Lecture 16:
Modelling “events”

- **Focus on states or events?**
  - E.g. SCR table-based models
  - Explicit event semantics
- **Comparing notations for state transition models**
  - FSMs vs. Statecharts vs. SCR
- **Checking properties of state transition models**
  - Consistency Checking
  - Model Checking, using Temporal Logic
- **When to use formal methods**

What are we modelling?

- **Starting point:**
  - States of the environment
  - Events that occur in the application domain (that change the state of the environment)
- **Requirements expressed as:**
  - Constraints over states and events of the application domain
    - E.g. “When the aircraft is in the air, the pilot should be prevented from accidentally engaging the reverse thrust”
- **To get to a specification:**
  - For each relevant application domain event, find a corresponding input event
  - For each relevant state, ensure there is a way for the machine to detect it
  - For each required action, find a corresponding output event

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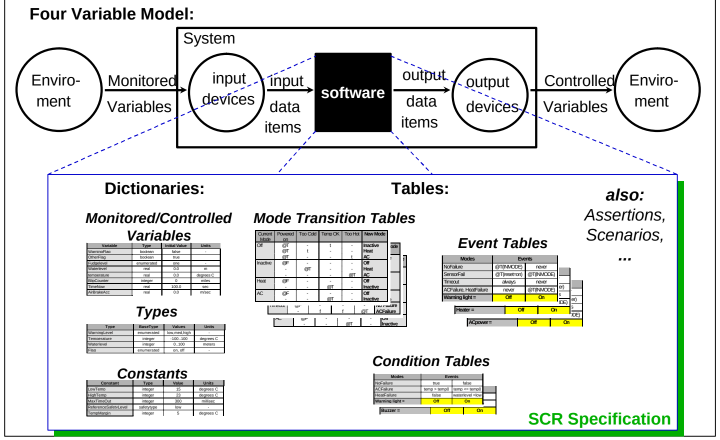
Tabular Specifications: SCR



Variable	Type	Initial Value	Units
WarningFlag	boolean	false	-
OtherFlag	boolean	true	
Fudgelevel	enumerated	one	-
Waterlevel	real	0.0	m
temperature	real	0.0	degrees C
BlipCounter	integer	0	miles
TimeNow	real	100.0	sec
AirBrakeAcc	real	0.0	m/sec

Type	BaseType	Values	Units
WarningLevel	enumerated	low,med,high	-
Temperature	integer	-100..100	degrees C
Waterlevel	integer	0..100	meters
Flag	enumerated	on, off	-

Constant	Type	Value	Units
LowTemp	integer	15	degrees C
HighTemp	integer	23	degrees C
MaxTimeOut	integer	300	millisec
ReferenceSafetyLevel	safetytype	low	-
TempMargin	integer	5	degrees C

Current Mode	Powered on	Too Cold	Temp OK	Too Hot	New Mode
Off	@T	-	t	-	Inactive
	@T	t	-	-	Heat
	@T	-	-	t	AC
Inactive	@F	-	-	-	Off
	-	@T	-	-	Heat
	-	-	-	@T	AC
Heat	@F	-	-	-	Off
	-	-	@T	-	Inactive
AC	@F	-	-	-	Off
	-	-	@T	-	Inactive

Modes	Events	
NoFailure	@T(INMODE)	never
SensorFail	@T(reset=on)	@T(INMODE)
Timeout	always	never
ACFailure, HeatFailure	never	@T(INMODE)
Warning light =	Off	On

Modes	Events	
NoFailure	true	false
ACFailure	temp > temp0	temp <= temp0
HeatFailure	false	waterlevel =low
Warning light =	Off	On

SCR basics

- **Modes and Mode classes**
  - A mode class is a finite state machine, with states called *system modes*
    - Transitions in each mode class are triggered by *events*
  - Complex systems described using several mode classes operating in parallel
  - System State is defined as:
    - the system is in exactly one mode from each mode class…
    - …and each variable has a unique value
- **Events**
  - Single input assumption - only one input event can occur at once
  - An event occurs when any system entity changes value
    - An *input event* occurs when an *input* variable changes value
  - Notation:
    - We may need to refer to both the old and new value of a variable:
    - Used primed values to denote values after the event
    - @T(c) ° Øc Ù c’ e.g. @T(y=1) ° y¹1 Ù y’=1
    - @F(c) ° c Ù Øc
  - A conditioned event is an event with a predicate
    - @T(c) WHEN d ° Øc Ù c’ Ù d

Source: *Adapted from Heitmeyer et. al. 1996.*

Defining Mode Classes

- **Mode Class Tables**
  - Define a (disjoint) set of *modes* (states) that the software can be in.
  - A complex system will have many different modes classes
    - Each mode class has a mode table showing the events that cause transitions between modes
  - A mode table defines a *partial function* from modes and events to modes
- **Example:**

Current Mode	Powered on	Too Cold	Temp OK	Too Hot	**New Mode**
Off	@T	-	t	-	**Inactive**
	@T	t	-	-	**Heat**
	@T	-	-	t	**AC**
Inactive	@F	-	-	-	**Off**
	-	@T	-	-	**Heat**
	-	-	-	@T	**AC**
Heat	@F	-	-	-	**Off**
	-	-	@T	-	**Inactive**
AC	@F	-	-	-	**Off**
	-	-	@T	-	**Inactive**

