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Model Checking. Part I

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Summary. This text includes definitions of the Kripke structure, CTL (Computation Tree Logic), and verification of the basic algorithm for Model Checking based on CTL in [10].

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The articles [21], [20], [16], [9], [18], [14], [6], [7], [4], [3], [5], [11], [2], [8], [13], [12], [17], [15], [1], and [19] provide the notation and terminology for this paper.

Let x, S be sets and let a be an element of S. The functor $\mathrm{k.id}(x, S, a)$ yields an element of S and is defined by:

(Def. 1) $\mathrm{k.id}(x, S, a) = \begin{cases} x, & \text{if } x \in S, \\ a, & \text{otherwise.} \end{cases}$

Let x be a set. The functor $\mathrm{k.nat}\, x$ yields an element of $\mathbb{N}$ and is defined by:

(Def. 2) $\mathrm{k.nat}\, x = \begin{cases} x, & \text{if } x \in \mathbb{N}, \\ 0, & \text{otherwise.} \end{cases}$

Let f be a function and let x, a be sets. The functor $\mathrm{UnivF}(x, f, a)$ yielding a set is defined by:

(Def. 3) $\mathrm{UnivF}(x, f, a) = \begin{cases} f(x), & \text{if } x \in \mathrm{dom}\, f, \\ a, & \text{otherwise.} \end{cases}$

Let a be a set. The functor $\mathrm{Castboolean}\, a$ yields a boolean set and is defined by:

(Def. 4) $\mathrm{Castboolean}\, a = \begin{cases} a, & \text{if } a \text{ is a boolean set}, \\ \mathit{false}, & \text{otherwise.} \end{cases}$

Let X, a be sets. The functor $\mathrm{CastBool}(a, X)$ yielding a subset of X is defined as follows:

(Def. 5) $\mathrm{CastBool}(a, X) = \begin{cases} a, & \text{if } a \subseteq X, \\ \emptyset, & \text{otherwise.} \end{cases}$

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For simplicity, we adopt the following rules: n denotes an element of $\mathbb{N}$, a denotes a set, D denotes a non empty set, and p, q denote finite sequences of elements of $\mathbb{N}$.

Let x be a variable. Then $\langle x \rangle$ is a finite sequence of elements of $\mathbb{N}$.

Let us consider n. The functor $\mathrm{atom.}\, n$ yields a finite sequence of elements of $\mathbb{N}$ and is defined by:

(Def. 6) $\mathrm{atom.}\, n = \langle 5 + n \rangle$.

Let us consider p. The functor $\neg p$ yielding a finite sequence of elements of $\mathbb{N}$ is defined by:

(Def. 7) $\neg p = \langle 0 \rangle \frown p$.

Let us consider q. The functor $p \wedge q$ yielding a finite sequence of elements of $\mathbb{N}$ is defined by:

(Def. 8) $p \wedge q = \langle 1 \rangle \frown p \frown q$.

Let us consider p. The functor $\mathrm{EX}\, p$ yielding a finite sequence of elements of $\mathbb{N}$ is defined as follows:

(Def. 9) $\mathrm{EX}\, p = \langle 2 \rangle \frown p$.

The functor $\mathrm{EG}\, p$ yielding a finite sequence of elements of $\mathbb{N}$ is defined by:

(Def. 10) $\mathrm{EG}\, p = \langle 3 \rangle \frown p$.

Let us consider q. The functor $p\,\mathrm{EU}\,q$ yields a finite sequence of elements of $\mathbb{N}$ and is defined as follows:

(Def. 11) $p\,\mathrm{EU}\,q = \langle 4 \rangle \frown p \frown q$.

The non empty set CTL-WFF is defined by the conditions (Def. 12).

(Def. 12) For every a such that $a \in$ CTL-WFF holds a is a finite sequence of elements of $\mathbb{N}$ and for every n holds $\mathrm{atom.}\, n \in$ CTL-WFF and for every p such that $p \in$ CTL-WFF holds $\neg p \in$ CTL-WFF and for all p, q such that $p \in$ CTL-WFF and $q \in$ CTL-WFF holds $p \wedge q \in$ CTL-WFF and for every p such that $p \in$ CTL-WFF holds $\mathrm{EX}\, p \in$ CTL-WFF and for every p such that $p \in$ CTL-WFF holds $\mathrm{EG}\, p \in$ CTL-WFF and for all p, q such that $p \in$ CTL-WFF and $q \in$ CTL-WFF holds $p\,\mathrm{EU}\,q \in$ CTL-WFF and for every D such that for every a such that $a \in D$ holds a is a finite sequence of elements of $\mathbb{N}$ and for every n holds $\mathrm{atom.}\, n \in D$ and for every p such that $p \in D$ holds $\neg p \in D$ and for all p, q such that $p \in D$ and $q \in D$ holds $p \wedge q \in D$ and for every p such that $p \in D$ holds $\mathrm{EX}\, p \in D$ and for every p such that $p \in D$ holds $\mathrm{EG}\, p \in D$ and for all p, q such that $p \in D$ and $q \in D$ holds $p\,\mathrm{EU}\,q \in D$ holds CTL-WFF $\subseteq D$.

Let I_1 be a finite sequence of elements of $\mathbb{N}$. We say that I_1 is CTL-formula-like if and only if:

(Def. 13) I_1 is an element of CTL-WFF.

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Let us mention that there exists a finite sequence of elements of $\mathbb{N}$ which is CTL-formula-like.

A CTL-formula is a CTL-formula-like finite sequence of elements of $\mathbb{N}$.

One can prove the following proposition

(1) a is a CTL-formula iff $a \in$ CTL-WFF .

In the sequel F, G, H, H_1, H_2 denote CTL-formulae.

Let us consider n. One can verify that $\mathrm{atom}.\, n$ is CTL-formula-like.

Let us consider H. One can verify the following observations:

* $\neg H$ is CTL-formula-like,
* $\mathrm{EX}\, H$ is CTL-formula-like, and
* $\mathrm{EG}\, H$ is CTL-formula-like.

Let us consider G. One can verify that $H \wedge G$ is CTL-formula-like and $H \,\mathrm{EU}\, G$ is CTL-formula-like.

Let us consider H. We say that H is atomic if and only if:

(Def. 14) There exists n such that $H = \mathrm{atom}.\, n$.

