Oded Maler
Barbaric Science from a Captive Poet

Our Work with Oded Maler and his Impact

Manfred Morari, UPenn and ETH

HSCC Montreal April 18, 2019

Research at Caltech and ETH around 1997

Control of systems integrating logic, dynamics, and constraints

Alberto Bemporad, Manfred Morari*

Institut für Automatik, ETH - Swiss Federal Institute of Technology, ETHZ - ETL, CH 8092 Zürich, Switzerland

Received 17 March 1998; received in final form 16 September 1998

Systems described by interdependent physical laws, logic rules, and operating constraints are described by linear equations and inequalities involving continuous and integer variables. Model predictive control based on mixed-integer quadratic programming provides a systematic controller synthesis procedure.

Automatica 35 (1999) 407–427

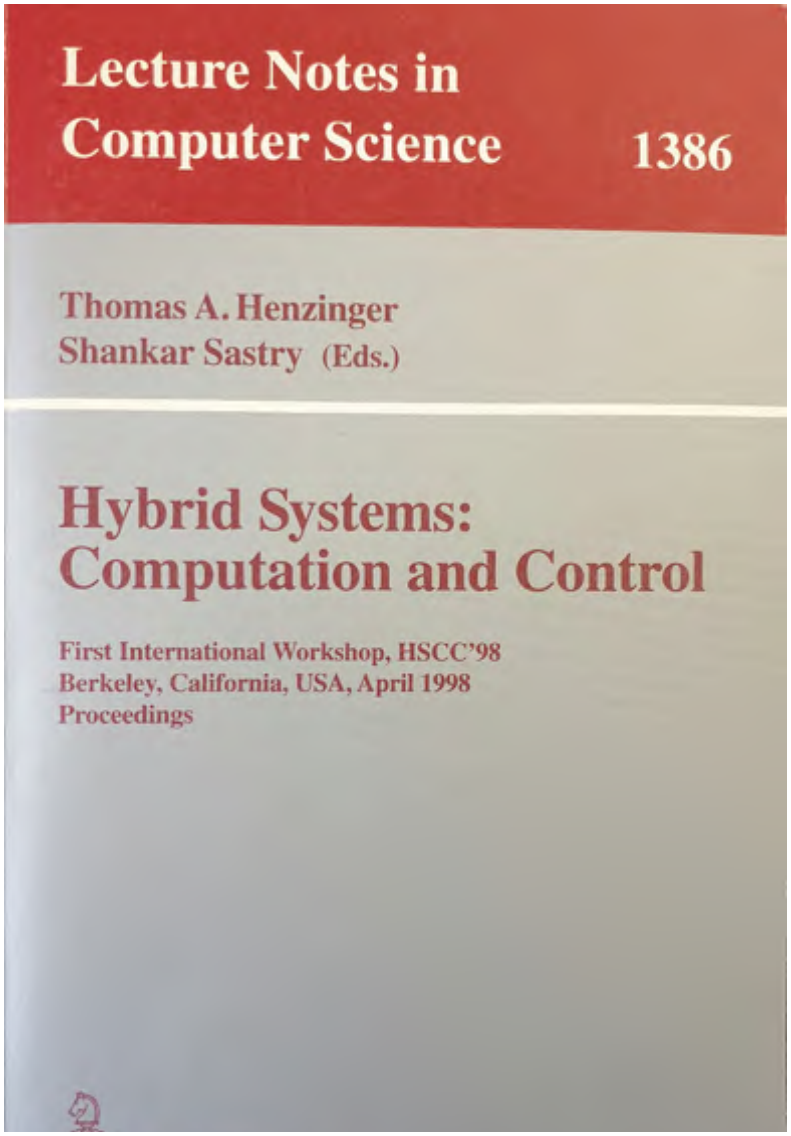
Research at Caltech and ETH around 1997

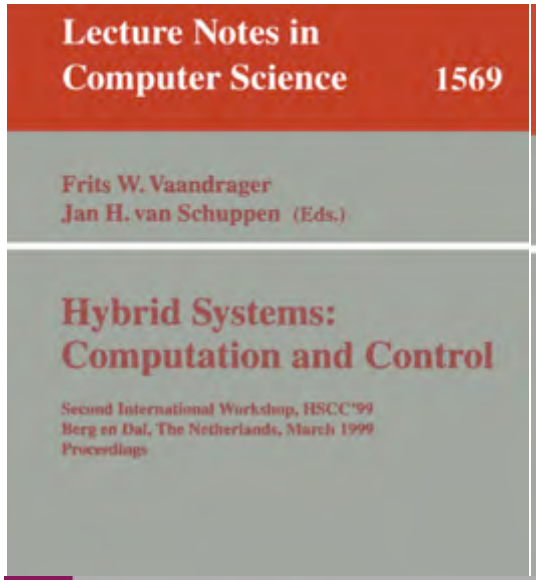
Precursors to

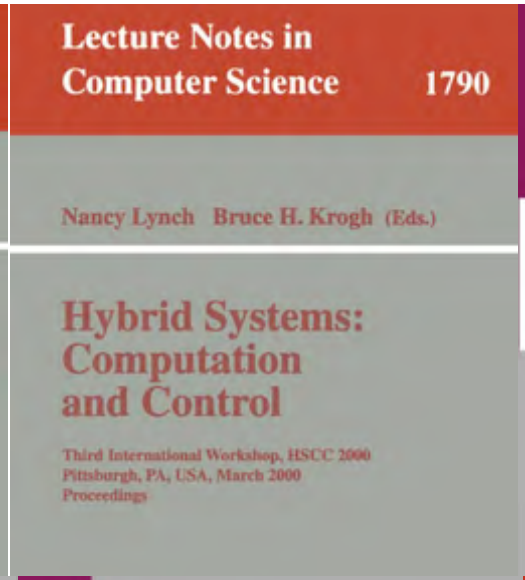
- LTL specifications for controller synthesis
  - Tabuada, Pappas; *Linear Time Logic Control of Discrete-Time Linear Systems,* IEEE TAC 2006
- MPC controller design with stability and performance guarantees for linear switched (hybrid) systems
  - Borrelli, Constrained Optimal Control of Linear and Hybrid Systems, Springer, 2003
  - Borrelli, Bemporad, MM; Predictive Control for Linear and Hybrid Systems, Cambridge 2017
  - Marcucci & Tedrake, *Mixed Integer Formulations for Optimal Control of Piecewise-Affine Systems*, HSCC 2019

Then we discovered Hybrid Systems...

