SC(R)^3: Towards Usability of Formal Methods

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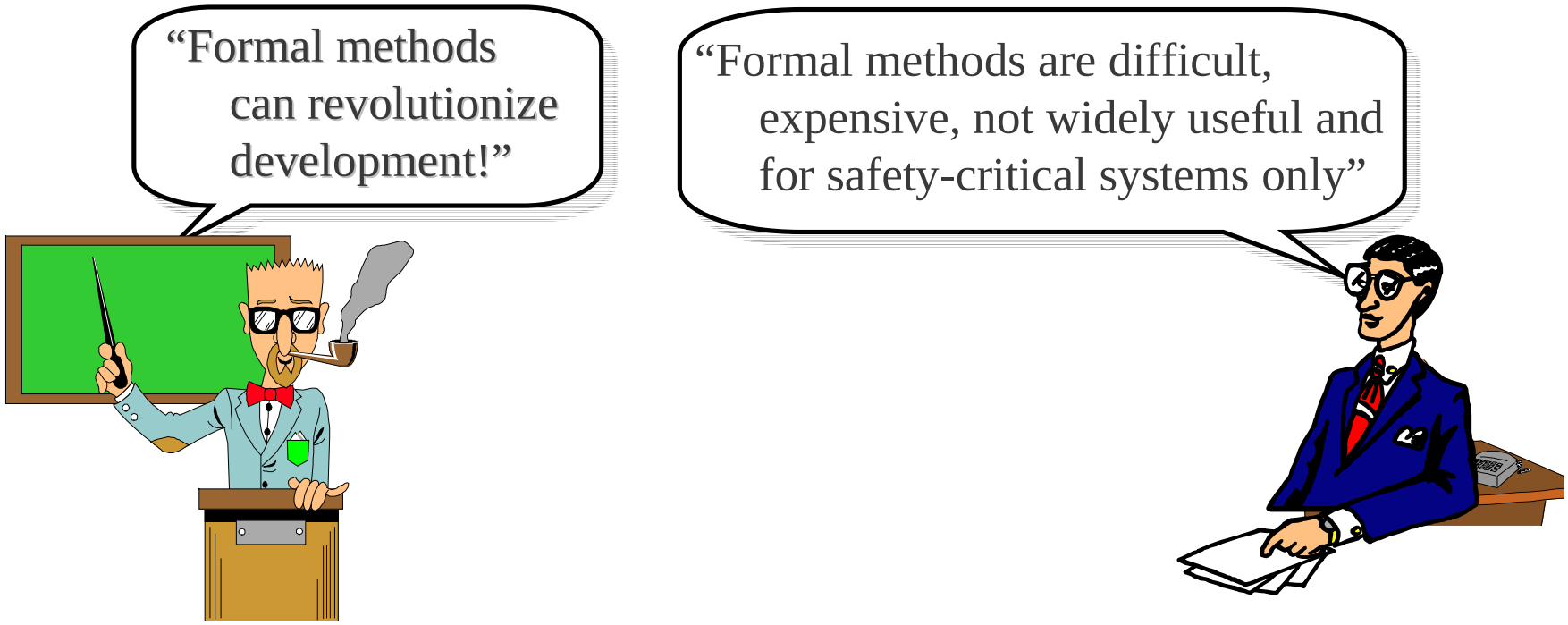
Formal Methods

"The use of mathematical modeling, calculation and prediction in the specification, design, analysis, construction and assurance of computer systems and software."

- Engineering - partial differential equations to model variations in physical quantities over time or space.
- Software - model discrete quantities. Need concepts like sets, graphs, partial-orders, finite-state machines.
- "Calculation" is in terms of formal logic rather than numerical computation.

