An in-Depth Investigation of Interval Temporal Logic Model Checking with Regular Expressions

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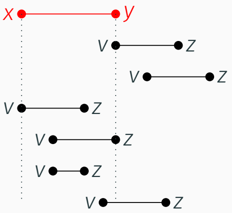
Point-based vs. interval-based model checking

- 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 and CTL
- Interval-based model checking:
  - Interval-based properties express conditions on computation stretches: accomplishments, actions with duration, and temporal aggregations
  - they are specified by means of interval temporal logics, e.g., HS

The logic HS

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

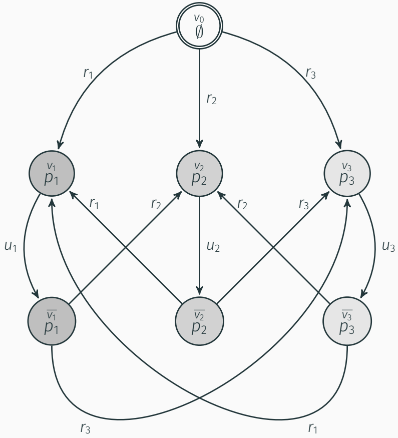
Allen rel.	HS	Definition	Example
meets	$\langle A \rangle$	$[x,y]\mathcal{R}_A[v,z] \iff y = v$	
before	$\langle L \rangle$	$[x,y]\mathcal{R}_L[v,z] \iff y < v$	
started-by	$\langle B \rangle$	$[x,y]\mathcal{R}_B[v,z] \iff x = v \wedge z < y$	
finished-by	$\langle E \rangle$	$[x,y]\mathcal{R}_E[v,z]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



$$\boxed{\psi ::= p \mid \neg\psi \mid \psi \vee \psi \mid \langle X \rangle \psi \mid \langle \overline{X} \rangle \psi} \qquad X \in \{A, L, B, E, D, O\}.$$

However, all modalities can be expressed by means of $\langle A \rangle$, $\langle B \rangle$, $\langle E \rangle$ and their inverse modalities $\langle \overline{A} \rangle$, $\langle \overline{B} \rangle$, $\langle \overline{E} \rangle$ only

Kripke structures

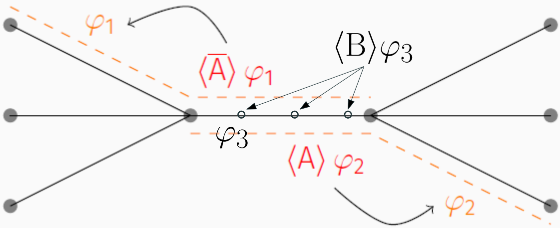


An example of Kripke structure

- HS formulas are interpreted over (finite) state-transition systems whose states are labelled with sets of proposition letters (Kripke structures)
- An interval is a trace (finite path) in a Kripke structure
- How to determine the properties of a trace (i.e. its proposition letters), in terms of its states?

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

- $\mathcal{K}, \rho \models p$ iff $p \in \bigcap_{w \in \mathsf{states}(\rho)} \mu(w)$, for any letter $p \in \mathcal{AP}$ (homogeneity assumption)



HS semantics and model checking

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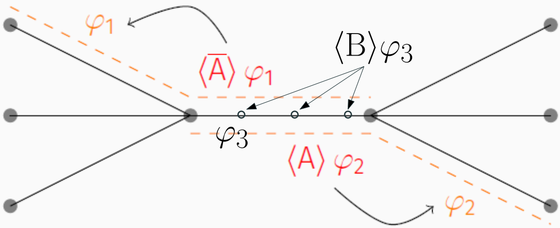

Model Checking

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

Possibly infinitely many traces!

