Symbolic Model Checking of Domain Models for Autonomous Spacecrafts

Vérification symbolique

Raisonnement sur modèles
Intelligence artificielle

Autonomie
Logiciel spatial

Charles Pecheur (RIACS / NASA Ames)

Introduction

Past:

Time-stamped control sequences

Future:

On-board intelligence

\+ Can respond to unanticipated scenarios!

– How do we verify all those scenarios?

Outline

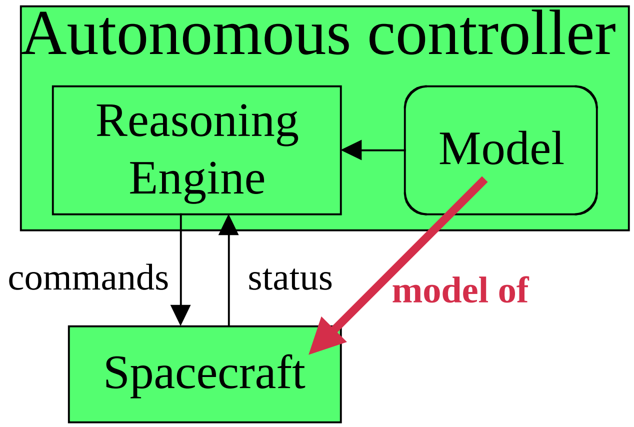
- Model-Based Autonomy and Livingstone
- Symbolic Model Checking and SMV
- Verification of Livingstone Models

Model-Based Autonomy

Goal: "intelligent" autonomous spacecrafts

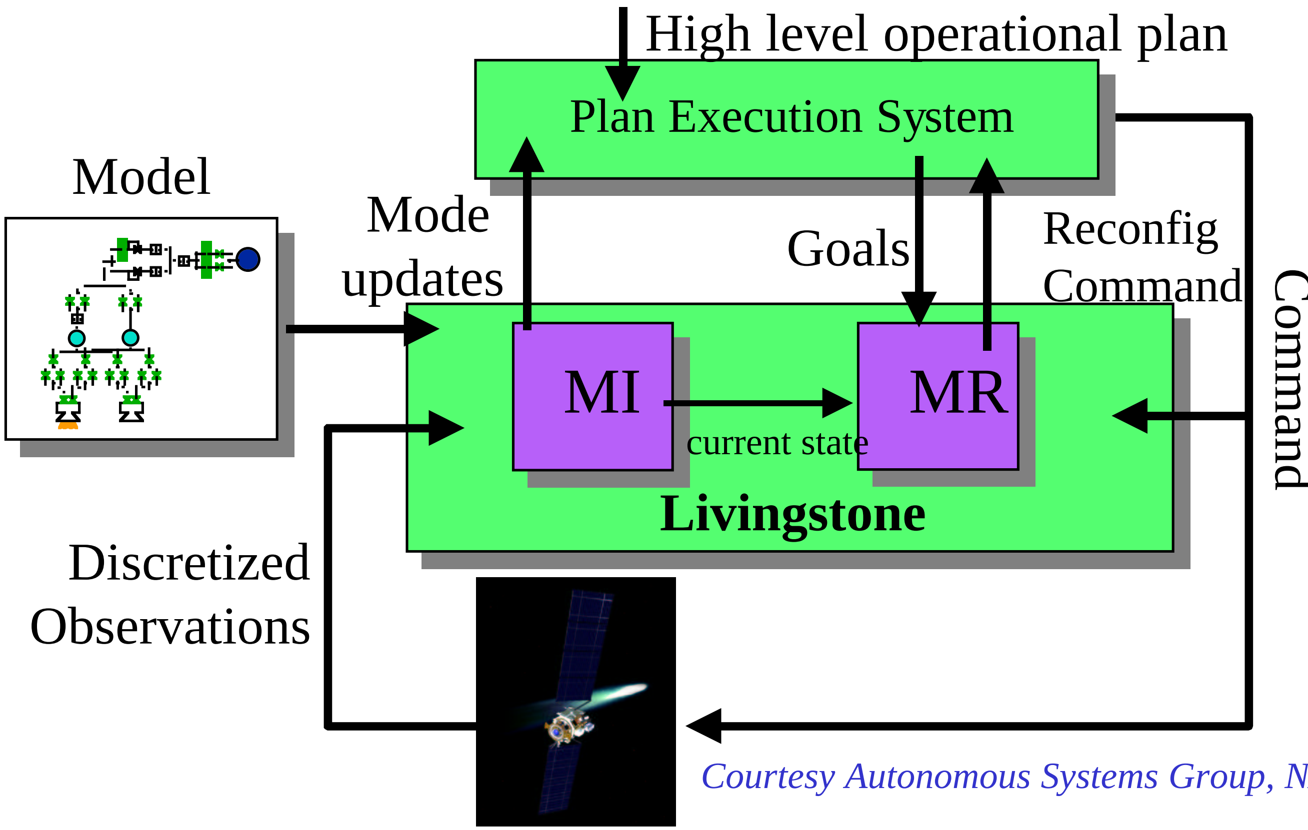
- cheaper (smaller ground control)
- more capable (delays, blackouts)

- General reasoning engine + application-specific model
- Use model to respond to unanticipated situations
- For planning, diagnosis
- **Huge state space, reliability is critical**



