Continuous models of computation: computability, complexity, universality

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Joint work with Olivier Bournez and Daniel Graça

21 january 2019

What is a computer?

What is a computer ?

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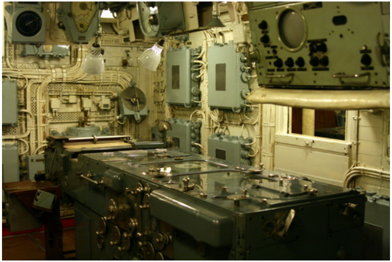
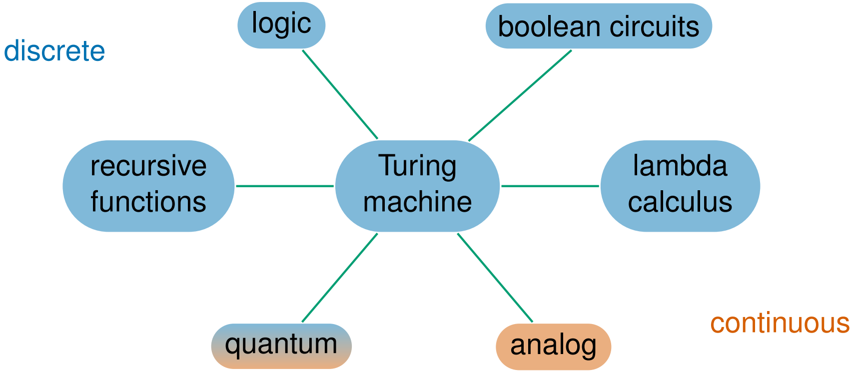
VS



Computability

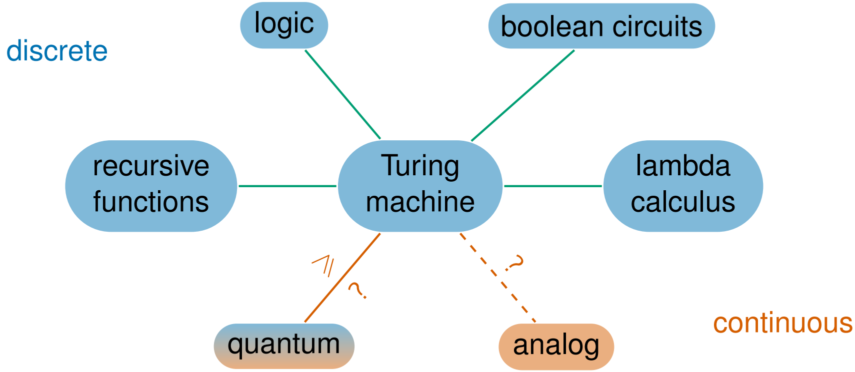


Church Thesis

All **reasonable** models of computation are equivalent.

Church Thesis

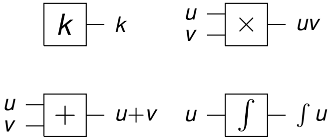
Complexity



Effective Church Thesis

All **reasonable** models of computation are equivalent for complexity.

Polynomial Differential Equations



General Purpose
Analog Computer

Differential Analyzer

Newton mechanics

Reaction networks :

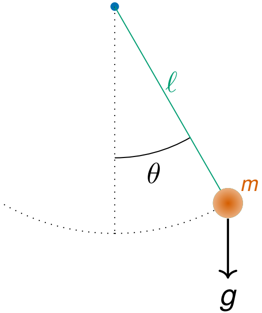
- chemical
- enzymatic

polynomial differential equations :

$$\begin{cases} y(0) = y_0 \\ y'(t) = p(y(t)) \end{cases}$$

- Rich class
- Stable (+, ×, ∘, /, ED)
- No closed-form solution

Example of dynamical system



$$\ddot{\theta} + \frac{g}{\ell}\sin(\theta) = 0$$

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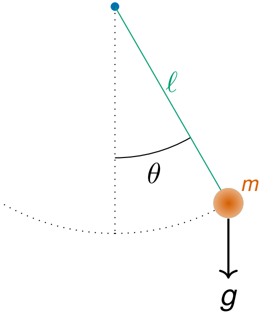
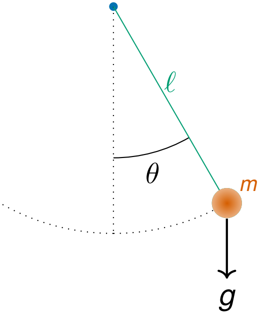


