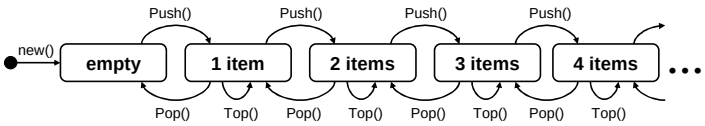
Lecture 8, Part 1: Modelling "State"

- What is State?
  - statespace for an object
  - concrete vs. abstract states
- Finite State Machines
  - states and transitions
  - events and actions
- Modularized State machine models: Statecharts
  - superstates and substates
  - Guidelines for drawing statecharts

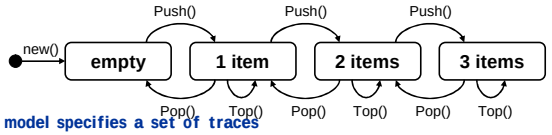
Getting objects to behave

- All objects have "state"
  - The object either exists or it doesn't
  - If it exists, then it has a value for each of its attributes
  - Each possible assignment of values to attributes is a "state"
    - (and non-existence is a state, although we normally ignore it)
- E.g. For a stack object



What does the model mean?

- Finite State Machines
  - There are a finite number of states (all attributes have finite ranges)
    - E.g. imagine a stack with max length = 3

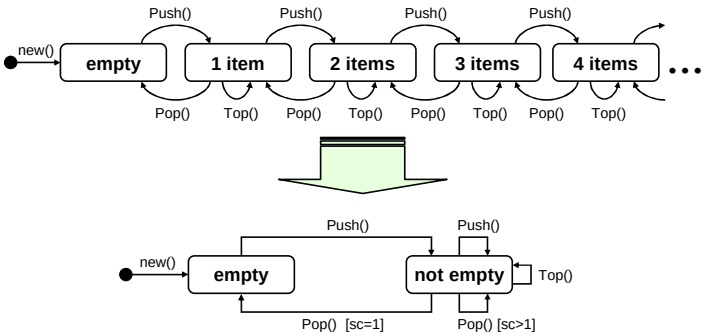


  - The model specifies a set of traces
    - E.g. new();Push();Push();Top();Pop();Push()…
    - E.g. new();Push();Pop();Push();Pop()…
    - There may be an infinite number of traces (and traces may be of infinite length)
  - The model excludes some behaviours
    - E.g. no trace can start with a Pop()
    - E.g. no trace may have more Pops than Pushes
    - E.g. no trace may have more than 3 Pushes without a Pop in between

Abstraction

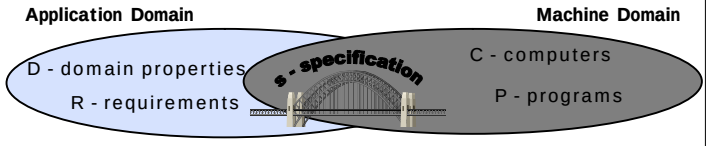
- The state space of most objects is enormous
  - State space size is the product of the range of each attribute
    - E.g. object with five boolean attributes: 2^5+1 states
    - E.g. object with five integer attributes: $(maxint)^5$+1 states
    - E.g. object with five real-valued attributes: …?
  - If we ignore computer representation limits, the state space is infinite
- Only part of that state space is "interesting"
  - Some states are not reachable
  - Integer and real values usually only vary within some relevant range
  - We're usually not interested in the actual values, just certain ranges:
    - E.g. for Age, we may be interested in age<18; 18=age=65; and age>65
    - E.g. for Cost, we may only be interested in cost=budget, cost=0, cost>budget, and cost>(budget+10%)

Collapsing the state space



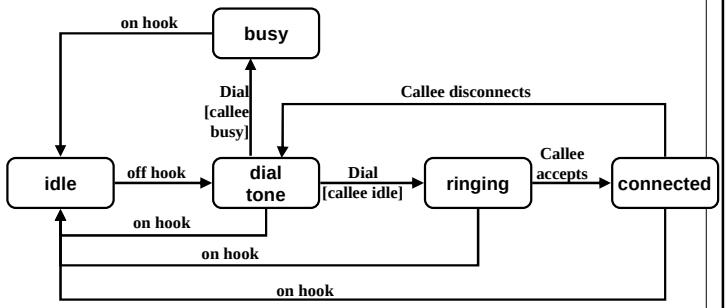
- The abstraction usually permits more traces
  - E.g. this model does not prevent traces with more pops than pushes
  - But it still says something useful

What are we modelling?

