The Versatile Synchronous Observer

John Rushby

Computer Science Laboratory
SRI International
Menlo Park CA USA

Model Checking

- It's called model checking because we check
  - Whether our system (or program or design), represented as a state machine
  - Is a Kripke model of
  - Our specification, represented as a temporal logic formula
- Typically, the specification is translated into a state machine
- And composed with the system state machine
- And we try to prove that all reachable states satisfy the specification, or we exhibit a counterexample
- Automated by explicit state (exhaustive simulation, e.g., SPIN), symbolic finite state methods (BDDs, or BMC and k-induction with SAT, e.g., NuSMV), or symbolic infinite state methods (BMC and k-induction with SMT, e.g., SAL)
- Nowadays, model checking means any fully automated FM

Safety and Liveness

- If the specification is a liveness/eventuality property (typically, one involving the **F** or $\Diamond$ modalities)
- Then it will be translated to a Büchi automaton, and the checker will apply special acceptance rules
  - Must reach a goal state infinitely often
- But for safety properties, it is just a regular automaton, i.e., state machine
- In practice, we only care about safety properties
  - Note that bounded liveness is a safety property

Synchronous Observers

- For safety properties, instead of writing the specification as a temporal logic formula and translating it to a state machine
- We could just write the specification directly as a state machine
- Specifically, a state machine that is synchronously composed with the system state machine
- And that observes its state variables
- And signals an alarm if the intended behavior is violated, or ok if it is not (these are duals)
- This is called a synchronous observer
- Then we check that alarm or NOT ok are unreachable

Example (in SAL)

```
observer: MODULE =
BEGIN
  INPUT
    <state variables>
  OUTPUT
    ok: BOOLEAN
  INITIALIZATION
    ok = TRUE
  TRANSITION
  [
    <property> --> ok' = TRUE
  []
    ELSE --> ok' = FALSE
  ]
END;
```

```
check: FORMULA (system || observer) |- G(ok)
```

```
check_alt: FORMULA (system || observer) |- G(NOT alarm)
```

Origins

- Both the concept and the term synchronous observer were introduced in the context of the synchronous languages developed in France
- In particular, by the Lesar model checker for the language Lustre
- Synchronous observers used to specify
  - Properties
  - Assumptions

Benefits

- We only have to learn one language
  - The state machine language
- Instead of two
  - State machine plus temporal logic specification language
- And only one way of thinking

The Versatility of Synchronous Observers

- There are several other uses for synchronous observers
- I'll describe four, there are probably more
  1. Increased expressivity
  2. Specifying/discovering constraints/assumptions
  3. And axioms
  4. Test generation

Expressivity

- This is about ease of specifying the state machine
- For specifying properties, synchronous observers and temporal logics are more or less equivalent (see paper)
- Modern industrial languages, such as
    - Accellera/IEEE Property Specification Language (PSL)
    - SystemVerilog Assertions (SVA)

  Extend LTL with regular expressions and thereby provide ways to encode synchronous observers in the property specification

Increased Expressivity via Synchronous Observers (1)

- Typical state machine language allows new values of variable to be defined in terms of the old (notation here is SAL)
  - e.g., `x' = x + y`
    or `x' IN {a: nat | a >= 25 AND a <= 50}`
- What if we want to specify that the new value of `x` is simply larger than the old?
- Some languages allow for this in nondeterministic assignments
  - e.g., `x' IN {a: nat | a > x}`
- And some by allowing new values to appear in guards
  - e.g., `(x' > x) --> x' IN {a: nat | TRUE}`
- But one method that always works is to specify it using a synchronous observer. . .

