Crossing the Gap between Semantics and Practice: Crafting a Compiler for Statecharts

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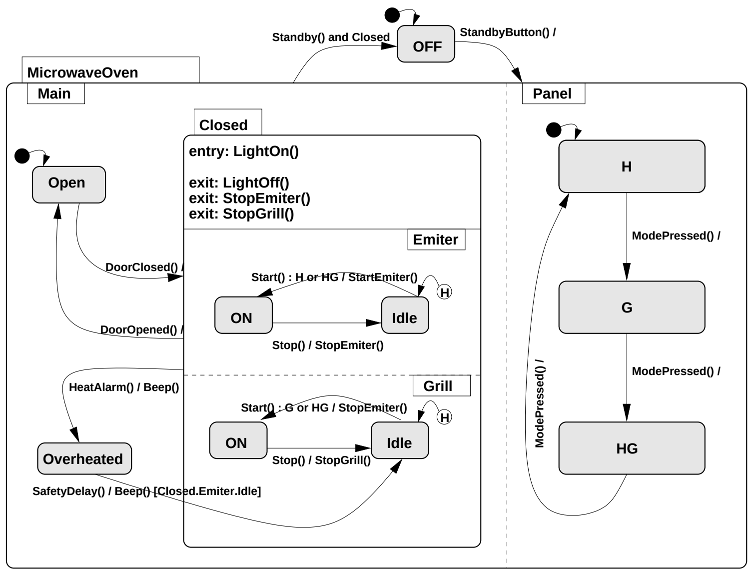
22th November 2002

Content

- Challenges in compiling statecharts
- Short survey of approaches
- Lessons learnt from implementation of SCOPE

Cooking a Statechart System



Statechart Compilation Challanges

Is it at all that challenging? An idiosyncratic list of hard problems:

- Meeting constraints: binary size, runtime memory consumption, time (often speed), power consumption
- Controlling trade offs = meeting constraints possibly cheaply (for example: balance speed and size)
- Support automatic tools: model-checkers, schedulability analysis, memory consumption analysis
- Separation of reaction speed from model size:
  - Natural for Java programs!
- From explicit states to implicit states: Algorithm abstraction and model minimization via transformations.

Not all are solvable, some not solved, some not yet solved satisfactorily.

Methods Overview

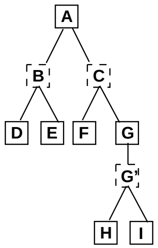
Only methods compiling *for execution* (not for model-checking, etc)

- Simple interpretive
  - Transformation based
  - Flattening
  - Object-oriented
- Reducing to SAT problem (BDD based)
- Synchronous

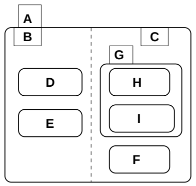
Disclaimer: tool and authors references are mostly examples of use, not contributions.

More in upcoming survey report on compiling statecharts (time analysis oriented, verification oriented, hardware oriented, other target formalisms, etc).

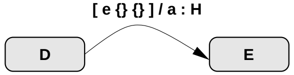
Language of Statecharts



- State hierarchy:
  - parallel and sequential decompositions
  - The *root* is an and-state
  - Basic states (leaves) are and-states
  - State type alternation



- Entry/exit actions.
- Transitions:
  - condition side: event + guard
  - executable side: action + targets



Language of Statecharts (II)

Abundance of additional constructs:

- initial, history and deep history states
- internal reactions
- join and fork transitions
- do reactions, final states and termination transitions
- event-less transitions
- special events, f.eg. en(s), ex(s), timer events
- special actions (timer actions)
- call events and signal events

Dynamic Semantics

- Semantics of statecharts is usually defined in operational way
- Decomposed into several relations:
  - macrostep
  - microstep
  - fire
  - exit
  - enter
  - execute action/evaluate guard
  - init
- Details differ among authors (no standard semantics)

