Some control problems in linear dynamical systems

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Joint work with Nathanaël Fijalkow, Joël Ouaknine, João Sousa-Pinto, James Worrell

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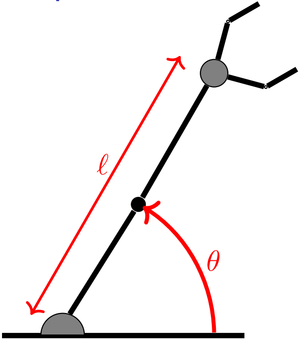
Example: 2D robot



Available actions:

- rotate arm
- change arm length

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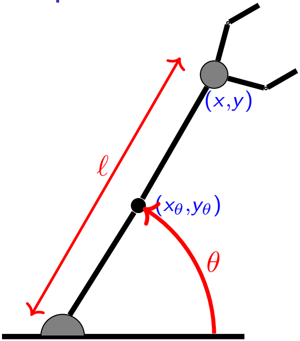

State: $X = (x_\theta, y_\theta, x, y) \in \mathbb{R}^4$

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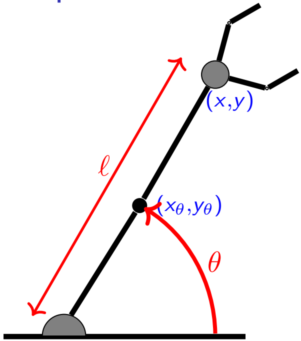

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Rotate arm (increase θ):

$$\begin{bmatrix} x \\ y \end{bmatrix}' = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

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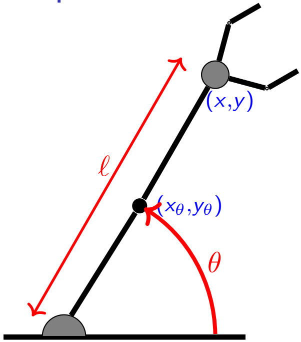

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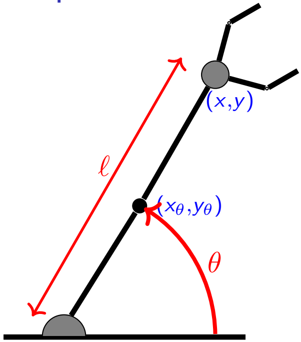

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→ Switched linear system:

$$X' = AX$$

where $A \in \{A_{rot}, A_{arm}\}$.

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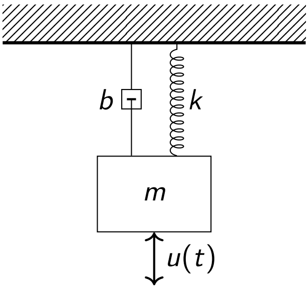
Example: mass-spring-damper system



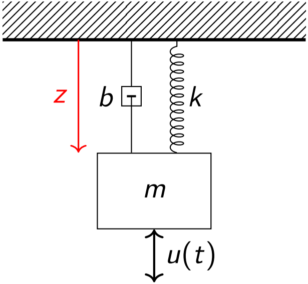
State: $X = z \in \mathbb{R}$

Equation of motion:

$$mz'' = -kz - bz' + mg + u$$

Model with external input $u(t)$

Example: mass-spring-damper system



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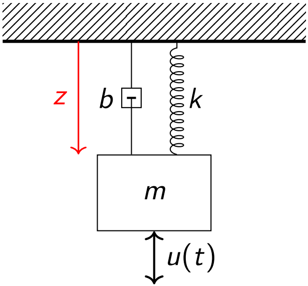

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$\rightarrow$ Affine but not first order

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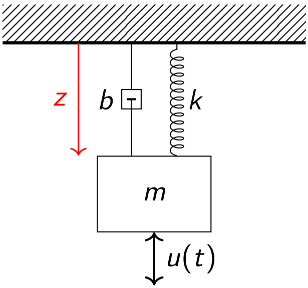

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→ Affine but not first order

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Equation of motion:

$$\begin{bmatrix} z \\ z' \\ 1 \end{bmatrix}' = \begin{bmatrix} z' \\ -\frac{k}{m}z - \frac{b}{m}z' + g + \frac{1}{m}u \\ 0 \end{bmatrix}$$

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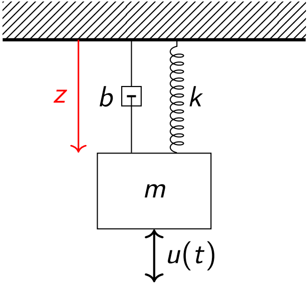

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Model with external input $u(t)$

$\rightarrow$ Linear time invariant system:

$$X' = AX + Bu$$

with some constraints on u.

