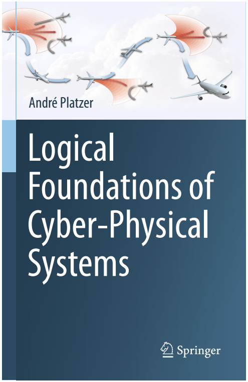
02: Differential Equations & Domains

Logical Foundations of Cyber-Physical Systems



André Platzer

Carnegie Mellon University
Computer Science Department

Outline

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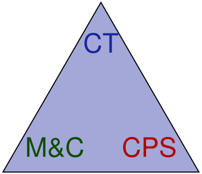
Learning Objectives

semantics of differential equations
descriptive power of differential equations
syntax versus semantics



continuous dynamics
differential equations
evolution domains
first-order logic

continuous operational effects

Outline

Example (Vector field and one solution of a differential equation)

$$\begin{pmatrix} y'(t) = f(t, y) \\ y(t_0) = y_0 \end{pmatrix}$$

Intuition:

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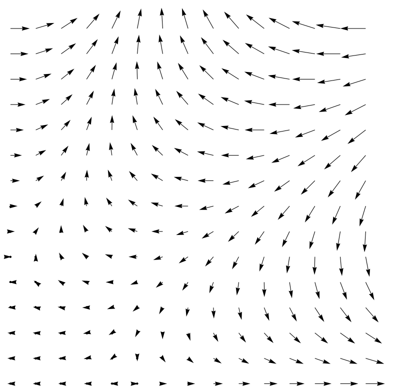

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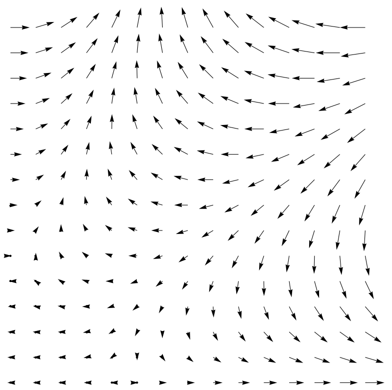

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2. Start at initial state y_0 at initial time t_0

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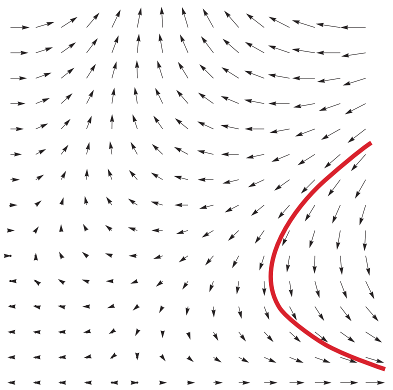

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1. At each point in space, plot the value of RHS $f(t,y)$ as a vector
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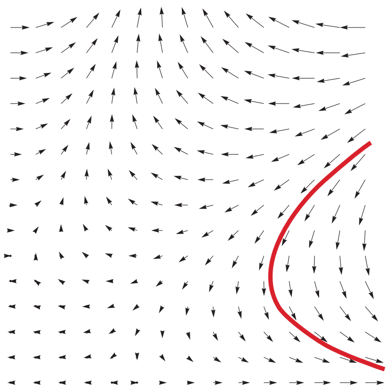
↯ The diagram should really show infinitely many vectors . . .



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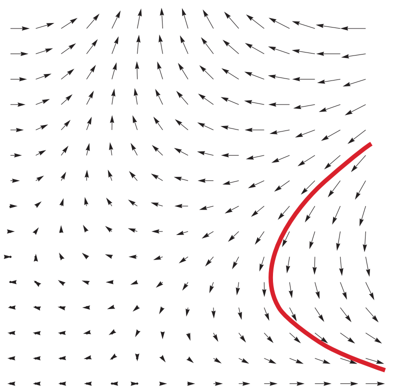

Your car's ODE: $x' = v, v' = a$

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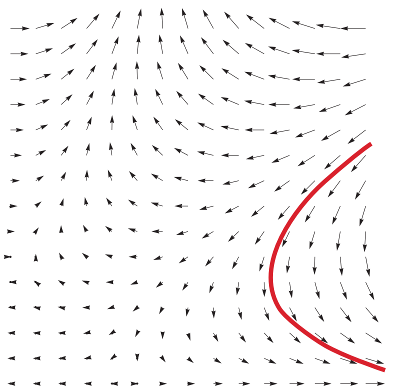
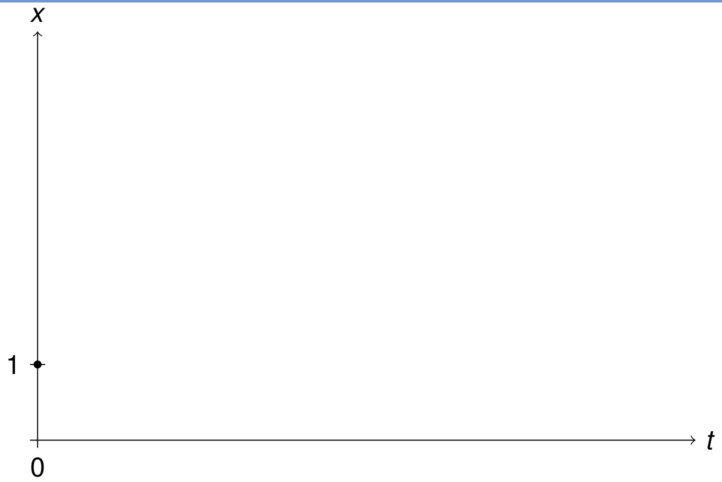


