SPECIFICATION AND ANALYSIS OF REAL-TIME SYSTEMS IN REAL-TIME MAUDE

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CONTENT

FORMAL METHODS: KEY TRADE-OFF

expressiveness/modeling convenience $\longleftrightarrow$ analytic power

REWRITING LOGIC AND MAUDE

- modeling convenience!
- simple and intuitive
- any data type
- unbounded data structures
- simple model of concurrent objects
    - dynamic object/message creation/deletion
    - easy to define forms of communication
- hierarchical structures

- properties in general undecidable

- analysis by system execution

MAUDE AND REAL-TIME SYSTEMS

(How) can we model and analyze real-time systems in rewriting logic so that the advantages of Maude are maintained?

MODELING AND ANALYZING REAL-TIME SYSTEMS WITH REAL-TIME MAUDE

MOTIVATION

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  - toasters
  - cars, airplanes, ...
  - e-banking

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- timed models enable reasoning about performance

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- time key in most systems
  - toasters
  - cars, airplanes, ...
  - e-banking
- scheduling algorithms
- timed models enable reasoning about performance
- timed properties important
  - airbag must deploy within 10ms of a crash

MAIN CHALLENGE

How to deal with dense time?

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Why dense time ($\mathbb{R}_{\geq 0}$, $\mathbb{Q}_{\geq 0}$, ...)?

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Why dense time ($\mathbb{R}_{\geq 0}$, $\mathbb{Q}_{\geq 0}$, ...)?

- "real" real-time system
- techniques useful for discrete-time systems
  - example: events take place approximately once per 10,000 ms

REAL-TIME MAUDE [ÖLVECZKY AND MESEGUER '04, '06, ÖLVECZKY'14]

Real-Time Maude:

- Extends Maude to model and analyze real-time systems
- Object-oriented modeling of distributed real-time systems
- Implemented in Maude as an extension of Full Maude
- `http://www.ifi.uio.no/RealTimeMaude`

REAL-TIME MAUDE MODELING

- Data types modeled by algebraic equational specification
  - parametric time domain
  - built-in time domains `NAT-TIME-DOMAIN-WITH-INF`, `POSRAT-TIME-DOMAIN-WITH-INF`, ...

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- Instantaneous transitions modeled by rewrite rules

```
crl [l] : t => t' if cond
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- Instantaneous transitions modeled by rewrite rules

crl [*l*] : *t* => *t′* if *cond*

- Time advance modeled explicitly by tick rewrite rules

crl [*l*] : {*t*} => {*t′*} in time τ if *cond*

  - global state has form {*t*}
  - ensures uniform time elapse

REAL-TIME MAUDE ANALYSIS

- Timed rewriting
  - simulate system to time T
- Timed reachability analysis
  - find states reachable in time interval
- LTL model checking
  - unbounded
  - time-bounded
    - finite reachable state space

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- Timed CTL model checking
- “Find earliest” and “find latest” ...

“Time sampling” discretization of dense time (see below)

MODELING IN REAL-TIME MAUDE

EXAMPLE: "RETROGRADE" CLOCK

- State: {clock(r)} or {stopped-clock(r)}
- Dense time domain
- Clock can stop at any time
- Retrograde clock: clock(12) must be reset to clock(0)

REAL-TIME MAUDE SPECIFICATION

```
(tmod DENSE-CLOCK is pr POSRAT-TIME-DOMAIN .
  ops clock stopped-clock : Time -> System .
  vars R R' : Time .

  crl [tickWhenRunning] :
      {clock(R)} => {clock(R + R')} in time R'
        if  R' <= 12 - R  [nonexec] .

  rl [tickWhenStopped] :
     {stopped-clock(R)} => {stopped-clock(R)} in time R'
                                    [nonexec] .

  rl [reset] :   clock(12) => clock(0) .

  rl [batteryDies] :  clock(R) => stopped-clock(R) .
endtm)
```

NEXT EXAMPLE: SINGLE IMPRECISE CLOCK

- One clock
- Imprecise: goes faster or slower than "real time"
  - given by its rate

MODELING SINGLE IMPRECISE CLOCK

```
(tomod SINGLE-SKEWED-CLOCK is pr POSRAT-TIME-DOMAIN .

  class Clock | running : Bool, time : Time, rate : PosRat .

  var C : Oid .  vars R R' : Time .  var RATE : PosRat .

  crl [tickRunning] :
      {< C : Clock | running : true, time : R, rate : RATE >}
    =>
      {< C : Clock | time : R + (RATE * R') >} in time R'
    if R' <= (12 - R) / RATE [nonexec] .

  rl [tickStopped] :
     {< C : Clock | running : false >}  =>  {< C : Clock | >}
      in time R'  [nonexec] .
```

MODELING SINGLE IMPRECISE CLOCK (CONT.)