We say that H is negative if and only if:

(Def. 15) There exists H_1 such that $H = \neg H_1$.

We say that H is conjunctive if and only if:

(Def. 16) There exist F, G such that $H = F \wedge G$.

We say that H is exist-next-formula if and only if:

(Def. 17) There exists H_1 such that $H = \mathrm{EX}\, H_1$.

We say that H is exist-global-formula if and only if:

(Def. 18) There exists H_1 such that $H = \mathrm{EG}\, H_1$.

We say that H is exist-until-formula if and only if:

(Def. 19) There exist F, G such that $H = F \,\mathrm{EU}\, G$.

Let us consider F, G. The functor $F \vee G$ yielding a CTL-formula is defined by:

(Def. 20) $F \vee G = \neg(\neg F \wedge \neg G)$.

One can prove the following proposition

(2) H is atomic, or negative, or conjunctive, or exist-next-formula, or exist-global-formula, or exist-until-formula.

Let us consider H. Let us assume that H is negative, or exist-next-formula, or exist-global-formula. The functor $\mathrm{Arg}(H)$ yielding a CTL-formula is defined as follows:

(Def. 21)(i) $\neg\,\mathrm{Arg}(H) = H$ if H is negative,

(ii) $\mathrm{EX}\,\mathrm{Arg}(H) = H$ if H is exist-next-formula,

(iii) $\mathrm{EG}\,\mathrm{Arg}(H) = H$, otherwise.

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Let us consider H. Let us assume that H is conjunctive or exist-until-formula. The functor $\mathrm{LeftArg}(H)$ yields a CTL-formula and is defined as follows:

(Def. 22)(i) There exists H_1 such that $\mathrm{LeftArg}(H) \wedge H_1 = H$ if H is conjunctive,

(ii) there exists H_1 such that $\mathrm{LeftArg}(H)\,\mathrm{EU}\,H_1 = H$, otherwise.

The functor $\mathrm{RightArg}(H)$ yielding a CTL-formula is defined by:

(Def. 23)(i) There exists H_1 such that $H_1 \wedge \mathrm{RightArg}(H) = H$ if H is conjunctive,

(ii) there exists H_1 such that $H_1\,\mathrm{EU}\,\mathrm{RightArg}(H) = H$, otherwise.

Let x be a set. The functor $\mathrm{CastCTLformula}\,x$ yields a CTL-formula and is defined by:

(Def. 24) $\mathrm{CastCTLformula}\,x = \begin{cases} x, & \text{if } x \in \text{CTL-WFF}, \\ \mathrm{atom}.\,0, & \text{otherwise.} \end{cases}$

Let P_1 be a set. We consider Kripke structures over P_1 as systems

$\langle$ worlds, starts, possibilities, a label $\rangle$,

where the worlds constitute a set, the starts constitute a subset of the worlds, the possibilities constitute a total relation between the worlds and the worlds, and the label is a function from the worlds into 2^{P_1}.

We introduce CTL model structures which are systems

$\langle$ assignations, basic assignations, a conjunction, a negation, a next-operation, a global-operation, an until-operation $\rangle$,

where the assignations constitute a non empty set, the basic assignations constitute a non empty subset of the assignations, the conjunction is a binary operation on the assignations, the negation is a unary operation on the assignations, the next-operation is a unary operation on the assignations, the global-operation is a unary operation on the assignations, and the until-operation is a binary operation on the assignations.

Let V be a CTL model structure. An assignation of V is an element of the assignations of V.

The subset the atomic WFF of CTL-WFF is defined by:

(Def. 25) The atomic WFF $= \{x; x$ ranges over CTL-formulae: x is atomic$\}$.

Let V be a CTL model structure, let K_1 be a function from the atomic WFF into the basic assignations of V, and let f be a function from CTL-WFF into the assignations of V. We say that f is an evaluation for K_1 if and only if the condition (Def. 26) is satisfied.

(Def. 26) Let H be a CTL-formula. Then

(i) if H is atomic, then $f(H) = K_1(H)$,

(ii) if H is negative, then $f(H) = (\text{the negation of } V)(f(\mathrm{Arg}(H)))$,

(iii) if H is conjunctive, then $f(H) = (\text{the conjunction of } V)(f(\mathrm{LeftArg}(H)), f(\mathrm{RightArg}(H)))$,

(iv) if H is exist-next-formula, then $f(H) = (\text{the next-operation of } V)(f(\mathrm{Arg}(H)))$,

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(v) if H is exist-global-formula, then $f(H)$ = (the global-operation of V)$(f(\mathrm{Arg}(H)))$, and

(vi) if H is exist-until-formula, then $f(H)$ = (the until-operation of V)$(f(\mathrm{LeftArg}(H)),\ f(\mathrm{RightArg}(H)))$.

Let V be a CTL model structure, let K_1 be a function from the atomic WFF into the basic assignations of V, let f be a function from CTL-WFF into the assignations of V, and let n be an element of $\mathbb{N}$. We say that f is a n-pre-evaluation for K_1 if and only if the condition (Def. 27) is satisfied.

(Def. 27) Let H be a CTL-formula such that $\mathrm{len}\, H \leq n$. Then

(i) if H is atomic, then $f(H) = K_1(H)$,

(ii) if H is negative, then $f(H)$ = (the negation of V)$(f(\mathrm{Arg}(H)))$,

(iii) if H is conjunctive, then $f(H)$ = (the conjunction of V)$(f(\mathrm{LeftArg}(H)),\ f(\mathrm{RightArg}(H)))$,

(iv) if H is exist-next-formula, then $f(H)$ = (the next-operation of V)$(f(\mathrm{Arg}(H)))$,

(v) if H is exist-global-formula, then $f(H)$ = (the global-operation of V)$(f(\mathrm{Arg}(H)))$, and

(vi) if H is exist-until-formula, then $f(H)$ = (the until-operation of V)$(f(\mathrm{LeftArg}(H)),\ f(\mathrm{RightArg}(H)))$.