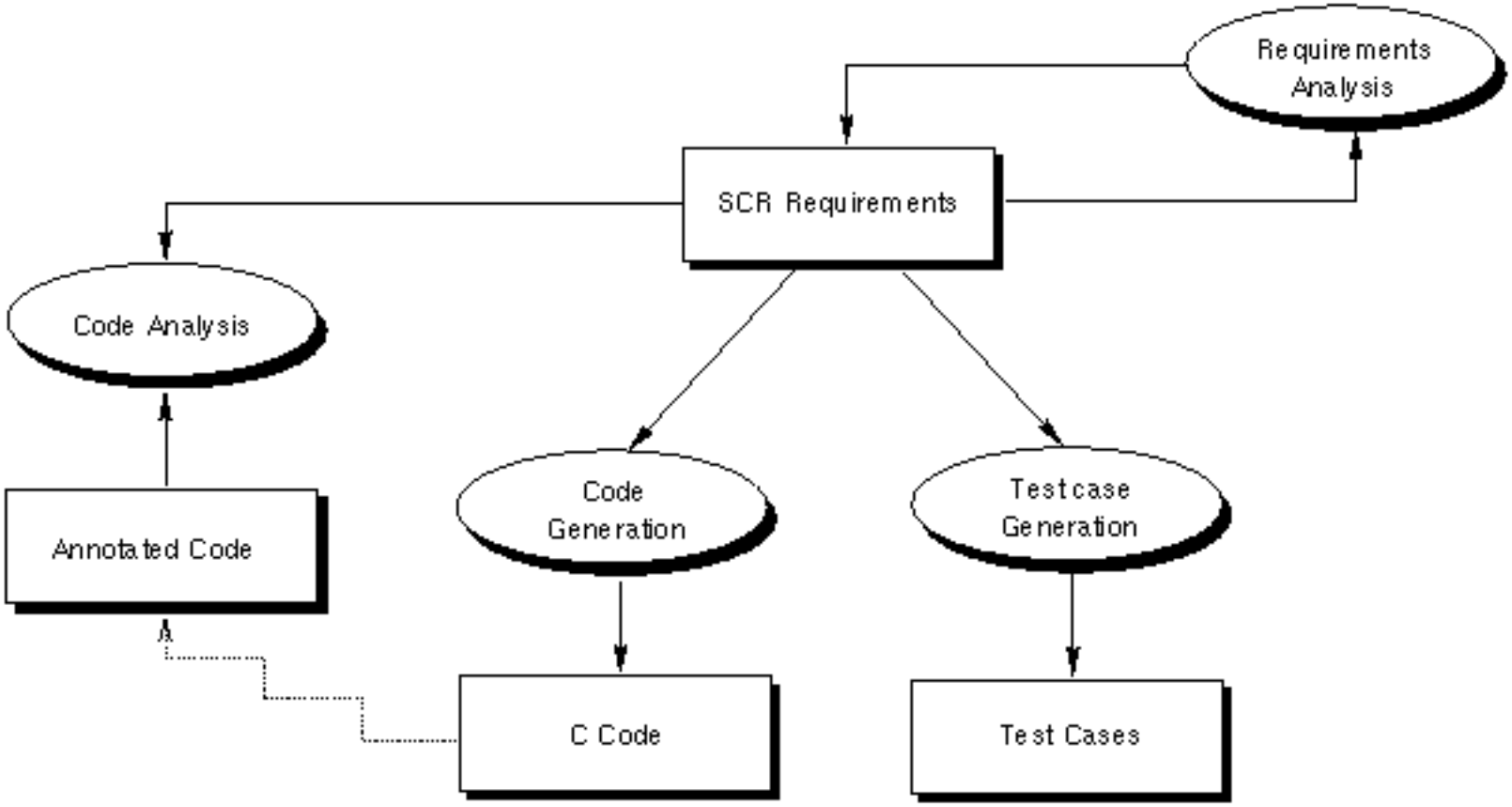
Why aren't FMs used more?



Need to improve *Usability* of Formal Methods

- $$$ - Amortize the cost of creating formal documentation throughout software lifecycle
- Use (create?) easy to read and review notations
  - state machines, tables
- Decrease analysis cost through automation
  - create computer tools requiring minimum user-guidance
- Adopt existing technology wherever possible