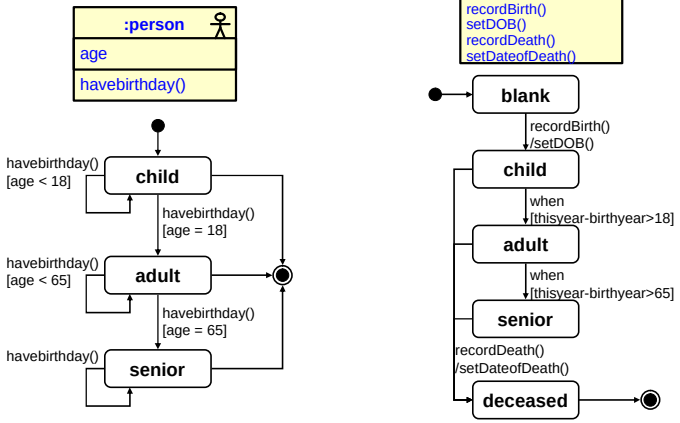


- **Observed states of an application domain entity?**
  - E.g. a phone can be idle, ringing, connected, …
  - Model shows the states an entity can be in, and how events can change its state
  - This is an indicative model
- **Required behaviour of an application domain entity?**
  - E.g. a telephone switch shall connect the phones only when the callee accepts the call
  - Model distinguishes between traces that are desired and those that are not
  - This is an optative model
- **Specified behaviour of a machine domain entity?**
  - E.g. when the user presses the 'connect' button the incoming call shall be connected
  - Model specifies how the machine should respond to input events
  - This is an optative model, in which all events are shared phenomena

Is this model indicative or optative?



the world vs. the machine



StateCharts

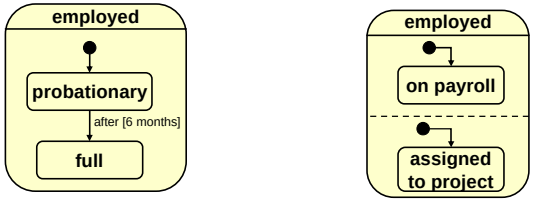
- **Notation:**
  - **States**
    - "interesting" configurations of the values of an object's attributes
    - may include a specification of action to be taken on entry or exit
    - States may be nested
    - States may be "on" or "off" at any given moment
  - **Transitions**
    - Are enabled when the state is "on"; disabled otherwise
    - Every transition has an event that acts as a trigger
    - A transition may also have a condition (or guard)
    - A transitions may also cause some action to be taken
    - When a transition is enabled, it can fire if the trigger event occurs and it guard is true
    - Syntax: event [guard] / action
  - **Events**
    - occurrence of stimuli that can trigger an object to change its state
    - determine when transitions can fire

Superstates

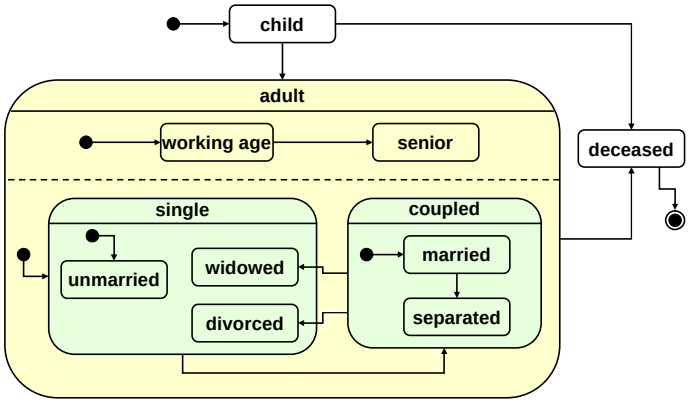
- **States can be nested, to make diagrams simpler**
  - A superstate consists of one or more states.
  - Superstates make it possible to view a state diagram at different levels of abstraction.

