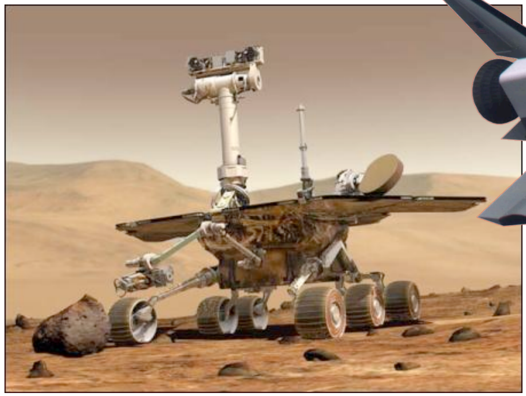
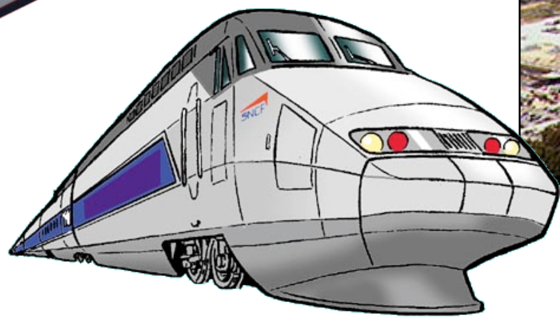
Verification of Intelligent Controllers using Model Checking

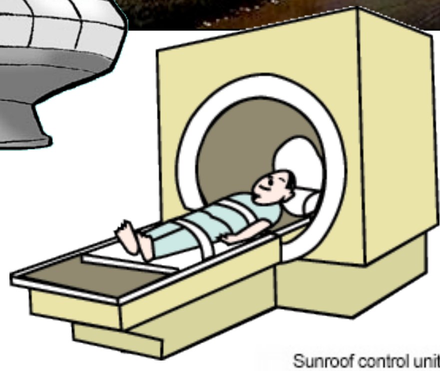
Charles Pecheur, UC Louvain

(formerly RIACS / NASA Ames)

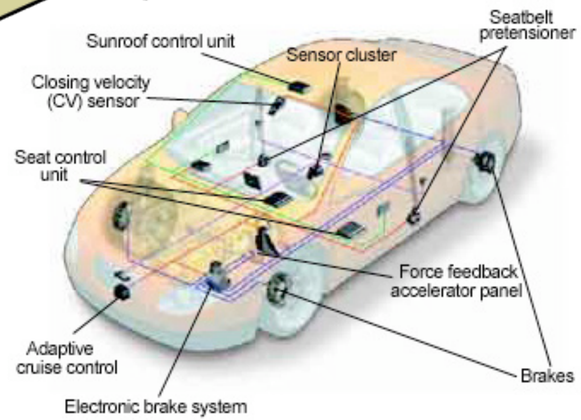
Embedded Controllers







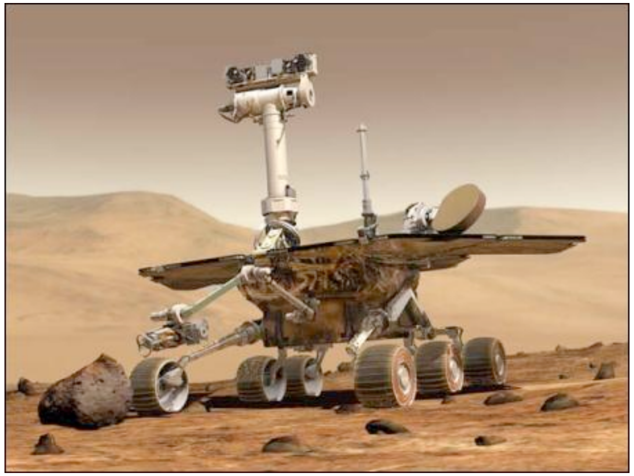
- Everywhere
  - more and more so
- Dependability is critical
  - human risks
  - material risks
  - economic risks
- Logic (vs. physical) part is increasing



Autonomy (at NASA)

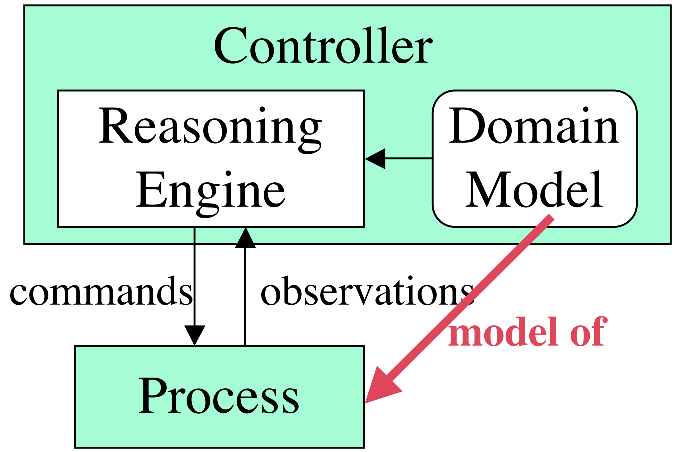
Autonomous spacecraft = on-board intelligence (AI)

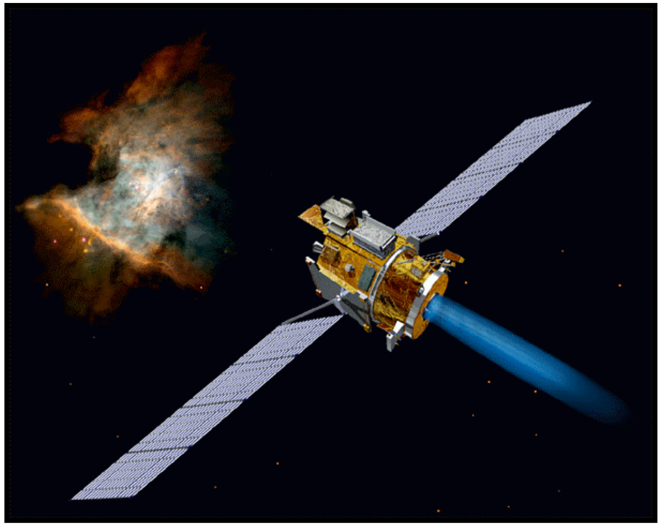
- **Goal:** Unattended operation in an unpredictable environment
- **Approach:** **model-based reasoning**
- **Pros**: smaller mission control crews, no communication delays/blackouts
- **Cons:** **Verification and Validation ???** Much more complex, huge state space
- Better verification is critical for adoption