Increased Expressivity via Synchronous Observers (2)

- First, in main system, make an unconstrained assignment to `x`
  - `x' IN {a: nat | TRUE}`

- Then, in a synchronous observer for constraints, we enforce the desired relation (using `aok` as our flag variable)
  - `NOT (x' > x) --> aok' = FALSE`

  (if new variables not allowed in guards, then we will need to introduce history variables and be careful about off-by-one)

- Then we model check for whatever property `p` we had in mind, only in cases where `aok` is `TRUE`
  - `check: FORMULA (system || constraints) |- G(aok => p)`, or
  - `check: FORMULA (system || observer || constraints) |- G(aok => ok)`

Increased Expressivity via Synchronous Observers (3)

- This method is particularly useful when need to update multiple variables in a way that enforces a relation on them
  - e.g., $x^2 + y^2 \leq 1$
- Often have multiple constraints that are conjoined
- But guards are disjoined
- So we use De Morgan's rule and disjoin the negations
- Application: relational abstraction for hybrid automata
  - Due to Sankaranarayanan and Tiwari (there's a SAL tool)
  - Keeps same state space as the hybrid automata but replaces differential equations by overapproximate relations
  - E.g., instead of a differential equation relating aircraft pitch angle and rate of climb, we simply say that if pitch angle is positive, than altitude increases

Fragment of Constraints from FMIS 2011 Example

```
INITIALIZATION
   ok = TRUE;
TRANSITION
[  actual_mode = op_des AND pitch > 0 --> ok' = FALSE;
[] actual_mode = op_clb AND pitch < 0 --> ok' = FALSE;
[] actual_mode = vs_fpa AND fcu_fpa <= 0 AND pitch > 0
    --> ok' = FALSE;
[] actual_mode = vs_fpa AND fcu_fpa >= 0 AND pitch < 0
    --> ok' = FALSE;
[] pitch > 0 AND altitude' < altitude --> ok' = FALSE;
[] pitch < 0 AND altitude' > altitude --> ok' = FALSE;
[] pitch=0 AND altitude' /= altitude --> ok' = FALSE;
[] ELSE -->
] END;
```

Synchronous Observers for Assumptions

- Most properties are not expected to be true unconditionally
- They are expected to be true only in environments that satisfy certain assumptions
- Assumptions should generally be stated as constraints, not by specifying an ideal environment
  - Our job is to specify the environment, not implement it
- So the method just described for constraints can be applied to assumptions
  - `NOT` $\texttt{assumption}_i$ `--> aok' = FALSE`

Synchronous Observers for Axioms (1)

- One of the disadvantages of model checking compared to theorem proving in a system like PVS is that model checking requires us to be too explicit
  - For most model checking technologies, the system has to be a (possibly nondeterministic) implementation
- Suppose we want to examine the bypass logic of a CPU pipeline; typically want to prove the sequence of values out of the pipelined implementation is same as nonpipelined one
- There's an ALU at end of the pipeline; we don't care what fn's it computes, just that at step i it does some f_i`(a, b)`
- But to model check, must put a specific circuit there
  - e.g., an adder: and some bugs may then go undetected because of the special properties of that implementation (e.g., commutativity, associativity)

Synchronous Observers for Axioms (2)

- SMT: solvers for Satisfiability Modulo Theories
- Roughly, these combine decision procedures for useful theories like equality with uninterpreted functions, linear arithmetic on integers and reals, arrays, and several others
  - These work on conjunctions of formulas
- With SAT solvers
  - These handle propositionally complex formulas
- The combination uses an abstraction/refinement/learning loop, plus a lot of engineering
- SMT brings effective automation to many formal methods
- In particular, SMT solvers can be used for model checking via BMC and k-induction
  - Here, model checking is used to mean fully automatic
- This technology is called infinite bounded model checking or infBMC ('cos some of the theories are over infinite models)

Synchronous Observers for Axioms (3)

- The reason theorem provers are more attractive than model checkers for these kinds of situation is that they allow use of uninterpreted functions: $f(x)$ where we know nothing about f

- Can constrain f by adding axioms
  - e.g., `x > y => f(x) > f(y)`

- SMT solvers decide this theory

- So now we can model check over specifications that use uninterpreted functions etc.

