Guided Simulation of Autonomous Controllers

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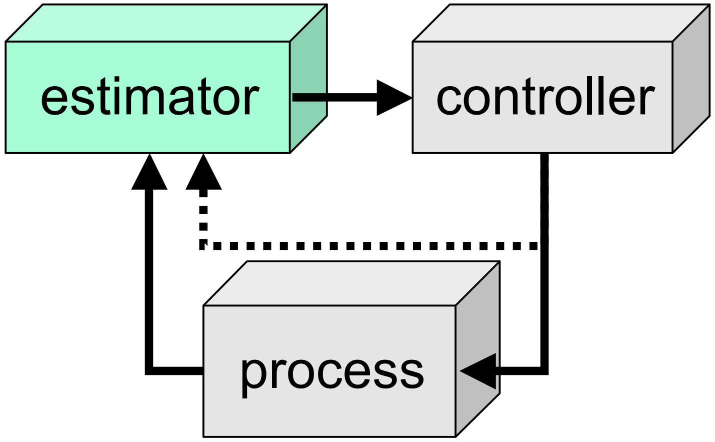
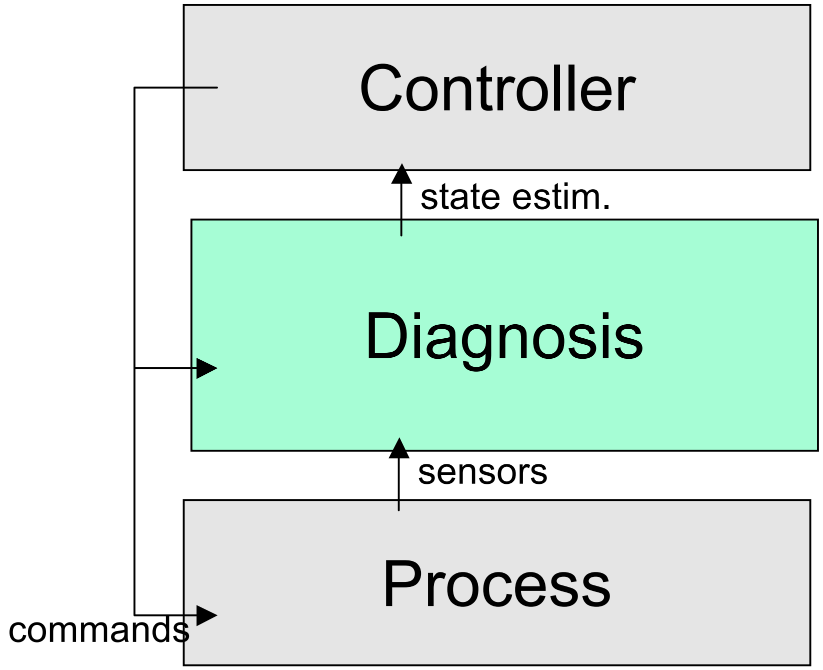
performed at NASA Ames Research Center

