Theoretical Foundations of the UML

Lecture 17: Introduction to Statecharts

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Outline

1. Background
2. Ingredients of Statecharts
   - Mealy Machines
   - State Hierarchy
   - Orthogonality
   - Broadcast Communication
   - Some Small Examples
   - Other Features: Priority, Nondeterminism and Negated Events
3. Semantics of Statecharts
4. Formal Definition of UML Statecharts

Overview

Statecharts

- MSCs are a visual modelling formalism for requirements
- Statecharts is a visual modelling formalism for describing the behaviour of discrete-event systems
  - automata + hierarchy + communication + concurrency
- Developed by David Harel in 1987
  - professor at Weizmann Institute (Israel); co-founder of I-Logix Inc.
- Extensively used in embedded systems, automotive and avionics
- Variants: UML Statecharts, Stateflow, hierarchical state machines
  - supported by Statemate toolset, and Matlab/Simulink

Overview

What are Statecharts?

Statecharts constitute a visual formalism for: [Harel, 1987]

- Describing states and transitions in a modular way
- Enabling clustering of states
- Orthogonality, i.e., concurrency
- Refinement, and
- Encouraging "zoom" capabilities for moving easily back and forth between levels of abstraction

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What are Statecharts?

$$\begin{aligned}\text{Statecharts} := &\ \text{Mealy machines}\\ &+ \text{State hierarchy}\\ &+ \text{Broadcast communication}\\ &+ \text{Orthogonality}\end{aligned}$$

Mealy machines [Mealy, 1953]

Definition (Mealy machine)

A Mealy machine $\mathcal{A} = (Q, q_0, \Sigma, \Gamma, \delta, \omega)$ with:

- Q is a finite set of states with initial state $q_0 \in Q$
- Σ is the input alphabet
- Γ is the output alphabet
- $\delta : Q \times \Sigma \to Q$ is the deterministic (input) transition function, and
- $\omega : Q \times \Sigma \to \Gamma$ is the output function

Intuition

A Mealy machine (or: finite-state transducer) is a finite-state automaton that produces output on a transition, based on current input and state.

Moore machines

In a Moore machine $\omega : Q \to \Gamma$, output is purely state-based.

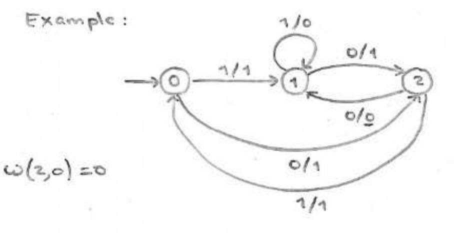
Mealy machines

Mealy machines

- No final (accepting) states
- Transitions produce output
- Deterministic input transition function

⇒ Acceptance of input words is not important, but the generation of output words from input words is important

Example

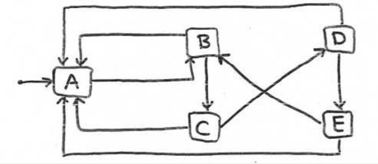


Limitations of Mealy machines

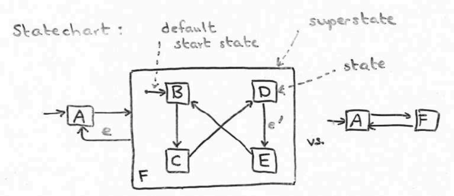
- No support for hierarchy
  - all states are arranged in a flat fashion
  - no notion of substates
- Realistic systems require complex transition structure and huge number of states
  - scalability problems yields unstructured state diagrams
- No notion of concurrency
  - need for modeling independent components
- No notion of communication between automata.

