Some Thoughts on Runtime Verification

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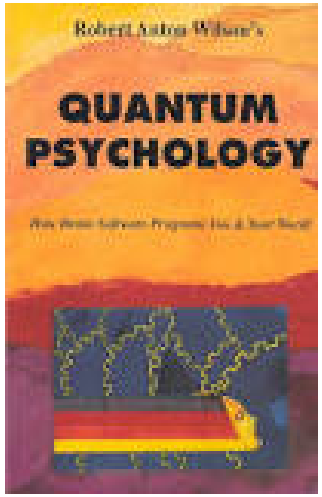
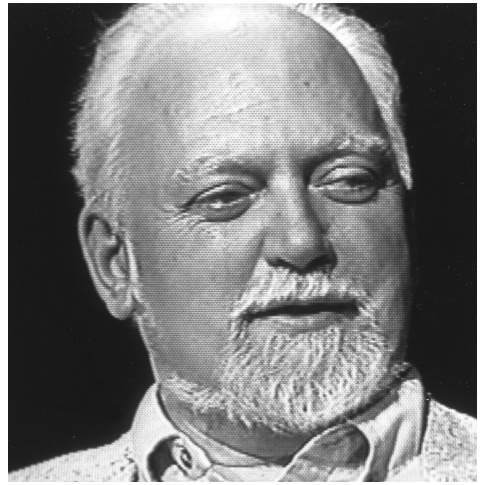
Before Dinner Speech

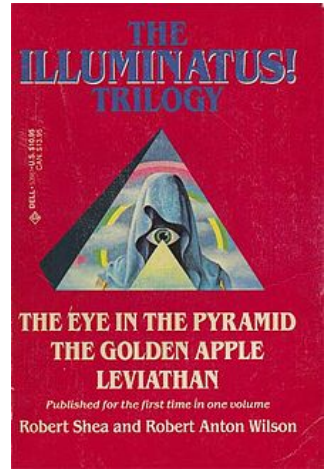
- I like long and general introductions in my papers and talks
- Not everybody does: recently someone protested that such ramblings belong in style to an **after dinner speech**
- But I will unfortunately miss the banquet
- So I allow myself to start my presentation with some reflection in this spirit on the **meaning of words**

What IS Runtime Verification?

- Robert Anton Wilson, (1932-2007), a writer and thinker



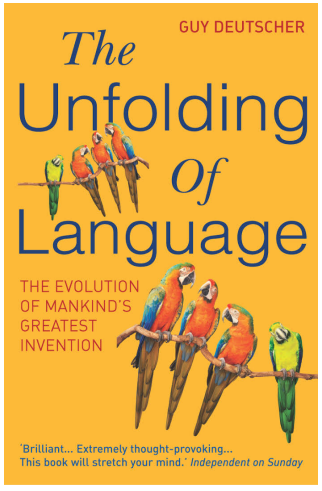


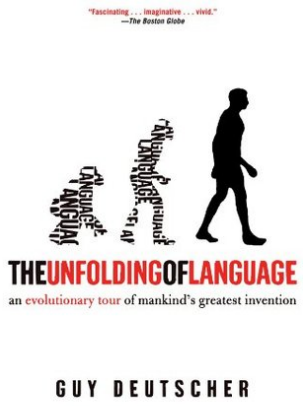


- *"Is", "is." "is" the idiocy of the word haunts me. If it were abolished, human thought might begin to make sense. I don't know what anything "is"; I only know how it seems to me at this moment.*

On The Meaning of Words

- Words do **not** have absolute meaning
- They are just tools to create the (very useful) illusion of common understanding between people
- Their meaning may be different for different individuals, communities and periods in time





- Analyzing a new word/expression, we should look at what **new distinctions** it makes with respect to **existing background**