Source: *Adapted from Heitmeyer et. al. 1996.*

Defining Controlled Variables

- **Event Tables**
  - defines how a controlled variable changes in response to input events
  - Defines a *partial function* from modes and events to variable values
  - Example:

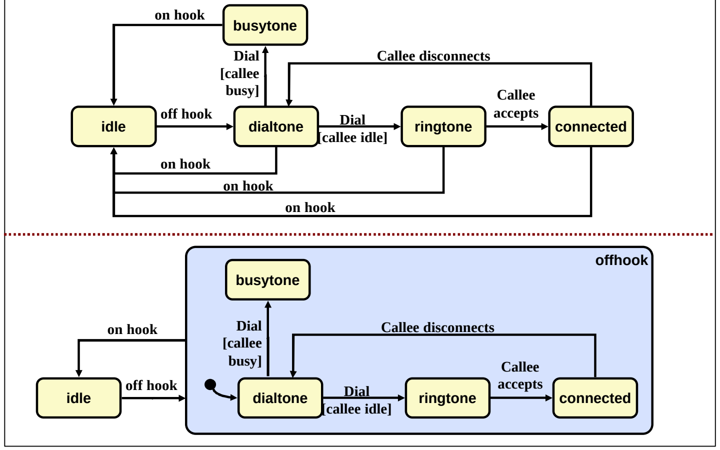
Modes		
Heat, AC	@C(target)	never
Inactive, Off	never	@C(target)
Ack_tone =	**Beep**	**Clang**

- **Condition Tables**
  - defines the value of a controlled variable under every possible condition
  - Defines a *total function* from modes and conditions to variable values
  - Example:

Modes		
Heat	target - temp ² 5	target - temp >5
AC	temp - target ² 5	temp - target >5
Inactive, Off	true	never
Warning light =	**Off**	**On**

Source: *Adapted from Heitmeyer et. al. 1996.*

Refresher: FSMs and Statecharts



SCR Equivalent

Current Mode	offhook	dial	callee offhook	New Mode
Idle	@T	-	-	**Dialtone**
Dialtone	-	@T	F	**Ringtone**
	-	@T	T	**Busytone**
	@F	-	-	**Idle**
Busytone	@F	-	-	**Idle**
Ringtone	-	-	@T	**Connected**
	@F	-	-	**Idle**
Connected	-	-	@F	**Dialtone**
AC	@F	-	-	**Idle**

- **Interpretation:**
  - In Dialtone: @T(offhook) WHEN callee_offhook takes you to Ringing
  - In Ringtone: @F(offhook) takes you to Idle
  - Etc…

State Machine Models vs. SCR

- All 3 models on previous slides are (approx) equivalent
- State machine models
  - Emphasis is on states & transitions
    - No systematic treatment of events
    - Different event semantics can be applied
  - Graphical notation easy to understand (?)
  - Composition achieved through statechart nesting
  - Hard to represent complex conditions on transitions
  - Hard to represent real-time constraints (e.g. elapsed time)
- SCR models
  - Emphasis is on events
    - Clear event semantics based on changes to environmental variables
    - Single input assumption simplifies modelling
  - Tabular notation easy to understand (?)
  - Composition achieved through parallel mode classes
  - Hard to represent real-time constraints (e.g. elapsed time)

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formal analysis

- Consistency analysis and typechecking
  - "Is the formal model well-formed?"
    - [assumes a modeling language where well-formedness is a useful thing to check]
- Validation:
  - Animation of the model on small examples
  - Formal challenges:
    - "if the model is correct then the following property should hold..."
  - 'What if' questions:
    - reasoning about the consequences of particular requirements;
    - reasoning about the effect of possible changes
  - State exploration
    - E.g. use a model checking to find traces that satisfy some property
  - Checking application properties:
    - "will the system ever do the following..."
- Verifying design refinement
    - "does the design meet the requirements?"

E.g. Consistency Checks in SCR

- Syntax
  - did we use the notation correctly?
- Type Checks
  - do we use each variable correctly?
- Disjointness
  - is there any overlap between rows of the mode tables?
    - ensures we have a deterministic state machine
- Coverage
  - does each condition table define a value for all possible conditions?
- Mode Reachability
  - is there any mode that cannot ever happen?
- Cycle Detection
  - have we defined any variable in terms of itself?