$$\ddot{\theta} + \frac{g}{\ell}\sin(\theta) = 0$$

$$\begin{cases} y_1' = y_2 \\ y_2' = -\frac{g}{l} y_3 \\ y_3' = y_2 y_4 \\ y_4' = -y_2 y_3 \end{cases} \Leftrightarrow \begin{cases} y_1 = \theta \\ y_2 = \dot{\theta} \\ y_3 = \sin(\theta) \\ y_4 = \cos(\theta) \end{cases}$$

Example of dynamical system



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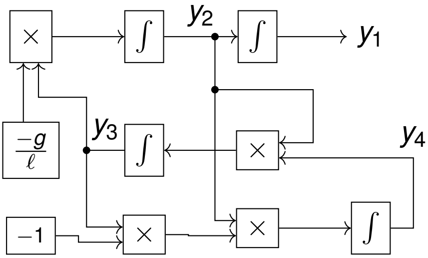

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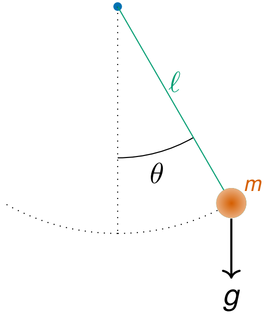

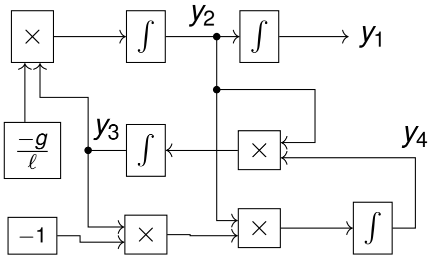

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Historical remark : the word “analog”

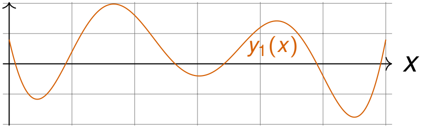
The pendulum and the circuit have the same equation. One can study one using the other by analogy.

Computing with differential equations

Generable functions

$$\begin{cases} y(0) = y_0 \\ y'(x) = p(y(x)) \end{cases} \qquad x \in \mathbb{R}$$

$$f(x) = y_1(x)$$



Shannon's notion

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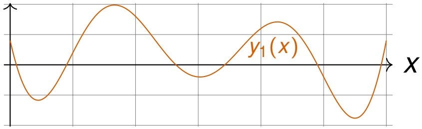

Shannon's notion

sin, cos, exp, log, ...

Strictly weaker than Turing machines [Shannon, 1941]

Computing with differential equations

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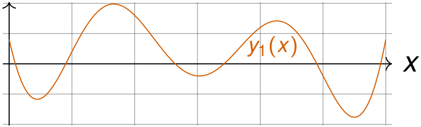

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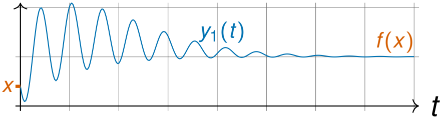
sin, cos, exp, log, ...

Strictly weaker than Turing machines [Shannon, 1941]

Computable

$$\begin{cases} y(0) = q(x) & x \in \mathbb{R} \\ y'(t) = p(y(t)) & t \in \mathbb{R}_+ \end{cases}$$

$$f(x) = \lim_{t\to\infty} y_1(t)$$



Modern notion

Computing with differential equations

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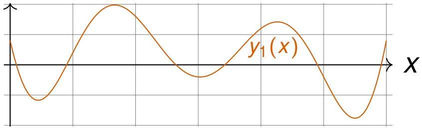

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$\sin, \cos, \exp, \log, \ldots$

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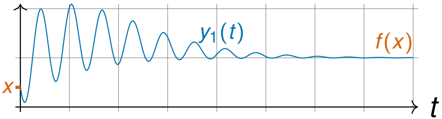