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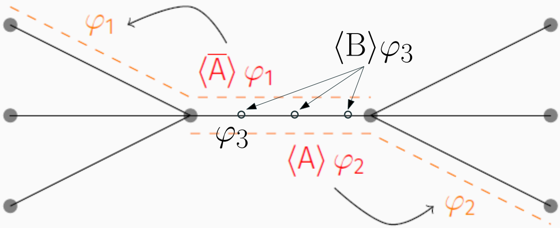
Truth of a formula ψ over a trace ρ of a Kripke structure $\mathcal{K} = (\mathcal{AP}, W, \delta, \mu, w_0)$:

- $\mathcal{K}, \rho \models p$ iff $p \in \mu(\mathsf{fst}(\rho), \mathsf{lst}(\rho))$, for any letter $p \in \mathcal{AP}$ (endpoint-based labeling);



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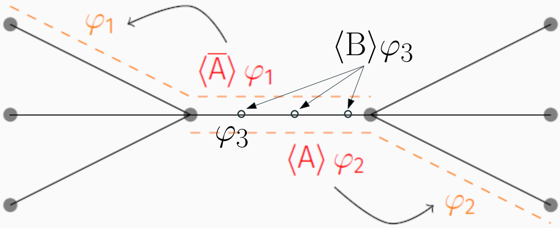
HS semantics and model checking

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

- $\mathcal{K}, \rho \models p$ other semantic variants?



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

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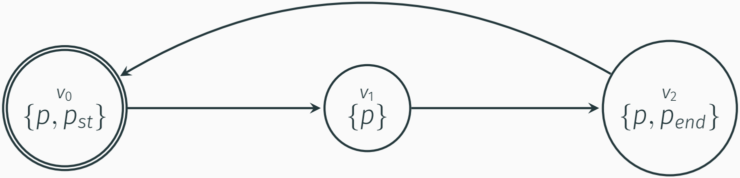
Example—Printer

Adapted from [Lomuscio A., Michaliszyn J.]



Imagine we want to label the process of printing a single sheet of paper with p.

- Under homogeneity,
  $v_0v_1v_2$ labeled by $p \Rightarrow v_0v_1$ and v_1v_2 labeled by p

Example—Printer

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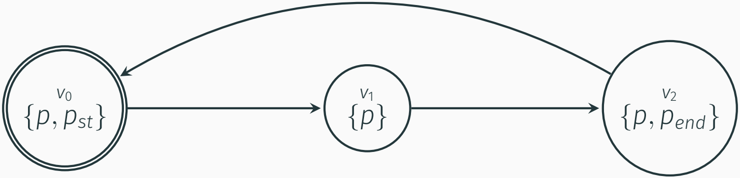


Imagine we want to label the process of printing a single sheet of paper with p.

- Under endpoint-based labeling, assuming $p \in \mu(v_0, v_2)$, then $(v_0 v_1 v_2)^n$ are all labeled by p

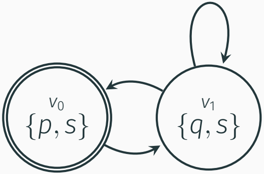
Our regular expressions

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

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

Examples:

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

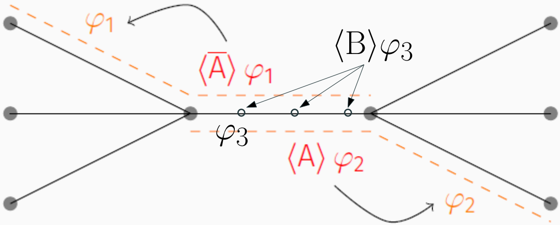


- $\rho = v_0 v_1 v_0 v_1 v_1$
- $\mu(\rho) = \{p, s\}\{q, s\}\{p, s\}\{q, s\}\{q, s\}$
- $\rho' = v_0 v_1 v_1 v_1 v_0$
- $\mu(\rho') = \{p, s\}\{q, s\}\{q, s\}\{q, s\}\{p, s\}$
  - $\mu(\rho) \notin \mathcal{L}(r_1)$, but $\mu(\rho') \in \mathcal{L}(r_1)$
  - $\mu(\rho) \notin \mathcal{L}(r_2)$, and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

HS semantics with regular expressions

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

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



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!

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- To force homogeneity, all regular expressions in the formula:

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

- for endpoint-based labeling, regular expressions in the formula:

$$\bigcup_{(i,j)\in I} (q_i \cdot \top^* \cdot q_j)$$

for some $I \subseteq \{1, \ldots, |W|\}^2$, where $q_i \in \mathcal{AP}$ labels only $w_i \in W$.