Model-Based Autonomy

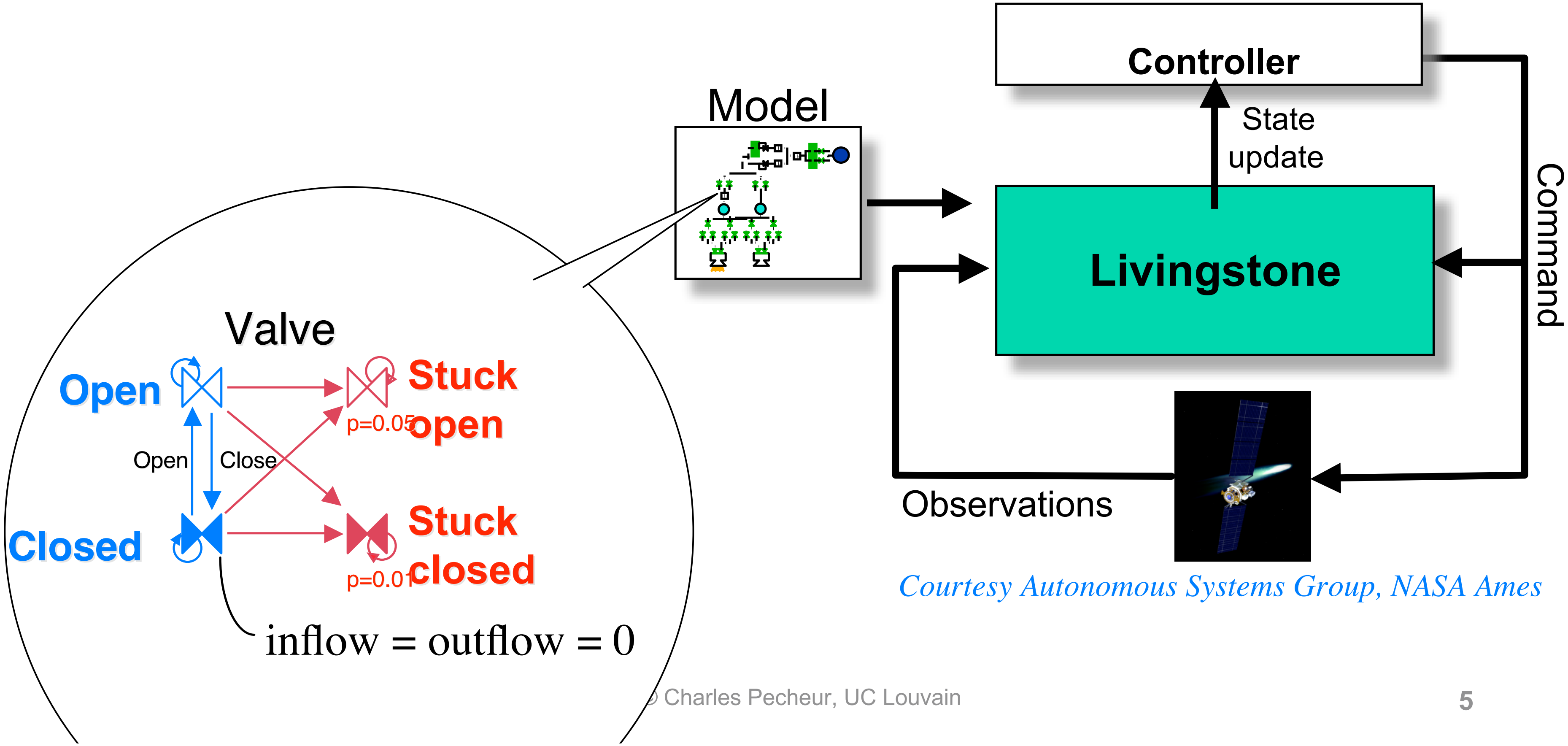
- Based on AI technology
- Generic **reasoning engine**
  + application-specific **model**
- Model describes (normal and faulty) behaviour of the process
- Engine selects control actions "on-the-fly" based on the model
  – ... rather than pre-coded decision rules
  – better able to respond to unanticipated situations