Modern notion

$\sin, \cos, \exp, \log, \Gamma, \zeta, \ldots$

Turing powerful [Bournez et al., 2007]

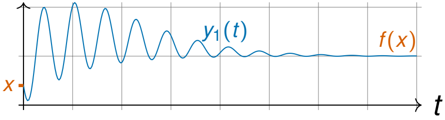
Equivalence with computable analysis

Definition (Bournez et al, 2007)

f **computable by GPAC** if $\exists p$ polynomial such that $\forall x \in [a, b]$

$$y(0) = (x, 0, \ldots, 0) \qquad y'(t) = p(y(t))$$

satisfies $|f(x) - y_1(t)| \leqslant y_2(t)$ et $y_2(t) \xrightarrow[t\to\infty]{} 0$.



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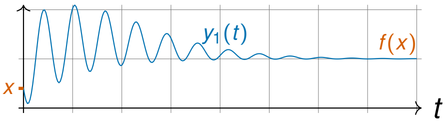

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Theorem (Bournez et al, 2007)

$f : [a, b] \to \mathbb{R}$ *computable*[1] $\Leftrightarrow$ *f computable by GPAC*

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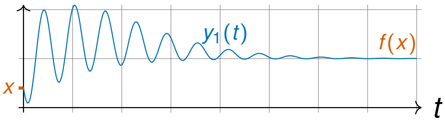

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1. In Computable Analysis, a standard model over reals built from Turing machines.

Complexity of analog systems

- Turing machines : $T(x) =$ number of steps to compute on x

Complexity of analog systems

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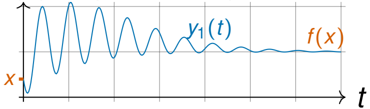
- GPAC :

Tentative definition

$T(x) = ??$

$y(0) = (x, 0, \ldots, 0) \qquad y' = p(y)$



Complexity of analog systems

- Turing machines : $T(x) =$ number of steps to compute on x
- GPAC :

Tentative definition

$T(x, \mu) =$

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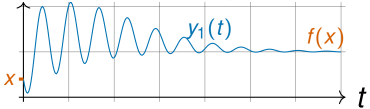

Complexity of analog systems

- Turing machines : $T(x) =$ number of steps to compute on x
- GPAC :

Tentative definition

$T(x,\mu) =$ first time t so that $|y_1(t) - f(x)| \leqslant e^{-\mu}$

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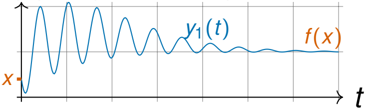

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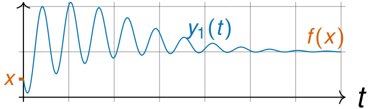
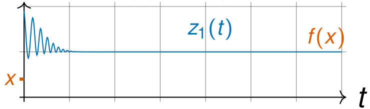


$\rightsquigarrow$

$z(t) = y(e^t)$



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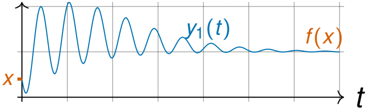

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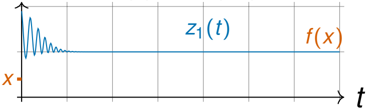
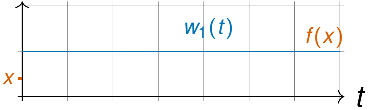


$w(t) = y(e^{e^t})$



Complexity of analog systems

- Turing machines : $T(x)$ = number of steps to compute on x
- GPAC : time contraction problem $\rightarrow$ **open problem**

Tentative definition

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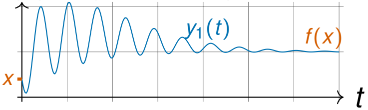
$y(0) = (x, 0, \ldots, 0)$ $\quad$ $y' = p(y)$



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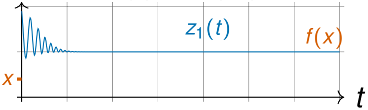

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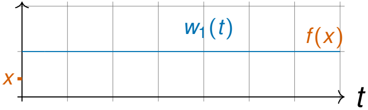
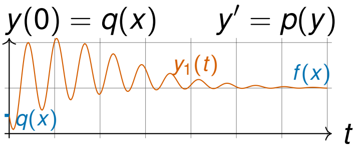


Something is wrong...