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

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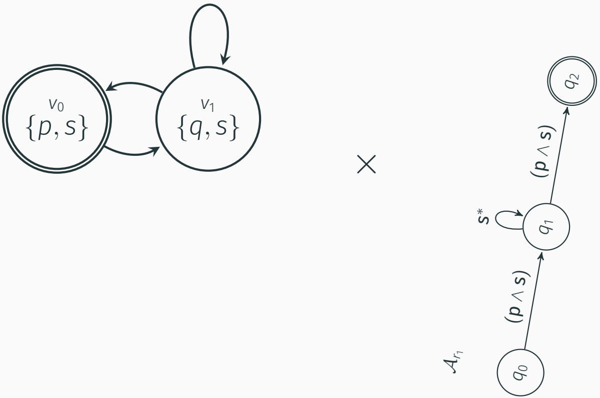
Decidability of MC for HS + regular expressions

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 $\mathcal{K}, \rho \models \varphi$.

Idea: for a regular expression r



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- for $\psi = \psi_1 \vee \psi_2$: we do the usual construction;
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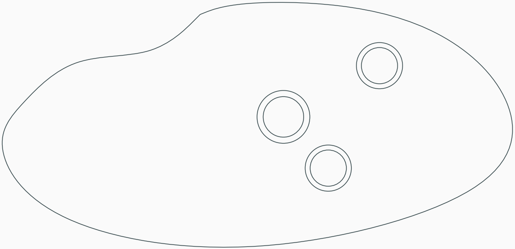
$\mathcal{A}_{\psi'}$:



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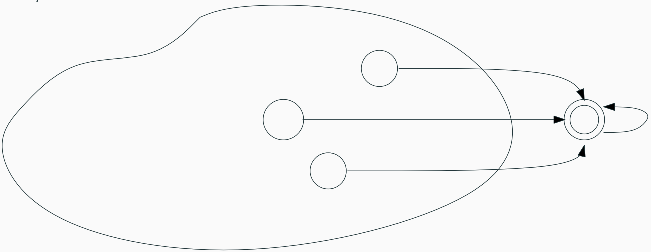
$\mathcal{A}_{\langle B \rangle \psi'}$:



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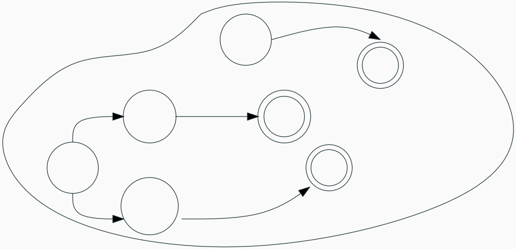

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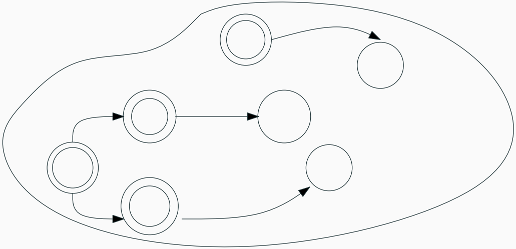

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Theorem

The MC problem for HS (+ regular expressions) over finite Kripke structures is decidable.

The $A\overline{A}B\overline{B}$ fragment + regular expressions

Formulas of $A\overline{A}B\overline{B}$ + regular expressions can be checked by using polynomial working space.

The following theorem is a building block of the **PSPACE**-model checking algorithm for $A\overline{A}B\overline{B}$.

Theorem (Exponential small-model for $A\overline{A}B\overline{B}$)

Let ρ be a trace of $\mathcal{K}$ and φ be an $A\overline{A}B\overline{B}$ formula with RE's $r_1, \ldots, r_u$ such that

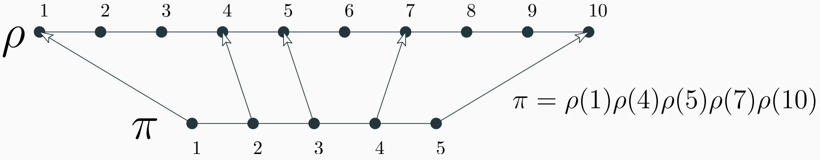
$$\mathcal{K}, \rho \models \varphi.$$

Then, there exists a trace π of $\mathcal{K}$ such that

$$\mathcal{K}, \pi \models \varphi \quad \text{and} \quad |\pi| \leq |W| \cdot (|\varphi| + 1) \cdot 2^{2 \sum_{\ell=1}^{u} |r_\ell|}.$$

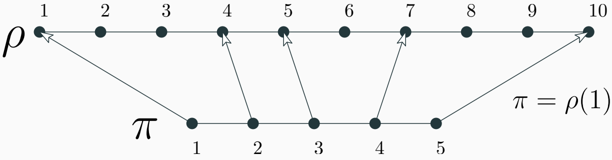
Proved by a contraction technique.