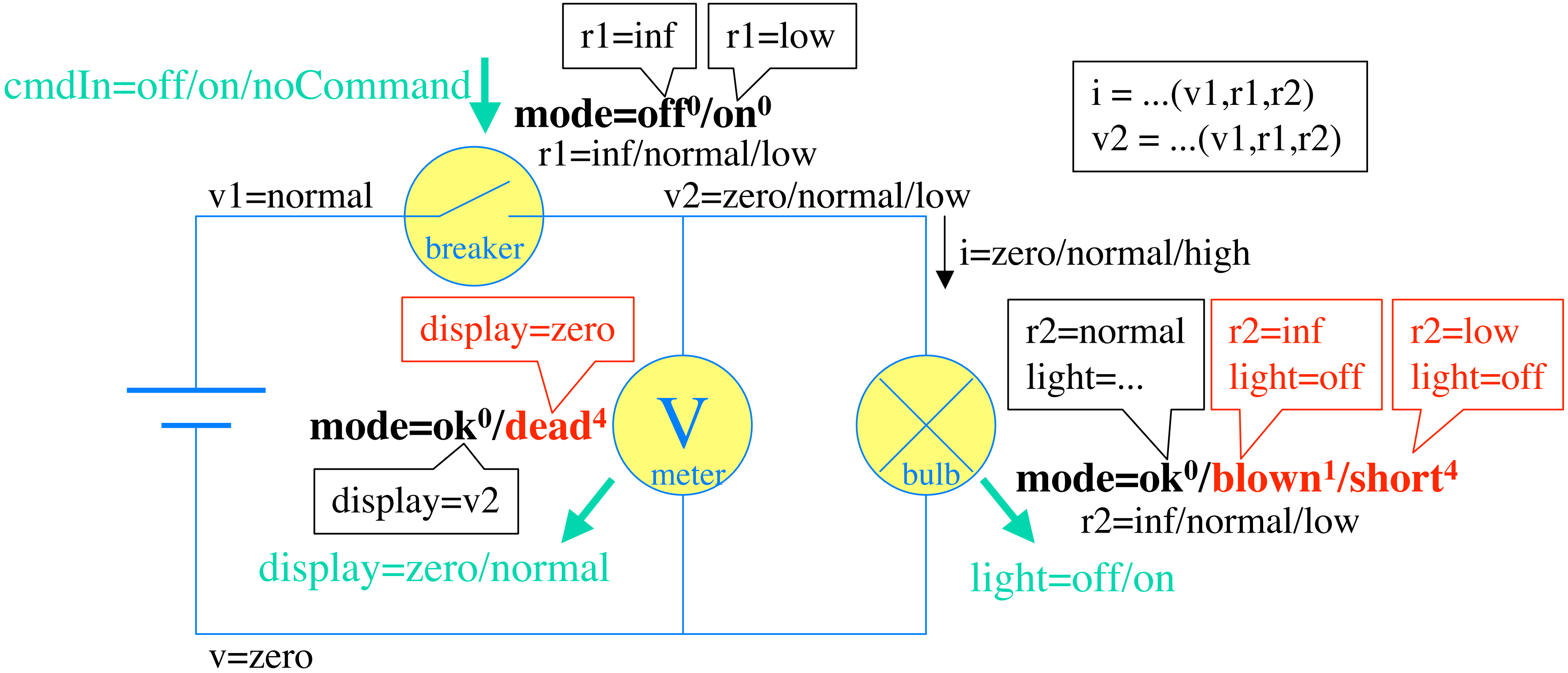
Livingstone

- Model-based diagnosis system from NASA Ames
  - i.e. an advanced state estimator
- Uses a discrete, qualitative model to reason about faults
  => naturally amenable to formal analysis



Courtesy Autonomous Systems Group, NASA Ames

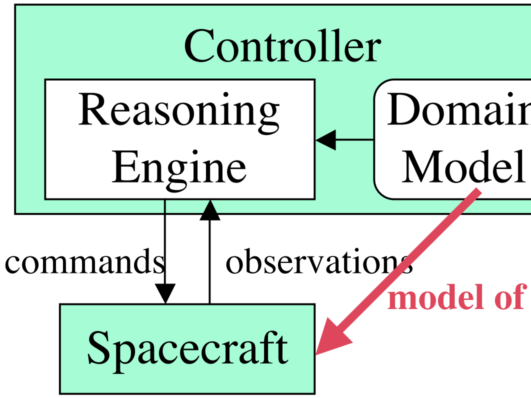
A Simple Livingstone Model



Goal: determine **modes** from observations
Generates and tracks *candidates*

breaker	bulb	meter	rank
off^0	**ok^0**	**ok^0**	**0**
off^0	**ok^0**	**blown^1**	**1**
on^0	**dead^4**	**short^4**	**8**

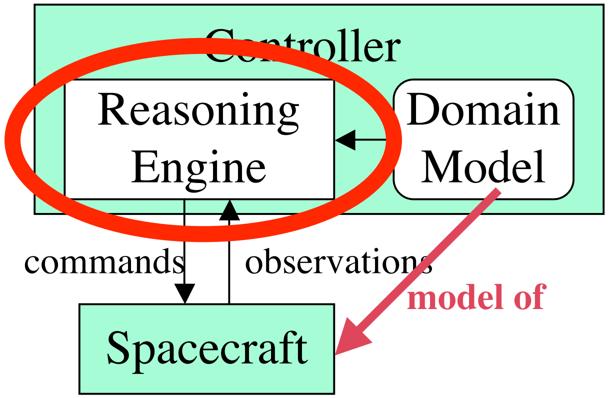
Verify Model-Based Control?



Of course, but what exactly?

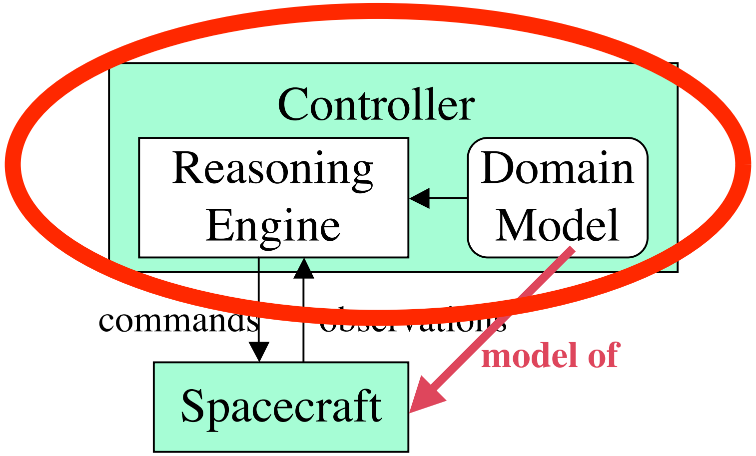
- The model?
- The engine?
- The whole controller?
- **All of the above!**

Verification of the Engine



- A (technically complex) computer program
  - Use traditional software verification approaches
  - Maybe full-blown proof on core algorithms
- Generic, re-used across applications
  - More likely to be stable and trustable
  - Like compilers, interpreters, virtual machines, etc