Linear dynamical systems

Discrete case

$$x(n+1) = Ax(n)$$

- biology,
- software verification,
- probabilistic model checking,
- combinatorics,
- ....

Continuous case

$$x'(t) = Ax(t)$$

- biology,
- physics,
- probabilistic model checking,
- electrical circuits,
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Typical questions

- reachability
- safety

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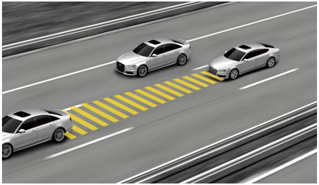
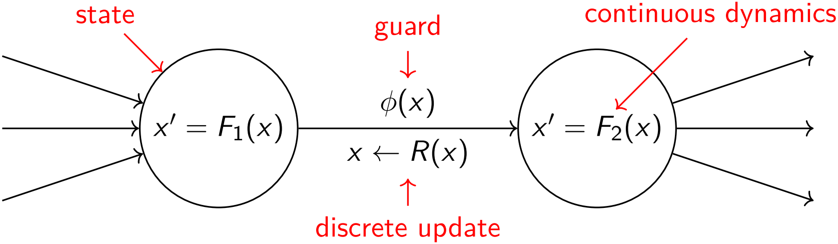
Hybrid/Cyber-physical systems



- physics: continuous dynamics
- electronics: discrete states



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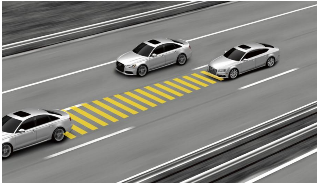

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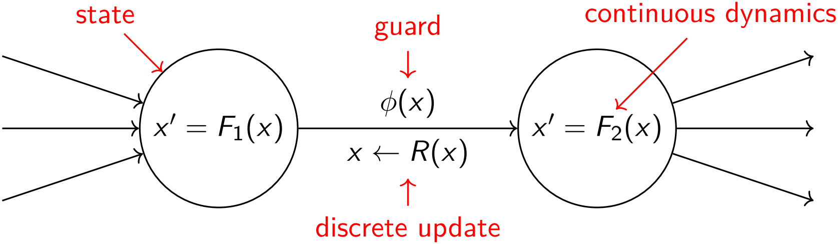

Some classes:

- $F_i(x) = 1$: timed automata
- $F_i(x) = c_i$: rectangular hybrid automata
- $F_i(x) = A_i x$: linear hybrid automata

Typical questions

- reachability
- safety
- controllability

Related work in the discrete case

Input: $A, C \in \mathbb{Q}^{d\times d}$ matrices

Output: $\exists n \in \mathbb{N}$ such that $A^n = C$?

Example: $\exists n \in \mathbb{N}$ such that

$$\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}^n = \begin{bmatrix} 1 & 100 \\ 0 & 1 \end{bmatrix} \quad ?$$

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Example: $\exists n, m \in \mathbb{N}$ such that

$$\begin{bmatrix} 2 & 3 \\ 0 & 1 \end{bmatrix}^n \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ 0 & 1 \end{bmatrix}^m = \begin{bmatrix} 1 & 60 \\ 0 & 1 \end{bmatrix} \quad ?$$

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Input: $A_1, \ldots, A_k, C \in \mathbb{Q}^{d\times d}$ matrices
Output: $\exists n_1, \ldots, n_k \in \mathbb{N}$ such that $\prod_{i=1}^{k} A_i^{n_i} = C$?