Scalability

A bit unstructured Mealy machine



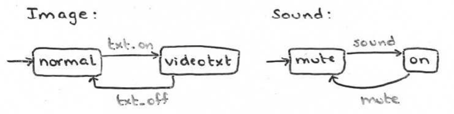
An equivalent statechart



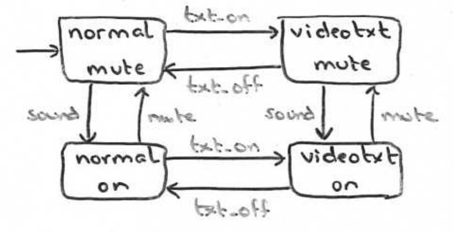
State hierarchy yields modular, hierarchical and structured models.

Orthogonality

Two independent components



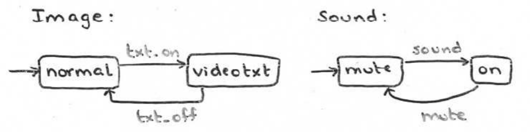
Mealy machine for $Image \| Sound$



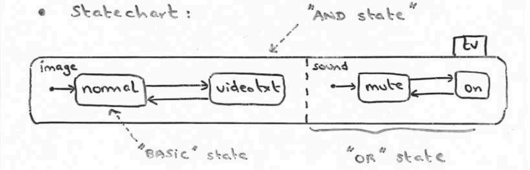
Number of states is exponential in size of concurrent components

Orthogonality

Two independent components



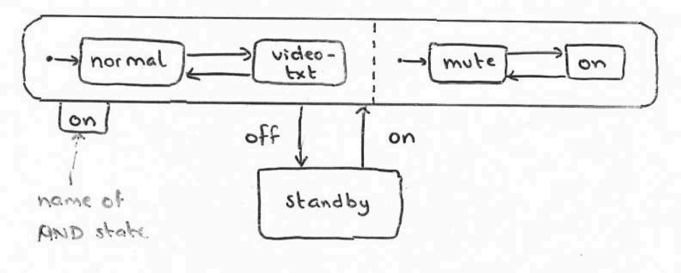
Statechart for $Image \parallel Sound$



Concurrency modeled by independence

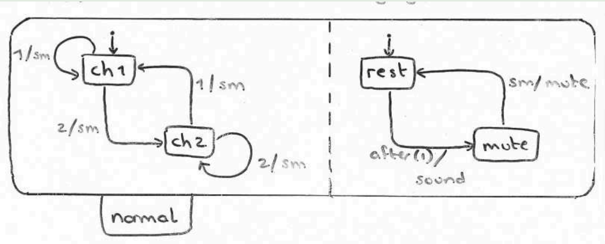
Combined with state hierarchy

Switching on and off the television



Broadcast

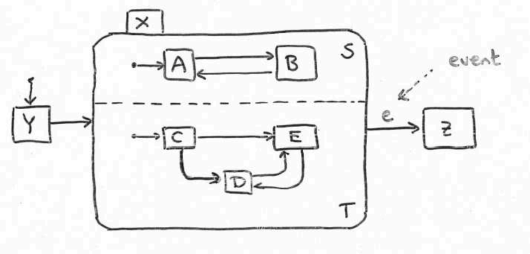
Turn off sound on switching a tv channe



- Output is broadcast that can be received by any other component
- When pushing button 1, channel switches to its state channel 1, while generating signal *sm* on which component *SM* switches off the sound.

Concurrency

Example concurrency in statecharts

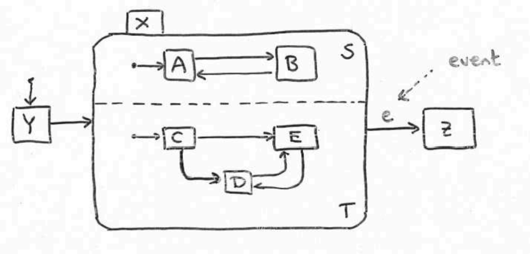


Active

- As long as node X is active, nodes S and T are active
- Node S is active when either node A or B is active
- Node T is active if one of C, D or E is active

