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Investigating nondeterministic processes*

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Event structures have widely been proposed as a basis for constructing models of nondeterministic processes. However, not all event structures are turned out to be suitable for this purpose. One way to get around this problem is to adapt Petri's concurrency axioms (including K-density and related properties) to event structures. In this paper we study the above properties in the context of flow event structures [5].

1. Introduction

Many models (Petri nets, posets, event structures, etc.) are currently used to describe the possible behaviours of concurrent/distributed systems. However, not all instances of these models are suitable for an adequate representation of 'reasonable' concurrent processes. To overcome this problem there has been a line of research originating from [10] such as [1], [2], [7], where interest has mainly concentrated on concurrency axioms (namely the density, crossing and discreteness versus continuity properties) of occurrence nets. In [10], a property called K-density has been defined, motivated by intuitive idea that every sequential subprocess of a process should always be in a well-defined state. [1] characterizes K-density in terms of other related properties and some consequences of this are proved in [2]. The remaining axioms (including the D-continuity, coherence and reducedness properties) of occurrence nets have been investigated in [4], [7]. L- and M-density as meaningful properties for the Petri nets with nondeterministic choices have been introduced in [8]. Finally, Plünnecke [11] proved a variety of results on the relationship between K- and N-density in the context of posets in general. The interdependencies between these and other related properties of posets have been summarized in [3].

Event structures are reminiscent of many poset models. The advantage of event structures is that the nondeterministic aspects of concurrent processes are explicitly described and the choices can naturally be expressed. The relative strength and significance of the mentioned above axioms are

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not self-evident for event structures. To clarify these issues we have considered it desirable to obtain a characterization of the properties in terms of prime event structures [9] and have shown how the properties fit together in [13]. From our point of view, an investigation of K-density and related concepts for event structures is interesting for several reasons. First, it is always intriguing to see what are the consequences of small modifications and generalizations of important definitions. Algebraically, these properties lead to elegant and simple laws [5], [12]. Moreover, we expect that event structures possessing the properties have a good characterization in terms of temporal logic languages [14].

The present paper is devoted to furthering the study of the power of K-density and related properties in the context of a more extended class of event structures – flow event structures [5]. In Section 2 we shortly recall some basic notions of flow event structures. This model allows us to give a unified characterization of the density, reducedness, coherence properties which are presented in Section 3. We give sufficient and necessary conditions for these properties to hold. The final section contains our concluding remarks and directions to future work.

2. Preliminaries

Our framework is flow event structures (here, event structures for the sake of brevity) introduced by Boudol and Castellani in [5] as a fundamental model for nondeterministic processes.

Definition 1. *An event structure* is a triple $S = (E, \leq, \#)$, where

- E is a set of events,
- $\leq \subseteq E \times E$ is a partial order *(the causality relation)*,
- $\# \subseteq E \times E$ is a symmetrical and irreflexive relation *(the conflict relation)*.

In graphic representations the $<$-relation is drawn by arcs (omitting those derivable by transitivity), and conflicts are also pictured. Following these conventions, a trivial example of the event structure is shown in Figure 1.

From now on for an event structure $S = (E, \leq, \#)$, let $\smile = (E \times E) \setminus (\leq \cup \geq \cup \#)$ (*the concurrency relation*). In order to avoid many useless repetitions we shall name each of the relations $\leq$, $\#$, $\smile$ a connective of a given structure S.

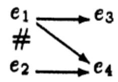

Figure 1

Let us introduce some notions and notations which will be useful throughout the paper. Let $R \subseteq E \times E$ be a relation on a set E. Then

- $R^\sigma = R \cup R^{-1}$ is the symmetrical closure of R,
- $R^\varepsilon = R^\sigma \cup R^0$ is the reflexive and symmetrical closure of R, which we shall call the R-comparability relation,
- $\ddagger R = (E \times E) \setminus R^\varepsilon$ is the symmetric, irreflexive R-incomparability relation,
- $R^\delta = R \setminus R^2$ is the irreflexive, intransitive relation.

For instance, the comparability relation determined by $\smile$ is simply its reflexive closure, $\ddagger \leq \, = \# \cup \smile$, and $\#^\delta = \#$. For the event structure shown in Figure 1:

$$\begin{aligned} \leq^\varepsilon &= \{(e_1, e_3), (e_3, e_1), (e_1, e_1), \ldots, (e_4, e_4)\}, \\ \ddagger \leq &= \{(e_1, e_2), (e_2, e_1), (e_2, e_3), (e_3, e_2), (e_3, e_4), (e_4, e_3)\}, \\ \leq^\delta &= \{(e_1, e_3), (e_1, e_4), (e_2, e_4)\}. \end{aligned}$$

Let $S = (E, \leq, \#)$ be an event structure, let V be a connective of S. Then $A \subseteq E$ is a *V-set* iff $\forall e_1, e_2 \in A : e_1 \ V^\varepsilon \ e_2$, A is a *V-section* iff A is a maximal V-set. The set of V-sections in S is denoted by $V(S)$. An event structure $S = (E, \leq, \#)$ is *V-finite* iff any V-section in S is finite.