Example: Reactive Systems

On the Development of Reactive Systems*

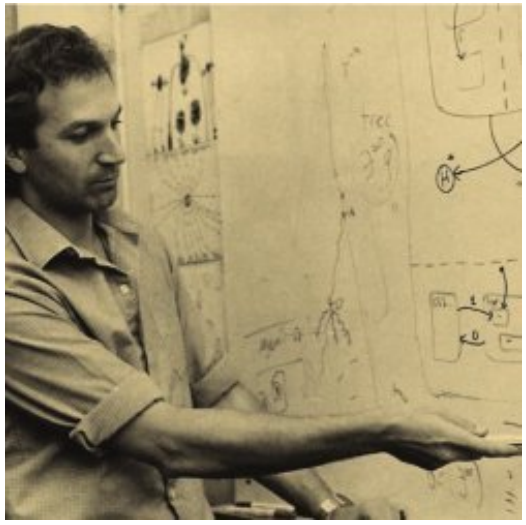
D. Harel and A. Pnueli

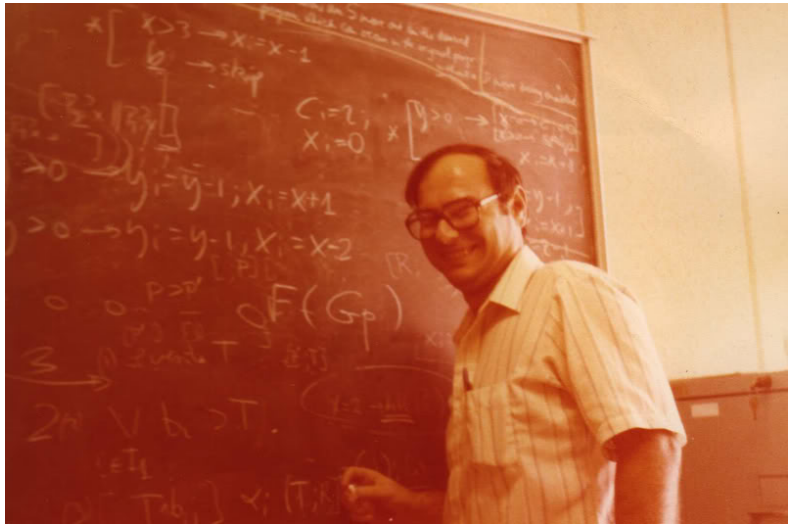
Department of Applied Mathematics
The Weizmann Institute of Science
Rehovot 76100, Israel

January, 1985

Abstract

Some observations are made concerning the process of developing complex systems. A broad class of systems, termed *reactive*, is singled out as being particularly problematic when it comes to finding satisfactory methods for behavioral description. In this paper we recommend the





Reactive Systems

- In this classical paper, more cited than read, reactive systems are defined as
- **Systems that maintain an ongoing interaction with their external environment**
- Real-time, embedded, cyber-physical ... in **contrast** with
- Programs that compute a static function from an input domain to an output domain without **being in time**
- Unlike classical theory of **computability**, **complexity** and **program semantics** dealing with static "autistic" computations[1]
- It is only against this background that the word **reactive** obtains its intended meaning

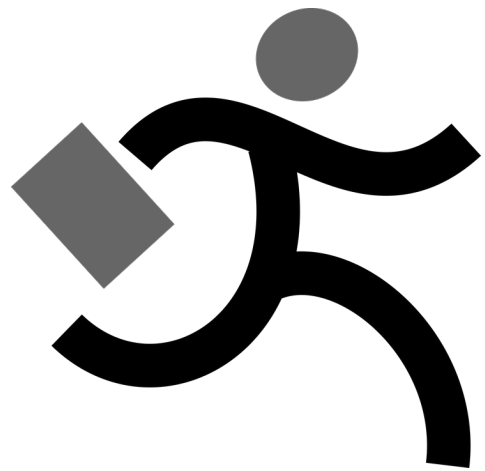
[1] See my pamphlet Hybrid Systems and Real-World Computations

Reactive Systems

- But if you say "reactive" to a **control engineer**, I am not sure he will understand what's the point
- All control systems are reactive by definition, implementing **feedback loops** against a **dynamic environment**
- And when you preach reactive systems to biologists, you really tell them to consider automata as an additional modeling tool
- To AI types exposed to cognitive science, reactive systems may sound like behaviorist **stimulus-response** psychology
-
- Another example: **reachability** (and **controllability**) are precise technical terms in linear control theory which were kidnapped to another meaning in hybrid systems research

So What is Runtime Verification?