Livingstone

Remote Agent's model-based diagnosis sub-system



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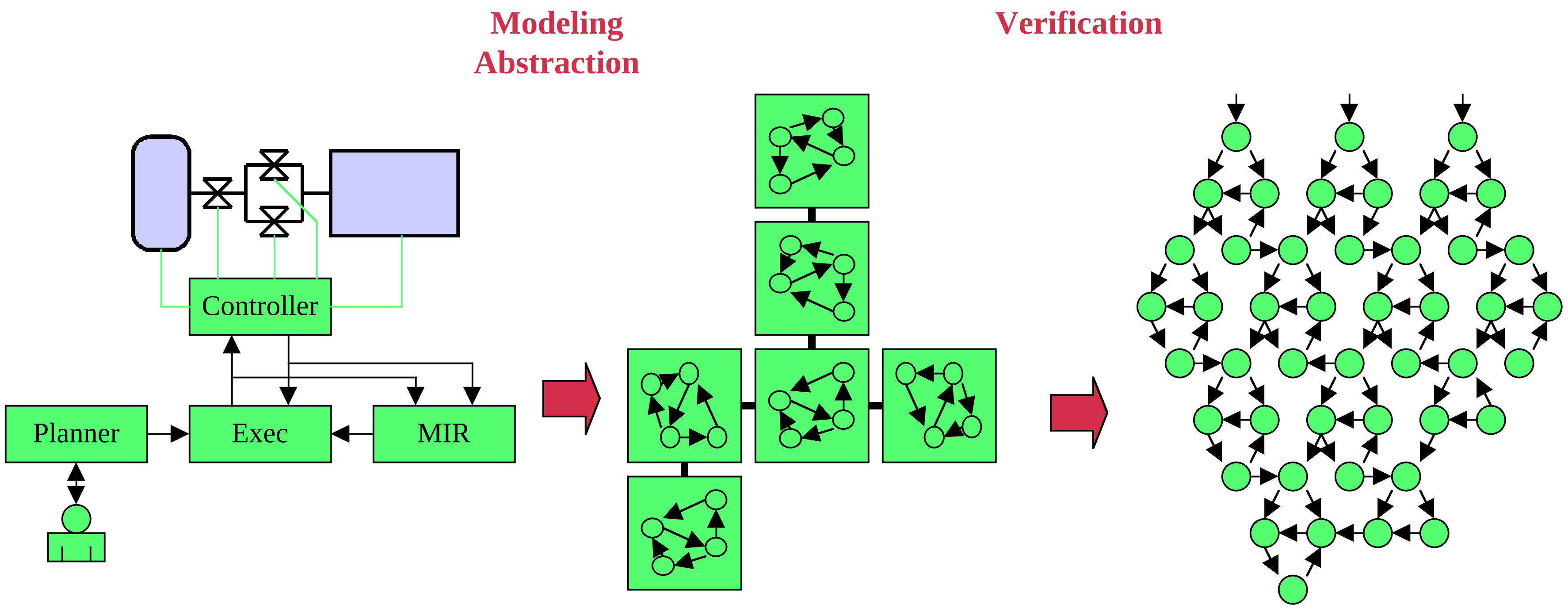
Outline

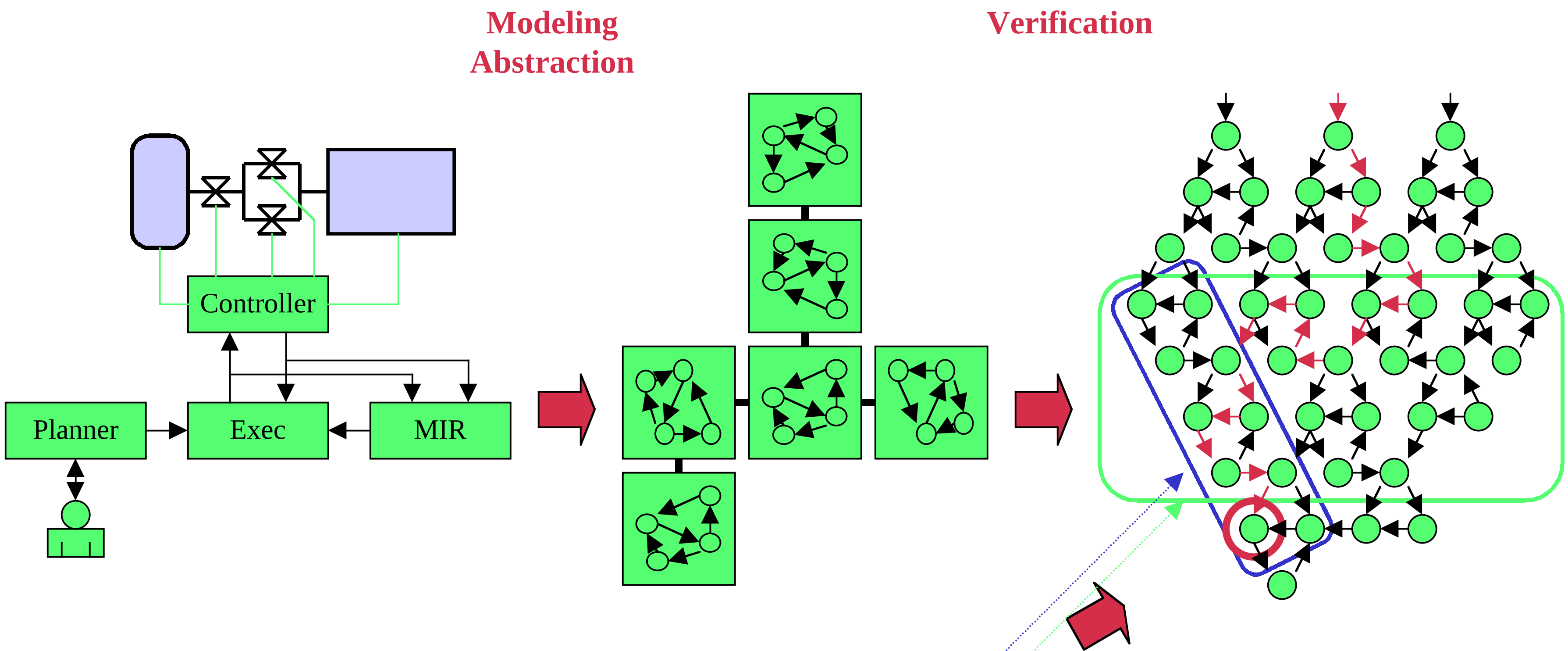
- Model-Based Autonomy and Livingstone
- Symbolic Model Checking and SMV
- Verification of Livingstone Models

Model ...



