Compile-time Scope Resolution for Statecharts Transitions

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Resource Constrained Embedded Systems

- Wide perspective – RCES: high level programming language technology for embedded software.
- Narrower – SCOPE: efficient code synthesis for reactive concurrent control algorithms
  - aware of usage of resources (mainly memory)
  - meeting space constraints
  - control the trade-off between speed and size
- Concretely:
  - UML is a promising framework for that
  - Source language: UML-like statecharts
  - Target language: ISO C99 (perhaps more)

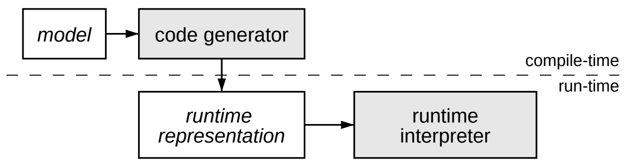
An Optimization for Statecharts Compiler

Content:

- Environment:
  - visualSTATE tool
  - visualSTATE language
- The problem
  - Multitarget transitions
  - Dynamic scopes problem
- The solution: an algorithm
- Evaluation
  - Basic properties of the algotihm
  - Relation to standard UML
  - A bit on compile-time analysis

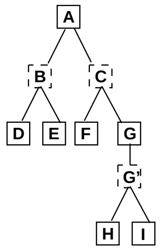
IAR visualSTATE

- Industrial CASE tool for to development of embedded software
  - UML-like statechart language
  - design environment
  - model-checker
  - animating debugger
  - code generator
- Compilation scheme:

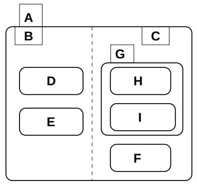


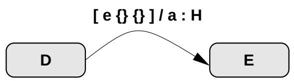
Remark: Moving some work from run-time to compile-time (across the dashed line) is a fundamental software optimization approach.

VisualSTATE Statecharts



- State hierarchy:
  - parallel and sequential decompositions
  - The *root* is an and-state
  - Basic states (leaves) are and-states
  - State type alternation
  - Orthogonal states: NCA is an and-state.
- Entry/exit actions.
- Transitions:
  - condition side: event + guard
  - executable side: action + targets





VisualSTATE Statecharts (II)

- Transitions guards:

$$g \quad ::= \quad true \mid g \wedge s \mid g \wedge \neg s \ ,$$

  where s stands for any state name.

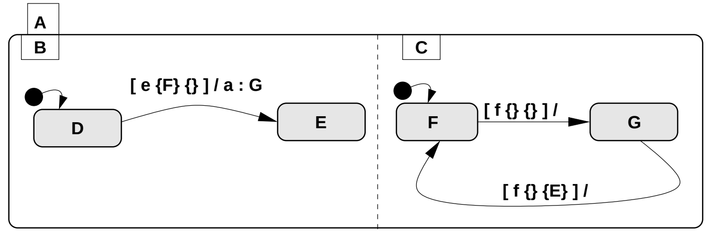
- Textual notation for transitions:

$$t: \ [e \ pos \ neg] \ / \ a \ : s_1 \ldots s_k$$

t	optional rule name,	neg	must-be-inactive states
e	triggering event,	a	action,
pos	must-be-active states,	s_i	targets

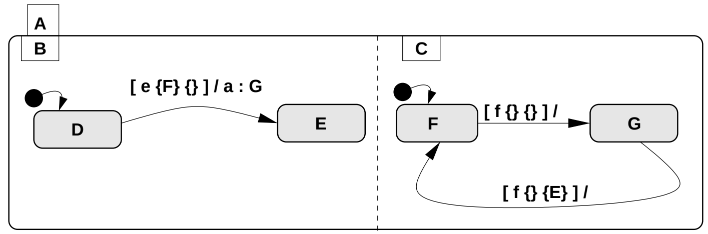
- Differences from standard UML:
  - no fork and join transitions,
  - generalized multiple targets

Multitarget Transitions: example



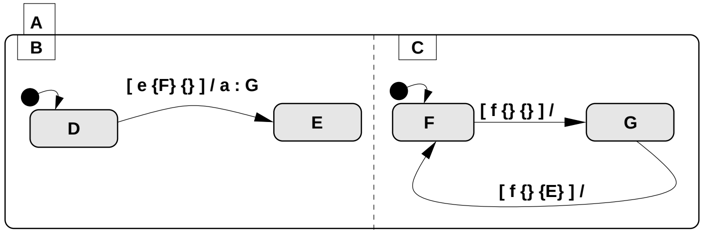
- UML conditions on targets relaxed
- Enter a state orthogonal to source of the transition

