Model Checking: the Interval Way

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Model checking

Model checking: the desired properties of a system are checked against a model of it

- the model is usually a (finite) state-transition system
- system properties are specified by a temporal logic (LTL, CTL, CTL^* and the like)

Distinctive features of model checking:

- exaustive check of all the possible behaviours
- fully automatic process
- a counterexample is produced for a violated property

The Interval Way

Model checking is usually point-based:

- properties express requirements over points (snapshots) of a computation (states of the state-transition system)
- they are specified by means of point-based temporal logics such as LTL, CTL, and CTL*

Interval properties express conditions on computation stretches instead of on computation states

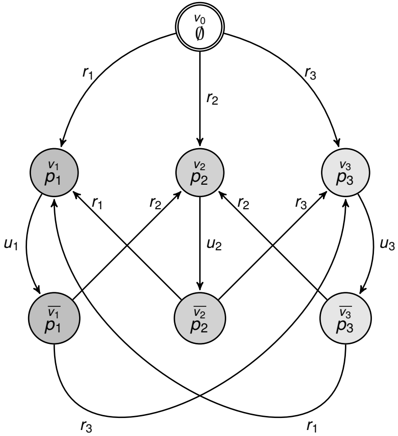
A lot of work has been done on interval temporal logic (ITL) satisfiability checking (a comprehensive survey can be found at: *https://users.dimi.uniud.it/~angelo.montanari/Movep2016-partI.pdf*).

ITL model checking entered the research agenda only in the last years (Bozzelli, Lomuscio, Michaliszyn, Molinari, Montanari, Murano, Perelli, Peron, Sala)

Outline of the talk

- The model checking problem for interval temporal logics
- Complexity results: the general picture
- Interval vs. point temporal logic model checking: an expressiveness comparison (a short account)
- Interval temporal logic model checking with regular expressions (a short account)
- Ongoing work and future developments

The modeling of the system: Kripke structures



An example of Kripke structure

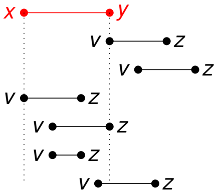
- ITL formulas are interpreted over (finite) state-transition systems, whose states are labeled with sets of proposition letters (Kripke structures)
- An interval is a trace (finite path) in a Kripke structure

HS: the modal logic of Allen's interval relations

Allen's interval relations: the 13 binary ordering relations between 2 intervals on a linear order. They give rise to corresponding unary modalities over frames where intervals are primitive entities:

- HS features a modality for any Allen ordering relation between pairs of intervals (except for equality)

Allen rel.	HS	Definition	Example
meets	$\langle A \rangle$	$[x,y]\mathcal{R}_A[v,z] \iff y = v$	
before	$\langle L \rangle$	$[x,y]\mathcal{R}_L[v,z] \iff y < v$	
started-by	$\langle B \rangle$	$[x,y]\mathcal{R}_B[v,z] \iff x = v \wedge z < y$	
finished-by	$\langle E \rangle$	$[x,y]\mathcal{R}_E[v,z] \iff y = z \wedge x < v$	
contains	$\langle D \rangle$	$[x,y]\mathcal{R}_D[v,z] \iff x < v \wedge z < y$	
overlaps	$\langle O \rangle$	$[x,y]\mathcal{R}_O[v,z] \iff x < v < y < z$	



All modalities can be expressed by means of $\langle A \rangle$, $\langle B \rangle$, $\langle E \rangle$, and their transposed modalities only (if point intervals are admitted, $\langle B \rangle$, $\langle E \rangle$, and their transposed modalities suffice)

HS semantics and model checking

Truth of a formula ψ over a trace ρ of a Kripke structure $\mathcal{K} = (\mathcal{AP}, W, \delta, \mu, w_0)$ defined by induction on the complexity of ψ:

- $\mathcal{K}, \rho \models p$ iff $p \in \bigcap_{w \in \text{states}(\rho)} \mu(w)$, for any letter $p \in \mathcal{AP}$ (homogeneity assumption);
- clauses for negation, disjunction, and conjunction are standard;
- $\mathcal{K}, \rho \models \langle \mathrm{A} \rangle \psi$ iff there is a trace ρ' s.t. $\text{lst}(\rho) = \text{fst}(\rho')$ and $\mathcal{K}, \rho' \models \psi$;
- $\mathcal{K}, \rho \models \langle \mathrm{B} \rangle \psi$ iff there is a proper prefix ρ' of ρ s.t. $\mathcal{K}, \rho' \models \psi$;
- $\mathcal{K}, \rho \models \langle \mathrm{E} \rangle \psi$ iff there is a proper suffix ρ' of ρ s.t. $\mathcal{K}, \rho' \models \psi$;
- the semantic clauses for $\langle \overline{\mathrm{A}} \rangle$, $\langle \overline{\mathrm{B}} \rangle$, and $\langle \overline{\mathrm{E}} \rangle$ are similar

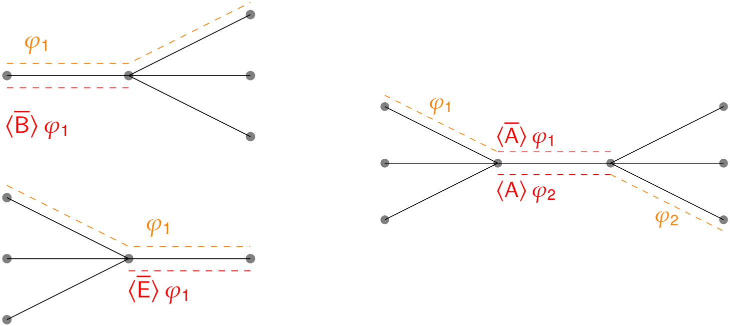
Model Checking

$\mathcal{K} \models \psi \iff$ for all initial traces ρ of $\mathcal{K}$, it holds that $\mathcal{K}, \rho \models \psi$

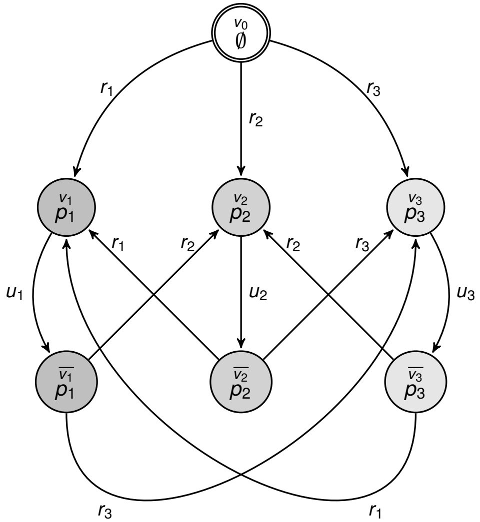
Possibly infinitely many traces!

Remark: HS state semantics (HS_{st})

- According to the given semantics, HS modalities allow one to branch both in the past and in the future



The Kripke structure $\mathcal{K}_{Sched}$ for a simple scheduler



A short account of $\mathcal{K}_{Sched}$

$\mathcal{K}_{Sched}$ models the behaviour of a scheduler serving 3 processes which are continuously requesting the use of a common resource (it can be easily generalised to an arbitrary number of processes)

Initial state: v_0 (no process is served in that state)

In v_i and $\overline{v}_i$ the i-th process is served (p_i holds in those states)

The scheduler cannot serve the same process twice in two successive rounds:

- process i is served in state v_i, then, after "some time", a transition u_i from v_i to $\overline{v}_i$ is taken; subsequently, process i cannot be served again immediately, as v_i is not directly reachable from $\overline{v}_i$
- a transition r_j, with $j \neq i$, from $\overline{v}_i$ to v_j is then taken and process j is served

Some meaningful properties to be checked over $\mathcal{K}_{Sched}$

Validity of properties over all legal computation intervals can be forced by modality $[E]$ (they are suffixes of at least one initial trace)

Property 1: in any computation interval of length at least 4, at least 2 processes are witnessed (YES/no process can be executed twice in a row)

$$\mathcal{K}_{Sched} \models [E]\big(\langle \mathrm{E} \rangle^3 \top \rightarrow (\chi(p_1, p_2) \vee \chi(p_1, p_3) \vee \chi(p_2, p_3))\big),$$

where $\chi(p, q) = \langle \mathrm{E} \rangle \langle \overline{\mathrm{A}} \rangle p \wedge \langle \mathrm{E} \rangle \langle \overline{\mathrm{A}} \rangle q$