Synchronous Observers for Axioms (4)

- But how do we convey the axioms about our uninterpreted functions to the SMT solver underlying our infBMC?
- Synchronous observers!
- As before, just check for violations of the axioms
  - `NOT axiom`$_i$ `--> aok' = FALSE`
  - e.g., `x > y AND NOT (f(x) > f(y)) --> aok' = FALSE`
- Whew!
- That was a lot of setup to get to a simple conclusion
- Let's extract more from the same setup

Discovering Assumptions with Synchronous Observers

- In civil aircraft, all accidents and incidents caused by software are due to flaws in the system requirements specification or to gaps between this and the software specification
  - i.e., none are due to coding errors
- Modern system requirements specifications look a lot like software: lots of case analysis
- But are very abstract (box and arrow diagrams)
- There's no accepted technology for analyzing these
- But infBMC can do it
- Use uninterpreted functions for the boxes and arrows
- Incrementally add constraints/axioms to a synchronous observer
- Until the desired properties are satisfied

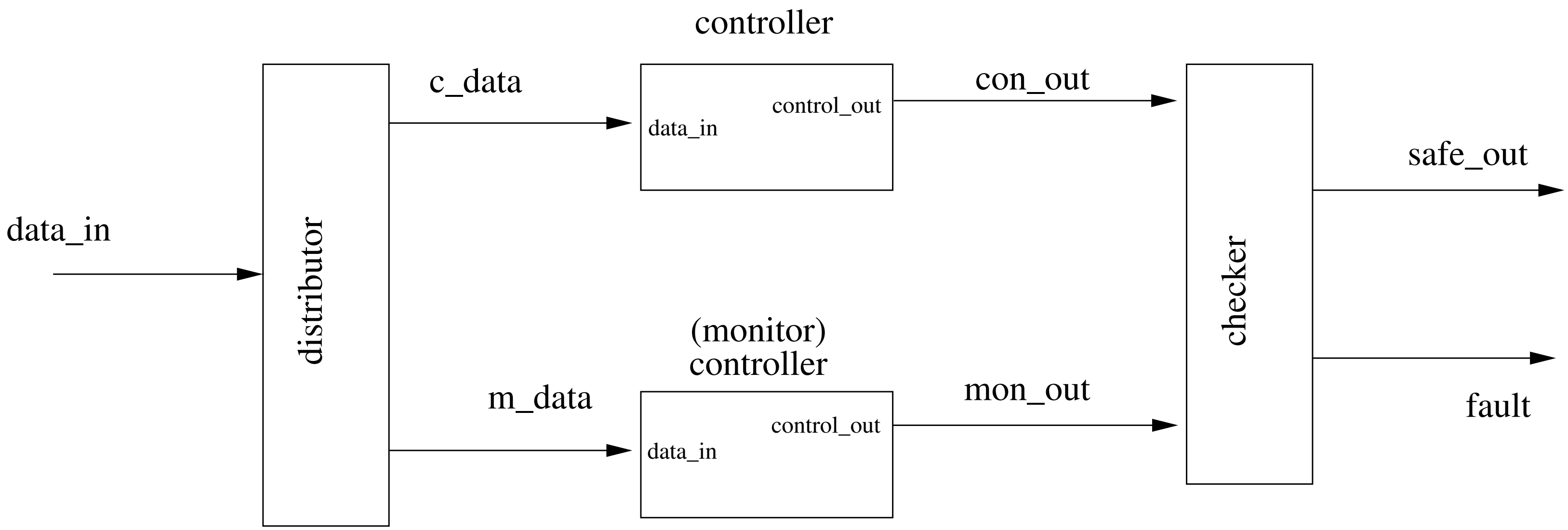
Example: Protecting Against Random Faults