Let V be a CTL model structure, let K_1 be a function from the atomic WFF into the basic assignations of V, let f, h be functions from CTL-WFF into the assignations of V, let n be an element of $\mathbb{N}$, and let H be a CTL-formula. The functor $\mathrm{GraftEval}(V, K_1, f, h, n, H)$ yields a set and is defined as follows:

(Def. 28) $\mathrm{GraftEval}(V, K_1, f, h, n, H) =$

$$\begin{cases} f(H), \text{ if } \mathrm{len}\, H > n+1, \\ K_1(H), \text{ if } \mathrm{len}\, H = n+1 \text{ and } H \text{ is atomic}, \\ (\text{the negation of } V)(h(\mathrm{Arg}(H))), \text{ if } \mathrm{len}\, H = n+1 \text{ and } H \text{ is negative}, \\ (\text{the conjunction of } V)(h(\mathrm{LeftArg}(H)),\ h(\mathrm{RightArg}(H))), \\ \quad \text{if } \mathrm{len}\, H = n+1 \text{ and } H \text{ is conjunctive}, \\ (\text{the next-operation of } V)(h(\mathrm{Arg}(H))), \text{ if } \mathrm{len}\, H = n+1 \text{ and } H \text{ is} \\ \quad \text{exist-next-formula}, \\ (\text{the global-operation of } V)(h(\mathrm{Arg}(H))), \text{ if } \mathrm{len}\, H = n+1 \text{ and } H \text{ is} \\ \quad \text{exist-global-formula}, \\ (\text{the until-operation of } V)(h(\mathrm{LeftArg}(H)),\ h(\mathrm{RightArg}(H))), \\ \quad \text{if } \mathrm{len}\, H = n+1 \text{ and } H \text{ is exist-until-formula}, \\ h(H), \text{ if } \mathrm{len}\, H < n+1, \\ \emptyset, \text{ otherwise}. \end{cases}$$

We follow the rules: V is a CTL model structure, K_1 is a function from the atomic WFF into the basic assignations of V, and f, f_1, f_2 are functions from CTL-WFF into the assignations of V.

Let V be a CTL model structure, let K_1 be a function from the atomic

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WFF into the basic assignations of V, and let n be an element of $\mathbb{N}$. The functor $\mathrm{EvalSet}(V, K_1, n)$ yields a non empty set and is defined by:

(Def. 29) $\mathrm{EvalSet}(V, K_1, n) = \{h; h$ ranges over functions from CTL-WFF into the assignations of V: h is a n-pre-evaluation for $K_1\}$.

Let V be a CTL model structure, let v_0 be an element of the assignations of V, and let x be a set. The functor $\mathrm{CastEval}(V, x, v_0)$ yielding a function from CTL-WFF into the assignations of V is defined by:

(Def. 30) $\mathrm{CastEval}(V, x, v_0) = \begin{cases} x, \text{ if } x \in (\text{the assignations of } V)^{\text{CTL-WFF}}, \\ \text{CTL-WFF} \longmapsto v_0, \text{ otherwise.} \end{cases}$

Let V be a CTL model structure and let K_1 be a function from the atomic WFF into the basic assignations of V. The functor $\mathrm{EvalFamily}(V, K_1)$ yielding a non empty set is defined by the condition (Def. 31).

(Def. 31) Let p be a set. Then $p \in \mathrm{EvalFamily}(V, K_1)$ if and only if the following conditions are satisfied:

(i) $p \in 2^{(\text{the assignations of } V)^{\text{CTL-WFF}}}$, and

(ii) there exists an element n of $\mathbb{N}$ such that $p = \mathrm{EvalSet}(V, K_1, n)$.

We now state two propositions:

(3) There exists f which is an evaluation for K_1.

(4) If f_1 is an evaluation for K_1 and f_2 is an evaluation for K_1, then $f_1 = f_2$.

Let V be a CTL model structure, let K_1 be a function from the atomic WFF into the basic assignations of V, and let H be a CTL-formula. The functor $\mathrm{Evaluate}(H, K_1)$ yields an assignation of V and is defined by:

(Def. 32) There exists a function f from CTL-WFF into the assignations of V such that f is an evaluation for K_1 and $\mathrm{Evaluate}(H, K_1) = f(H)$.

Let V be a CTL model structure and let f be an assignation of V. The functor $\neg f$ yields an assignation of V and is defined as follows:

(Def. 33) $\neg f = (\text{the negation of } V)(f)$.

Let V be a CTL model structure and let f, g be assignations of V. The functor $f \wedge g$ yielding an assignation of V is defined by:

(Def. 34) $f \wedge g = (\text{the conjunction of } V)(f, g)$.

Let V be a CTL model structure and let f be an assignation of V. The functor $\mathrm{EX}\, f$ yields an assignation of V and is defined by:

(Def. 35) $\mathrm{EX}\, f = (\text{the next-operation of } V)(f)$.

The functor $\mathrm{EG}\, f$ yielding an assignation of V is defined as follows:

(Def. 36) $\mathrm{EG}\, f = (\text{the global-operation of } V)(f)$.

Let V be a CTL model structure and let f, g be assignations of V. The functor $f\, \mathrm{EU}\, g$ yields an assignation of V and is defined as follows:

(Def. 37) $f\, \mathrm{EU}\, g = (\text{the until-operation of } V)(f, g)$.

The functor $f \vee g$ yielding an assignation of V is defined as follows:

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(Def. 38) $f \vee g = \neg(\neg f \wedge \neg g)$.

Next we state several propositions:

(5) $\mathrm{Evaluate}(\neg H, K_1) = \neg\,\mathrm{Evaluate}(H, K_1)$.

(6) $\mathrm{Evaluate}(H_1 \wedge H_2, K_1) = \mathrm{Evaluate}(H_1, K_1) \wedge \mathrm{Evaluate}(H_2, K_1)$.

(7) $\mathrm{Evaluate}(\mathrm{EX}\,H, K_1) = \mathrm{EX}\,\mathrm{Evaluate}(H, K_1)$.

(8) $\mathrm{Evaluate}(\mathrm{EG}\,H, K_1) = \mathrm{EG}\,\mathrm{Evaluate}(H, K_1)$.

(9) $\mathrm{Evaluate}(H_1\,\mathrm{EU}\,H_2, K_1) = \mathrm{Evaluate}(H_1, K_1)\,\mathrm{EU}\,\mathrm{Evaluate}(H_2, K_1)$.

