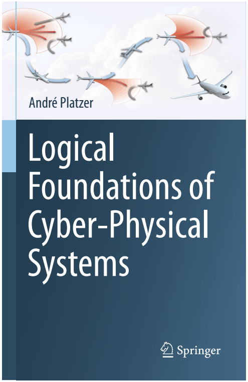
11: Differential Equations & Proofs

Logical Foundations of Cyber-Physical Systems



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Outline

1. Learning Objectives
2. Differential Invariants
   - Recap: Ingredients for Differential Equation Proofs
   - Soundness: Derivations Lemma
   - Differential Weakening
   - Equational Differential Invariants
   - Differential Invariant Inequalities
   - Disequational Differential Invariants
   - Example Proof: Damped Oscillator
   - Conjunctive Differential Invariants
   - Disjunctive Differential Invariants
   - Assuming Invariants
3. Differential Cuts
4. Soundness
5. Summary

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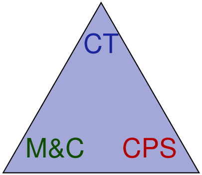
Learning Objectives

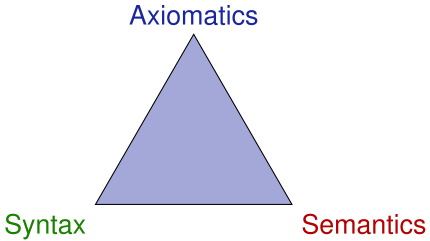
Differential Equations & Proofs

discrete vs. continuous analogy
rigorous reasoning about ODEs
beyond differential invariant terms
differential invariant formulas
cut principles for differential equations
axiomatization of ODEs
differential facet of logical trinity



understanding continuous dynamics
relate discrete+continuous

operational CPS effects
state changes along ODE



Syntax defines the notation
What problems are we allowed to write down?

Semantics what carries meaning.
What real or mathematical objects does the syntax stand for?

Axiomatics internalizes semantic relations into universal syntactic transformations.
How does the semantics of $e \geq \tilde{e}$ relate to semantics of $e - \tilde{e} \geq 0$, syntactically? What about derivatives?

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Differentials

Syntax

$$e ::= x \mid x' \mid c \mid e+k \mid e\cdot k \mid (e)'$$

Semantics

$$\omega[\![(e)']\!] = \sum_x \omega(x') \frac{\partial [\![e]\!]}{\partial x}(\omega)$$

Axioms

$$\begin{aligned}
(e+k)' &= (e)' + (k)' \\
(e\cdot k)' &= (e)'\cdot k + e\cdot(k)' \\
(c())' &= 0 && \text{for constants/numbers } c() \\
(x)' &= x' && \text{for variables } x \in \mathscr{V}
\end{aligned}$$

ODE

$$[\![x' = f(x)\,\&\,Q]\!] = \{(\varphi(0)|_{\{x'\}^\complement}, \varphi(r)) : \varphi \models x' = f(x) \land Q$$
$$\text{for some } \varphi : [0,r] \to \mathscr{S}, \text{ some } r \in \mathbb{R}\}$$

$$\varphi(z)(x') = \frac{\mathrm{d}\varphi(t)(x)}{\mathrm{d}t}(z) \qquad \ldots$$

Differential Substitution Lemmas

Lemma (Differential lemma) (Differential value vs. Time-derivative)

If $\varphi \models x' = f(x) \land Q$ *for duration* $r{>}0$, *then for all* $0{\le}z{\le}r$, $FV(e) \subseteq \{x\}$:

$$\varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Lemma (Differential assignment) (Effect on Differentials)

If $\varphi \models x' = f(x) \land Q$ *then* $\varphi \models P \leftrightarrow [x' := f(x)]P$

Lemma (Derivations) (Equations of Differentials)

$$
\begin{aligned}
(e+k)' &= (e)' + (k)' \\
(e \cdot k)' &= (e)' \cdot k + e \cdot (k)' \\
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Differential Substitution Lemmas $\rightsquigarrow$ Proofs

Lemma (Differential lemma) (Differential value vs. Time-derivative)

If $\varphi \models x' = f(x) \land Q$ *for duration* $r>0$, *then for all* $0\le z\le r$, $FV(e) \subseteq \{x\}$:

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$$DE\quad [x' = f(x)\,\&\, Q]P \leftrightarrow [x' = f(x)\,\&\, Q][x' := f(x)]P$$

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$$
\begin{array}{lll}
+' & (e+k)' = (e)' + (k)' \\
\cdot' & (e\cdot k)' = (e)'\cdot k + e\cdot (k)' \\
c' & (c())' = 0 \\
x' & (x)' = x'
\end{array}
$$

Soundness: Proof of Derivations Lemma

Lemma (Derivations) (Equations of Differentials)

$+'$	$(e+k)' = (e)' + (k)'$
$\cdot'$	$(e \cdot k)' = (e)' \cdot k + e \cdot (k)'$
c'	$(c())' = 0$
x'	$(x)' = x'$

Soundness: Proof of Derivations Lemma

Lemma (Derivations) (Equations of Differentials)

$+'$ $\quad (e+k)' = (e)' + (k)'$

Proof.

$$\omega[\![(e+k)']\!] =$$

$\square$

Soundness: Proof of Derivations Lemma

Lemma (Derivations) (Equations of Differentials)

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Proof.

$$\omega[\![(e+k)']\!] = \sum_x \omega(x') \frac{\partial [\![e+k]\!]}{\partial x}(\omega)$$

□

Soundness: Proof of Derivations Lemma

Lemma (Derivations) (Equations of Differentials)

$+'$ $\quad (e+k)' = (e)' + (k)'$

Proof.

$$\omega[\![(e+k)']\!] = \sum_x \omega(x') \frac{\partial [\![e+k]\!]}{\partial x}(\omega) = \sum_x \omega(x') \frac{\partial ([\![e]\!] + [\![k]\!])}{\partial x}(\omega)$$

$\square$

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$$\omega[\![(e+k)']\!] = \sum_x \omega(x') \frac{\partial [\![e+k]\!]}{\partial x}(\omega) = \sum_x \omega(x') \frac{\partial ([\![e]\!] + [\![k]\!])}{\partial x}(\omega)$$

$$= \sum_x \omega(x') \Big(\frac{\partial [\![e]\!]}{\partial x}(\omega) + \frac{\partial [\![k]\!]}{\partial x}(\omega) \Big)$$

□

Lemma (Derivations) (Equations of Differentials)

$+'$ $\quad (e+k)' = (e)' + (k)'$

Proof.

$$\omega[\![(e+k)']\!] = \sum_x \omega(x')\frac{\partial[\![e+k]\!]}{\partial x}(\omega) = \sum_x \omega(x')\frac{\partial([\![e]\!]+[\![k]\!])}{\partial x}(\omega)$$
$$= \sum_x \omega(x')\Big(\frac{\partial[\![e]\!]}{\partial x}(\omega) + \frac{\partial[\![k]\!]}{\partial x}(\omega)\Big)$$
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&= \sum_x \omega(x') \Big(\frac{\partial [\![e]\!]}{\partial x}(\omega) + \frac{\partial [\![k]\!]}{\partial x}(\omega) \Big) \\
&= \sum_x \omega(x') \frac{\partial [\![e]\!]}{\partial x}(\omega) + \sum_x \omega(x') \frac{\partial [\![k]\!]}{\partial x}(\omega) \\
&= \omega[\![(e)']\!] + \omega[\![(k)']\!]
\end{aligned}$$

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&= \omega[\![(e)']\!] + \omega[\![(k)']\!] = \omega[\![(e)' + (k)']\!]
\end{aligned}
$$

$\square$

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&= \omega[\![(e)']\!] + \omega[\![(k)']\!] = \omega[\![(e)'+(k)']\!] \quad \text{for all } \omega
\end{aligned}$$

□

Differential Substitution Lemmas $\rightsquigarrow$ Proofs

Lemma (Differential lemma) (Differential value vs. Time-derivative)

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$$\varphi(z)[\![(e)']\!] = \frac{\mathrm{d}\varphi(t)[\![e]\!]}{\mathrm{d}t}(z)$$

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c' $\quad (c())' = 0$

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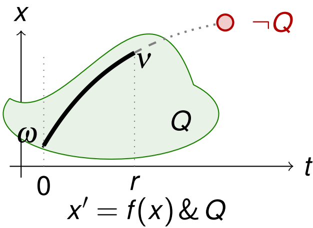

ODE

$$[\![x' = f(x) \,\&\, Q]\!] = \{(\varphi(0)|_{\{x'\}^\complement}, \varphi(r)) : \varphi \models x' = f(x) \land Q$$
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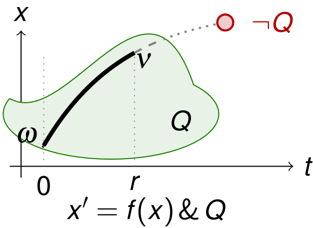
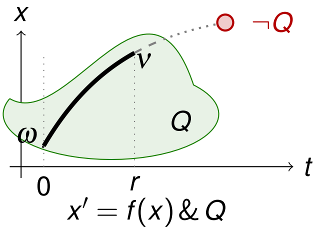


DW $[x' = f(x) \,\&\, Q]P \leftrightarrow [x' = f(x) \,\&\, Q](Q \rightarrow P)$

ODE

$$[\![x' = f(x) \,\&\, Q]\!] = \{(\varphi(0)|_{\{x'\}^\complement}, \varphi(r)) : \varphi \models x' = f(x) \wedge Q$$
$$\text{for some } \varphi : [0,r] \rightarrow \mathscr{S}, \text{ some } r \in \mathbb{R}\}$$
$$\varphi(z)(x') = \frac{\mathrm{d}\varphi(t)(x)}{\mathrm{d}t}(z)$$

Differential equations cannot leave their domains.