Your car's ODE: $x' = v, v' = a$

Well it's a wee bit more complicated

Intuition for Differential Equations



$$\begin{pmatrix} x'(t) = \frac{1}{4}x(t) \\ x(0) = 1 \end{pmatrix}$$

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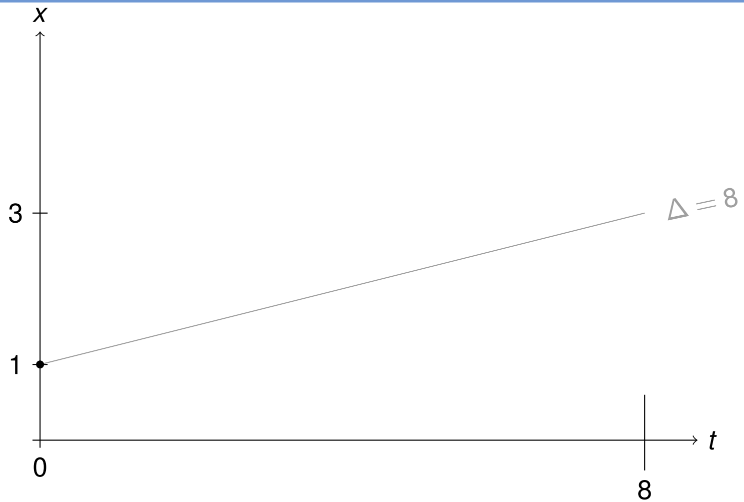

$$\begin{pmatrix} x'(t) = \frac{1}{4}x(t) \\ x(0) = 1 \end{pmatrix} \rightsquigarrow \begin{pmatrix} x(t+\Delta) := x(t) + \frac{1}{4}x(t)\Delta \\ x(0) := 1 \end{pmatrix}$$

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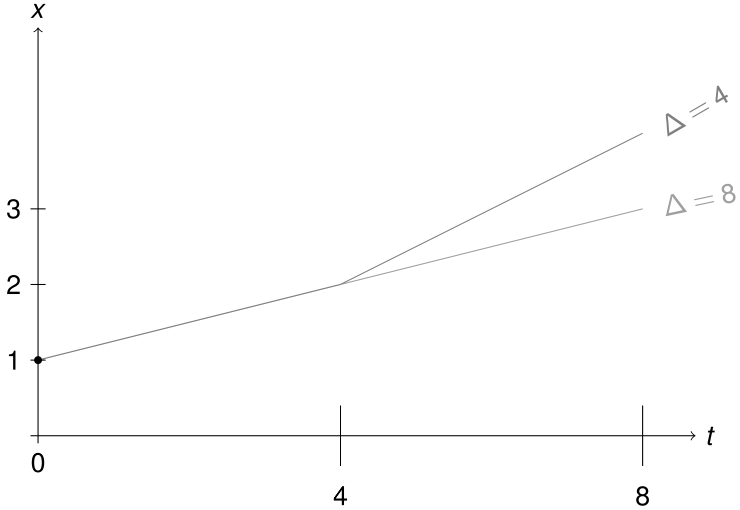

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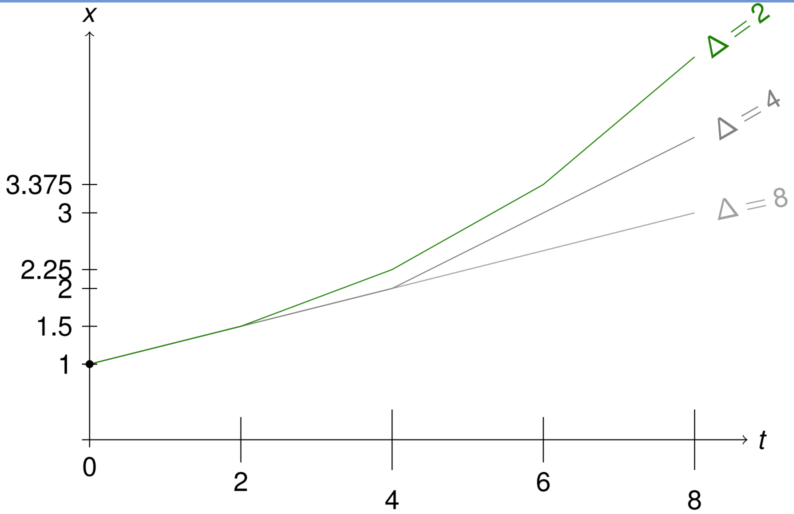