- In this talk I will give three **interpretations** of what runtime verification is, in contrast with verification tout court

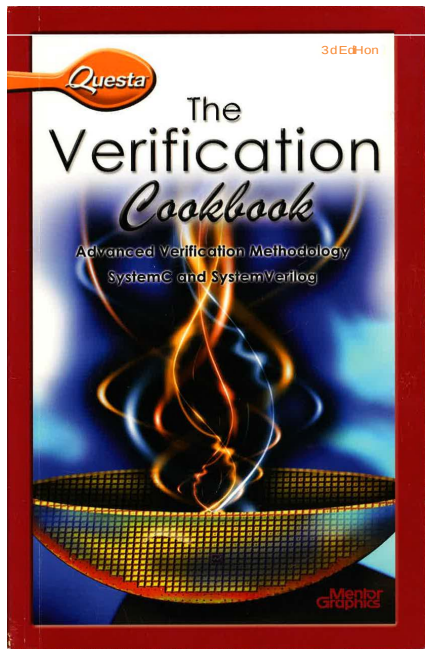


Outline

1. **So what is verification?**
2. RV as **lightweight verification**, non-exhaustive simulation (testing) plus formal specifications
3. RV as getting **closer** to **implementation**, away from abstract models
4. RV as checking systems **after** deployment while they are up and **running**
5. The **limitations** (if not impossibility) of classical formal verification in the cyber-physical world
6. **Qualitative** properties and **quantitative** measures

Verification

- The meaning of **verification** may also vary even among those who pretend to care about correct systems
- It may depend on whether you are a **theoretician** looking for an excuse for your math or a **practitioner** who needs to publish, or any linear combination of those
- I once got this industrial verification book and its intersection with the CAV literature was practically empty



My Version of Verification

- You have a system which is **open** (reactive)
- Each of its dynamic inputs may induce a **different** behavior
- Behaviors are viewed as **trajectories** in the state-space, typically the states of a **product of automata**
- You want to ensure that **all** those behaviors are **correct**, they comply with some restrictions on observed sequences
- These restrictions (specifications, requirements) are formulated either in a **declarative language** (temporal logic, regular expressions) or encoded directly into **observers**

My Version of Verification

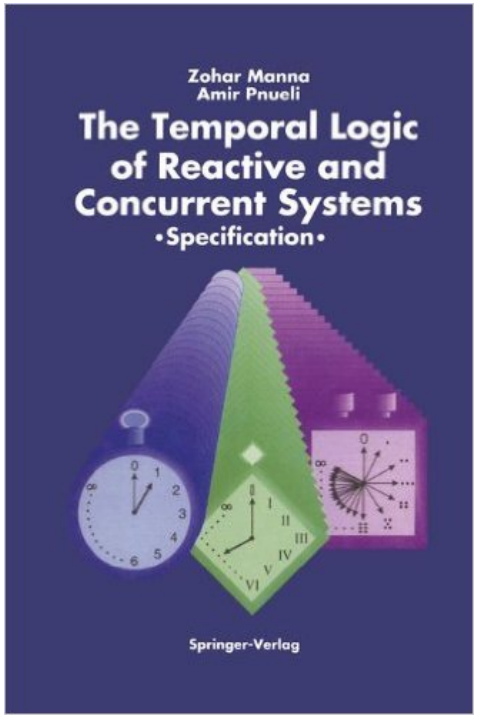
- Rather than stimulate the system with **all** admissible input sequences (exponential in the graph diameter)
- You use the **transition graph** and the **Bellman-Nerode principle** to explore possible behaviors more efficiently
- When systems are small enough you can explore all the paths
- Otherwise you either try to prove things analytically (**deductively**) or use **symbolic** techniques
- Run **set-based breadth-first** simulation while representing reachable states at time t by logic formulae, BDD, etc.
- And most of the rest is efficient implementation