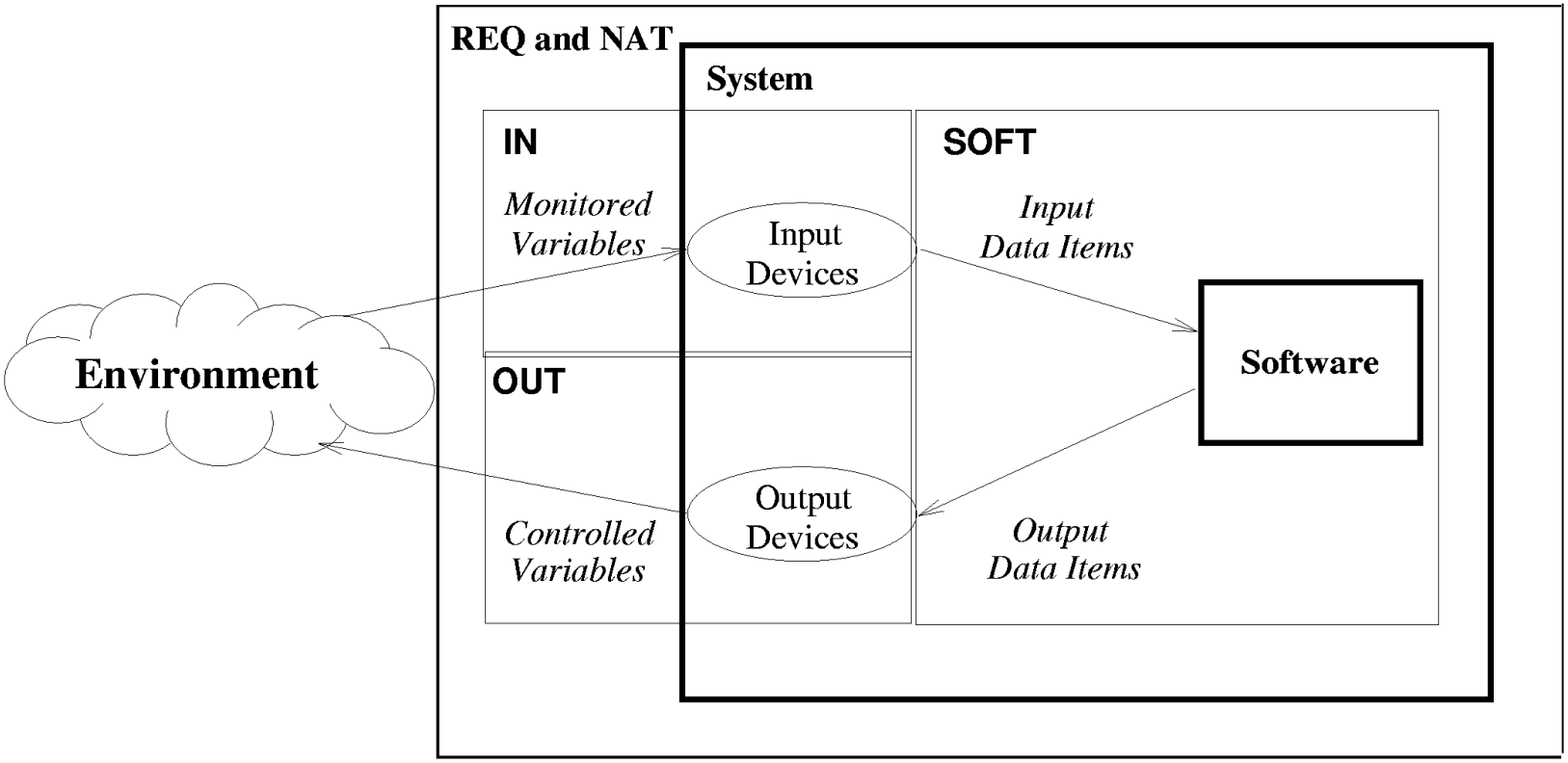
Overview of the Approach



Overview of the Rest of the Talk

- Specifications: SCR and global properties
- Running example: Cruise Control System
- Requirements analysis
  - Translating specifications
  - Verification and counter-example
- Code analysis
  - Annotations
  - Analysis
- Summary and future work

SCR and 4-Variable Model



SCR Requirements

- A state is a mapping of variables to values
- A modeclass is a set of system states, called modes, which partition the monitored environment's state space.

  One mode is designated as the initial mode
- A condition is a predicate on monitored variables

  Running, ButtonPressed
- An event is a point in time when a condition's value changes:

  @T(ButtonPressed)

  @F(Running) WHEN [ButtonPressed]

Cruise Control System

- Specified by Jim Kirby in 1988
- Activated by driver when at desired speed
- Speed is maintained until
  - The driver presses the brake pedal
  - The driver presses the gas pedal
  - The car's speed becomes uncontrollable
  - The engine stops running
  - The driver turns the ignition off
  - The driver turns the cruise control off

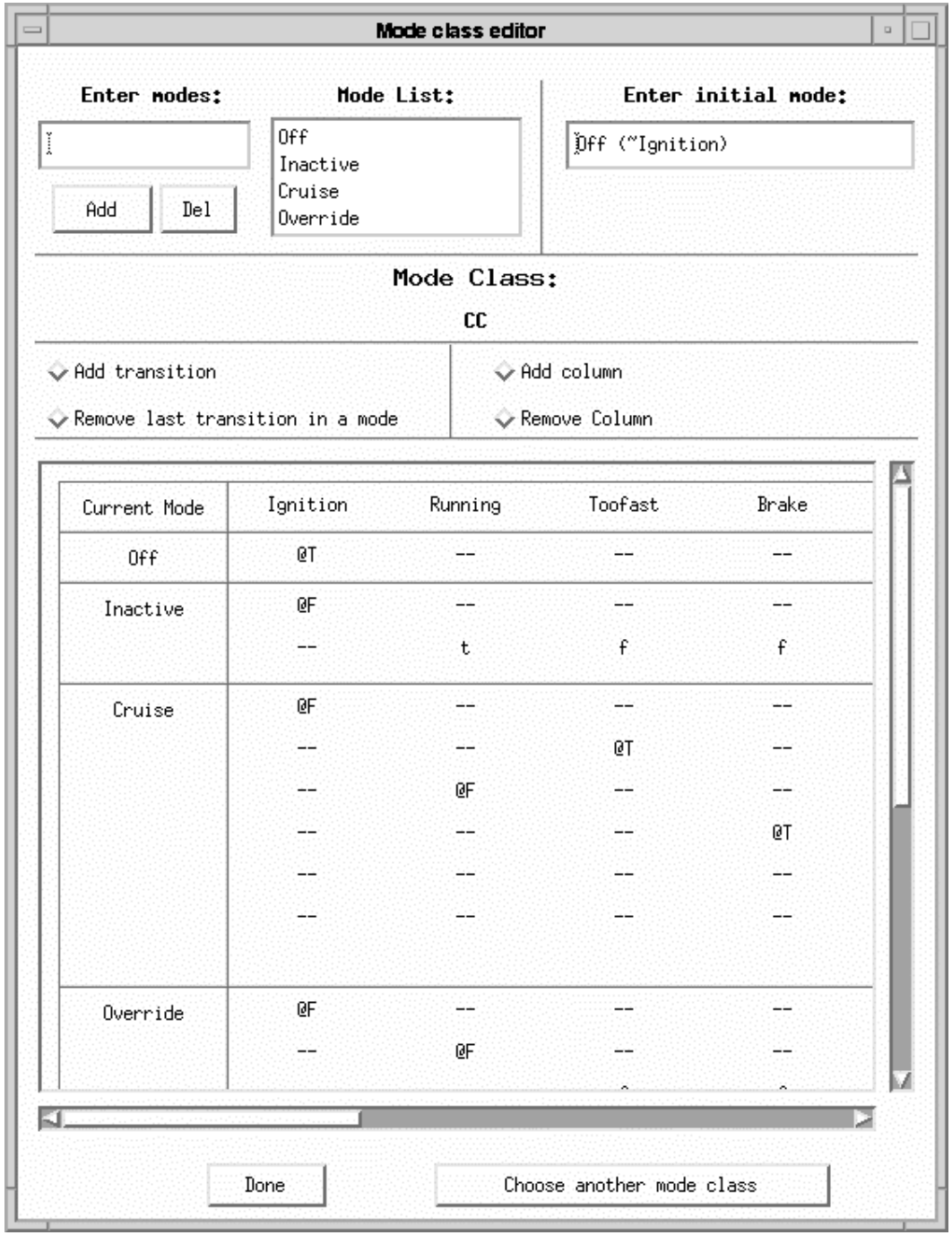
Driver can reactivate system by pressing "Resume" button