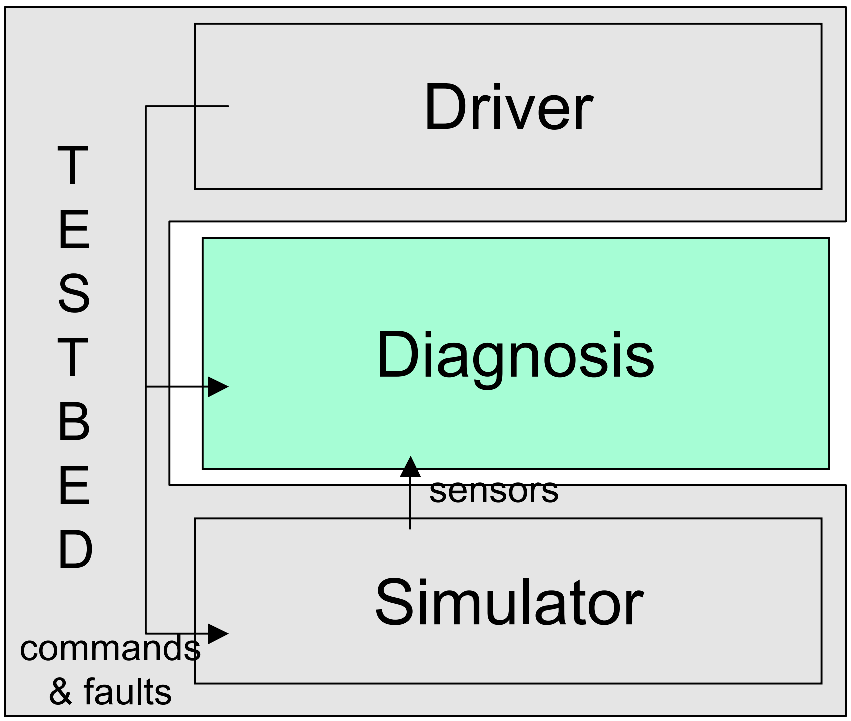
Ames Research Center

Diagnosis

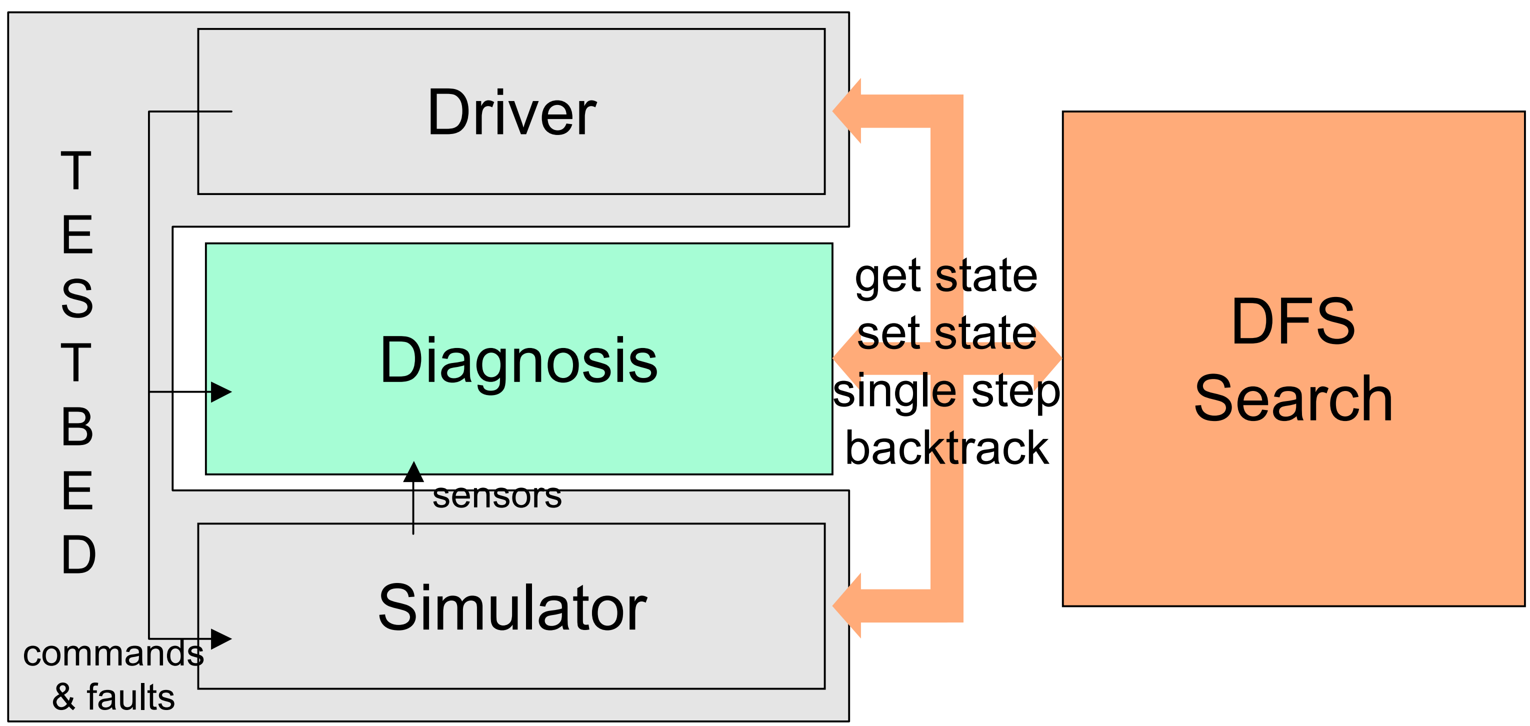

estimator
controller
process


Controller
state estim.
Diagnosis
sensors
Process
commands

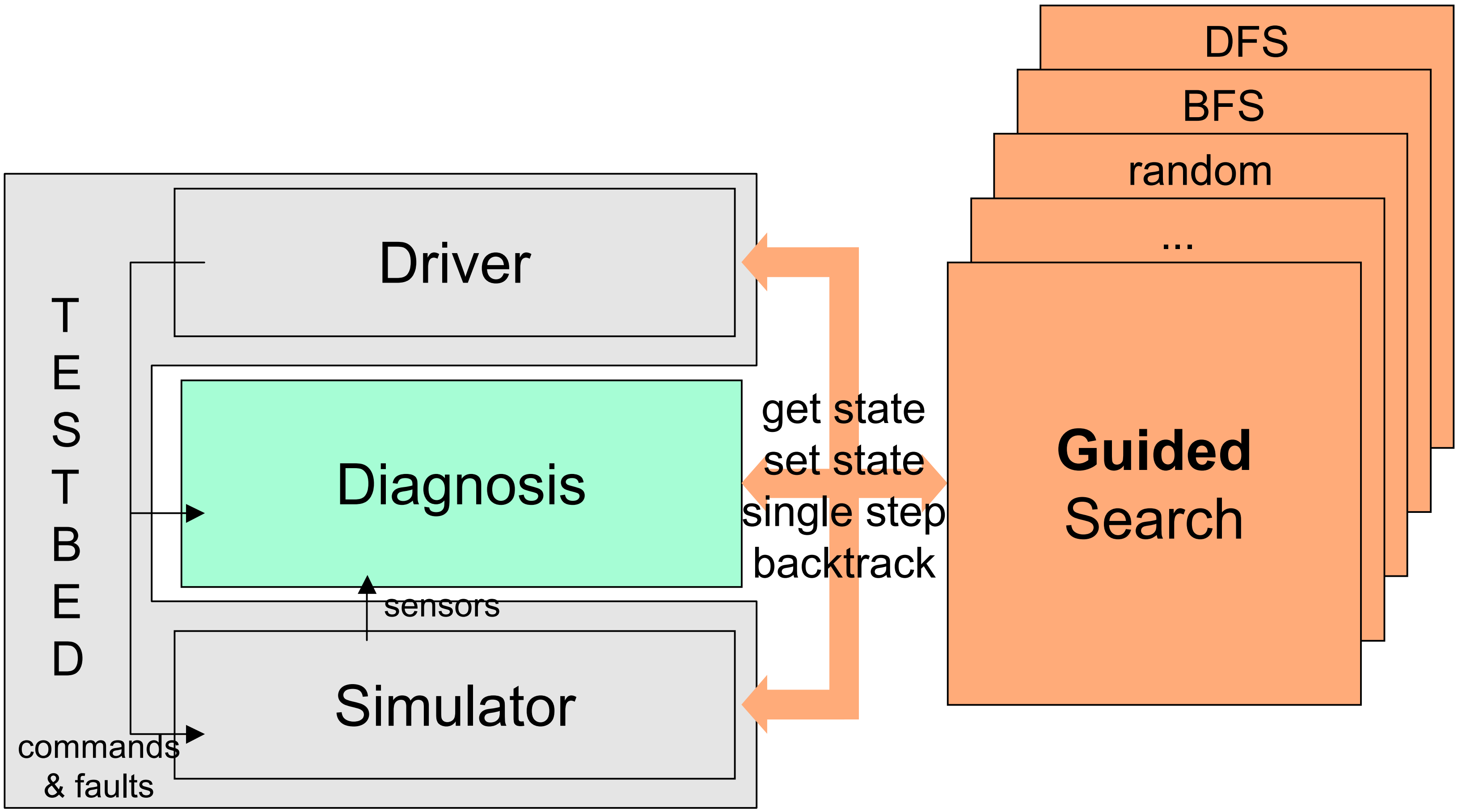