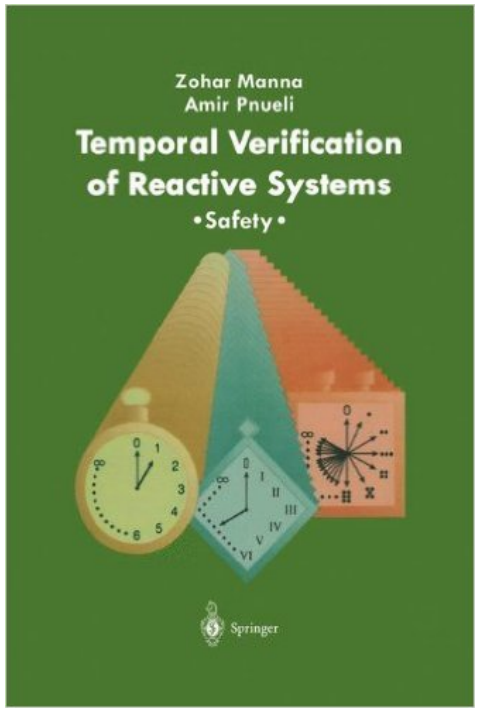
Another Linguistic Observation: Model Checking

- Algorithmic verification is known as **model checking**
- When you try to sell it to an outsider, say a biologist, she probably interprets it in the usual everyday sense:
- I have a **mathematical** model of my **physical** phenomenon and these guys help me to **check** if it makes sense internally
- The origin of MC has nothing to do with this sense of a model
- It comes from the technical notion of a **model** of a **logical theory**
- Verification checks algorithmically whether all system sequences are models of (satisfy) an LTL formula
- Or in branching time: whether the transition system is a model (Kripke structure) of a CTL formula

Another Linguistic Observation: Model Checking

- MC was coined as an alternative to **theorem proving**, where you prove **deductively** the logical specification based on axioms that include the system's description
- The deductive approach is described in these books:





Implicit Assumptions in the Verification Story

- Verification takes place during the **design** and **development** process **before** the system is up and running
- It is often done on an **abstract** model of the system
  - An **automaton** that abstracts from data and implementation details (actual code and platform)
  - The more abstract the model is, the **easier** it is to verify
  - But you need **syntax** to express the system and connect eventually to the real application
- The properties against which you verify are traditionally **qualitative**, providing a **yes/no** answer concerning correctness
- They clearly **partition** the set of global behaviors into acceptable and unacceptable ones
- Some of these assumptions will be dropped in the sequel

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5. The limitations (if not impossibility) of cyber-physical formal verification
6. Qualitative Properties and Quantitative Measures

RV as Lightweight Verification (Monitoring)

- Verification is glorious and romantic but **practically impossible** beyond certain complexity
- **Simulation/testing** is here to stay with or without attempts to guarantee some coverage
- So let us add to this practice some **formal properties** and property **monitors** that check the simulation traces
- Instead of **language inclusion** $L_s \subseteq L_\varphi$ as in verification, we check **membership** $w \in L_\varphi$, one trace at a time
- Monitoring is less sensitive to system complexity
- I does not require a **mathematical model** of the system, a program or a black box is sufficient
- In fact, it does not care who generates the simulation traces, it could be **measurements** of a real physical process

