

Formal Verification of Cyber-Physical Systems

An Invitation

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Pop Quiz

Solve this:

$$\frac{dx}{dt} = xe^{-t}$$

$$x(0) = 5$$

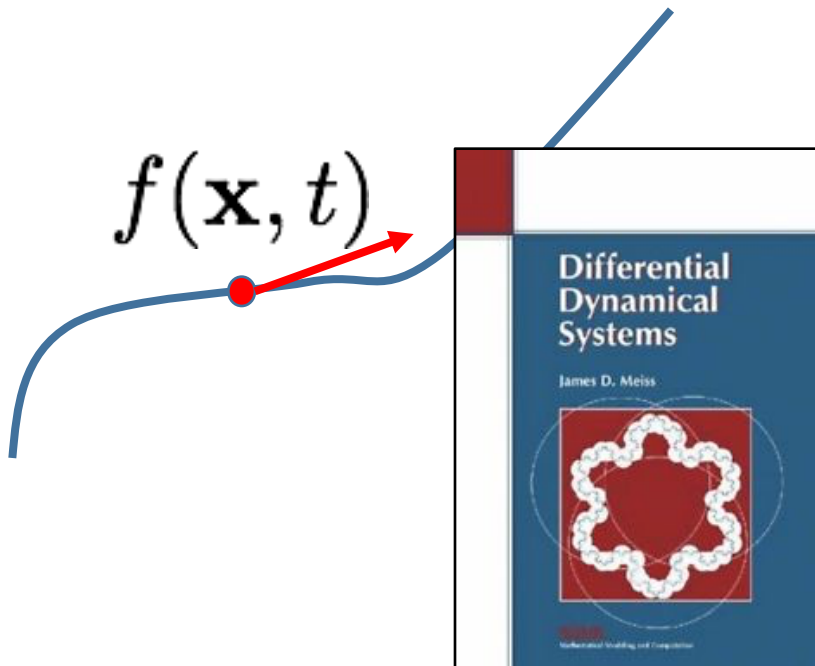
Dynamical Systems

- State: x
- Rule describing how to go from one state to next.

Continuous vs. Discrete Time

$$\frac{d\mathbf{x}}{dt} = f(\mathbf{x}, t)$$

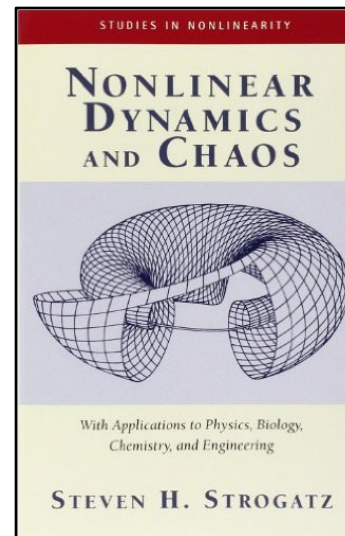
$$t \in \mathbb{R}$$



$$\mathbf{x}(t + 1) = f(\mathbf{x}(t), t)$$

$$t \in \mathbb{N}$$

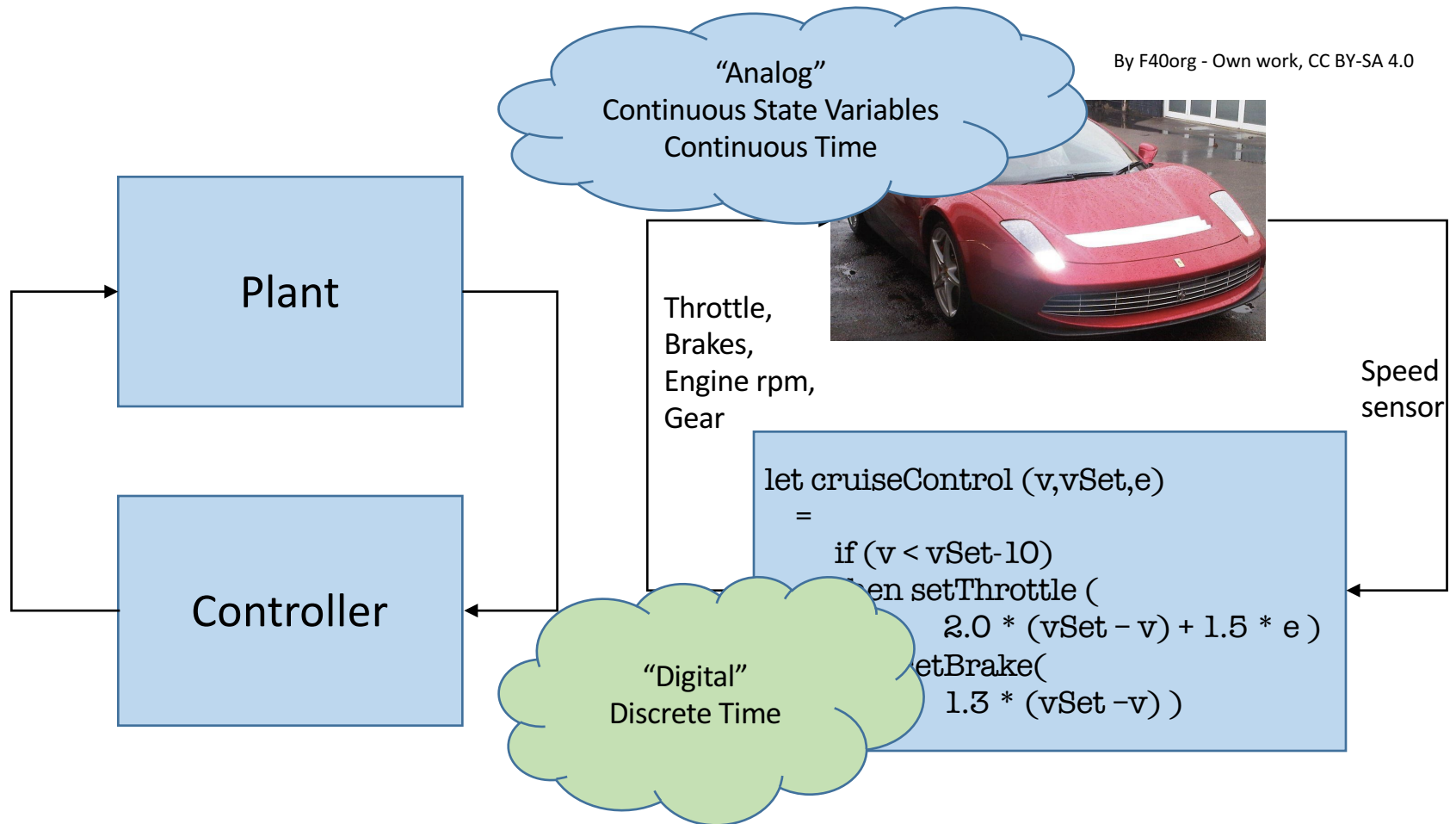
$$\mathbf{x}(t + 1)$$



Outline

- Cyber-Physical Systems.
- Theoretical Challenges.
- Application Challenges.
- Research Directions.
- PhD in formal methods for CPS.