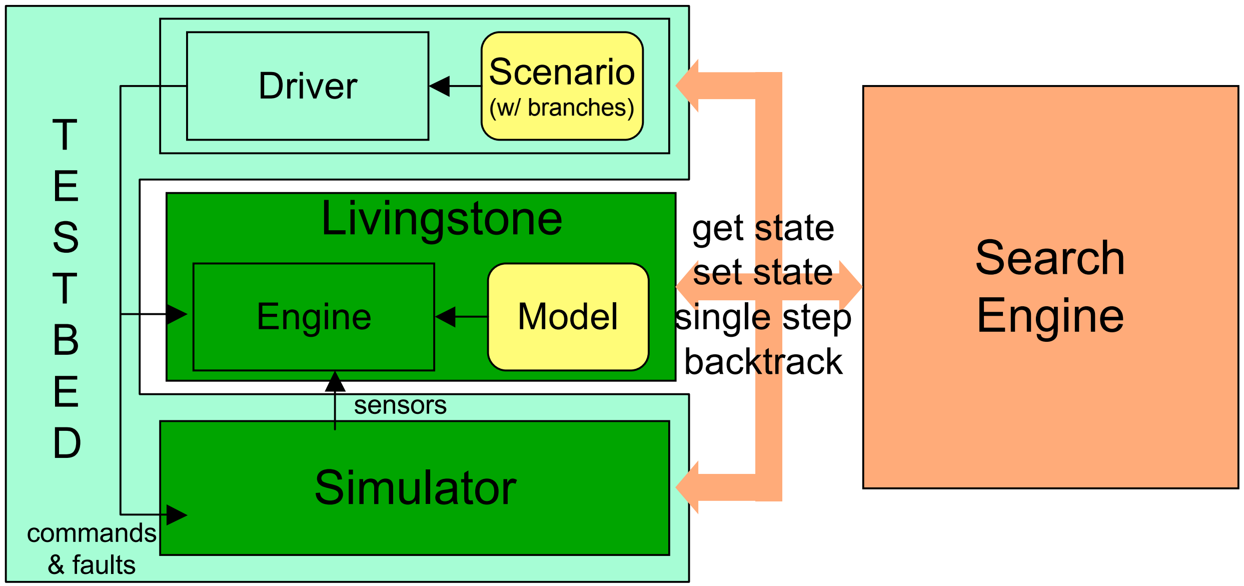
Verification of the Controller



- good model + good engine ≠> good controller
  - Heuristics in engine, simplifications in model
- System-level verification
  - Controller as black (or grey) box
  - Need a model of the environment (test harness)
  - Applicable to others than model-based

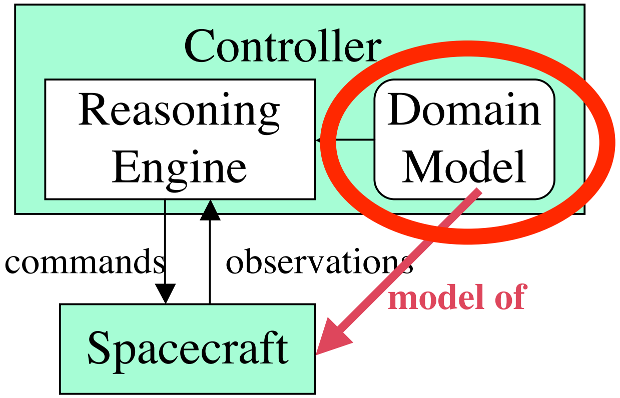
Livingstone PathFinder

with Tony Lindsey (QSS @ ARC)



- An advanced testing/simulation framework for Livingstone applications
  - Executes the **Real Livingstone Program** in a simulated environment (testbed)
  - **Instrument** the code to be able to **backtrack** between alternate paths
- **Scenarios** = non-deterministic test cases (defined in custom language)
- **Modular** architecture with generic APIs (in Java)
  - allows different diagnosers, simulators (can use Livingstone), search algorithms (depth-first, breadth-first, heuristic, random, ...)
- See TACAS'04 paper

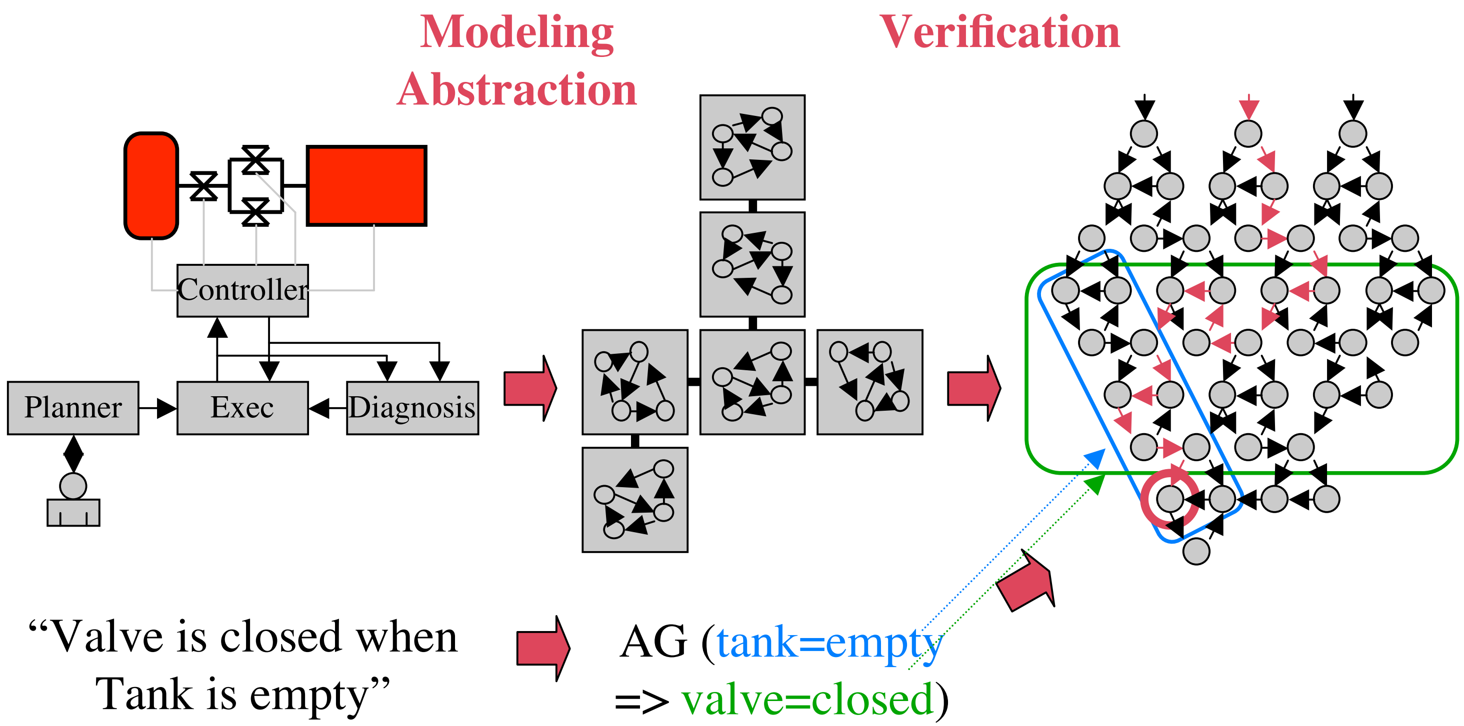
Verification of the Model



- This is the "application code"
  - where the development effort (and bugs) are
- Abstract, concise, amenable to formal analysis
  - this is another benefit of model-based approaches
  - ... or model-based design in general