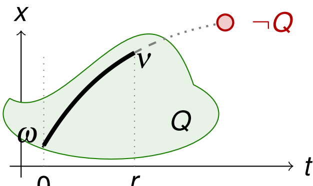
DW $[x' = f(x) \,\&\, Q]P \leftrightarrow [x' = f(x) \,\&\, Q](Q \rightarrow P)$

Example (Bouncing ball)

$$\text{DW}\frac{}{\vdash [x' = v, v' = -g \,\&\, x \geq 0]0 \leq x}$$

No need to solve any ODEs to prove that bouncing ball is above ground.

Differential Weakening



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$$\dfrac{\overline{\vdash [x' = v, v' = -g \,\&\, x \geq 0](x \geq 0 \rightarrow 0 \leq x)}\ \text{G}}{\vdash [x' = v, v' = -g \,\&\, x \geq 0]0 \leq x}\ \text{DW}$$

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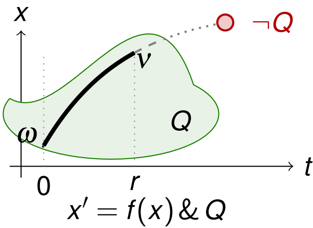

DW $[x' = f(x) \& Q]P \leftrightarrow [x' = f(x) \& Q](Q \rightarrow P)$

Example (Bouncing ball)

$$\dfrac{\dfrac{\overline{\vdash x \geq 0 \rightarrow 0 \leq x}\;\mathbb{R}}{\vdash [x' = v, v' = -g \& x \geq 0](x \geq 0 \rightarrow 0 \leq x)}\;\text{G}}{\vdash [x' = v, v' = -g \& x \geq 0]0 \leq x}\;\text{DW}$$

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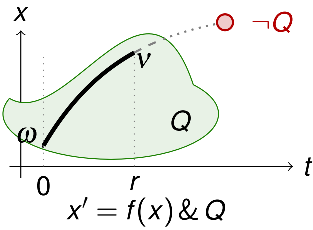

Example (Bouncing ball)

$$\dfrac{\dfrac{\dfrac{*}{\vdash x \geq 0 \rightarrow 0 \leq x}\,\mathbb{R}}{\vdash [x' = v, v' = -g \,\&\, x \geq 0](x \geq 0 \rightarrow 0 \leq x)}\,\mathrm{G}}{\vdash [x' = v, v' = -g \,\&\, x \geq 0]\, 0 \leq x}\,\mathrm{DW}$$

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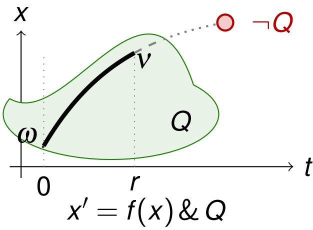
Differential Weakening

Differential Weakening

$$\text{dW}\ \frac{}{\Gamma \vdash [x' = f(x)\,\&\, Q]P, \Delta}$$

$$\text{DW}\quad [x' = f(x)\,\&\, Q]P \leftrightarrow [x' = f(x)\,\&\, Q](Q \rightarrow P)$$



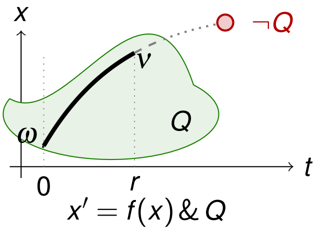
Example (Bouncing ball)

$$\dfrac{\dfrac{\dfrac{*}{\vdash x \geq 0 \rightarrow 0 \leq x}\ \mathbb{R}}{\vdash [x' = v, v' = -g\,\&\, x \geq 0](x \geq 0 \rightarrow 0 \leq x)}\ \text{G}}{\vdash [x' = v, v' = -g\,\&\, x \geq 0]\, 0 \leq x}\ \text{DW}$$

No need to solve any ODEs to prove that bouncing ball is above ground.

Differential Weakening

$$\text{dW}\ \frac{Q \vdash P}{\Gamma \vdash [x' = f(x) \,\&\, Q]P, \Delta}$$



$$\text{DW}\ \ [x' = f(x) \,\&\, Q]P \leftrightarrow [x' = f(x) \,\&\, Q](Q \to P)$$

Example (Bouncing ball)

$$\cfrac{\cfrac{\cfrac{*}{\vdash x \geq 0 \to 0 \leq x}\ \mathbb{R}}{\vdash [x' = v, v' = -g \,\&\, x \geq 0](x \geq 0 \to 0 \leq x)}\ \text{G}}{\vdash [x' = v, v' = -g \,\&\, x \geq 0]0 \leq x}\ \text{DW}$$

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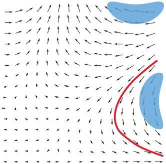

Differential Invariant

$$\text{dI}\quad \frac{\vdash [x' := f(x)](e)' = 0}{e = 0 \vdash [x' = f(x) \,\&\, Q] e = 0}$$

$$\text{DI}\quad \big([x' = f(x)]\, e = 0 \leftrightarrow e = 0\big) \leftarrow [x' = f(x)]\,(e)' = 0$$

$$\text{DE}\quad [x' = f(x) \,\&\, Q]P \leftrightarrow [x' = f(x) \,\&\, Q][x' := f(x)]P$$

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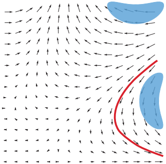

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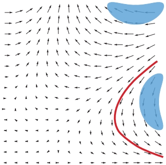

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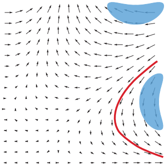
DW $[x' = f(x)\,\&\,Q]P \leftrightarrow [x' = f(x)\,\&\,Q](Q \rightarrow P)$

Proof (dI is a derived rule).

$$\text{DI}\ \frac{}{e = 0 \vdash [x' = f(x)\,\&\,Q]e = 0}$$

□



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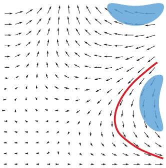

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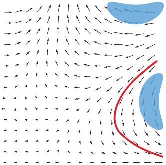
$\square$



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Proof (dI is a derived rule).

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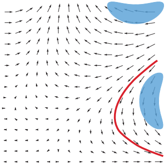


Differential Invariant

$$\text{dI}\ \frac{Q \vdash [x' := f(x)](e)' = 0}{e = 0 \vdash [x' = f(x) \,\&\, Q]e = 0}$$

DI $\big([x' = f(x) \,\&\, Q]\, e = 0 \leftrightarrow [?Q]e = 0\big) \leftarrow [x' = f(x) \,\&\, Q]\, (e)' = 0$

DE $[x' = f(x) \,\&\, Q]P \leftrightarrow [x' = f(x) \,\&\, Q][x' := f(x)]P$

DW $[x' = f(x) \,\&\, Q]P \leftrightarrow [x' = f(x) \,\&\, Q](Q \rightarrow P)$

Proof (dI is a derived rule).

$$\dfrac{\dfrac{\dfrac{\dfrac{Q \vdash [x' := f(x)](e)' = 0}{\vdash [x' = f(x) \,\&\, Q](Q \rightarrow [x' := f(x)](e)' = 0)}\text{G},\rightarrow\text{R}}{\vdash [x' = f(x) \,\&\, Q][x' := f(x)](e)' = 0}\text{DW}}{\vdash [x' = f(x) \,\&\, Q](e)' = 0}\text{DE}}{e = 0 \vdash [x' = f(x) \,\&\, Q]e = 0}\text{DI}$$

$$\text{G}\ \frac{P}{[\alpha]P}$$

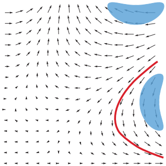
□

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r\;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI}\;\; \frac{}{e = k \vdash [x' = f(x)]e = k}$$

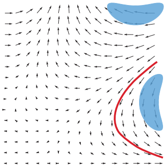


Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI} \;\; \frac{\vdash [x' := f(x)](e)' = (k)'}{e = k \vdash [x' = f(x)]e = k}$$



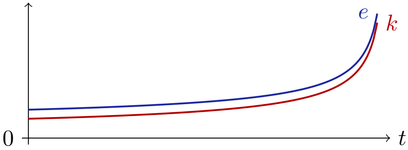
$$\text{DI} \;\; \big([x' = f(x)]\, e = k \leftrightarrow e = k\big) \leftarrow [x' = f(x)]\,(e)' = (k)'$$

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI} \quad \frac{\vdash [x' := f(x)](e)' = (k)'}{e = k \vdash [x' = f(x)]e = k}$$



$$\text{DI} \quad \big([x' = f(x)]\, e = k \leftrightarrow e = k\big) \leftarrow [x' = f(x)]\,(e)' = (k)'$$

Proof (= rate of change from = initial value. Mean-value theorem).

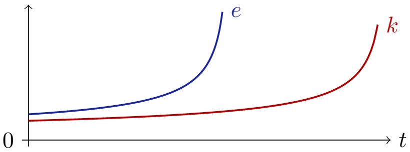
$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] = \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z) \qquad \square$$

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI}\; \frac{\vdash [x' := f(x)](e)' \geq (k)'}{e \geq k \vdash [x' = f(x)]e \geq k}$$



$$\text{DI}\;\; \big([x' = f(x)]\, e \geq k \leftrightarrow e \geq k\big) \leftarrow [x' = f(x)]\,(e)' \geq (k)'$$

Proof ($\geq$ rate of change from $\geq$ initial value. Mean-value theorem).