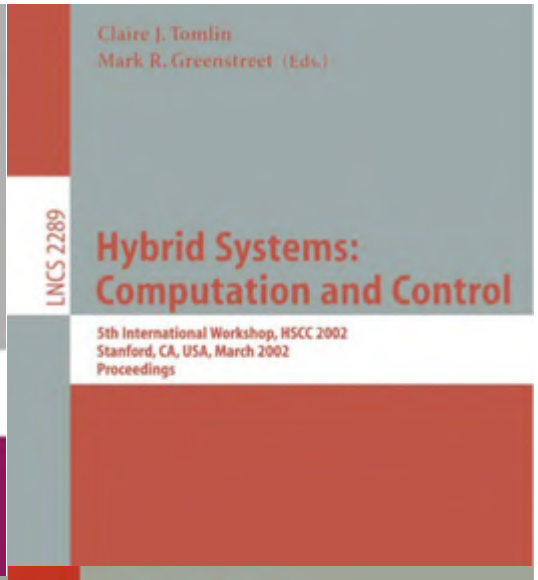
...and met Oded

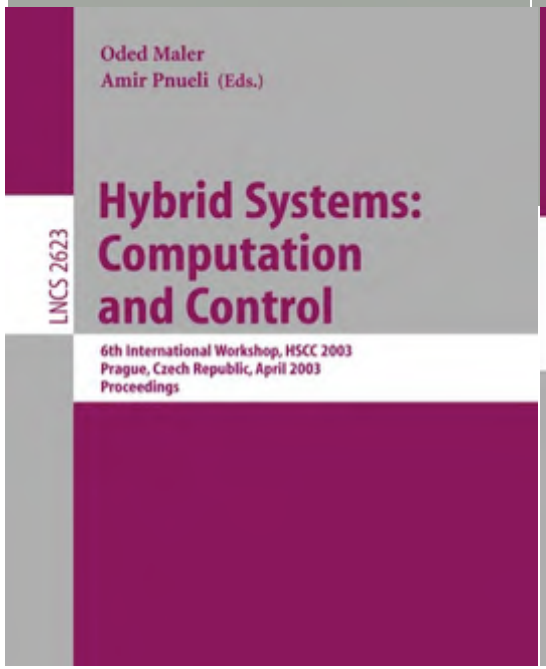


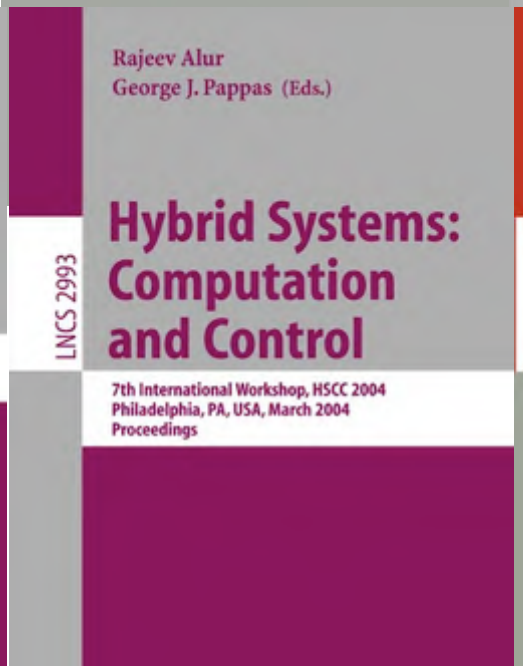

Lecture Notes in Computer Science 1569
Frits W. Vaandrager
Jan H. van Schuppen (Eds.)
Hybrid Systems: Computation and Control
Second International Workshop, HSCC'99
Berg en Dal, The Netherlands, March 1999
Proceedings

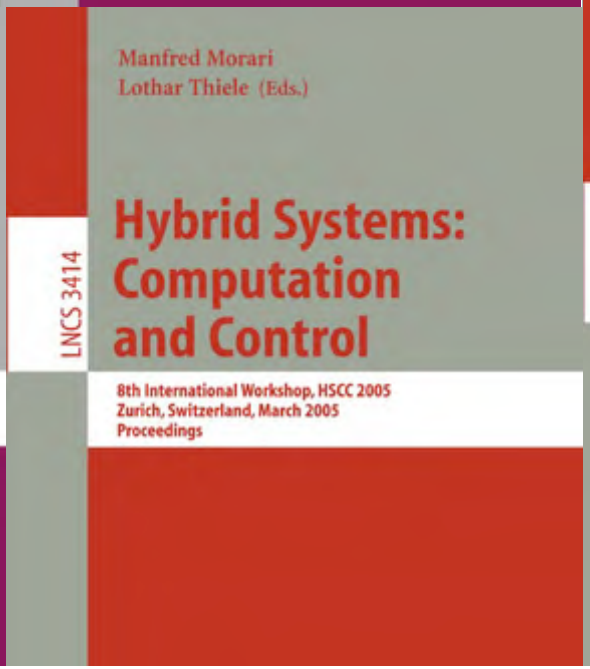

Lecture Notes in Computer Science 1790
Nancy Lynch Bruce H. Krogh (Eds.)
Hybrid Systems: Computation and Control
Third International Workshop, HSCC 2000
Pittsburgh, PA, USA, March 2000
Proceedings

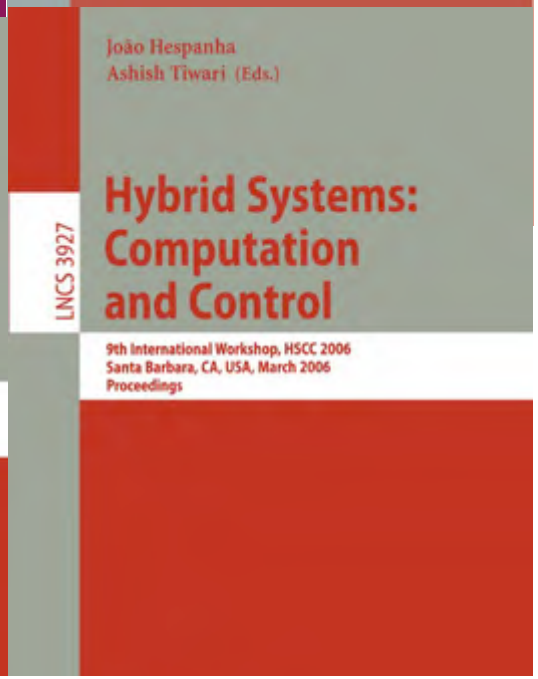

Maria Domenica Di Benedetto
Alberto Sangiovanni-Vincentelli (Eds.)
LNCS 2034
Hybrid Systems: Computation and Control
4th International Workshop, HSCC 2001
Rome, Italy, March 2001
Proceedings


Claire J. Tomlin
Mark R. Greenstreet (Eds.)
LNCS 2289
Hybrid Systems: Computation and Control
5th International Workshop, HSCC 2002
Stanford, CA, USA, March 2002
Proceedings


Oded Maler
Amir Pnueli (Eds.)
LNCS 2623
Hybrid Systems: Computation and Control
6th International Workshop, HSCC 2003
Prague, Czech Republic, April 2003
Proceedings


Rajeev Alur
George J. Pappas (Eds.)
LNCS 2993
Hybrid Systems: Computation and Control
7th International Workshop, HSCC 2004
Philadelphia, PA, USA, March 2004
Proceedings


Manfred Morari
Lothar Thiele (Eds.)
LNCS 3414
Hybrid Systems: Computation and Control
8th International Workshop, HSCC 2005
Zurich, Switzerland, March 2005
Proceedings


João Hespanha
Ashish Tiwari (Eds.)
LNCS 3927
Hybrid Systems: Computation and Control
9th International Workshop, HSCC 2006
Santa Barbara, CA, USA, March 2006
Proceedings

Oded Maler, 1957-2018

- 1957 born in Haifa
- 1976-79 BA Computer Science, Technion
- 1980-84 MSc Management Science, Tel-Aviv University
  - *"Evidence Propagation and Control Strategies in Bayesian Inference Networks"* w/ Moshe Ben-Bassat
- 1986-90 PhD Computer Science, Weizmann Institute
  - *"Finite Automata: Infinite Behavior, Learnability and Decomposition" w/ Amir Pnueli*
- 2000 Habilitation, Univ. J. Fourier, Grenoble
  - *"Discrete,Timed and Hybrid Systems"*
- 1992- Researcher, Research Director, CNRS, VERIMAG

Oded Maler, 1957-2018

- Postdocs (12)
  - Peter Niebert, Hou Jianmin, Goran Frehse, Antoine Girard, Gregory Batt, Victor Schuppan, Ramzi Ben Salah, Alexandre Donze, Scott Cotton, Jiansheng Xing, Stefano Minopoli, Marcelo Forets

- PhD Students (19)
  - Thao Dang, Yasmina Abdeddaïm, Moez Mahfoudh, Abdelkarin Kerbaa, Alexandre Donze, Ramzi Ben Salah, Dejan Nickovic, Scott Cotton, Colas Le Guernic, Aldrich Degorre, Julien Legriel, Selma Saidi, Jean Francois Kempf, Pranav Tendulkar, Jan Lanic, Thomas Ferrere, Abhinav Srivastav, Inrini-Eleftheria Mens, Dogan Ulus

Oded Maler, 1957-2018

- Numerous courses, organization of workshops, invited presentations, research projects
- 1997 – 2000: Coordinator the *Esprit/LTR project 26270 VHS (Verification of Hybrid Systems)*, with the participation of UJF-Verimag, Dortmund, Nijmegen, Aalborg-Brics, Kiel, INPG-LAG, Weizmann, CWI, Ghent, Uppsala, ETH-Zurich, Nylstar SA, Sidmar, Krupp-Uhde.
- 2002 – 2005: Coordinator of the project *IST 33520 CC (Control and Computation)* with the participation of INPG-Verimag, ETHZ, Parades, Lund, CWI, Sienna, EDF and ABB.