```
  rl [reset] :
     < C : Clock | running : true, time : 12 >
  =>
     < C : Clock | time : 0 > .

  rl [break] :
     < C : Clock | running : true >
  =>
     < C : Clock | running : false > .
endtom)
```

ANOTHER EXAMPLE: MULTIPLE IMPRECISE CLOCKS

We now model many imprecise clocks.

- Instantaneous rules as before
- Single tick rule:

```
var CLOCKS : Configuration .   var R' : Time .

crl [tick] :
    {CLOCKS}  =>  {advanceTime(CLOCKS)} in time R'
    if R' <= maxTimeAdvance(CLOCKS) .
```

MULTIPLE IMPRECISE CLOCKS (CONT.)

```
vars CLOCKS CLOCKS' : Configuration .

op advanceTime : Configuration Time -> Configuration [frozen (1)]

ceq advanceTime(CLOCKS CLOCKS', R)
  = advanceTime(CLOCKS, R)  advanceTime(CLOCKS', R)
   if CLOCKS =/= none and CLOCKS' =/= none .

eq advanceTime(< C : Clock | running : true, time : R,
                             rate : RATE >, R')
 = < C : Clock | time : R + (R' * RATE) >

eq advanceTime(< C : Clock | running : false >, R')
 = < C : Clock | > .
```

MULTIPLE IMPRECISE CLOCKS (CONT.)

```
op maxTimeAdvance : Configuration -> TimeInf [frozen (1)] .

ceq maxTimeAdvance(CLOCKS CLOCK')
  = min(maxTimeAdvance(CLOCKS), maxTimeAdvance(CLOCKS'))
   if CLOCKS =/= none and CLOCKS' =/= none .

eq maxTimeAdvance(< C : Clock | running : true, time : R,
                                rate : RATE >)
 = (12 - R) / RATE .

eq maxTimeAdvance(< C : Clock | running : false >) = INF .
```

MULTIPLE IMPRECISE CLOCKS (CONT.)

Suitable initial state is

```
{< ap : Clock | running : true, time : 0, rate : 5/4 >
 < seiko : Clock | running : true, time : 0, rate : 1 >
 < casio : Clock | running : true, time : 0, rate : 99/100 >}
```

ANOTHER EXAMPLE: POPULATIONS

Many people (cont):

- Time passes uniformly for all living persons
    - everybody birthday same time

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- Time passes uniformly for all living persons
    - everybody birthday same time
- Engagements, weddings, etc. instantaneous actions
- Must ensure nobody older than 1000!

POPULATIONS (CONT.)

Engagement normal instantaneous rule:

```
crl [engagement] :
    < P : Person | age : N, status : single >
    < P' : Person | age : M, status : single >
  =>
    < P : Person | status : engaged(P') >
    < P' : Person | status : engaged(P) >
  if N > 15 and M > 15 .
```

POPULATIONS: TICK RULE

Time can pass by many milliseconds/days/years up to age limit:

```
var PERSONS : Configuration .  var R : Time .

crl [tick] :
    {PERSONS}  =>  {advanceAge(PERSONS, R)}  in time R
   if R <= maxTimeAdvance(PERSONS) [nonexec] .
```

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```

- `advanceAge` increases age of each living person by `R`
- `maxTimeAdvance` ensures noone gets older than 1000

Exercise

Define the functions `advanceAge` and `maxTimeAdvance`

OO SPECIFICATIONS

Generalizing: OO system has many instantaneous rules and usually one tick rule

```
var STATE : Configuration .  var R : Time .

crl [tick] :
    {STATE}  =>  {timeEffect(STATE, R)}  in time R
   if R <= maxTimeAdvance(STATE) .
```

- `timeEffect(STATE, R)` defines how the elapse of time `R` affects the state `STATE`
- `maxTimeAdvance(STATE)` defines how much time can advance before something must happen

OO SPECIFICATIONS II

timeEffect and maxTimeAdvance distribute over objects and messages in a configuration:

```
vars C1 C2 : Configuration .