Example: $\exists n, m, p \in \mathbb{N}$ such that

$$\begin{bmatrix} 2 & 3 \\ 0 & 1 \end{bmatrix}^n \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ 0 & 1 \end{bmatrix}^m \begin{bmatrix} 2 & 5 \\ 0 & 1 \end{bmatrix}^p = \begin{bmatrix} 81 & 260 \\ 0 & 1 \end{bmatrix} ?$$

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Input: $A_1, \dots, A_k, C \in \mathbb{Q}^{d\times d}$ matrices
Output: $C \in \langle$semi-group generated by $A_1, \dots, A_k\rangle$?

Semi-group: $\langle A_1, \dots, A_k\rangle$ = all finite products of $A_1, \dots, A_k$
Examples:

$$A_1A_3A_2 \quad A_1A_2A_1A_2 \quad A_3^8A_2A_1^3A_3^{42}$$

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Recap on linear differential equations

Let $x : \mathbb{R}_+ \to \mathbb{R}^n$ function, $A \in \mathbb{Q}^{n\times n}$ matrix

$$x(t) = \begin{bmatrix} x_1(t) \\ \vdots \\ x_n(t) \end{bmatrix} \qquad A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

Linear differential equation:

$$x'(t) = Ax(t) \qquad x(0) = x_0$$

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Examples:

$$x'(t) = 7x(t)$$

$$\rightsquigarrow x(t) = e^{7t}$$

$$\begin{cases} x_1'(t) = x_2(t) \\ x_2'(t) = -x_1(t) \end{cases} \quad \Leftrightarrow \quad \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}' = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\rightsquigarrow \begin{cases} x_1(t) = \sin(t) \\ x_2(t) = \cos(t) \end{cases}$$

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General solution form:

$$x(t) = \exp(At)x_0$$

$$\text{where } \exp(M) = \sum_{n=0}^{\infty} \frac{M^n}{n!}$$

Related work in the continuous case

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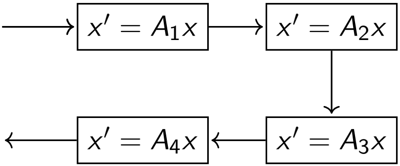
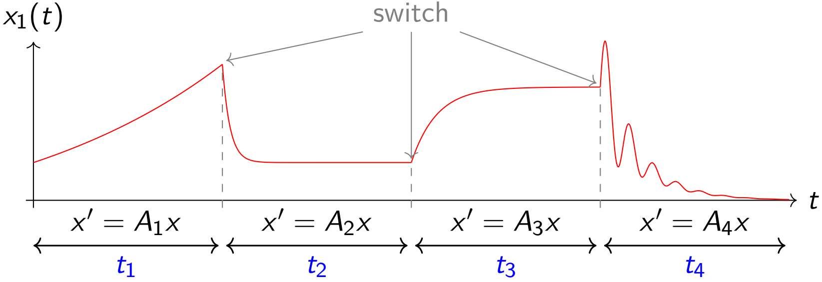
Switching system



Restricted hybrid system:

- linear dynamics
- no guards (nondeterministic)
- no discrete updates



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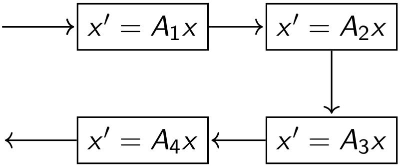

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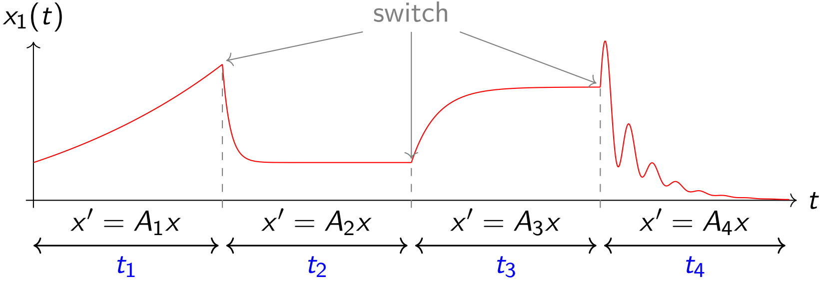

Dynamics:

$$e^{A_4 t_4} e^{A_3 t_3} e^{A_2 t_2} e^{A_1 t_1}$$

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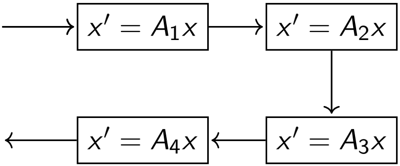