Modeling
Abstraction
Verification
Controller
Planner
Exec
MIR

Model Checking

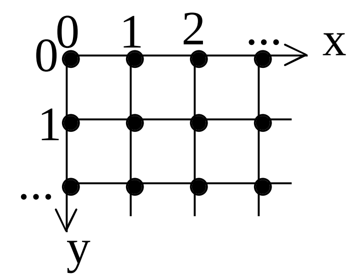


"Valve is closed when
Tank is empty"

AG (tank=empty
=> valve=closed)

Symbolic Model Checking

Instead of considering each individual state,
Symbolic model checking...

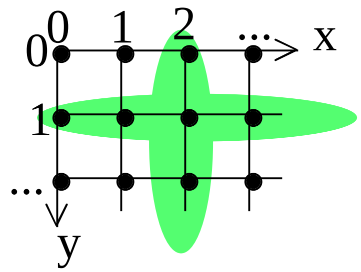


Symbolic Model Checking

Instead of considering each individual state,

Symbolic model checking...

- Manipulates sets of states,

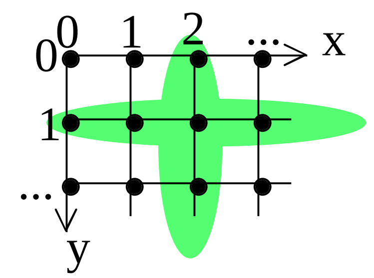


Symbolic Model Checking

Instead of considering each individual state,

Symbolic model checking...

- Manipulates sets of states,
- Represented as boolean formulas,



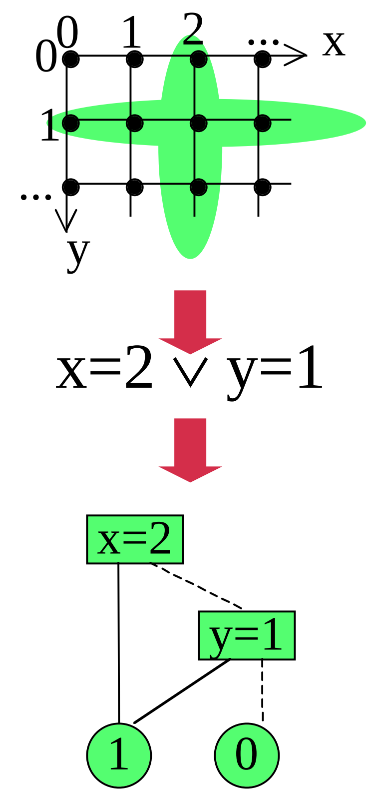
$x=2 \vee y=1$

Symbolic Model Checking

Instead of considering each individual state,

Symbolic model checking...

- Manipulates sets of states,
- Represented as boolean formulas,
- Encoded as binary decision diagrams.

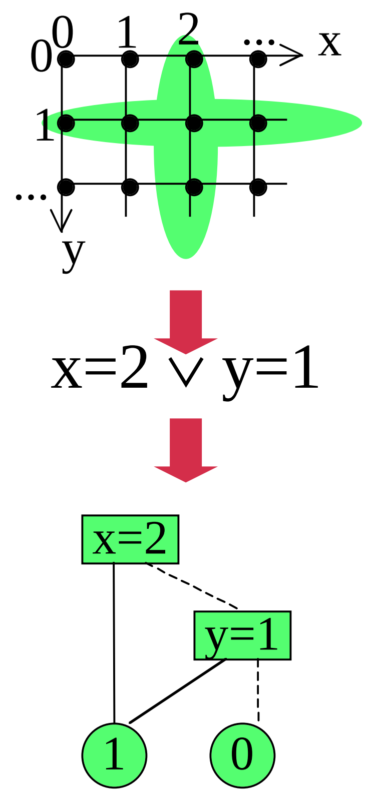


Symbolic Model Checking

Instead of considering each individual state,

Symbolic model checking...

- Manipulates sets of states,
  - Can handle very large state spaces (10^{50} +)
- Represented as boolean formulas,
  - Suited for boolean/abstract models
- Encoded as binary decision diagrams.
  - The limit is BDD size (hard to control)



Boolean Functions

- Represent a state as boolean variables

$$s = b_1, \ldots, b_n$$

Non-boolean variables => use boolean encoding

- A set of states as a boolean function

$$s \text{ in } S \;\text{ iff }\; f(b_1, \ldots, b_n) = 1$$

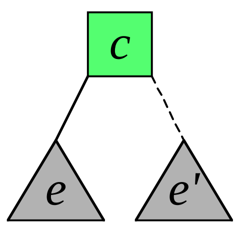
- A transition relation as a boolean function over two states

$$s \rightarrow s' \;\text{ iff }\; f(b_1, \ldots, b_n, b'_1, \ldots, b'_n) = 1$$

Binary Decision Trees

- Encoding for boolean functions

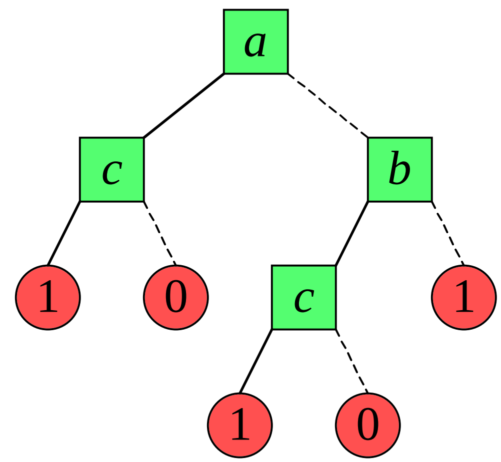
- Notational convention:



= **if** c **then** e **else** e'

= $(c\ ?\ e : e')$

- Always exists
  but not unique

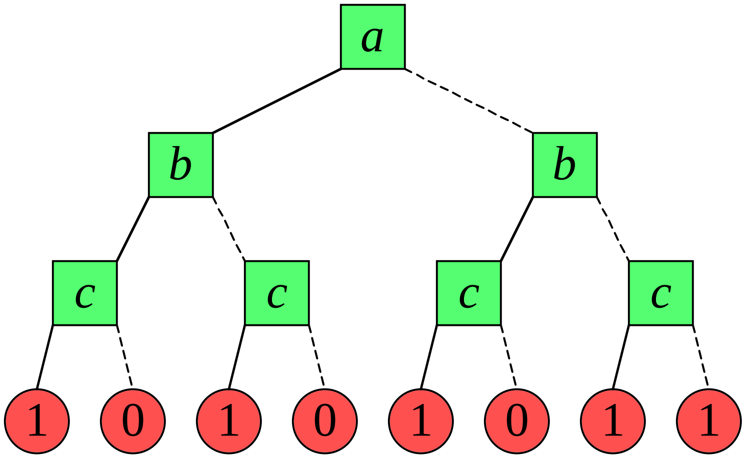


$(a \mid b) \Rightarrow c$

From Trees to Diagrams

- Fixed variable ordering

  "layered" tree



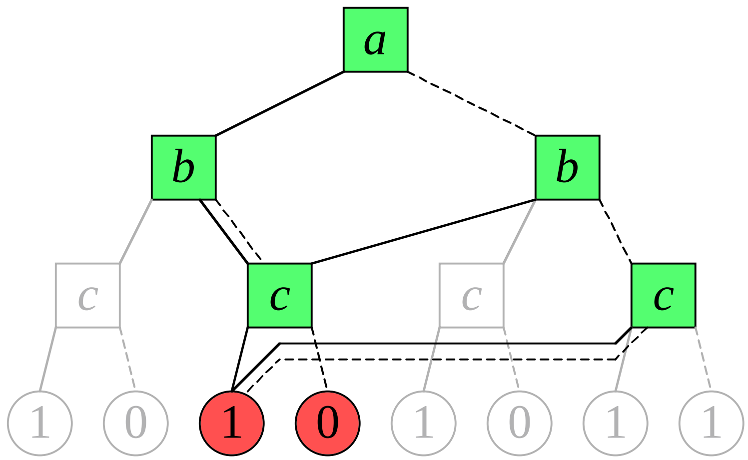
$(a \mid b) \Rightarrow c$

From Trees to Diagrams

- Fixed variable ordering

  "layered" tree

- Merge equal subtrees



$(a \mid b) \Rightarrow c$

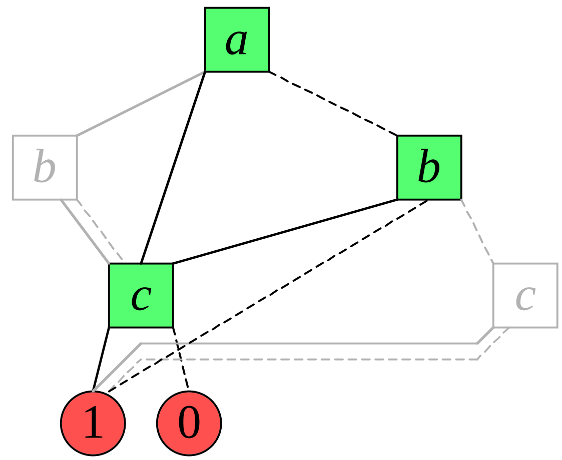
From Trees to Diagrams

- Fixed variable ordering

  "layered" tree

- Merge equal subtrees

- Remove nodes with equal subtrees



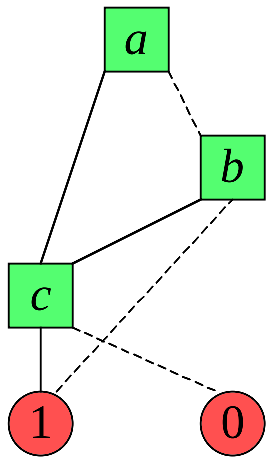
$(a \mid b) \Rightarrow c$

=> Ordered Binary Decision Diagram

[Ordered] Binary Decision Diagrams

- [O]BDDS for short
- Unique normal form
  - for a given ordering and
  - up to isomorphism

  => compare in constant time (using hash table)



$(a \mid b) \Rightarrow c$

Computations with BDDs

- All needed operations can be efficiently computed using BDDS
- Example: boolean combinator $f\&g$:

  $(b\ ?\ f' : f'')\ \&\ (b\ ?\ g' : g'') = (b\ ?\ f'\&g' : f''\&g'')$

  cache results –> O($|f|.|g|$) time
- Other operations:
  - Negation $!f$
  - Instantiation $f[b=1]$, $f[b=0]$
  - Quantifiers **exists** b . f, **forall** b . f