Scope of Firing a Transition



- Two transitions on the left fire within region C (the scope)
- Scope is important because it determines exit and entry actions
- Multiple targets yield multiple scopes
- Scopes for the left transition are regions B and C
  - B is the scope for target E
  - C is the scope for target G

Scope of Firing a Transition (II)



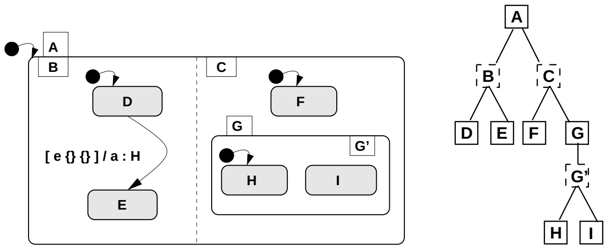
- Targets statically annotated with scopes:

$$\begin{array}{llllllllll} t_1 & : & [\ e & \{D,F\} & \{\} &]\ / & a & : & [B]E\ [C]G \\ t_2 & : & [\ f & \{F\} & \{\} &]\ / & - & : & [C]G \\ t_3 & : & [\ f & \{G\} & \{E\} &]\ / & - & : & [C]F \end{array}$$

- Cannot always be done
  - The scope occasionally depends on current configuration.

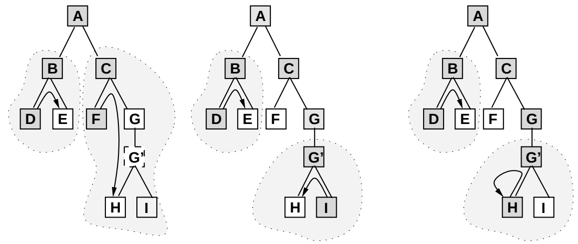
Dynamic Scope: example

- Three legal configurations activating the transition.
- All contain D.
- Also contain one of F, H or I

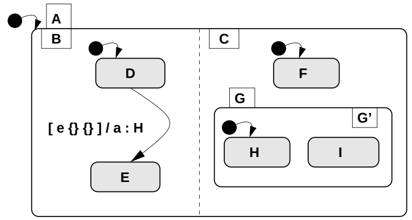


- Scope of target E is always B
- Scope of target H depends on active configuration of C ....

Dynamic Scope: example (II)



a) b) c)

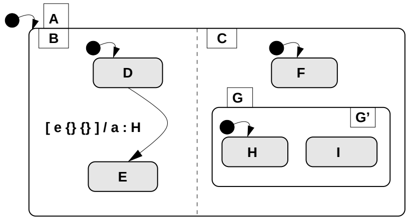


The Problem and The Solution

- Dynamic scope can only be identified at runtime.
- Detection algorithm is complicated
  - efficiency suffers
  - quality/security issues (trusted code base)
- Also all normal transitions with static scopes suffer (the majority).
- If dynamic scopes are bad – get rid of them!
  - Identify dynamically scoped transitions
  - Remove them from the model
  - Add new, equivalent, statically scoped transitions.
  - Use scope annotations at runtime

The Problem and The Solution (II)

The problematic transition in our example:



can be rewritten with two rules:

$$
\begin{array}{lcl}
[\ e\ \{D, F\}\ \{\}\ ]\ /\ a & : & [B]E\ [C]H \\
[\ e\ \{D, G\}\ \{\}\ ]\ /\ a & : & [B]E\ [G']H
\end{array}
$$

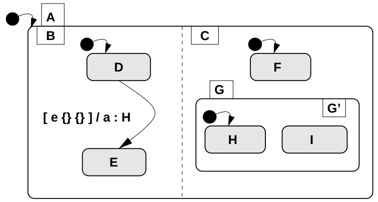
Adding extra positive conditions can ensure static scopes.

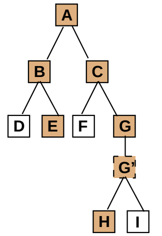
Let's make it automatic ...

Algorithm: overview

- Describe hierarchy as a boolean formula
  - For each and-state s and children $s_1, ..., s_k$ conjoin $(s \Rightarrow s_1 \wedge ... \wedge s_k) \wedge (\neg s \Rightarrow \neg s_1 \wedge ... \wedge \neg s_k)$
  - For each or-state s and children $s_1, ..., s_k$ conjoin $(s \Rightarrow s_1 \text{ XOR } ... \text{ XOR } s_k) \wedge (\neg s \Rightarrow \neg s_1 \wedge ... \wedge \neg s_k)$
  - Conjoin a simple term $(root)$, where $root$ is the top state of the hierarchy.
- Restrict it with the transition's guard.
- Eliminate irrelevant variables.
- Check the number of satisfiable assignments:
  - no solutions: transition will never fire
  - single solution: determine the static scope
  - multiple solution: the scope is dynamic