- Components that fail by stopping cleanly are fairly easy to deal with
- The danger is components that do the wrong thing
- We have to eliminate design faults by analysis, but we still have to worry about random faults
    - e.g., when an α-particle flips a bit in instruction counter
- Our goal here is to design a component that fails cleanly in the presence of random faults

Example: Self-Checking Pair (1)

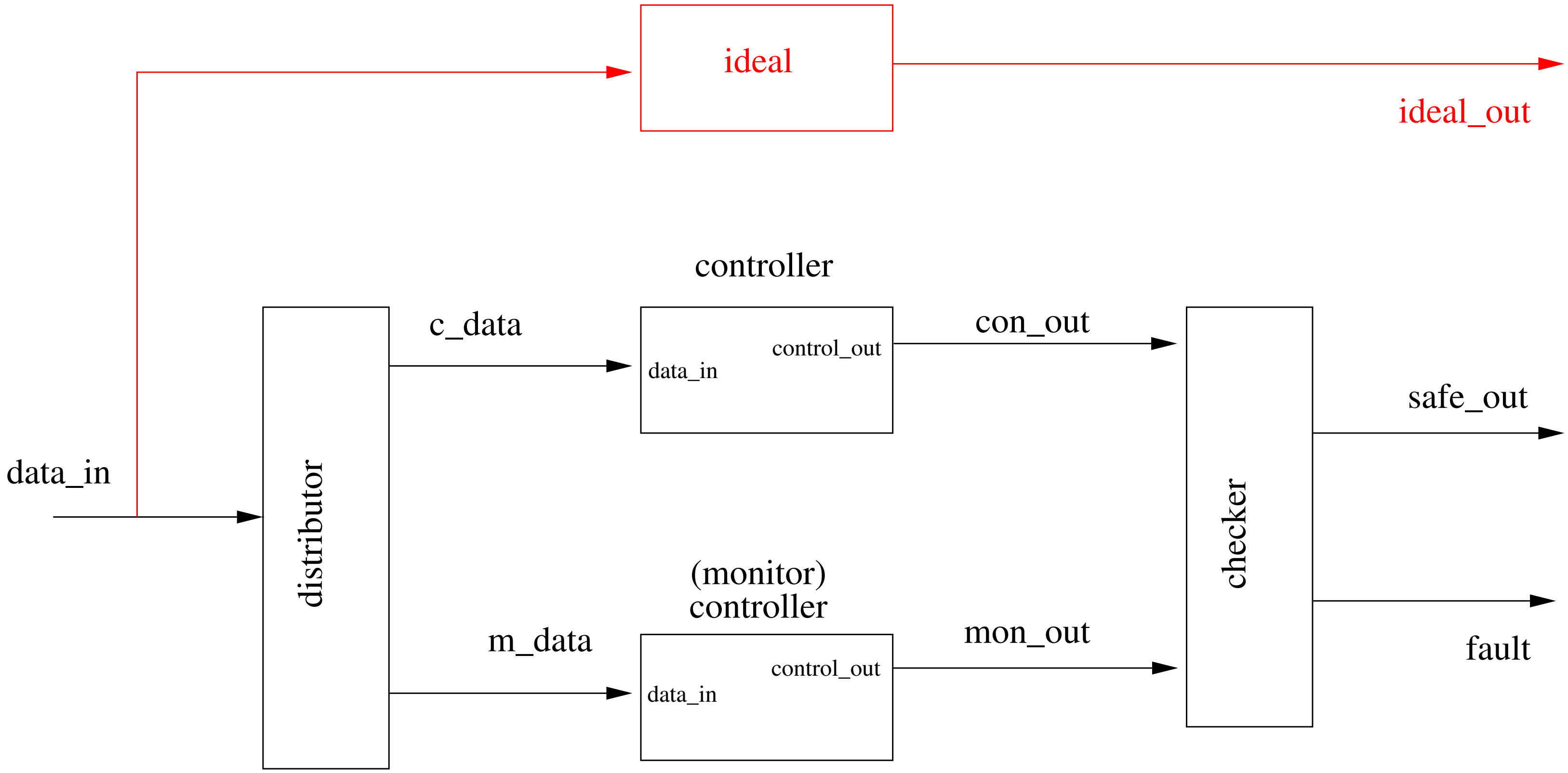
- If they are truly random, faults in separate components should be independent
  - Provided they are designed as fault containment units
    - ⋆ Independent power supplies, locations etc.
  - And ignoring high intensity radiated fields (HIRF)
    - ⋆ And other initiators of correlated faults
- So we can duplicate the component and compare the outputs
  - Pass on the output when both agree
  - Signal failure on disagreement
- Under what assumptions does this work?