Transition Systems with BDDs

Given boolean state variables $v = b_1, \ldots, b_n$

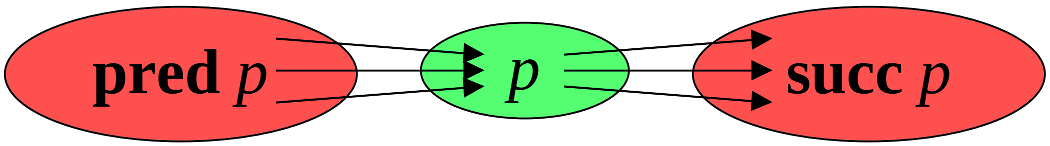
a set of states as a BDD $p(v)$

a transition relation as a BDD $T(v, v')$

we can compute the predecessors and successors of p as BDDs:

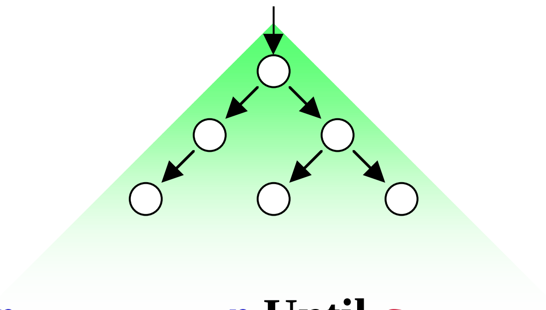
$(\mathbf{pred}\ p)(v) = \mathbf{exists}\ v' \,.\, T(v, v')\ \&\ p(v')$

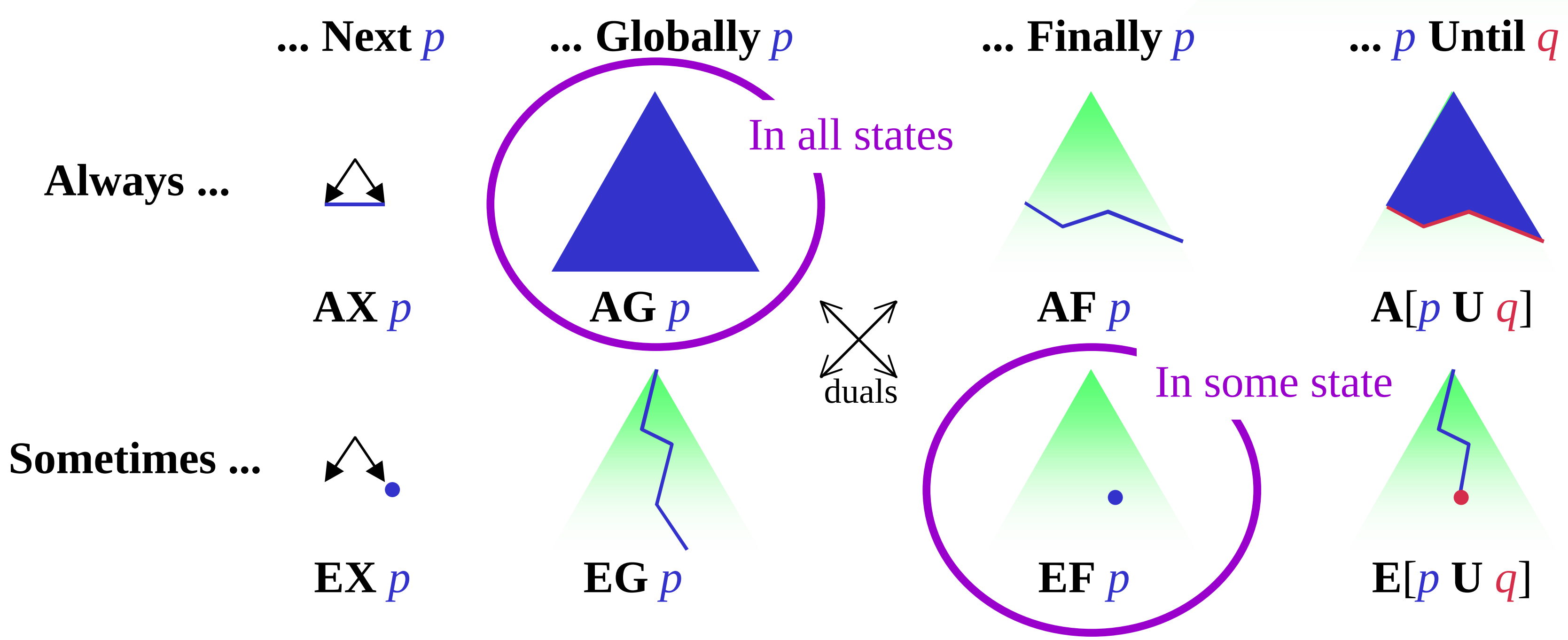
$(\mathbf{succ}\ p)(v) = \mathbf{exists}\ v' \,.\, p(v')\ \&\ T(v', v)$



CTL temporal logic

Computation Tree Logic (branching):
Consider the tree of possible executions





Evaluating CTL with BDDS

Example: compute **EF** p from p with BDDs:

EF p = **lfp** U . (p | **EX** U)

= least solution of $U = p$ | **EX** U

$U_0 = 0$

$U_1 = p$ | **EX** $U_0 = p$

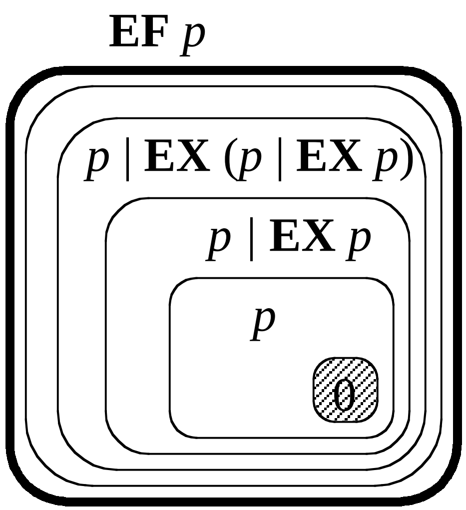
…

$U_{n+1} = p$ | **EX** $U_n = p$ | **EX** p | … | **EX**^{n} p

until $U_n = U_{n+1} =$ **EF** p

– Convergence assured because finite domain

– Backward search from p to **EF** p



Variable Ordering

- Must be the same for all BDDs
- Size of BDDs depends critically on ordering
- Worst case: exponential w.r.t. #variables
  - sometimes exponential for any ordering
    e.g. middle output bit of n-bit multiplier
- Finding optimum is hard (NP-complete)
  => optimization uses heuristics