Monitoring Continuous and Hybrid Systems with STL

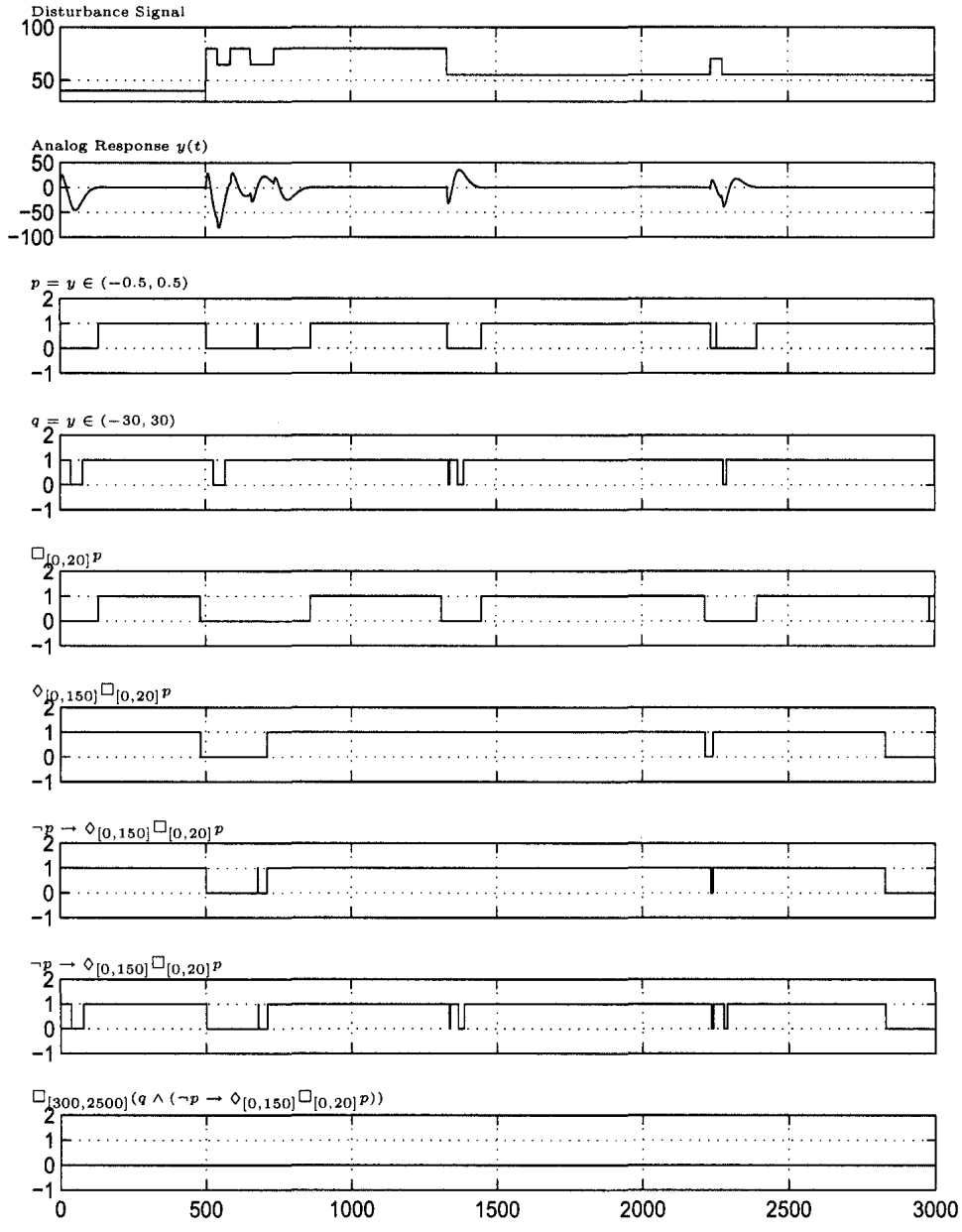
- In digital circuit verification, monitoring is called **dynamic verification** or **assertion checking**
- Motivated by analog and mixed-signal circuits, we extended LTL and MTL into **signal temporal logic** (STL)
- STL can express properties that speak of the **temporal distance** between **threshold-crossings** of continuous signals
- We developed novel monitoring techniques for this logic and implemented them into a tool called **AMT**
- It can **liberate** designers and verifiers from the need to **inspect** and analyze long simulation traces
- It remains an open question whether having a **clean declarative specification language** is a feature or a bug
- These issues were described in the summer school by Dejan Nickovic, a major contributor to this work

Example: Specifying Stabilization in STL

- A **water-level controller** for a **nuclear plant** should maintain a controlled variable y around a fixed level despite external disturbances x
- We want y to stay always in the interval $[-30, 30]$ except, possibly, for an initialization period of duration 300
- If, due to disturbances, y goes **outside** the interval $[-0.5, 0.5]$, it should **return** to it **within** 150 time units and **remain** there for **at least** 20 time units
- The property is expressed as

$$\Box_{[300,2500]}((|y| \leq 30) \wedge ((|y| > 0.5) \Rightarrow \Diamond_{[0,150]} \Box_{[0,20]} (|y| \leq 0.5)))$$