Small model for $A\overline{A}B\overline{B}$



We guarantee that:
for all corresponding positions i, j : $\mathcal{A}^s(\mu(\pi[1 \ldots j])) = \mathcal{A}^s(\mu(\rho[1 \ldots i]))$

Small model for $A\overline{A}B\overline{B}$



$$\pi = \rho(1)\rho(4)\rho(5)\rho(7)\rho(10)$$

We guarantee that:
for all corresponding positions i, j : $\mathcal{A}^s(\mu(\pi[1 \ldots j])) = \mathcal{A}^s(\mu(\rho[1 \ldots i]))$

If $\mathcal{K}, \rho \models \varphi \quad \Rightarrow$ there is a trace π of $\mathcal{K}$, induced by ρ, such that

$$\mathcal{K}, \pi \models \varphi \quad \text{and} \quad |\pi| \leq |W| \cdot (|\varphi| + 1) \cdot 2^{2\sum_{\ell=1}^{u} |r_\ell|}.$$

This small model is “strict”!

A PSPACE MC algorithm for $\mathsf{A}\overline{\mathsf{A}}\mathsf{B}\overline{\mathsf{B}}$—Trials

- The algorithm can consider only traces having length bounded by the exponential small model
- However, they are still too long! $\Rightarrow$ triples summarizing traces,

$$(G, D(\psi), w)$$

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  - $G \subseteq \mathsf{Subf}_{\langle \mathsf{B} \rangle}(\psi)$
    contains the subformulas that hold on some prefix

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  - $D(\psi)$ is the configuration of the DFAs after reading the trace (only the current states, not the whole DFAs!),

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  - w is the last state of the trace

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Lemma

If ρ and ρ' summarized by the same triple $(G, D(\psi), w)$, then $(\psi \in \mathsf{B\overline{B}})$

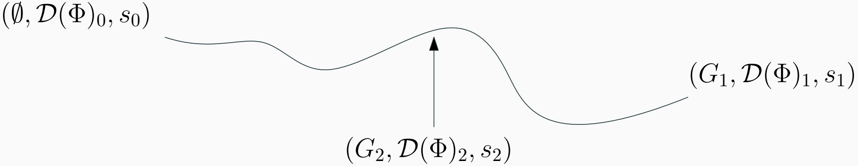
$$\mathcal{K}, \rho \models \psi \iff \mathcal{K}, \rho' \models \psi.$$

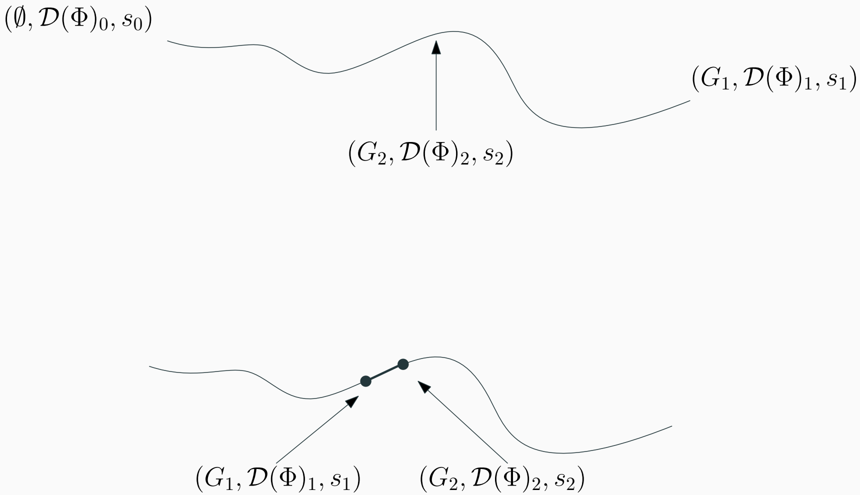
A PSPACE MC algorithm for $A\overline{A}B\overline{B}$