$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] \geq \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z)$$

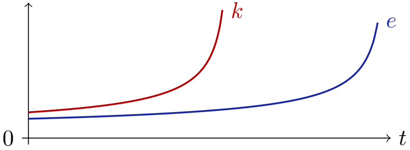
□

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI}\;\frac{\vdash [x' := f(x)](e)' \le (k)'}{e \le k \vdash [x' = f(x)]e \le k}$$



$$\text{DI}\;\big([x' = f(x)]\,e \le k \leftrightarrow e \le k\big) \leftarrow [x' = f(x)]\,(e)' \le (k)'$$

Proof ($\le$ rate of change from $\le$ initial value. Mean-value theorem).

$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] \le \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z)$$ □

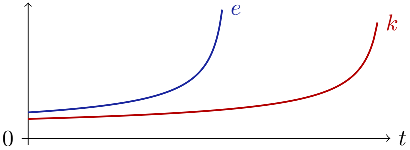
Differential Invariant Inequalities

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI} \;\; \frac{\vdash [x' := f(x)](e)' > (k)'}{e > k \vdash [x' = f(x)]e > k}$$



$$\text{DI} \;\; \big([x' = f(x)]\, e > k \leftrightarrow e > k\big) \leftarrow [x' = f(x)]\,(e)' > (k)'$$

Proof ($>$ rate of change from $>$ initial value. Mean-value theorem).

$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] > \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z)$$

□

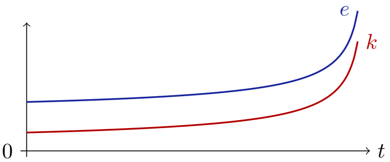
Differential Invariant Inequalities

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI}\;\frac{\vdash [x' := f(x)](e)' \ge (k)'}{e > k \vdash [x' = f(x)]e > k}$$



$$\text{DI}\;\;\big([x' = f(x)]\,e > k \leftrightarrow e > k\big) \leftarrow [x' = f(x)]\,(e)' \ge (k)'$$

Proof ($\ge$ rate of change from $>$ initial value. Mean-value theorem).

$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] \ge \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z)$$

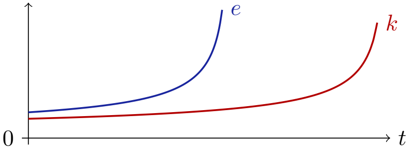
□

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \Rightarrow \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI} \quad \frac{\vdash [x' := f(x)](e)' \neq (k)'}{e \neq k \vdash [x' = f(x)]e \neq k}$$



$$\text{DI} \quad \big([x' = f(x)]\, e \neq k \leftrightarrow e \neq k\big) \leftarrow [x' = f(x)]\,(e)' \neq (k)'$$

Proof ($\neq$ rate of change from $\neq$ initial value. Mean-value theorem).

$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] \neq \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z)$$

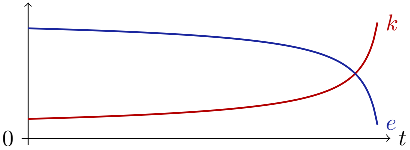
□

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI}\;\frac{\vdash [x' := f(x)](e)' \neq (k)'}{e \neq k \vdash [x' = f(x)]e \neq k}$$



$$\text{DI}\;\big([x' = f(x)]\,e \neq k \leftrightarrow e \neq k\big) \leftarrow [x' = f(x)]\,(e)' \neq (k)'$$

Proof ($\neq$ rate of change from $\neq$ initial value. Mean-value theorem).

$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] \neq \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z)$$

$\square$

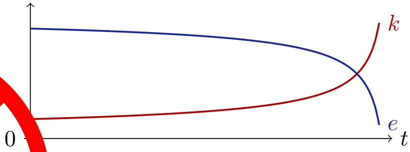
Differential Invariant Inequalities

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \wedge Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI}\;\frac{\vdash [x' := f(x)](e)' \neq (k)'}{e \neq k \vdash [x' = f(x)]e \neq k}$$



$$\text{DI}\;\; ([x' = f(x)]\,e \neq k \leftrightarrow e \neq k) \leftarrow [x' = f(x)]\,(e)' \neq (k)'$$

Proof ($\neq$ rate of change from $\neq$ initial value. Mean-value theorem).

$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] \neq \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z)$$ □

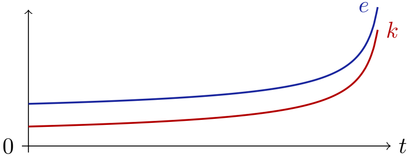
Differential Invariant Inequalities

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0 \le z \le r \;\; \varphi(z)[\![(e)']\!] = \frac{d\varphi(t)[\![e]\!]}{dt}(z)$$

Differential Invariant

$$\text{dI} \;\; \frac{\vdash [x' := f(x)](e)' = (k)'}{e \neq k \vdash [x' = f(x)]e \neq k}$$



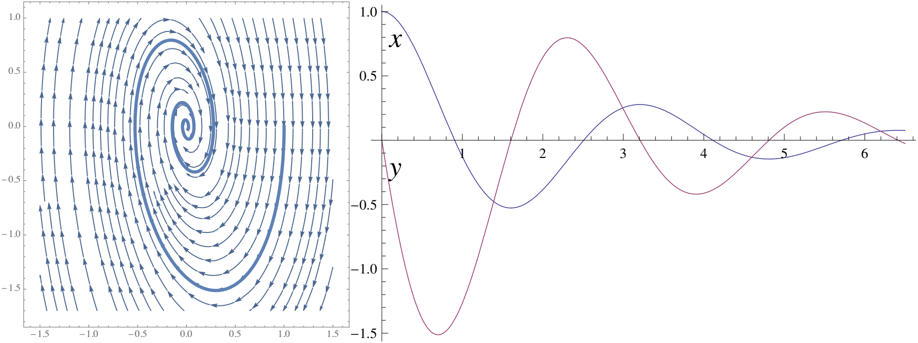
$$\text{DI} \;\; \big([x' = f(x)]\, e \neq k \leftrightarrow e \neq k\big) \leftarrow [x' = f(x)]\,(e)' = (k)'$$

Proof (= rate of change from ≠ initial value. Mean-value theorem).

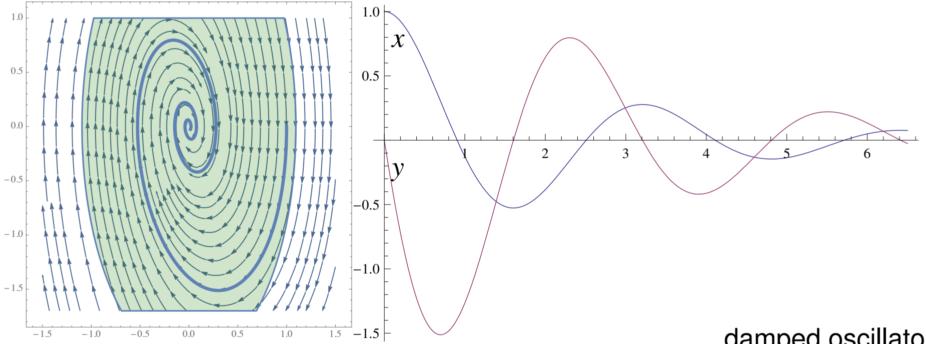
$$\frac{d\varphi(t)[\![e]\!]}{dt}(z) = \varphi(z)[\![(e)']\!] = \varphi(z)[\![(k)']\!] = \frac{d\varphi(t)[\![k]\!]}{dt}(z) \qquad \square$$

Example: Differential Invariant Inequalities

$$\frac{}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y \,\&\, \omega\geq 0 \land d\geq 0]\,\omega^2x^2+y^2\leq c^2}$$

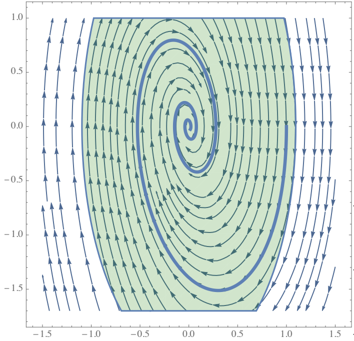


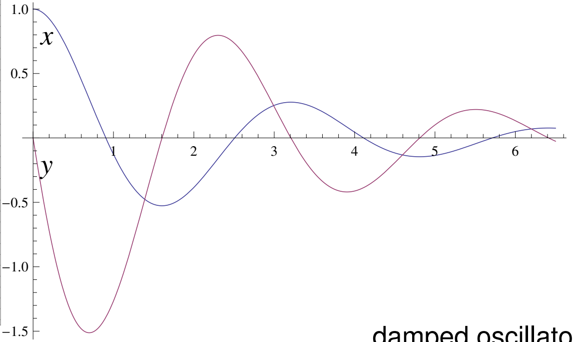
$$\frac{}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y \,\&\, \omega\ge0 \land d\ge0]\,\omega^2x^2+y^2\le c^2}$$



damped oscillator

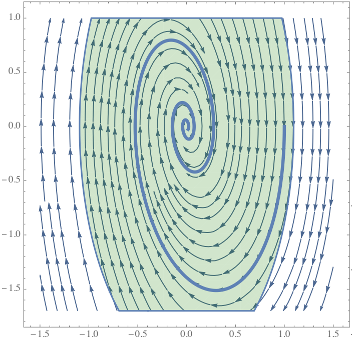
$$\dfrac{\omega\geq 0 \land d\geq 0 \vdash [x':=y][y':=-\omega^2 x - 2d\omega y]\, 2\omega^2 x x' + 2y y' \leq 0}{\omega^2 x^2 + y^2 \leq c^2 \vdash [x' = y, y' = -\omega^2 x - 2d\omega y \,\&\, \omega\geq 0 \land d\geq 0]\, \omega^2 x^2 + y^2 \leq c^2}$$