Monitoring Stabilization



The Success of STL

- This is **not** rocket science, much **simpler** than our heroic attempts to scale-up timed and hybrid **verification**
- But it turned out to be very **useful** or, at least, **popular** and also led to a better understanding of real-time logics
- There was **industrial** interest, including a thesis supported by **Mentor Graphics** on combining analog and digital simulators and design flows
- STL has been applied to **circuit** verification, **control** systems (verification, synthesis, falsification), **robotics** planning and **systems biology**
- So let us take a short publicity break

Annotated Bibliography I

- OM, D Nickovic, **Monitoring Temporal Properties of Continuous Signals**, FORMATS/FTRTFT 2004 (first paper)
- D Nickovic, OM, **AMT: A Property-based Monitoring Tool for Analog Systems**, FORMATS 2007 (tool)
- OM, D Nickovic, A Pnueli, **From MITL to Timed Automata**, FORMATS 2006 (theoretical byproduct)
- OM, D Nickovic, A Pnueli, **Checking Temporal Properties of Discrete, Timed and Continuous Behaviors**, Pillars of Computer Science, 2008 (good and long introduction)
- OM, D Nickovic, **Monitoring Properties of Analog and Mixed-Signal Designs**, STTT 2013 (more up to date)
- A Donze, OM, **Robust Satisfiability of Temporal Logic over Real-Valued Signals**, FORMATS 2010 (quantitative semantics)
- A Donze, T Ferrere, OM, **Efficient Robust Monitoring for STL**, CAV 2013 (improved algorithm)

Annotated Bibliography II

- E Asarin, A Donze, OM, D Nickovic, **Parametric Identification of Temporal Properties**, RV 2011 (inverse problem, learning)
- A Donze, OM, E Bartocci, D Nickovic, R Grosu, S Smolka, **On Temporal Logic and Signal Processing**, ATVA 2012 (preliminary extension to frequency domain)
- T Ferrere, OM, D Nickovic, **Trace Diagnostics using Temporal Implicants**, ATVA 2015 (minimal explanation for violation)
- D Ulus, T Ferrere, E Asarin, OM, **Timed Pattern Matching**, FORMATS 2014 (monitoring timed regular expressions)
- D Ulus, T Ferrere, E Asarin, OM, **Online Timed Pattern Matching using Derivatives**, TACAS 2016 (online monitring)
- T Ferrere, OM, D Nickovic, D Ulus, **Measuring with Timed Patterns**, CAV 2015 (a declarative measurement language)

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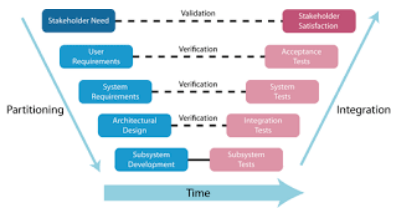
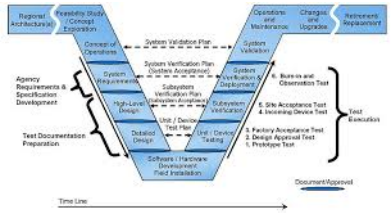
RV as Getting More real 

- Runtime can be interpreted as "while some **program** is running", so we have real piece of **code**
- Already generated from the abstract model or written directly without such a model
- Unlike abstract models, programs are **not** naturally amenable to set-based simulation
- You need to **instrument** the code to generate traces
- The program might (or not) run on the target platform
- There are many degrees of being closer to the final product

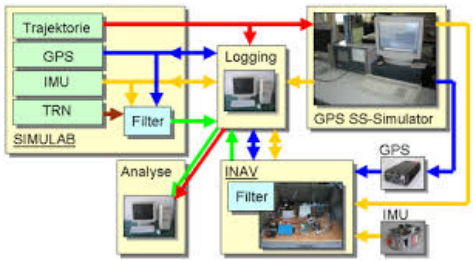
To V or not to V

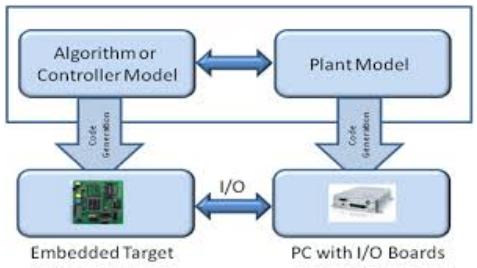
- CPS have heterogenous components, including the **external environment** which is **modeled** but **not** implemented
- The implemented system consists of software, hardware and physical components
- The development process follows some structure