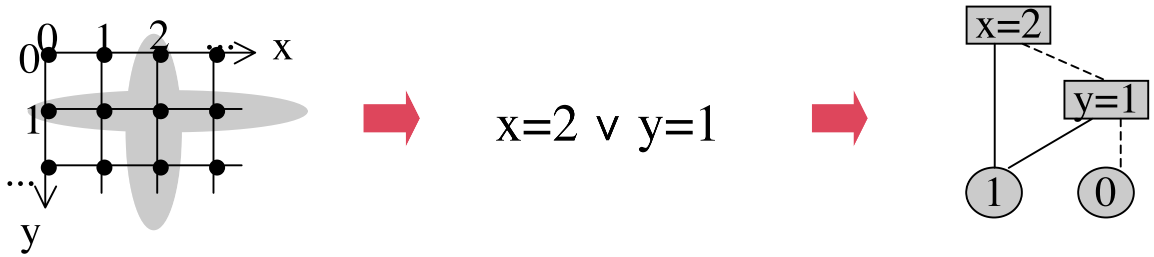
Model Checking

- **Model checking** = (ideally) exhaustive exploration of the (finite) state space of a system
  - ≈ exhaustive testing with loop / join detection



Symbolic Model Checking

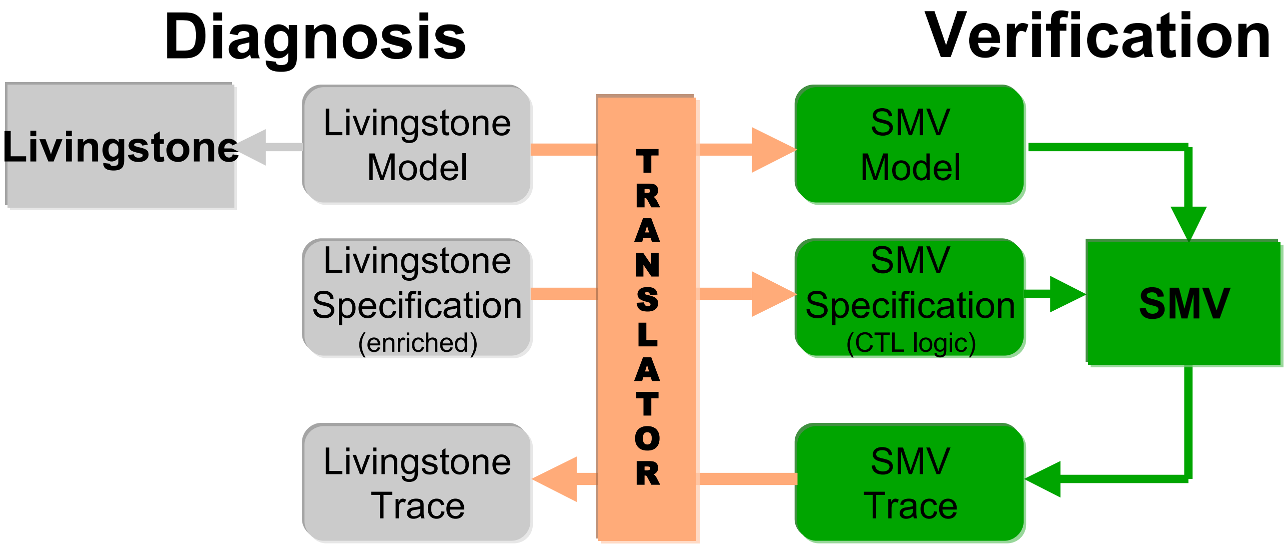
- **Symbolic** model checking =
  - compute sets of states,
  - using symbolic representations,
  - that can be efficiently encoded and computed.



- Can handle very large state spaces (10^{50+}), or even infinite domains (continuous time and variables)
- Example: **SMV/NuSMV** (Carnegie Mellon/IRST)
  - finite state using boolean encoding (BDD, SAT)

Livingstone-to-SMV Translator

Joint work with Reid Simmons (Carnegie Mellon)



- A translator that converts Livingstone models, specs, traces to/from SMV (in Java)
  - SMV: symbolic model checker (both BDD and SAT-based) allows exhaustive analysis of very large state spaces (10^{50+})
- Hides away SMV, offers a **model checker for Livingstone**
- Enriched specification syntax (vs. SMV's core temporal logic)
- Graphical interface, integration in Livingstone development tools

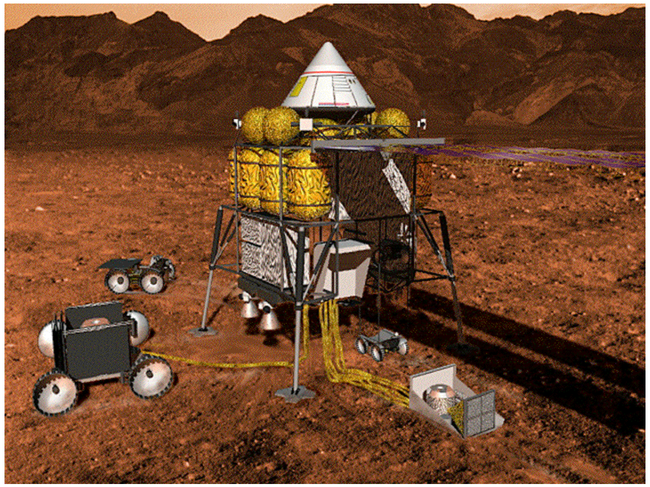
In-Situ Propellant Production

- Use atmosphere from Mars to make fuel for return flight.
- Livingstone controller developed at NASA KSC.
- Components are tanks, reactors, valves, sensors...
- Exposed improper flow modeling.
- Latest model is 10^{50} states.