Property 2: in any computation interval of length at least 11, process 3 is executed at least once (NO/if there are at least 3 processes, the scheduler can postpone the execution of one of them ad libitum—starvation)

$$\mathcal{K}_{Sched} \not\models [E](\langle \mathrm{E} \rangle^{10} \top \rightarrow \langle \mathrm{E} \rangle \langle \overline{\mathrm{A}} \rangle p_3)$$

Property 3: in any computation interval of length at least 6, all processes are witnessed (NO/the scheduler should be forced to execute them in a strictly periodic manner, which is not the case)

$$\mathcal{K}_{Sched} \not\models [E](\langle \mathrm{E} \rangle^5 \rightarrow (\langle \mathrm{E} \rangle \langle \overline{\mathrm{A}} \rangle p_1 \wedge \langle \mathrm{E} \rangle \langle \overline{\mathrm{A}} \rangle p_2 \wedge \langle \mathrm{E} \rangle \langle \overline{\mathrm{A}} \rangle p_3))$$

Model checking: the key notion of BE_k-descriptor

- The BE-nesting depth of an HS formula ψ ($\mathrm{Nest}_{\mathrm{BE}}(\psi)$) is the maximum degree of nesting of modalities B and E in ψ
- Two traces ρ and ρ' of a Kripke structure $\mathcal{K}$ are k-equivalent if and only if $\mathcal{K}, \rho \models \psi$ iff $\mathcal{K}, \rho' \models \psi$ for all HS-formulas ψ with $\mathrm{Nest}_{\mathrm{BE}}(\psi) \leq k$

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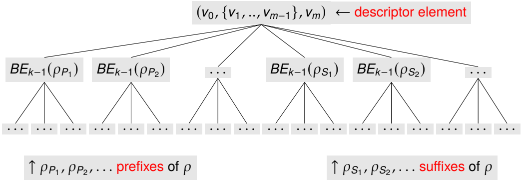
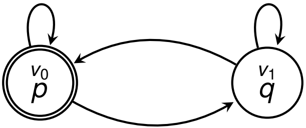
For any given k, we provide a suitable tree representation for a trace, called a BE_k-descriptor

The BE_k-descriptor for a trace $\rho = v_0 v_1 .. v_{m-1}\ v_m$, denoted $BE_k(\rho)$, has the following structure:

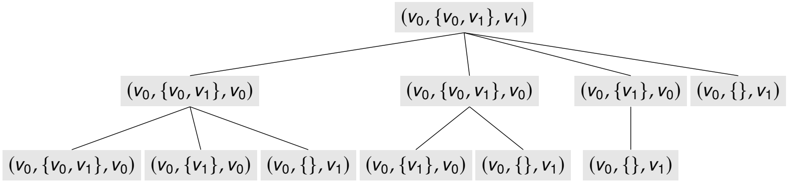


Remark: the descriptor does not feature sibling isomorphic subtrees

An example of a BE_2-descriptor



The BE_2-descriptor for the trace $\rho = v_0 v_1 v_0^4 v_1$ - point intervals are excluded (for the sake of readability, only the subtrees for prefixes are displayed)



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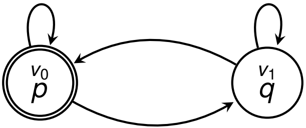

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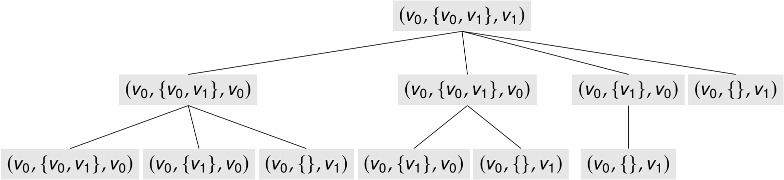

Remark: the subtree to the left is associated with both prefixes $v_0 v_1 v_0^3$ and $v_0 v_1 v_0^4$ (no sibling isomorphic subtrees in the descriptor)

Decidability of model checking for full HS

FACT 1: For any Kripke structure $\mathcal{K}$ and any BE-nesting depth $k \geq 0$, the number of different BE_k-descriptors is finite (and thus at least one descriptor has to be associated with infinitely many traces)

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Theorem

The model checking problem for full HS *on finite Kripke structures is decidable (with a non-elementary algorithm)*

A. Molinari, A. Montanari, A. Murano, G. Perelli, and A. Peron, Checking Interval Properties of Computations, Acta Informatica, Special Issue: Temporal Representation and Reasoning (TIME'14), Vol. 56, n. 6-8, October 2016, pp. 587-619

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What about lower bounds?