An example





Hierarchy structure:

$$
\begin{aligned}
\phi \ = \ & A \wedge (A \Rightarrow B \wedge C) \wedge (B \Rightarrow D \text{ XOR } E) \wedge (C \Rightarrow F \text{ XOR } G) \wedge \\
& \wedge \ (G \Leftrightarrow G') \ \wedge \ (G' \Rightarrow H \text{ XOR } I) \wedge (\neg G' \Rightarrow \neg H \ \wedge \ \neg I) \ .
\end{aligned}
$$

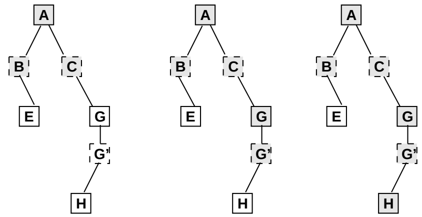
Constrained with guard:

$$\phi'(t) = \phi \wedge D$$

Existentially quantifed over all non-ancestors and non-target:

$$\phi''(t) = (\exists D, F, I).\ \phi'(t)$$

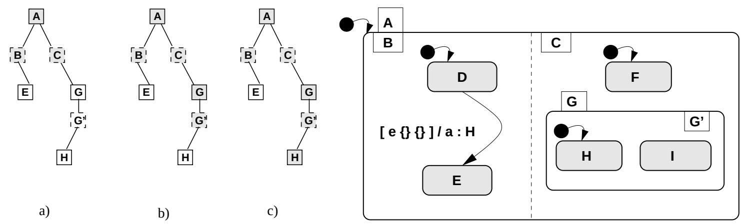
Identify Branch Exclusions



a) b) c)

Guard propagation ensures a regular shape of solutions.

Identify Branch Exclusions (II)



- Decorate transitions with branch exclusions

$$\begin{array}{lcl} [\ e\ \{D, C\}\ \{G\}\ ]\ /\ a & : & [B]E\ [C]H \\ [\ e\ \{D, G\}\ \{H\}\ ]\ /\ a & : & [B]E\ [G']H \\ [\ e\ \{D, G, H\}\ \{\}\ ]\ /\ a & : & [B]E\ [G']H \end{array}$$

- Cases b) and c) can be unified with little effort (disjoin conditions)

Characteristics

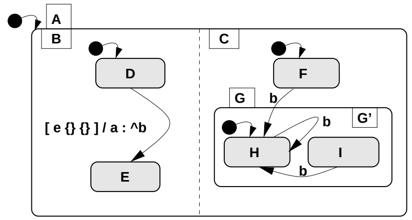
- Can entirely be performed at compile time
- Multiplies transitions only occasionally
- Multiplicity is small (and bound by depth of the hierarchy)
- Preserves the semantics
  - New guards are stronger than original
  - Newly added transitions are mutually exclusive
  - Disjunction of new guards is equivalent to original guard.
  - Other components of transition (action, targets) remain unmodified.
- Can be conveniently combined with other model transformations
  - guard minimization, transition compaction, message elimination, etc
- Demands a boolean logics SAT-solver
  - We use Binary Decision Diagrams (BDDs)
  - Implementation Buddy/Muddy

Efficiency

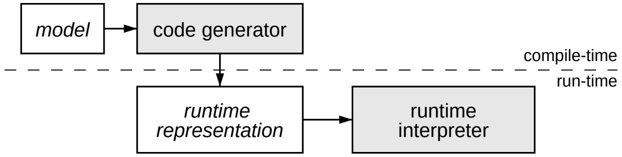
- The problem solved is substantially smaller than typical model-checking problems:
  - Only static structure is considered (no time progressing).
  - Only a subset of states needs to be represented.
  - The number of solutions is bound by the depth of hierarchy.
- 2.5s to compile a 200 transitions model (SCOPE, all incurred translation cost included)

Applications for UML

- Multitarget transitions more efficient than UML broadcasts
  - at least two microsteps are needed in message passing
- Multitarget transitions perform similar communication task as message passing.
  - RTC semantics allows to replace message passing with multitarget transition
- Conclusion: multitarget transitions may play role in compact runtime representations for statechart models.



Advocating Compile-time Analysis



- We moved scope resolution algorithm from runtime to compile time.
- A fundamental approach in compiler optimizations.
- Is it possible to propose more shifts like that?
  - Concurrent transition compaction
  - Sequential transition compaction
  - Collapsing of entry/exit rules.
  - ...
- Model-checking ...

The End

Questions?