Control Systems

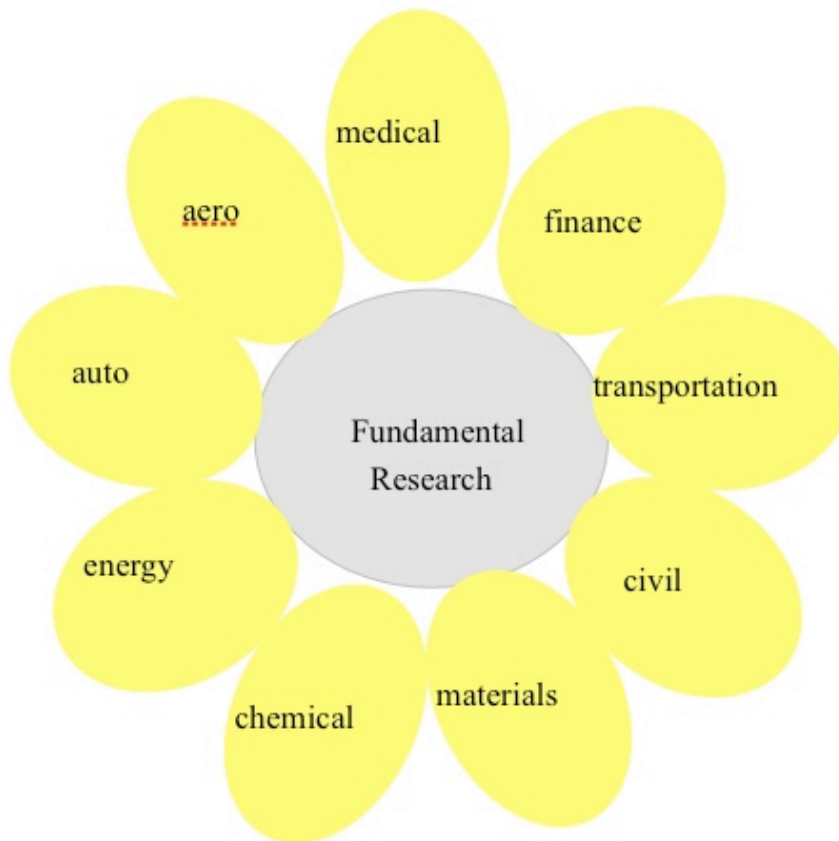


Cyber-Physical Systems (CPS)

- Computer Control of a Physical Process.
 - “Deeply” embedded, real-time computation.
- Discrete-time (digital) system interacting with continuous time (analog) system.
- Natural systems: physics, biology, ecology, climate,...
- Common examples around us!

CPS Application Domains

Large variety of application domains.



“CPS Flower” by P.R. Kumar and Jeannette Wing.

Safety Critical Systems

Failure => (Injury | Death)

Verification of CPS: Automotive Systems

NHTSA Campaign Number: 12V504000

BMW 7-series model years 2005-2007

Due to a **software problem**, the **doors may appear to be closed** and latched, but, in fact, may inadvertently open.

CONSEQUENCE:

The door may unexpectedly open due to road or driving conditions or occupant contact with the door.

The sudden opening **may result in occupant ejection** or increase the **risk of injury** in the event of a crash.

NHTSA Campaign Number: 11V248000

Honda CR-Z model year 2011

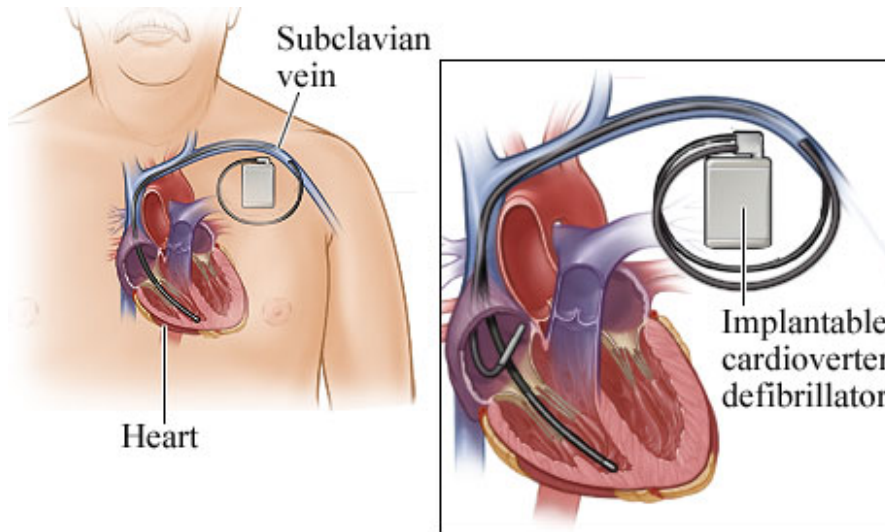
There is possibility that the **engine control unit software may cause** the electric motor of the hybrid system to **move the vehicle unexpectedly in the opposite direction of the selected gear**.

CONSEQUENCE:

Unexpected Vehicle Movement could increase the risk of a crash or **personal injury** to the persons in the path of the moving vehicle.

Source: safercar.gov

Cardioverter Defibrillators (ICD)



© Healthwise, Incorporated

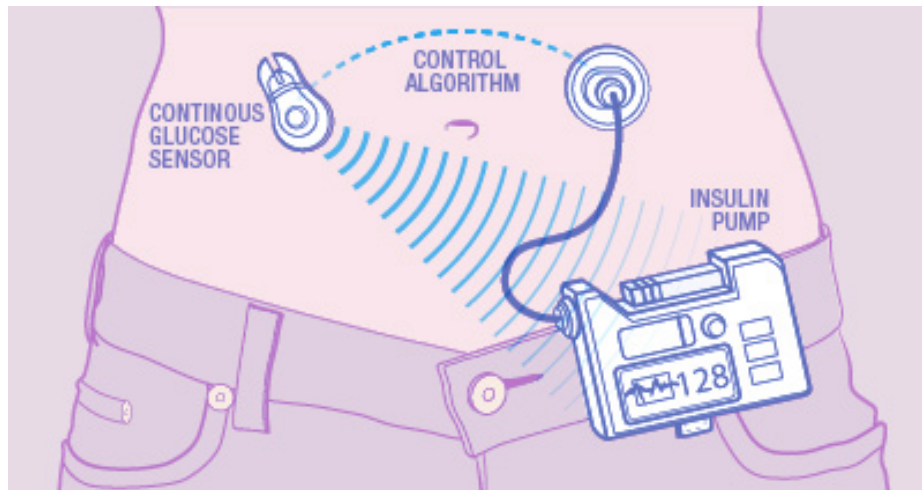
Image source: webmd.com

Injuries/Deaths due to

- Inappropriate shocks delivered.
- Appropriate shock not delivered.

[Smolka, Grosu et al., Mangharam et al.]

Artificial Pancreas



Source: MayoClinic.com

Too much insulin delivery:
loss of consciousness, coma, death.