SCR Table for Cruise Control System

Current Mode	*Ignition*	*Running*	*Toofast*	*Brake*	*Accel*	*b_Cruise*	*b_Off*	**New Mode**
Inactive	@T	--	--	--	--	--	--	Off
	--	true	false	false	false	@T	--	Cruise
Cruise	@F	--	--	--	--	--	--	Off
	--	--	@T	--	--	--	--	Inactive
	--	@F	--	--	--	--	--	Inactive
	--	--	--	@T	--	--	--	Inactive
	--	--	--	--	@T	--	--	Inactive
Override	@F	--	--	--	--	--	--	Off
	--	@F	--	--	--	--	--	Off
	--	--	false	false	false	--	@T	Inactive
	--	--	false	false	false	@T	--	Cruise
Off	@T	--	--	--	--	--	--	Inactive

Initial: Off (~Ignition)

SC(R)^3 mode class editor



Controlled Variables for Cruise Control System

Mode	True	False
Cruise	@T(speed_slow)	@F(Inmode)
Cruise	@T(Inmode) WHEN [b_Resume & speed_slow]	@F(speed_slow)

Initial: False

Assumptions

Assumptions specify constraints on the values of conditions, imposed by laws of nature or by other mode classes in the system

- The engine is running only if the ignition is on

```
Running ->> Ignition
```

- The car can be going "too fast" only if it is running

```
Toofast ->> Running
```

- Variables relating vehicle's speed are connected by enumeration

```
speed_slow / speed_ok / speed_fast
```

Properties for Cruise Control System

- Expressed in CTL - Computational Tree Logic + SCR events
- Invariant properties

```
AG(CC=Override -> (Ignition & Running)
  AG(ThrottleOff | ThottleMaintain |
     ThrottleAccel | ThrottleDecel)
```

- "Progress" properties - system behaves according to specifications

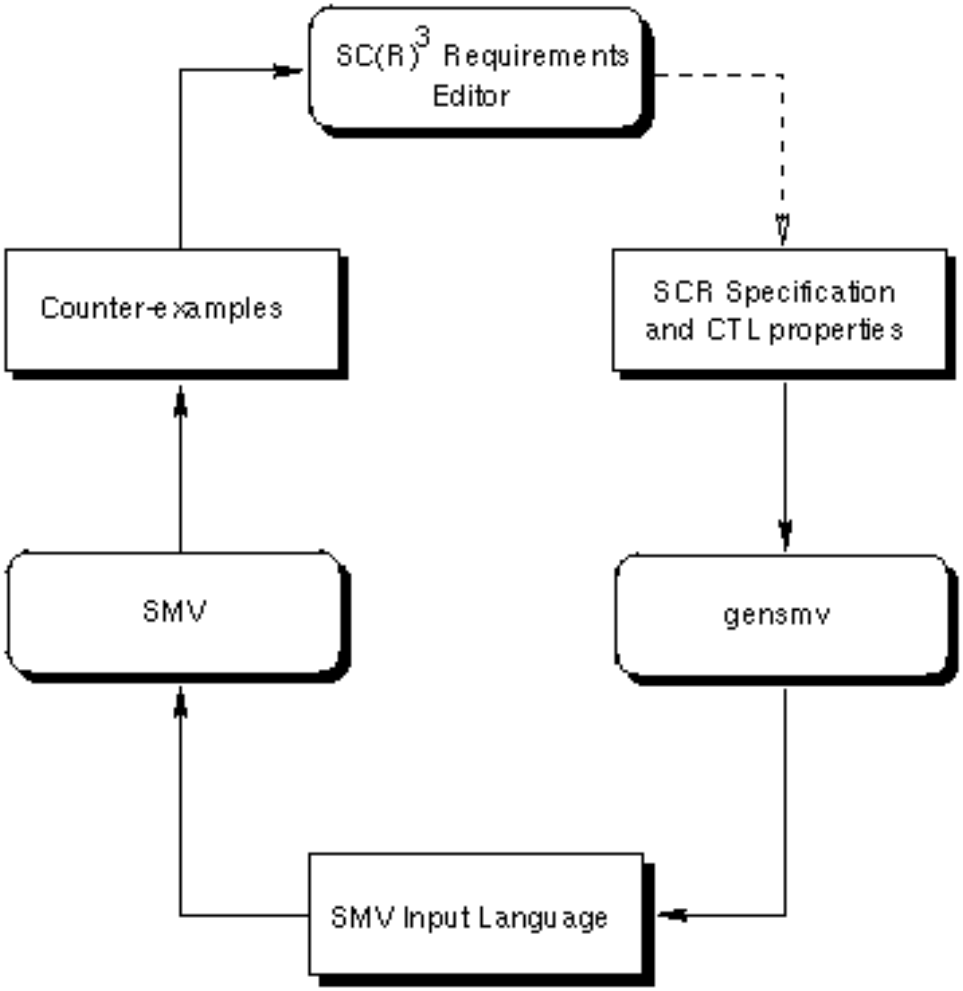
```
AG(CC=Cruise ->
   AX(@F(Ignition) -> CC=Off)
```

Model-Checking

- Model-checker SMV [McMillan93]
  - Takes CTL formulas and a model
  - Uses state exploration
  - Verifies properties or gives counter-examples