We shall call $S = (E, \leq, \#)$ *discrete* iff $\forall e_1, e_2 \in E$, $\forall A \in \leq(S)$: $| [e_1, e_2] \cap A | < \infty$, where $[e_1, e_2] = \{e \in E \mid e_1 \leq e \leq e_2\}$. This means that in a discrete event structure there is no infinite $\leq$-set between any pair of events. In the following we will consider only discrete event structures and will call them simply event structures.

Lemma 1. *Let $S = (E, \leq, \#)$ be an event structure, let V, V' be connectives of S ($V \neq V'$). Then $\forall A \in V(S)$, $\forall B \in V'(S) : | A \cap B | \leq 1$.*

Proof. This follows from the definitions of the connectives of S. □

Definition 2. Let $S = (E, \leq, \#)$, $S' = (E', \leq', \#')$ be event structures, let V be a connective of S and S'. Then

- S' is a *substructure* of S ($S' \subseteq S$) iff $E' \subseteq E$, $\leq' \subseteq (\leq \cap E'^2)$, $\#' \subseteq (\# \cap E'^2)$,
- S' is *a maximal substructure* of S iff for any substructure S'' of S such that $S' \subseteq S''$ is valid that $S' = S''$,
- S' is *a maximal VF-substructure* of S iff S' is a maximal substructure of S and $V^\delta = \emptyset$ in S'.

For the event structure shown in Figure 1 we draw its maximal VF-substructures in Figures 2(a), 2(b) and 2(c) for V among $\#$, $\smile$ and $\leq$, respectively.

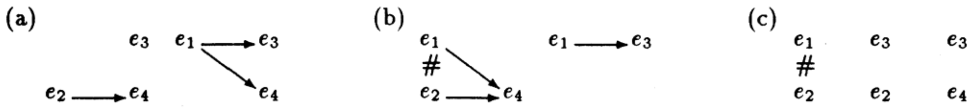

Figure 2

Lemma 2. *Let $S = (E, \leq, \#)$ be an event structure, let V, V' be connectives of S ($V \neq V'$). Then for any V-section A in S there exists a maximal V'F-substructure S' of S such that A is the V-section in S'.*

Proof. It immediately follows from the definitions of a V-section and a maximal V′F-substructure of S. □

In such a way, we have recalled basic terminology of event structures and defined some additional notions needed to introduce the density and related concepts for event structures.

3. Some properties of event structures

3.1. Density and crossing

Our aim in this section is to introduce a hierarchy of density and crossing properties which are motivated by the wish to exclude unreasonable processes and to give a few key results pertaining to the properties. In so doing it will be convenient to adopt the following notations.

Let $S = (E, \leq, \#)$ be an event structure and $X \subseteq E$. Then $\downarrow X = \{e' \mid e' \in E \;\&\; \exists e \in X : e' \leq e\}$, and $\uparrow X = \{e' \mid e' \in E \;\&\; \exists e \in X : e \leq e'\}$.

Definition 3. Let $S = (E, \leq, \#)$ be an event structure, let V be a connective of S, let $S' = (E', \leq', \#')$ be a maximal VF-substructure of S , let V', V'' be connectives of S and S' ($V', V'' \in \ddagger V$, $V' \neq V''$). Then

- S' is *K_V-dense* iff $\forall A \in V'(S'), \forall B \in V''(S') : | A \cap B | = 1$,
- S' is *V-crossing* iff $\forall A \in V'(S'), \forall B \in V''(S') : A \cap \uparrow B \neq \emptyset$ & $A \cap \downarrow B \neq \emptyset$,
- S is *K_V-dense* (V-crossing) iff any maximal VF-substructure of S is K_V-dense (V-crossing),
- S is *N_V-dense* if it satisfies

$$\begin{cases} \text{for any } e_0, e_1, e_2, e_3 \in E \\ \text{if } e_0 \; V'^{\delta} \; e_1 \text{ and } e_0 \; V''^{\delta} \; e_2, \\ \text{if } e_2 \; V'^{\delta} \; e_3 \text{ and } e_1 \; V''^{\delta} \; e_3, \\ \text{then } e_0 \; V'^{\delta} \; e_3 \Rightarrow e_1 \; V'^{\delta} e_2. \end{cases}$$

According to the above definition, the event structure shown in Figure 3(a) is K_V-dense, N_V-dense and V-crossing for $V = \leq$, whereas the event structure shown in Figure 3(b) is V-crossing, but neither K_V-dense nor N_V-dense for $V = \#$.