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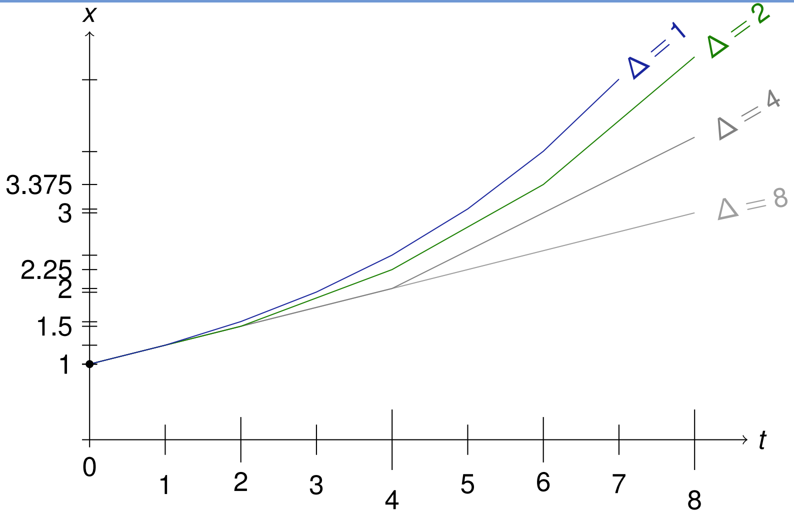

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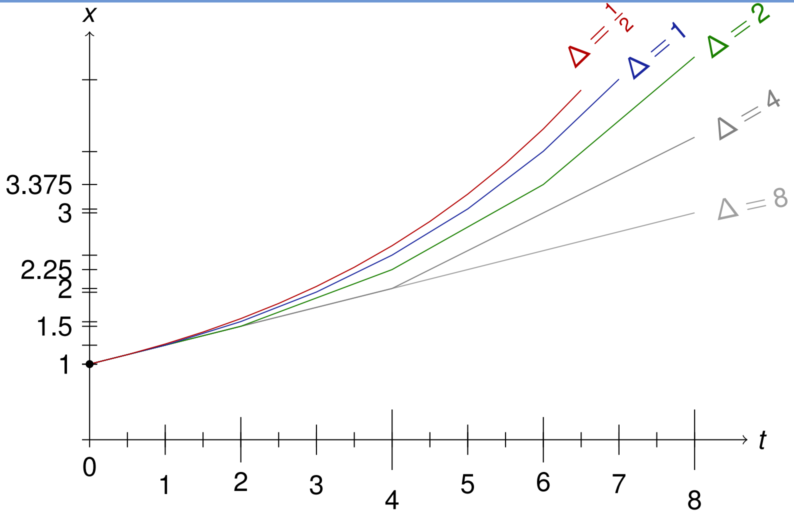

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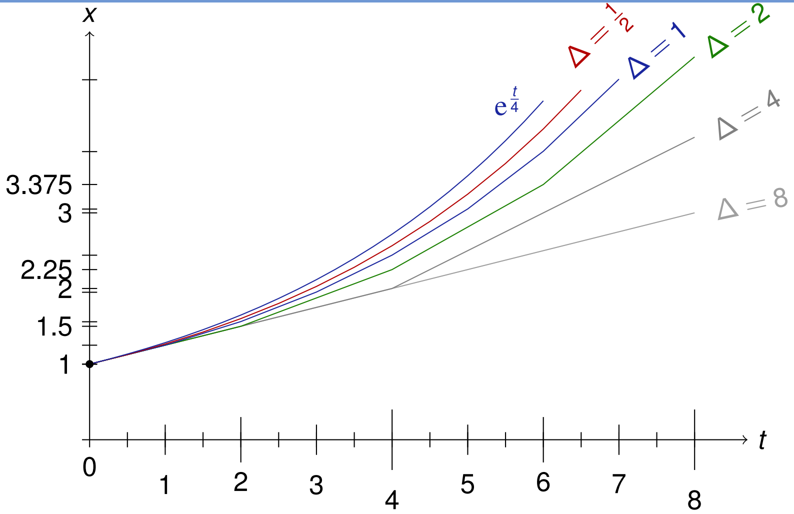

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Outline

The Meaning of Differential Equations

1. What exactly is a vector field?
2. What does it mean to describe directions of evolution at *every* point in space?
3. Could these directions possibly contradict each other?

Importance of meaning

The physical impacts of CPSs do not leave much room for failure. We immediately want to get into the habit of studying the behavior and exact meaning of all relevant aspects of CPS.

Definition (Ordinary Differential Equation, ODE)

$f : D \to \mathbb{R}^n$ on domain $D \subseteq \mathbb{R} \times \mathbb{R}^n$ (i.e., open connected set). Then $Y : I \to \mathbb{R}^n$ is *solution* of initial value problem (IVP)

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Differential Equations & Initial Value Problems

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If $f \in C(D, \mathbb{R}^n)$, then $Y \in C^1(I, \mathbb{R}^n)$.
If f continuous, then Y continuously differentiable.

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Example: A Constant Differential Equation

Example (Initial value problem)

$$\begin{pmatrix} x'(t) = \frac{1}{2} \\ x(0) = -1 \end{pmatrix} \quad \text{has a solution}$$

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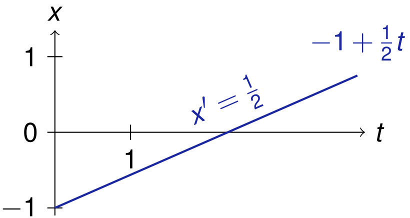

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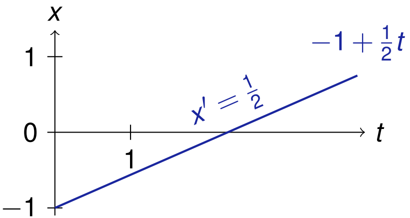

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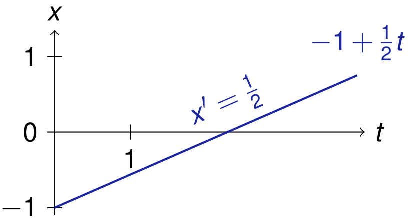