Simple Interpretive Method

- Remain close to semantics.
- Code Generator: runtime representations of
  - hierarchy,
  - transitions,
  - queues,
  - state vectors, etc.
- Runtime library: counterparts of behavioral relations:

```
macrostep : event   * state -> state
microstep : event   * state * queue -> state * queue
fire      : tran    * state * queue -> state * queue
exit      : orstate * state * queue -> state * queue
enter     : targets * orstate * state * queue
                                    -> state * queue
```


Simple Interpretive Method (II)

- Advantages:
  - Easier to understand and communicate
  - Raises confidence in correctness
- Disadvantage: complicated runtime logics
- In generic form does not addresses any of the challanges

[Behrmann/Kirstoffersen/Larsen NWPT'99]

[STARC, Erpenbach, PhD thesis, Paderborn, 2000]

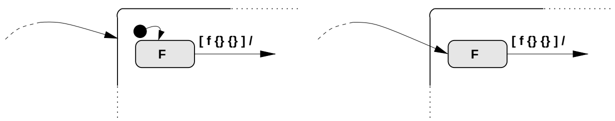
[SCOPE, Wasowski, IT Copenhagen, 2002]

Reductions in Execution Model

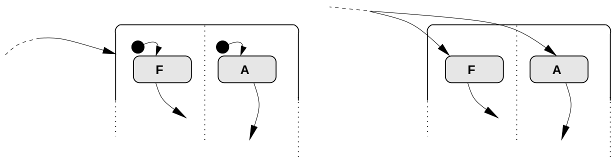
- Express some model elements in terms of simpler constructs
- Expand runtime representation (Code Generator)
- Simplify execution model (runtime interpreter)
- Example of reductions:
  - Initial states elimination
  - Entry/exit actions elimination
  - Hierarchy elimination
  - Message passing elimination
- Reduction calls for proof of correctness of respective transformation

Initial States Elimination

- Trivial in absence of history and concurrency



- Explodes in presence of heavy concurrency

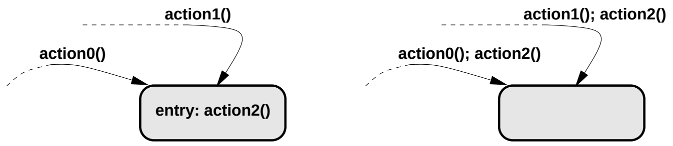


- In presence of history explodes even more.

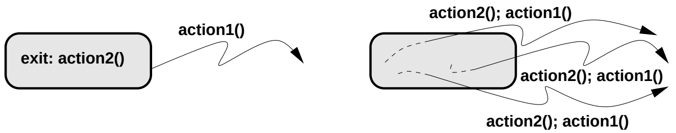
[iState, Sekerinski Zurob, McMaster University, Ontario, 2001]

Elimination of Entry/Exit Actions

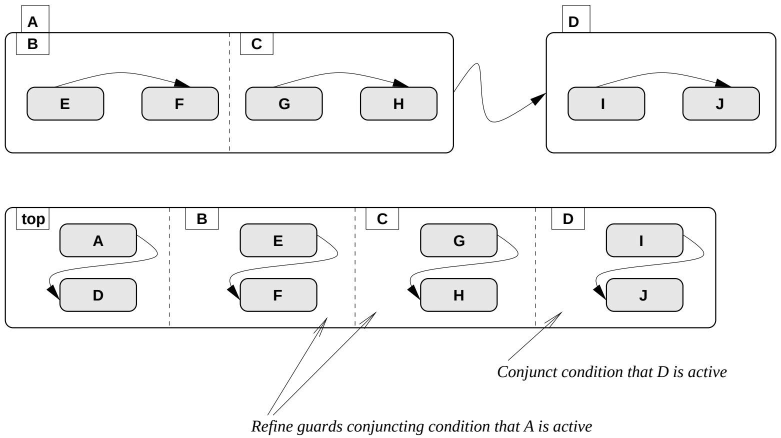
- Add entry actions of all states on the way (not only the last one!)
- Expensive for dense models (many entry actions + many transitions targetting the same state)



- Much more expensive for exit actions.