- Need to create input to SMV, translate properties and interpret results

Requirements Analysis



Translating SCR Specifications

- Tool `gensmv` [Atlee,Sreemani 96]
  - Detail mode transition tables with information derived from environmental assumptions

    ```
    Running ->> Ignition
    ```

  - Translate into `SMV`. Express @T and @F by introducing additional variables to store previous values

    ```
    AG(CC=Cruise ->
     AX((Pignition & ~Ignition)-> CC=Off)
    ```

  - We extended `gensmv` to reason about controlled variables

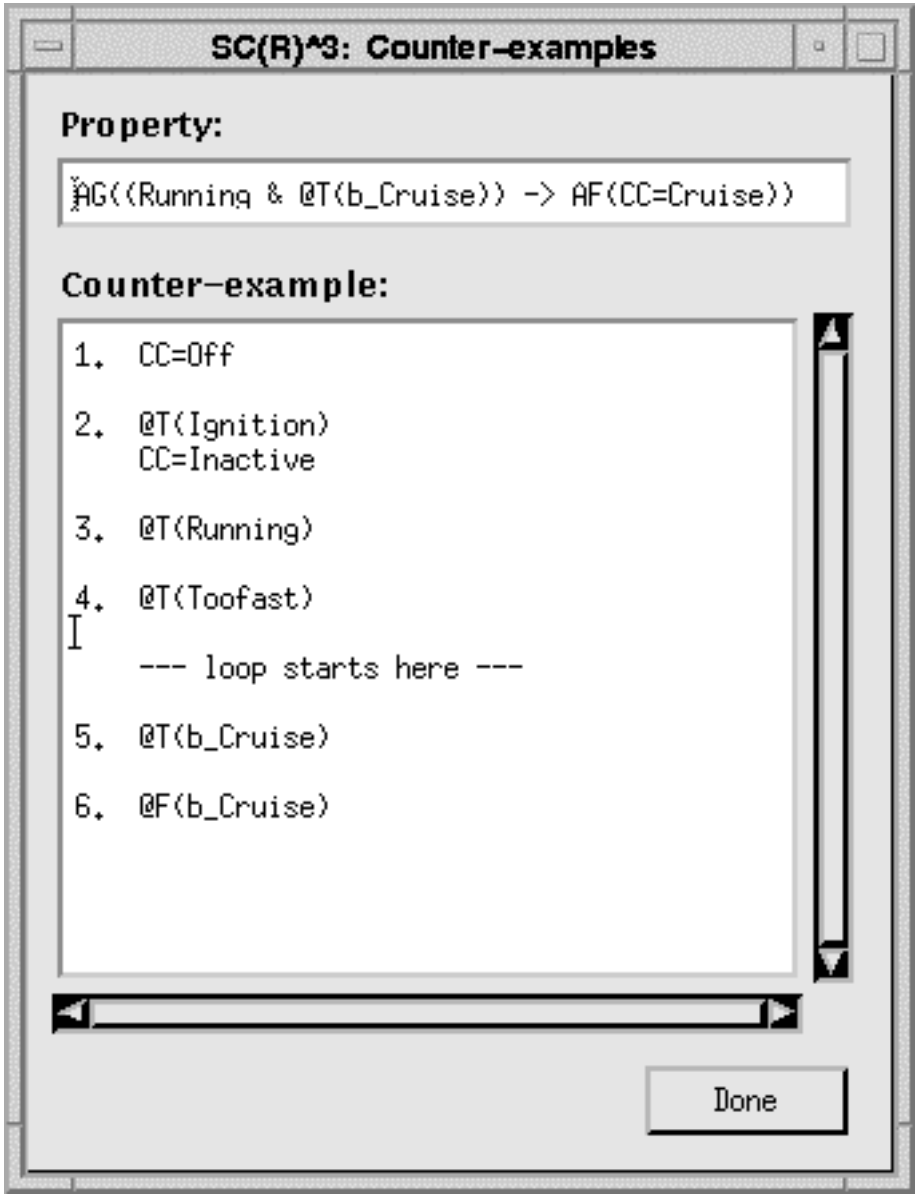
Counter-Example Facility

- Want to make SMV completely transparent for users
- Capture SMV's counter-examples, translate into SCR

Example property:

```
AG(Running &
@T(b_Cruise)) ->
AF(CC=Cruise)
```

Property fails when the car is running too fast



Checking Cruise Control System

- Checking done on SPARCstation 20 (2 x 75 MHz processors), 256 megabytes of RAM, using SMV version 2.4
- Size of system:
  - 22 monitored and 13 controlled variables
  - translated into 47 SMV variables
- To make the analysis more tractable:
  - "Slicing" - remove variables that do not appear in any properties and that others do not depend on (by hand)
  - Variable reordering
    - option `-reorder` (default in version 2.5 of SMV)
  - Building state-space incrementally (`-f`, `-inc`)

Checking Cruise Control System

Test	User time	System time	BDD nodes	Total number of vars
Full specification				
-reorder	26487.25s	420.31s	34315278	47
Throttle properties				
Base	5.67s	0.2s	112687	26
-f -inc	11.06s	0.07s	18714	26
-reorder	5.69s	0.15s	75356	26
-f -inc -reorder	12.28s	0.1s	18830	26
All but throttle				
Base	8102.76s	50.59s	9780674	43
-f -inc	18783.8s	263.46s	3408360	43
-reorder	4237.56s	7.37s	4425504	43
-f -inc -reorder	13599.5s	12.54s	3408360	43