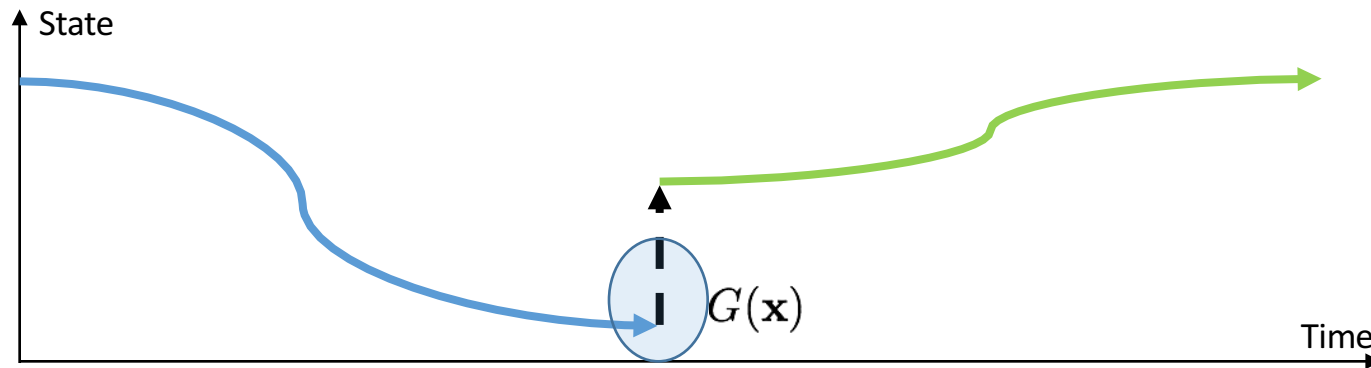
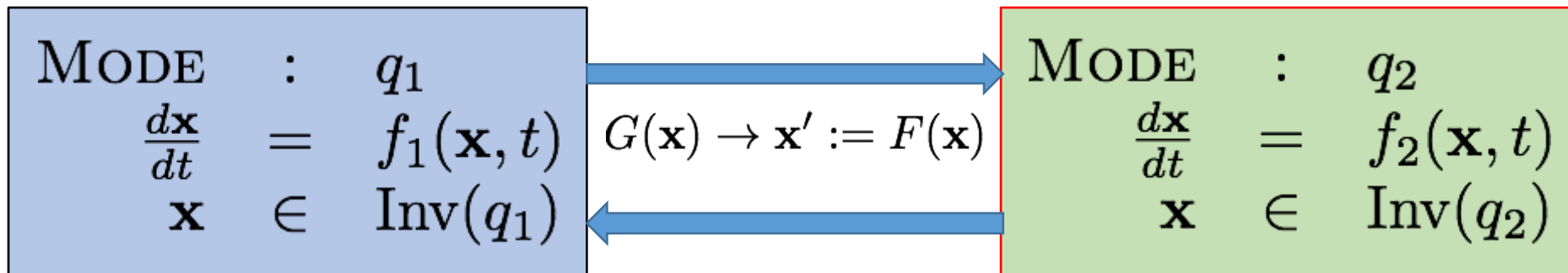
Too little insulin delivered:
diabetic ketacidosis

[Sankaranarayanan et al.'15,'16; Sanjian Chen et al.'15]

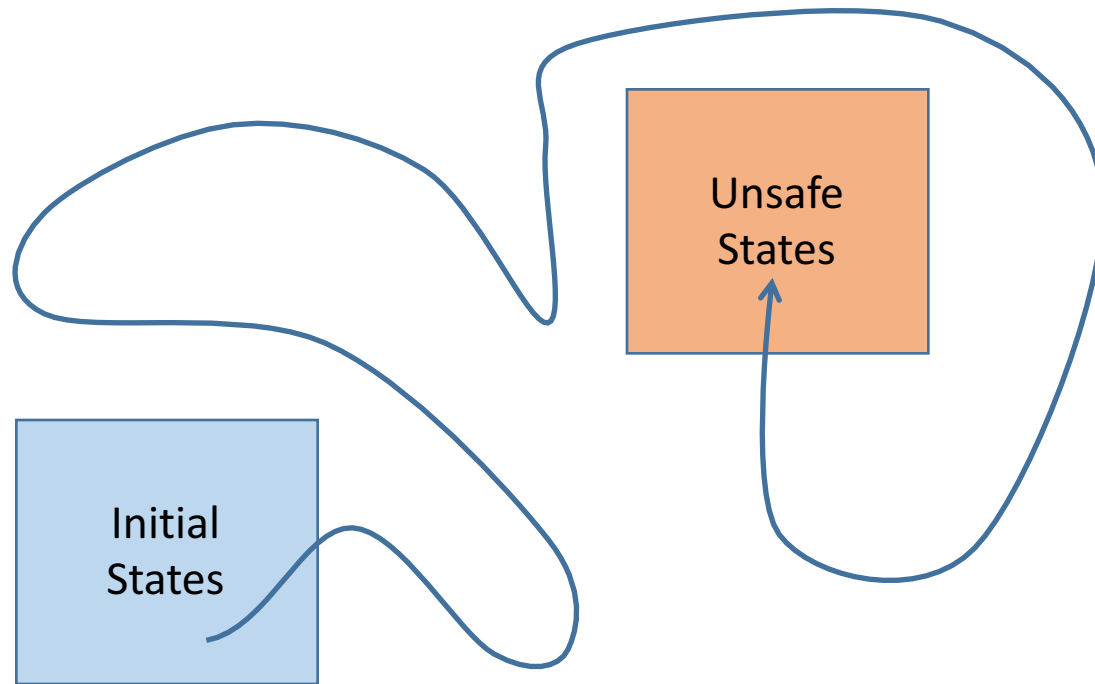
Foundations of CPS

[Alur, Henzinger,
Dill, Pnueli,
Manna, Maler,
Sastry, Lygeros, Tomlin,...]

Hybrid Automata

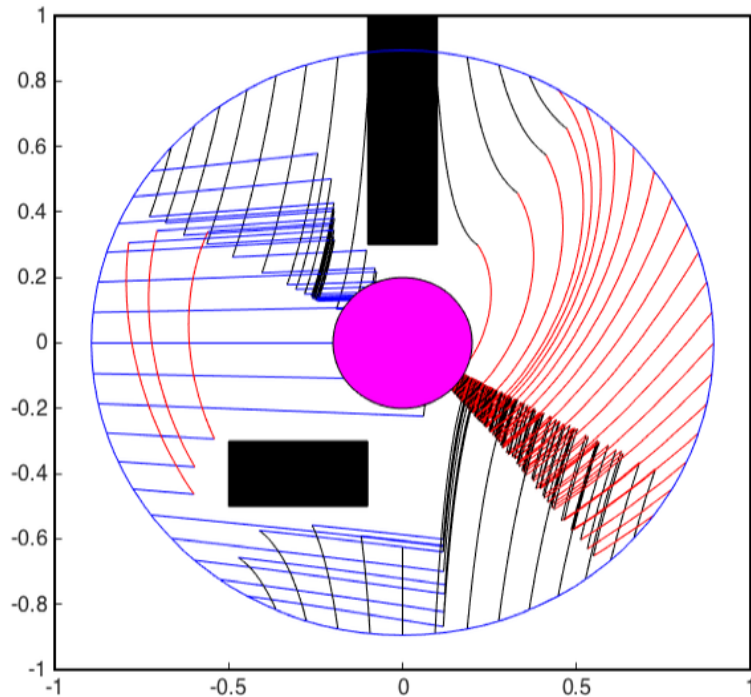


Specifications



Reachability: trajectory from initial to unsafe state?