Diagnosis + Testbed



Diagnosis + Testbed + Search



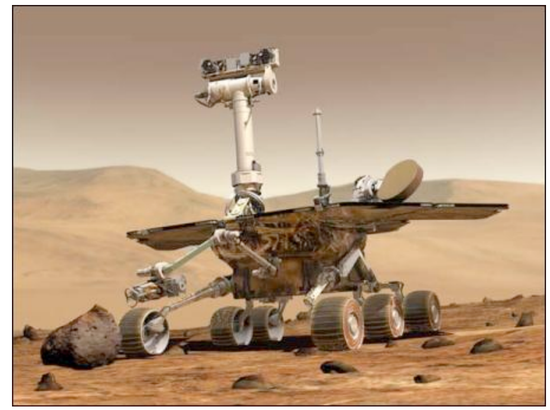
Diagnosis + Testbed + Searches

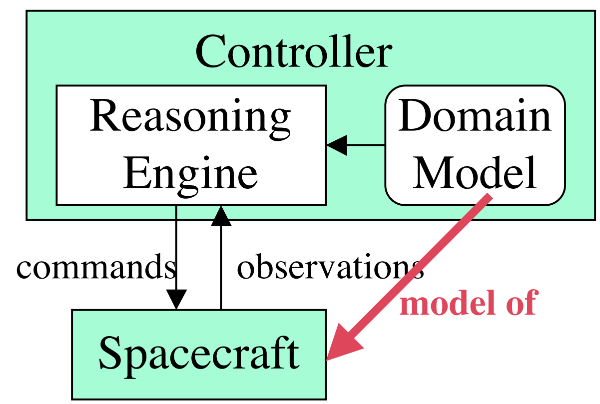


Autonomy (in Space)

Autonomous spacecraft = on-board intelligence (AI)