All functions have constant time complexity.

Time-space correlation of the GPAC



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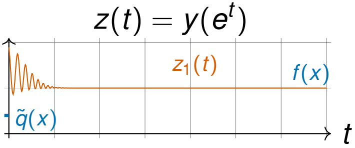

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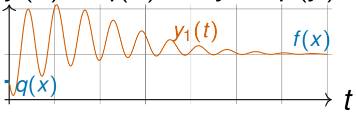

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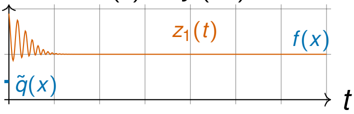
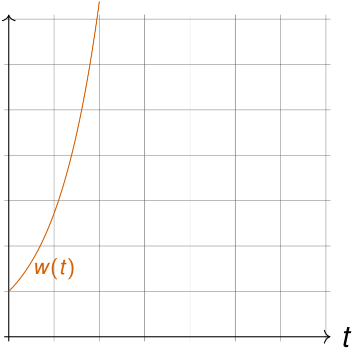


extra component : $w(t) = e^t$



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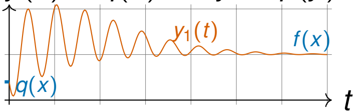

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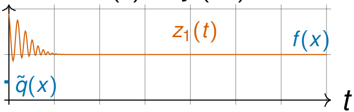

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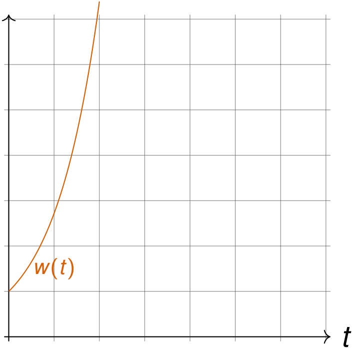


Observation

Time scaling costs “space”.

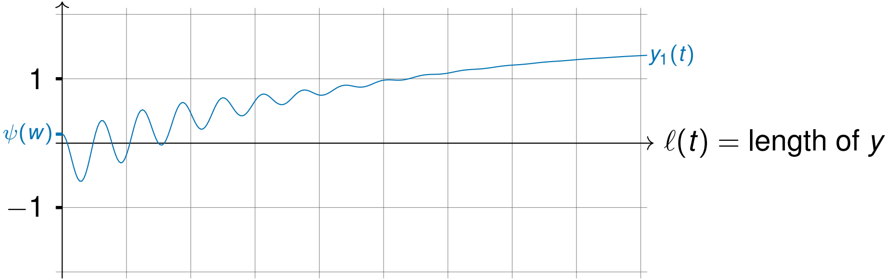
$\rightsquigarrow$

Time complexity for the GPAC must involve time and space !

Characterization of polynomial time

Definition : $\mathcal{L} \in$ ANALOG-PTIME $\Leftrightarrow \exists p$ polynomial, $\forall$ word w

$$y(0) = (\psi(w), |w|, 0, \ldots, 0) \qquad y' = p(y) \qquad \psi(w) = \sum_{i=1}^{|w|} w_i 2^{-i}$$



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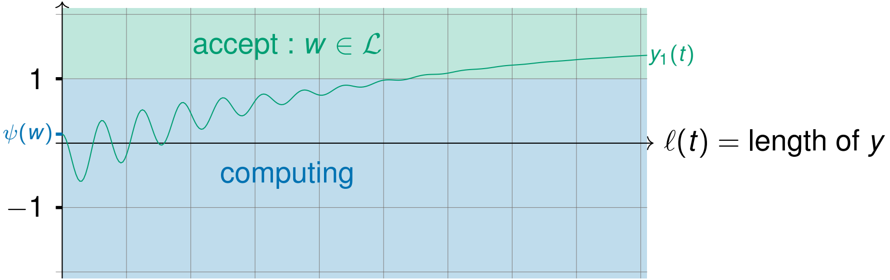