OR superstates
- when the superstate is "on", only one of its substates is "on"

AND superstates (concurrent substates)
- When the superstate is "on", all of its states are also "on"
- Usually, the AND substates will be nested further as OR superstates



A more detailed example



States in UML

- **A state represents a time period during which**
  - A predicate is true
    - e.g. (budget - expenses) > 0,
  - An action is being performed, or an event is awaited:
    - e.g. checking inventory for order items
    - e.g. waiting for arrival of a missing order item
- **States can have associated activities:**
  - do/activity
    - carries out some activity for as long as the state is "on"
  - entry/action and exit/action
    - carry out the action whenever the state is entered (exited)
  - include/stateDiagramName
    - "calls" another state diagram, allowing state diagrams to be nested

Events in UML

- Events are happenings the system needs to know about
  - Must be relevant to the system (or object) being modelled
  - Must be modellable as an instantaneous occurance (from the system's point of view)
    - E.g. completing an assignment, failing an exam, a system crash
  - Are implemented by message passing in an OO Design
- In UML, there are four types of events:
  - *Change events* occur when a condition becomes true
    - denoted by the keyword 'when'
    - e.g. when[balance < 0]
  - *Call events* occur when an object receives a call for one of its operations to be perfomed
  - *Signal events* occur when an object receives an explicit (real-time) signal
  - *Elapsed-time events* mark the passage of a designated period of time
    - e.g. after[10 seconds]

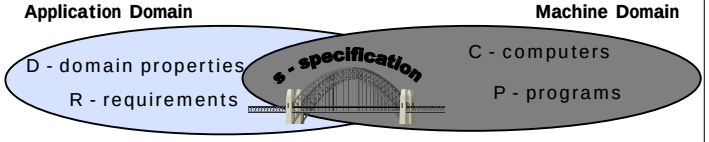
Checking your Statecharts

- Consistency Checks
  - All events in a statechart should appear as:
    - operations of an appropriate class in the class diagram
  - All actions in a statechart should appear as:
    - operations of an appropriate class in the class diagram and
- Style Guidelines
  - Give each state a unique, meaningful name
  - Only use superstates when the state behaviour is genuinely complex
  - Do not show too much detail on a single statechart
  - Use guard conditions carefully to ensure statechart is unambiguous
    - Statecharts should be deterministic (unless there is a good reason)
- You probably shouldn't be using statecharts if:
  - you find that most transitions are fired "when the state completes"
  - many of the trigger events are sent from the object to itself
  - your states do not correspond to the attribute assignments of the class

Lecture 8, Part 2: 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

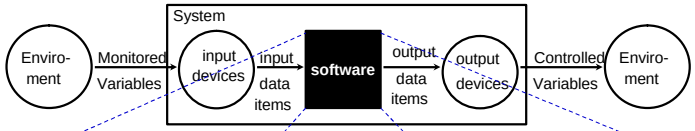
What are we modelling?



- 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

Tabular Specifications: SCR

Four Variable Model:



Dictionaries:

Monitored/Controlled Variables

Types

Constants

Tables:

Mode Transition Tables

Event Tables

Condition Tables

also: *Assertions, Scenarios, ...*

SCR Specification

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

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**

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:

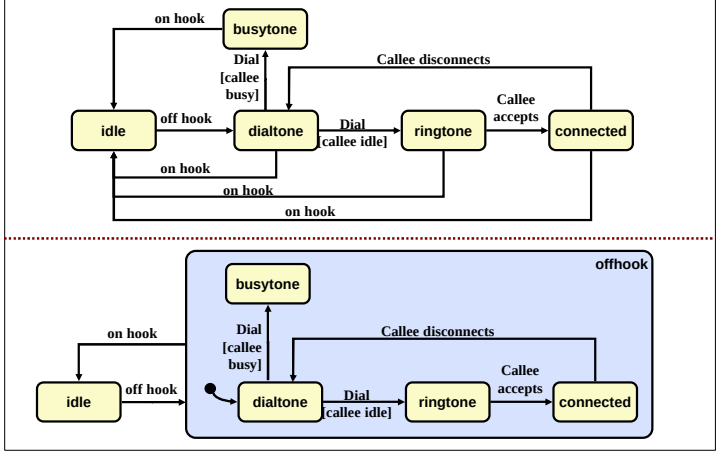
Modes		
Heat, AC	@C(target)	never
Inactive, Off	never	@C(target)
Ack_tone =	**Beep**	**Clang**

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**

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)

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

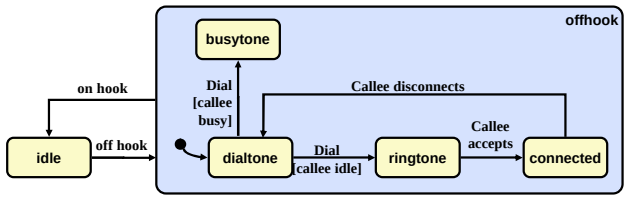
Model Checking Basics

- **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