Stability

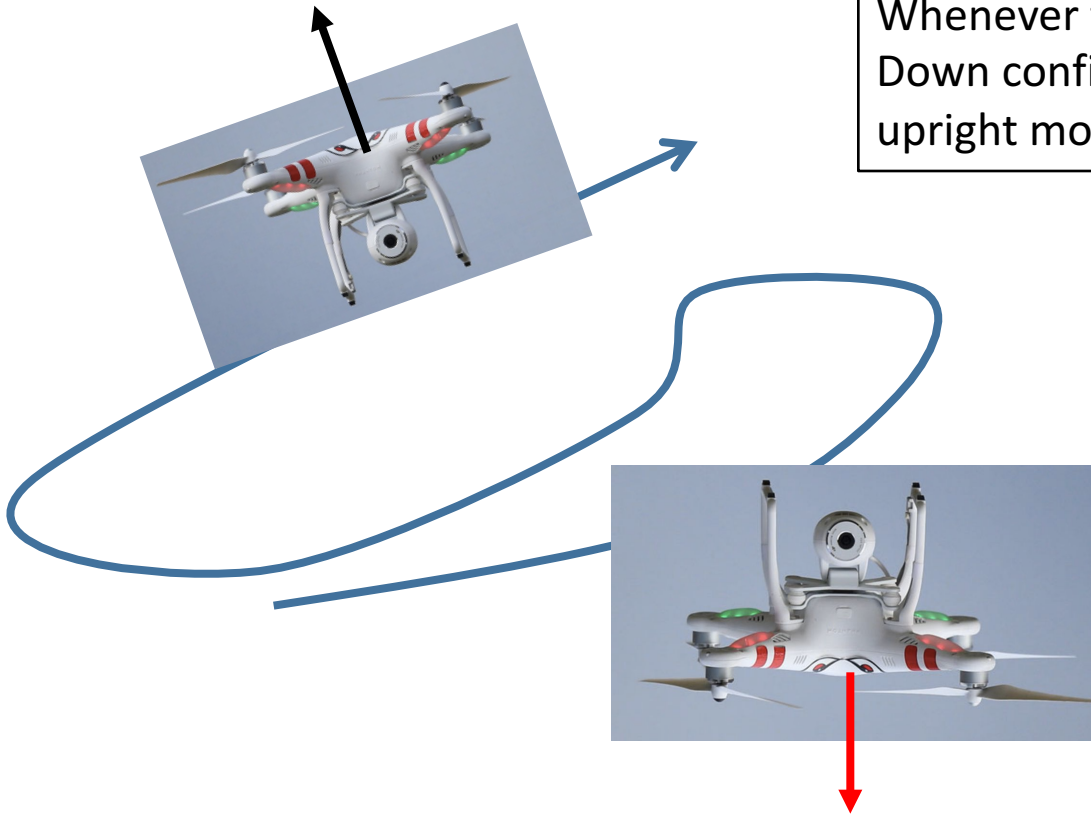


Stability

1. System converges towards an equilibrium
2. Trajectories that start close to the equilibrium remain close.

Real-Time Temporal Properties

Whenever the UAV reaches an Upside-Down configuration, it must reach an upright mode within 2 seconds.



Verification Techniques

Challenges

Murphy's Law for Hybrid Systems

Class of Hybrid Systems
with “interesting”
examples.



Verification Problems are
Undecidable.

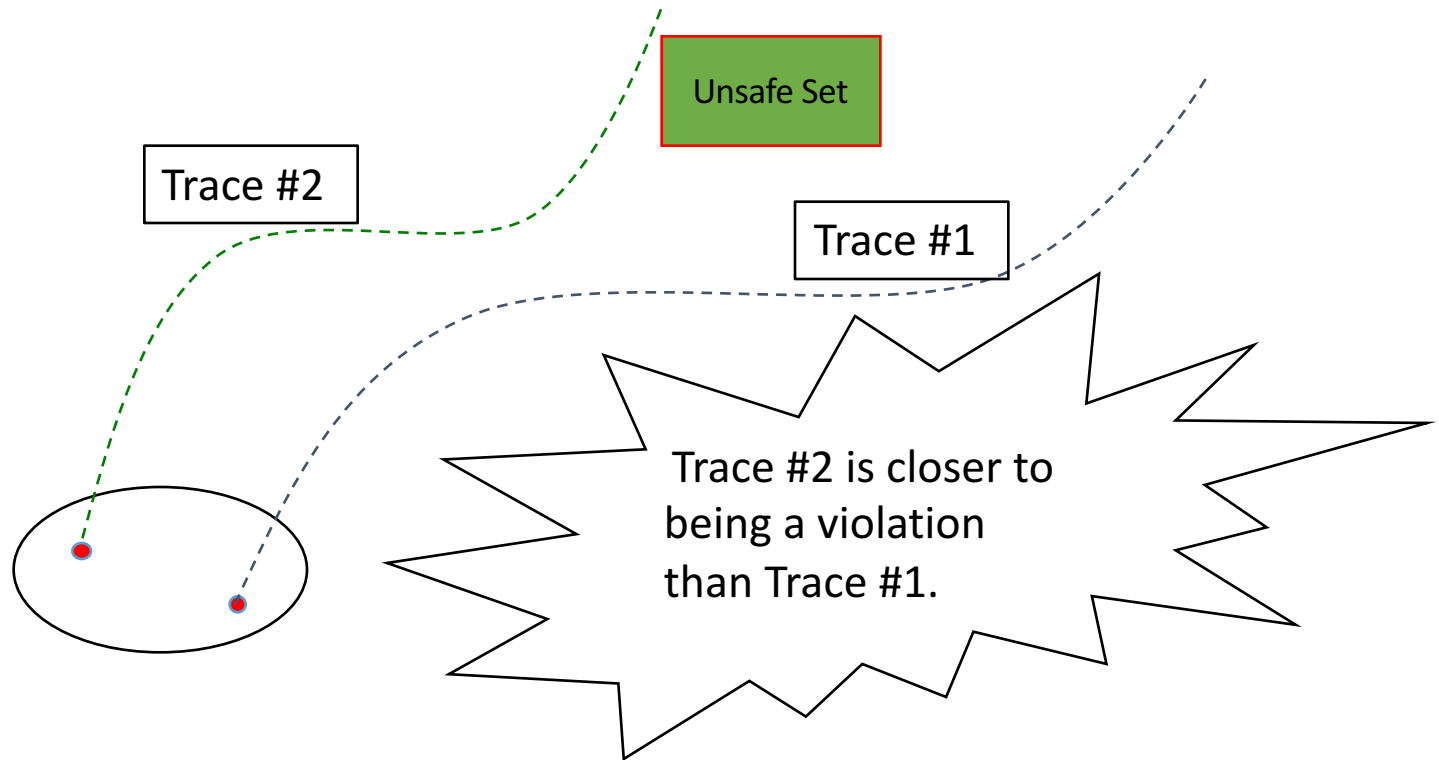
[Ken's One System Per Paper Syndrome]

Falsification Approaches

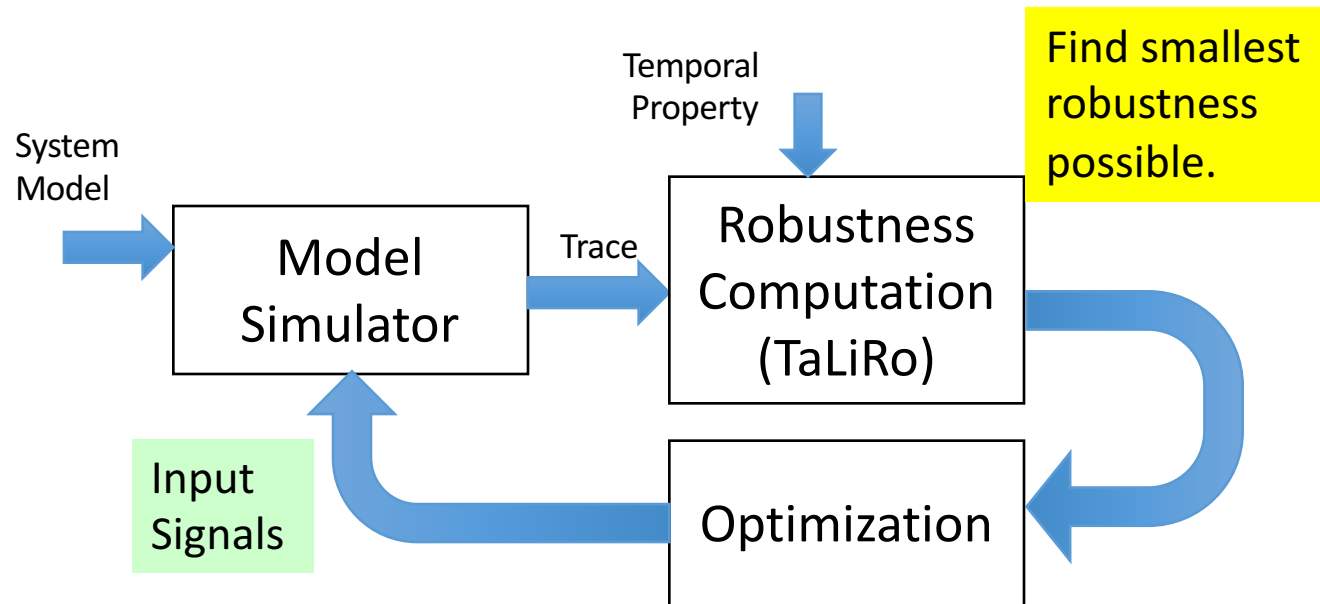
Lower Expectations, Throw away
the Baby.