SMV

- **SMV** = **S**ymbolic **M**odel **V**erifier.
- Modeling language based on parallel assignments.
- Specifications in temporal logic CTL.
- BDD-based symbolic model checking.
- Several versions:
  - (CMU) SMV: original work by McMillan (Carnegie Mellon)
  - NuSMV: clean re-writing, faster (ITC-IRST and CMU)
  - Cadence SMV: following McMillan (Cadence Berkeley Labs)

What SMV Does

mutex.smv

Model

```
MODULE user(...) ...

MODULE main
VAR turn: {1, 2};
    user1: user(...);
...
```

```
SPEC AG !(
    (user1.state = c) &
    (user2.state = c))
```

Specification

smv mutex.smv

<stdout>

```
-- specification AG ...
   is false
-- as demonstrated by ...
state 1.1:
turn = 1
user1.state = n
user2.state = n

state 1.2:
...
```

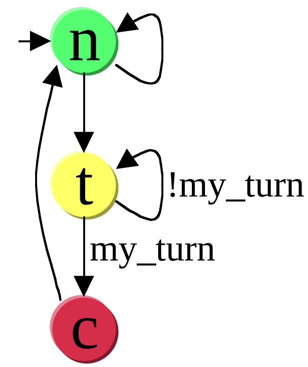
Counter-example

```
resources used: ...
```

SMV Program Example (1/2)

```
MODULE user(turn,id,other)
VAR state: {n, t, c};
DEFINE my_turn :=
   (other=n) | ((other=t) & (turn=id));
ASSIGN
init(state) := n;
next(state) := case
   (state = n) : {n, t};
   (state = t) & my_turn: c;
   (state = c) : n;
   1 : state;
esac;

SPEC AG((state = t) -> AF (state = c))
```



SMV Program Example (2/2)

```
MODULE main
VAR turn: {1, 2};
    user1: user(turn, 1, user2.state);
    user2: user(turn, 2, user1.state);
ASSIGN
init(turn) := 1;
next(turn) := case
   (user1.state=n) & (user2.state=t): 2;
   (user2.state=n) & (user1.state=t): 1;
   1: turn;
esac;

SPEC AG !((user1.state=c) & (user2.state=c))
SPEC AG !(user1.state=c)     -- false!
```

Diagnostic Trace Example

```
-- specification AG (state = t -> AF state = c) (in module
   user1) is true
-- specification AG (state = t -> AF state = c) (in module
   user2) is true
-- specification AG (!(user1.state = c & user2.state = c)...
   is true
-- specification AG (!user1.state = c) is false
-- as demonstrated by the following execution sequence
state 1.1:
turn = 1
user1.state = n
user2.state = n

state 1.2:
user1.state = t

state 1.3:
user1.state = c
```

The Essence of SMV

- The SMV program defines:
  - a finite transition model M (Kripke structure),
  - a set of possible initial states I (may be several),
  - specifications P_1 .. P_m (CTL formulas).
- SMV checks that each specification P is satisfied in all initial states s_o of model M.

$$\forall s_o \in I \ . \ M, s_o \models P$$

Outline

- Model-Based Autonomy and Livingstone
- Symbolic Model Checking and SMV
- Verification of Livingstone Models

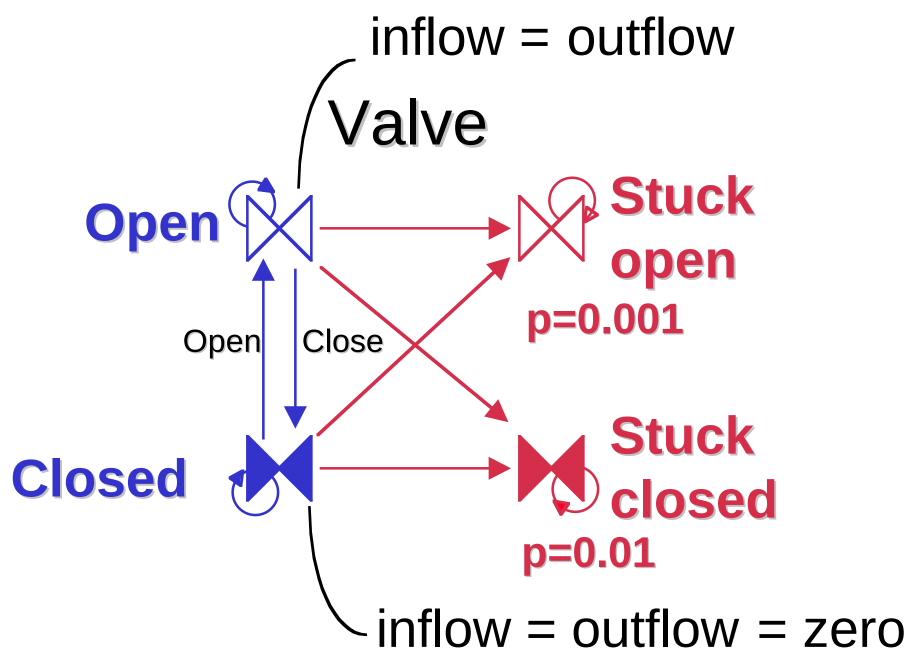
Livingstone Models

inflow, outflow : {zero,low,high}

- concurrent transition systems (components)
- synchronous product
- enumerated types => finite state

Essentially ≈ SMV model

\+ nominal/fault modes, commands/monitors (I/O), probabilities on faults, ...