satisfies

1. if $y_1(t) \geqslant 1$ then $w \in \mathcal{L}$

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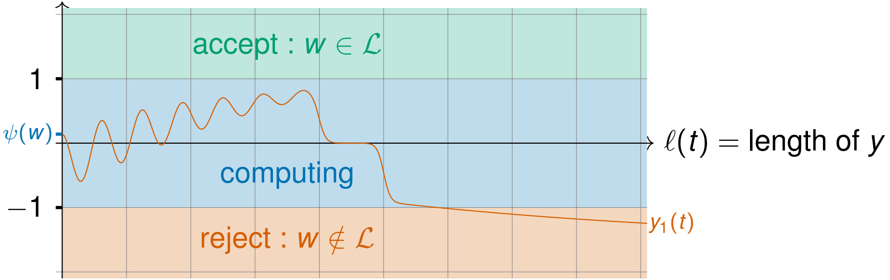

satisfies

2. if $y_1(t) \leqslant -1$ then $w \notin \mathcal{L}$

Characterization of polynomial time

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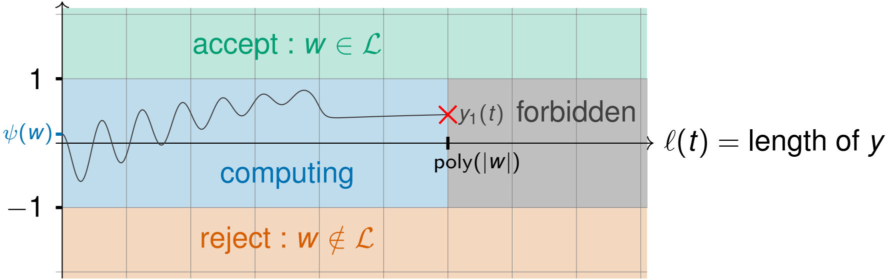

satisfies

3. if $\ell(t) \geqslant \text{poly}(|w|)$ then $|y_1(t)| \geqslant 1$

Characterization of polynomial time

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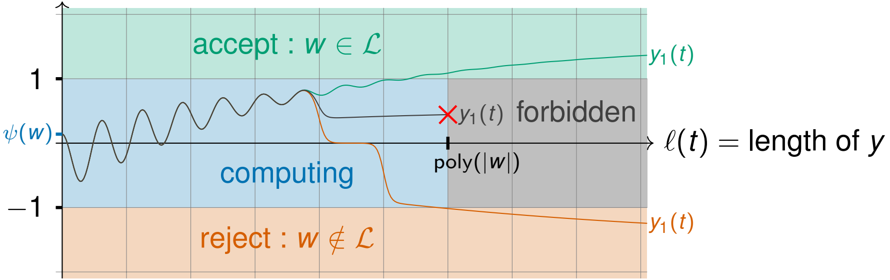
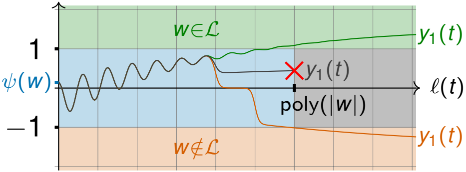


Theorem

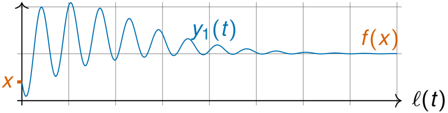
PTIME = ANALOG-PTIME

Summary

ANALOG-PTIME



ANALOG-$P_{\mathbb{R}}$



Theorem

- $\mathcal{L} \in$ PTIME *of and only if* $\mathcal{L} \in$ ANALOG-PTIME
- $f : [a, b] \to \mathbb{R}$ *computable in polynomial time* $\Leftrightarrow f \in$ ANALOG-$P_{\mathbb{R}}$