- Best effort search to find counterexamples.
- No correctness proofs.
- Falsification tools:
 - S-Talro [Fainekos+S+Others],
 - Breach [Donze+Others].

Robustness: Idea

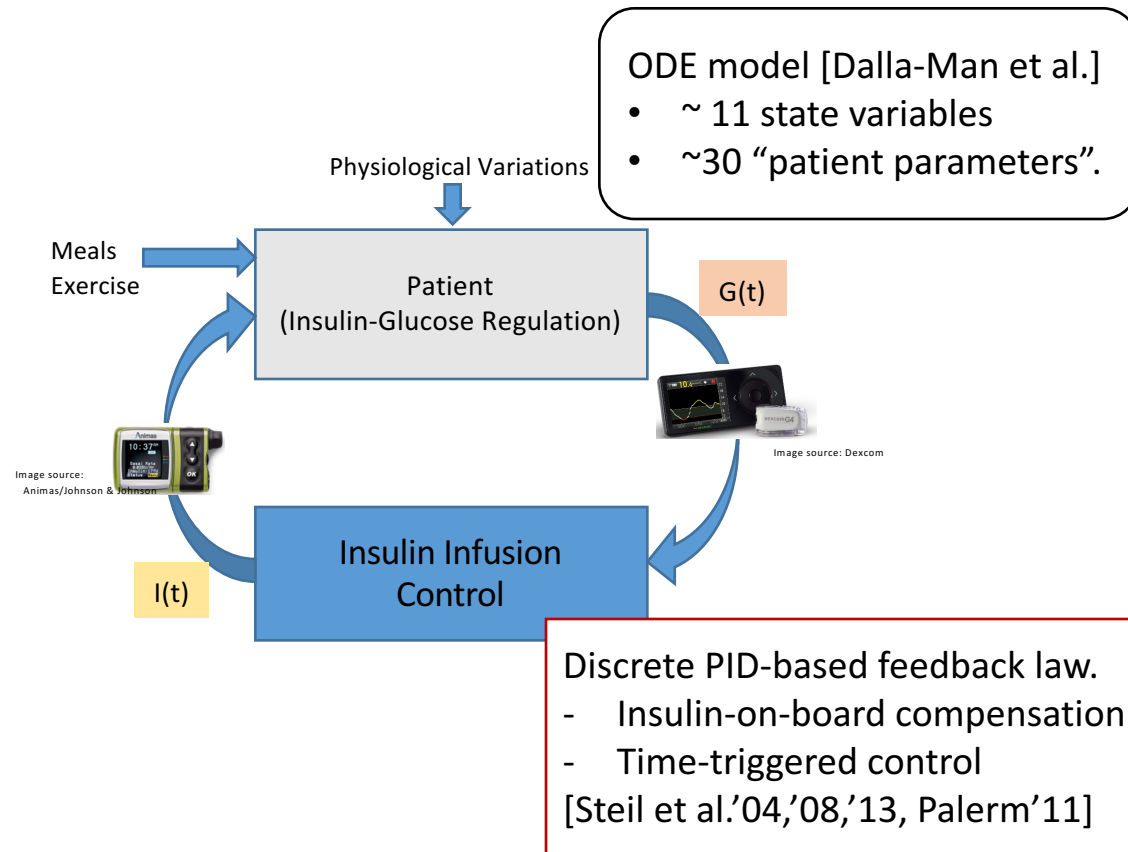


S-Taliro: Falsification Using Robustness



[Fainekos+S+Abbas+Ivancic+Gupta]

Case-Study: Artificial Pancreas Control.



S-Taliro Results

[Cameron et al.'15, S. et al. '16]

1. Hypoglycemia: Can blood glucose level go below 70 mg/dl?

"Near" Violation!

2. Hyperglycemia: Can blood glucose level go above 350 mg/dl?

Violation!

3. Insulin infusion below target: Can controller deliver insulin below target level of 90 mg/dl?

Violation!

4. Can "wakeup" hyperglycemia above 200 mg/dl happen?

No Violation!

5. Can the patient suffer a "prolonged" hyperglycemic episode?

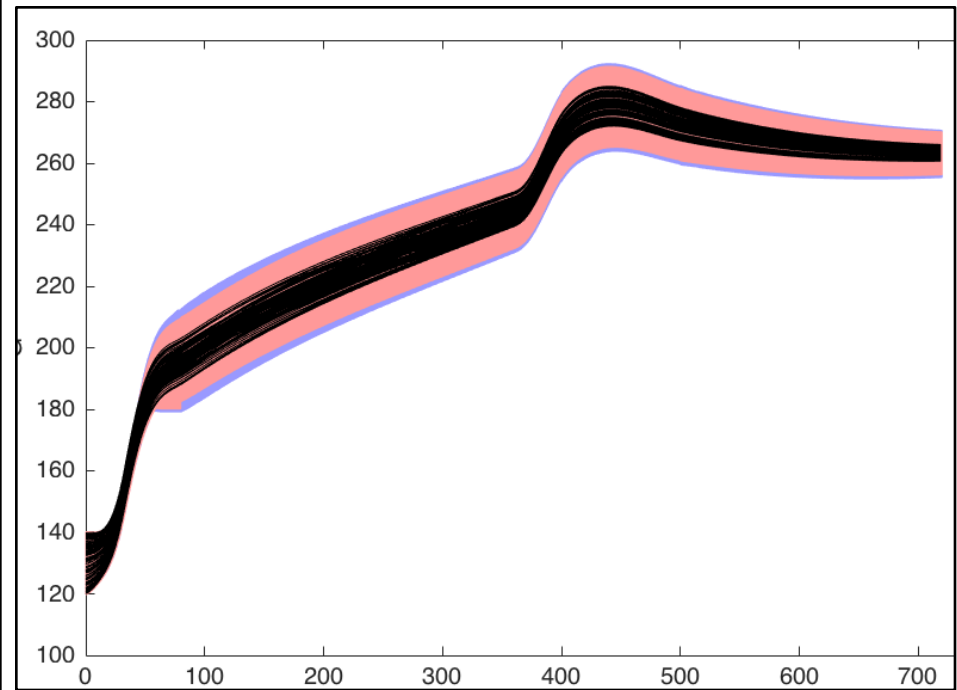
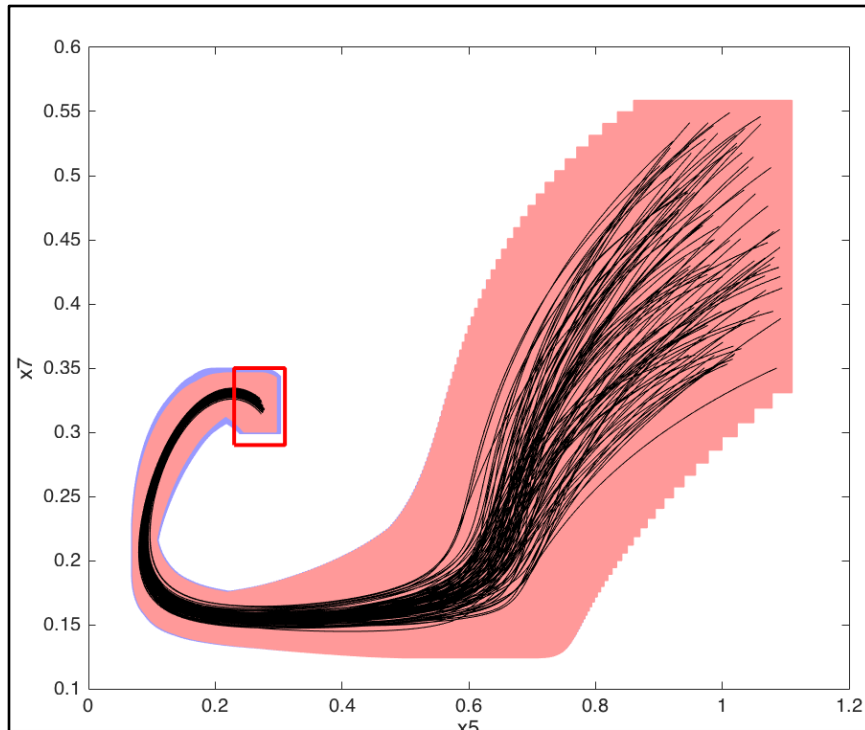
Violation!

