Unification of Model-Checking, Scheduling, and Code Synthesis:

From UPPAAL to TIMES

OUTLINE

- A Brief Introduction
  - Motivation ... what are the problems to solve
  - CTL, LTL and basic model-checking algorithms
- Timed Systems
  - Timed automata and verification problems
  - UPPAAL tutorial: data stuctures & algorithms
  - TIMES: schedulability analysis using timed automata
- Recent Work
  - The multicore timing analysis problems
  - Some solutions: WCET analysis and multiprocessor scheduling

”Who is Who” in Real Time Systems

- Real Time Scheduling [RTSS ...]
  - Task models, Schedulability analysis
  - Real time operating systems
- Automata/logic-based methods [CAV,TACAS ...]
  - FSM, PetriNets, Statecharts, Timed Automata
  - Modelling, Model checking ...
- (RT) Programming Languages [...]
  - Esterel, Signal, Lustre, Ada ...
- ... ...

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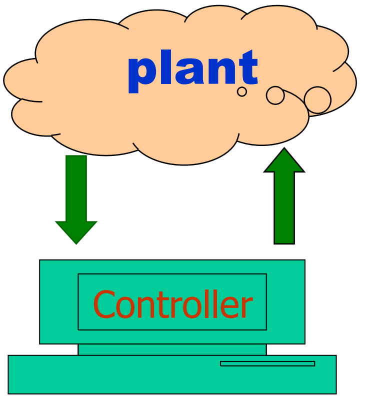
The Same Goal: Reliable Controllers

(with minimal resource consumption)



The main components of a controller
a set of tasks: P1, P2 ... Pn running on
a platform (RTOS: scheduler)

P1 || P2 || ...|| Pn || Scheduler

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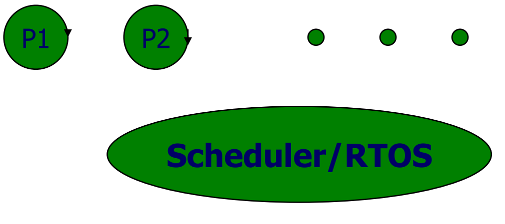
The design problem

- A set of computation tasks
  - Timing constraints: e.g. Deadlines
  - (QoS constraints: 80% of deadlines met, liveness?)
  - Release patterns i.e Task models
- Design a controller/Schedule
  - To ensure the constraints

”Classic” Real Time Scheduling

- Periodic tasks



- well-developed techniques e.g. Rate-Monotonic Scheduling

Rate-Monotonic Scheduling

- P1...Pn arrive at fixed rates
- Fixed Prioirity Order: Higher frequency => Higher priority
- Always run the task with highest priority (FPS)

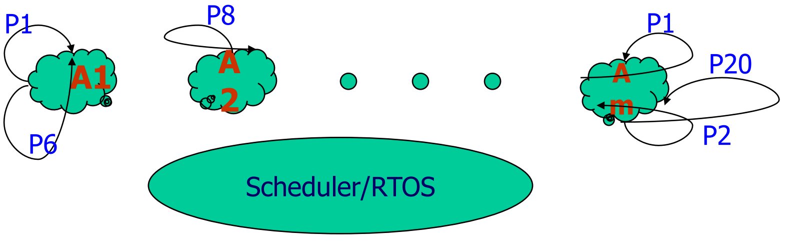
  P1 || P2 || ...|| Pn || FPS
- Schedulability can be tested by utilization bound (or equation solving)

In real life, tasks may

- share many resources (not only CPU time)
- have complex control stuctures and interactions
- have to satisfy mixed logical, temporal & resouce constraints

Automata-based Approaches

A controller = a set of timed automata accepting tasks Pi's



How to schedule tasks/automata?

The TIMES project

Tools for Modeling and Implementation of Embedded Systems

Uppsala University

Vision

- Timed Model to Executable Code Guaranteeing Timing Constraints
- Timing analysis of Concurrent and Time-Critical Software
  - Response time estimation

Problems to solve

- Schedulability analysis: check
  (A1 || A2 || ... || An || Scheduler) satisfies K
  - A scheduler is given e.g. FPS, RMS, EDF etc
  - K is a requirement specifying e.g. safety & liveness
- Schedule synthesis: find X such that
  (A1 || A2 || ... || An || X) satisfies K