- Subject: More place on the Titanic, Date: Oct. 27, 1998

Dear Alberto [Bemporad] and Manfred,

Thank you for showing interest in our project. On one hand I would be glad to cooperate with you. On the other I am not very enthusiastic about re-entering into the process of proposal editing, partners consultation, Brussels discussions, and all that. We have just added a 13th partner recently and I am not sure how authorities will react to further modification.

If you are not convinced by these humanitarian arguments, I can try to ask the other partners concerning their attitude as well as the European project officer….

VERIMAG

UNITE MIXTE DE RECHERCHE

Centre Equation
2 avenue de Vignate
38610 GIERES
Tel. +33 4 76 63 48 48
Fax +33 4 76 63 48 50

Pierre's Fiton
European Commission DG-III - Industry
Rue de la Loi 200
B-1049 Bruxelles Belgique

Le 19 janvier 1999

Dear Mr. Fiton

As a coordinator of the Esprit project VHS 20270, I would like to ask your permission for adding ETH-Zurich, led by Prof. M. Morari to the project, starting from 1.12.98. The role in the project is described by the documents they sent you.

Sincerely yours

Work Plan:
Project 26270 VHS (Verification of Hybrid Systems)

- Case Studies supplied by Dortmund and [chemical] industry
- Comparative study of models, techniques, tools from the verification community
- Theoretical and practical conclusions from the experience leading to improvements of models and tools
- Surveying the current practice of control software development in the industry and suggesting improvements based on formal and semiformal methods

40th IEEE CDC, 2001

ThA12-6

Discrete-Time Hybrid Modeling and Verification

Fabio Danilo Torrisi[1] and Alberto Bemporad[2,1]

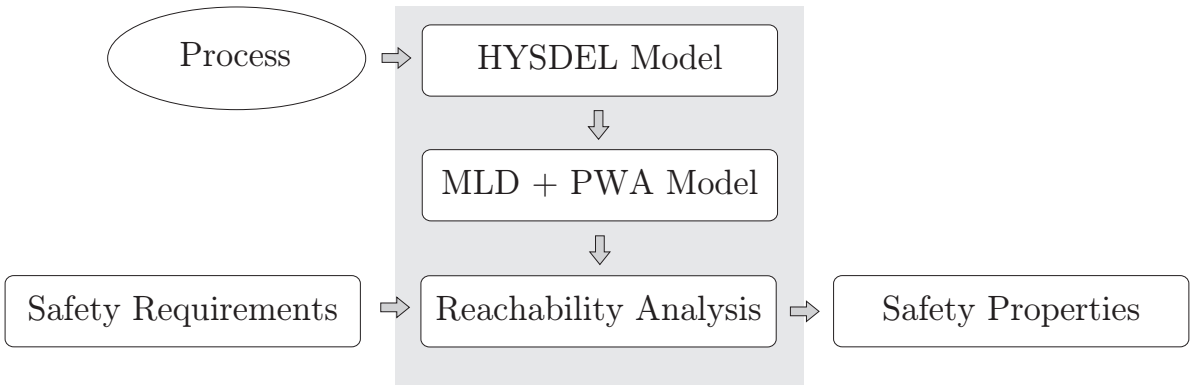


Figure 1: Verification of hybrid systems: The process is modeled in HYSDEL. The model is automatically translated it into MLD and PWA form, and used for proving safety properties

Also: European Journal of Control (2001)7:382-399

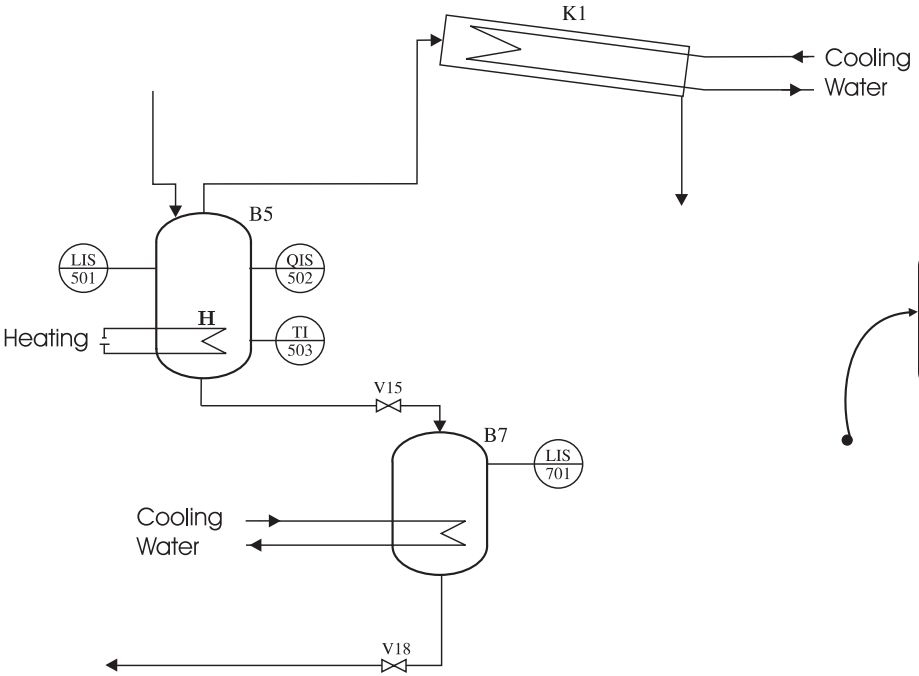


Fig. 6. Flowchart of the benchmark evaporator system.

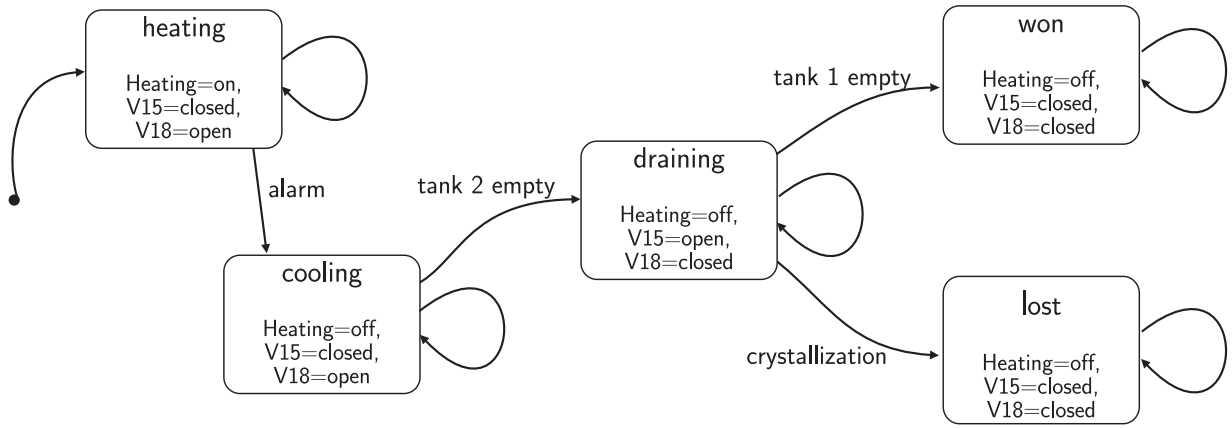


Fig. 7. State transition diagram of the controller.