~ 3.5 hours of wall clock time.

Formal Verification

- Goal #1: Establish presence or absence of bugs.
- Goal #2: handle semantics with mathematical precision.

Approach #1: Flowpipe Construction



Goal: explore all reachable states up to a finite time horizon.

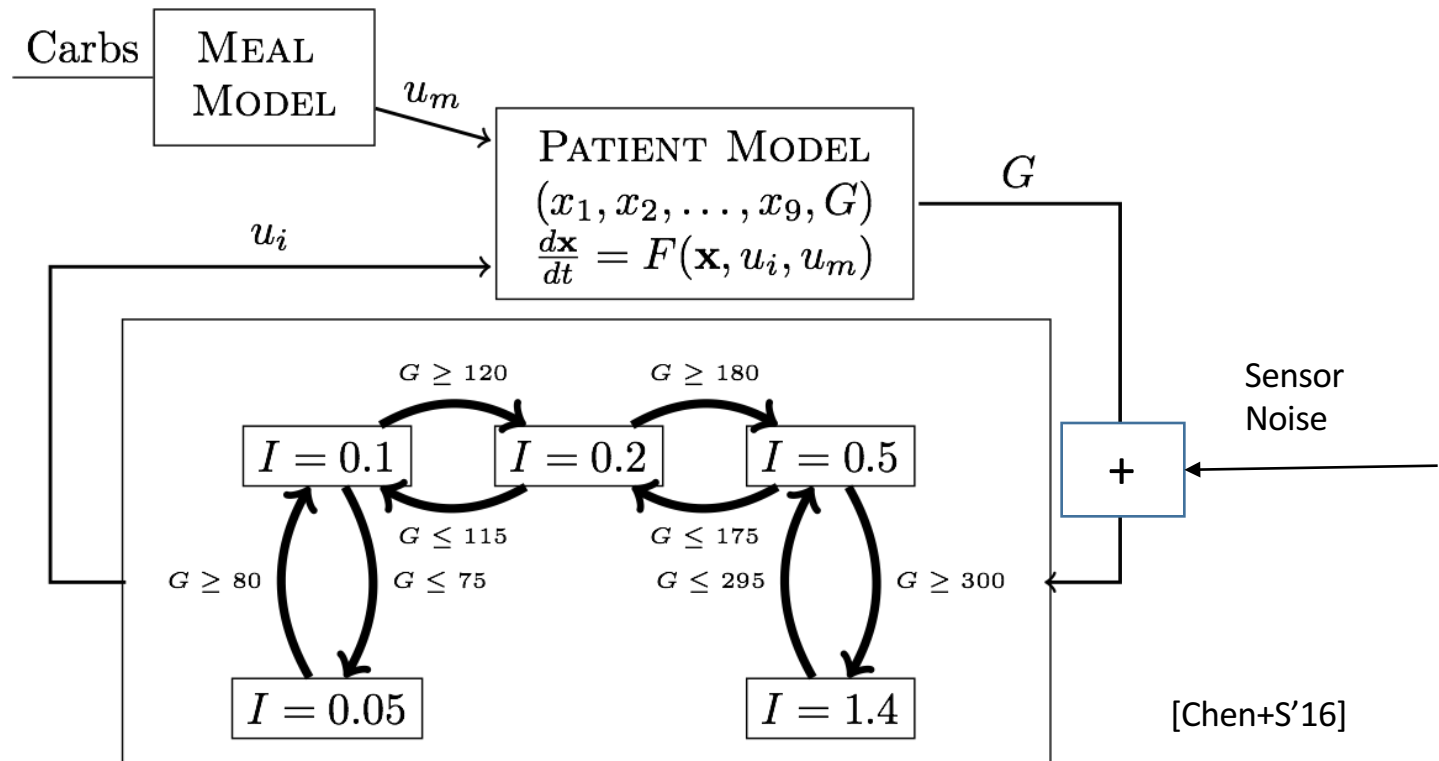
Symbolic Model Checkers For Hybrid Systems

- Linear hybrid systems:
 - SpaceEx [Frehse+Others, Verimag].
- Nonlinear hybrid systems:
 - Flow* [Chen+Abraham+S, Univ. of Colorado + RWTH Aachen University].
 - Cora [Althoff et al., TU Munich].
 - iSAT [Franzle+Others, Oldenburg].
 - dReach(*) [Gao+Kong+Clarke, MIT/CMU].

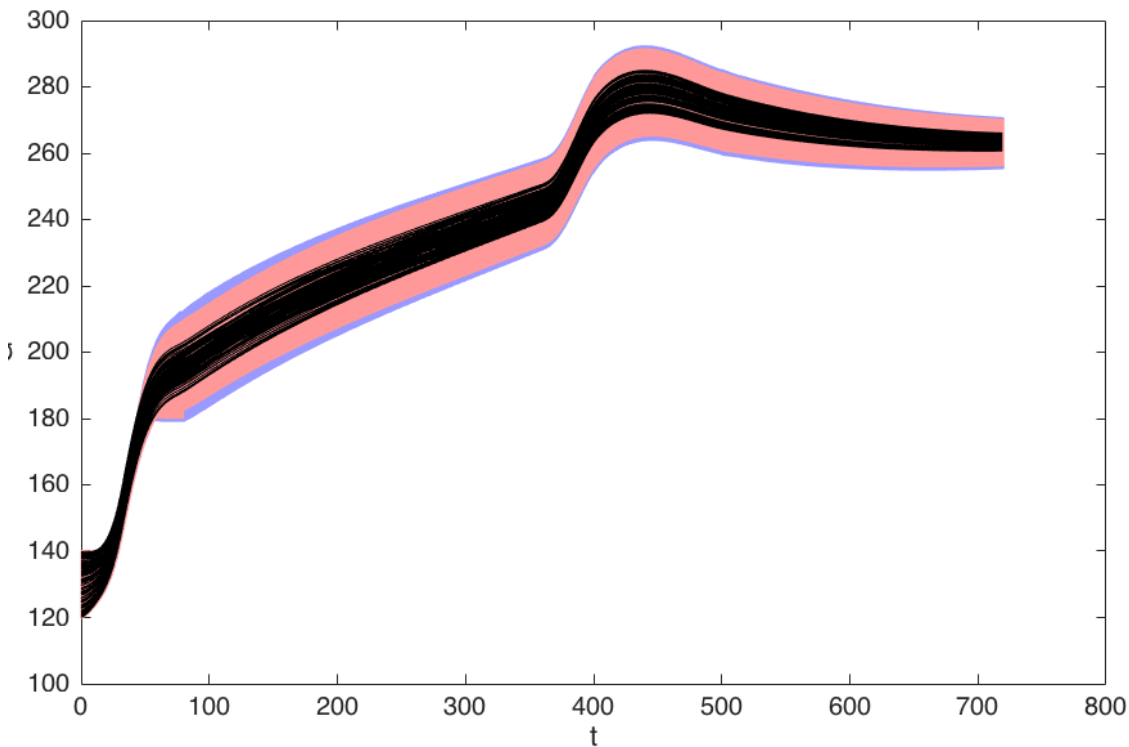
State-of-the-Art

- SpaceX: linear systems with 50+ state variables.
 - Interesting commercial applications at this scale.
- Nonlinear Systems:
 - Smaller systems: 5-10 variables.
- Recent work by Xin Chen + **S**:
 - 30+ variables if “structurally sparse”