$(\emptyset, \mathcal{D}(\Phi)_0, s_0)$

$(G_1, \mathcal{D}(\Phi)_1, s_1)$

A PSPACE MC algorithm for $\mathsf{A\overline{A}B\overline{B}}$

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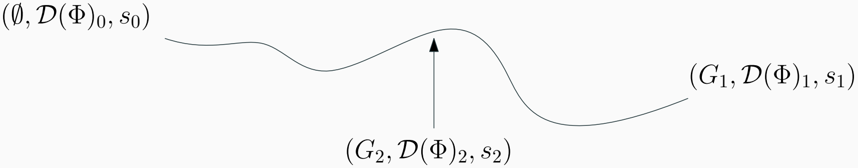
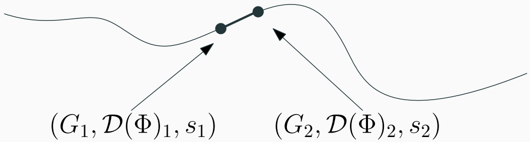
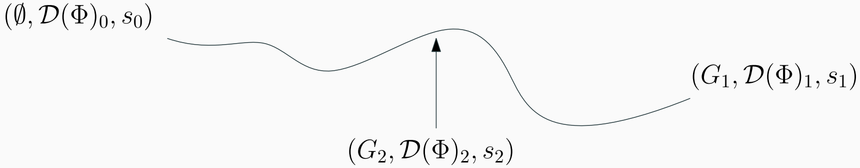
A PSPACE MC algorithm for $\mathsf{A\overline{A}B\overline{B}}$



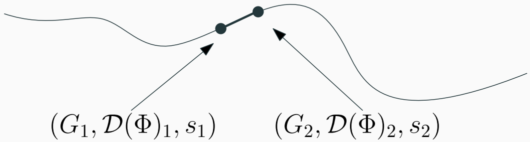


Compatible?

A PSPACE MC algorithm for $\mathsf{A}\overline{\mathsf{A}}\mathsf{B}\overline{\mathsf{B}}$



Bisection $\rightsquigarrow$ polynomial depth recursion



Compatible?

A PSPACE MC algorithm for $A\overline{A}B\overline{B}$

Algorithm 1 Check$(\mathcal{K}, \psi, w, G, D(\psi))$

if $\psi = r$ **then** ◁ *r is a regular expression*
  if the current state of the DFA for r in advance$(D(\psi), \mu(w))$ is final **then**
    return $\top$
  else
    return $\bot$
else if $\psi = \neg\psi'$ or $\psi = \psi_1 \wedge \psi_2$ **then**
  Call Check recursively
else if $\psi = \langle B \rangle\, \psi'$ **then**
  return $\psi' \in G$
else if $\psi = \langle \overline{B} \rangle\, \psi'$ **then**
  for all $b \in \{1, \ldots, |W| \cdot (2|\psi'| + 1) \cdot 2^{2^{\sum_{\ell=1}^{u} |r_\ell|}} - 1\}$, all $(G', D(\psi)', w')$ **do**
    if Reach$(\mathcal{K}, \psi', (G, D(\psi), w), (G', D(\psi)', w'), b)$ **and** Check$(\mathcal{K}, \psi', w', G', D(\psi)')$ **then**
      return $\top$
  return $\bot$

Algorithm 2 Check($\mathcal{K}, \psi, w, G, D(\psi)$)

if $\psi = r$ **then** ◁ *r is a regular expression*
  if the current state of the DFA for r in advance($D(\psi), \mu(w)$) is final **then**
    return $\top$
  else
    return $\bot$
else if $\psi = \neg\psi'$ or $\psi = \psi_1 \wedge \psi_2$ **then**
  Call Check recursively
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    if Reach($\mathcal{K}, \psi', (G, D(\psi), w), (G', D(\psi)', w'), b$) and Check($\mathcal{K}, \psi', w', G', D(\psi)'$) **then**
      return $\top$
  return $\bot$

$\mathsf{A}\overline{\mathsf{A}}\mathsf{B}\overline{\mathsf{B}}$ is PSPACE-complete

Theorem

The MC problem for formulas of $\mathsf{A}\overline{\mathsf{A}}\mathsf{B}\overline{\mathsf{B}}$ *(+ regular expressions) over finite Kripke structures is* PSPACE*-complete.*

Proof.