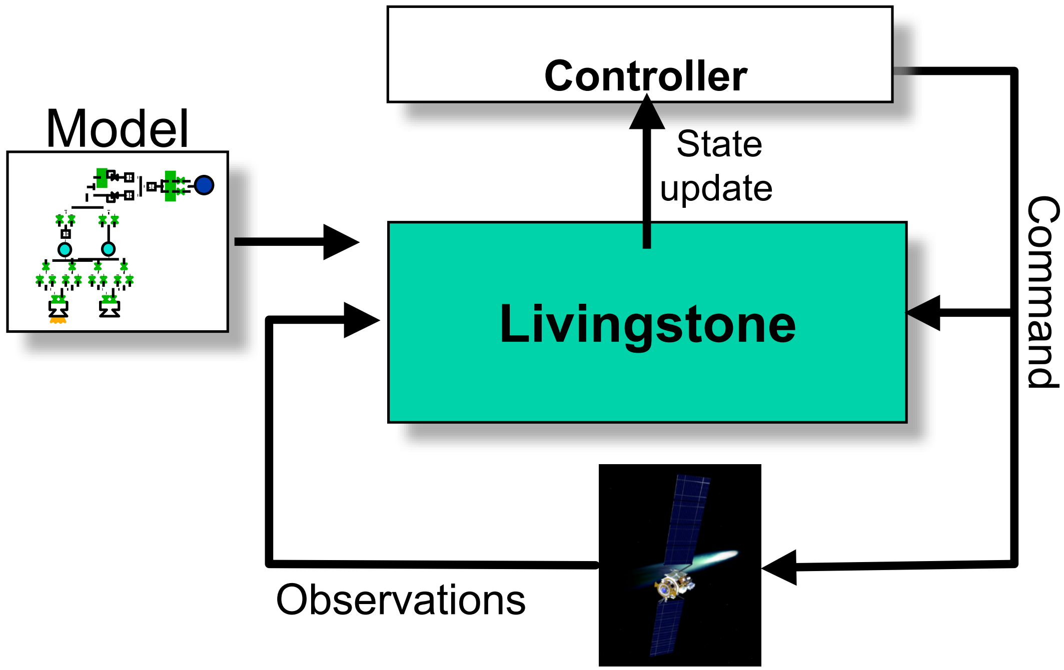
- **Goal:** Unattended operation in an unpredictable environment
- **Approach:** **model-based** reasoning
- **Pros**: smaller mission control crews, no communication delays/blackouts
- **Cons:** **Verification and Validation ???** Much more complex, huge state space
- Better verification is critical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





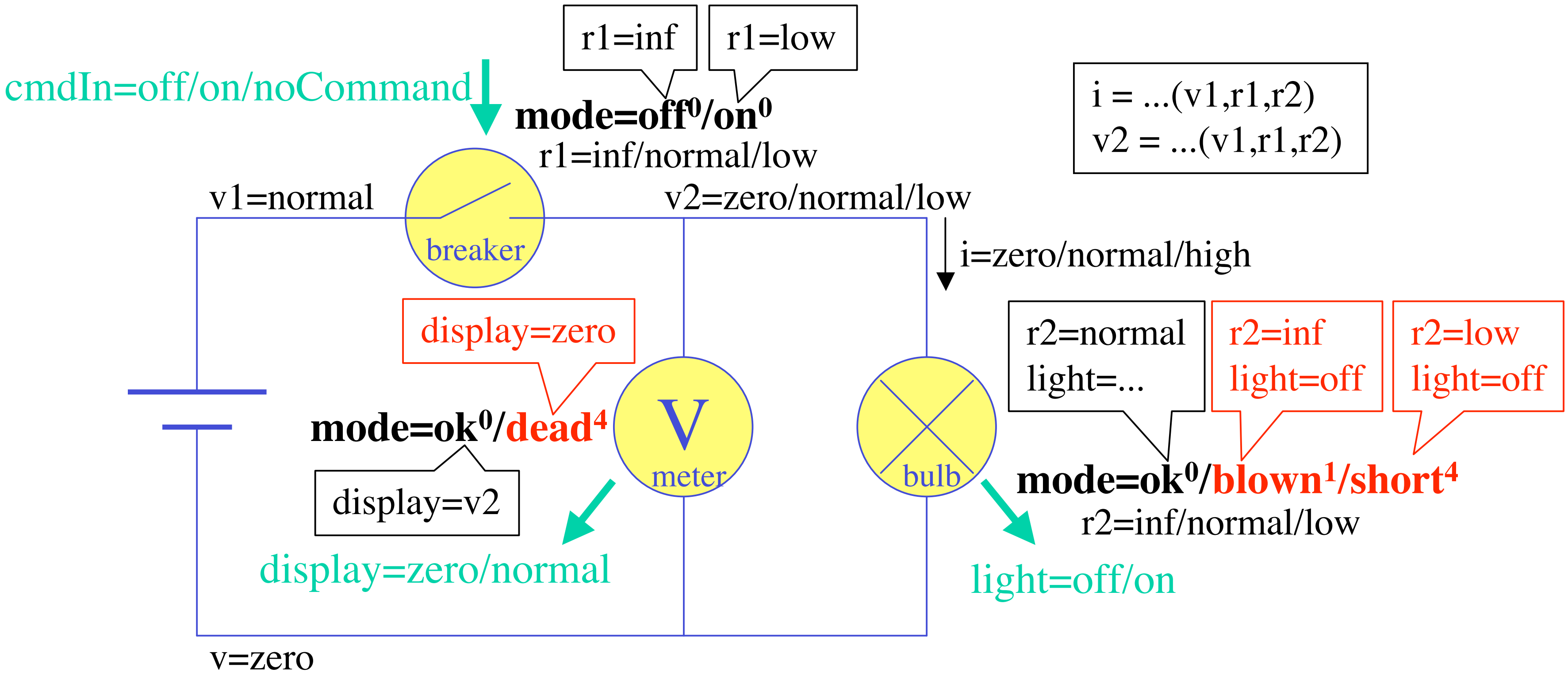
Model-Based Diagnosis

- Focus on **Livingstone** system from NASA Ames.
- Uses a discrete, qualitative model to reason about faults