The logic BE

Theorem

The model checking problem for BE, *over finite Kripke structures, is EXPSPACE-hard*

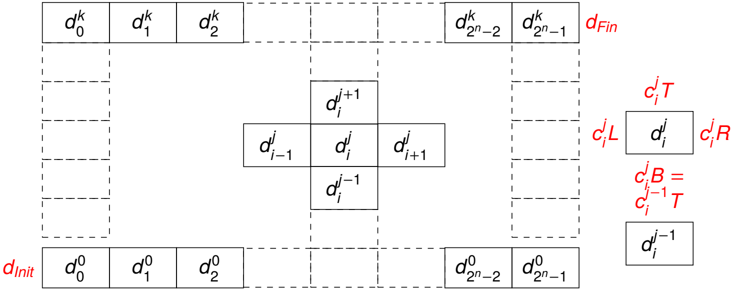
Bozzelli L., Molinari A., Montanari A., Peron A., and Sala P., "Which Fragments of the Interval Temporal Logic HS are Tractable in Model Checking?", Theoretical Computer Science, 764:125-144, 2019.

Proof: a polynomial-time reduction from a domino-tiling problem for grids with rows of single exponential length

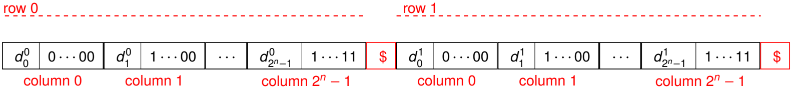
- for an instance $\mathcal{I}$ of the problem, we build a Kripke structure $\mathcal{K}_{\mathcal{I}}$ and a BE formula $\varphi_{\mathcal{I}}$ in polynomial time
- there is an initial trace of $\mathcal{K}_{\mathcal{I}}$ satisfying $\varphi_{\mathcal{I}}$ iff there is a tiling of $\mathcal{I}$
- $\mathcal{K}_{\mathcal{I}} \models \neg\varphi_{\mathcal{I}}$ iff there exists no tiling of $\mathcal{I}$

BE hardness: encoding of the domino-tiling problem

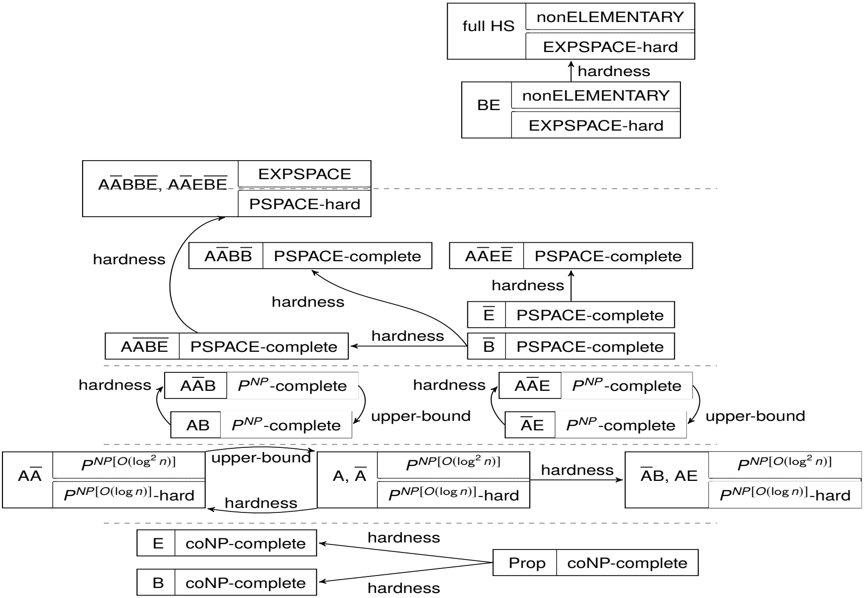
Instance of the tiling problem: $(C, \Delta, n, d_{init}, d_{final})$, with C a finite set of colors and $\Delta \subseteq C \times C \times C \times C$ a set of tuples (c_B, c_L, c_T, c_R)