ceq timeEffect(C1 C2, R)
  = timeEffect(C1, R)  timeEffect(C2, R)
 if C1 =/= none and C2 =/= none .

eq timeEffect(none, R) = none .

ceq maxTimeAdvance(C1 C2)
  = min(maxTimeAdvance(C1), maxTimeAdvance(C2))
 if C1 =/= none and C2 =/= none .

eq maxTimeAdvance(none) = INF .
```

These functions must be defined for single objects and messages

MODELING MESSAGE DELAYS

Message delays (communication time):

1. Message delay any value $\in [0, \infty]$
2. Message delay exactly Δ
3. Message delay at least Δ
4. Message delay between 0 and Δ
5. Message delay Δ_1 and Δ_2

MODELING MESSAGE DELAYS: CASE 1

Case 1: delay could be anything:

- sender sends standard message
- receiver reads standard message
- `eq timeEffect(msg, R) = msg .`
- `eq maxTimeAdvance(msg) = INF .`

MODELING MESSAGE DELAYS: CASES 2 AND 3

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“Delayed” message `dly(msg, r)` where r is remaining delay

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op dly : Msg Time -> DlyMsg [ctor right id: 0]
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How do we model Case 3 (delay at least Δ)?

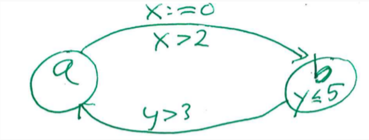
Only change: `eq maxTimeAdvance(dly(M, R)) = INF`

MORE MESSAGE DELAY

Exercise

How do we model Cases 4 and 5?

REPRESENTING TIMED AUTOMATA



State: {*location*, *xVal*, *yVal*}

```
vars X Y R : Time .

rl [tick-a] : {a, X, Y} => {a, X+R, Y+R} in time R [nonexec] .

crl [tick-b] :  {b, X, Y}  =>  {b, X+R, Y+R} in time R
                if R <= 5-Y [nonexec] .

crl [ab] :  {a, X, Y}  =>  {b, 0, Y} if X > 2 .

crl [ba] :  {b, X, Y}  =>  {a, X, Y} if Y > 3 .
```

ANALYSIS IN REAL-TIME MAUDE

REAL-TIME MAUDE ANALYSIS

- Timed rewriting
  - simulate system to time T
- Timed reachability analysis
- LTL model checking
  - unbounded
  - time-bounded
- Timed CTL model checking

INTERNAL REPRESENTATION

- Uses Maude rewriting, search and LTL model checking
- Internal representation of states:
    1. `{`t`} in time` *totalDuration*
        - time-bounded analysis
        - reachable state space infinite

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- Internal representation of states:
  1. `{`*t*`} in time` *totalDuration*
     - time-bounded analysis
     - reachable state space infinite
  2. `{`*t*`}`
     - "system time" / "duration" abstracted away
     - does not add states
     - analysis without time bounds

RETROGRADE WATCH (AGAIN)

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  vars R R' : Time .

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MAIN CHALLENGE

How to deal with dense time?

TIME SAMPLING

- Tick rules “cover” dense time domain
  - not executable

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- “On-the-fly discretization:” time sampling strategies
  - advance time by default value Δ
  - advance time as much as possible (“event-driven simulation”)

TIME SAMPLING

- Tick rules "cover" dense time domain
  - not executable
- "On-the-fly discretization:" time sampling strategies
  - advance time by default value Δ
  - advance time as much as possible ("event-driven simulation")
- Analysis incomplete: all behaviors not covered

SIMULATION

Define time sampling:

```
Maude> (set tick def 1 .)
```

- analysis w.r.t. this strategy

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Rewriting simulates one possible behavior:

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Maude> (trew {clock(0)} in time <= 100 .)
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SIMULATION

Define time sampling:

```
Maude> (set tick def 1 .)
```

- analysis w.r.t. this strategy

Rewriting simulates one possible behavior:

```
Maude> (trew {clock(0)} in time <= 100 .)

Result ClockedSystem :
  {stopped-clock(12)} in time 100
```

TIME-BOUNDED SEARCH

- Can `{clock(8)}` be reached in time $\in [23, 25]$?