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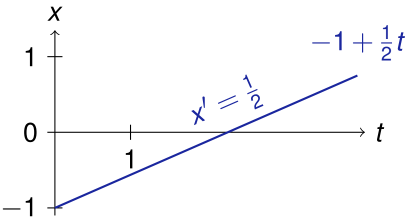

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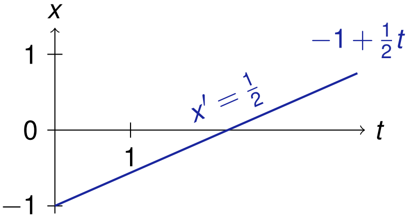
Check by inserting solution into ODE+IVP.

$$\begin{pmatrix} (x(t))' = (\frac{1}{2}t - 1)' = \frac{1}{2} \\ x(0) = \frac{1}{2} \cdot 0 - 1 = -1 \end{pmatrix}$$

□



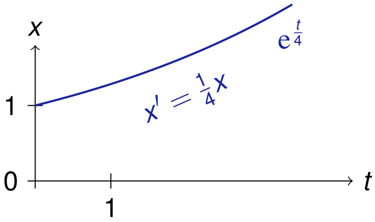
Example (Initial value problem)

$$\begin{pmatrix} x'(t) = \frac{1}{4}x(t) \\ x(0) = 1 \end{pmatrix} \quad \text{has a solution}$$

Example: A Linear Differential Equation from before

Example (Initial value problem)

$$\begin{pmatrix} x'(t) = \frac{1}{4}x(t) \\ x(0) = 1 \end{pmatrix} \quad \text{has a solution } x(t) = e^{\frac{t}{4}}$$



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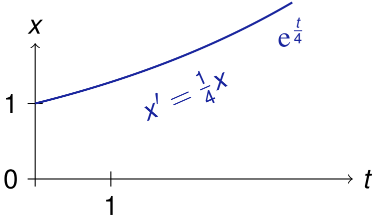

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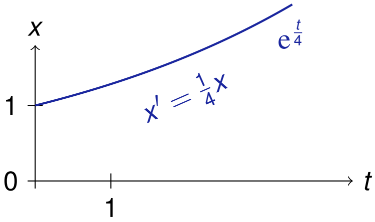

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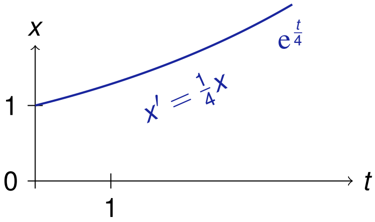

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$$\begin{pmatrix} (x(t))' = (e^{\frac{t}{4}})' = e^{\frac{t}{4}}(\frac{t}{4})' = e^{\frac{t}{4}}\frac{1}{4} = \frac{1}{4}x(t) \\ x(0) = e^{\frac{0}{4}} = 1 \end{pmatrix}$$

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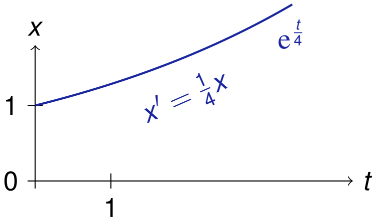


Example: Linear Dynamics

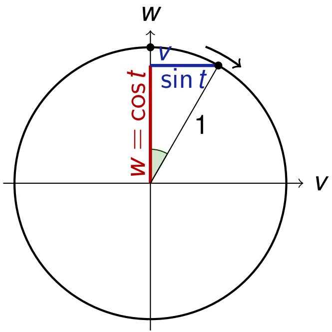
Example (Initial value problem)

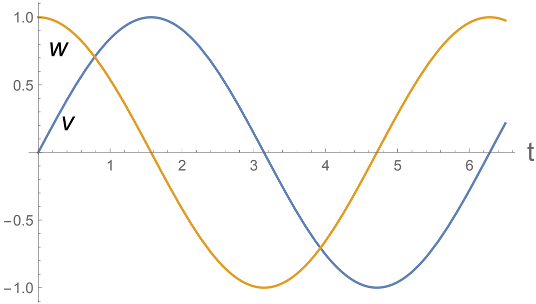
$$\begin{pmatrix} v'(t) = w(t) \\ w'(t) = -v(t) \\ v(0) = 0 \\ w(0) = 1 \end{pmatrix} \quad \text{has solution}$$

Example: Rotational Dynamics

Example (Initial value problem)

$$\begin{pmatrix} v'(t) = w(t) \\ w'(t) = -v(t) \\ v(0) = 0 \\ w(0) = 1 \end{pmatrix} \quad \text{has solution} \quad \begin{pmatrix} v(t) = \sin(t) \\ w(t) = \cos(t) \end{pmatrix}$$