The purely propositional fragment of HS is hard for PSPACE: reduction from the PSPACE-complete *universality problem for regular expressions.* □

Complexity results

	Homogeneity	Regular expressions
Full HS, BE	non-elementary **EXPSPACE**-hard	non-elementary **EXPSPACE**-hard
$A\bar{A}B\bar{B}\bar{E}$, $A\bar{A}E\bar{B}\bar{E}$	**EXPSPACE** **PSPACE**-hard	non-elementary **PSPACE**-hard
$A\bar{A}\bar{B}\bar{E}$	**PSPACE**-complete	non-elementary **PSPACE**-hard
$A\bar{A}B\bar{B}$, $B\bar{B}$, $\bar{B}$, $A\bar{A}E\bar{E}$, $E\bar{E}$, $\bar{E}$	**PSPACE**-complete	**PSPACE**-complete
$A\bar{A}B$, $A\bar{A}E$, AB, $\bar{A}E$	$\mathbf{P}^{\mathbf{NP}}$-complete	**PSPACE**-complete
$A\bar{A}$, $\bar{A}B$, AE, A, $\bar{A}$	$\mathbf{P}^{\mathbf{NP}[O(\log^2 n)]}$ $\mathbf{P}^{\mathbf{NP}[O(\log n)]}$-hard	**PSPACE**-complete
Prop, B, E	**co-NP**-complete	**PSPACE**-complete

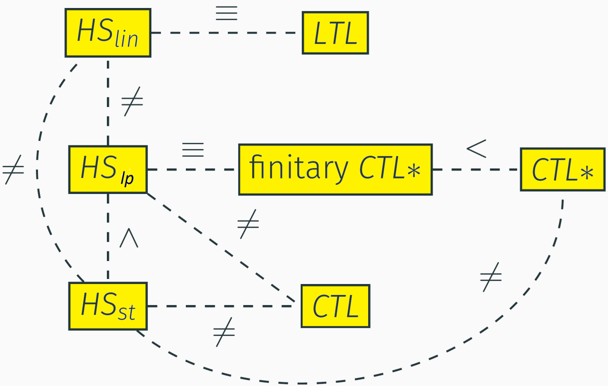
Complexity results

	Homogeneity	Regular expressions
Full HS, BE	non-elementary **EXPSPACE**-hard	non-elementary **EXPSPACE**-hard
$A\overline{A}B\overline{B}\overline{E}$, $A\overline{A}E\overline{B}\overline{E}$	**EXPSPACE** **PSPACE**-hard	non-elementary **PSPACE**-hard
$A\overline{A}\overline{B}\overline{E}$	**PSPACE**-complete	non-elementary **PSPACE**-hard
$A\overline{A}B\overline{B}$, $B\overline{B}$, $\overline{B}$, $A\overline{A}E\overline{E}$, $E\overline{E}$, $\overline{E}$	**PSPACE**-complete	**PSPACE**-complete
$A\overline{A}B$, $A\overline{A}E$, AB, $\overline{A}E$	$\mathbf{P}^{\mathbf{NP}}$-complete	**PSPACE**-complete
$A\overline{A}$, $\overline{A}B$, AE, A, $\overline{A}$	$\mathbf{P}^{\mathbf{NP}[O(\log^2 n)]}$ $\mathbf{P}^{\mathbf{NP}[O(\log n)]}$-hard	**PSPACE**-complete
Prop, B, E	**co-NP**-complete	**PSPACE**-complete

Future work

- Determining the precise complexity of full HS
- MC over visibly pushdown systems (for recursive programs, infinite state systems)
- Application: Planning as Model Checking with HS
- Come up with inherently interval-based models of systems (Kripke structures are oriented to the description of point-based properties of systems, and their state-by-state evolution)

Expressiveness comparison



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