Verification of Multi-Basal Artificial Pancreas System



Flow* Verification



- ✓ Absence of hypoglycemia
- ✓ No ketacidosis ($G \geq 300$ mg/dl)
- Blood glucose does not settle inside range [70,180]

dReal/dReach

- Delta-Complete decision procedure over reals.
- Reason about type-2 computable real functions.
 - Solutions to Ordinary Differential Equations.
- Numerous applications:
 - Artificial Pancreas parameter selection [Chen+Lee'15]
 - ICD (Cardiac) Devices [Islam+Smolka+Grosu+Others]

Theorem Proving

- Early work on STeP Theorem Prover [Manna+Sipma..'90s]
- Keymera [Platzzer+Others' CMU]
 - Differential Dynamic Logic.
 - Integrates with decision procedures over reals.
 - Extensions to concurrent and parameterized systems.
- Successes of KeyMera:
 - ACAS-X collision avoidance protocol verification.
 - Numerous application case studies.

Combining Simulations + Proofs

- C2E2 [Duggirala+Mitra + Viswanathan , UIUC]
- Testing + Proofs using discrepancy functions.
 - Compositional reasoning.
 - Inference of discrepancy functions from simulations.
- **Applications:** medical devices, airtraffic management protocols, automotive systems.

Formal Synthesis

Formal Synthesis for CPS

- Interesting combination of CS + Control theory approaches for synthesis.
- Control approach: find feedback functions to obtain reachability/stability properties.
- CS approach: synthesize control for temporal objectives.

Tutorial Tomorrow



CAV 2016 tutorial on synthesis by Paulo Tabuada

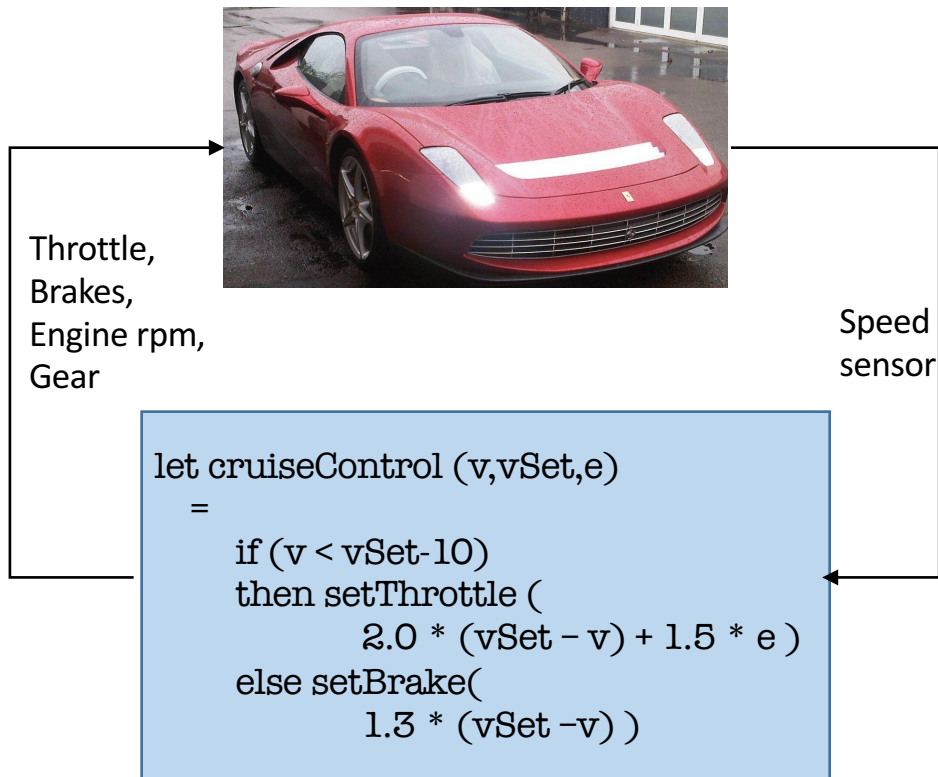
Tomorrow afternoon.

“Hot” Research Directions

Foundations of CPS

- Understanding properties of hybrid systems.
 - Invariant Sets.
 - Lyapunov Functions.
 - Equivalences between systems.
- Efficient inference of properties.
 - Invariant Synthesis for nonlinear systems.
 - Nonlinear Lyapunov synthesis.
- Formal synthesis.
- Stochastic Hybrid Systems

From the model to implementation.

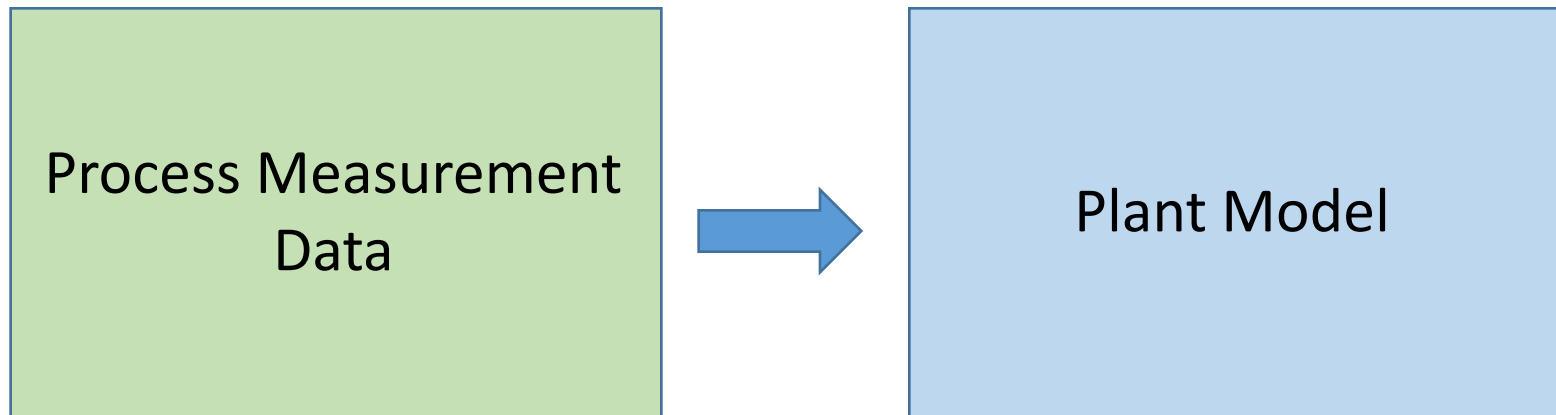


Goal

Integrate code analysis
with models of physical
dynamics.