All these can be automated

OUTLINE

- A Model for Timed Systems [1998]
  - Timed automata with tasks
- Schedulability and (un)Decidability [TACAS 02, IC 07]
  - Timed automata with bounded subtraction
- More Efficient Algoritms [TACAS 03, TCS 06]
  - Schedulability analysis using 2 clocks
  - (similar to Rate-Monotonic Scheduling)

Implemented in the TIMES tool

- TIMES demo

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The MODEL

(Timed Automata with Tasks)

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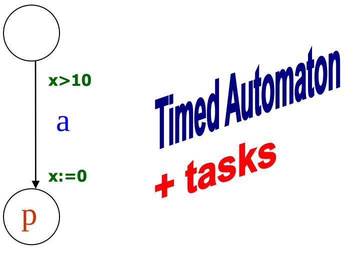
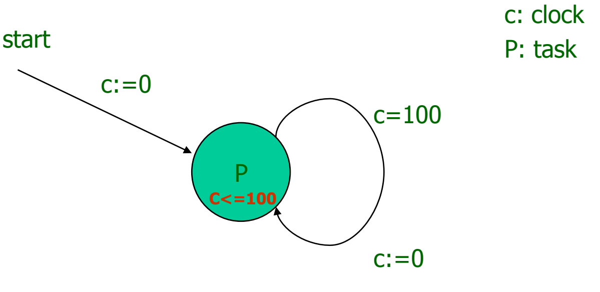
Modelling Real Time Systems

- Events
  - synchronization
  - interrupts
- Timing constraints
  - specifying event arrivals
  - e.g. Periodic and sporadic
- Tasks (executable programs)
  - interrupt processing
  - Internal computation
  - triggered by events and scheduled in the reday queue of RTOS



Example: periodic tasks



Tasks = Executable Programs (e.g. C, Java)

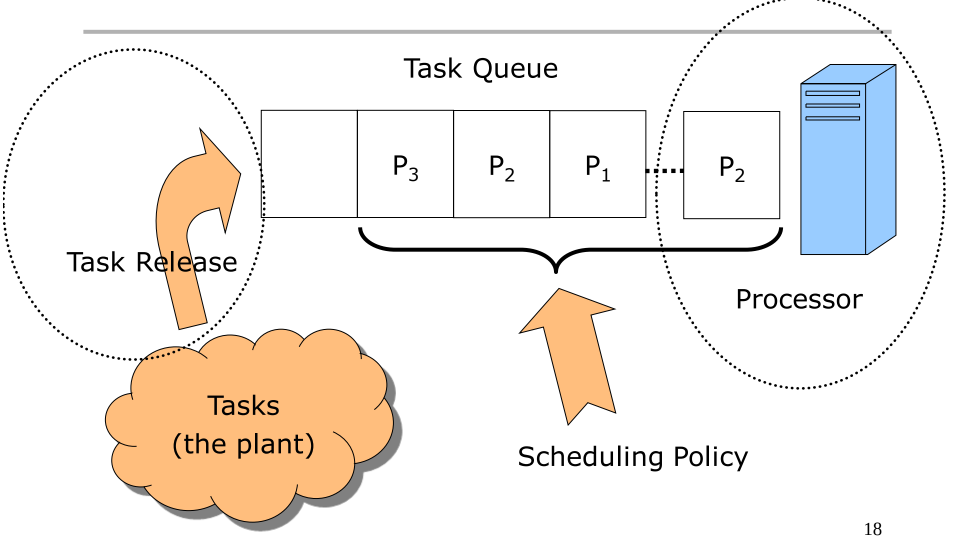
- Task parameters:
  - C: WCET
  - D: Relative Deadline
  - (other parameters for schedulling e.g. Priority)

- Task Interface:

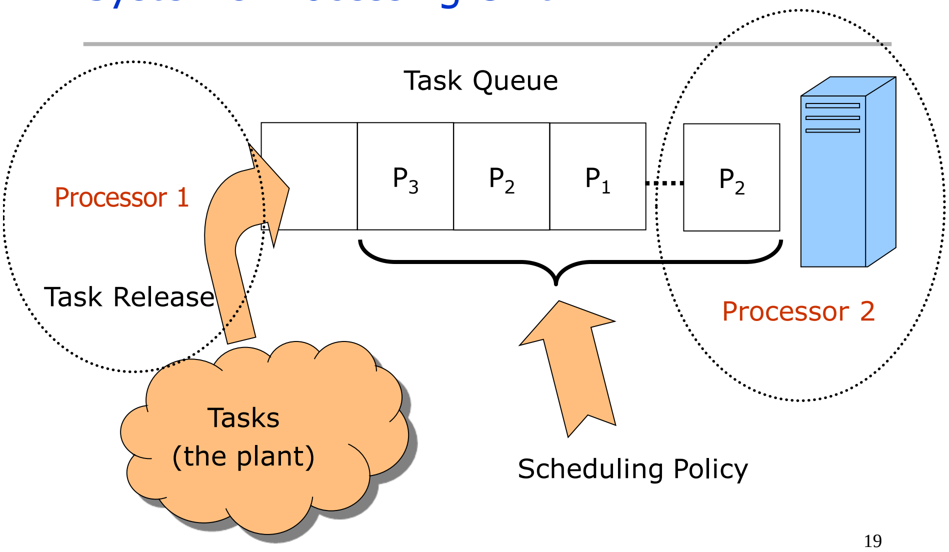
Task P
{
$v_1 := F_1(v_1 \ldots v_n)$
…
$v_n := F_n(v_1 \ldots v_n)$
}

(a set of variables updated)

System's Processing Unit



System’s Processing Unit



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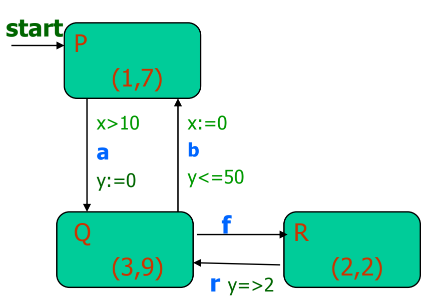
Timed Automata with Tasks (Example)



- Processor 1 (event handler)
  - Initially, P in the queue
  - Run-to-Completion/Stablization
    - Whenever **a** available and x>10, Q is put in the queue
    - Then
      - Whenever **b** available and y<=50, P is put in the queue
      - Whenever **f** available, R is put in the queue.
- Processor 2 (task handler)
  - Schedule and Compute tasks in the queue

P	P	Q	Q	Q	R	…	…	…

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Timed Automata withTasks [1998]

- Assume a set of tasks Pr
- A timed automaton with tasks is a tuple: $<N, n_0, T, M>$
  - $<N, n_0, T>$ is a standard timed automaton
    - N is a set of nodes
    - n_0 is the initial node
    - $T \subseteq N \times (B(C) \times Act \times 2^C) \times N$ is the set of 'edges'
      - C is a set of clocks
      - Act is a set of actions
      - B(C) is the set of clock constraints e.g. X <10 etc
  - $M: N \rightarrow 2^{Pr}$ is a mapping which assigns each node a set of tasks

States/Configurations of automata

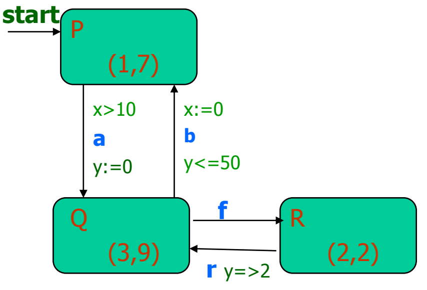
A state is a triple: (m, u, q)

Location (node)

clock assignment (valuation)

task queue

Example



Initial State: (P, x=y=0, [P(1,7)])

Example transitions:

(P, x=y=0, [P(1,7)]) –0.6→

(P, x=y=0.6, [P(0.4, 6.4)]) –9.5→

(P, x=y=10.1, []) –a→

(Q, x=10.1,y=0, [Q(3,9)]) –f→

(R, x=10.1,y=0, [Q(3,9),R(2,2)]) –2→

(R, x=12.1,y=2, [Q(3,7)]) –r→

(Q, x=12.1,y=2, [Q(3,7),Q(3,9)]) –b→

(P, x=0,y=2, [Q(3,7),Q(3,9),P(1,7]) ...

We need to handle the queue by Run and Sch

Sch and Run

- Sch is a function sorting task queues according to a given scheduling strategy e.g FPS,EDF,FIFO etc

  Example: EDF [P(2, 10), Q(4, 7)] = [Q(4, 7), P(2, 10)]

- Run is a function corresponding to running the first task of the queue for a given amount of time.