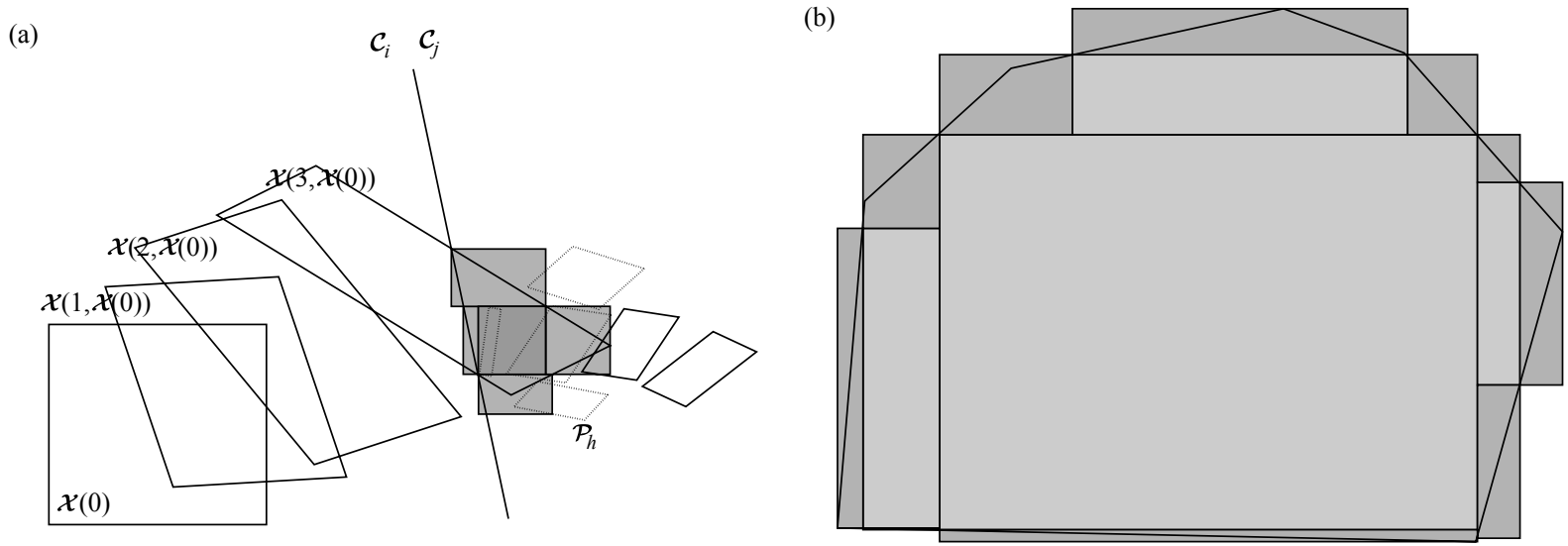


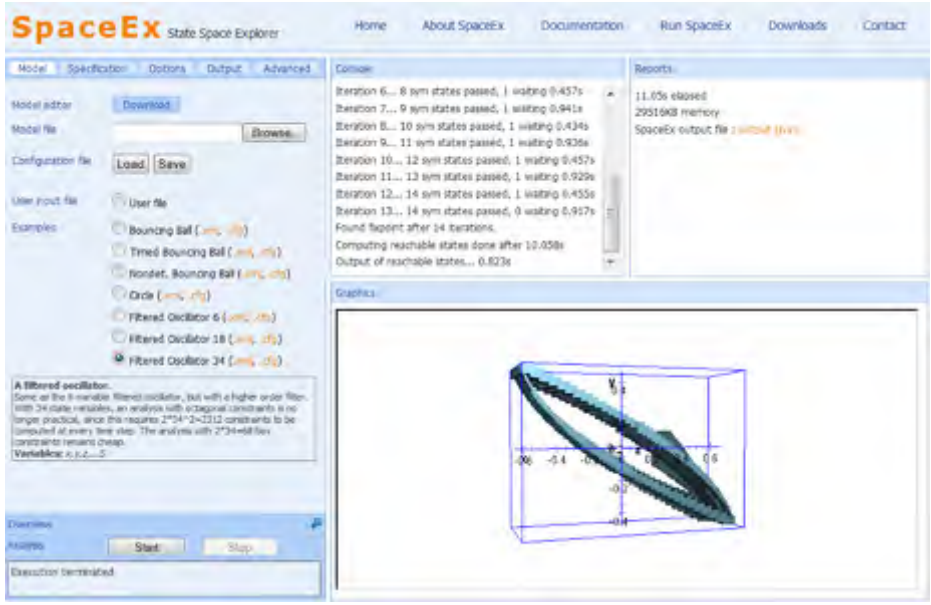
Fig. 5. Reachability analysis. (a) Reach set evolution, guardline crossing, outer approximation of a new intersection, (b) Outer rectangular approximation of a new region intersection.

Lessons learned:

- Polytope manipulations are numerically challenging
- Take advantage of commercial MILP / MIQP solvers

Some Examples of Contributions from Oded's Group

- Antoine Girard, Colas Le Guernic
  - Introduction of Zonotopes to our community
  - Rigorous analysis of computational complexity vs error and good heuristics to reduce it
  - Use of support functions
- Goran Frehse
  - Extensions
  - Tool Development: SpaceEx



CC (Control & Computation)Mtg. 2003, Siena

Cover Story

The front cover shows how by working together, Jura Cement and ABB Switzerland Ltd achieved the first known successful application of a MLD system on a cement mill. ABB's wide and successful experience with this technology made it keen to see what benefits it could bring to other parts of the cement process and therefore approached Jura Cement about a collaboration to apply this cutting edge technology to one of their grinding units. The outcome for Jura Cement's Wildegg plant has been that the mill can be run for maximum production, achieving their Blaine targets, and also ensuring energy inputs and additives are used efficiently and effectively. Jura Cement has the first plant in the world the experience the benefits of ABB applying MLD to a cement mill.

Press release | Zurich, Switzerland, 07 March 2019

ABB introduces ACS6080 drive for high performance motor control

ABB's MP^{3}C technology combines model predictive control with optimized pulse pattern to modulate the semiconductors. This means that at every point in time this control can anticipate the best motor operation point by finding the perfect compromise between dynamics, efficiency and harmonic distortion.