```
Maude> (tsearch {clock(0)}  =>*  {clock(8)}
            in time-interval between >= 23 and <= 25 .)
```

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- ... in time ≥ 31?

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```

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No solution
```

- ... in time ≥ 31?

```
Maude> (tsearch {clock(0)}  =>*  {clock(8)}
          in time >= 31 .)

Solution 1
TIME_ELAPSED:Time --> 32
```

SEARCH

- Can `{clock(13)}` be reached?

```
(utsearch [1] {clock(0)} =>* {clock(13)} .)
```

SEARCH

- Can `{clock(13)}` be reached?

  `(utsearch [1] {clock(0)} =>* {clock(13)} .)`

- State `{clock(13)}` not found:

  `(utsearch [1] {clock(0)} =>* {clock(1/2)} .)`

SOUND AND COMPLETE UNTIMED ANALYSIS

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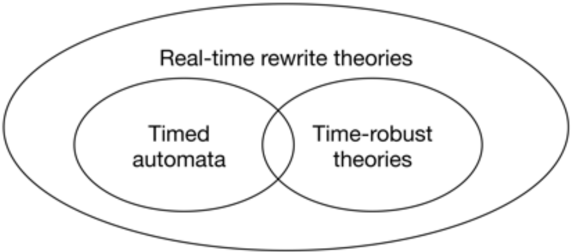
- All behaviors not covered
  - analysis not sound/complete
  - states reached and LTL counterexamples are correct

SOUND AND COMPLETE UNTIMED ANALYSIS

- Time sampling discretization of dense time
- All behaviors not covered
  - analysis not sound/complete
  - states reached and LTL counterexamples are correct
- Maximal time sampling analysis sound and complete for time-robust models [Ölveczky-Meseguer'06]
  - events at given times
  - atomic propositions not modified by ticks
- Sound/complete analysis for systems beyond timed automata



TIMED TEMPORAL LOGIC

- So far: untimed properties/temporal logic
  - "the airbag must eventually deploy after crash detected"
  - "BO eventually closes G"

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- So far: untimed properties/temporal logic
  - “the airbag must eventually deploy after crash detected”
  - “BO eventually closes G”
- Timed temporal logics
  - “the airbag must deploy within 10ms after crash”
  - “BO closes G within one year of inauguration”

REAL-TIME MAUDE'S TCTL MODEL CHECKER

- Explicit-state timed CTL model checker for Real-Time Maude
- TCTL: temporal operators with time intervals: $\exists\, \phi\, \mathcal{U}_{[r_1,r_2]}\, \phi'$
  - $\forall\Box\,(\mathit{crash} \implies \forall\Diamond_{\leq 10ms}\ \mathit{airbagDeployed})$
  - $\forall\Box\,((\mathit{inauguration}(BO) \wedge \mathit{open}(G)) \implies \forall\Diamond_{\leq one\ year}\ \mathit{closed}(G))$

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- Explicit-state timed CTL model checker for Real-Time Maude
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  - $\forall\Box\,(\mathit{crash} \Longrightarrow \forall\Diamond_{\leq 10ms}\, \mathit{airbagDeployed})$
  - $\forall\Box\,((\mathit{inauguration}(BO) \wedge \mathit{open}(G)) \Longrightarrow \forall\Diamond_{\leq \mathit{one\ year}}\, \mathit{closed}(G))$
- `(mc-tctl {clock(6)}|= EF[<= than 8] clock-is(12) .)`

D. Lepri, E. Ábrahám, P.C. Ölveczky: Sound and complete timed CTL model checking of timed Kripke structures and real-time rewrite theories. Science of Computer Programming 99 (2015)

INTENDED SEMANTICS

What is the intended semantics of a Real-Time Maude model?

$\{clock(R)\} \to \{clock(R + R')\}$ **in time** R' **if** $R' \leq 12 - R$

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- Should $\forall \Diamond_{[1,2]}$ `True` hold from $\{clock(0)\}$?
- Pointwise semantics
  - only visited states into account
  - $\forall \Diamond_{[1,2]}$ `True` does not hold from $\{clock(0)\}$
- Continuous semantics
  - tick rule interpreted as representing continuous process
  - $\forall \Diamond_{[1,2]}$ `True` holds from $\{clock(0)\}$

SOUNDNESS AND COMPLETENESS

Soundness and completeness for maximal time sampling analyses of untimed TL do not carry over to timed CTL

- maximal time sampling analysis does not satisfy $\exists \Diamond_{[1,2]} \texttt{True}$
- ... or $\forall \Diamond_{[1,2]} \texttt{True}$