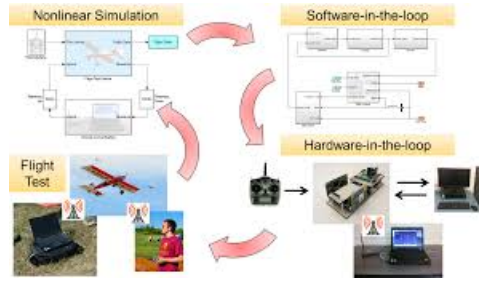




- Coming up from the bottom of the V, you integrate more real components (hardware in the loop, system in the loop)







- Runtime can refer to the verification and testing of those

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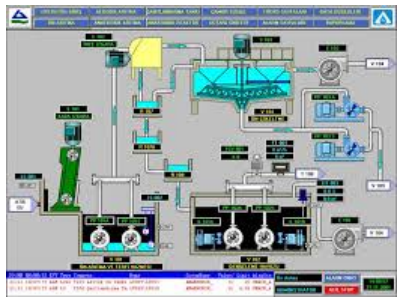
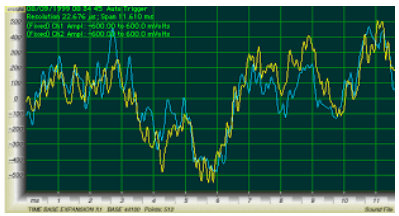
RV as Verifying Systems while they Run

- Monitoring real systems during their **normal** and **abnormal** execution is the most radical interpretation of RV
- Many systems are observed and **monitored** during execution
- Nuclear and industrial plants, airplanes and cars, medical patients, military control rooms, sound systems in rock concerts, stock markets, google analytics, traffic control ...





New Opprotunities

- A monitoring process which is **simultaneous** with the ongoing behavior of the systems offers new opportunities
- You can detect important **events** and **patterns** of activity in **real time**, almost as soon as they occur
- And **react** to them by **alerting** a **human operator** or triggering an **automatic action**
- These opportunities are new only in the context of verification
- Control panels, displays and alarms exist in low-tech ever since the electrical revolution
- In cars they range from **speed**, **fuel level** and **temperature** indicators to
- More modern ABS, **collision avoidance** systems and **airbags** that detect collisions if they are not avoided

Rethinking Specifications in this Context

- What are the **properties** against which we should monitor online in real time?
- To answer the question I will use the method of the naive **straw man**, a true believer in verification
- Well, he would say, let φ be the **complete specification** of the system, then we monitor for $\neg\varphi$ and shout when it occurs
- But anyway, this will **not happen** if we have **verified** the system (or synthesized the controller properly)
- To see what is wrong here we need to discuss the limitations of **verification** in the **physical** world

The Narrow Scope of Formal Verification

- The verification story depends on the following ingredients:
- 1) A very **faithful model** of the system under verification
- 2) Formal requirements that indeed trace the **boundary** between acceptable and unacceptable behaviors
- In addition, the system should be sufficiently **small** so that formal verification is computationally feasible
- For CPS, (1) and (2) above hold for a very small niche
- Some **hardware** and **software** components, analyzed for their **functional** properties, without physical aspects such as power consumption or timing

The Narrow Scope of Formal Verification

- Software is special, admitting a chain of **semantics preserving** models from **programs** down to **gates** and transistors
- **Nothing** like that exists in the **physical world** where models are just **useful approximations**
- The same holds for **specifications**: you can characterize the valid behaviors of a chip realizing a hardware **protocol**
- You can verify them on a faithful model of the chip and expect that it will indeed work correctly
- For physical systems there is never a comprehensive list of requirements that holds **globally** over the **whole state-space**, which is not part of the conceptual map of engineers
- You have domain-specific **intuitions** on the form of **response curves** but not an explicit formalized partition of behaviors in this huge state-space
- Airplanes fly, nevertheless, most of the time