String (interval) encoding of the problem



The complexity picture



Three main gaps to fill

There are three main gaps to fill:

- full HS and BE are in between nonELEMENTARY and EXPSPACE
- $A\overline{A}B\overline{B}\overline{E}$, $A\overline{A}E\overline{B}\overline{E}$, $AB\overline{B}\overline{E}$, $AE\overline{B}\overline{E}$, $\overline{A}B\overline{B}\overline{E}$, and $\overline{A}E\overline{B}\overline{E}$ are in between EXPSPACE and PSPACE
- A, $\overline{A}$, $A\overline{A}$, $\overline{A}B$, and AE are in between $P^{NP[O(\log^2 n)]}$ and $P^{NP[O(\log n)]}$

The first gap is definitely the most significant one

Point vs. interval temporal logic model checking

Question: is there any advantage in replacing points by intervals as the primary temporal entities, or is it just a matter of taste?

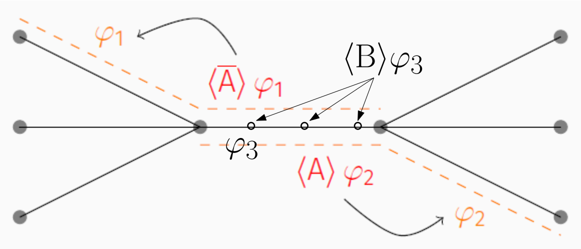
In order to compare the expressiveness of HS in model checking with those of LTL, CTL, and CTL*, we consider three semantic variants of HS:

- HS with state-based semantics (the original one)
- HS with computation-tree-based semantics
- HS with trace-based semantics

These variants are compared with the above-mentioned standard temporal logics and among themselves

L. Bozzelli, A. Molinari, A. Montanari, A. Peron, and P. Sala, Interval vs. Point Temporal Logic Model Checking: an Expressiveness Comparison. ACM Transactions on Computational Logic, Volume 20(1), Article No. 4, January 2019.

Branching semantic variant of HS

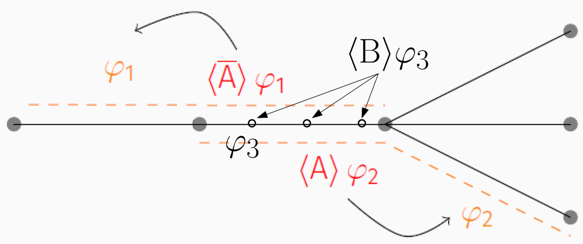


State-based semantics of HS (HS_{st}):

- both the future and the past are branching

A. Molinari, A. Montanari, A. Murano, G. Perelli, and A. Peron, Checking Interval Properties of Computations, Acta Informatica, Special Issue: Temporal Representation and Reasoning (TIME'14), Vol. 56, n. 6-8, October 2016, pp. 587-619

Linear-past semantic variant of HS

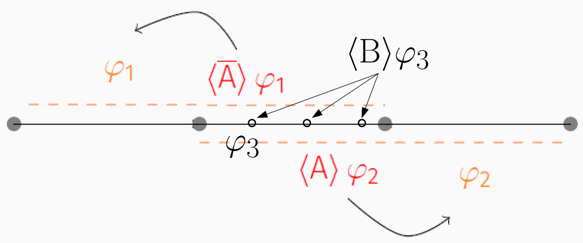


Computation-tree-based semantics of HS (HS_{ct}):

- the future is branching
- the past is linear, finite and cumulative
- similar to CTL* + linear past

A. Lomuscio and J. Michaliszyn, Decidability of model checking multi-agent systems against a class of EHS specifications, Proc. of the 21st European Conference on Artificial Intelligence (ECAI), August 2014, pp. 543–548