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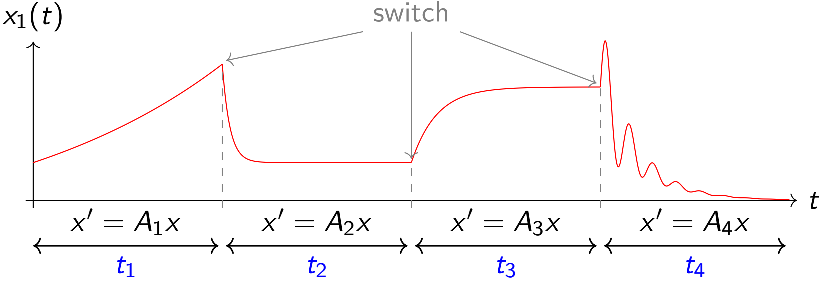
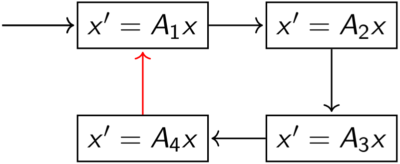


Problem:

$$e^{A_4 t_4} e^{A_3 t_3} e^{A_2 t_2} e^{A_1 t_1} = C \quad ?$$

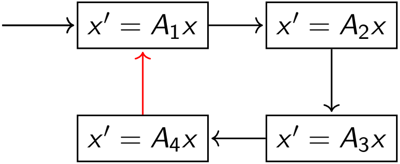
What we control: $t_1, t_2, t_3, t_4 \in \mathbb{R}_+$

Switching system



What about a loop ?

Switching system



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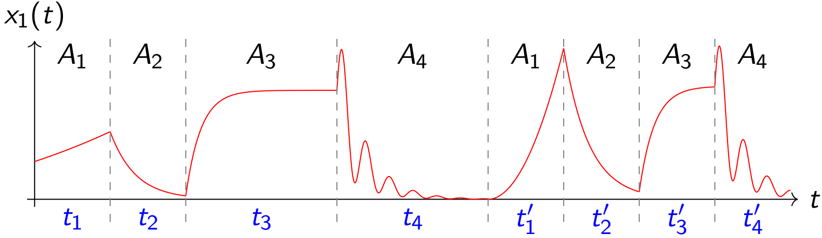

Dynamics:

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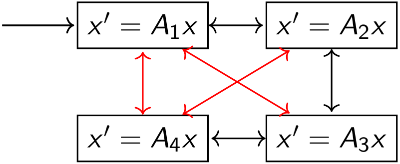
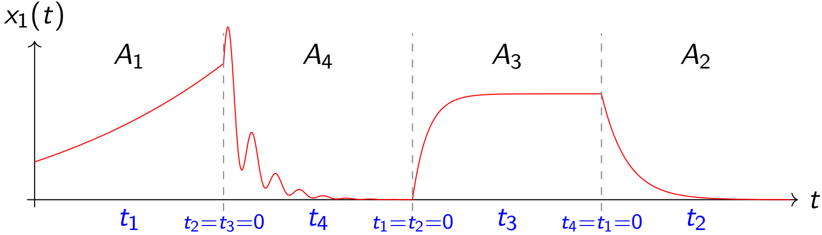


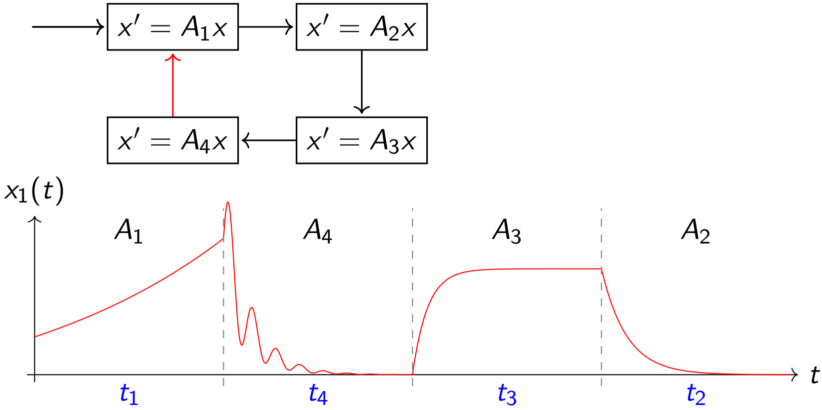
Loop $\Leftrightarrow$ clique



Remark:

zero time dynamics ($t_i = 0$) are allowed

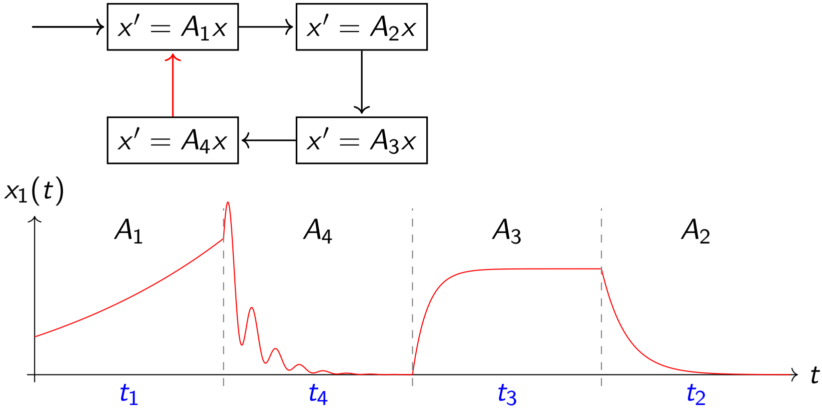
Switching system



Dynamics:

$$\text{any finite product of } e^{A_i t} \quad \rightsquigarrow \quad \text{semigroup!}$$

Switching system



Problem:

$$C \in \mathcal{G} \quad ?$$

where

$$\mathcal{G} = \langle \text{semi-group generated by } e^{A_i t} \text{ for all } t \geqslant 0 \rangle$$

Switching system: results

Input: $A_1, \ldots, A_k, C \in \mathbb{Q}^{d\times d}$ matrices
Output: $\exists t_1, \ldots, t_k \geqslant 0$ such that

$$\prod_{i=1}^{n} e^{A_i t_i} = C \quad ?$$

Input: $A_1, \ldots, A_k, C \in \mathbb{Q}^{d\times d}$ matrices
Output:

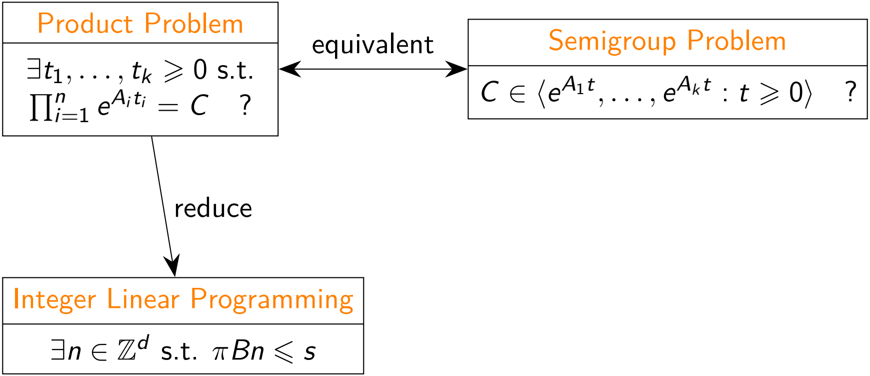
$$C \in \langle \text{semigroup generated by } e^{A_1 t}, \ldots, e^{A_k t} : t \geqslant 0 \rangle \quad ?$$

Theorem

Both problems are:

- Undecidable in general
- Decidable when all the A_i commute

Some words about the proof (commuting case)



Some words about the proof (commuting case)

Product Problem

$\exists t_1, \dots, t_k \geqslant 0$ s.t. $\prod_{i=1}^{n} e^{A_i t_i} = C$?

equivalent

Semigroup Problem

$C \in \langle e^{A_1 t}, \dots, e^{A_k t} : t \geqslant 0 \rangle$?