(10) $\mathrm{Evaluate}(H_1 \vee H_2, K_1) = \mathrm{Evaluate}(H_1, K_1) \vee \mathrm{Evaluate}(H_2, K_1)$.

Let f be a function and let n be an element of $\mathbb{N}$. We introduce f^n as a synonym of f^n.

Let S be a set, let f be a function from S into S, and let n be an element of $\mathbb{N}$. Then f^n is a function from S into S.

We use the following convention: S is a non empty set, R is a total relation between S and S, and s, s_0, s_1 are elements of S.

The scheme *ExistPath* deals with a non empty set $\mathcal{A}$, a total relation $\mathcal{B}$ between $\mathcal{A}$ and $\mathcal{A}$, an element $\mathcal{C}$ of $\mathcal{A}$, and a unary functor $\mathcal{F}$ yielding a set, and states that:

> There exists a function f from $\mathbb{N}$ into $\mathcal{A}$ such that $f(0) = \mathcal{C}$ and for every element n of $\mathbb{N}$ holds $\langle f(n), f(n+1)\rangle \in \mathcal{B}$ and $f(n+1) \in \mathcal{F}(f(n))$

provided the following requirement is met:

- For every element s of $\mathcal{A}$ holds $\mathcal{B}^\circ\{s\} \cap \mathcal{F}(s)$ is a non empty subset of $\mathcal{A}$.

Let S be a non empty set and let R be a total relation between S and S. A function from $\mathbb{N}$ into S is said to be an infinity path of R if:

(Def. 39) For every element n of $\mathbb{N}$ holds $\langle \mathrm{it}(n), \mathrm{it}(n+1)\rangle \in R$.

Let S be a non empty set. The functor $\mathrm{ModelSP}\,S$ yields a non empty set and is defined by:

(Def. 40) $\mathrm{ModelSP}\,S = \mathit{Boolean}^S$.

Let S be a non empty set. Observe that $\mathrm{ModelSP}\,S$ is non empty.

Let S be a non empty set and let f be a set. The functor $\mathrm{Fid}(f, S)$ yielding a function from S into *Boolean* is defined by:

(Def. 41) $\mathrm{Fid}(f, S) = \begin{cases} f, & \text{if } f \in \mathrm{ModelSP}\,S, \\ S \longmapsto \mathit{false}, & \text{otherwise.} \end{cases}$

Now we present several schemes. The scheme *Func1EX* deals with a non empty set $\mathcal{A}$, a function $\mathcal{B}$ from $\mathcal{A}$ into *Boolean*, and a binary functor $\mathcal{F}$ yielding a boolean set, and states that:

> There exists a set g such that $g \in \mathrm{ModelSP}\,\mathcal{A}$ and for every set s such that $s \in \mathcal{A}$ holds $\mathcal{F}(s, \mathcal{B}) = \mathit{true}$ iff $(\mathrm{Fid}(g, \mathcal{A}))(s) = \mathit{true}$

for all values of the parameters.

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The scheme *Func1Unique* deals with a non empty set $\mathcal{A}$, a function $\mathcal{B}$ from $\mathcal{A}$ into *Boolean*, and a binary functor $\mathcal{F}$ yielding a boolean set, and states that:

Let g_1, g_2 be sets. Suppose that
(i) $g_1 \in \mathrm{ModelSP}\,\mathcal{A}$,
(ii) for every set s such that $s \in \mathcal{A}$ holds $\mathcal{F}(s,\mathcal{B}) = \mathit{true}$ iff $(\mathrm{Fid}(g_1,\mathcal{A}))(s) = \mathit{true}$,
(iii) $g_2 \in \mathrm{ModelSP}\,\mathcal{A}$, and
(iv) for every set s such that $s \in \mathcal{A}$ holds $\mathcal{F}(s,\mathcal{B}) = \mathit{true}$ iff $(\mathrm{Fid}(g_2,\mathcal{A}))(s) = \mathit{true}$.
Then $g_1 = g_2$

for all values of the parameters.

The scheme *UnOpEX* deals with a non empty set $\mathcal{A}$ and a unary functor $\mathcal{F}$ yielding an element of $\mathcal{A}$, and states that:

There exists a unary operation o on $\mathcal{A}$ such that for every set f such that $f \in \mathcal{A}$ holds $o(f) = \mathcal{F}(f)$

for all values of the parameters.

The scheme *UnOpUnique* deals with a non empty set $\mathcal{A}$, a non empty set $\mathcal{B}$, and a unary functor $\mathcal{F}$ yielding an element of $\mathcal{B}$, and states that:

Let o_1, o_2 be unary operations on $\mathcal{B}$. Suppose for every set f such that $f \in \mathcal{B}$ holds $o_1(f) = \mathcal{F}(f)$ and for every set f such that $f \in \mathcal{B}$ holds $o_2(f) = \mathcal{F}(f)$. Then $o_1 = o_2$

for all values of the parameters.

The scheme *Func2EX* deals with a non empty set $\mathcal{A}$, a function $\mathcal{B}$ from $\mathcal{A}$ into *Boolean*, a function $\mathcal{C}$ from $\mathcal{A}$ into *Boolean*, and a ternary functor $\mathcal{F}$ yielding a boolean set, and states that:

There exists a set h such that $h \in \mathrm{ModelSP}\,\mathcal{A}$ and for every set s such that $s \in \mathcal{A}$ holds $\mathcal{F}(s,\mathcal{B},\mathcal{C}) = \mathit{true}$ iff $(\mathrm{Fid}(h,\mathcal{A}))(s) = \mathit{true}$

for all values of the parameters.

The scheme *Func2Unique* deals with a non empty set $\mathcal{A}$, a function $\mathcal{B}$ from $\mathcal{A}$ into *Boolean*, a function $\mathcal{C}$ from $\mathcal{A}$ into *Boolean*, and a ternary functor $\mathcal{F}$ yielding a boolean set, and states that:

Let h_1, h_2 be sets. Suppose that
(i) $h_1 \in \mathrm{ModelSP}\,\mathcal{A}$,
(ii) for every set s such that $s \in \mathcal{A}$ holds $\mathcal{F}(s,\mathcal{B},\mathcal{C}) = \mathit{true}$ iff $(\mathrm{Fid}(h_1,\mathcal{A}))(s) = \mathit{true}$,
(iii) $h_2 \in \mathrm{ModelSP}\,\mathcal{A}$, and
(iv) for every set s such that $s \in \mathcal{A}$ holds $\mathcal{F}(s,\mathcal{B},\mathcal{C}) = \mathit{true}$ iff $(\mathrm{Fid}(h_2,\mathcal{A}))(s) = \mathit{true}$.
Then $h_1 = h_2$

for all values of the parameters.