Flattening = Hierarchy Elimination



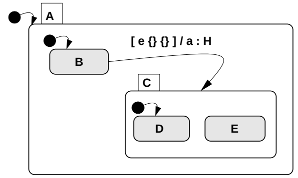
[Patent by Leerberg, Hulgaard, Lind-Nielsen, Andersen, Larsen, Kristoffersen, Behrmann, 1999]

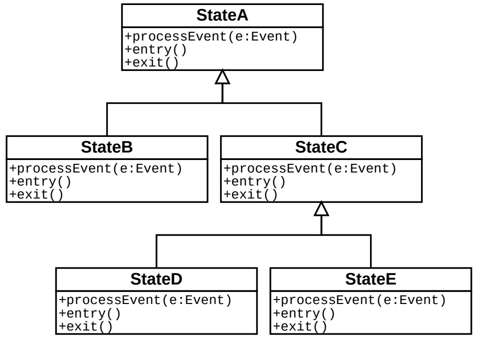
[Björklund, Lilius, Porres, Turku, Finland, 2001]

Object-Oriented Approach: New?

[Rhapsody (I-Logix), Rose RT (Rational Rose), Fujaba (Zündorf)...]

- Mostly variations of simple interpretive method
  - encode semantics using objects, methods and switch statements
- State pattern





- Reflect complete metamodel to obtain all features

[Hugo (Knapp, Merz, Munich, 2002)]

Reducing to SAT (BDD based)

- Encode state diagram semantics as SAT problem.
- Transition:

$$t_i \ : \ [\ e_i\ pos_i\ neg_i\ ]/a_i : s_1^i, ..., s_k^i]$$

  a conjunction of boolean formulas representing elements.
- actions being an integer identifier (handle guards similarly)
- A separate set of variables for target states (in addition to one used in guard)
- System encoded as disjunction of all transitions:

$$\phi = \bigvee_{t_i \in Trans} (\phi_{e_i} \wedge \phi_{pos_i} \wedge \phi_{neg_i} \wedge \phi a_i \wedge \phi_{s_1^i} \ldots \wedge \phi_{s_k^i})$$

- Compile-time: build the BDD representing ϕ
- Runtime: traverse satisfying paths of BDD to find out the next state

BDD engine becomes an interpreter!

Reducing to SAT (BDD based) (II)

- Peter Jacobsen (masters thesis, Technical Univeristy of Denmark, Lyngby 1999)
- Implemented for sublanguage
  - no internal signals, no variables and no hierarchy
- Advantage: cute theoretical formulation
- Drawback: Rather mean results (hardly beats visualSTATE)
- Useless if heavy synchronization via message passing employed.

The Argos Way

[Florence Maraninchi, VERIMAG, 1991]

- Argos: a variant of statecharts
- No queues, no level-crossing transitions, no fancy elements
- Fully synchronous semantics (after model of Esterel)
- Semantics by expansion to single Mealy machine (flat&sequential).
- Implicitly encoded in system of boolean flow equations
- Flows are sequences of boolean values

The Argos Way (II)

- $i := \mathrm{EQU}(b, g, v)$ defines i to be

$$i_0 = \begin{cases} b_0 & \text{if } g_0 \\ v & \text{otherwise} \end{cases} \qquad i_n = \begin{cases} b_n & \text{if } g_n \\ i_{n-1} & \text{otherwise} \end{cases}$$

- $i := \mathrm{MEM}(b, g, v)$ defines i to be

$$i_0 = v \qquad i_n = \begin{cases} b_{n-1} & \text{if } g_{n-1} \\ i_{n-1} & \text{otherwise} \end{cases}$$