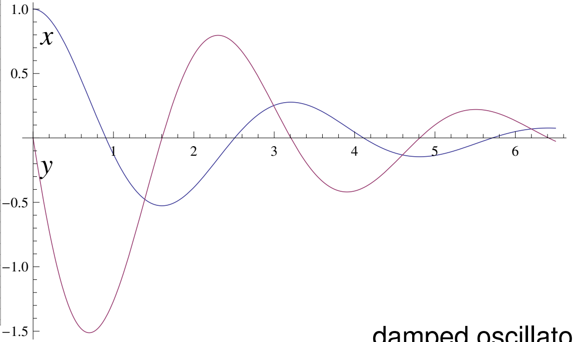




damped oscillator

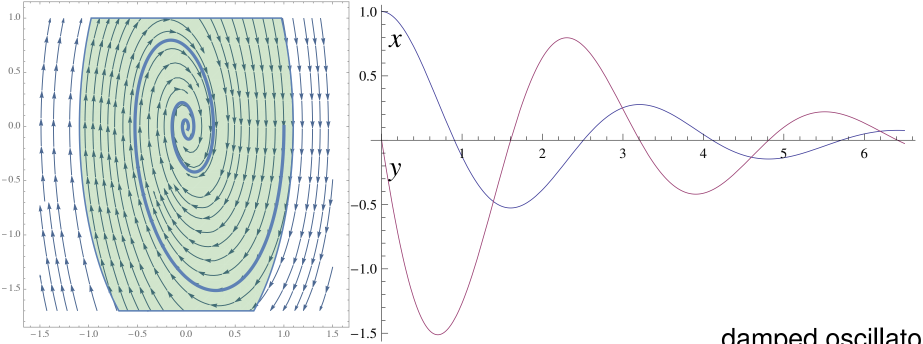
$$\dfrac{\dfrac{\omega{\geq}0 \land d{\geq}0 \vdash 2\omega^2 x y + 2y(-\omega^2 x - 2d\omega y) \leq 0}{\omega{\geq}0 \land d{\geq}0 \vdash [x' := y][y' := -\omega^2 x - 2d\omega y]\, 2\omega^2 x x' + 2 y y' \leq 0}}{\omega^2 x^2 + y^2 \leq c^2 \vdash [x' = y, y' = -\omega^2 x - 2d\omega y \,\&\, \omega{\geq}0 \land d{\geq}0]\, \omega^2 x^2 + y^2 \leq c^2}$$





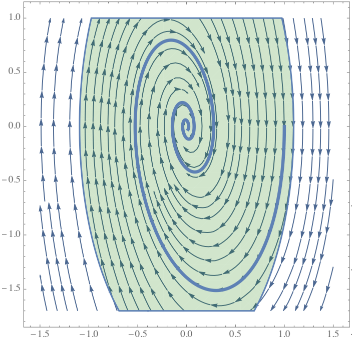
damped oscillator

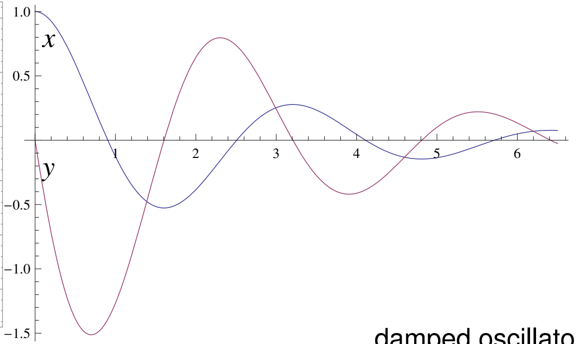
$$\dfrac{\dfrac{\dfrac{*}{\omega\geq 0 \land d\geq 0 \vdash 2\omega^2 xy + 2y(-\omega^2 x - 2d\omega y) \leq 0}}{\omega\geq 0 \land d\geq 0 \vdash [x':=y][y':=-\omega^2 x - 2d\omega y]\, 2\omega^2 x x' + 2yy' \leq 0}}{\omega^2x^2+y^2\leq c^2 \vdash [x' = y, y' = -\omega^2 x - 2d\omega y \,\&\, \omega\geq 0 \land d\geq 0]\, \omega^2x^2+y^2\leq c^2}$$



damped oscillator

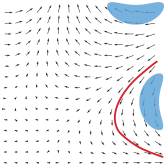
$$\dfrac{\dfrac{\dfrac{*}{\omega\geq 0\land \color{red}{d\geq 0}\vdash 2\omega^2xy+2y(-\omega^2x-2d\omega y)\leq 0}}{\omega\geq 0\land \color{red}{d\geq 0}\vdash [x':=y][y':=-\omega^2x-2d\omega y]\,2\omega^2xx'+2yy'\leq 0}}{\omega^2x^2+y^2\leq c^2\vdash [x'=y,y'=-\omega^2x-2d\omega y\;\&\;\omega\geq 0\land \color{red}{d\geq 0}]\,\omega^2x^2+y^2\leq c^2}$$





damped oscillator

Differential Invariant Conjunctions

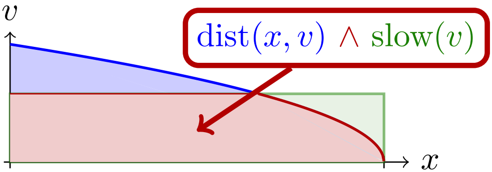


Differential Invariant

$$\text{dI}\ \frac{}{A \wedge B \vdash [x' = f(x)](A \wedge B)}$$

Differential Invariant

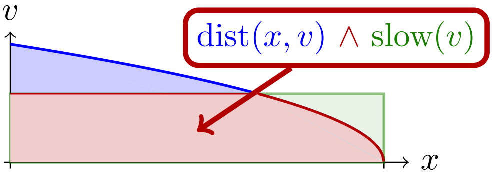
$$\text{dI}\ \frac{\vdash [x' := f(x)]((A)' \land (B)')}{A \land B \vdash [x' = f(x)](A \land B)}$$



$$\text{DI}\ \ \big([x' = f(x)](A \land B) \leftrightarrow (A \land B)\big) \leftarrow [x' = f(x))]((A)' \land (B)')$$

Differential Invariant

$$\text{dI}\ \frac{\vdash [x' := f(x)]((A)' \land (B)')}{A \land B \vdash [x' = f(x)](A \land B)}$$



$$\text{DI}\ \big([x' = f(x)](A \land B) \leftrightarrow (A \land B)\big) \leftarrow [x' = f(x))]((A)' \land (B)')$$

Proof (separately).

$$\text{[]}\land\text{,WL}\ \frac{\text{DI}\ \dfrac{\vdash [x' = f(x)](A)'}{A \vdash [x' = f(x)]A} \qquad \text{DI}\ \dfrac{\vdash [x' = f(x)](B)'}{B \vdash [x' = f(x)]B}}{A \land B \vdash [x' = f(x)](A \land B)}$$

□

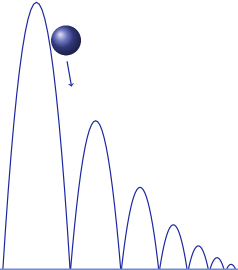
$$[]\land\ \ [\alpha](P \land Q) \leftrightarrow [\alpha]P \land [\alpha]Q$$

$$\frac{}{2gx = 2gH - v^2 \vdash [x'' = -g \,\&\, x \geq 0](2gx = 2gH - v^2 \wedge x \geq 0)}$$

No solutions but still a proof.

Simple proof with simple arithmetic.

Independent proofs for independent questions.



Quantum's Back for a Differential Invariant Proof

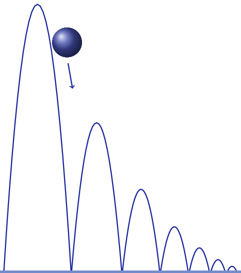
$$[]\wedge \quad [\alpha](P \wedge Q) \leftrightarrow [\alpha]P \wedge [\alpha]Q$$

$$[]\wedge \frac{\dfrac{}{2gx{=}2gH{-}v^2 \vdash [x''{=}{-}g \,\&\, x{\geq}0]2gx{=}2gH{-}v^2} \qquad \dfrac{}{\vdash [x''{=}{-}g \,\&\, x{\geq}0]x{\geq}0}}{2gx{=}2gH{-}v^2 \vdash [x'' = -g \,\&\, x{\geq}0](2gx{=}2gH{-}v^2 \wedge x{\geq}0)}$$

No solutions but still a proof.

Simple proof with simple arithmetic.

Independent proofs for independent questions.