- Use both options on a fast machine with limited memory
- Use reorder alone on a slower machine

Errors in Controlled Variable Tables

- [Orig. Spec.]: `OilOn` is evaluated when we enter any mode other than `Off`

  `@T(Inmode) WHEN [Omiles_low]`

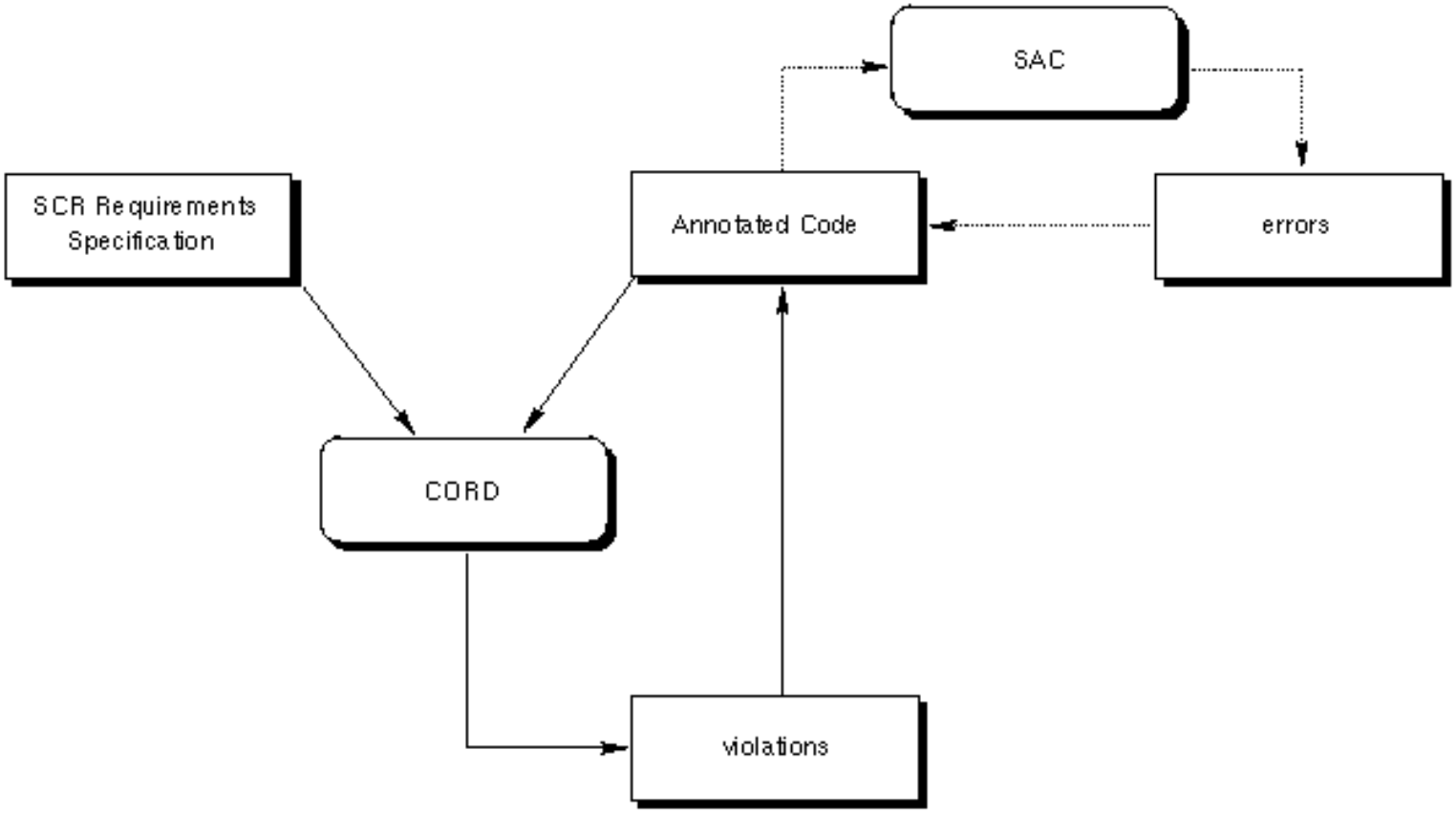
- [Orig.Spec.] `Throttle` never becomes `Off`

Throttle Setting				
Mode	Condition			
Cruise	speed_slow	speed_ok & ~Accel	speed_fast & ~Accel	Accel & ~ speed_slow
Throttle	Accel	Maintain	Decel	Off

  - Property

    `~Throttle = Off -> AG(~Throttle=Off)`

Checking Correctness of Code



Annotation Language

- Goal: annotate code with statements which describe changes in system state on the requirements level.
- Statements involve local (rather than invariant) info
- Language constructs:
  - Initial: assigns values to variables in starting state
  - Update: assigns values to variables indicating a state change
  - Assert: documents developer assumptions about the system at a given point and helps make analysis more precise

Annotations (Cont'd)

```
If (vIgnition) {
    @@ Assert ~Ignition;
     vIgnition = true;
    @@ Update Ignition;
    vCC = mInactive;
    @@ Update CC=Inactive;
}
else {
    @@ Assert Ignition;
    vIgnition = false;
    @@ Update ~Ignition;
    vCC = mOff;
    @@ Update CC=Off;
}
```