Let S be a non empty set and let f be a set. The functor $\mathrm{Not}_0(f,S)$ yielding an element of $\mathrm{ModelSP}\,S$ is defined as follows:

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(Def. 42) For every set s such that $s \in S$ holds $\neg\,\mathrm{Castboolean}(\mathrm{Fid}(f,S))(s) = \mathit{true}$ iff $(\mathrm{Fid}(\mathrm{Not}_0(f,S),S))(s) = \mathit{true}$.

Let S be a non empty set. The functor $\mathrm{Not}\,S$ yields a unary operation on $\mathrm{ModelSP}\,S$ and is defined by:

(Def. 43) For every set f such that $f \in \mathrm{ModelSP}\,S$ holds $(\mathrm{Not}\,S)(f) = \mathrm{Not}_0(f,S)$.

Let S be a non empty set, let R be a total relation between S and S, let f be a function from S into *Boolean*, and let x be a set. The functor $\mathrm{EneXt}_{\mathrm{univ}}(x,f,R)$ yielding an element of *Boolean* is defined by:

(Def. 44) $$\mathrm{EneXt}_{\mathrm{univ}}(x,f,R) = \begin{cases} \mathit{true}, & \\ \quad \text{if } x \in S \text{ and there exists an infinity path } p_1 & \\ \quad\; \text{of } R \text{ such that } p_1(0) = x \text{ and } f(p_1(1)) = \mathit{true}, & \\ \mathit{false}, \ \text{otherwise.} & \end{cases}$$

Let S be a non empty set, let R be a total relation between S and S, and let f be a set. The functor $\mathrm{EneXt}_0(f,R)$ yielding an element of $\mathrm{ModelSP}\,S$ is defined as follows:

(Def. 45) For every set s such that $s \in S$ holds $\mathrm{EneXt}_{\mathrm{univ}}(s,\mathrm{Fid}(f,S),R) = \mathit{true}$ iff $(\mathrm{Fid}(\mathrm{EneXt}_0(f,R),S))(s) = \mathit{true}$.

Let S be a non empty set and let R be a total relation between S and S. The functor $\mathrm{EneXt}\,R$ yields a unary operation on $\mathrm{ModelSP}\,S$ and is defined by:

(Def. 46) For every set f such that $f \in \mathrm{ModelSP}\,S$ holds $(\mathrm{EneXt}\,R)(f) = \mathrm{EneXt}_0(f,R)$.

Let S be a non empty set, let R be a total relation between S and S, let f be a function from S into *Boolean*, and let x be a set. The functor $\mathrm{EGlobal}_{\mathrm{univ}}(x,f,R)$ yielding an element of *Boolean* is defined by:

(Def. 47) $$\mathrm{EGlobal}_{\mathrm{univ}}(x,f,R) = \begin{cases} \mathit{true}, & \\ \quad \text{if } x \in S \text{ and there exists an infinity path} & \\ \quad p_1 \text{ of } R \text{ such that } p_1(0) = x \text{ and for every} & \\ \quad \text{element } n \text{ of } \mathbb{N} \text{ holds } f(p_1(n)) = \mathit{true}, & \\ \mathit{false}, \ \text{otherwise.} & \end{cases}$$

Let S be a non empty set, let R be a total relation between S and S, and let f be a set. The functor $\mathrm{EGlobal}_0(f,R)$ yielding an element of $\mathrm{ModelSP}\,S$ is defined as follows:

(Def. 48) For every set s such that $s \in S$ holds $\mathrm{EGlobal}_{\mathrm{univ}}(s,\mathrm{Fid}(f,S),R) = \mathit{true}$ iff $(\mathrm{Fid}(\mathrm{EGlobal}_0(f,R),S))(s) = \mathit{true}$.

Let S be a non empty set and let R be a total relation between S and S. The functor $\mathrm{EGlobal}\,R$ yields a unary operation on $\mathrm{ModelSP}\,S$ and is defined as follows:

(Def. 49) For every set f such that $f \in \mathrm{ModelSP}\,S$ holds $(\mathrm{EGlobal}\,R)(f) = \mathrm{EGlobal}_0(f,R)$.

Unauthenticated
Download Date | 8/24/17 5:18 AM

Let S be a non empty set and let f, g be sets. The functor $\mathrm{And}_0(f, g, S)$ yields an element of ModelSP S and is defined as follows:

(Def. 50) For every set s such that $s \in S$ holds $\mathrm{Castboolean}(\mathrm{Fid}(f, S))(s) \wedge \mathrm{Castboolean}(\mathrm{Fid}(g, S))(s) = \mathit{true}$ iff $(\mathrm{Fid}(\mathrm{And}_0(f, g, S), S))(s) = \mathit{true}$.

Let S be a non empty set. The and S yielding a binary operation on ModelSP S is defined by:

(Def. 51) For all sets f, g such that $f \in \mathrm{ModelSP}\, S$ and $g \in \mathrm{ModelSP}\, S$ holds (the and S)$(f, g) = \mathrm{And}_0(f, g, S)$.

Let S be a non empty set, let R be a total relation between S and S, let f, g be functions from S into *Boolean*, and let x be a set. The functor $\mathrm{EUntill}_{\mathrm{univ}}(x, f, g, R)$ yielding an element of *Boolean* is defined as follows:

(Def. 52) $$\mathrm{EUntill}_{\mathrm{univ}}(x, f, g, R) = \begin{cases} \mathit{true}, \text{if } x \in S \text{ and there exists an infinity path} \\ \quad p_1 \text{ of } R \text{ such that } p_1(0) = x \text{ and there exists} \\ \quad \text{an element } m \text{ of } \mathbb{N} \text{ such that for every} \\ \quad \text{element } j \text{ of } \mathbb{N} \text{ such that } j < m \text{ holds} \\ \quad f(p_1(j)) = \mathit{true} \text{ and } g(p_1(m)) = \mathit{true}, \\ \mathit{false}, \text{otherwise.} \end{cases}$$

Let S be a non empty set, let R be a total relation between S and S, and let f, g be sets. The functor $\mathrm{EUntill}_0(f, g, R)$ yields an element of ModelSP S and is defined by:

(Def. 53) For every set s such that $s \in S$ holds $\mathrm{EUntill}_{\mathrm{univ}}(s, \mathrm{Fid}(f, S), \mathrm{Fid}(g, S), R) = \mathit{true}$ iff $(\mathrm{Fid}(\mathrm{EUntill}_0(f, g, R), S))(s) = \mathit{true}$.