  Examples: Run(0.5, [Q(4, 7), P(2, 10)]) = [Q(3.5, 6.5), P(2, 9.5)]
  Run(5, [Q(4, 7), P(2, 10)]) = [P(1, 5)]

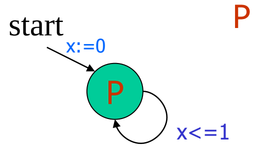
Semantics (as transition systems)

- States: <m,u,q>
  - m is a location
  - u is a clock assignment (valuation)
  - q is a queue of tasks (ready to run)

- Transitions:
  1. (m,u,q) $\xrightarrow{a}$ (n, r(u), Sch[M(n)::q]) if $m \xrightarrow{g\ a\ r} n$ & g(u)
  2. (m,u,q) $\xrightarrow{d}$ (m, u+d, Run(d,q)) where d is a real

OBS: q is growing (by actions) and shrinking (by delays)

Zenoness = Non-Schedulability



P=(2,3)

Zeno: ∞ many P's may arrive within 1 time unit !

P(2,3)	P(2,3)	P(2,3)	P(2,3)	P(2,3)	...						...

But after 2 copies, the queue will be non-schedulable

SCHEDULABILITY

Schedulability of automata

a state is a triple: (m, u, q)

location

clock assignment

task queue

- A state is schedulable if q is schedulable
- An automaton is schedulable if all reachable states are

Schedulability of Automata

Assume a scheduling policy Sch:

- A state (m,u,q) is schedulable with Sch if
  - Sch(q)= $[P_1(c_1,d_1)P_2(c_2,d_2)\ldots P_n(c_n,d_n)]$ and
  - $(c_1+\ldots+c_i)<=d_i$ for all $i<=n$ (i.e. all deadlines met)
- An automaton is schedulable with Sch if all its reachable states are schedulable
- An automaton is schedulable with a class of scheduling policies if it is schedulable with every Sch in the class.

Other verification/scheduling problems

- Location Reachability (just as for timed automata)
  - a nice property of the model !
- Boundedness of the task queue |q|<M
  - memory requirement
- Schedule synthesis

DECIDABILITY

Schedulability Analysis (Non-preemptive scheduling)

FACT [1998]

For Non-preemptive scheduling strategies,
the schedulability of an automaton can be checked
by reachability analysis on ordinary timed automata.

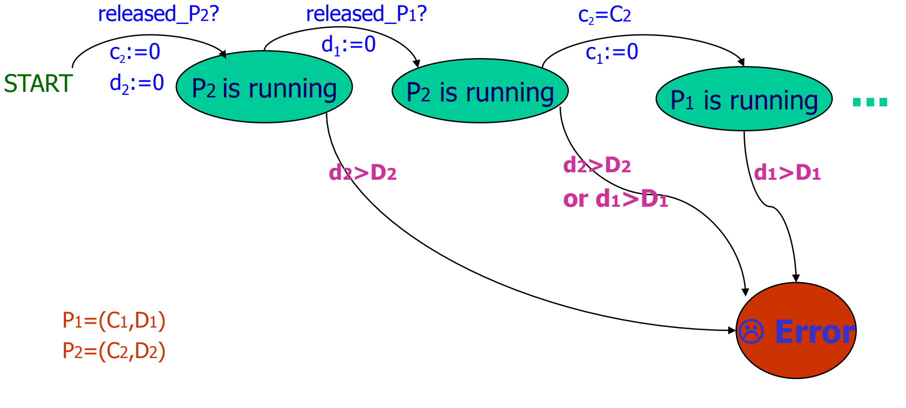
Proof ideas (1):
Size of schedulable queues is bounded

- The maximal number of instances of P_i in a schedulable queue is bounded by $Mi = \lceil Di/Ci \rceil$
- The maximal size of schedulable queues is bounded by $M1 + M2+...+Mn$

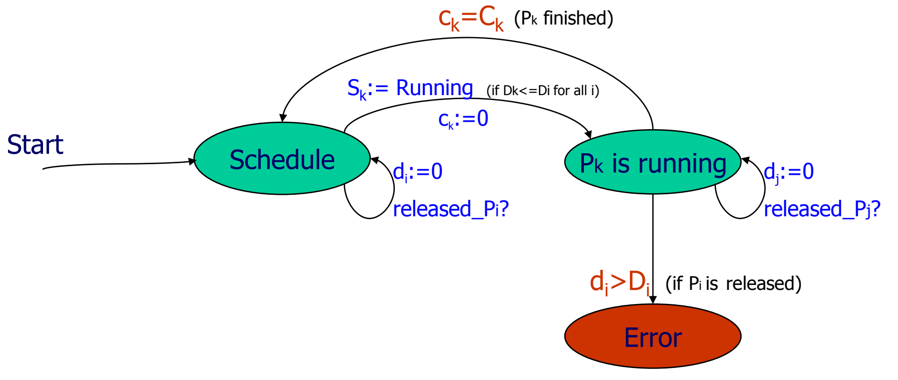
- To code the queue/scheduler, for each task instance, use 2 clocks:
  - c_i remembers the computing time
  - d_i remembers the deadline