SOUND AND COMPLETE TCTL MODEL CHECKING

- Continuous and pointwise interpretation

SOUND AND COMPLETE TCTL MODEL CHECKING

- Continuous and pointwise interpretation
- Time-sampling-based sound and complete TCTL model checking for time-robust Real-Time Maude models
  - advance time by

$$\frac{gcd(numbers\ in\ formulas, max-tick\ durations)}{2}$$

TIMED CTL MODEL CHECKING (II)

- Not reducible to Maude model checking
- No counterexamples/witnesses

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- Crossing-the-Bridge benchmark comparison:

Initial state	TSMV	Real-Time Maude (pointwise)	Real-Time Maude (continuous)	RED 7.0
init(1)	0.074	0.149	1.266	0.429
init(10)	0.148	0.168	0.999	0.408
init(100)	1.443	0.168	1.012	0.404
init(1000)	57.426	0.327	1.014	0.426
init+(2)	0.191	0.746	6.864	1.044
init+(4)	0.280	1.772	17.752	2.153
init+(8)	0.759	5.227	57.580	16.912
init+(12)	1.080	11.198	129.957	79.319
init+(16)	1.515	19.620	233.414	241.098

Execution times for the bridge crossing problem (in seconds).

IN CONTEXT (I)

- Timed automata
  - restricted formalism . . .
  - . . . many properties decidable
  - state-of-the-art tools: UPPAAL, RED
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- IF, TE-LOTOS, etc:
  - separate formalisms for data types, dynamic behavior, and time
  - unclear or non-existing semantics
  - based on fixed communication primitives
- MOBY/RT
  - designs specified as PLC-automata
  - translated into timed automata for model checking
- BIP (Behavior, Interaction, Priority)
  - "Behavior is described as a Petri net extended with data and functions described in C"

IN CONTEXT (II)

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- expressive
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- properties in general undecidable
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APPLICATIONS

THE MAIN QUESTION

Complex data types; unbounded data structures; flexible communication models; hierarchical objects; dynamic object creation/deletion; ...

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Are there systems where Real-Time Maude's expressiveness needed

and

Real-Time Maude analysis yields interesting results?

CLASSES OF APPLICATIONS

- “Concrete” systems/protocols
- Semantic framework for real-time systems
- Formal analysis tool for other languages
- ...

AER/NCA [WITH C. TALCOTT AND OTHERS]

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Key Real-Time Maude features:

- detailed parametric model of communication
- laaaaarge functions
- multiple class inheritance to combine subprotocols

CASH SCHEDULING ALGORITHM [ÖLVECZKY-CACCAMO'06]

CASH: State-of-the-art scheduling algorithm

- A job can use more or less time than allocated
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Key Real-Time Maude feature: unbounded data structures

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Key Real-Time Maude features:

- easy to define “new” model of communication
- complex data types and functions (areas, angles, distances)
- simulation

MEGASTORE AND MEGASTORE-CGC [GROV-ÖLVECZKY'14]

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Key Real-Time Maude features:

- simple and intuitive language
- automatic "testing" highly appreciated
- analysis of performance and correctness

HUMAN MULTITASKING [BROCCIA-MILAZZO-ÖLVECZKY'18]

Modeling and analysis framework for human multitasking

- human short-term memory
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- Will GPS distract driver for more than n seconds?
- Will other tasks make driver/pilot forget important things?

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- Found several bugs in embedded car software used by major car makers (Japan)
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- ERMTS/ETCS railway signaling and control system
- Leader election for mobile ad hoc networks
- EIGRP Cisco routing protocol (Riesco, Verdejo)
- Parts of NORM multicast protocol developed by IETF

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  - timed model transformations
    - Real-Time MOMENT-2
    - e-Motions
  - Orc, Timed Rebeca, . . .

PTOLEMY II DE MODELS [JOINT WORK WITH KYUNGMIN BAE ET AL.]