Courtesy Autonomous Systems Group, NASA Ames

A Simple Diagnosis 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**

Faults vs. Errors

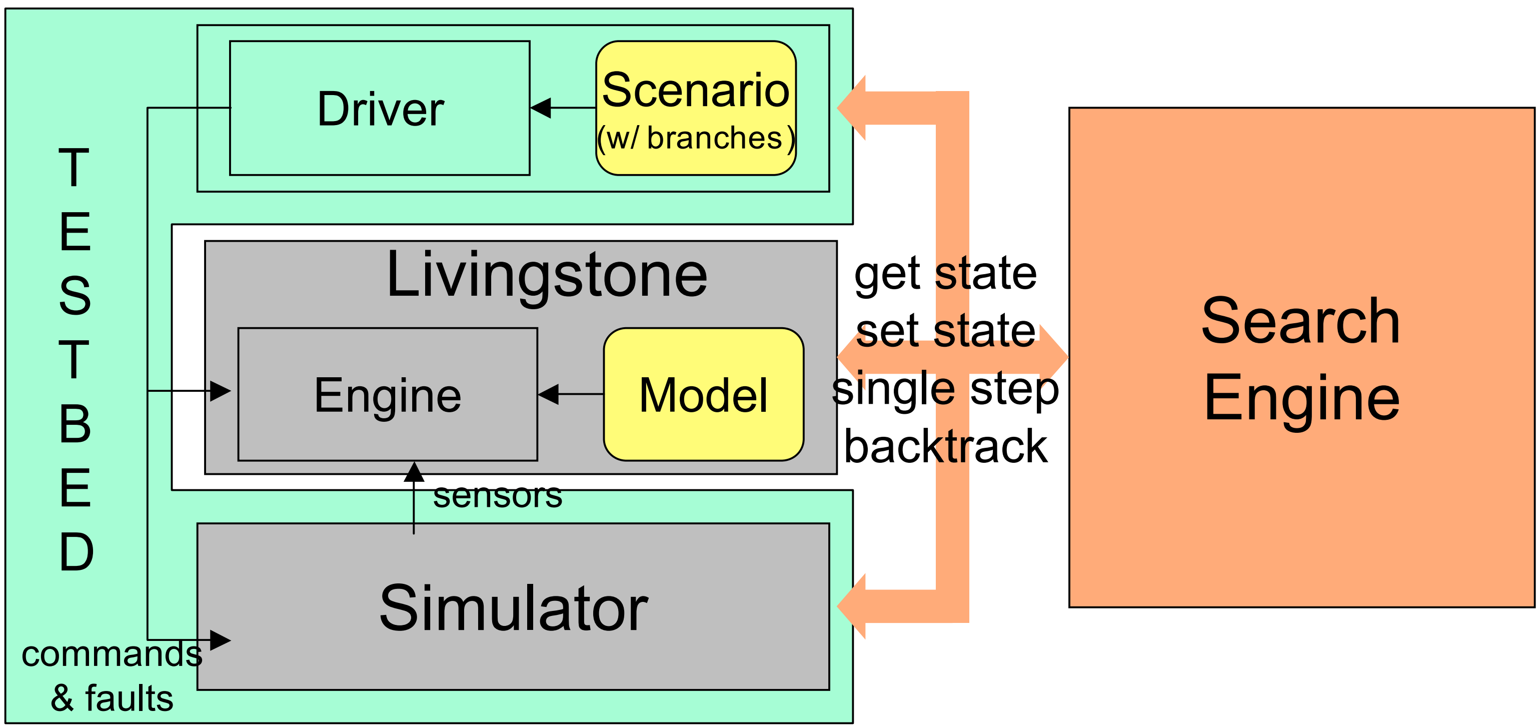
Faults	Errors
Ex: valve is stuck	Ex: fault not detected
in Process/Simulator	in Diagnosis/Design
Spontaneous physical event	Human design flaw
To de detected by Diagnosis	**To be detected by Verification**

Verification of Model-Based Autonomy

Two complementary approaches:

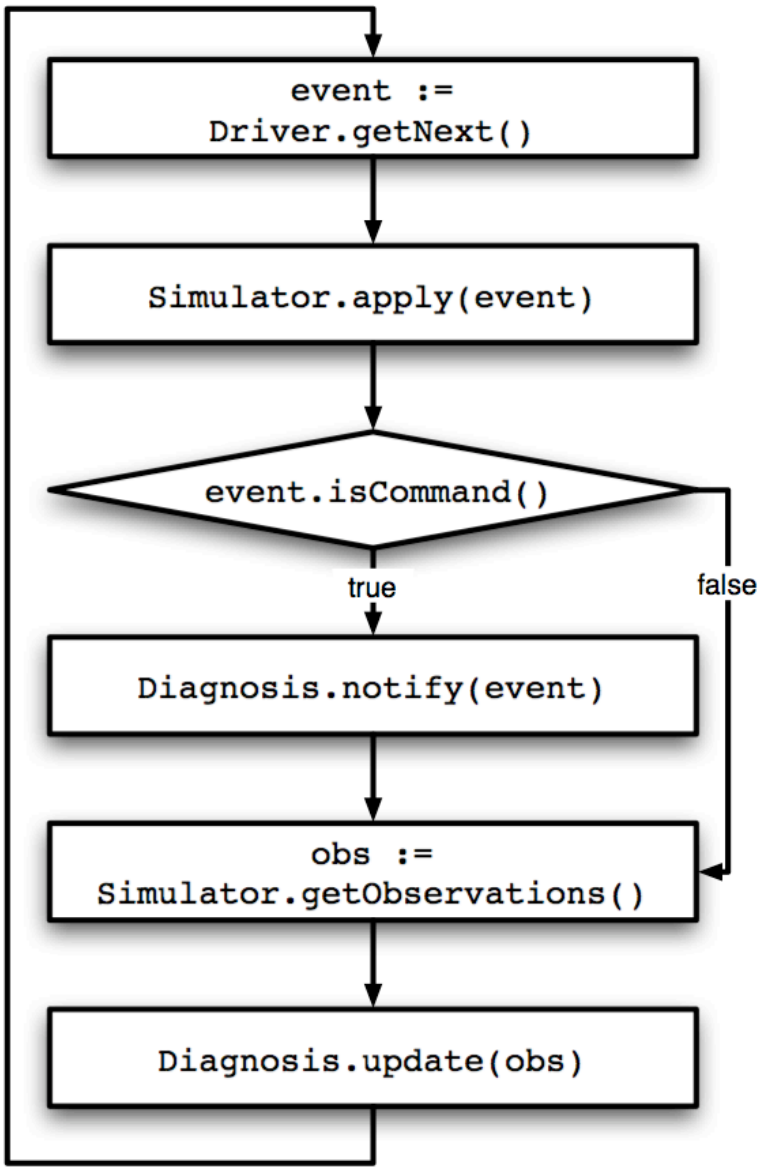
- Model-based verification
  - Analyze the model
  - That's the application "source code"
  - Symbolic model checking (NuSMV, SAT-based BMC)
- **Simulation-based verification**
  - Analyze the whole program (engine+model+testbed)
  - More comprehensive but less coverage
  - Controlled execution of the actual program

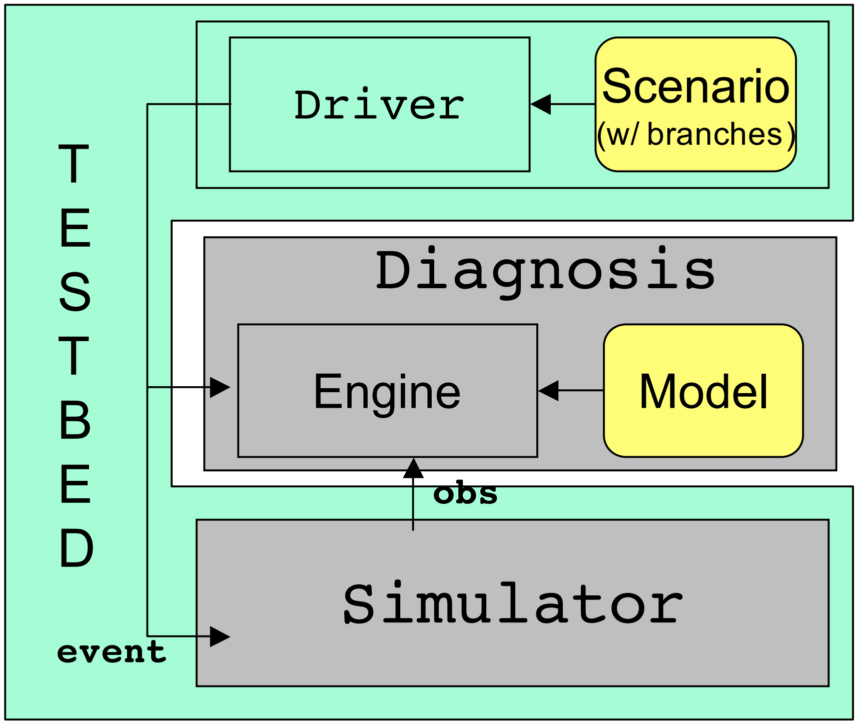
Livingstone PathFinder (LPF)



- Similar to VeriSoft[Godefroid 97]
- Uses checkpointing implemented in Livingstone
- In Java, accesses Livingstone (C++) through JNI