From: Oded Maler <Oded.Maler@univ-grenoble-alpes.fr>

Subject: Hi From Dagstuhl

Date: February 21, 2018 at 1:21:11 PM GMT+1

To: "Engell, Sebastian" <Sebastian.Engell@bci.tu-dortmund.de>, Morari Manfred <morari@control.ee.ethz.ch>, "Bruce H. Krogh" <krogh@ece.cmu.edu>

Hi Friends, I'm there in a formal methods for synthetic biology seminar. In parallel there is a seminar on MINLP, and the only name I recognized there is Ignacio Grossmann but he did not recognize me. It's a pity because I wanted to offer him a heretic guest lecture on the sacrilege and inutility of treating the Booleans as integers ;-)

Best,

--Oded

System Biology

- A cynical view
- An arrogant view
- A humble view
- A (relatively) sober view
- A sober (but subjective) view

Systems Biology: a Cynical View

- Systems Biology: the current **gold rush** for many **mathematical** and technical disciplines looking for **nutrition** (funding, self-esteem) in the **scientific food chain**
- Biophysics, Biomatics, Bioinformatics, Biostatistics...
- The story goes like this:
- I do X
- I do it for my pleasure, because I studied it, and anyway, this is the **only** thing I will do in my current incarnation...
- ...fortunately X is **very** useful for Biology
- When you have a **hammer**, everything looks like a **nail**
- Personally this is how I came to the domain ($X =$ **automata**, **verification** and **hybrid systems**)
- Fortunately, my hammer is **universal**

Systems Biology: an Arrogant View

- Biologists are essentially very **concrete** beings, spending most of their time in the **kitchen** doing manual work
- They were not selected (initially) based on ability to manipulate **imaginary concepts** or creativity and rigor in the abstract world of ideas but rather..
- ..based on their **rigor** and **efficiency** at the **bench**
- Now when they need to make a **real science** out of their details they need noble white collar brahmins, namely..
- ... physicists, mathematicians, computer scientists, as **spiritual guides**
- Like monotheists converting the pagans, these merchants of abstract methodologies try to impress the poor savage with their **logics** and **miracles**

Systems Biology: a Humble View

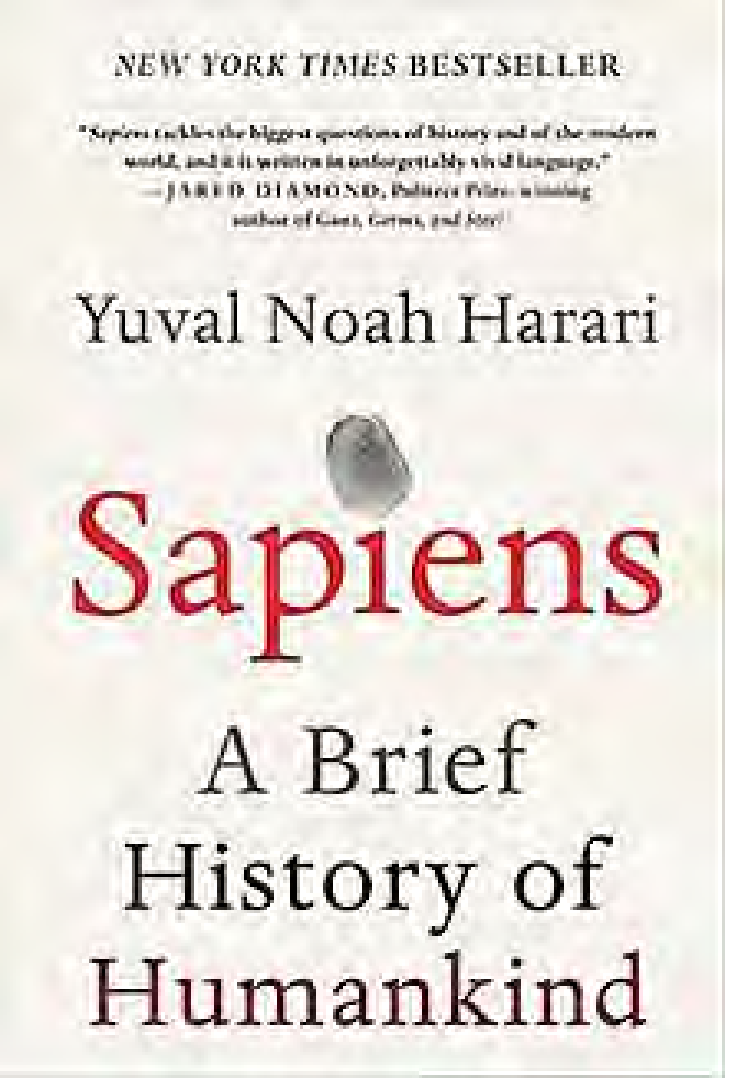
- Biologists are working with the most fascinating, complex and mysterious **real-life** phenomena
- Living systems are more complex than the **hydrogen atom** or the **electromagnetic field** (and are not effectively reducible to them)
- Living systems are more sophisticated than your **dumb terminal** or **smart phone** or mobile robot or car
- Living systems are more mysterious and primordial than the **prime numbers**, the **algebra of Boole** or the **free monoid**
- If some of our dry tricks can help them, even a bit, in their grand march toward..
- ..understanding something about **Life Itself** or helping doctors kill less patients
- We should be very happy and proud for doing, for once, something **meaningful**

Systems Biology: a (relatively) Sober View

- The dynamics of a scientific discipline may have different periods with various **trends** and **fashions**
- This dynamics is not always optimized towards **truth**
- Many aspects (politics, social dynamics, commercial interests, cognitive inertia, media distortion) play an important role
- Probably most of what is published today in top journals will go to the **garbage can of history**
- Few centuries ago, the science of this guy (**chemistry**, **medicine**, **metaphysics**) was debated extensively in prime time

Systems Biology: a Sober (but subjective) View

- Today there is an **over emphasis** on doing something with data provided by new experimental machinery (omics)
- The main question about "knowing" all these details is whether this knowledge:
  - Is **sufficient** for understanding and learning something about underlying mechanisms ? (certainly not)
  - Is **necessary** for that ? (very hopefully not)
  - Is **helpful** or **counter-productive** ?
- Systems Biology is about seeking some clearer (conceptual and mathematical) models of **dynamical systems** at various **levels** of **abstraction**
- These models, if thoughtfully constructed, and carefully and **systematically analyzed/simulated** may help reducing the gap between cellular biochemistry and physiology



Ouri Maler is creating stories | Patreon

Hey there. My name is Ouri Maler. I'm known by a couple of aliases online, including "sun tzu".
I enjoy writing fiction, which I've been putting online for years. If you're reading this, odds are you enjoy some of my writing. Maybe you like Saga of Soul, my deconstructive-slash-reconstructive magical girl webnovel about a teenage girl with a fondness for the scientific method, who applies it to her newfound abilities in-between trying to save the world from a procession of monsters and villains. Maybe you like Souls in a Vacuum, my short story of religion meeting politics meeting space-opera aboard Concordia, a massive space station where delegates from the various religions of the galaxy meet. Maybe you like my fanfics, be they comedic rewrites of My Little Pony that gradually grew into a script-format equivalent of abridged series, or more serious tales of a paragon of superheroism being transported to the the grim supervillain story of Worm, or stories of a ludicrously intelligent, hypercompetent mastermind wandering into that very same setting and doing his best to fix it with little

Safety Verification and Robustness Analysis of Neural Networks via Quadratic Constraints and Semidefinite Programming[1]

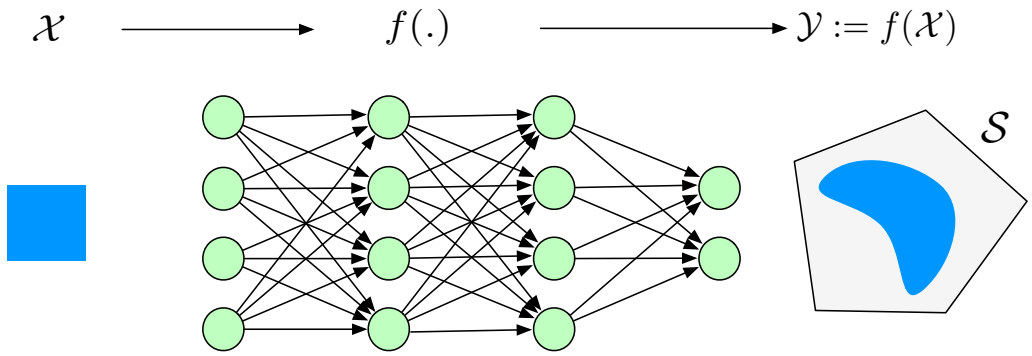
Mahyar Fazlyab, Manfred Morari, George J. Pappas