Mars atmosphere   on-board

$$\underset{\text{Mars atmosphere}}{CO_2} + \underset{\text{on-board}}{2H_2} \;\text{—>}\; \underset{\text{fuel}}{CH_4} + \underset{\text{oxidizer}}{O_2}$$

fuel   oxidizer



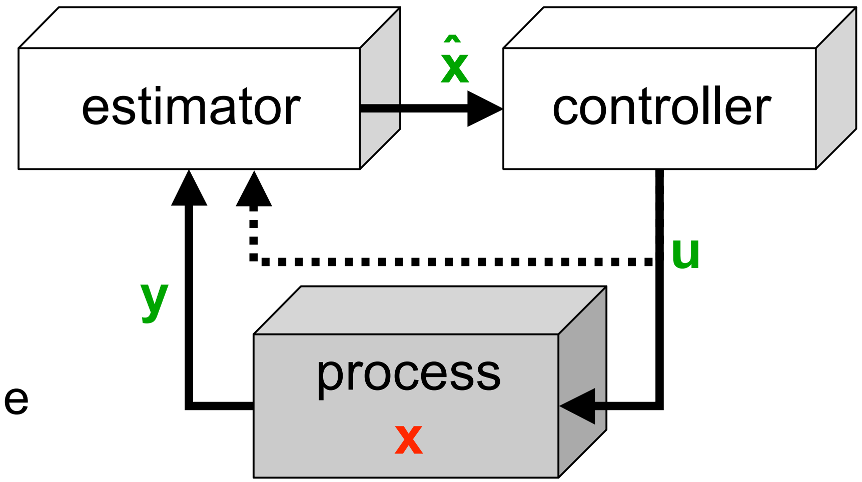
Verification of Diagnosis Models

- Coding Errors
  - e.g. Consistency, well-defined transitions, ...
  - Generic
  - Compare to Lint for C
- Model Correctness
  - Expected properties of modeled system
  - e.g. flow conservation, operational scenarios, ...
  - Application-specific
- **Diagnosability**
  - Are faults detectable/diagnosable?
    - Given available sensors
    - In all/specific operational situations (dynamic)

Process Control

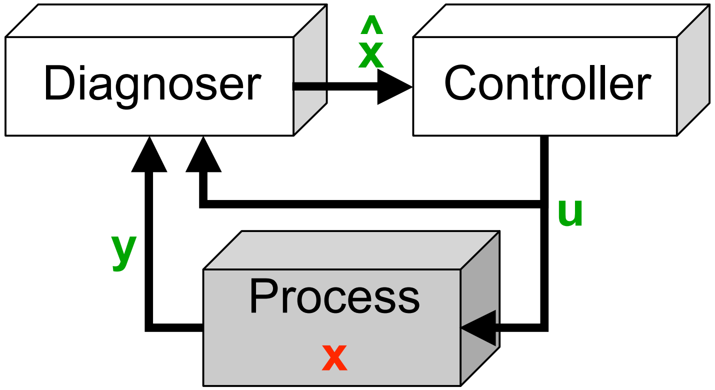
- Partially observable process (hidden state **x**, estimated by $\hat{\mathbf{x}}$)

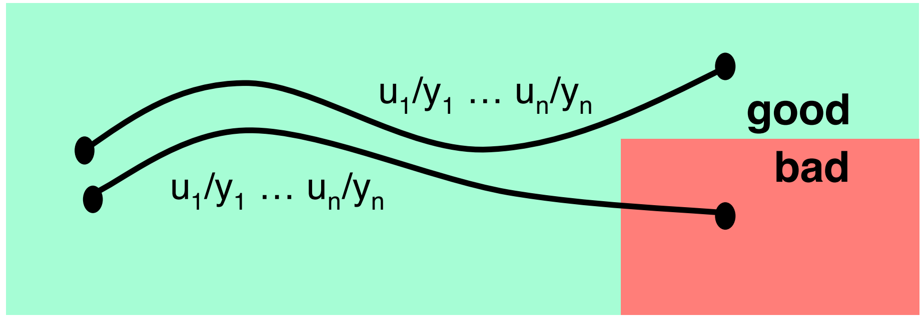
- **observability** :
  infer **x** from **y** (and **u**)
- **commandability** :
  impose **x** through **u**



- **control theory** :
  x = physical quantities, differentiable
  → linear models, PDI controllers
- **logic processes** :
  x = states, modes, **failures**, discrete
  → state machines, programmable automata

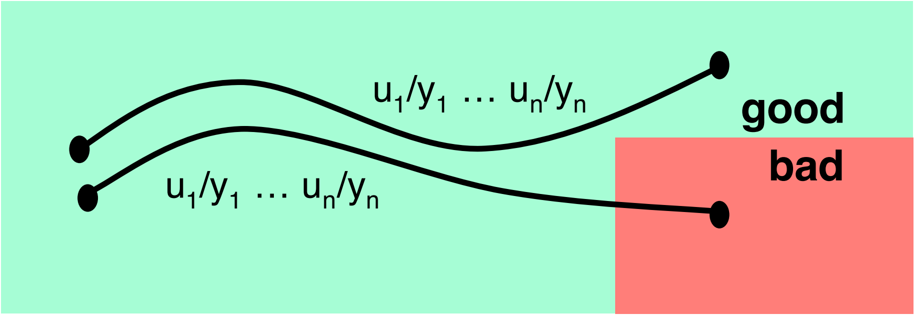
Diagnosability

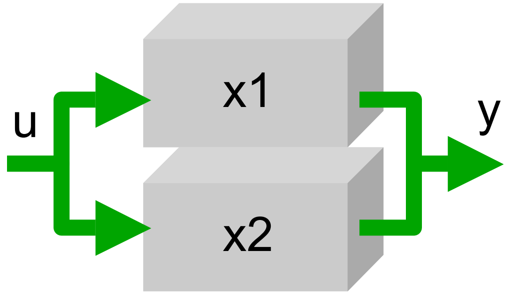




- **Diagnosis:** estimate the hidden state **x** (incl. failures) given observable commands **u** and sensors **y**.
- **Diagnosability**: Can (a smart enough) *Diagnoser* always tell when *Process* comes to a **bad** state?
- **Property of the Process** (not the Diagnoser)
  - even for non-model-based diagnosers
  - but analysis needs a (process) model