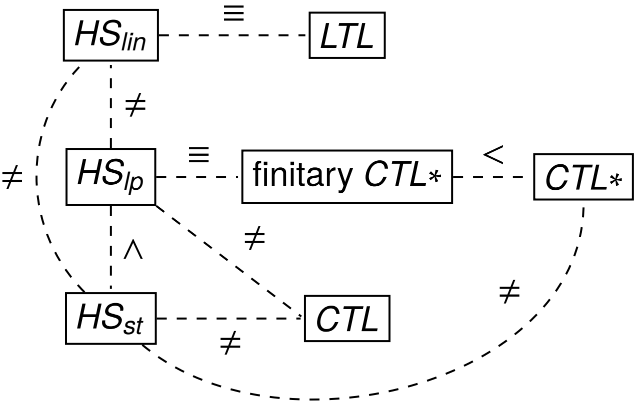
Linear semantic variant of HS



Trace-based semantics of HS (HS_{lin}):

- neither the past not the future is branching
- similar to LTL + past

The expressiveness picture



ITL model checking with regular expressions

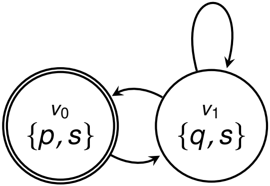
Can we relaxe the homogeneity assumption? The addition of regular expressions:

$$r ::= \varepsilon \mid \phi \mid r \cup r \mid r \cdot r \mid r^*$$

where ϕ is a Boolean (propositional) formula over $\mathcal{AP}$.

Examples:

- $r_1 = (\mathbf{p} \wedge \mathbf{s}) \cdot \mathbf{s}^* \cdot (\mathbf{p} \wedge \mathbf{s})$
- $r_2 = (\neg \mathbf{p})^*$



- $\rho = v_0 v_1 v_0 v_1 v_1$
- $\mu(\rho) = \{p,s\}\{q,s\}\{p,s\}\{q,s\}\{q,s\}$
- $\rho' = v_0 v_1 v_1 v_1 v_0$
- $\mu(\rho') = \{p,s\}\{q,s\}\{q,s\}\{q,s\}\{p,s\}$
  - $\mu(\rho) \notin \mathcal{L}(r_1)$, but $\mu(\rho') \in \mathcal{L}(r_1)$
  - $\mu(\rho) \notin \mathcal{L}(r_2)$ and $\mu(\rho') \notin \mathcal{L}(r_2)$

ITL model checking with regular expressions

In the definition of the truth of a formula ψ over a trace ρ of a Kripke structure $\mathcal{K} = (\mathcal{AP}, W, \delta, \mu, w_0)$, we replace the clause for propositional letters by a clause for regular expressions:

- $\mathcal{K}, \rho \models r$ iff $\mu(\rho) \in \mathcal{L}(r)$

Homogeneity can be recovered as a special case. To force it, all regular expressions in the formula must be of the form:

$$p \cdot (p)^*$$

Solution: given $\mathcal{K}$ and an HS formula φ over $\mathcal{AP}$, we build an NFA over $\mathcal{K}$ accepting the set of traces ρ such that $\mathcal{K}, \rho \models \varphi$.

Bozzelli L., Molinari A., Montanari A., Peron A., "Model Checking Interval Temporal Logics with Regular Expressions", Information and Computation, accepted for publication on October 25, 2018 (to appear).

Ongoing work and future developments - 1

Ongoing work: to determine the exact complexity of the satisfiability / model checking problems for BE over finite linear orders, under the homogeneity assumption (the three semantic variants of HS coincide over BE)

We know that the satisfiability/model checking problems for D over finite linear orders, under the homogeneity assumption, are PSPACE-complete (we exploit a spatial encoding of the models for D and a suitable contraction technique)

L. Bozzelli, A. Molinari, A. Montanari, A. Peron, and P. Sala, Satisfiability and Model Checking for the Logic of Sub-Intervals under the Homogeneity Assumption, Proc. of the 44th International Colloquium on Automata, Languages, and Programming(ICALP), LIPIcs 80, July 2017, pp. 120:1–120:14

There is no a natural way to generalize the solution for D to BE

Ongoing work and future developments - 2

Ongoing work: we are looking for possible replacements of Kripke structures by more expressive system models

- inherently interval-based models, that allows one to directly describe systems on the basis of their interval behavior/properties, such as, e.g., those involving actions with duration, accomplishments, or temporal aggregations (no restriction on the evaluation of proposition letters)
  - timeline-based (planning) systems: a set of timelines (transition functions) plus a set of synchronization rules
- visibly pushdown systems, that can encode recursive programs and infinite state systems

A different direction: model checking a single interval model (for temporal dataset evaluation)