Concurrency

Example concurrency in statecharts

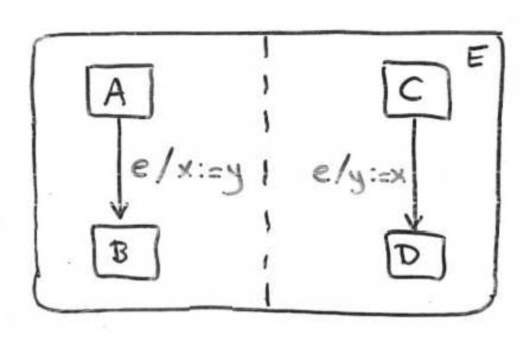


Exit behaviour

- When node X exits, both nodes S and T exit
- When Y exits, X starts, S starts in A, and T starts in C
- On the occurrence of event e, node X exits (regardless of current state in S or T)

Swapping two variables

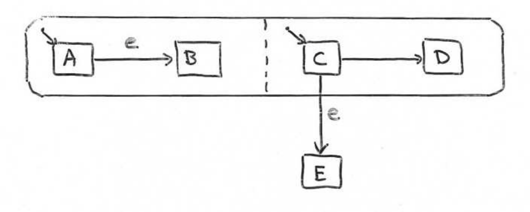
Swapping the value of variables x and y



- If nodes A and C are active, assume $x = 1$, $y = 2$
- On occurrence of event e, B and D are active, and $x = 2$, $y = 1$

⇒ In Harel's statecharts, memory is shared, i.e., concurrent components have access to shared variables.

What if event e occurs when A and C are active?



Solution:

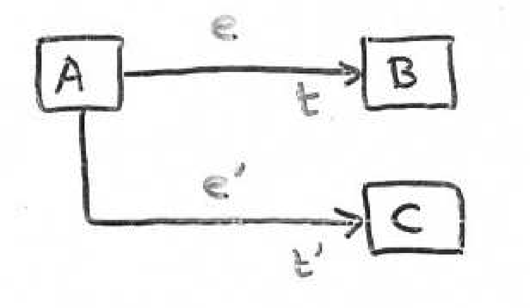
Add a priority mechanism that decides whether:

- inter-level transitions (such as $C \to E$), or
- intra-level transitions (such as $A \to B$)

prevail in case both are enabled.

Nondeterminism

What if event e and e' occur in A?

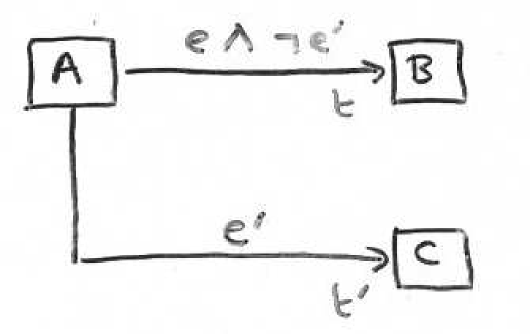


Solution:

Choice is resolved nondeterministically, i.e., the next state is either B or C, but not both.

Negation of events

Priority of events by negated events



Note:

In UML statecharts, negated events do not occur

Overview

Semantic problems with Statecharts

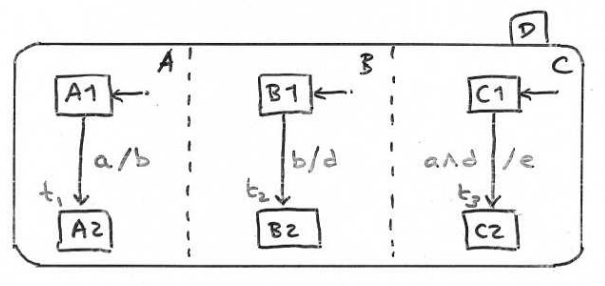
- Synchrony hypothesis (or: zero response time)
- Self-triggering
- Negated trigger events
- Transition effect is contradicting its cause
- Interrupts

Note: [von der Beeck, 1994]

Due to all these problems, hundred(s) (!) of different semantics for Statecharts have been defined in the literature.