Verification of Diagnosability



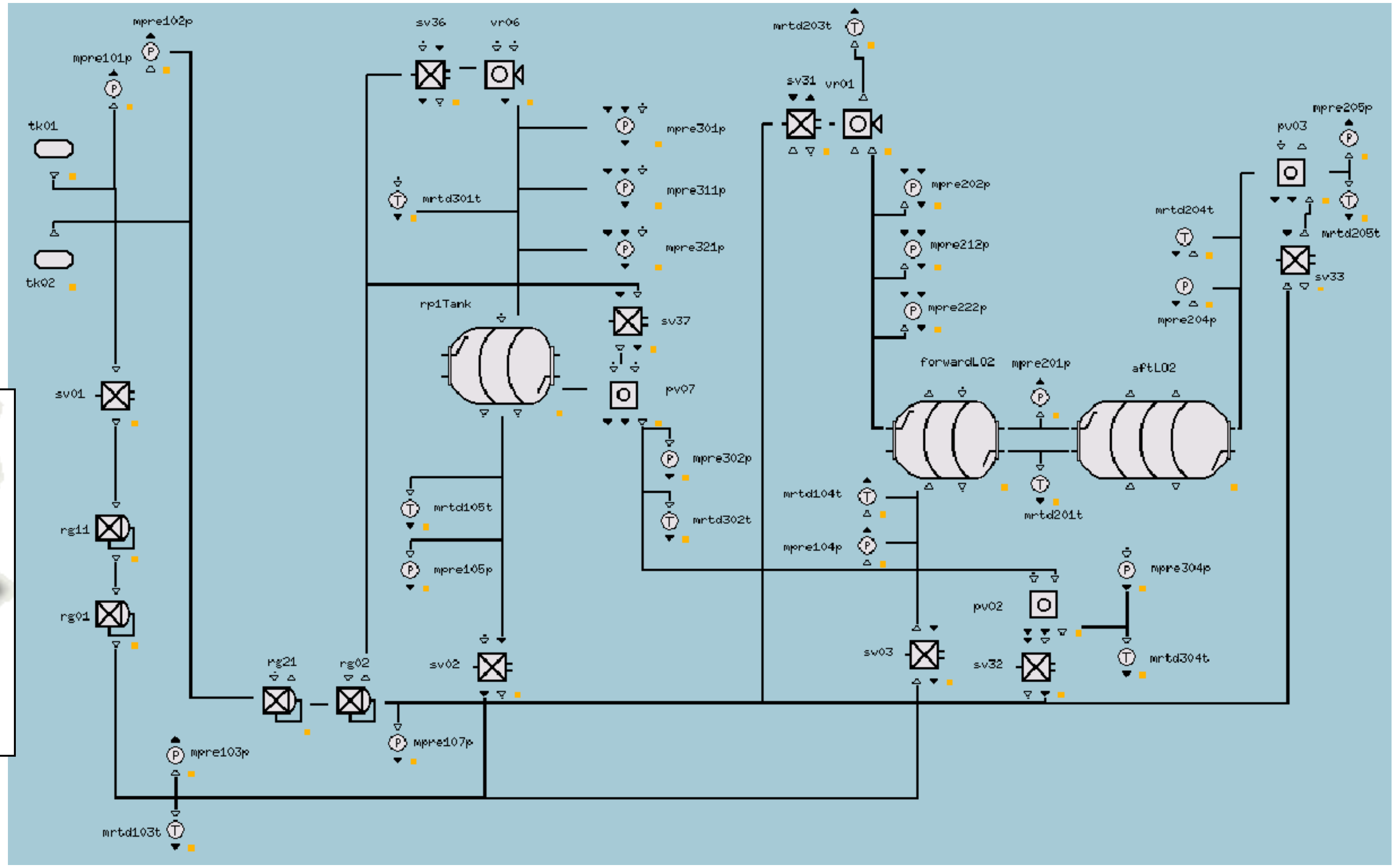


- **Intuition**: **bad** is diagnosable if and only if there is no pair of trajectories, one reaching a **bad** state, the other reaching a **good** state, with identical observations.
  - or some generalization of that: (context, two different faults, ...)
- **Principle**:
  - consider two concurrent copies *x1*, *x2* of the process, with coupled inputs *u* and outputs *y*
  - check for reachability of (good(x1) && bad(x2))
- Back to a classical (symbolic) model checking problem !
- Supported by Livingstone-to-SMV translator

UCL Université catholique de Louvain INGI

X-34 / PITEX

- Propulsion IVHM Technology Experiment (ARC, GRC)
- Livingstone applied to propulsion feed system of space vehicle
- Livingstone model is $4 \cdot 10^{33}$ states



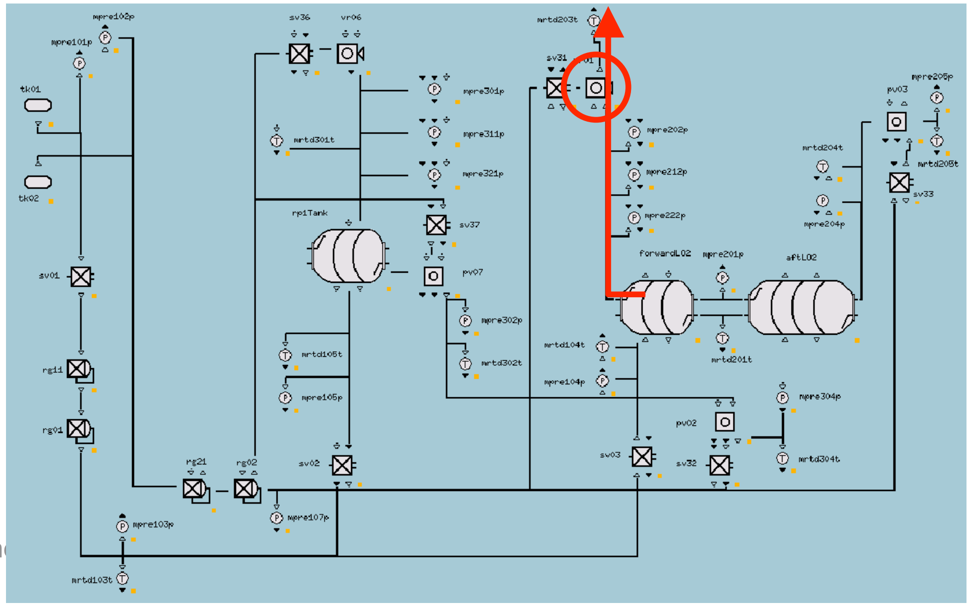
PITEX Diagnosability Error

with Roberto Cavada (IRST, NuSMV developer)

- *"Diagnosis can decide whether the venting valve VR01 is closed or stuck open (assuming no other failures)"*