Let S be a non empty set and let R be a total relation between S and S. The functor EUntill R yields a binary operation on ModelSP S and is defined as follows:

(Def. 54) For all sets f, g such that $f \in \mathrm{ModelSP}\, S$ and $g \in \mathrm{ModelSP}\, S$ holds $(\mathrm{EUntill}\, R)(f, g) = \mathrm{EUntill}_0(f, g, R)$.

Let S be a non empty set, let X be a non empty subset of ModelSP S, and let s be a set. The functor $\mathrm{F\text{-}LABEL}(s, X)$ yields a subset of X and is defined as follows:

(Def. 55) For every set x holds $x \in \mathrm{F\text{-}LABEL}(s, X)$ iff $x \in X$ and there exists a function f from S into *Boolean* such that $f = x$ and $f(s) = \mathit{true}$.

Let S be a non empty set and let X be a non empty subset of ModelSP S. The functor Label X yields a function from S into 2^X and is defined by:

(Def. 56) For every set x such that $x \in S$ holds $(\mathrm{Label}\, X)(x) = \mathrm{F\text{-}LABEL}(x, X)$.

Let S be a non empty set, let S_0 be a subset of S, let R be a total relation between S and S, and let P_1 be a non empty subset of ModelSP S. The functor $\mathrm{KModel}(R, S_0, P_1)$ yields a Kripke structure over P_1 and is defined as follows:

(Def. 57) $\mathrm{KModel}(R, S_0, P_1) = \langle S, S_0, R, \mathrm{Label}\, P_1 \rangle$.

Unauthenticated
Download Date | 8/24/17 5:18 AM

Let S be a non empty set, let S_0 be a subset of S, let R be a total relation between S and S, and let P_1 be a non empty subset of ModelSP S. One can check that the worlds of KModel(R, S_0, P_1) is non empty.

Let S be a non empty set, let S_0 be a subset of S, let R be a total relation between S and S, and let P_1 be a non empty subset of ModelSP S. One can verify that ModelSP (the worlds of KModel(R, S_0, P_1)) is non empty.

Let S be a non empty set, let R be a total relation between S and S, and let B_1 be a non empty subset of ModelSP S. The functor CTLModel(R, B_1) yielding a CTL model structure is defined as follows:

(Def. 58) $\mathrm{CTLModel}(R, B_1) = \langle \mathrm{ModelSP}\, S, B_1, \text{ the and } S, \mathrm{Not}\, S, \mathrm{EneXt}\, R, \mathrm{EGlobal}\, R, \mathrm{EUntill}\, R \rangle$.

In the sequel B_1 is a non empty subset of ModelSP S and k_1 is a function from the atomic WFF into the basic assignations of CTLModel(R, B_1).

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, let s be an element of S, and let f be an assignation of CTLModel(R, B_1). The predicate $s \models f$ is defined by:

(Def. 59) $(\mathrm{Fid}(f, S))(s) = \mathit{true}$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, let s be an element of S, and let f be an assignation of CTLModel(R, B_1). We introduce $s \not\models f$ as an antonym of $s \models f$.

Next we state several propositions:

(11) For every assignation a of CTLModel(R, B_1) such that $a \in B_1$ holds $s \models a$ iff $a \in (\mathrm{Label}\, B_1)(s)$.

(12) For every assignation f of CTLModel(R, B_1) holds $s \models \neg f$ iff $s \not\models f$.

(13) For all assignations f, g of CTLModel(R, B_1) holds $s \models f \wedge g$ iff $s \models f$ and $s \models g$.

(14) For every assignation f of CTLModel(R, B_1) holds $s \models \mathrm{EX}\, f$ iff there exists an infinity path p_1 of R such that $p_1(0) = s$ and $p_1(1) \models f$.

(15) Let f be an assignation of CTLModel(R, B_1). Then $s \models \mathrm{EG}\, f$ if and only if there exists an infinity path p_1 of R such that $p_1(0) = s$ and for every element n of $\mathbb{N}$ holds $p_1(n) \models f$.

(16) Let f, g be assignations of CTLModel(R, B_1). Then $s \models f\, \mathrm{EU}\, g$ if and only if there exists an infinity path p_1 of R such that $p_1(0) = s$ and there exists an element m of $\mathbb{N}$ such that for every element j of $\mathbb{N}$ such that $j < m$ holds $p_1(j) \models f$ and $p_1(m) \models g$.

(17) For all assignations f, g of CTLModel(R, B_1) holds $s \models f \vee g$ iff $s \models f$ or $s \models g$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, let k_1 be a function from the atomic

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WFF into the basic assignations of CTLModel(R, B_1), let s be an element of S, and let H be a CTL-formula. The predicate $s \models_{k_1} H$ is defined by:

(Def. 60) $s \models \mathrm{Evaluate}(H, k_1)$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, let k_1 be a function from the atomic WFF into the basic assignations of CTLModel(R, B_1), let s be an element of S, and let H be a CTL-formula. We introduce $s \not\models_{k_1} H$ as an antonym of $s \models_{k_1} H$.

The following propositions are true:

(18) If H is atomic, then $s \models_{k_1} H$ iff $k_1(H) \in (\mathrm{Label}\, B_1)(s)$.

(19) $s \models_{k_1} \neg H$ iff $s \not\models_{k_1} H$.

(20) $s \models_{k_1} H_1 \wedge H_2$ iff $s \models_{k_1} H_1$ and $s \models_{k_1} H_2$.

(21) $s \models_{k_1} H_1 \vee H_2$ iff $s \models_{k_1} H_1$ or $s \models_{k_1} H_2$.