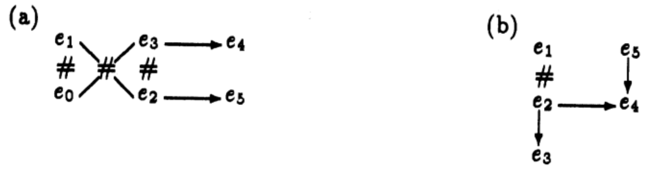

Figure 3

The following result states a connection between the properties defined prior to that.

Proposition 1. *Let $S = (E, \leq, \#)$ be an N_V-dense event structure, let V be a connective of S. Then S is K_V-dense iff S is V-crossing.*

Proof.
($\Rightarrow$) : Trivial.
($\Leftarrow$) : Let V', V'' be connectives of S such that $V', V'' \in \ddagger V$ and $V' \neq V''$. Suppose S is not K_V-dense. This means that there exists a maximal VF-substructure $S' = (E', \leq', \#')$ of S in which there are a V'-section A and a V''-section B such that $| A \cap B | = 0$. Three cases are admissible.

- If $V = \leq$. Trivial.
- If $V = \smile$. W.l.o.g. assume $V' = \leq$ and $V'' = \smile$. According to V-crossing and discreteness of S, there exist a maximal element $e \in A \cap \downarrow B$ and a minimal element $e' \in A \cap \uparrow B$. Then there are

$a, a' \in B$ such that $e\ V'^{\varepsilon}\ a$ and $e'\ V'^{\varepsilon}\ a'$. If $e = e'$ then we get the contradiction $a, a' \notin B$. Otherwise, the possible cases are the following.

1. If $(e\ V'^{\delta}\ e')$. Then we consider two cases.
   (a) If $(a = a')$. Then
      - If $(e = a$ or $e' = a')$. The result is proved.
      - If $\neg(e = a$ or $e' = a')$. We get the contradiction $\neg(e\ V'^{\delta}\ e')$.

   (b) If $\neg(a = a')$. Then
      - If $(e = a$ or $e' = a')$. We are done.
      - If $\neg(e = a$ or $e' = a')$. This contradicts N_V-density of S.
2. If $\neg(e\ V'^{\delta}\ e')$. Then w.l.o.g. assume $e\ V'^{\delta}\ e''\ V'^{\delta}\ e'$. The possible cases are the following.
   (a) If $(a = a')$. Then
      - If $(e''\ V'^{\varepsilon}\ a)$. This contradicts either the minimality of e' or the maximality of e.
      - If $\neg(e''\ V'^{\varepsilon}\ a)$. If, moreover, there exists $e''' \in B$ such that $e''\ V'\ e'''$ then we get a contradiction to N_V-density of S. Otherwise, B is not a V''-section of S.

   (b) If $(\neg a = a')$. The proof is similar to that of the previous case.

- If $V = \#$. This case is symmetric to the previous one. □

The next proposition establishes the relationship between some finiteness constraints and the properties above.

Proposition 2. *Let $S = (E, \leq, \#)$ be an N_V-dense event structure, let V, V', V'' be connectives of S ($V', V'' \in \ddagger V$, $V' \neq V''$). Then S is K_V-dense if either condition holds:*

(i) S is V'-finite,

(ii) S is V''-finite.

Proof. (i) Suppose S is not K_V-dense. Then there exists a maximal non-K_V-dense VF-substructure $S' = (E', \leq', \#')$ of S in which there are a V'-section A and a V''-section B such that $\mid A \cap B \mid = 0$. Let $A = \{e_0, e_1, \ldots, e_n\}$ and $B = \{e'_0, e'_1, \ldots\}$.

- If $V = \leq$. Then we have $\exists e_i, e_j \in A$ and $\exists e'_k, e'_l \in B$ such that $e_i\ V'^{\delta}\ e'_k$ and $e_i\ V''^{\delta}\ e'_l$, $e'_l\ V'^{\delta}\ e_j$ and $e_j\ V''^{\delta}\ e'_k$, $e_i\ V'^{\delta}\ e_j$ and $e'_k\ V''^{\delta}\ e'_l$. This contradicts N_V-density of S.
- If $V = \smile$. By Proposition 1, we have $A \cap \uparrow B = \emptyset$ or $A \cap \downarrow B = \emptyset$. Since $\uparrow B \cup \downarrow B = E$, $A \subseteq (\downarrow B \setminus B)$ or $A \subseteq (\uparrow B \setminus B)$, respectively. Then there exists $e'_j \in B$ such that $e'_j\ V'^{\sigma}\ e_i$ for all $e_i \in A$. This means that A is not a V'-section of S.
- If $V = \#$. This case is symmetric to the previous one.