Checking Consistency of Annotations

- "Analysis is as good as annotations"
- Code maintenance greatly reduces correspondence between code and annotations
- Tool `sac`
  - Create a list of correspondences between req. and code variables

```
correspondences:
{Ignition} -> {vIgnition}
{CC} -> {vCC}
```

  - `sac` ensures that an assignment (or check) of a code variable is always followed by an Update (an Assert) of an appropriate requirements variable

Analysis by `cord`

- Check that transitions in the code are exactly the same as specified in requirements:
  - The code and spec start out in the same initial state
  - The code implements *all* specified transitions (ALT properties)

  E.g., "there is a transition from `Cruise` to `Off` on event `@F(Ignition)`"
  - The code implements *only* specified transitions (OLT properties)

  E.g., "The only transitions into `Off` are from modes `Inactive`, `Cruise` or `Override` on event `@F(Ignition)`"

Summary of Analysis

- Static analysis (similar to constant propagation) on annotations and control-flow statements in code
- Aggressive state-folding strategy aimed at minimizing the number of states (bound above by #annotations + # control-flow contracts)
- Automatically generate OLT and ALT properties (involving 2-3-state fragments => efficient checking)
- Also can check invariants and reachability properties and violations of environmental assumptions

Summary of Analysis (Cont'd)

Verification is inexact: `cord` computes more behaviors then can be present in code

- OLT props and invariants are checked *pessimistically* (more errors are found then present)
- ALT and reachability properties are checked *optimistically* (some errors can not be reported)

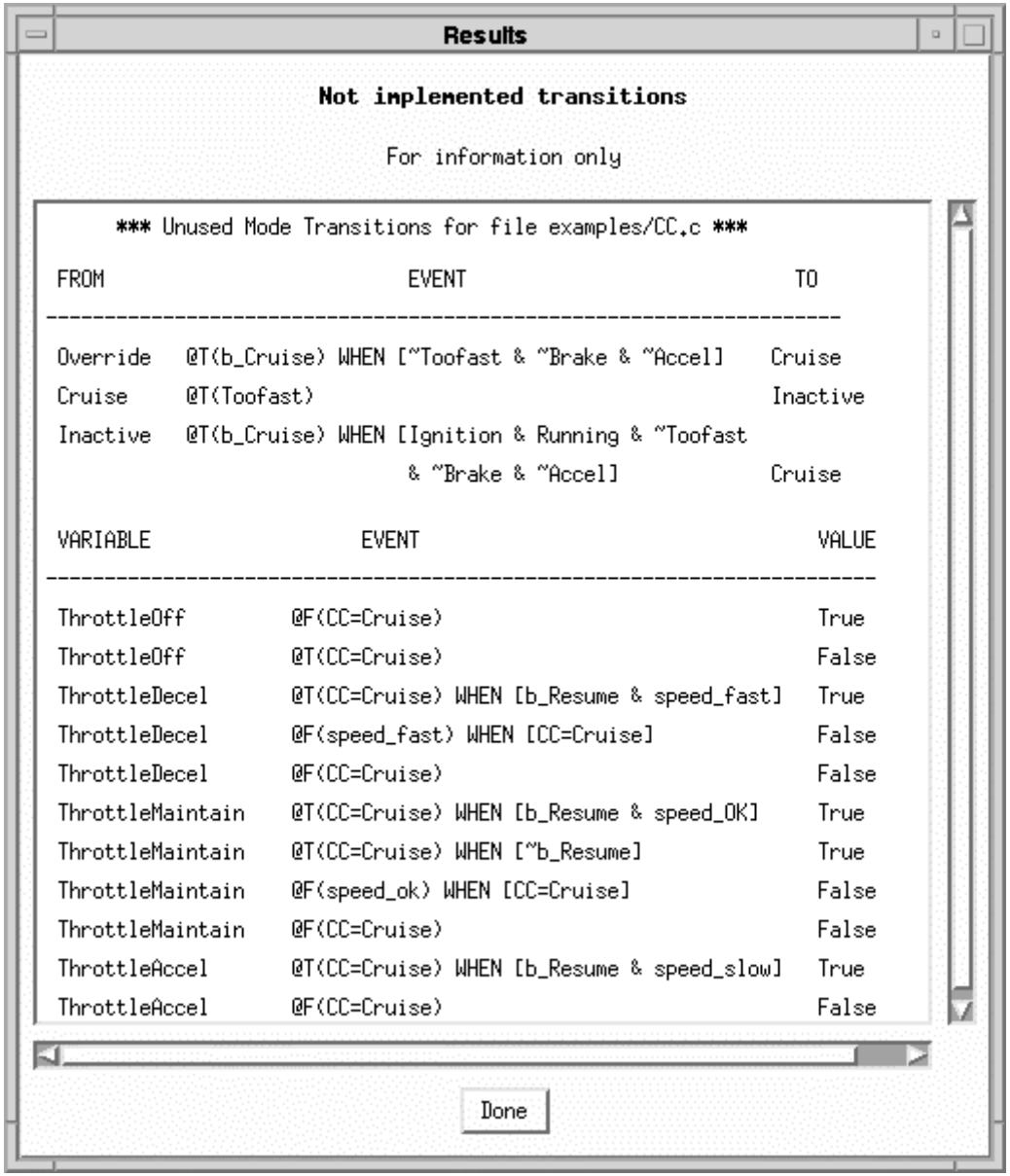
Thus, use `cord` as a debugging rather than verification tool

- So far - booleans and enumerated types, but current work is on *abstract interpretation* of code (i.e. not annotations)
  - approximation of infinite types
  - operations like addition and comparison