• • •	(c_i,d_i)	• • •

Proof ideas (2):
The scheduler as an automaton



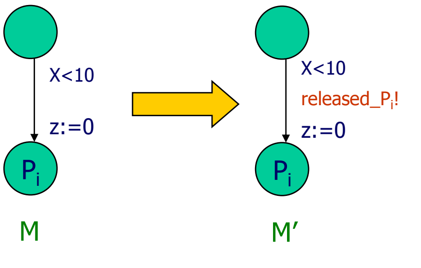
The scheduler automaton



SCHEDULER

Proof Ideas (3)

- Modify the original automaton M: adding 'release!' to inform the scheduler



- Check reachability of the error state for

  M' || SCHEDULER

How about preemptive scheduling?

- We may try the same ideas
  - Use clocks to remember computing times and deadlines
- BUT a running task may be stopped to run a more 'urgent' task
  - Thus we need stop-watches to remember computing times

Conjecture (1998):

- The schedulability problem for Preemptive scheduling is undecidable.
- The intuition: we need stop-watch to code the scheduler and the reachability problem for stop-watch automata is undecidable
- This is wrong !!!

Decidability Result [TACAS 2002]

FACT

For Preemptive scheduling strategies, the schedulability of an automaton can be checked by reachability analysis on Bounded Substraction Timed Automata (BSA).

NOTE
- Reachability for BSA is decidable
- Preemptive EDF is optimal; thus the general schedulability checking problem is decidable.

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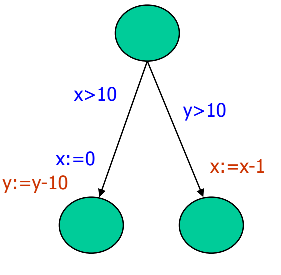
Timed automata with subtraction
i.e. Subtraction Automata, [McManis and Varaiya, CAV94]

- Subtraction automata are timed automata extended with subtraction on clocks
- That is, in addition to reset x:=0, it is also allowed to update a clock x with x:= x-n where n is a natural number



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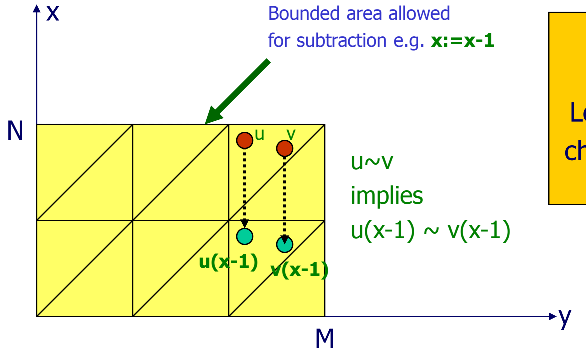
Bounded Subtraction Automata

- A subtraction automaton is bounded if its clocks are non-negative and bounded with a maximal constant (or subtraction is only allowed in the bounded zone).

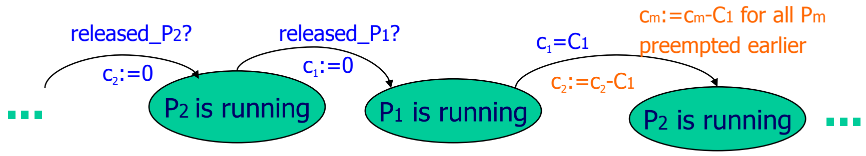


FACT:

Location Reachability checking is decidable!

Schedulability Checking as a reachability problem for Bounded Subtraction Automata

Proof ideas (no stop but subtraction :-)



- Model the scheduler as a subtraction automaton
  - Do not stop the computing clock c_2 when a new task P_1 is released
  - Let c_2 for P_2 (preempted) run until the task P_1 (with higher priority) finishes, then perform $c_2 := c_2 - C_1$ (note: C_1 is the computing time for P_1).