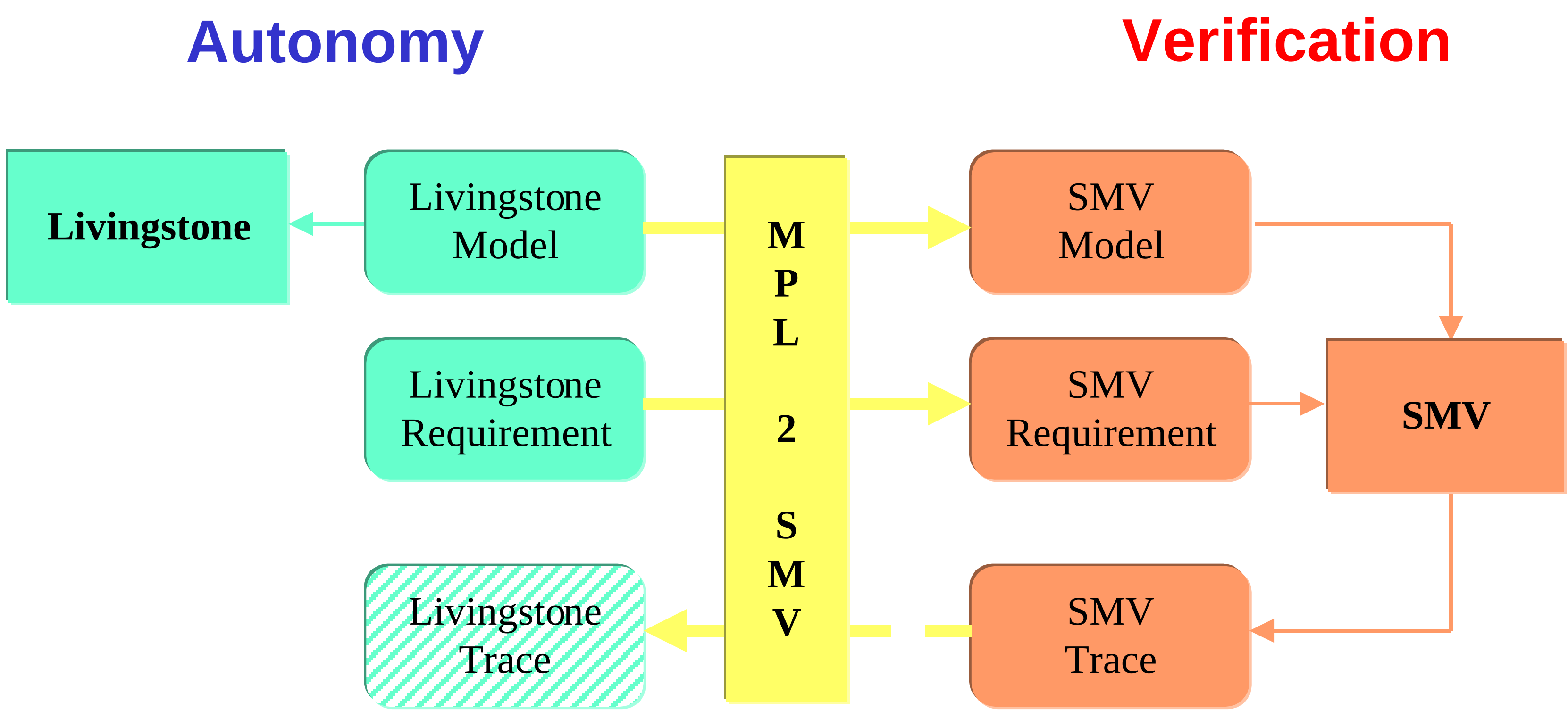
Courtesy Autonomous Systems Group, NASA Ames

Diagnosis = find the most likely assumptions (modes) that are consistent with the observations (commands/monitors)

Large State Space?

- Example: model of ISPP = $7.16 \cdot 10^{55}$ states
- This is only the Livingstone model – a complete verification model could be
  - Exec driver (10-100 states)
  - x Spacecraft simulator (10^{55} states)
  - x Livingstone system (keeps history – $10^{n \cdot 55}$ states)
- Verify a system that analyzes a large state space!
- Approach: the model is the program
  - – Verify it (using symbolic model checking)
  - – Assume Livingstone correct (and complete)

MPL2SMV


Autonomy
Verification
Livingstone
Livingstone Model
Livingstone Requirement
Livingstone Trace
MPL2SMV
SMV Model
SMV Requirement
SMV Trace
SMV

Translator from Livingstone to SMV

- Co-developed with CMU (Reid Simmons)
- Similar semantics => translation is easy
- Properties in temporal logic + pre-defined patterns
- Initially for Livingstone 1 (Lisp),
  upgraded to Livingstone 2 (C++/Java)

Principle of Operations

Lisp shell

```
(load "mpl2smv.lisp")
;; load the translator
;; Livingstone not needed!

(translate "ispp.lisp" "ispp.smv")
;; do the translation

(smv "ispp.smv")
;; call SMV
;; (as a sub-process)
```

ispp.lisp

```
(defcomponent  heater …)
(defmodule valve-mod …)
…
(defverify
  :structure (ispp)
  :specification (all (globally …)))
```

ispp.smv

```
MODULE Mheater …
MODULE Mvalve-mod …
…
MODULE main
VAR Xispp:Mispp
SPEC AG …
```

SMV output

```
Specification AG … is false as shown …
State 1.1: …
State 1.2: …
```