[1] https://arxiv.org/abs/1903.01287

Canonical Problem

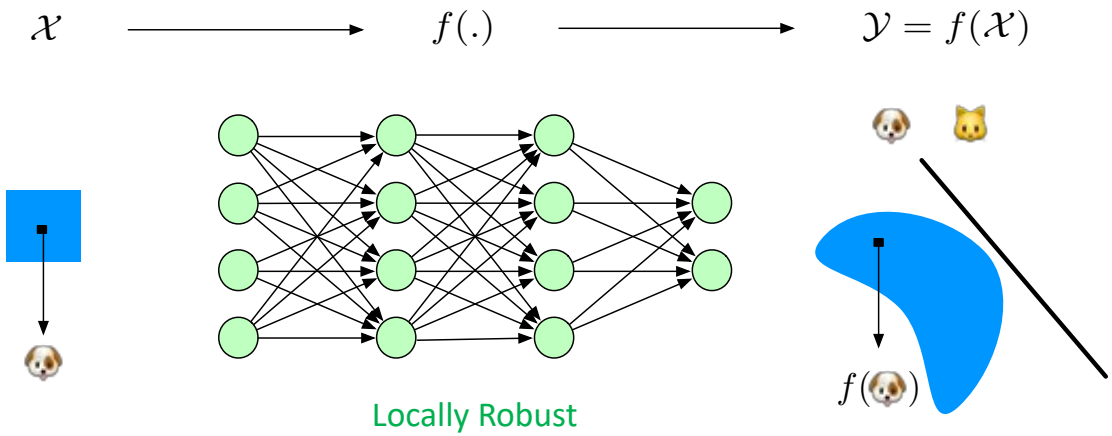
- **Given**
  - Trained neural network described by $f\colon \mathbb{R}^{n_x} \to \mathbb{R}^{n_y}$
  - Bounded set $\mathcal{X} \subset \mathbb{R}^{n_x}$ of infinite number of inputs
  - Set $\mathcal{S} \subset \mathbb{R}^{n_y}$ on the output space



- **Goal:**
  - Check whether $f(\mathcal{X}) \subseteq \mathcal{S}$

Example: Local Robustness in Image Classification

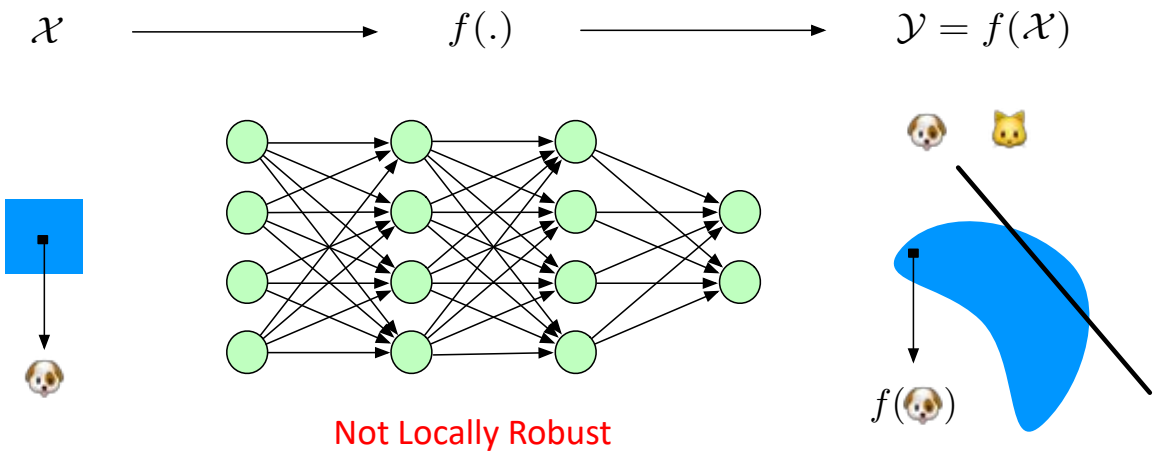
- $\mathcal{X}$ is the set of all perturbations of an image



Local robustness: $\mathrm{Class}(x)$ is the same for all $x \in \mathcal{X}$

Example: Local Robustness in Image Classification

- $\mathcal{X}$ is the set of all perturbations of an image

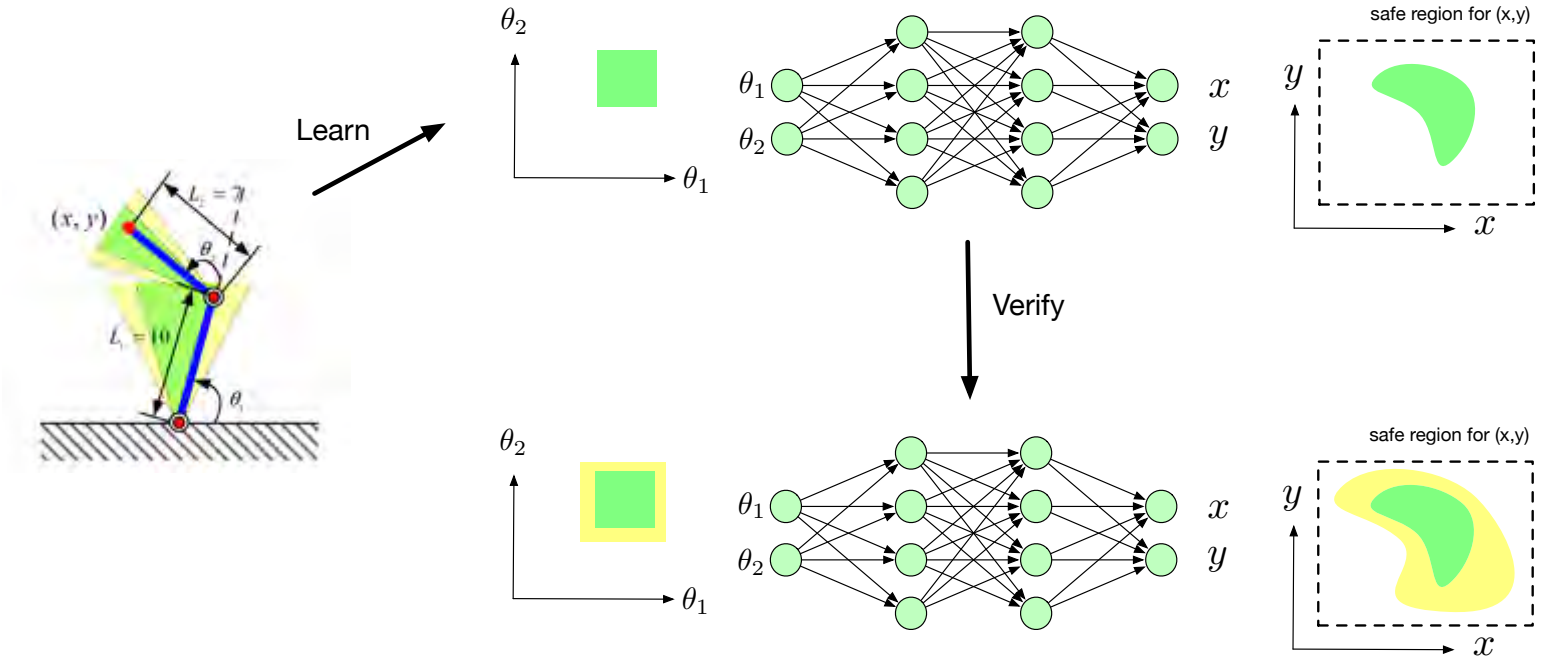


$\mathrm{Class}(x)$ is NOT the same for all $x \in \mathcal{X}$

- How can we certify local robustness of a trained NN around a test image?