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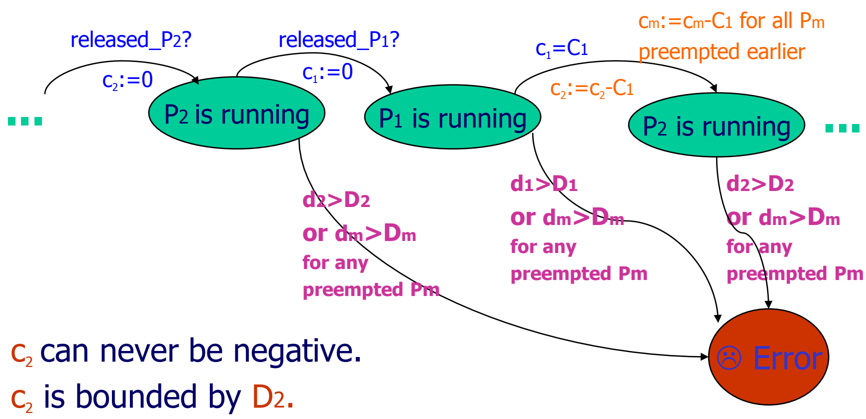
Proof ideas (clocks are bounded):



- c_2 can never be negative.
- c_2 is bounded by D_2.

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END of proof

Complexity

#clocks (needed)
= 2 x #instances (maximal number of schedulable task instances)
= 2 x $\sum_i \lceil Di/Ci \rceil$

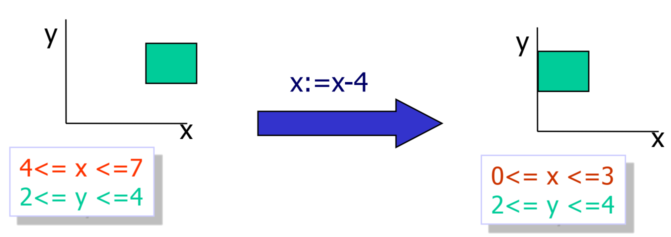
This is a huge number in the worst case
But the run-time complexity is not so bad!

It works anyway !!!

- #active tasks in the queue is normally small, and the run-time complexity is only related to #active clocks
- If Too many active tasks in the queue (i.e. Too many active clocks), the check will stop sooner and report ”non-schedulable”
- AND the analysis can be done symbolically!

Schedulability analysis based on Constraints (DBM’s)

Subtraction on Clocks, added to DBM-library (UPPAAL, Kronos)



WE CAN DO BETTER ! [TACAS 03]

For fixed priority scheduling strategies (FPS),
we need only 2 clocks (and ordinary timed automata)!

The 2-CLOCK ENCODING

(for fixed-priority scheduling strategies)

Main Idea

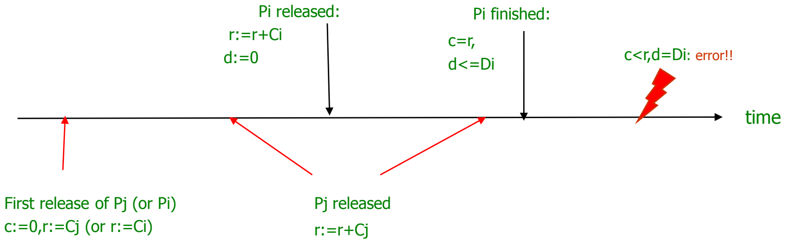
- Check the schedulability of tasks one by one according to priority order (highest priority first)
- This is similar to response time analysis in RMS

To code the queue/scheduler, we need:

- 1 integer variable for Pi:
  - r denotes the response time as in RMS (the total computing time needed before Pi finishes)
- 2 clocks for Pi:
  - c remembers the accumulated computing time (so much has been computed so far)
  - d remembers the ”deadline”

Intuition of the encoding: Ri = Ci + $\Sigma_{pri(Pj)>pri(Pi)}$ Cj

– Assume: priority(Pj) > priority(Pi) and Pi is analyzed



When Pi finishes, r = Ri

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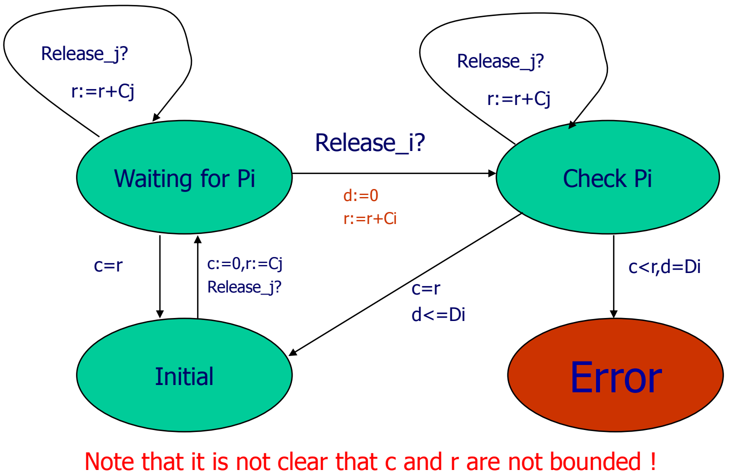
The "FPS scheduler": analyzing Pi



Note that it is not clear that c and r are not bounded !