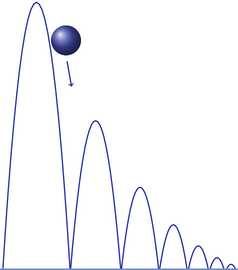


$$\mathrm{[]\wedge}\;\cfrac{\mathrm{dI}\;\cfrac{\overline{x\geq0 \vdash [{\color{red}x'}:=v][{\color{red}v'}:=-g]2g{\color{red}x'} = -2v{\color{red}v'}}}{2gx=2gH-v^2 \vdash [x''=-g\,\&\,x\geq0]2gx=2gH-v^2} \qquad \overline{\vdash [x''=-g\,\&\,x\geq0]x\geq0}}{2gx=2gH-v^2 \vdash [x''=-g\,\&\,x\geq0](2gx=2gH-v^2 \wedge x\geq0)}$$

No solutions but still a proof.

Simple proof with simple arithmetic.

Independent proofs for independent questions.



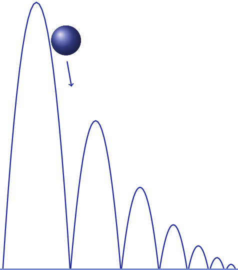
Quantum's Back for a Differential Invariant Proof

$$\text{[]}\land\,\dfrac{\text{dI}\,\dfrac{\text{[:=]}\,\dfrac{\overline{x\geq0 \vdash 2gv = -2v(-g)}}{x\geq0 \vdash [x':=v][v':=-g]2gx' = -2vv'}}{2gx=2gH-v^2 \vdash [x''=-g \,\&\, x\geq0]2gx=2gH-v^2} \qquad \overline{\vdash [x''=-g\,\&\,x\geq0]x\geq0}}{2gx=2gH-v^2 \vdash [x''=-g\,\&\,x\geq0](2gx=2gH-v^2 \land x\geq0)}$$

No solutions but still a proof.

Simple proof with simple arithmetic.

Independent proofs for independent questions.



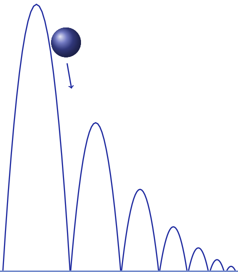
Quantum's Back for a Differential Invariant Proof

$$[]\wedge\,\dfrac{\mathrm{dI}\,\dfrac{[:=]\,\dfrac{\mathbb{R}\,\dfrac{*}{x\geq 0 \vdash 2gv = -2v(-g)}}{x\geq 0 \vdash [x':=v][v':=-g]2gx' = -2vv'}}{2gx=2gH-v^2 \vdash [x''=-g \,\&\, x\geq 0]2gx=2gH-v^2} \qquad \dfrac{}{\vdash [x''=-g \,\&\, x\geq 0]x\geq 0}}{2gx=2gH-v^2 \vdash [x''=-g \,\&\, x\geq 0](2gx=2gH-v^2 \wedge x\geq 0)}$$

No solutions but still a proof.

Simple proof with simple arithmetic.

Independent proofs for independent questions.



Quantum's Back for a Differential Invariant Proof

$$\dfrac{\dfrac{\dfrac{\dfrac{*}{x\geq0 \vdash 2gv = -2v(-g)}\;\mathbb{R}}{x\geq0 \vdash [x':=v][v':=-g]2gx' = -2vv'}\;[:=]}{2gx=2gH-v^2 \vdash [x''=-g\,\&\,x\geq0]2gx=2gH-v^2}\;\mathrm{dI} \qquad \dfrac{\overline{\color{red}{x\geq0} \vdash x\geq0}}{\vdash [x''=-g\,\&\,\color{red}{x\geq0}]x\geq0}\;\mathrm{dW}}{2gx=2gH-v^2 \vdash [x''=-g\,\&\,x\geq0](2gx=2gH-v^2 \land x\geq0)}\;[]\land$$

No solutions but still a proof.

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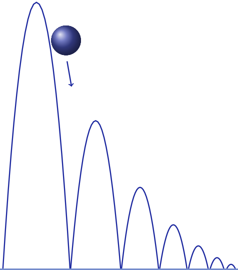

Quantum's Back for a Differential Invariant Proof

$$\dfrac{\dfrac{\dfrac{\dfrac{*}{x\geq0 \vdash 2gv = -2v(-g)}\,\mathbb{R}}{x\geq0 \vdash [x':=v][v':=-g]2gx' = -2vv'}\,[:=]}{2gx=2gH-v^2 \vdash [x''=-g \,\&\, x\geq0]2gx=2gH-v^2}\,\mathrm{dI} \qquad \dfrac{\dfrac{*}{x\geq0\vdash x\geq0}\,\mathrm{id}}{\vdash [x''=-g\,\&\,x\geq0]x\geq0}\,\mathrm{dW}}{2gx=2gH-v^2 \vdash [x''=-g\,\&\,x\geq0](2gx=2gH-v^2 \wedge x\geq0)}\,[]\wedge$$

No solutions but still a proof.

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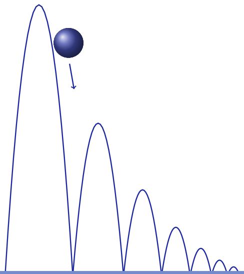
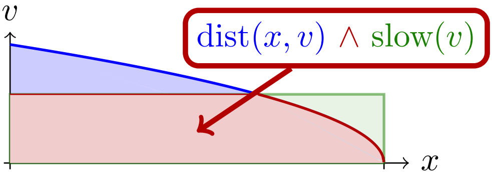


Differential Invariant

$$\text{dI}\ \frac{\vdash [x' := f(x)]((A)' \land (B)')}{A \land B \vdash [x' = f(x)](A \land B)}$$

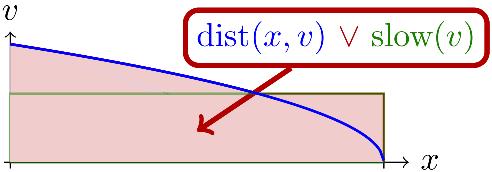


$$\text{DI}\ \big([x' = f(x)](A \land B) \leftrightarrow (A \land B)\big) \leftarrow [x' = f(x))]((A)' \land (B)')$$

Differential Invariant Disjunctions

Differential Invariant

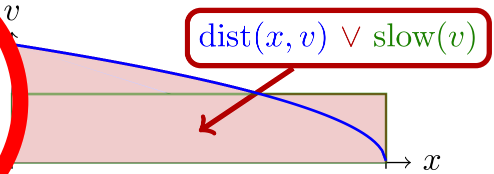
$$\text{dI}\ \frac{\vdash [x' := f(x)]((A)' \lor (B)')}{A \lor B \vdash [x' = f(x)](A \lor B)}$$



$$\text{DI}\ \big([x' = f(x)](A \lor B) \leftrightarrow (A \lor B)\big) \leftarrow [x' = f(x))]((A)' \lor (B)')$$

Differential Invariant

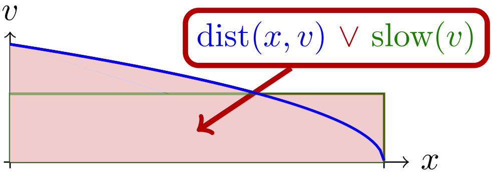
$$\text{dI}\ \frac{\vdash [x' := f(x)]((A)' \vee (B)')}{A \vee B \vdash [x' = f(x)](A \vee B)}$$



$$\text{DI}\ \big([x' = f(x)](A \vee B) \leftrightarrow (A \vee B)\big) \leftarrow [x' = f(x))]((A)' \vee (B)')$$

Differential Invariant

$$\text{dI}\ \frac{\vdash [x' := f(x)]((A)' \land (B)')}{A \lor B \vdash [x' = f(x)](A \lor B)}$$

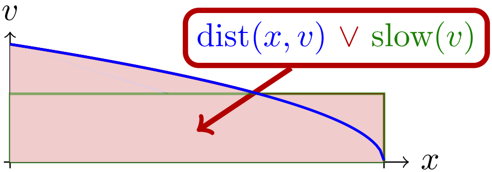


$$\text{DI}\ \big([x' = f(x)](A \lor B) \leftrightarrow (A \lor B)\big) \leftarrow [x' = f(x))]((A)' \land (B)')$$

Differential Invariant Disjunctions

Differential Invariant

$$\text{dI}\quad \frac{\vdash [x' := f(x)]((A)' \land (B)')}{A \lor B \vdash [x' = f(x)](A \lor B)}$$



$$\text{DI}\quad \big([x' = f(x)](A \lor B) \leftrightarrow (A \lor B)\big) \leftarrow [x' = f(x))]((A)' \land (B)')$$

Proof (separately).

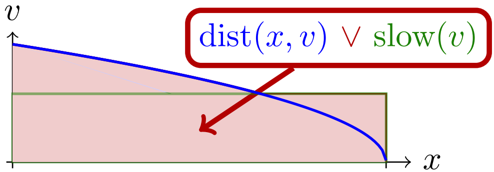
$$\vee\text{L}\;\dfrac{\text{MR}\;\dfrac{\dfrac{*}{A \vdash A \lor B} \quad \text{DI}\;\dfrac{\vdash [x'=f(x)](A)'}{A \vdash [x'=f(x)]A}}{A \vdash [x' = f(x)](A \lor B)} \qquad \text{MR}\;\dfrac{\dfrac{*}{B \vdash A \lor B} \quad \text{DI}\;\dfrac{\vdash [x'=f(x)](B)'}{B \vdash [x'=f(x)]B}}{B \vdash [x' = f(x)](A \lor B)}}{A \lor B \vdash [x' = f(x)](A \lor B)}$$

$\square$

Differential Invariant Disjunctions

Differential Invariant

$$\text{dI}\ \frac{\vdash [x' := f(x)]((A)' \land (B)')}{A \lor B \vdash [x' = f(x)](A \lor B)}$$



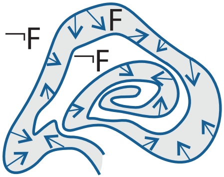
$$\text{DI}\ \big([x' = f(x)](A \lor B) \leftrightarrow (A \lor B)\big) \leftarrow [x' = f(x))]((A)' \land (B)')$$

Proof (separately).