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- hierarchical composition of actors

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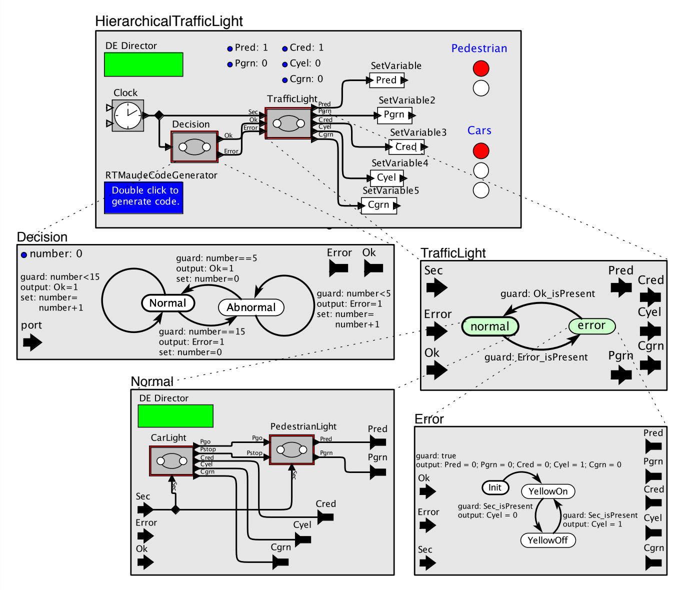
- Discrete Event (DE) models:
  - timed
  - fixed-point semantics of synchronous languages

Key Maude features:

- hierarchical configurations
- expressiveness
- unbounded data structures
- parametric atomic propositions

PTOLEMY II: FAULT-TOLERANT TRAFFIC LIGHTS



FORMAL ANALYSIS OF PTOLEMY DE MODELS

Predefined parametric propositions:

$$\textit{actorId}\ \texttt{|}\ \textit{var}_1 = \textit{value}_1, \ldots, \textit{var}_n = \textit{value}_n$$

$$\textit{actorId}\ \texttt{@}\ \textit{location}$$

$$\textit{actorId}\ \texttt{|}\ \texttt{port}\ p\ \texttt{is}\ \textit{value}$$

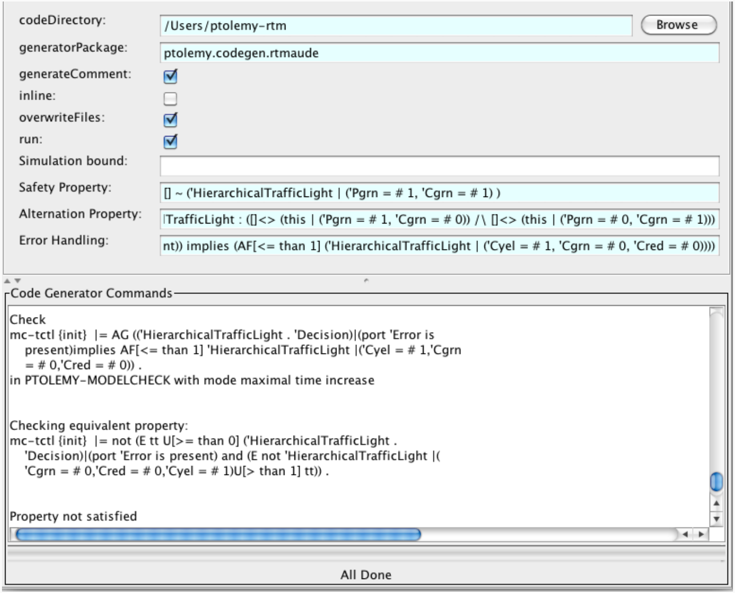
$$\textit{actorId}\ \texttt{|}\ \texttt{port}\ p\ \texttt{is}\ \textit{status}$$

A TIMED CTL PROPERTY

Car light will show only yellow within time 1 of a failure:

```
AG (('HierarchicalTrafficLight . 'Decision |
        port 'Error is present)
   => AF[<= 1] ('HierarchicalTrafficLight |
                   'Cyel = 1, 'Cgrn = 0, 'Cred = 0))
```

ANALYZING PTOLEMY II MODELS WITHIN PTOLEMY



CONCLUDING REMARKS

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- Useful both as simulation tool and model checker
- Semantics and analysis tool for modeling languages
  - model checker for free for those languages

IMMEDIATE RESEARCH CHALLENGES

COMBINING REAL-TIME AND PROBABILITIES

- Large distributed systems often real-time and probabilistic

COMBINING REAL-TIME AND PROBABILITIES

- Large distributed systems often real-time and probabilistic
- PVeStA and MultiVeStA: statistical model checking
    - estimate value of expression with statistical guarantees
    - scalable formal method
    - apply to fully probabilistic rewrite theories

COMBINING REAL-TIME AND PROBABILITIES (CONT.)