- Analog complexity theory based on length
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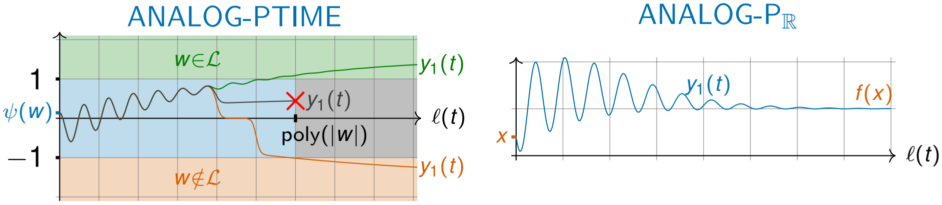
Summary



Theorem

- $\mathcal{L} \in$ PTIME *of and only if* $\mathcal{L} \in$ ANALOG-PTIME
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- Analog complexity theory based on length
- Time of Turing machine ⇔ length of the GPAC
- Purely continuous characterization of PTIME
- Only rational coefficients needed

In the remaining time...

Two applications of the techniques we have developed :

$\rightsquigarrow$ Chemical Reaction Networks

Universal differential equation

Chemical Reaction Networks

Definition : a **reaction system** is a finite set of

- molecular species $y_1, \dots, y_n$
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Theorem (Folklore)

Every polynomial ODE can be rewritten as a quadratic ODE.

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Theorem (Work with François Fages, Guillaume Le Guludec)

Elementary mass-action-law reaction system on finite universes of molecules are Turing-complete under the differential semantics.

Notes :

- proof preserves polynomial length
- in fact the following elementary reactions suffice :

$$\varnothing \xrightarrow{k} x \qquad x \xrightarrow{k} x + z \qquad x + y \xrightarrow{k} x + y + z \qquad x + y \xrightarrow{k} \varnothing$$

In the remaining time...

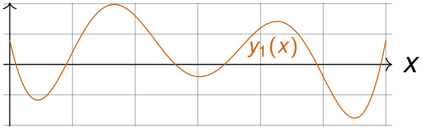
Two applications of the techniques we have developed :

Chemical Reaction Networks

$\rightsquigarrow$ Universal differential equation

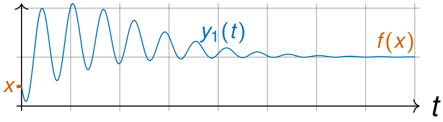
Universal differential equations

Generable functions



subclass of analytic functions

Computable functions



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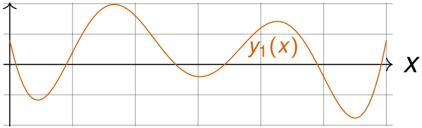

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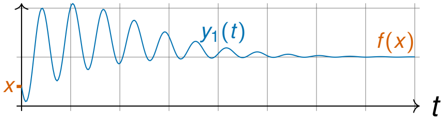

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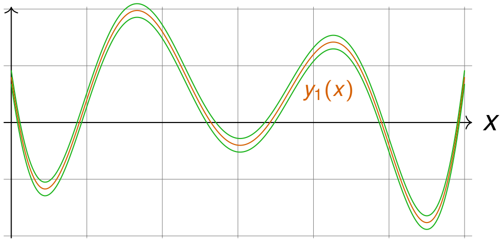
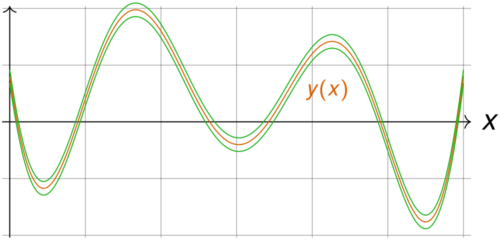


Universal differential algebraic equation (DAE)



Theorem (Rubel, 1981)

For any continuous functions f and ε, there exists $y : \mathbb{R} \to \mathbb{R}$ solution to

$$
\begin{aligned}
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such that $\forall t \in \mathbb{R}$,

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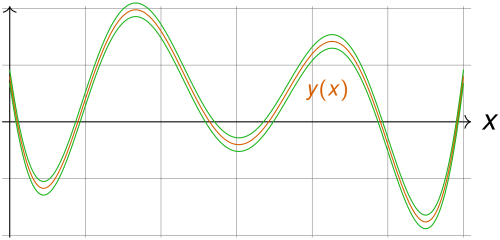

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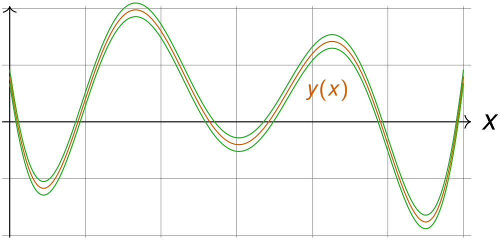

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Problem : this is «weak» result.