reduce

Integer Linear Programming

$\exists n \in \mathbb{Z}^d$ s.t. $\pi B n \leqslant s$

! s of the form:

$$a_0 + \log(a_1) + \cdots + \log(a_k)$$

✓ $B, a_0, \dots, a_k$ are algebraic

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How did we get from reals to integers with π ?

$$e^{it} = \alpha \quad \Leftrightarrow \quad t \in \log(\alpha) + 2\pi\mathbb{Z}$$

Integer Linear Programming

$$\exists n \in \mathbb{Z}^d \text{ such that } \pi B n \leqslant s \quad ?$$

where s is a linear form in logarithms of algebraic numbers

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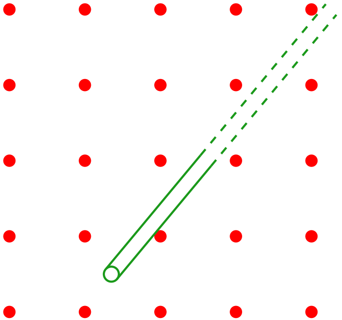
Key ingredient: Diophantine approximations

- Finding integer points in cones: Kronecker's theorem



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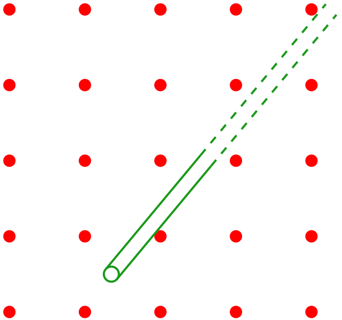
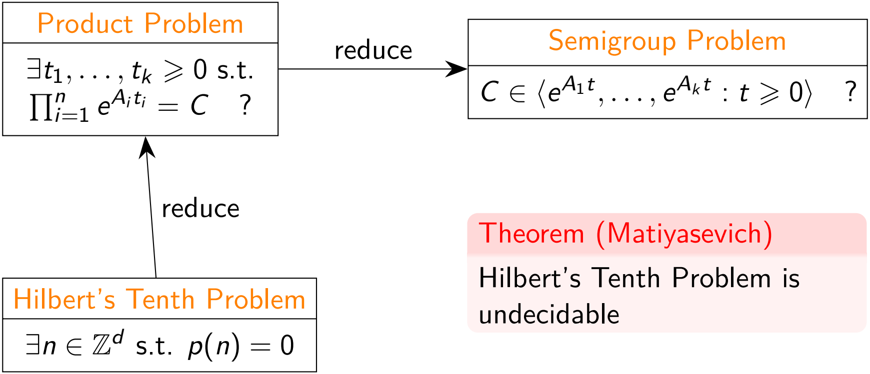


- Compare linear forms in logs: Baker's theorem

$$\sqrt{2} + \log\sqrt{3} - 3\log\sqrt{7} \quad \stackrel{?}{=} \quad 1 + \log 9 - \log\sqrt[42]{666}$$

Some words about the proof (general case)



Theorem (Matiyasevich)

Hilbert's Tenth Problem is undecidable

Discrete-time LTI system

Consider the system:

$$x(n+1) = Ax(n) + u(n) \qquad\qquad x(n) \in \mathbb{R}^d$$

where:

- $x(0)$ and A are given (rational/algebraic coefficients)
- $u(n) \in \mathcal{U}$ the input/control set

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Controllability question

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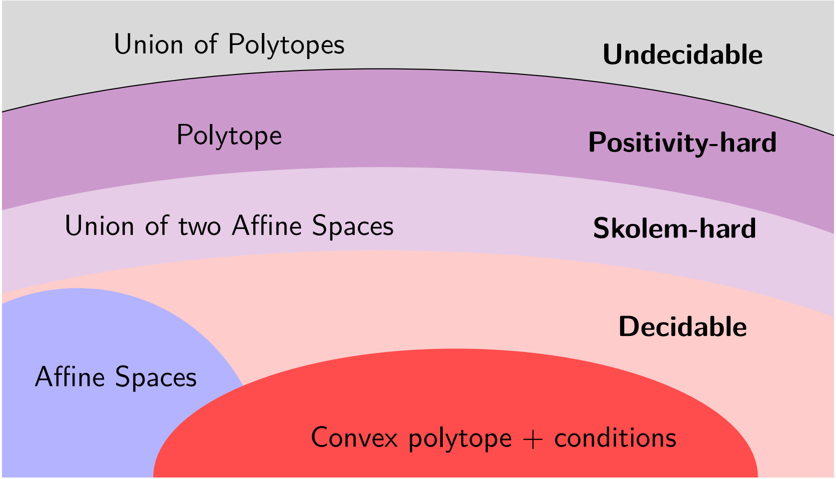
Example: $u(n)$ = user input
→ can we make the system do what we want?