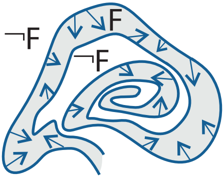
$$\cfrac{\cfrac{\cfrac{*}{A \vdash A \lor B} \quad \text{DI}\cfrac{\vdash [x'=f(x)](A)'}{A \vdash [x'=f(x)]A}}{A \vdash [x' = f(x)](A \lor B)}\text{MR} \quad \cfrac{\cfrac{*}{B \vdash A \lor B} \quad \text{DI}\cfrac{\vdash [x'=f(x)](B)'}{B \vdash [x'=f(x)]B}}{B \vdash [x' = f(x)](A \lor B)}\text{MR}}{A \lor B \vdash [x' = f(x)](A \lor B)}\lor\text{L}$$

□

$$[]\land\ \ [\alpha](P \land Q) \leftrightarrow [\alpha]P \land [\alpha]Q$$

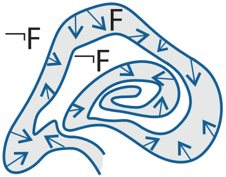


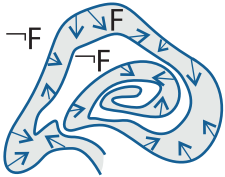
$$\frac{Q \rightarrow [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$



$$\frac{F \land Q \rightarrow [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$

$$\text{loop} \quad \frac{F \vdash [\alpha]F}{F \vdash [\alpha^*]F}$$



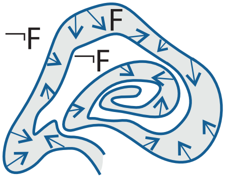


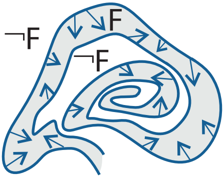
$$\frac{Q \to [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$

$$\frac{F \land Q \to [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Example (Restrictions)

$$\frac{}{v^2 - 2v + 1 = 0 \vdash [v' = w, w' = -v]\, v^2 - 2v + 1 = 0}$$

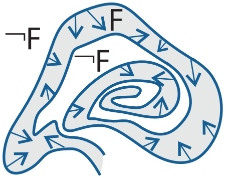




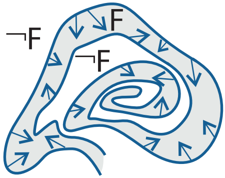
$$\frac{Q \to [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F} \qquad \frac{F \land Q \to [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Example (Restrictions)

$$\cfrac{\cfrac{}{v^2 - 2v + 1 = 0 \vdash [v' := w][w' := -v]\, 2vv' - 2v' = 0}}{v^2 - 2v + 1 = 0 \vdash [v' = w, w' = -v]\, v^2 - 2v + 1 = 0}$$



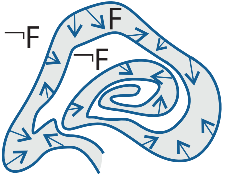
$$\frac{Q \rightarrow [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$



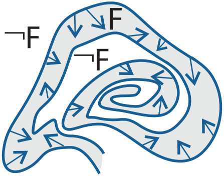
$$\frac{F \land Q \rightarrow [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Example (Restrictions)

$$\cfrac{\cfrac{\cfrac{}{v^2 - 2v + 1 = 0 \vdash 2vw - 2w = 0}}{v^2 - 2v + 1 = 0 \vdash [v' := w][w' := -v]\, 2vv' - 2v' = 0}}{v^2 - 2v + 1 = 0 \vdash [v' = w, w' = -v]\, v^2 - 2v + 1 = 0}$$



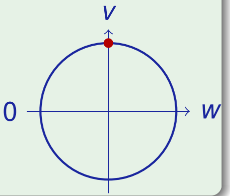
$$\frac{Q \rightarrow [x' := f(x)](F)'}{F \vdash [x' = f(x)\,\&\,Q]F}$$

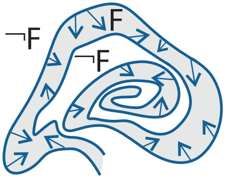


$$\frac{F \wedge Q \rightarrow [x' := f(x)](F)'}{F \vdash [x' = f(x)\,\&\,Q]F}$$

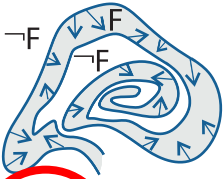
Example (Restrictions)

$$\dfrac{\dfrac{\dfrac{}{v^2-2v+1=0 \vdash 2vw-2w=0}}{v^2-2v+1=0 \vdash [v':=w][w':=-v]\,2vv'-2v'=0}}{v^2-2v+1=0 \vdash [v'=w, w'=-v]\,v^2-2v+1=0}$$





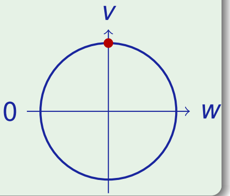
$$\frac{Q \to [x' := f(x)](F)'}{F \vdash [x' = f(x)\,\&\,Q]F}$$



$$\frac{{\color{red}F} \wedge Q \to [x' := f(x)](F)'}{F \vdash [x' = f(x)\,\&\,Q]F}$$

Example (Restrictions are unsound!)

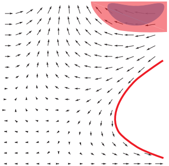
$$\cfrac{\cfrac{\cfrac{\text{(unsound)}}{v^2 - 2v + 1 = 0 \vdash 2vw - 2w = 0}}{v^2 - 2v + 1 = 0 \vdash [v' := w][w' := -v]\, 2vv' - 2v' = 0}}{v^2 - 2v + 1 = 0 \vdash [v' = w, w' = -v]\, v^2 - 2v + 1 = 0}$$



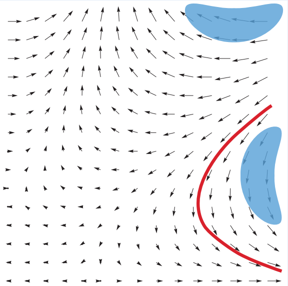
Outline

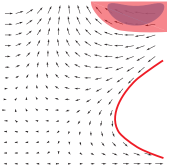
Differential Cut

$$\frac{}{F \vdash [x' = f(x)]F}$$



Differential Cut

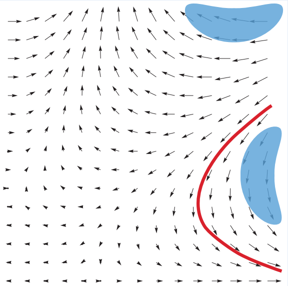




Differential Cut

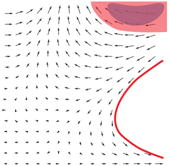
$$\frac{F \vdash [x' = f(x)]C}{F \vdash [x' = f(x)]F}$$

Differential Cut

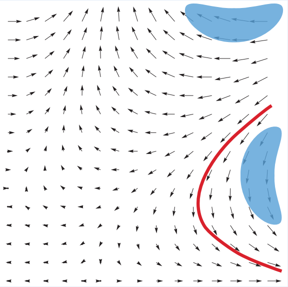


Differential Cut

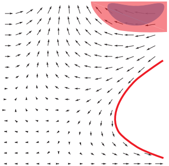
$$\frac{F \vdash [x' = f(x)]C \qquad F \vdash [x' = f(x) \,\&\, C]F}{F \vdash [x' = f(x)]F}$$



Differential Cut



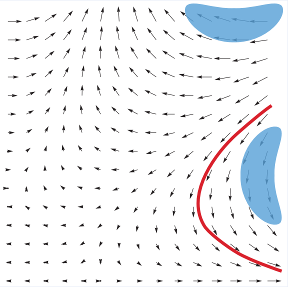
Differential Cuts

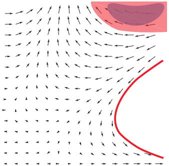


Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]C \quad F \vdash [x' = f(x) \,\&\, Q \land C]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut

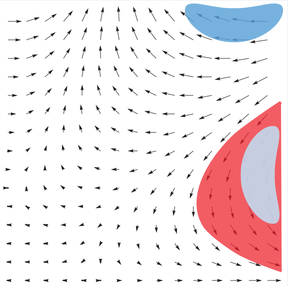


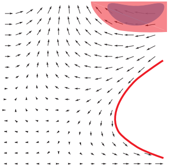


Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]C \quad F \vdash [x' = f(x) \,\&\, Q \land C]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut

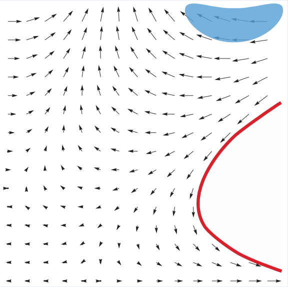




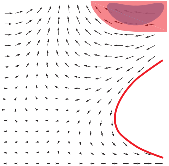
Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]{\color{red}C} \quad F \vdash [x' = f(x) \,\&\, Q \land {\color{red}C}]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut



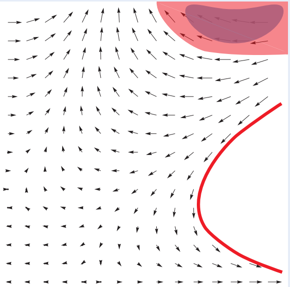
Differential Cuts

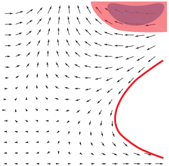


Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]C \quad F \vdash [x' = f(x) \,\&\, Q \wedge C]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut

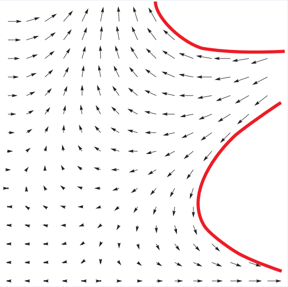


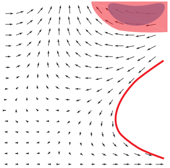


Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]C \quad F \vdash [x' = f(x) \,\&\, Q \wedge C]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut

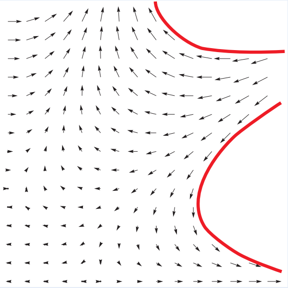




Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]C \quad F \vdash [x' = f(x) \,\&\, Q \land C]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut



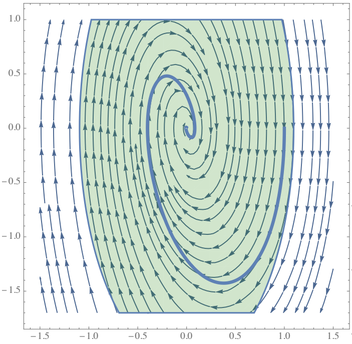
Proof (Soundness).

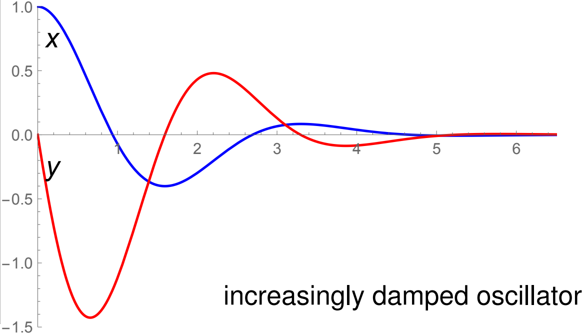
Let $\varphi \models x' = f(x) \land Q$ starting in $\omega \in [\![F]\!]$.
$\omega \in [\![[x' = f(x) \,\&\, Q]C]\!]$ by left premise.
Thus, $\varphi \models x' = f(x) \land Q \land C$.
Thus, $\varphi(r) \in [\![F]\!]$ by second premise. $\square$

Differential Cut Example: Increasingly Damped Oscillator

$$\text{dC}\ \frac{}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7\ \&\ \omega\ge 0]\, \omega^2x^2+y^2\le c^2}$$

$$\text{dC}\ \frac{}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7\ \&\ \omega\geq 0]\,\omega^2x^2+y^2\leq c^2}$$





Differential Cut Example: Increasingly Damped Oscillator

$$\dfrac{\dfrac{}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0 \land d\ge 0]\, \omega^2x^2+y^2\le c^2}\text{dI}}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0]\, \omega^2x^2+y^2\le c^2}\text{dC}$$

increasingly damped oscillator

Differential Cut Example: Increasingly Damped Oscillator

$$\text{dC}\;\dfrac{\text{dI}\;\dfrac{}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0 \land d\ge 0]\, \omega^2x^2+y^2\le c^2}}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0]\, \omega^2x^2+y^2\le c^2}$$

$$\text{dI}\;\dfrac{}{d\ge 0 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0]\, d\ge 0}$$

increasingly damped oscillator

$$\dfrac{\dfrac{}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0 \land d\ge 0]\, \omega^2x^2+y^2\le c^2}\,\text{dI}}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0]\, \omega^2x^2+y^2\le c^2}\,\text{dC}$$

$$\dfrac{\dfrac{}{\omega\ge 0 \vdash [d':=7]\, d'\ge 0}\,[:=]}{d\ge 0 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge 0]\, d\ge 0}\,\text{dI}$$

increasingly damped oscillator

Differential Cut Example: Increasingly Damped Oscillator

$$\text{dC}\dfrac{\text{dI}\dfrac{}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7\ \&\ \omega\ge 0\land d\ge 0]\,\omega^2x^2+y^2\le c^2}}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7\ \&\ \omega\ge 0]\,\omega^2x^2+y^2\le c^2}$$

$$\text{dI}\dfrac{[:=]\dfrac{\mathbb{R}\dfrac{}{\omega\ge 0 \vdash 7\ge 0}}{\omega\ge 0 \vdash [d':=7]\,d'\ge 0}}{d\ge 0 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7\ \&\ \omega\ge 0]\,d\ge 0}$$

increasingly damped oscillator

$$\text{dC}\;\dfrac{\text{dI}\;\dfrac{}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge0\land d\ge0]\,\omega^2x^2+y^2\le c^2}}{\omega^2x^2+y^2\le c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge0]\,\omega^2x^2+y^2\le c^2}$$

$$\text{dI}\;\dfrac{[:=]\;\dfrac{\mathbb{R}\;\dfrac{*}{\omega\ge0 \vdash 7\ge0}}{\omega\ge0 \vdash [d':=7]\,d'\ge0}}{d\ge0 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7 \,\&\, \omega\ge0]\,d\ge0}$$

ask

increasingly damped oscillator

Differential Cut Example: Increasingly Damped Oscillator

$$\dfrac{\dfrac{\dfrac{}{\omega\geq 0\land d\geq 0 \vdash [x':=y][y':=-\omega^2 x - 2d\omega y]\,2\omega^2 x x' + 2yy' \leq 0}\;[:=]}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7\,\&\,\omega\geq 0\land d\geq 0]\,\omega^2x^2+y^2\leq c^2}\;\mathrm{dI}}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y, y'=-\omega^2x-2d\omega y, d'=7\,\&\,\omega\geq 0]\,\omega^2x^2+y^2\leq c^2}\;\mathrm{dC}$$

$$\dfrac{\dfrac{\dfrac{*}{\omega\geq 0 \vdash 7\geq 0}\;\mathbb{R}}{\omega\geq 0 \vdash [d':=7]\,d'\geq 0}\;[:=]}{d\geq 0 \vdash [x' = y, y' = -\omega^2 x - 2d\omega y, d'=7\,\&\,\omega\geq 0]\,d\geq 0}\;\mathrm{dI}$$

increasingly damped oscillator

$$\dfrac{\dfrac{\dfrac{\dfrac{}{\omega\geq0\land d\geq0 \vdash 2\omega^2xy+2y(-\omega^2x-2d\omega y)\leq 0}\ \mathbb{R}}{\omega\geq0\land d\geq0 \vdash [x':=y][y':=-\omega^2x-2d\omega y]2\omega^2xx'+2yy'\leq 0}\ [:=]}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq0\land d\geq0]\,\omega^2x^2+y^2\leq c^2}\ \mathrm{dI}}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq0]\,\omega^2x^2+y^2\leq c^2}\ \mathrm{dC}$$

$$\dfrac{\dfrac{\dfrac{*}{\omega\geq0 \vdash 7\geq0}\ \mathbb{R}}{\omega\geq0 \vdash [d':=7]\,d'\geq0}\ [:=]}{d\geq0 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq0]\,d\geq0}\ \mathrm{dI}$$

increasingly damped oscillator

$$
{\scriptstyle \mathrm{dC}}\dfrac{{\scriptstyle \mathrm{dI}}\dfrac{{\scriptstyle [:=]}\dfrac{{\scriptstyle \mathbb{R}}\dfrac{*}{\omega\geq 0\land d\geq 0 \vdash 2\omega^2xy+2y(-\omega^2x-2d\omega y)\leq 0}}{\omega\geq 0\land d\geq 0 \vdash [x':=y][y':=-\omega^2x-2d\omega y]2\omega^2xx'+2yy'\leq 0}}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0\land d\geq 0]\,\omega^2x^2+y^2\leq c^2}}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0]\,\omega^2x^2+y^2\leq c^2}
$$

DC

$$
{\scriptstyle \mathrm{dI}}\dfrac{{\scriptstyle [:=]}\dfrac{{\scriptstyle \mathbb{R}}\dfrac{*}{\omega\geq 0 \vdash 7\geq 0}}{\omega\geq 0 \vdash [d':=7]\,d'\geq 0}}{d\geq 0 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0]\,d\geq 0}
$$

increasingly damped oscillator

Differential Cut Example: Increasingly Damped Oscillator

$$\dfrac{\dfrac{\dfrac{\dfrac{*}{\omega\geq 0\land d\geq 0 \vdash 2\omega^2xy+2y(-\omega^2x-2d\omega y)\leq 0}\mathbb{R}}{\omega\geq 0\land d\geq 0 \vdash [x':=y][y':=-\omega^2x-2d\omega y]2\omega^2xx'+2yy'\leq 0}[:=]}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0\land d\geq 0]\,\omega^2x^2+y^2\leq c^2}\mathrm{dI}}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0]\,\omega^2x^2+y^2\leq c^2}\mathrm{dC}$$

init

$$\dfrac{\dfrac{\dfrac{*}{\omega\geq 0 \vdash 7\geq 0}\mathbb{R}}{\omega\geq 0 \vdash [d':=7]\,d'\geq 0}[:=]}{d\geq 0 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0]\,d\geq 0}\mathrm{dI}$$