Constructing Models from Data

System Identification



Goal: Identify models more suitable for verification.

Reasoning about pattern recognition/machine learning.



Image Credit: google.com

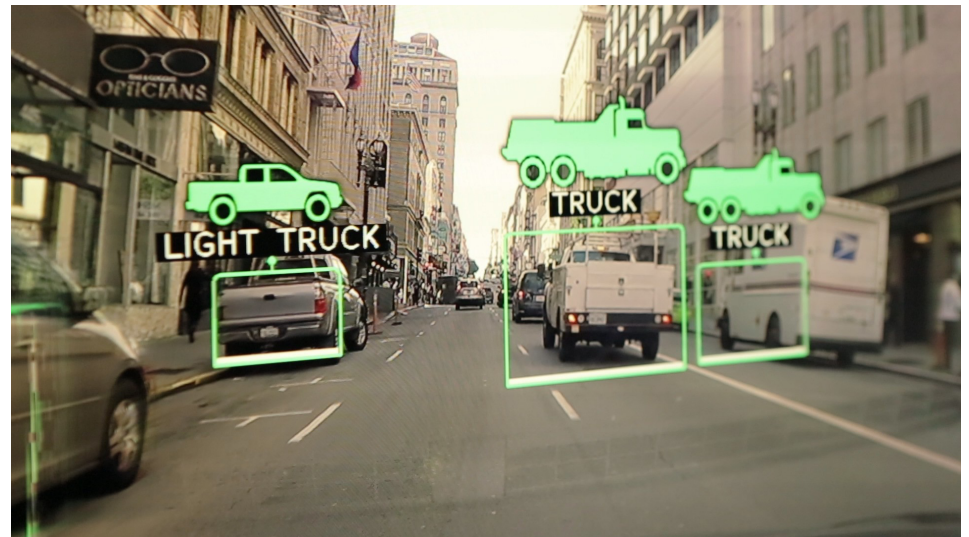


Image Credit: nvidia.com

Closed-Loop Medical Systems

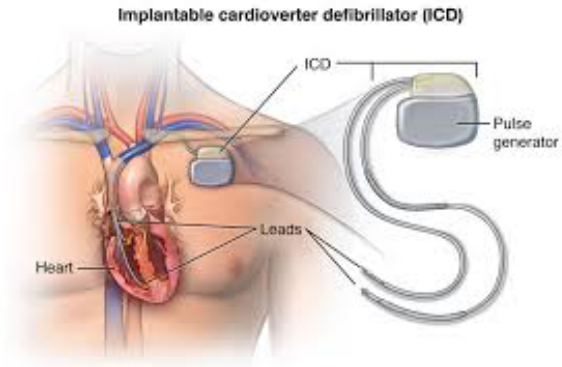
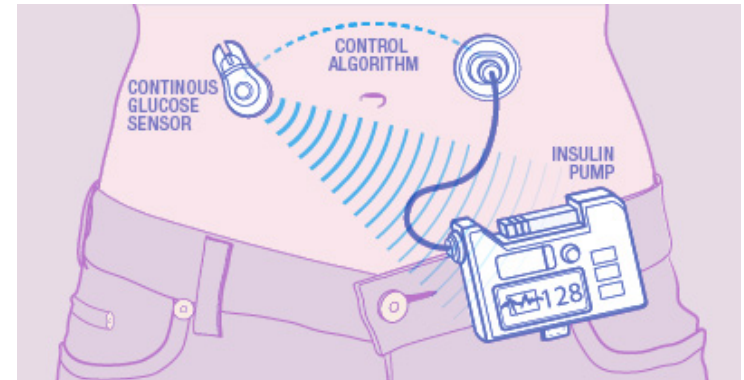
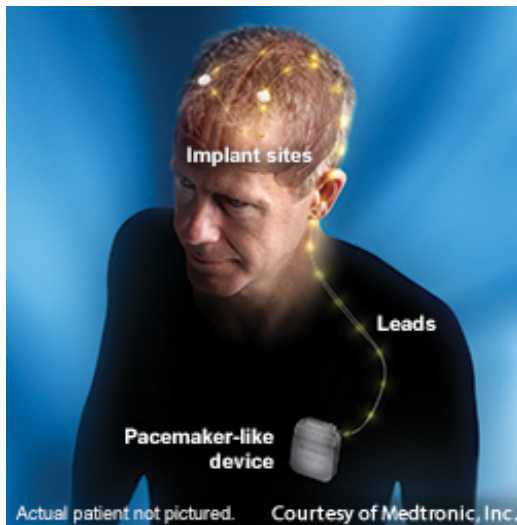


Image source: hopkinsmedicine.com



Source: MayoClinic.com



Resources for Closed Loop Medical Devices

<https://www.cs.colorado.edu/~srirams/courses/clMedDevices-spr16/clDevices.html>

CSCI 7000 Spring 2015

[Basic information](#)

[News](#)

[Closed-Loop Topics](#)

[Schedule](#)

[Topics](#)

[Course work](#)

Closed-Loop Devices

I have attempted to organize some basic references for various devices below. Your task for Week 1 is to expand and enlarge the list by doing a literature search.

Artificial Pancreas

The artificial pancreas is a great example of a closed loop medical device. A large portion of this class will focus on this device.

Scientific Survey Articles

- Claudio Cobelli, Eric Renard and Boris Kovatchev, [Artificial Pancreas: Past, Present, Future](#), Diabetes November 2011 vol. 60 no. 11 2672-2682.
- B. Kovatchev, M. Breton, C. Dalla Man and C. Cobelli, [In Silico Preclinical Trials: A Proof of Concept in Closed-Loop Control of Type 1 Diabetes](#), J Diabetes Sci Technol. Jan 2009; 3(1): 44-55.
- Francis J. Doyle, Lauren M. Huyett, Joon Bok Lee, Howard C. Zisser and Eyal Dassau, [Closed-Loop Artificial Pancreas Systems: Engineering the Algorithms](#), Diabetes Care, May 2014 vol. 37 no. 5 1191-1197.
- Hovorka R, Canonico V, Chassin LJ, Haueter U, Massi-Benedetti M, Orsini Federici M, Pieber TR, Schaller HC, Schaupp L, Vering T, and Wilinska ME. [Nonlinear model predictive control of glucose concentration in subjects with type 1 diabetes](#). Physiol Meas. 2004 Aug;25(4):905-20.

Videos

- [Bruce Buckingham's TEDxDelMar Talk.](#)
- [Ed Damiano's TEDx Talk.](#)

Press Articles

Human-in-the-loop CPS

- Many CPS are operated by humans in the loop.
- How do we reason formally about humans?
 - Modeling human behavior: ideas from psychology/cognitive science.
 - Collecting data about human actions and mistakes.

How to get started?

CPS-focused conferences

- CAV: plenty of papers on hybrid systems.
 - ETAPS/TACAS.
- CPSWeek: multiple conferences under single umbrella.
 - Hybrid Systems: Computation and Control (part of CPSWeek).
- ESWeek.
 - ACM/IEEE conference on Embedded Software (EMSOFT)
- RTSS:
 - IEEE Real Time Systems Symposium.

CPS Courses

- Formal Methods.
- Control Theory and Dynamical Systems.
- Real-Time and Embedded Systems.
- Convex Optimization.
- Robotics.

CPS Books

- Lee and Seshia, Introduction to Embedded Systems.
 - <http://leeseshia.org>
- Rajeev Alur, Principles of Cyber-Physical Systems.
 - <https://mitpress.mit.edu/books/principles-cyber-physical-systems>
- Andre Platzer, Logical Analysis of Hybrid Systems
- Handbook of hybrid systems (good reference).

Acknowledgments

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