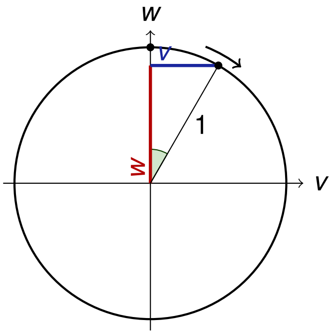


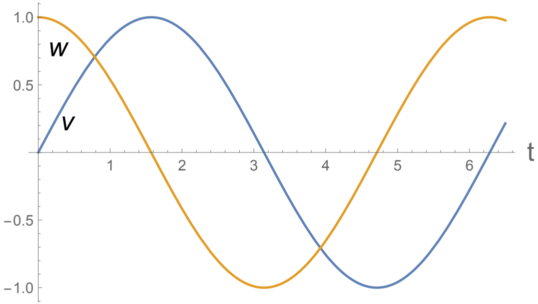


Example: Rotational Dynamics

Example (Initial value problem)

$$\begin{pmatrix} v'(t) = \omega w(t) \\ w'(t) = -\omega v(t) \\ v(0) = 0 \\ w(0) = 1 \end{pmatrix}$$ has solution





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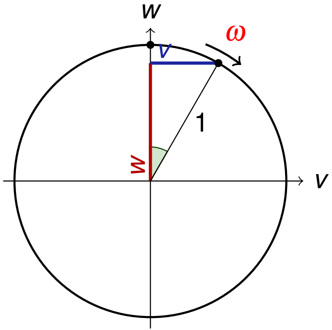
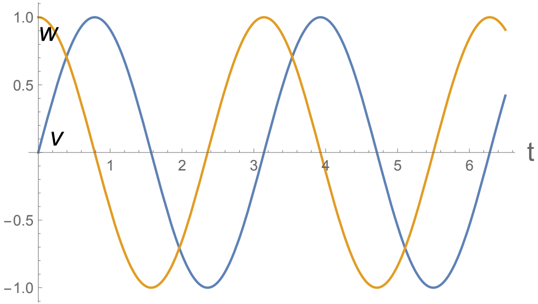
$$\begin{pmatrix} v'(t) = \omega w(t) \\ w'(t) = -\omega v(t) \\ v(0) = 0 \\ w(0) = 1 \end{pmatrix} \quad \text{has solution} \quad \begin{pmatrix} v(t) = \sin(\omega t) \\ w(t) = \cos(\omega t) \end{pmatrix}$$





Example: More Dynamics

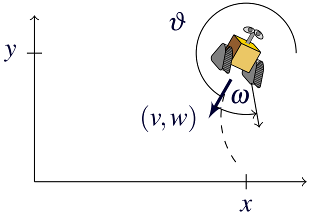
Example (Initial value problem)

$$\begin{pmatrix} x'(t) = v(t) \\ y'(t) = w(t) \\ v'(t) = \omega w(t) \\ w'(t) = -\omega v(t) \\ x(0) = x_0 \\ y(0) = y_0 \\ v(0) = v_0 \\ w(0) = w_0 \end{pmatrix}$$

Example: Planar Motion Dynamics

Example (Initial value problem)

$$\begin{pmatrix} x'(t) = v(t) \\ y'(t) = w(t) \\ v'(t) = \omega w(t) \\ w'(t) = -\omega v(t) \\ x(0) = x_0 \\ y(0) = y_0 \\ v(0) = v_0 \\ w(0) = w_0 \end{pmatrix}$$



ODE Examples

ODE	Solution
$x' = 1, x(0) = x_0$	$x(t) = x_0 + t$
$x' = 5, x(0) = x_0$	$x(t) = x_0 + 5t$
$x' = x, x(0) = x_0$	$x(t) = x_0 e^t$
$x' = x^2, x(0) = x_0$	$x(t) = \frac{x_0}{1 - tx_0}$
$x' = \frac{1}{x}, x(0) = 1$	$x(t) = \sqrt{1 + 2t} \dots$
$y'(x) = -2xy, y(0) = 1$	$y(x) = e^{-x^2}$
$x'(t) = tx, x(0) = x_0$	$x(t) = x_0 e^{\frac{t^2}{2}}$
$x' = \sqrt{x}, x(0) = x_0$	$x(t) = \frac{t^2}{4} \pm t\sqrt{x_0} + x_0$
$x' = y, y' = -x, x(0) = 0, y(0) = 1$	$x(t) = \sin t, y(t) = \cos t$
$x' = 1 + x^2, x(0) = 0$	$x(t) = \tan t$
$x'(t) = \frac{2}{t^3} x(t)$	$x(t) = e^{-\frac{1}{t^2}}$ non-analytic
$x' = x^2 + x^4$	???
$x'(t) = e^{t^2}$	non-elementary

Solutions more complicated than ODE

ODE	Solution
$x' = 1, x(0) = x_0$	$x(t) = x_0 + t$
$x' = 5, x(0) = x_0$	$x(t) = x_0 + 5t$
$x' = x, x(0) = x_0$	$x(t) = x_0 e^t$
$x' = x^2, x(0) = x_0$	$x(t) = \frac{x_0}{1 - tx_0}$
$x' = \frac{1}{x}, x(0) = 1$	$x(t) = \sqrt{1 + 2t} \ldots$
$y'(x) = -2xy, y(0) = 1$	$y(x) = e^{-x^2}$
$x'(t) = tx, x(0) = x_0$	$x(t) = x_0 e^{\frac{t^2}{2}}$
$x' = \sqrt{x}, x(0) = x_0$	$x(t) = \frac{t^2}{4} \pm t\sqrt{x_0} + x_0$
$x' = y, y' = -x, x(0) = 0, y(0) = 1$	$x(t) = \sin t, y(t) = \cos t$
$x' = 1 + x^2, x(0) = 0$	$x(t) = \tan t$
$x'(t) = \frac{2}{t^3} x(t)$	$x(t) = e^{-\frac{1}{t^2}}$ non-analytic
$x' = x^2 + x^4$	???
$x'(t) = e^{t^2}$	non-elementary

Takeaway Message

Descriptive power of differential equations

1. Solutions of differential equations can be much more involved than the differential equations themselves.
2. Representational and descriptive power of differential equations!
3. Simple differential equations can describe quite complicated physical processes.
4. Local description as the direction into which the system evolves.