Simple Properties

- Supported by the translator:
  - syntax sugar
  - iterate over model elements (e.g. all component modes)
- Examples
  - Reachability (no dead code)

    EF heater.mode = on

  - Path Reachability (scenario)

    AG (s1 –> EF (s2 & EF (s3 & EF s4)))

Probabilistic Properties

- Use probabilities associated to failure transitions
- Use order of magnitude: -log(p), rounded to a small integer
- Combine additively, OK for BDD computations
- Approximate – but so are the proba. values

```
heater.mode = overheat -> heater.proba = 2;      (p = 0.01)
proba = heater.proba + valve.proba + sensor.proba;
SPEC AG (broken  &  proba < 3  –>  EF working)
```

Functional Dependency

- Check that y=f(x) for some unknown f
- Use universally quantified variables in CTL
  = undetermined constants in SMV

```
VAR x0,y0 : {a,b,c};
TRANS next(x0) = x0
TRANS next(y0) = y0
SPEC (EF x=x0 & y=y0) –> (AG x=x0 –> y=y0)
```

$\approx \forall$ x0, y0

- Limitation: counter-example needs two traces, SMV gives only one
  => instantiate second half by hand, re-run SMV

Temporal Queries

- Temporal Query = CTL formula with a hole:

  AG (**?** –> EF working)

- Search (canonical) condition for ? that satisfies the formula (computable for useful classes of queries)
- Recent research, interrupted (William Chan, †1999)
- Problem: visualize solutions (CNF, projections, ...)
- Core algorithm implemented in NuSMV (Wolfgang Heinle)
- Deceptive initial results, to probe further

SMV with Macro Expansion

- Custom version of SMV (Bwolen Yang, CAV 99)
- Eliminates variables by Macro Expansion:
  - analyzes static constraints of the model (invariants),
  - find dependent variables x=f(x1,...,xn),
  - substitute f(x1,...,xn) for x everywhere,
  - eliminate x from the set of BDD variables.
- For models with lots of invariants
  => useful for Livingstone models
- Full ISPP model in < 1 min, vs. SMV runs out of memory.

Ames Research Center

ISPP Model Statistics

- In Situ Propellant Production (ISPP)
  = turn Mars atmosphere into rocket fuel (NASA KSC)
- Original model state = 530 bits (trans. = 1060 bits)
- Total BDD vars 588 bits
  Macro expanded -209 bits
  Reduced BDD vars 379 bits

Total BDD vars	588 bits	
Macro expanded	-209 bits	
Reduced BDD vars	379 bits	

- Reachable state space $7.16 \cdot 10^{55} = 2^{185.5}$
  Total state space $1.06 \cdot 10^{81} = 2^{269.16}$
- Reachability of all modes (163):
  29.14" CPU time in 63.6 Mb RAM

Diagnosis Properties

- Can fault F always be diagnosed?
(assuming perfect diagnosis and accurate model)
= is F unambiguously observable?

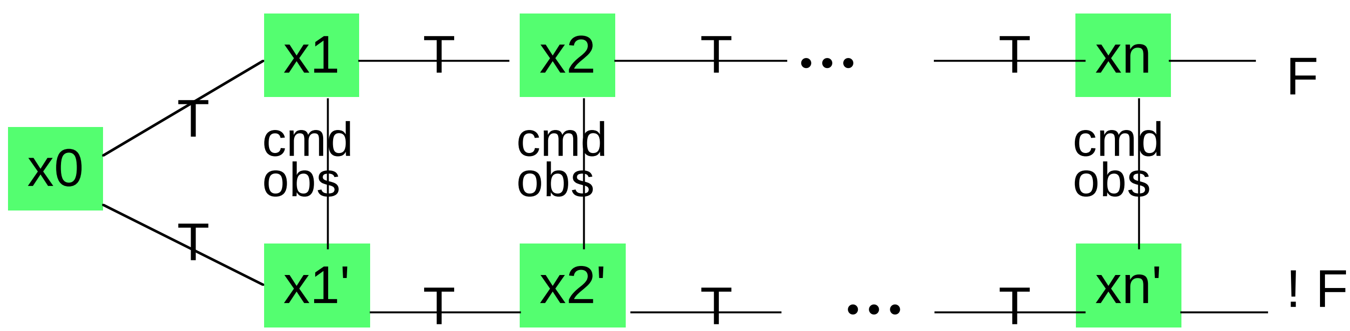
  ∀ obs0 . (EF F & obs=obs0) –> (AG F –> obs=obs0)

- Similar to functional dependency
- obs = observable variables (many of them)
- Static variant (ignore transitions):
SAT on two states S, S' such that

  F & ! F' & obs=obs'

Diagnosis Properties Revisited

- Very recent (yesterday), with Alessandro Cimatti
- Can fault F be diagnosed knowing the last n steps?
- Apply SAT to:



- Variants are possible (e.g. fork at n-1 intead of 0)

Diagnosis Properties (cont'd)

- Does it work?
  - Computational cost of extra variables
- Has it been done?
  - Similar work in hardware testability?
- Is it useful?
  - It is unrealistic to expect all faults to be immediately observable (e.g. valve closed vs. stuck-closed)
  - What weaker properties? Are they verifiable?
- To be explored

Summary

- Verification of model-based diagnosis:
  - Space flight => safety critical.
  - Huge state space (w.r.t. fixed command sequence).
- Focus on models (the model is the program)
- Quite different from executable programs
  - Loose coupling, no threads of control, passive.
  - Huge but shallow state spaces.
- <u>Symbolic</u> model checking is very appropriate
- Verify well-formedness + validity w.r.t. hardware
- Verify suitability for diagnosis: to be explored

Thank You

Symbolic Model Checking References

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The seminal paper on Binary Decision Diagrams.

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SMV
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