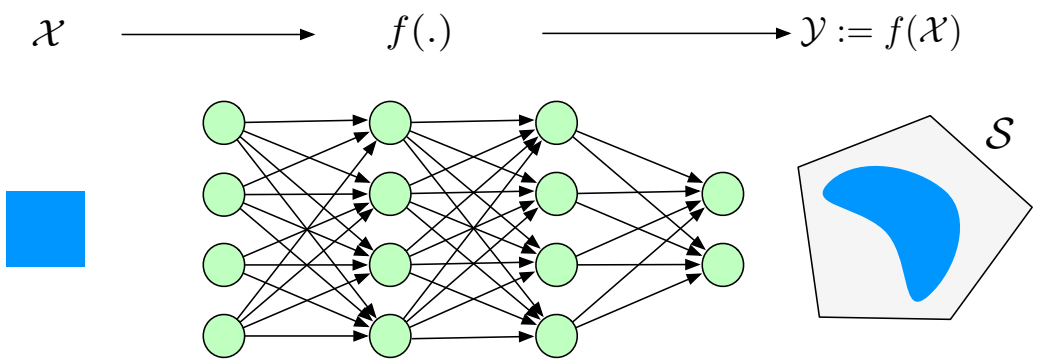
Example: Safety Verification

- Learning forward kinematics of robotic arms [Xiang et al., 2018]



Safety Verification Problem

- **Goal:** Check whether $\mathcal{Y} \subseteq \mathcal{S}$



- **Challenge:** Computation of $\mathcal{Y}$ is NP-complete
  - Exhaustive evaluation of an "infinite" number of input examples
- **Our goal:** Convex relaxation of this problem: polynomial-time solvable

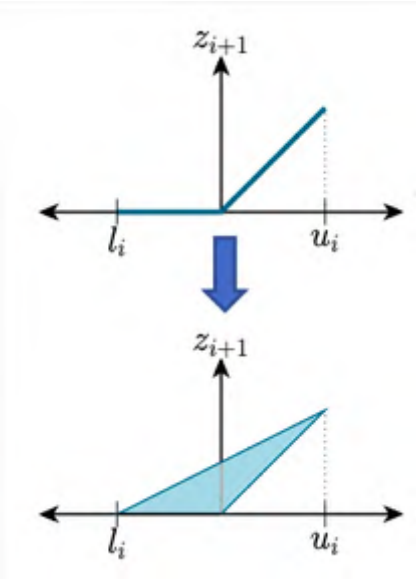
Related Work

- **Exact** (complete) verifiers for ReLU networks with exponential run-time (in the worst-case)
  - Satisfiability Modulo Theory (SMT) [Ehlers, 2017, Katz et al., 2017, Lomuscio and Maganti, 2017, Carlini and Wagner, 2017]
  - Mixed-Integer Linear Programming (MILP) solvers [Fischetti and Jo, 2017, Dutta et al., 2018, Tjeng et al., 2017]

Related Work

- **Exact** (complete) verifiers for ReLU networks with exponential run-time (in the worst-case)

- **Inexact** (incomplete) verifiers
  - Relaxation of activation functions [Kolter and Wong, 2017, Raghunathan et al., 2018a, Raghunathan et al., 2018b, Mirman et al., 2018, Weng et al., 2018, Zhang et al., 2018]

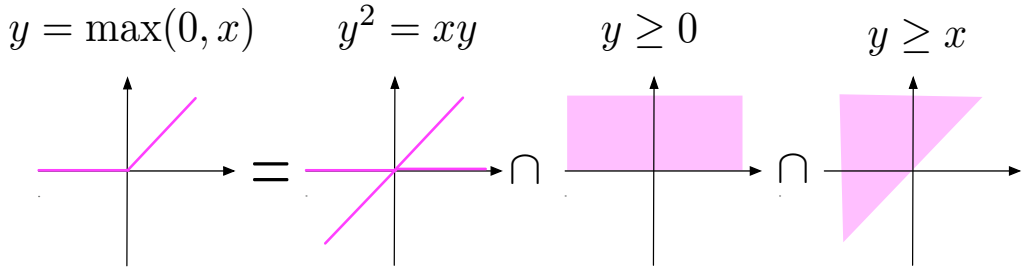


Related Work

- **Exact** (complete) verifiers for ReLU networks with exponential run-time (in the worst-case)
- **Inexact** (incomplete) verifiers
- **This work:** convex relaxation by adapting tools from robust control

ReLU Function

- Precisely described by 3 constraints



- Relaxation: for any $(\lambda, \nu, \eta) \in \mathbb{R} \times \mathbb{R}_+ \times \mathbb{R}_+$

$$\lambda(y^2 - xy) + \nu(y - x) + \eta y \geq 0$$

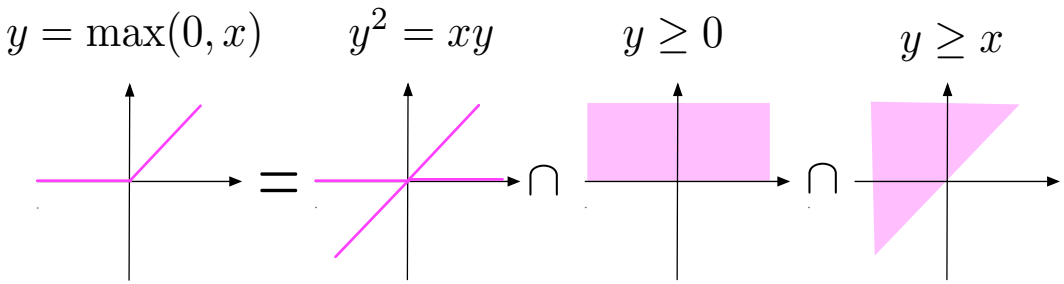
- Can be written as

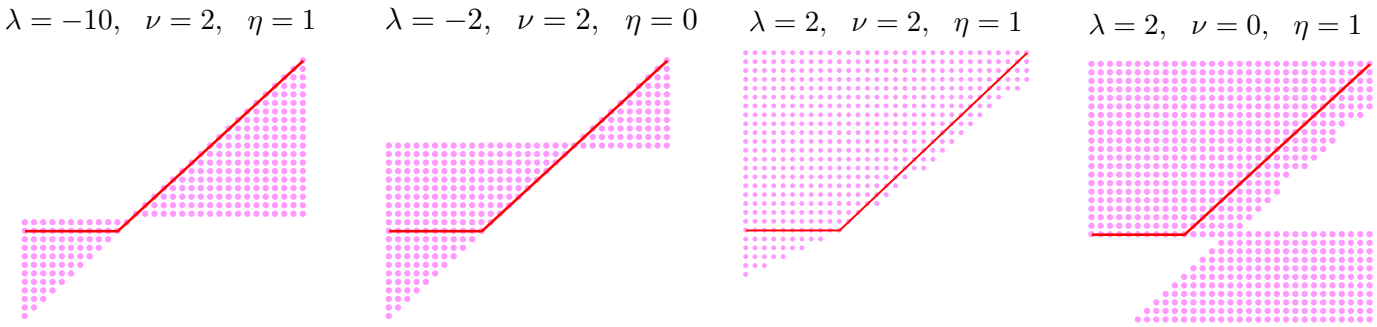
$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}^\top \begin{bmatrix} 0 & \lambda & -\nu \\ \lambda & -2\lambda & \nu + \eta \\ -\nu & \nu + \eta & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \geq 0.$$

- The multipliers (λ, ν, η) will be decision variables

ReLU Function

- Precisely described by 3 constraints





- We converted the safety verification problem into an **LMI feasibility problem**
  - A convex problem: can be solved in polynomial time
- Pros:
  - We can use various forms of QCs to abstract any type of activation function.
  - Our method is able to capture the cross-coupling between neurons across different layers, thereby reducing conservatism, especially for deep networks.
  - We can control the trade-off between computational complexity and conservatism by systematically including or excluding different types of QCs.
  - Requires much less memory compared to similar (SDP-based) approaches
- Cons:
  - Limited scalability of SDP solvers.