Evolution Domain Constraints

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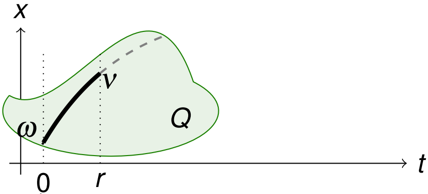
Definition (Evolution domain constraints)

A *differential equation* $x' = f(x)$ *with evolution domain* Q is denoted by

$$x' = f(x) \,\&\, Q$$

conjunctive notation (&) signifies that the system obeys the differential equation $x' = f(x)$ **and** the evolution domain Q.



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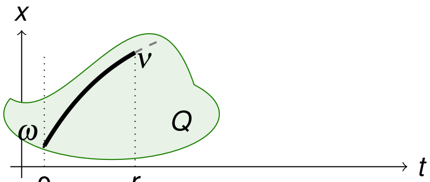

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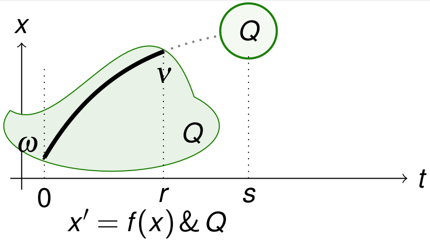

Evolution Domain Constraints

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conjunctive notation (&) signifies that the system obeys the differential equation $x' = f(x)$ **and** the evolution domain Q.

$x' = v, v' = a, t' = 1 \,\&\, t \leq \varepsilon$	stops at clock ε at the latest
$x' = v, v' = a, t' = 1 \,\&\, v \geq 0$	stops before velocity negative
$x' = y, y' = x + y^2 \,\&\, true$	no constraint

Evolution Domain Constraints

Define: Terms

… Cyber to interact with Physics

Define: Formulas

Definition (Evolution domain constraints)

A *differential equation* $x' = f(x)$ *with evolution domain* Q is denoted by

$$x' = f(x) \,\&\, Q$$

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$x' = y, y' = x + y^2 \,\&\, \mathit{true}$	no constraint

Terms: Syntax

Definition (Syntax of terms)

A *term* e is a polynomial term defined by the grammar:

$$e, \tilde{e} ::= x \mid c \mid e + \tilde{e} \mid e \cdot \tilde{e}$$

where $e, \tilde{e}$ are terms, $x \in \mathscr{V}$ is a variable, $c \in \mathbb{Q}$ a rational number constant

Terms: Syntax

Definition (Syntax of terms)

A *term* e is a polynomial term defined by the grammar:

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Variable Constant Add Multiply

Terms: Syntax & Semantics

Definition (Syntax of terms)

A *term* e is a polynomial term defined by the grammar:

$$e, \tilde{e} ::= x \mid c \mid e + \tilde{e} \mid e \cdot \tilde{e}$$

Definition (Semantics of terms) $([\![\cdot]\!] : \mathrm{Trm} \to (\mathscr{S} \to \mathbb{R}))$

The *value of term* e in state $\omega : \mathscr{V} \to \mathbb{R}$ is a real number denoted $\omega[\![e]\!]$ and is defined by induction on the structure of e:

$$\omega[\![x]\!] = \omega(x) \quad \text{if } x \in \mathscr{V} \text{ is a variable}$$

$$\omega[\![c]\!] = c \quad \text{if } c \in \mathbb{Q} \text{ is a rational constant}$$

$$\omega[\![e + \tilde{e}]\!] = \omega[\![e]\!] + \omega[\![\tilde{e}]\!] \quad \text{addition of reals}$$

$$\omega[\![e \cdot \tilde{e}]\!] = \omega[\![e]\!] \cdot \omega[\![\tilde{e}]\!] \quad \text{multiplication of reals}$$

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$\omega[\![e \cdot \tilde{e}]\!] = \omega[\![e]\!] \cdot \omega[\![\tilde{e}]\!]$	multiplication of reals

$\omega[\![4 + x \cdot 2]\!] =$ if $\omega(x) = 5$

Terms: Syntax & Semantics

Definition (Syntax of terms)

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$$\omega\llbracket 4 + x \cdot 2\rrbracket = \omega\llbracket 4\rrbracket + \omega\llbracket x\rrbracket \cdot \omega\llbracket 2\rrbracket = 4 + \omega(x) \cdot 2 = 14 \qquad \text{if } \omega(x) = 5$$

Terms: Syntax & Semantics

Definition (Syntax of terms)

A *term* e is a polynomial term defined by the grammar:

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\omega\llbracket e\cdot\tilde{e}\rrbracket &= \omega\llbracket e\rrbracket \cdot \omega\llbracket \tilde{e}\rrbracket && \text{multiplication of reals}
\end{aligned}$$

What about $x-y$?