The problem with Rubel's DAE

The solution y is not unique, **even with added initial conditions** :

$$p(y, y', \ldots, y^{(k)}) = 0, \quad y(0) = \alpha_0, y'(0) = \alpha_1, \ldots, y^{(k)}(0) = \alpha_k$$

In fact, this is fundamental for Rubel's proof to work !

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- Rubel's statement : this DAE is universal
- More realistic interpretation : this DAE allows almost anything

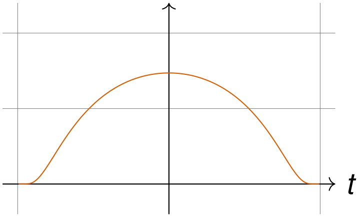
Open Problem (Rubel, 1981)

Is there a universal ODE $y' = p(y)$?
Note : explicit polynomial ODE $\Rightarrow$ unique solution

Rubel's proof in one slide

- Take $f(t) = e^{\frac{-1}{1-t^2}}$ for $-1 < t < 1$ and $f(t) = 0$ otherwise.

  It satisfies $\quad (1 - t^2)^2 f''(t) + 2tf'(t) = 0.$



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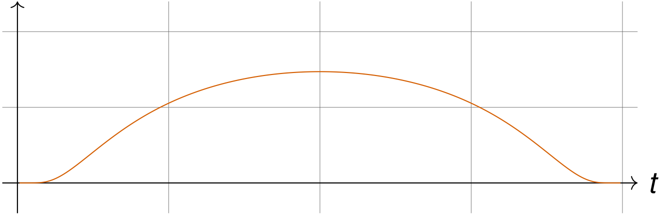

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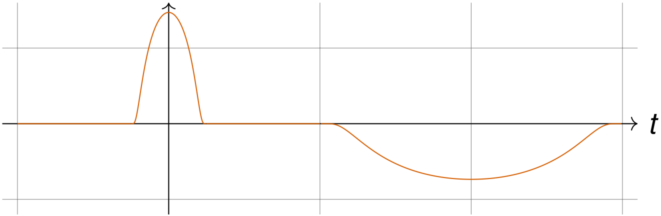

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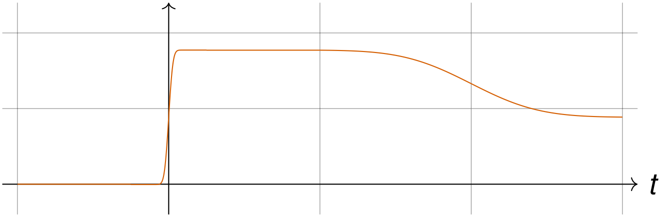

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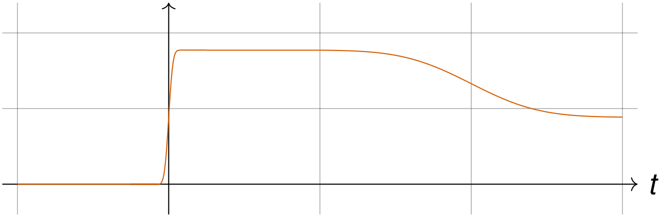
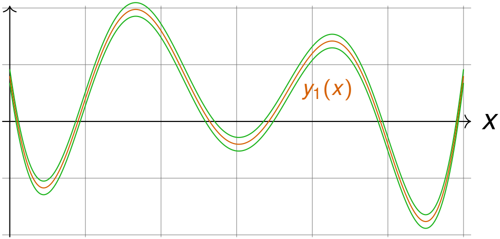


Conclusion : Rubel's equation allows any piecewise pseudo-linear functions, and those are **dense in** C^0

Universal initial value problem (IVP)