Synchrony hypothesis

Event may yield chain of reactions

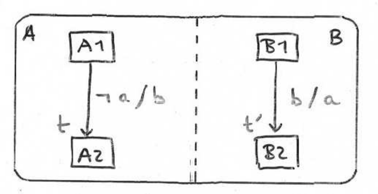


Note:

- If $A1$, $B1$ and $C1$ are active and event a occurs, a chain of reactions occurs: transition t_1 triggers t_2, and t_2 triggers t_3
- But transitions t_1, t_2, t_3 occur at the same time as events do not take time (except for $\mathit{after}(d)$ events with real d)

Paradox

Negated events and synchrony may yield paradox



The paradox:

- Assume events a and b are not alive
- Transition t can be taken, generating event b
- Transition t' can be taken, generating event a
- But then t should not have taken place as it is not enabled
- But then t' cannot be taken since b does not occur
- Hence, a does not occur and t cannot be taken

Simplifications in UML statecharts

1. No shared variables
2. No negated and no compound events (like $e \wedge e'$)
3. Two-party communication rather than broadcast
4. No synchrony hypothesis:
   - events generated in step i can only be consumed in step $i{+}1$,
   - and die otherwise, i.e., when they are not consumed in step $i{+}1$, events disappear

Overview

Statecharts

Definition (Statecharts)

A statechart SC is a triple $(N, E, Edges)$ with:

1. N is a set of nodes (or: states) structured in a tree
2. E is a set of events
    - pseudo-event $after(d)$ denotes a delay of $d \in \mathbb{R}_{\geqslant 0}$ time units
    - $\bot \notin E$ stands for "no event available"
3. $Edges$ is a set of (hyper-) edges, defined later on.

Definition (System)

A system is described by a finite collection of statecharts $(SC_1, \ldots, SC_k)$.

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Syntactic sugar

this is an elementary form; the UML allows more constructs
that can be defined in terms of these basic elements

- Deferred events — simulate by regeneration
- Parametrised events — simulate by set of parameter-less events
- Activities that take time — simulate by start and end event
- Dynamic choice points — simulate by intermediate state
- Synchronization states — use a hyperedge with a counter
- History states — (re)define an entry point

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Tree structure

Function *children*

Nodes obey a tree structure defined by function $children : N \rightarrow 2^N$ where $x \in children(y)$ means that x is a child of y, or equivalently, y is the parent of x.

Partial order $\trianglelefteq$

The partial order $\trianglelefteq \subseteq N \times N$ is defined by:

- $\forall x \in N.\, x \trianglelefteq x$
- $\forall x, y \in N.\, x \trianglelefteq y$ if $x \in children(y)$
- $\forall x, y, z \in N.\, x \trianglelefteq y \wedge y \trianglelefteq z \Rightarrow x \trianglelefteq z$

$x \trianglelefteq y$ means that x is a descendant of y, or equivalently, y is an ancestor of x. If $x \trianglelefteq y$ or $y \trianglelefteq x$, nodes x and y are ancestrally related.

Root node

There is a unique root with no ancestors, and $\forall x \in N.\, x \trianglelefteq \text{root}$.

Functions on nodes

The type of nodes

Nodes are typed, $\mathit{type}(x) \in \{ \textsc{basic}, \textsc{and}, \textsc{or} \}$ such that for $x \in N$:

- $\mathit{type}(\text{root}) = \textsc{or}$
- $\mathit{type}(x) = \textsc{basic}$ iff $\mathit{children}(x) = \varnothing$, i.e., x is a leaf
- $\mathit{type}(x) = \textsc{and}$ implies $(\forall y \in \mathit{children}(x).\, \mathit{type}(y) = \textsc{or})$