Terms: Syntax & Semantics

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\omega[\![e \cdot \tilde{e}]\!] &= \omega[\![e]\!] \cdot \omega[\![\tilde{e}]\!] && \text{multiplication of reals}
\end{aligned}$$

What about $x - y$? Defined as $x + (-1) \cdot y$

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A *term* e is a polynomial term defined by the grammar:

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$\omega\llbracket c \rrbracket = c$	if $c \in \mathbb{Q}$ is a rational constant
$\omega\llbracket e + \tilde{e} \rrbracket = \omega\llbracket e \rrbracket + \omega\llbracket \tilde{e} \rrbracket$	addition of reals
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What about x^4?

Terms: Syntax & Semantics

Definition (Syntax of terms)

A *term* e is a polynomial term defined by the grammar:

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What about x^4? Defined as $x \cdot x \cdot x \cdot x$

Definition (Syntax of terms)

A *term* e is a polynomial term defined by the grammar:

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$\omega[\![e \cdot \tilde{e}]\!] = \omega[\![e]\!] \cdot \omega[\![\tilde{e}]\!]$	multiplication of reals

What about x^n?

Terms: Syntax & Semantics

Definition (Syntax of terms)

A *term* e is a polynomial term defined by the grammar:

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Definition (Semantics of terms) $(\llbracket\cdot\rrbracket : \mathrm{Trm} \to (\mathscr{S} \to \mathbb{R}))$

The *value of term* e in state $\omega : \mathscr{V} \to \mathbb{R}$ is a real number denoted $\omega\llbracket e\rrbracket$ and is defined by induction on the structure of e:

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\omega\llbracket e\cdot\tilde{e}\rrbracket &= \omega\llbracket e\rrbracket \cdot \omega\llbracket \tilde{e}\rrbracket && \text{multiplication of reals}
\end{aligned}$$

What about x^n? Defined as $x \cdot x \cdot x \cdot x \cdot x \cdot \ldots$, wait when do we stop???

First-Order Logic Formulas: Syntax

Definition (Syntax of first-order logic formulas)

The *formulas* of *FOL of real arithmetic* are defined by the grammar:

$$P, Q ::= e \geq \tilde{e} \mid e = \tilde{e} \mid \neg P \mid P \land Q \mid P \lor Q \mid P \rightarrow Q \mid P \leftrightarrow Q \mid \forall x\, P \mid \exists x\, P$$

Definition (Syntax of first-order logic formulas)

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Greater-or-equal | Not | And | Or | Imply | Equiv | All | Exists

First-Order Logic Formulas: Syntax & Semantics

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Definition (Semantics of first-order logic formulas)

First-order formula P is true in state ω, written $\omega \models P$, defined inductively:

$\omega \models e = \tilde{e}$	iff $\omega[\![e]\!] = \omega[\![\tilde{e}]\!]$
$\omega \models e \geq \tilde{e}$	iff $\omega[\![e]\!] \geq \omega[\![\tilde{e}]\!]$
$\omega \models \neg P$	iff $\omega \not\models P$, i.e., if it is not the case that $\omega \models P$
$\omega \models P \land Q$	iff $\omega \models P$ and $\omega \models Q$
$\omega \models P \lor Q$	iff $\omega \models P$ or $\omega \models Q$
$\omega \models P \to Q$	iff $\omega \not\models P$ or $\omega \models Q$
$\omega \models \forall x\, P$	iff $\omega_x^d \models P$ for all $d \in \mathbb{R}$
$\omega \models \exists x\, P$	iff $\omega_x^d \models P$ for some $d \in \mathbb{R}$

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

First-Order Logic Formulas: Syntax & Semantics

$\omega \models P$ formula P is true in state ω

$\models P$ formula P is *valid*, i.e., true in all states ω, i.e., $\omega \models P$ for all ω

$[\![P]\!] = \{\omega : \omega \models P\}$ set of all states in which P is true

Definition (Semantics of first-order logic formulas)

First-order formula P is true in state ω, written $\omega \models P$, defined inductively:

$\omega \models e = \tilde{e}$ iff $\omega[\![e]\!] = \omega[\![\tilde{e}]\!]$

$\omega \models e \geq \tilde{e}$ iff $\omega[\![e]\!] \geq \omega[\![\tilde{e}]\!]$

$\omega \models \neg P$ iff $\omega \not\models P$, i.e., if it is not the case that $\omega \models P$

$\omega \models P \land Q$ iff $\omega \models P$ and $\omega \models Q$

$\omega \models P \lor Q$ iff $\omega \models P$ or $\omega \models Q$

$\omega \models P \rightarrow Q$ iff $\omega \not\models P$ or $\omega \models Q$

$\omega \models \forall x\, P$ iff $\omega_x^d \models P$ for all $d \in \mathbb{R}$

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First-Order Logic Formulas: Syntax & Semantics

$\omega \models P$ formula P is true in state ω

$\models P$ formula P is *valid*, i.e., true in all states ω, i.e., $\omega \models P$ for all ω

$[\![P]\!] = \{\omega : \omega \models P\}$ set of all states in which P is true

$\exists y\,(y^2 \leq x)$ for $\omega(x) = 5$ and $\nu(x) = -5$

Definition (Semantics of first-order logic formulas)

First-order formula P is true in state ω, written $\omega \models P$, defined inductively:

$\omega \models e = \tilde{e}$ iff $\omega[\![e]\!] = \omega[\![\tilde{e}]\!]$

$\omega \models e \geq \tilde{e}$ iff $\omega[\![e]\!] \geq \omega[\![\tilde{e}]\!]$