Differential Cut Example: Increasingly Damped Oscillator

$$\dfrac{\dfrac{\dfrac{\dfrac{*}{\omega\geq 0\land d\geq 0 \vdash 2\omega^2xy+2y(-\omega^2x-2d\omega y)\leq 0}\,\mathbb{R}}{\omega\geq 0\land d\geq 0 \vdash [x':=y][y':=-\omega^2x-2d\omega y]2\omega^2xx'+2yy'\leq 0}\,[:=]}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0\land d\geq 0]\,\omega^2x^2+y^2\leq c^2}\,\mathrm{dI}}{\omega^2x^2+y^2\leq c^2 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0]\,\omega^2x^2+y^2\leq c^2}\,\mathrm{dC}$$

init

$$\dfrac{\dfrac{\dfrac{*}{\omega\geq 0 \vdash 7\geq 0}\,\mathbb{R}}{\omega\geq 0 \vdash [d':=7]\,d'\geq 0}\,[:=]}{d\geq 0 \vdash [x'=y,y'=-\omega^2x-2d\omega y,d'=7\,\&\,\omega\geq 0]\,d\geq 0}\,\mathrm{dI}$$

Could repeatedly diffcut in formulas to help the proof

$$\text{dC}\ \frac{}{x^3 \geq -1 \land y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]x^3 \geq -1}$$

$$\text{dC}\ \frac{}{x^3 \geq -1 \wedge y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]x^3 \geq -1}$$

$$\text{dI}\ \frac{}{y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]y^5 \geq 0}$$

$$\text{dC}\ \frac{}{x^3 \geq -1 \land y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]x^3 \geq -1}$$

$$\text{dI}\ \frac{[:=]\ \frac{}{\vdash [x' := (x-2)^4 + y^5][y' := y^2]5y^4 y' \geq 0}}{y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2] y^5 \geq 0}$$

Ex: Differential Cuts

$$\text{dC}\ \dfrac{}{x^3 \geq -1 \land y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]x^3 \geq -1}$$

$$\text{dI}\ \dfrac{[:=]\ \dfrac{\mathbb{R}\ \dfrac{}{\vdash 5y^4 y^2 \geq 0}}{\vdash [x':=(x-2)^4 + y^5][y':=y^2]5y^4 y' \geq 0}}{y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]y^5 \geq 0}$$

$$\text{dC}\ \dfrac{}{x^3 \geq -1 \land y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]x^3 \geq -1}$$

$$\text{dI}\ \dfrac{[:=]\ \dfrac{\mathbb{R}\ \dfrac{*}{\vdash 5y^4y^2 \geq 0}}{\vdash [x':=(x-2)^4 + y^5][y':=y^2]5y^4y' \geq 0}}{y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]y^5 \geq 0}$$

$$\text{dI}\;\dfrac{\dfrac{}{x^3 \geq -1 \vdash [x' = (x-2)^4 + y^5, y' = y^2 \,\&\, y^5 \geq 0]x^3 \geq -1} \;\triangleright}{x^3 \geq -1 \land y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]x^3 \geq -1}\;\text{dC}$$

$$\text{dI}\;\dfrac{[:=]\;\dfrac{\mathbb{R}\;\dfrac{*}{\vdash 5y^4y^2 \geq 0}}{\vdash [x' := (x-2)^4 + y^5][y' := y^2]5y^4y' \geq 0}}{y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]y^5 \geq 0}$$

$$\dfrac{\dfrac{\dfrac{}{y^5 \geq 0 \vdash [x':=(x-2)^4+y^5][y':=y^2]3x^2x' \geq 0}\,[:=]}{x^3 \geq -1 \vdash [x' = (x-2)^4+y^5, y' = y^2 \,\&\, y^5 \geq 0]x^3 \geq -1}\,\mathrm{dI} \quad \triangleright}{x^3 \geq -1 \land y^5 \geq 0 \vdash [x' = (x-2)^4+y^5, y' = y^2]x^3 \geq -1}\,\mathrm{dC}$$

$$\dfrac{\dfrac{\dfrac{*}{\vdash 5y^4y^2 \geq 0}\,\mathbb{R}}{\vdash [x':=(x-2)^4+y^5][y':=y^2]5y^4y' \geq 0}\,[:=]}{y^5 \geq 0 \vdash [x' = (x-2)^4+y^5, y' = y^2]y^5 \geq 0}\,\mathrm{dI}$$

$$\dfrac{\dfrac{\dfrac{\mathbb{R}\;\dfrac{}{y^5 \geq 0 \vdash 3x^2((x-2)^4 + y^5) \geq 0}}{[:=]\; y^5 \geq 0 \vdash [x':=(x-2)^4 + y^5][y':=y^2]3x^2x' \geq 0}}{\mathrm{dI}\; x^3 \geq -1 \vdash [x' = (x-2)^4 + y^5, y' = y^2 \,\&\, y^5 \geq 0]x^3 \geq -1 \;\triangleright}}{\mathrm{dC}\; x^3 \geq -1 \land y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]x^3 \geq -1}$$

$$\dfrac{\dfrac{\dfrac{*}{\mathbb{R}\; \vdash 5y^4y^2 \geq 0}}{[:=]\; \vdash [x':=(x-2)^4 + y^5][y':=y^2]5y^4y' \geq 0}}{\mathrm{dI}\; y^5 \geq 0 \vdash [x' = (x-2)^4 + y^5, y' = y^2]y^5 \geq 0}$$

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$$\dfrac{\dfrac{\dfrac{*}{\vdash 5y^4y^2 \geq 0}\;\mathbb{R}}{\vdash [x':=(x-2)^4+y^5][y':=y^2]5y^4y' \geq 0}\;[:=]}{y^5 \geq 0 \vdash [x' = (x-2)^4+y^5, y' = y^2]y^5 \geq 0}\;\mathrm{dI}$$

Outline

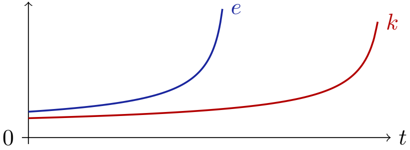
Soundness Proof: Differential Invariants

Lemma (Differential lemma) (Differential value vs. Time-derivative)

$$\varphi \models x' = f(x) \land Q \text{ for } r > 0 \;\Rightarrow\; \forall 0{\le}z{\le}r \;\; \varphi(z)[\![(e)']\!] = \frac{\mathrm{d}\varphi(t)[\![e]\!]}{\mathrm{d}t}(z)$$

Differential Invariant

$$\text{DI} \quad \begin{array}{l}([x' = f(x)]e \ge 0 \leftrightarrow e \ge 0) \\ \leftarrow [x' = f(x)](e)' \ge 0\end{array}$$



Proof ($\ge$ rate of change from $\ge$ initial value. Case $r = 0$ is easier.)

$h(t) \overset{\text{def}}{=} \varphi(t)[\![e]\!]$ is differentiable on $[0, r]$ if $r > 0$ by diff. lemma.

$\frac{\mathrm{d}h(t)}{\mathrm{d}t}(z) = \frac{\mathrm{d}\varphi(t)[\![e]\!]}{\mathrm{d}t}(z) = \varphi(z)[\![(e)']\!] \ge 0$ by lemma + assume for all z.

$h(r) - \underbrace{h(0)}_{\ge 0} = \underbrace{(r-0)}_{>0} \underbrace{\frac{\mathrm{d}h(t)}{\mathrm{d}t}(\xi)}_{\ge 0} \ge 0$ by mean-value theorem for some ξ. □

Outline

Summary: Differential Invariants for Differential Equations

Differential Weakening

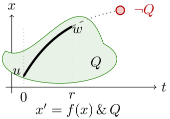
$$\frac{Q \vdash F}{\Gamma \vdash [x' = f(x) \,\&\, Q]F}$$

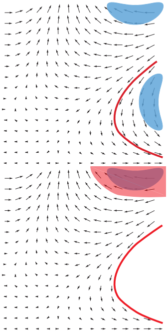
Differential Invariant

$$\frac{Q \vdash [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]C \quad F \vdash [x' = f(x) \,\&\, Q \land C]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$





Summary: Differential Invariants for Differential Equations

Differential Weakening

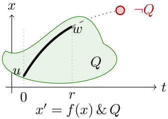
$$\frac{Q \vdash F}{\Gamma \vdash [x' = f(x) \,\&\, Q]F}$$

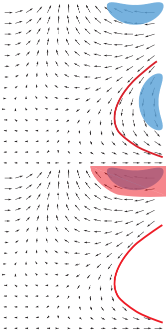
Differential Invariant

$$\frac{Q \vdash [x' := f(x)](F)'}{F \vdash [x' = f(x) \,\&\, Q]F}$$

Differential Cut

$$\frac{F \vdash [x' = f(x) \,\&\, Q]C \quad F \vdash [x' = f(x) \,\&\, Q \wedge C]F}{F \vdash [x' = f(x) \,\&\, Q]F}$$





DW $[x' = f(x) \,\&\, Q]F \leftrightarrow [x' = f(x) \,\&\, Q](Q \to F)$

DI $\big([x' = f(x) \,\&\, Q]F \leftrightarrow [?Q]F\big) \leftarrow (Q \to [x' = f(x) \,\&\, Q](F)')$

DC $\big([x' = f(x) \,\&\, Q]F \leftrightarrow [x' = f(x) \,\&\, Q \wedge C]F\big) \leftarrow [x' = f(x) \,\&\, Q]C$

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