};\ \text{if}(x=0)\ v:=-cv)^*]\ 0\le x\le H$$

Quantum the Acrophobic Bouncing Ball



Example (Bouncing Ball)

$$v=0 \land 1\geq c\geq 0 \land H=x\geq 0 \land g>0 \rightarrow \big[\big(\{x' = v, v' = -g \,\&\, x \geq 0\};$$
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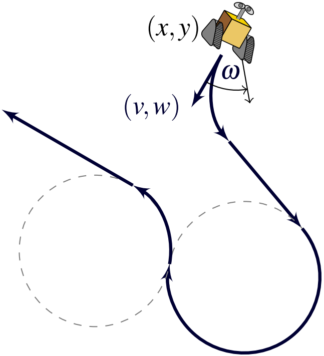
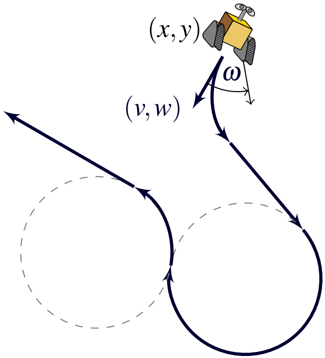
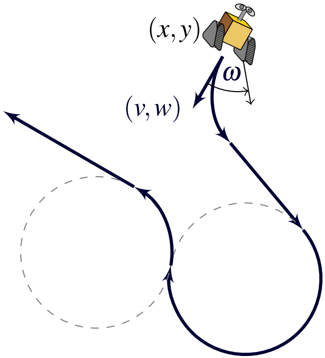
Ex: Runaround Robot





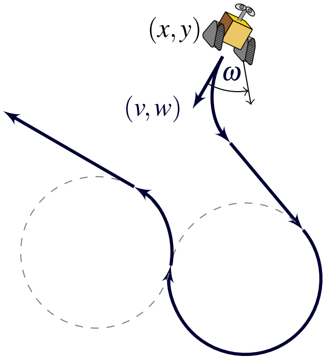
Example (Runaround Robot)

$$\big((\omega := -1 \cup \omega := 1 \cup \omega := 0);\\ \{x' = v, y' = w, v' = \omega w, w' = -\omega v\}\big)^*$$



Example (Runaround Robot)

$$(x,y) \neq o \rightarrow \Big[\Big((\omega := -1 \cup \omega := 1 \cup \omega := 0);$$
$$\{x' = v, y' = w, v' = \omega w, w' = -\omega v\}\Big)^*\Big]\,(x,y) \neq o$$



Example (Runaround Robot)

$$(x,y) \neq o \rightarrow \Big[\Big(\big(?Q_{-1}; \omega := -1 \cup ?Q_1; \omega := 1 \cup ?Q_0; \omega := 0\big);$$
$$\{x' = v, y' = w, v' = \omega w, w' = -\omega v\}\Big)^*\Big]\, (x,y) \neq o$$

Outline

Differential Dynamic Logic dL: Syntax

Definition (Hybrid program α)

$$\alpha, \beta ::= x := f(x) \mid ?Q \mid x' = f(x) \,\&\, Q \mid \alpha \cup \beta \mid \alpha ; \beta \mid \alpha^*$$

Definition (dL Formula P)

$$P, Q ::= e \geq \tilde{e} \mid \neg P \mid P \land Q \mid \forall x\, P \mid \exists x\, P \mid [\alpha]P \mid \langle \alpha \rangle P$$

Differential Dynamic Logic dL: Syntax

Discrete Assign | Test Condition | Differential Equation | Nondet. Choice | Seq. Compose | Nondet. Repeat

Definition (Hybrid program α)

$$\alpha, \beta \ ::= \ x := f(x) \mid ?Q \mid x' = f(x) \,\&\, Q \mid \alpha \cup \beta \mid \alpha ; \beta \mid \alpha^*$$

Definition (dL Formula P)

$$P, Q \ ::= \ e \geq \tilde{e} \mid \neg P \mid P \wedge Q \mid \forall x\, P \mid \exists x\, P \mid [\alpha] P \mid \langle \alpha \rangle P$$

All Reals | Some Reals | All Runs | Some Runs

Definition (Hybrid program semantics) $([\![\cdot]\!] : \mathrm{HP} \to \wp(\mathcal{S} \times \mathcal{S}))$

$$\begin{aligned}
[\![x := f(x)]\!] &= \{(\omega,\nu) : \nu = \omega \text{ except } \nu[\![x]\!] = \omega[\![f(x)]\!]\}\\
[\![?Q]\!] &= \{(\omega,\omega) : \omega \in [\![Q]\!]\}\\
[\![x' = f(x)]\!] &= \{(\varphi(0),\varphi(r)) : \varphi \models x' = f(x) \text{ for some duration } r\}\\
[\![\alpha \cup \beta]\!] &= [\![\alpha]\!] \cup [\![\beta]\!]\\
[\![\alpha;\beta]\!] &= [\![\alpha]\!] \circ [\![\beta]\!]\\
[\![\alpha^*]\!] &= [\![\alpha]\!]^* = \bigcup_{n\in\mathbb{N}} [\![\alpha^n]\!]
\end{aligned}$$

compositional semantics

Definition (dL semantics) $([\![\cdot]\!] : \mathrm{Fml} \to \wp(\mathcal{S}))$

$$\begin{aligned}
[\![e \geq \tilde{e}]\!] &= \{\omega : \omega[\![e]\!] \geq \omega[\![\tilde{e}]\!]\}\\
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[\![[\alpha]P]\!] &= [\![\neg\langle\alpha\rangle\neg P]\!] = \{\omega : \nu \in [\![P]\!] \text{ for all } \nu : (\omega,\nu) \in [\![\alpha]\!]\}\\
[\![\exists x\, P]\!] &= \{\omega : \omega_x^r \in [\![P]\!] \text{ for some } r \in \mathbb{R}\}
\end{aligned}$$

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