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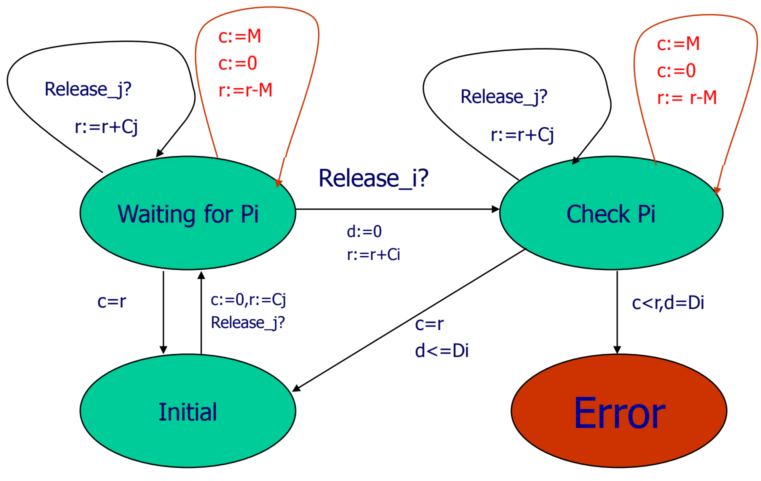
The "FPS scheduler": analyzing Pi
(we need the boundedness)



OBS: r-c is the only interesting info, so M can be any integer! Let M=Ci

c and r are bounded

- c is bounded by M
- r is bounded by r_{max} + Ci
  - Where r_{max} is the maximal value of r from previous analysis for all tasks Pj with higher priority

So the scheduler is a standard TA **END**

Decidability results

- For Non-preemptive scheduling, the problem can be solved using TA.

- For preemptive scheduling, the problem can be solved using BSA (Bounded Substraction Automata) [TACAS02]

- For fixed-priority scheduling, the problem can be solved using TA with only 2 extra clocks – similar to the classic RMA technique (Rate-Monotonic Analysis) [TACAS03]

Undecidability [TACAS 04]

Unfortunately, the problem will be undecidable if the following Conditions hold together:

1. Preemptive scheduling
2. Interval computation times
3. Feedback i.e. the finishing time of tasks may influence the release times of new tasks.

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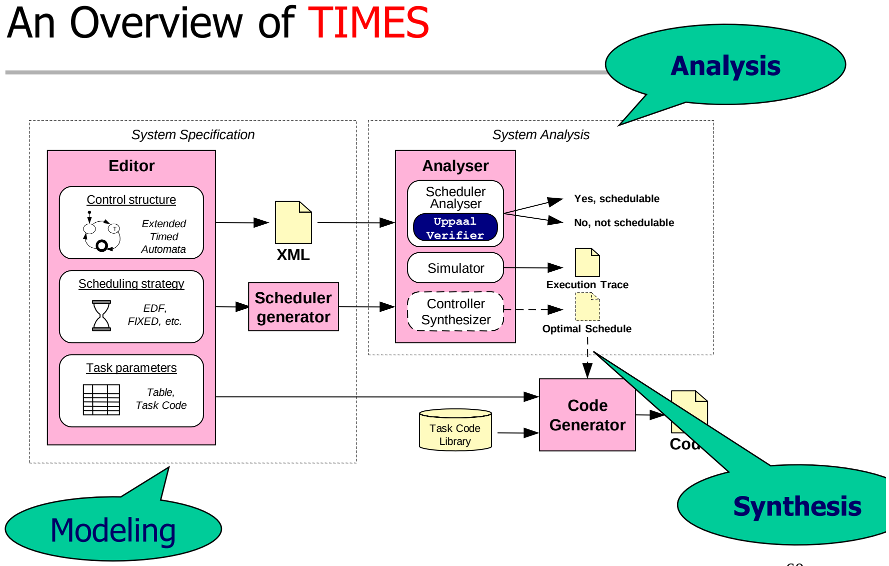
An Overview of TIMES