Example: Self-Checking Pair (2)



- Controllers apply some control law to their input
- Controllers and distributor can fail
  - For simplicity, checker is assumed not to fail
  - Can be eliminated by having the controllers cross-compare
- Need some way to specify requirements and assumptions
- Aha! correctness requirement can be an idealized controller

Example: Self-Checking Pair (3)

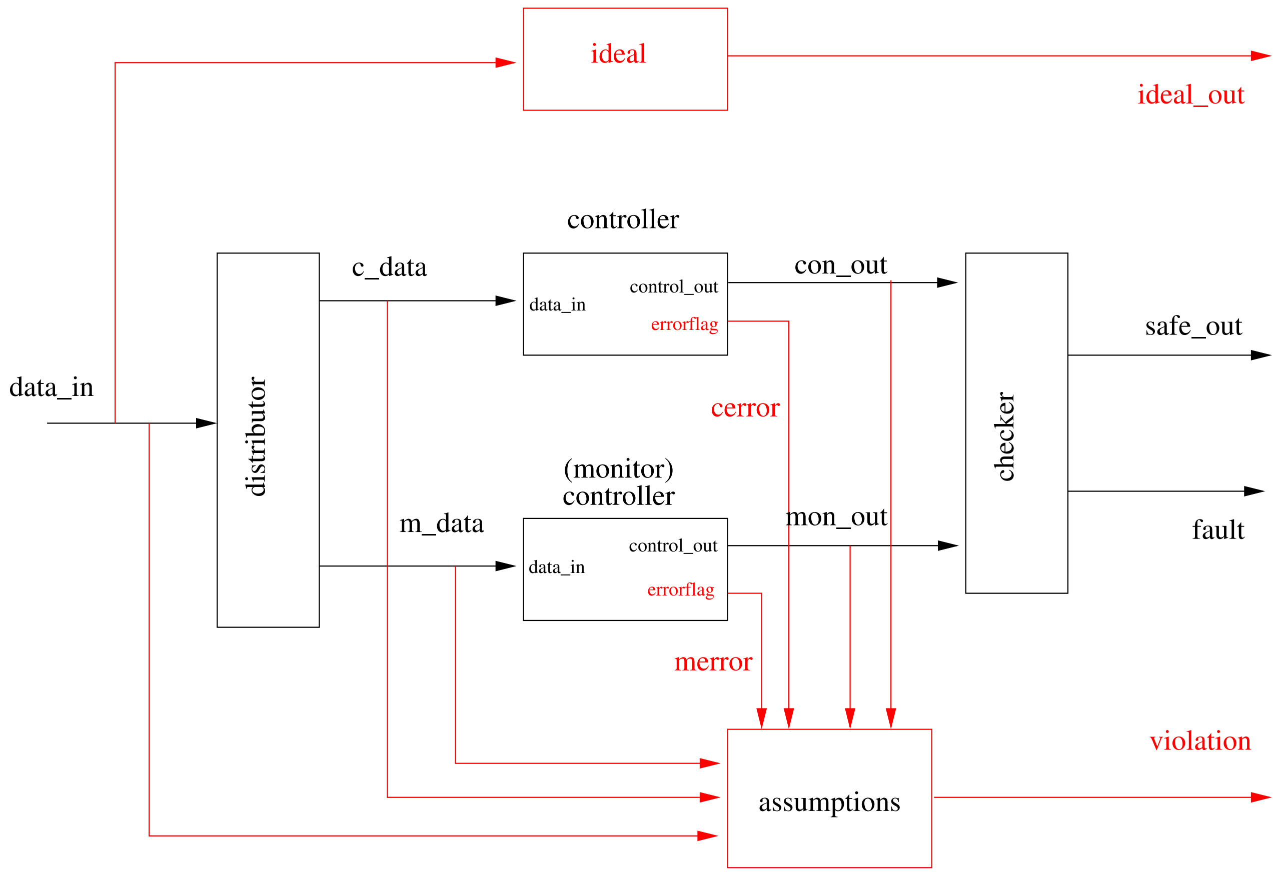


The controllers can fail, the ideal cannot

If no `fault` indicated `safe_out` and `ideal_out` should be the same

Model check for `G((NOT fault => safe_out = ideal_out))`

Example: Self-Checking Pair (4)



We need assumptions about the types of fault that can be tolerated: encode these in assumptions synchronous observer

`G(NOT violation => (NOT fault => safe_out = ideal_out))`

Example: Self-Checking Pair (5)

- Find four assumptions for the self-checking pair
  - When both members of pair are faulty, their outputs differ
  - When the members of the pair receive different inputs, their outputs should differ
    - ⋆ When neither is faulty: can be eliminated
    - ⋆ When one or more is faulty
  - When both members of the pair receive the same input, it is the correct input
- Can prove by 1-induction that these are sufficient
- One assumption can be eliminated by redesign
- Two require double faults
- Attention is directed to the most significant case

Compare with Simulation and Traditional Model Checking

- One of the assumptions is discovered through a counterexample in which
  - Distributor relays different wrong values x and y to the two members of the pair
  - But $f(x) = f(y)$
- In traditional simulation or model checking, would have to use some specific implementation for f, such as $x+1$, and we would be unlikely to chose one that could manifest this fault
- But infBMC can do it: synthesizes a model for f