(22) $s \models_{k_1} \mathrm{EX}\, H$ iff there exists an infinity path p_1 of R such that $p_1(0) = s$ and $p_1(1) \models_{k_1} H$.

(23) $s \models_{k_1} \mathrm{EG}\, H$ iff there exists an infinity path p_1 of R such that $p_1(0) = s$ and for every element n of $\mathbb{N}$ holds $p_1(n) \models_{k_1} H$.

(24) $s \models_{k_1} H_1 \,\mathrm{EU}\, H_2$ if and only if there exists an infinity path p_1 of R such that $p_1(0) = s$ and there exists an element m of $\mathbb{N}$ such that for every element j of $\mathbb{N}$ such that $j < m$ holds $p_1(j) \models_{k_1} H_1$ and $p_1(m) \models_{k_1} H_2$.

(25) For every s_0 there exists an infinity path p_1 of R such that $p_1(0) = s_0$.

(26) Let R be a relation between S and S. Then R is total if and only if for every set x such that $x \in S$ there exists a set y such that $y \in S$ and $\langle x, y\rangle \in R$.

Let S be a non empty set, let R be a total relation between S and S, let s_0 be an element of S, let p_1 be an infinity path of R, and let n be a set. The functor PrePath(n, s_0, p_1) yielding an element of S is defined as follows:

(Def. 61) $\mathrm{PrePath}(n, s_0, p_1) = \begin{cases} s_0, & \text{if } n = 0, \\ p_1(\mathrm{k.nat}(\mathrm{k.nat}\, n - 1)), & \text{otherwise.} \end{cases}$

The following propositions are true:

(27) If $\langle s_0, s_1\rangle \in R$, then there exists an infinity path p_1 of R such that $p_1(0) = s_0$ and $p_1(1) = s_1$.

(28) For every assignation f of CTLModel(R, B_1) holds $s \models \mathrm{EX}\, f$ iff there exists an element s_1 of S such that $\langle s, s_1\rangle \in R$ and $s_1 \models f$.

Let S be a non empty set, let R be a total relation between S and S, and let H be a subset of S. The functor Pred(H, R) yields a subset of S and is defined by:

(Def. 62) $\mathrm{Pred}(H, R) = \{s;\ s$ ranges over elements of S: $\bigvee_{t\,:\,\text{element of } S} (t \in H \wedge \langle s, t\rangle \in R)\}$.

Unauthenticated
Download Date | 8/24/17 5:18 AM

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, and let f be an assignation of CTLModel(R, B_1). The functor SIGMA f yields a subset of S and is defined as follows:

(Def. 63) SIGMA $f = \{s; s$ ranges over elements of S: $s \models f\}$.

One can prove the following proposition

(29) For all assignations f, g of CTLModel(R, B_1) such that SIGMA f = SIGMA g holds $f = g$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, and let T be a subset of S. The functor Tau(T, R, B_1) yielding an assignation of CTLModel(R, B_1) is defined as follows:

(Def. 64) For every set s such that $s \in S$ holds $(\mathrm{Fid}(\mathrm{Tau}(T, R, B_1), S))(s) = \chi_{T,S}(s)$.

The following propositions are true:

(30) For all subsets T_1, T_2 of S such that $\mathrm{Tau}(T_1, R, B_1) = \mathrm{Tau}(T_2, R, B_1)$ holds $T_1 = T_2$.

(31) For every assignation f of CTLModel(R, B_1) holds Tau(SIGMA $f, R, B_1) = f$.

(32) For every subset T of S holds SIGMA Tau$(T, R, B_1) = T$.

(33) For all assignations f, g of CTLModel(R, B_1) holds SIGMA $\neg f = S \setminus$ SIGMA f and SIGMA$(f \wedge g)$ = SIGMA $f \cap$ SIGMA g and SIGMA$(f \vee g)$ = SIGMA $f \cup$ SIGMA g.

(34) For all subsets G_1, G_2 of S such that $G_1 \subseteq G_2$ and for every element s of S such that $s \models \mathrm{Tau}(G_1, R, B_1)$ holds $s \models \mathrm{Tau}(G_2, R, B_1)$.

(35) For all assignations f_1, f_2 of CTLModel(R, B_1) such that for every element s of S such that $s \models f_1$ holds $s \models f_2$ holds SIGMA $f_1 \subseteq$ SIGMA f_2.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, and let f, g be assignations of CTLModel(R, B_1). The functor Fax(f, g) yielding an assignation of CTLModel(R, B_1) is defined by:

(Def. 65) $\mathrm{Fax}(f, g) = f \wedge \mathrm{EX}\, g$.

Next we state the proposition

(36) Let f, g_1, g_2 be assignations of CTLModel(R, B_1). Suppose that for every element s of S such that $s \models g_1$ holds $s \models g_2$. Let s be an element of S. If $s \models \mathrm{Fax}(f, g_1)$, then $s \models \mathrm{Fax}(f, g_2)$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, let f be an assignation of CTLModel(R, B_1), and let G be a subset of S. The functor SigFaxTau(f, G, R, B_1) yielding a subset of S is defined by:

Unauthenticated
Download Date | 8/24/17 5:18 AM

(Def. 66) $\mathrm{SigFaxTau}(f, G, R, B_1) = \mathrm{SIGMA}\,\mathrm{Fax}(f, \mathrm{Tau}(G, R, B_1))$.

One can prove the following proposition

(37) For every assignation f of $\mathrm{CTLModel}(R, B_1)$ and for all subsets G_1, G_2 of S such that $G_1 \subseteq G_2$ holds $\mathrm{SigFaxTau}(f, G_1, R, B_1) \subseteq \mathrm{SigFaxTau}(f, G_2, R, B_1)$.

Let S be a non empty set, let R be a total relation between S and S, let p_1 be an infinity path of R, and let k be an element of $\mathbb{N}$. The functor $\mathrm{PathShift}(p_1, k)$ yielding an infinity path of R is defined as follows:

(Def. 67) For every element n of $\mathbb{N}$ holds $(\mathrm{PathShift}(p_1, k))(n) = p_1(n + k)$.