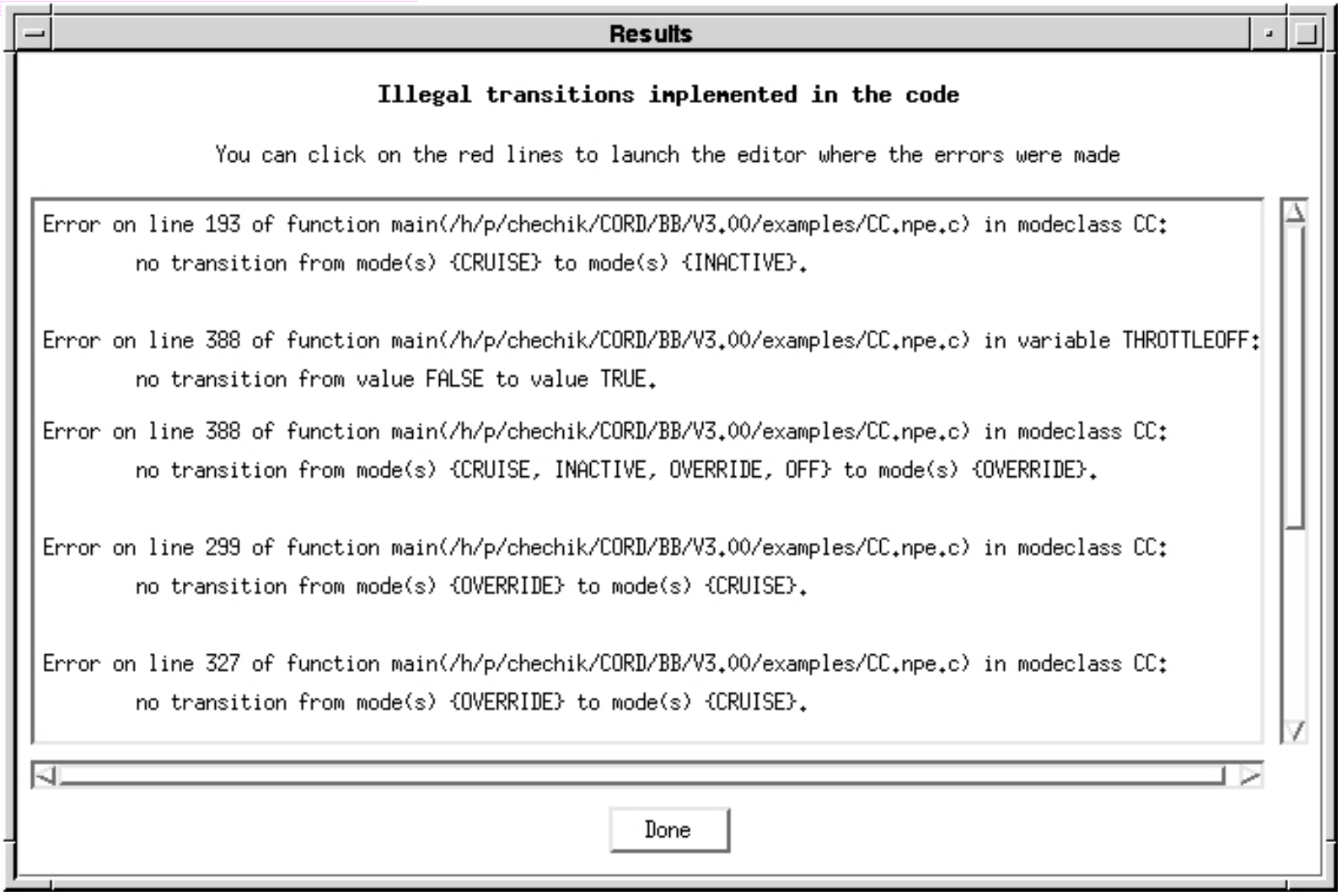
Checking Cruise Control System

- Implementation in C and Xlib, 675 lines of code (380 for GUI)
- Code annotated in 40 minutes with 37 Update, 25 Assert and 1 Initial annotation
- Analysis done in 7.52 sec (3.45 user, 0.74 system) on SPARCstation-4 (85 MHz processor) with 64 Mb of RAM
- Resulted in 14 ALT and 5 OLT violations:
  - Incorrect annotation (overlooked by `sac`)
  - Incorrect transition in code (to `Override` instead of `Cruise`)
  - Condition missing in code
  - One false negative

Violations of ALT Properties



Violations of OLT Properties



Summary

- SC(R)^3 - an integrated toolset for specification and reasoning about tabular requirements
- Check requirements for correctness
- Analyze consistency between annotated code and requirements
- Current work on test-case generation and generation of "usable" code

Step towards increasing usability of formal methods:

- Replace free-form logic by easy-to-read/review tables
- Amortize the cost of creating formal requirements over multiple automated analysis activities

New Process

- (Human) requirements designer provides specification and properties
- SC(R)^3 does model-checking of specification against properties
- SC(R)^3 generates an implementation of mode logic and stubs for interface code
- Using spec, SC(R)^3 generates test cases (for interface testing)
- Implementation analyzed for performance and (optionally) manually fine-tuned
- Code is checked for consistency with specification

Future Work

- Requirements analysis
  - model-checking (SMV) vs theorem-proving (PVS)
  - timing properties, data vs control, infinite-domain
- Code analysis
  - More expressive annotation language
  - Infinite-domain variables
  - Combining abstract interpretation with theorem-proving
- Test-case generation, code generation