Monitoring and Supervisory Control

- We want to use some formalism to express observable **conditions** and temporal **patterns** that trigger some response:

  if *some pattern is observed* **then** *do the right thing*

- When the reacting entity is a **human operator**, we should create an **alarm** to bring the situation to her attention
- If the action is **automatic**, this is another instance of feed-back control, appropriate for **high-level supervisory control** where discrete **decisions** are to be taken
- Intuitively, low level is likes controlling torques and velocities in cars or robots (continuous processes)
- Higher levels **decide** whether to bypass an obstacle from right or left or cancel the trip after observing traffic jams
- Similar motivations led in the past to **hybrid systems**

Do Not Wait for the Last Minute

- If we want to **react**, the specified patterns need not be the **complete** negations of properties but **prefixes** of those
- For property like $\square(x < c)$ we should raise a flag when x gets **too close** to c and try to **steer** the system in the opposite direction to **enforce** the property
- If every request should be granted within d time, a useful monitor will detect customers that wait for some $d' < d$ time, while there is a chance to serve them on time
- Note that monitoring is not immediately associated an **error**: fuel level in cars is displayed **continuously** and only when it crosses some **threshold** it is Booleanized into an **alarm**

Some Technicalities of Online Monitoring

- Offline monitoring can go **back and forth** on the simulation trace which has already been computed
- Going backwards is natural for **future** temporal logic which is **acausal**: truth at t depends on values at $t' > t$
- For real systems we cannot wait until the **end of time** and need to adopt **forward** techniques
- **Past** temporal logic is causal and can be monitored forward
- One may argue that unbounded liveness is useless, while **bounded liveness** (safety), translates to past TL and can be monitored causally
- In verification you consider behaviors starting at $t = 0$;
- For online monitoring you look for **segments** of the behavior that **match** some pattern
- **Regular expressions** (timed and hybrid) are more appropriate

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6. **Qualitative Properties and Quantitative Measures**

Quantitative Semantics, Robustness

- Properties map behaviors (sequences, signals) into $\{0, 1\}$ according to **satisfaction** or **violation**
- Sometimes we want more refined information about the **robustness** of the answer
- For a behavior satisfying $\Box(x < c)$, the distance $c - \max_t x(t)$ tells us how **close** we were to violation
- When we violate $\Box(e \rightarrow \Diamond_{[0,a]} e')$, the maximal temporal distance between e and e' defines the severity of violation
- The quantitative (robustness) semantics of STL returns a real value $\rho = \rho(\varphi, w)$ satisfying:

$$\rho(\varphi, w) > 0 \leftrightarrow w \models \varphi \text{ and } \forall w' d(w, w') < \rho \rightarrow (w \models \varphi \leftrightarrow w' \models \varphi)$$

- This number is used in optimization/search procedures for finding bad behaviors (falsification)
- Implemented in tools such as **S-Taliro** (Fainekos and Sankaranarayanan) and **Breach** (Donze)

Unifying Properties and Performance Measures

- Robustness gives more information but it still suffers from the **extremal** nature of logic
- The quantitative semantics is obtained by replacing Boolean predicates such as $x < c$ by numbers like $c - x$ and then replacing $\vee$, $\wedge$ and $\neg$ by max, min and $-$
- The value will always depend on the **worst case**, the largest value of x, the largest response time
- Some work is needed to reconcile STL with other **additive** (average) measures used elsewhere

Unifying Properties and Performance Measures

- Specification formalisms such as STL and TREG and their quantitative extensions should be viewed as
- Yet another family of **performance measures** which are good in terms of expressing **sequential** behaviors
- As nobody is perfect, they are **weak** in other aspects and should be inserted into the rich arsenal of measures existing already in **control**, **signal processing**, **statistics**, etc.
- A **unified declarative language** for qualitative properties and quantitative measures can be a useful contribution toward **monitoring complex systems**, simulated and real
- Thank you