Exists:

1. Formal model for probabilistic real-time rewrite theories

   [Bentea-Ölveczky'11]

COMBINING REAL-TIME AND PROBABILITIES (CONT.)

Exists:

1. Formal model for probabilistic real-time rewrite theories [Bentea-Ölveczky'11]
2. Obtain fully probabilistic "real-time" OO models [Meseguer et al'12]:
   - message delay sampled probabilistically from dense interval
     - zero probability that two message-triggered actions enabled same time
   - estimate performance, etc, of cloud computing systems and DoS defense mechanisms

COMBINING REAL-TIME AND PROBABILITIES (CONT.)

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1. Formal model for probabilistic real-time rewrite theories [Bentea-Ölveczky'11]
2. Obtain fully probabilistic "real-time" OO models [Meseguer et al'12]:
   - message delay sampled probabilistically from dense interval
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   - estimate performance, etc, of cloud computing systems and DoS defense mechanisms

Need: theoretical model and language/tool support

- larger class of systems (message-triggered; flat OO; ad-hoc timing)
- automatic transformation to PVeStA

SYMBOLIC METHODS

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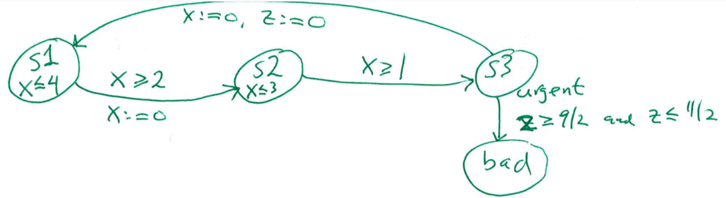
- Soundness/completeness for non-time-robust theories
  - events not at "fixed" times
- "Real-Time Maude modulo SMT"
  - full reachability analysis for timed automata (?)

REWRITING MODULO SMT: COMPLETE REACHABILITY FOR TIMED AUTOMATA (?)




```
vars x y z : Real .

crl < s1 ; x ; z > => < s2 ; 0/1 ; z >  if x >= 2/1 = true .
crl < s1 ; x ; z > => < s1 ; x + y ; z + y >  if x + y <= 4/1 =
crl < s2 ; x ; z > => < s3 ; x ; z >  if x >= 1/1 = true .
crl < s2 ; x ; z > => < s2 ; x + y ; z + y > if x + y <= 3/1 = t
crl < s3 ; x ; z > => < bad ; x ; z >  if z >= 9/2 and z <= 11/2
rl < s3 ; x ; z > => < s1 ; 0/1 ; 0/1 > .
```

REWRITING MODULO SMT: COMPLETE REACHABILITY FOR TIMED AUTOMATA (?) (CONT.)

Region reachable from some initial *x*-value?

```
Maude> smt-search [1]  < s1 ; x ; 0/1 > =>*  < bad ; y ; z >
         such that z > y and z > 2/1 = true .
```

```
Solution 1
rewrites: 26 in 21ms cpu (21ms real) (1233 rewrites/second)
state: < bad ; 0/1 + #2-y:Real ; 0/1 + #1-y:Real + #2-y:Real >
empty substitution
where z > y and z > 2/1 and x + #1-y:Real <= 4/1 and x + #1-y:Real >= 2/1 and 0
    #2-y:Real >= 1/1 and (0/1 + #1-y:Real + #2-y:Real >= 9/2 and 0/1 + #1-y:Rea
    0/1 + #2-y:Real and z === 0/1 + #1-y:Real + #2-y:Real)
```

REFERENCE PAPERS ON REAL-TIME MAUDE

- Peter C. Ölveczky: Real-Time Maude and its Applications. In Proc. WRLA 2014, volume 8663 of Lecture Notes in Computer Science, Springer, 2014.
- Peter C. Ölveczky and José Meseguer: Semantics and Pragmatics of Real-Time Maude. In volume 20(1/2) of Higher-Order and Symbolic Computation, Springer 2007.

EXERCISE

In rate-monotonic scheduling, you have given a set of periodic tasks, each with an execution time and period. When its period ends, it starts a new period. Within each period, it must execute for a total of its execution time. We assume that we have only one processor. The task with the shortest period has the highest priority to execute, and can preempt an executing task with a lpwer priority. Assume that you can have tasks with the same period/priority. Specify the rate-monotnic scheduling algorithm in Real-Time Maude, and try model checking of a few examples to check whetehr your task set is schedulable.