- A boolean flow for state s is $s := \mathrm{MEM}(rp, true, initial)$, where

$$rp = (s \wedge \bigwedge_{(s,g,\_,\_)\in Trans} (\neg g)) \quad \vee \quad (\bigvee_{(s',g,\_,s)\in Trans} (s' \wedge g))$$

- A boolean flow for output s is $o := \mathrm{EQU}(rp, true, v)$, where

$$rp = \bigwedge_{(s,g,o\in O,\_)\in Trans} (s \wedge g)$$

The Argos Way (III)

- A bit more complicated for full-blown Argos
  - Compositional (syntax directed)
  - Disjunct output string from concurrent components
  - Ensure exclusiveness of sequential components.
- Compiled to declarative format of flow equations (DC)
- The size of DC program is linear in size of Argos program (cool!)
- Original compiler had an option for controlling size-speed trade off.

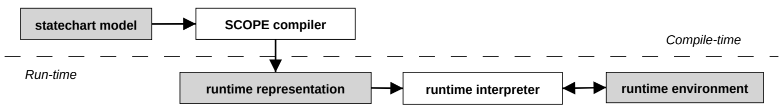
Equations for Statecharts

[Beauvais, Gautier, Le Geurnic, Houdebine, Rutten, IRISA, 1998]

- Statecharts semantics is not fully synchronous
- Each step consits of microstep
- Discrete sequences with one clock are not enough
- Need flows occuring with various frequencies wrt each other
  - So you need Signal (rather DC+) with full clock-calculus
- Flows at macrostep level, microstep level, etc
- Easy to obtain synchronous semantics for statecharts!
- Translation from DC(+) to C
  - Automaton generation explodes exponentially
    Automaton → equations → automaton ?
  - Equation preserving method: 10 × slower, hundreds × smaller
    [Amagbegnon, Besnard, Le Guernic, IRISA-INRIA, 1995]:
    canonicize equations and organize in hierarchy
    hierarchy → clock equations → hierarchy ?

StateChart cOmPilEr = SCOPE

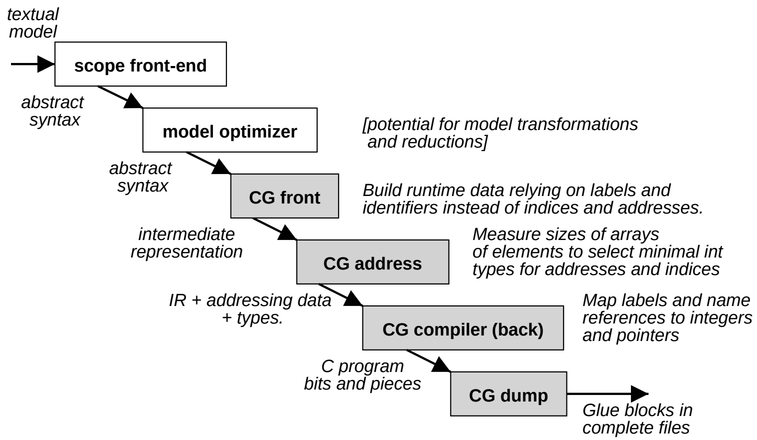
- Extremely high-level code generator, very close to operational semantics
- Compiles visualSTATE version of statecharts.



http://www.mini.pw.edu.pl/~wasowski/scope

- Code linear in size of the model.
- Hardly ever bigger than visualSTATE.
- For moderate and bigger models: 10%-50% smaller code.
- The speed is comparable with flattening (1-2 times slower)
- Open for further optimizations.

SCOPE HOW-TO



Summary

- Method Survey
  - Problems in domain of code synthesis from statecharts
  - Several fundamental methods
    - * Still worse than hand-coding!
    - * Difficulties in evaluation
  - Yet another semantics for statecharts?
- Experience with simple high level approach (SCOPE)
  - Works quite well
  - Platform for experimentation, optimization and comparison