One Diagnosis Step





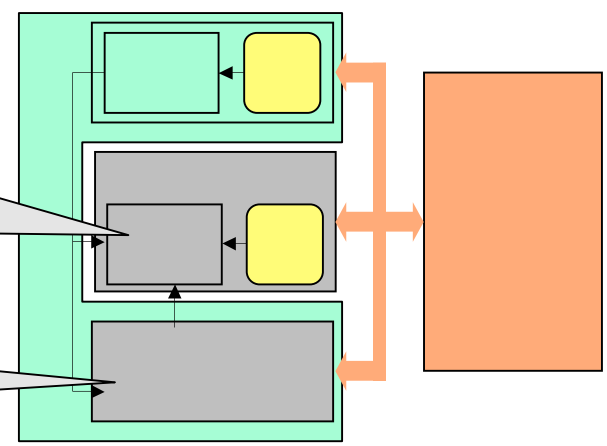
LPF Error Conditions

- Diagnosis candidates are "correct" w.r.t. Simulator modes
  - Mode Comparison (MC): first candidate is correct
  - Candidate Matching (CM): some candidate is correct
  - Candidate Subsumption (CS): some candidate's faults are included
- CS may miss errors but works best in practice

MC ✗
CM ✗
√ CS

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

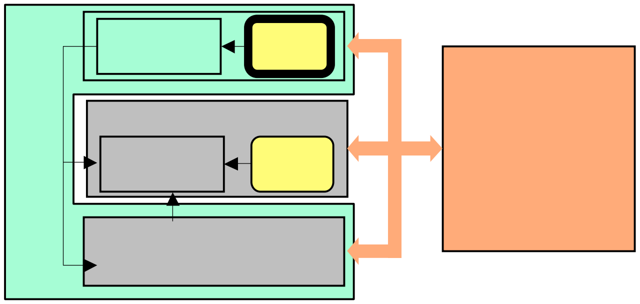
breaker	bulb	meter
off^0	**dead^4**	**blown^1**



LPF Simulation Scenarios

- Defines the tree of executions to be explored
- Described as a non-deterministic program using a simple scripting language

```
stmt  ::= " event "  ;                      single event
        |  { stmt* }                         sequence
        |  mix stmt (and stmt)*          interleaving
        |  choose stmt (or stmt)*           choice
```



- Implemented as a hierarchy of automata objects matching the scenario script structure

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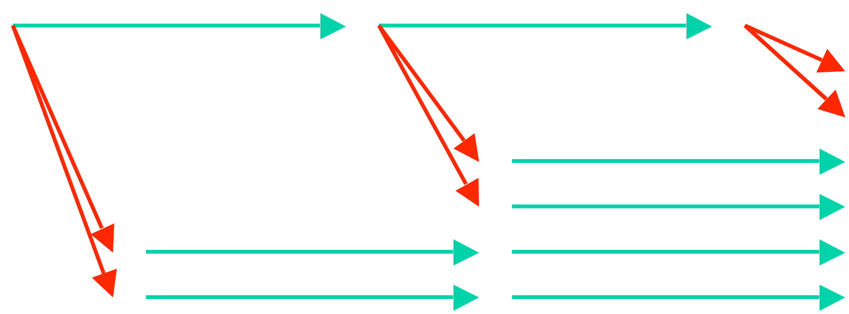
LPF Scenario Example

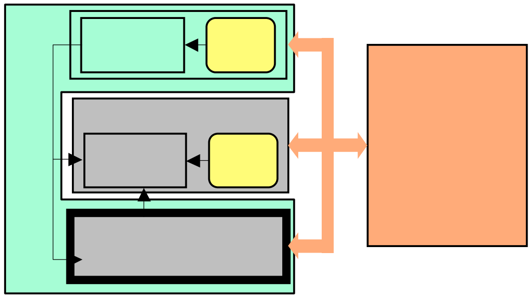
```
mix {
   "command test.sv02.valveCmdIn=close";
   "command test.sv02.valveCmdIn=open";
   ...
} and {
   choose
     "fault test.forwardLO2.mode=unknownFault"; or
     "fault test.mpre101p.mode=faulty"; or
     ...
}
```



- Sequence of commands || choice of faults
- "default" scenario, can be generated automatically

LPF Simulators

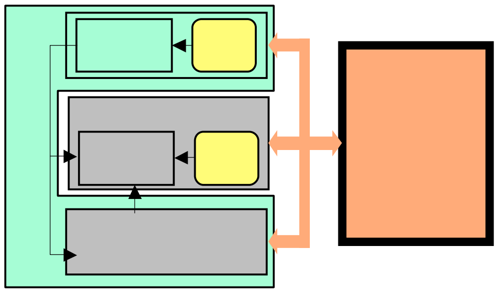
- Framework allows to use any (suitably instrumented) simulation software
  - Trade-off: higher-fidelity simulators may restrict instrumentation
- Current implementation uses **second Livingstone engine** as simulator
  - Same or different model
  - Different mode of operation:
    Diagnosis : cmds, obs –> modes
    Simulator : cmds, modes –> obs
  - Simulator comes "for free"
  - Rationale: verify diagnosis assuming the model is correct