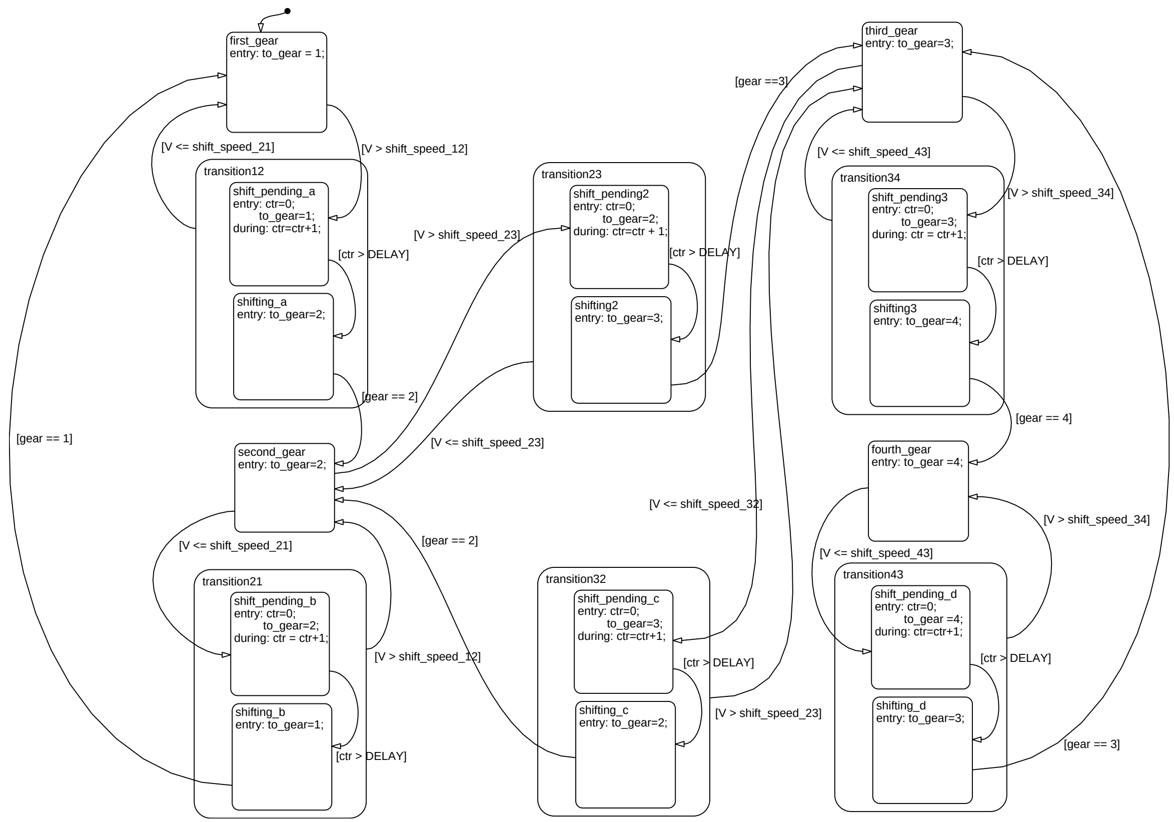
Test Generation

- Model checkers can be used for test generation
- e.g., to generate a test that reaches a target state characterized by property `p` just check for `NOT p`
  - `test: FORMULA system |- G(NOT p)`

  The counterexample generated by the model checker is a test scenario to reach the target state
- Can modify a model checker to generate single (long) counterexample to reach multiple targets
  - SAL-ATG does this
- But a cool alternative is to write a synchronous observer "tester" module that raises a flag `tok` when it has observed a scenario that satisfies the test purpose
- Then model check for `NOT tok`
  - `test: FORMULA (system || tester) |- G(NOT tok)`

Example: Shift Scheduler (1)

This is the Simulink/Stateflow design for the shift scheduler of an automatic transmission used in Ford cars



We want a test scenario that takes it through all its states

Example: Shift Scheduler (2)

- One input is the `gear` currently selected by the gearbox
- Tests often change this discontinuously (e.g., 1, 3, 4, 2)
- Can easily establish the test purpose to change only in single steps, and to change at every step
- Create a tester module whose body is

```
OUTPUT
 moving, continuous: BOOLEAN
INITIALIZATION
 moving = TRUE; continuous = (gear=1);
TRANSITION
 moving' = moving AND (gear /= gear');
 continuous' = continuous
  AND (gear - gear' <= 1)AND (gear' - gear <= 1);
```

- Then model check for the negation of these
  - `test: FORMULA (system || tester) |- G(NOT (moving AND continuous))`
- Actually, also need to check for a `DONE` flag on state coverage

Why This Works

- The basic system specification generates more behaviors than desired
- The synchronous observer recognizes those that are wanted
- It works (in the sense of being effective) because it is generally easier to specify recognizers than generators
- Let the model checker synthesize the required behavior
- May be costly with an explicit state model checker
    - Has to generate many behaviors, then throw them away

  But OK for symbolic ones

Conclusions

- Synchronous observers are a fairly obvious idea
- But I don't think their versatility is widely appreciated
- So I hope to have given you some ideas for novel ways to exploit them, and invite you to think of more
- Can also be used at runtime: interesting reliability results via probability of perfection (relates assurance to reliability)
- The power of modern tools like SMT solvers and infBMC is such that it often makes sense to specify required behavior by means of a recognizer, or in terms of constraints, rather than by a constructive specification
    - Let the automation synthesize the behavior
- The next step is to let the automation synthesize the constructive specification or implementation from constraints
- For that, need to develop effective Exists-Forall SMT solvers