  INVAR !test.multibroken() & twin(!test.broken())
  VERIFY INVARIANT !(test.vr01.mode=stuckOpen &
  twin(test.vr01.valvePosition=closed))

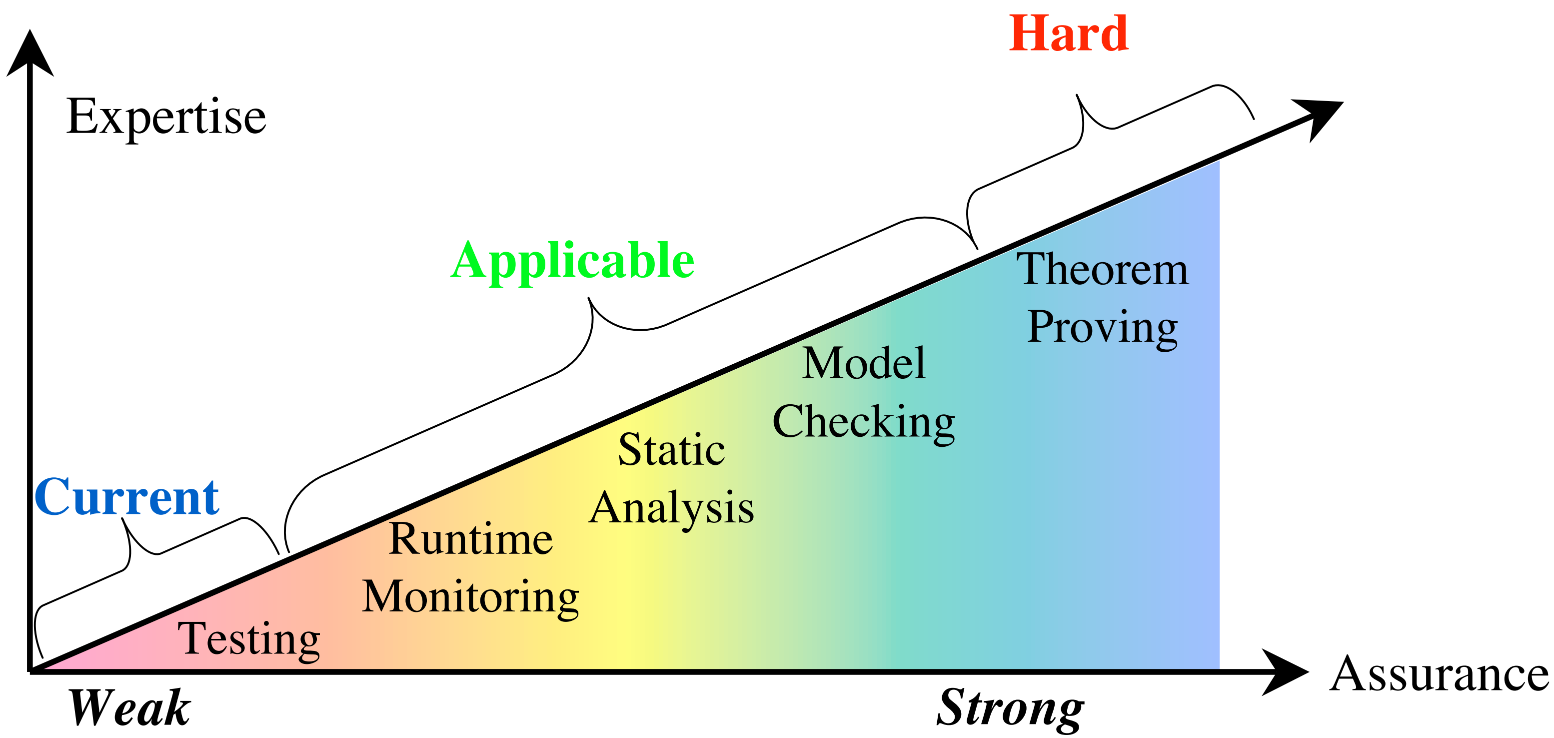
- Results show a pair of traces with same observations, one leading to **VR01 stuck open**, the other to **VR01 closed**. Application specialists fixed their model.



... and Verification of Software

- There is more to it than reasoning engines!
  - Device drivers, OS, navigation, communication, ...
  - real-time, **concurrent**, reactive, interrupts, priorities, ...
- All traditional good practices apply
  - **Sound software engineering practices** (requirements, design, modelling, documentation, reviews, testing, configuration management, ...)
  - Advanced software verification techniques (monitoring, static analysis, model checking, proofs)

The Program Verification Spectrum



(adapted from John Rushby)

Human Factors

- Adapt technology to its users
  - use their paradigms/languages (translation)
  - integrate in their tools and environments
  - vision : verification tools as advanced debuggers
- Technology maturation
  - From something that works to something that is usable
  - Lots of work and time
  - Polish the code but also documentation, training, etc
- Space mission adoption
  - Space missions take very conservative attitude w.r.t. new technologies (for good reason)
  - No-one wants to be the first adopter
  - Usefulness of technology validation missions

Conclusions

- Verification of **control software**
  - Particularity : control loop, observability/commandability
    - In particular, failure diagnosability and recoverability
- Verification of **model-based controllers**
  - **Needs** advanced verification (because of large state space)
  - **Facilitates** advanced verification (thanks to model)
- **Model checking**
  - Applicable to these problems
  - esp. symbolic model checking, esp. to model-based
  - Delicate precision/scalability trade-off
- Verification of **software**
  - All other principles still apply

Perspectives

- Key ideas:
  - **model-based analysis (model checking)**
  - **partial observability**
- Extensions
  - from discrete to continuous, real-time, **hybrid models**
  - from fault diagnosis to **planning**
- Connections
  - with classical **risk analysis** (fault trees, FMEA)
  - with **man-machine interface** issues (observability!)
  - with **epistemic logics** (diagnoser as knowledge agent)
- Keep in touch with reality
  - scalability, relevance to practical needs, tools, integration

References

- On this talk :

  Tim Menzies and Charles Pecheur. Verification and Validation and Artificial Intelligence. In: M. Zelkowitz, Ed., Advances in Computers, vol. 65, 2005, Elsevier.

- See also
  - http://www.info.ucl.ac.be/~pecheur/publi/
  - http://www.info.ucl.ac.be/~pecheur/talks/