$\omega \models \neg P$ iff $\omega \not\models P$, i.e., if it is not the case that $\omega \models P$

$\omega \models P \wedge Q$ iff $\omega \models P$ and $\omega \models Q$

$\omega \models P \vee Q$ iff $\omega \models P$ or $\omega \models Q$

$\omega \models P \rightarrow Q$ iff $\omega \not\models P$ or $\omega \models Q$

$\omega \models \forall x\, P$ iff $\omega_x^d \models P$ for all $d \in \mathbb{R}$

$\omega \models \exists x\, P$ iff $\omega_x^d \models P$ for some $d \in \mathbb{R}$

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

$\omega \models P$ formula P is true in state ω

$\models P$ formula P is *valid*, i.e., true in all states ω, i.e., $\omega \models P$ for all ω

$[\![P]\!] = \{\omega : \omega \models P\}$ set of all states in which P is true

$\omega \models \exists y\,(y^2 \leq x)$ but $\nu \not\models \exists y\,(y^2 \leq x)$ for $\omega(x) = 5$ and $\nu(x) = -5$

Definition (Semantics of first-order logic formulas)

First-order formula P is true in state ω, written $\omega \models P$, defined inductively:

$\omega \models e = \tilde{e}$ iff $\omega[\![e]\!] = \omega[\![\tilde{e}]\!]$

$\omega \models e \geq \tilde{e}$ iff $\omega[\![e]\!] \geq \omega[\![\tilde{e}]\!]$

$\omega \models \neg P$ iff $\omega \not\models P$, i.e., if it is not the case that $\omega \models P$

$\omega \models P \land Q$ iff $\omega \models P$ and $\omega \models Q$

$\omega \models P \lor Q$ iff $\omega \models P$ or $\omega \models Q$

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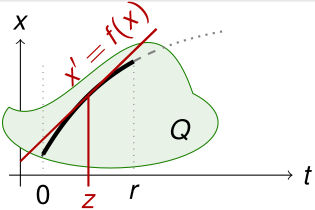
$$\omega_x^d(y) = \begin{cases} d & \text{if } y = x \\ \omega(y) & \text{if } y \neq x \end{cases}$$

Definition (Semantics of differential equations)

A function $\varphi : [0, r] \to \mathscr{S}$ of some duration $r \geq 0$ satisfies the differential equation $x' = f(x) \,\&\, Q$, written $\varphi \models x' = f(x) \land Q$, iff:

1. $\varphi(z)(x') = \frac{d\varphi(t)(x)}{dt}(z)$ exists at all times $0 \leq z \leq r$
2. $\varphi(z) \models x' = f(x) \land Q$ for all times $0 \leq z \leq r$
3. $\varphi(z) = \varphi(0)$ except at x, x'



$x' = f(x) \,\&\, Q$

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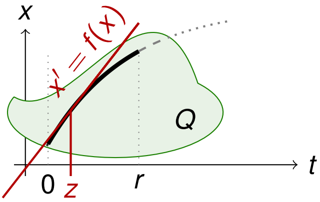
2. $\varphi(z) \models x' = f(x) \wedge Q$ for all times $0 \leq z \leq r$
3. $\varphi(z) = \varphi(0)$ except at x, x'



$x' = f(x)\,\&\,Q$

Definition (Semantics of differential equations)

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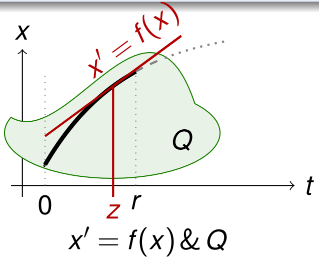

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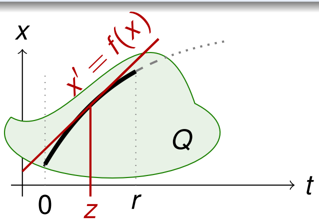


$x' = f(x) \,\&\, Q$

Outline

Summary: Differential Equations & Domains

Definition (Syntax of terms)

$$e, \tilde{e} \ ::= \ x \mid c \mid e + \tilde{e} \mid e \cdot \tilde{e}$$

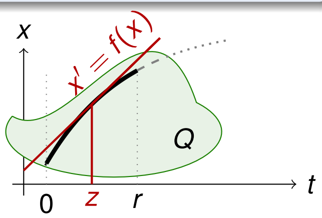
Definition (Syntax of first-order logic formulas)

$$P, Q ::= e \geq \tilde{e} \mid e = \tilde{e} \mid \neg P \mid P \wedge Q \mid P \vee Q \mid P \rightarrow Q \mid P \leftrightarrow Q \mid \forall x\, P \mid \exists x\, P$$

Definition (Syntax of continuous programs)

A *differential equation $x' = f(x)$ with evolution domain Q* is denoted by

$$x' = f(x) \,\&\, Q$$



André Platzer.
Logical Foundations of Cyber-Physical Systems.
Springer, Switzerland, 2018.
URL: http://www.springer.com/978-3-319-63587-3, doi:10.1007/978-3-319-63588-0.

André Platzer.
Logical Analysis of Hybrid Systems: Proving Theorems for Complex Dynamics.
Springer, Heidelberg, 2010.
doi:10.1007/978-3-642-14509-4.