Example: $u(n)$ = external force
→ can the system reach a bad state?

Complexity mostly depends on input space

$$x(n+1) = Ax(n) + u(n) \qquad x(n) \in \mathbb{R}^d, u(n) \in \mathcal{U}$$



Hardness in linear dynamical systems

Given $A, x(0)$ rationa/algebraic, consider:

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- Related to some hard number theory problems
- not known to (un)decidable

Some positive results

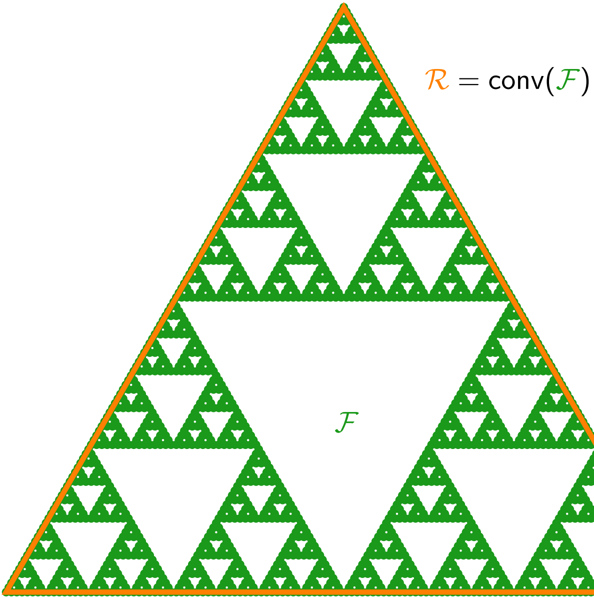
$$x(n+1) = Ax(n) + u(n) \qquad\qquad x(n) \in \mathbb{R}^d, u(n) \in \mathcal{U}$$

Theorem

Controllability to a given y is **decidable** if $\mathcal{U}$ is a **convex polytope** and A is **stable** $+$ some spectral conditions.

Reduce to: decide if y belongs to the convex hull of a self-affine fractal: a convex hull with infinitely many edges

Some positive results



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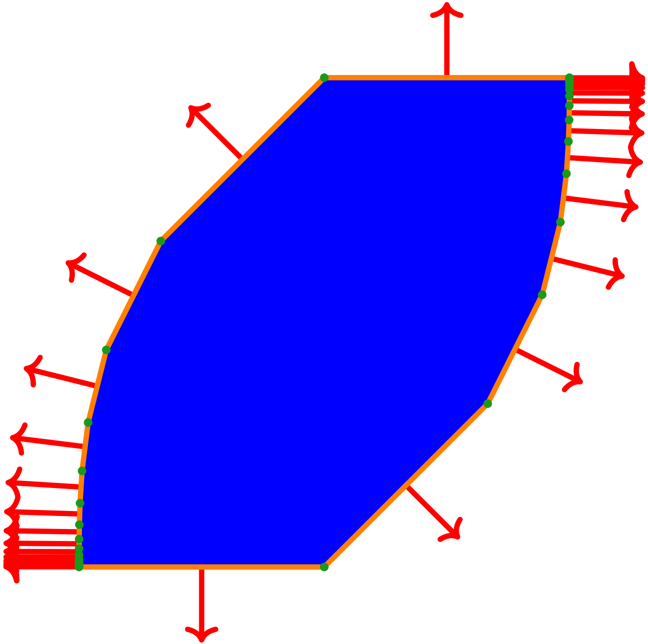

Conclusion

- Linear and hybrid dynamical systems
- Motivated by verification, synthesis and controllability problems for cyber-physical systems
- (Un-)decidability results achieved with number-theoretic tools and integer linear programming