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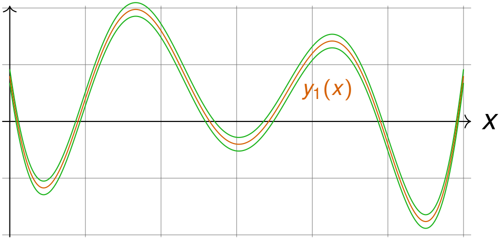

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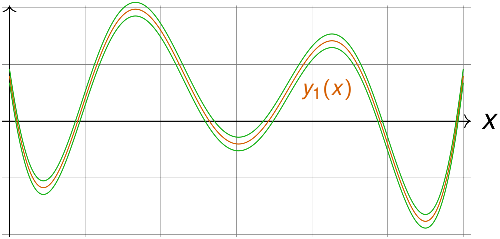

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Remark : α is usually transcendental, but computable from f and ε

Future work

Reaction networks :

- chemical
- enzymatic

$$y' = p(y)$$

?

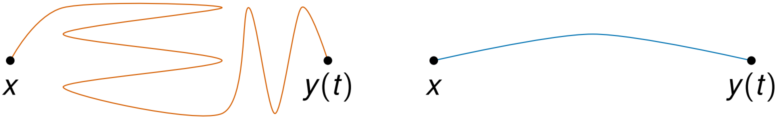
$$y' = p(y) + e(t)$$

- Finer time complexity (linear)
- Nondeterminism
- Robustness
- « Space» complexity
- Other models
- Stochastic

Backup slides

Complexity of solving polynomial ODEs

$$y(0) = x \qquad y'(t) = p(y(t))$$



Complexity of solving polynomial ODEs

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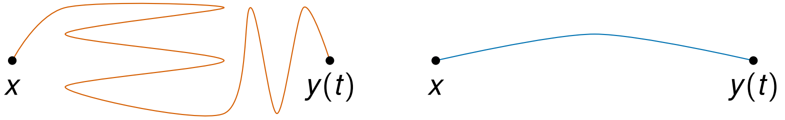
Theorem

If $y(t)$ exists, one can compute p, q such that $\left|\frac{p}{q} - y(t)\right| \leqslant 2^{-n}$ in time

$$\text{poly}\left(\textit{size of } x \textit{ and } p, n, \ell(t)\right)$$

where $\ell(t) \approx$ length of the curve (between x and $y(t)$)

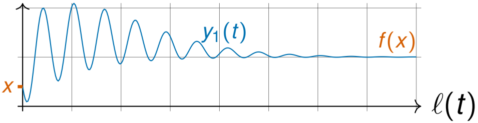


length of the curve = complexity = ressource

Characterization of real polynomial time

Definition : $f : [a, b] \to \mathbb{R}$ in ANALOG-P$_{\mathbb{R}}$ $\Leftrightarrow \exists p$ polynomial, $\forall x \in [a, b]$

$$y(0) = (x, 0, \ldots, 0) \qquad y' = p(y)$$



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   «greater length $\Rightarrow$ greater precision»

2. $\ell(t) \geqslant t$

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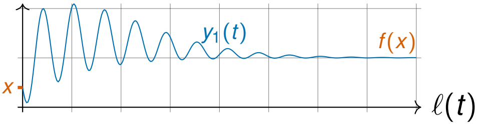

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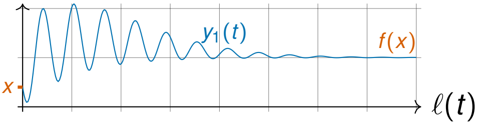
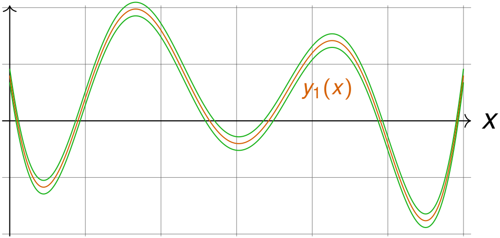


Theorem

$f : [a,b] \to \mathbb{R}$ computable in polynomial time $\Leftrightarrow$ $f \in$ ANALOG-P$_\mathbb{R}$.

Universal DAE revisited



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