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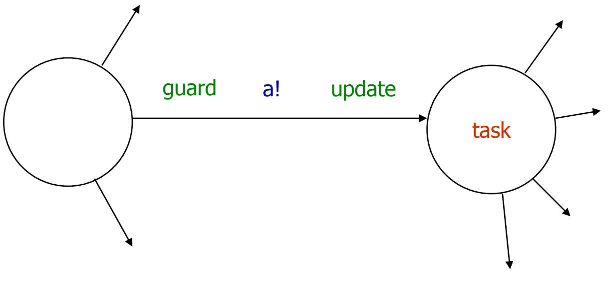
The **INPUT LANGUAGE** is very much like **”guarded commands”**

OBS: guard and update may contain data variables (integer, array)



- guard, update: ”synchronous” computation which takes ”no time”
  - we adopt the synchronous hypothesis
- task: ”asynchronous” computation whch takes time

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Tasks = Executable Programs (e.g. C, Java)

- Task Type
  - Synchronous or Asynchronous
  - Non-Periodic (triggered by events) or Periodic
- Task parameters: C, D etc
  - C: Computing time and D: Relative Deadline
  - other parameters for schedulling e.g. priority, period
- Task Interface (variables updated ’atomically’)
  - $X_i := F_i(X_1 \ldots X_n)$
- Tasks may have shared variables
  - with automata
  - with other tasks (priority ceiling protocols)
- Tasks with Precedence constraints

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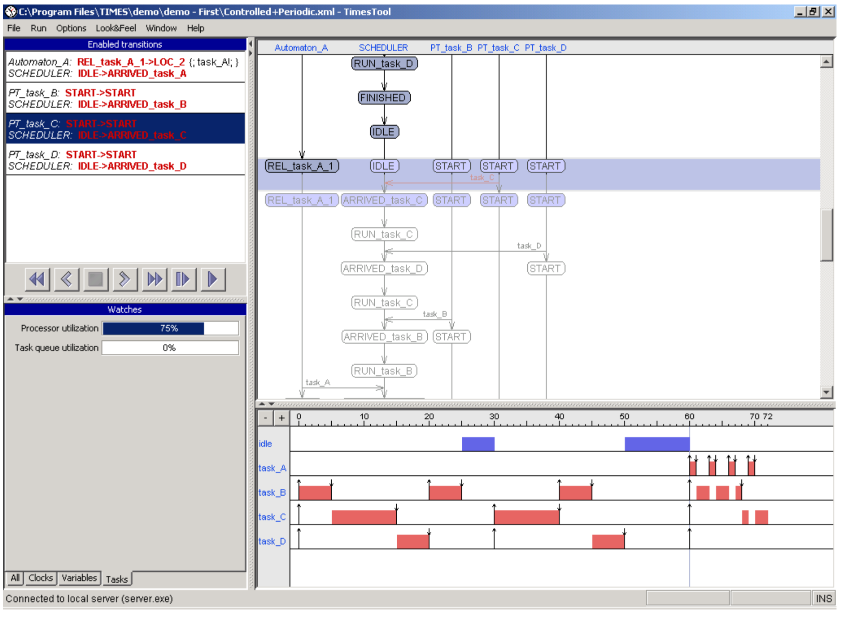
Functionality/Features of TIMES

- GUI
  - Modeling: automata with (a)synchronous tasks
  - editing, task library, visualization etc
- Simulation
  - Symbolic execution as MSC's and Gant Charts
- Verification
  - Safety, bounded liveness properties (all you do with UPPAAL)
  - Schedulability analysis
- Synthesis
  - Verified executable code (guaranteeing timing constraints)
    - Traces(Code) $\subseteq$ Traces(Model)
  - Schedule synthesis (ongoing)

CODE SYNTHESIS in TIMES

- Run Time Systems
  - Event Handler
    - OS interrupt processing system or Polling
  - Task scheduler
    - generated from task parameters
- Application Tasks = threads (or processes)
  - Already there! (written in C)
  - Current version of TIMES support LegoOS !

TIMES demo



Conclusions/Remarks

- A unified model for timed systems (can express synchronization, computation and complex temporal and resource constraints).
- The first decidability result (and efficient algorithms) for preemptive scheduling in dense time models:
  - The analysis is symbolic (using DBM's in the UPPAAL tool)
  - The results can be adopted for schedulability analysis of message transmission.
- Implementation: **TIMES**