Let S be a non empty set, let R be a total relation between S and S, let p_2, p_3 be infinity paths of R, and let n, k be elements of $\mathbb{N}$. The functor $\mathrm{PathChange}(p_2, p_3, k, n)$ yielding a set is defined by:

(Def. 68) $\mathrm{PathChange}(p_2, p_3, k, n) = \begin{cases} p_2(n), & \text{if } n < k, \\ p_3(n - k), & \text{otherwise.} \end{cases}$

Let S be a non empty set, let R be a total relation between S and S, let p_2, p_3 be infinity paths of R, and let k be an element of $\mathbb{N}$. The functor $\mathrm{PathConc}(p_2, p_3, k)$ yielding a function from $\mathbb{N}$ into S is defined as follows:

(Def. 69) For every element n of $\mathbb{N}$ holds $(\mathrm{PathConc}(p_2, p_3, k))(n) = \mathrm{PathChange}(p_2, p_3, k, n)$.

We now state four propositions:

(38) Let p_2, p_3 be infinity paths of R and k be an element of $\mathbb{N}$. If $p_2(k) = p_3(0)$, then $\mathrm{PathConc}(p_2, p_3, k)$ is an infinity path of R.

(39) For every assignation f of $\mathrm{CTLModel}(R, B_1)$ and for every element s of S holds $s \models \mathrm{EG}\, f$ iff $s \models \mathrm{Fax}(f, \mathrm{EG}\, f)$.

(40) Let g be an assignation of $\mathrm{CTLModel}(R, B_1)$ and s_0 be an element of S. Suppose $s_0 \models g$. Suppose that for every element s of S such that $s \models g$ holds $s \models \mathrm{EX}\, g$. Then there exists an infinity path p_1 of R such that $p_1(0) = s_0$ and for every element n of $\mathbb{N}$ holds $p_1(n) \models g$.

(41) Let f, g be assignations of $\mathrm{CTLModel}(R, B_1)$. Suppose that for every element s of S holds $s \models g$ iff $s \models \mathrm{Fax}(f, g)$. Let s be an element of S. If $s \models g$, then $s \models \mathrm{EG}\, f$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of $\mathrm{ModelSP}\, S$, and let f be an assignation of $\mathrm{CTLModel}(R, B_1)$. The functor $\mathrm{TransEG}\, f$ yielding a $\subseteq$-monotone function from 2^S into 2^S is defined as follows:

(Def. 70) For every subset G of S holds $(\mathrm{TransEG}\, f)(G) = \mathrm{SigFaxTau}(f, G, R, B_1)$.

One can prove the following two propositions:

(42) Let f, g be assignations of $\mathrm{CTLModel}(R, B_1)$. Then for every element s of S holds $s \models g$ iff $s \models \mathrm{Fax}(f, g)$ if and only if $\mathrm{SIGMA}\, g$ is a fixpoint of

Unauthenticated
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TransEG f.

(43) For every assignation f of CTLModel(R, B_1) holds SIGMA EG f = gfp$(S, \text{TransEG}\, f)$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, and let f, g, h be assignations of CTLModel(R, B_1). The functor Foax(g, f, h) yields an assignation of CTLModel(R, B_1) and is defined as follows:

(Def. 71) $\text{Foax}(g, f, h) = g \vee \text{Fax}(f, h)$.

We now state the proposition

(44) Let f, g, h_1, h_2 be assignations of CTLModel(R, B_1). Suppose that for every element s of S such that $s \models h_1$ holds $s \models h_2$. Let s be an element of S. If $s \models \text{Foax}(g, f, h_1)$, then $s \models \text{Foax}(g, f, h_2)$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, let f, g be assignations of CTLModel(R, B_1), and let H be a subset of S. The functor SigFoaxTau(g, f, H, R, B_1) yields a subset of S and is defined as follows:

(Def. 72) $\text{SigFoaxTau}(g, f, H, R, B_1) = \text{SIGMA}\, \text{Foax}(g, f, \text{Tau}(H, R, B_1))$.

Next we state three propositions:

(45) For all assignations f, g of CTLModel(R, B_1) and for all subsets H_1, H_2 of S such that $H_1 \subseteq H_2$ holds $\text{SigFoaxTau}(g, f, H_1, R, B_1) \subseteq \text{SigFoaxTau}(g, f, H_2, R, B_1)$.

(46) For all assignations f, g of CTLModel(R, B_1) and for every element s of S holds $s \models f\, \text{EU}\, g$ iff $s \models \text{Foax}(g, f, f\, \text{EU}\, g)$.

(47) Let f, g, h be assignations of CTLModel(R, B_1). Suppose that for every element s of S holds $s \models h$ iff $s \models \text{Foax}(g, f, h)$. Let s be an element of S. If $s \models f\, \text{EU}\, g$, then $s \models h$.

Let S be a non empty set, let R be a total relation between S and S, let B_1 be a non empty subset of ModelSP S, and let f, g be assignations of CTLModel(R, B_1). The functor TransEU(f, g) yields a $\subseteq$-monotone function from 2^S into 2^S and is defined by:

(Def. 73) For every subset H of S holds $(\text{TransEU}(f, g))(H) = \text{SigFoaxTau}(g, f, H, R, B_1)$.

One can prove the following propositions:

(48) Let f, g, h be assignations of CTLModel(R, B_1). Then for every element s of S holds $s \models h$ iff $s \models \text{Foax}(g, f, h)$ if and only if SIGMA h is a fixpoint of TransEU(f, g).

(49) For all assignations f, g of CTLModel(R, B_1) holds $\text{SIGMA}(f\, \text{EU}\, g) = \text{lfp}(S, \text{TransEU}(f, g))$.

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(50) For every assignation f of $\mathrm{CTLModel}(R, B_1)$ holds $\mathrm{SIGMA}\,\mathrm{EX}\,f = \mathrm{Pred}(\mathrm{SIGMA}\,f, R)$.

(51) For every assignation f of $\mathrm{CTLModel}(R, B_1)$ and for every subset X of S holds $(\mathrm{TransEG}\,f)(X) = \mathrm{SIGMA}\,f \cap \mathrm{Pred}(X, R)$.

(52) For all assignations f, g of $\mathrm{CTLModel}(R, B_1)$ and for every subset X of S holds $(\mathrm{TransEU}(f, g))(X) = \mathrm{SIGMA}\,g \cup \mathrm{SIGMA}\,f \cap \mathrm{Pred}(X, R)$.

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