Default nodes

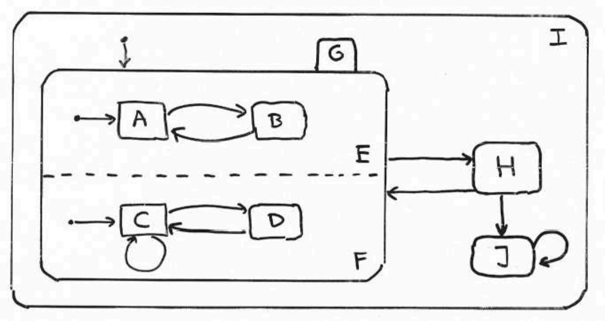
$\mathit{default} : N \to N$ is a partial function on domain $\{ x \in N \mid \mathit{type}(x) = \textsc{or} \}$ such that

$$\mathit{default}(x) = y \quad \text{implies} \quad y \in \mathit{children}(x).$$

The function *default* assigns to each OR-node x one of its children as default node that becomes active once x becomes active.

Example

Example statechart



Edges

Definition (Edges)

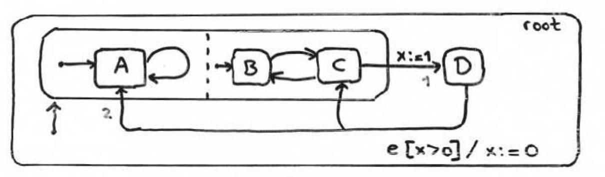
An edge is a quintuple (X, e, g, A, Y), denoted $X \xrightarrow{e[g]/A} Y$ with:

- $X \subseteq N$ is a set of source nodes with $X \neq \varnothing$
- $e \in E \cup \{ \perp \}$ is the trigger event
- $A \subseteq Act$ is a set of actions
  - such as $v :=$ expr or local variable v and expression expr
  - or *send* $j.e$, i.e., send event e to statechart SC_j
- Guard g is a Boolean expression over all variables in $(SC_1, \ldots, SC_k)$
- $Y \subseteq N$ is a set of target nodes with $Y \neq \varnothing$

The sets X and Y may contain nodes at different depth in the node tree.

Example (1)

Example statechart

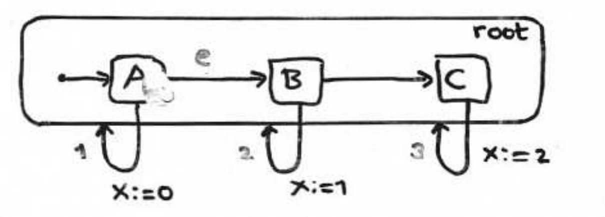


$$\text{edge 1: } \{\, C \,\} \xrightarrow{\perp[\mathit{true}]/\{\, x{:=}1 \,\}} \{\, D \,\}$$

$$\text{edge 2: } \{\, D \,\} \xrightarrow{e[x>0]/\{\, x{:=}0 \,\}} \{\, A, C \,\}$$

Example (2)

Example statechart

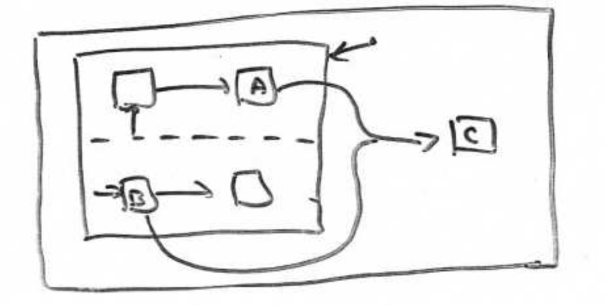


$$\text{edge 1: } \{ A \} \xrightarrow{e[true]/\varnothing} \{ B \}$$

$$\text{edge 2: } \{ B \} \xrightarrow{\bot[true]/\{ x{:=}1 \}} \{ \text{root} \}$$

Example (3)

Example statechart



$$\text{edge} : \{ A, B \} \overset{\dots}{\longrightarrow} \{ C \}$$