- Also considered: CONFIG (hybrid, NASA JSC)

LPF Search

- The whole testbed is seen as a transition system
- API to enumerate transitions, backtrack, get/set state
  - Shared with Java PathFinder (v.2)[Visser et al. 00]
  - Principle inspired from OPEN/CAESAR[Garavel 98]
- Search engine fixes exploration strategy
  - Depth-First
  - Breadth-First
  - **Heuristic**
  - Others are possible (random, pattern-based, interactive)
- + Halting conditions (for any strategy)
  - Find first / all / shortest error trace(s)



LPF Heuristic Search

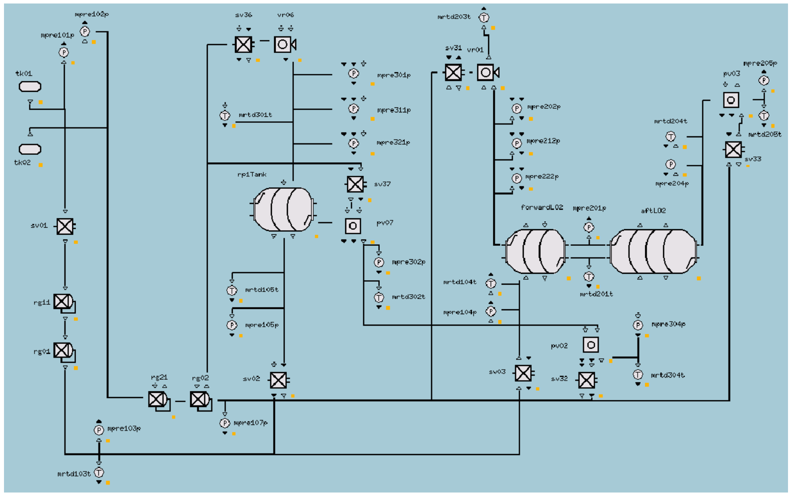
- Based on valuation function (heuristic) on states
- Greedy best-first search (priority queue)
- Current heuristic: **candidate-count**
  - number of diagnosis candidates
  - Less is better
  - Progress towards absence of valid candidate

Other Heuristics?

- Structural coverage
  - model states, faults, fault pairs, ...
  - or scenario events, ...
  - function on traces (or extended states) rather than states
- Ranks (probabilities)
  - of actual (simulator) states or estimated (candidates)
  - higher or lower probability best
    - ... except for nominal transitions
- To probe further...

Application: PITEX

- Propulsion feed system of space vehicle
- Livingstone model: 2300 lines, 823 vars, ≈10^{33} states (SMV)
- Two scenarios:
  - Random Scenario (10216 states): sequence of commands || choice of faults
  - PITEX Scenario (89 states): combines 29 test cases used by application team



LPF on PITEX: Results

scenario	strategy	search	condition	errors	non-trivial	states	states/min
baseline	DFS	all	CM	27	4	89	44
baseline	DFS	all	CS	0	0	89	67
random	DFS	all	CM	9621	137	10216	51
random	DFS	all	CS	5	5	10216	52

scenario	strategy	search	condition	max. depth	states	states/min
random	DFS	one	CS	16	8648	49
random	BFS	one	CS	3	154	38
random	CC	one	CS	5	154	38

DFS=depth-first, BFS=breadth-first, CC=candidate-count
all=all errors, one=first error, min=shortest trace
CM=candidate matching, CS=candidate subsumption

trivial error=no fault reported

Perspectives

- Extend search options
  - More heuristics (including application-specific)
  - New search strategies (randomized, coverage-based)
- Improve usability
  - GUI, post-process and display results
- Generalize to reactive control
  - From fault detection to fault recovery
  - Uncompleted: adapt LPF to Titan (MIT)
- Other approach: apply SMV (and BMC) to Livingstone models, verify diagnosability[Cimatti et al. 03]
  - using Livingstone-to-SMV translator[Pecheur et al. 00]

Extra Slides

Verification of Diagnosis systems

Verify what?

1. Model Correctness: the model is OK
   i.e. the model is a valid abstraction of the process
2. Engine Correctness: the software is OK
   i.e. all that can be diagnosed is correctly diagnosed
3. **Diagnosability: the design is OK**
   i.e. all that needs to be diagnosed can be diagnosed

In principle, 1+2+3 => diagnosis will be correct

Here we look at 3 only!

PITEX Scenarios

```
mix {
  "command test.sv02.valveCmdIn=close";
  "command test.sv02.valveCmdIn=open";
  ...
} and {
  choose
    "fault test.forwardLO2.mode=unknownFault"; or
    "fault test.mpre101p.mode=faulty"; or
    ...
}
```

```
{
  choose { "fault test.mpre202p.mode=biased"; }
  or { "fault test.mpre212p.mode=biased"; }
  or {
    "command test.sv31.valveCmdIn=open";
    choose {
      "fault test.sv31.sv.mode=stuckOpen";
      "command test.sv31.valveCmdIn=close";
    } or {
      "command test.sv31.valveCmdIn=close";
       ...
} } }
```