Model Checking

- Has revolutionized formal verification:
  - emphasis on partial verification of partial models
    - E.g. as a debugging tool for state machine models
  - fully automated
- What it does:
  - Mathematically – computes the "satisfies" relation:
    - Given a temporal logic theory, checks whether a given finite state machine is a model for that theory.
  - Engineering view – checks whether properties hold:
    - Given a model (e.g. a FSM), checks whether it obeys various safety and liveness properties
- How to apply it in RE:
  - The model is an (operational) Specification
    - Check whether particular requirements hold of the spec
  - The model is (an abstracted portion of) the Requirements
    - Carry out basic validity tests as the model is developed
  - The model is a conjunction of the Requirements and the Domain
    - Formalise assumptions and test whether the model respects them

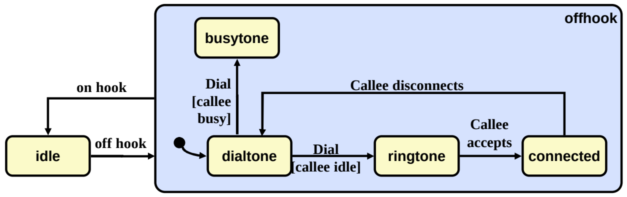
Model Checking Basics

- **Build a finite state machine model**
    - E.g. PROMELA - processes and message channels
    - E.g. SCR - tables for state transitions and control actions
    - E.g. RSML - statecharts + truth tables for action preconditions
- **Express validation property as a logic specification**
    - Propositions in first order logic (for invariants)
    - Temporal Logic (for safety & liveness properties)
        - E.g. CTL, LTL, ...
- **Run the model checker:**
    - Computes the value of: model |= property
- **Explore counter-examples**
    - If the answer is 'no' find out why the property doesn't hold
    - Counter-example is a trace through the model

Temporal Logic

- **LTL (Linear Temporal Logic)**
    - Expresses properties of infinite traces through a state machine model
    - adds two temporal operators to propositional logic:
        - ?p - p is true eventually (in some future state)
        - □p - p is true always (now and in the future)
- **CTL (Computational Tree Logic)**
    - branching-time logic - can quantify over possible futures
    - Each operator has two parts:
        - EX p - p is true in some next states
        - AX p - p is true in all next states
        - EF p - along some path, p is true in some future state
        - AF p - along all paths…
        - E[p U q] - along some path, p holds until q holds;
        - A[p U q] - along all paths…
        - EG p - along some path, p holds in every state;
        - AG p - along all paths…

Example



- **Sample Properties**
    - If you are connected you can hang up:
    - AG(CONNECTED ® EX(¬OFFHOOK)
    - If you are connected, hanging up always disconnects you:
    - AG(CONNECTED ® AX(¬OFFHOOK ® ¬CONNECTED))
    - A connection doesn't start until you pick up the phone:
    - AG(¬CONNECTED ® A[¬CONNECTED U OFFHOOK])
    - If you make a call, the phone cannot ring without returning to idle first:
    - AG((RINGTONE Ú BUSYTONE) ® A[¬RINGING U IDLE])

Complexity Issues

- **The problem:**
    - Model Checking is exponential in the size of the model and the property
    - Current MC engines can explore 10^{120} states…
        - using highly optimized data structures (BDDs)
        - …and state space reduction techniques
    - …that's roughly 400 propositional variables
        - integer and real variables cause real problems
    - Realistic models are often to large to be model checked
- **The solution:**
    - Abstraction:
        - Replace related groups of states with a single superstate
        - Replace real & integer variables with propositional variables
    - Projection:
        - Slice the model to remove parts unrelated to the property
    - Compositional verification - break large model into smaller pieces
        - (But it's hard to verify that the composition preserves properties)

Formal Methods in RE

➲What to formalize in RE?

- models of requirements knowledge (so we can reason about them)
- specifications of requirements (so we can document them precisely)

Why formalize in RE?

- Remove ambiguity and improve precision
- Provides a basis for verification that the requirements have been met
- Can reason about the requirements
  - Properties of formal requirements models can be checked automatically
  - Can test for consistency, explore the consequences, etc.
- Can animate/execute the requirements
  - Helps with visualization and validation
- Will have to formalize eventually anyway
  - RE is all about bridging from the informal world to a formal machine domain

Why people don't formalize in RE

- Formal Methods tend to be lower level than other analysis techniques
  - They force you to include too much detail
- Formal Methods tend to concentrate on consistent, correct models
  - …but most of the time your models are inconsistent, incorrect, incomplete…
- People get confused about which tools are appropriate:
  - E.g. modeling program behaviour vs. modeling the requirements
  - formal methods advocates get too attached to one tool!
- Formal methods require more effort
  - ...and the payoff is deferred

FM in practice

➲ From Shuttle Study [Crow & DiVito 1996]

- More errors found in the process of formalizing the requirements than were found in the formal analysis
  - Formalization forces you to be precise and explicit, hence reveals problems
  - Formal analysis then finds fewer, but more subtle problems
- Typical errors found include:
  - inconsistent interfaces
  - incorrect requirements (system does the wrong thing in response to an input)
  - clarity/maintainability problems

Issue Severity	*With FM*	*Existing*
High Major	2	0
Low Major	5	1
High Minor	17	3
Low Minor	6	0
Totals	30	4

Using Formal Methods

➲ Selective use of Formal Methods

- Amount of formality can vary
- Need not build complete formal models
  - Apply to the most critical pieces
  - Apply where existing analysis techniques are weak
- Need not formally analyze every system property
  - E.g. check safety properties only
- Need not apply FM in every phase of development
  - E.g. use for modeling requirements, but don't formalize the system design
- Can choose what level of abstraction (amount of detail) to model