Effect of Number of Hidden Neurons

- Network: one-layer with architecture (2-N-2) where $N = 100, 500, 1000$.
- ReLU activation function
- Input set: ℓ_∞-norm: $\mathcal{X} = \{x \colon \|x - x^\star\|_\infty \leq \epsilon\}$ with $x^\star = (0.5, 0.5)$ and $\epsilon = 0.1$

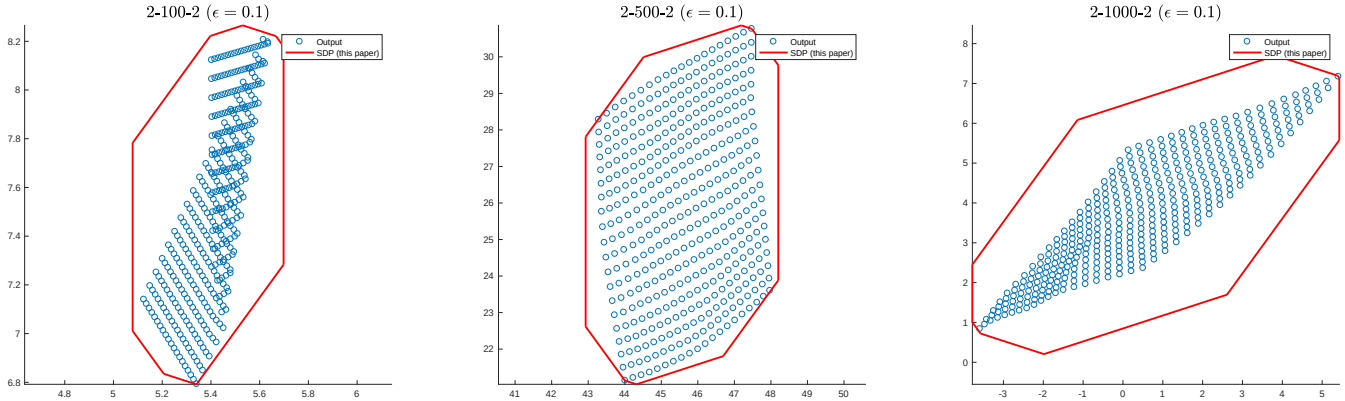


Figure: Increase in the number of hidden nodes

Effect of Magnitude of Perturbation

- Network: one-layer with architecture (2-500-2).
- ReLU activation function
- Input set: ℓ_∞-norm: $\mathcal{X} = \{x \colon \|x - x^\star\|_\infty \leq \epsilon\}$ with $x^\star = (0.5, 0.5)$ and $\epsilon = 0.1, 0.4, 0.8$.

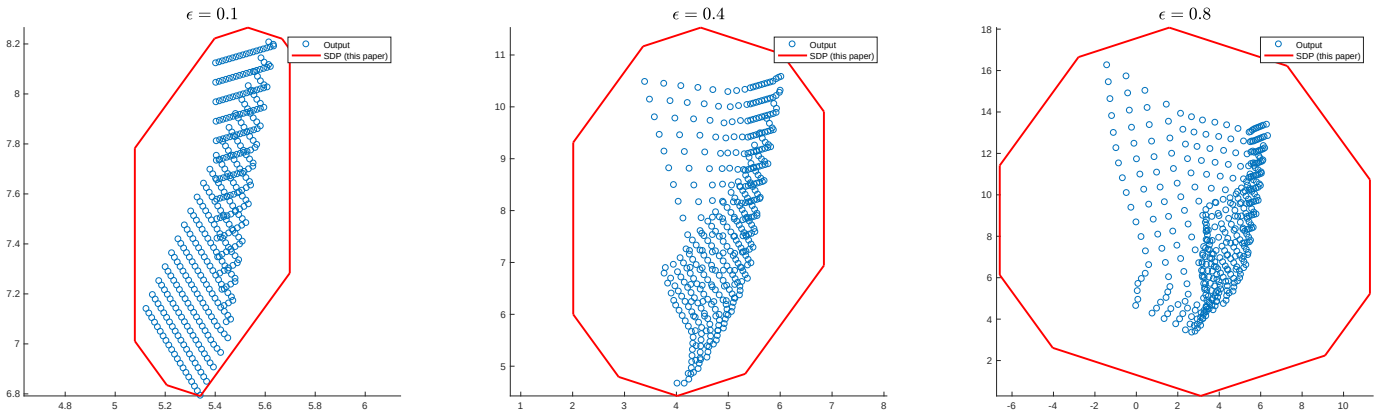
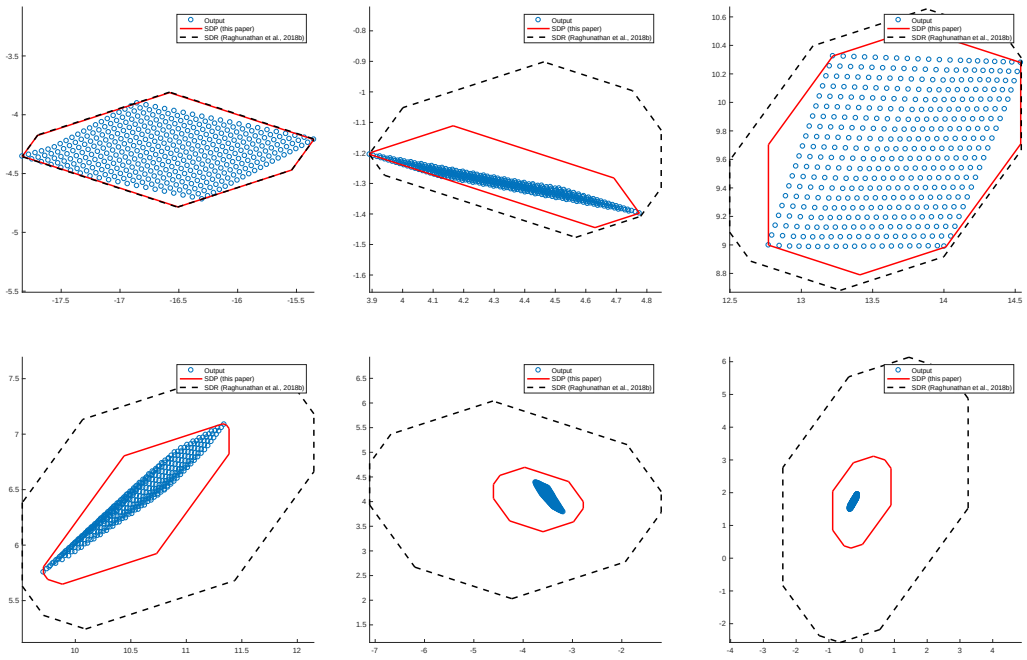


Figure: increase in the magnitude of input set

Effect of Number of Layers

- Network: one-layer with architecture (2-100-...-100-2) with $\ell = 1, 2, 4, 6, 8, 10$ layers.
- ReLU activation function
- Input set: ℓ_∞-norm: $\mathcal{X} = \{x \colon \|x - x^\star\|_\infty \leq \epsilon\}$ with $x^\star = (0.5, 0.5)$ and $\epsilon = 0.1$.



It is with deep sorrow that I announce the passing of our colleague and friend Oded Maler, in the evening of September 3rd, 2018.

Oded was a brilliant researcher, admired for his integrity and his scientific curiosity. He made substantial and original contributions in Formal Methods. He had a broad spectrum of interests including not only computer science and mathematics, but also biology and philosophy of science. His sense of humour and his human qualities, made him a dear and respected colleague to many at home and abroad.

For his colleagues at Verimag, he was a source of inspiration, an example, and the dearest friend. He leaves a huge void in our community.

Joseph Sifakis