The remaining part (ii) can be proved in the same way. □

We now aim at defining some modifications of the M-density concept [6], [8] for event structures as follows.

Definition 4. Let $S = (E, \leq, \#)$ be an event structure, let V, V', V'' be connectives of S ($V', V'' \in \ddagger V$, $V' \neq V''$). Then S is *M_V-dense* iff the intersection of any maximal V′F-substructure with any maximal V″F-substructure of S results in some (unique) V-section of S.

As an illustration, the event structure shown in Figure 4(a) is M_V-dense for $V = \leq$, when the event structure shown in Figure 4(b) is not for all the connectives of S.

Figure 4

In order to establish the close relationship between different density concepts it is necessary to define another requirement which we may call the triangle-feeness property: an event structure S with connectives V, V', V'' satisfies this property (referred to as *the ∇-freeness* property) if there do not exist $e_1, e_2, e_3 \in E$ such that $e_1\ V\ e_2$, $e_2\ V'\ e_3$, and $e_1\ V''\ e_3$.

Lemma 3. *Let $S = (E, \leq, \#)$ be a ∇-free event structure, let V, V', V'' be connectives of S ($V', V'' \in \ddagger V$, $V' \neq V''$). Then any V-section in a maximal V′F-substructure (maximal V″F-substructure) of S is a V-section in S.*

Proof. We only sketch the proof of the case with a maximal V′F-substructure $S' = (E', \leq', \#')$ of S. Assume a contrary, i.e., there exists a V-section A in S' such that A is not a V-section in S. So, there exists $e \in E$ such that $e\ V^{\varepsilon}\ e_i$ for all $e_i \in A$ and $e \notin E'$. Then we have $\exists e'' \in (E' \setminus A) : e\ V'\ e''$. Hence there is $e_i \in A$ such that $e''\ V''\ e_i$, contradicting $\bigtriangledown$-freeness of S. □

Proposition 3. *Let $S = (E, \leq, \#)$ be a $\bigtriangledown$-free event structure, let V, V', V'' be connectives of S ($V', V'' \in \ddagger V$, $V' \neq V''$), let S be V'-finite or V''-finite. Then S is K_V-dense iff S is M_V-dense.*

Proof. Assume S is V'-finite. The case that S is V″-finite is symmetric. ($\Rightarrow$) : Suppose S is not M_V-dense, i.e., there exist its maximal V′F-substructure $S' = (E', \leq', \#')$ and a maximal V″F-substructure $S'' = (E'', \leq'', \#'')$ such that $E' \cap E'' = A$ is not a V-section in S. We distiguish between two cases.

- If $A = \emptyset$. Let B be a V'-section in S'' and C be a V''-section in S'. By Lemma 3, B (C) is also a V'-section (V''-section) in S. Let us remark that the events in E' and E'' are V-incomparable, since S is $\bigtriangledown$-free and $A = \emptyset$. Then by Lemma 2, there exists a maximal VF-substructure S''' of S such that B (C) is a V'-section (V''-section) in S'''. Since $|\ E' \cap E''\ | = 0$, we get a contradiction to K_V-density of S.
- If $A \neq \emptyset$. This contradicts Lemma 3.

($\Leftarrow$) : Suppose S is not K_V-dense. This means that there exists a maximal VF-substructure $S''' = (E''', \leq''', \#''')$ of S with a V'-section B and a V''-section C such that $|\ B \cap C\ | = 0$. According to Lemma 3, B (C) is also a V'-section (V''-section) in S. By Lemma 2, there exist a maximal V′F-substructure $S' = (E', \leq', \#')$ and a maximal V″F-substructure $S'' = (E'', \leq'', \#'')$ of S such that B is a V'-section in S'' and C is a V''-section in S'.

Since S is M_V-dense, we have $|\ E' \cap E''\ | = A$ is a V-section in S. Hence $|\ A \cap B\ | = 0$ and $|\ A \cap C\ | = 0$. This means that S is neither $K_{V'}$-dense nor $K_{V''}$-dense. According to V'-finiteness of S, S is neither N_V-dense nor $N_{V''}$-dense, by Proposition 2. We only sketch the proof of the case that S is not $N_{V''}$-dense because the remaining one is similar. Then there exist $e_1, e_2 \in A$ and $e_1', e_2' \in B$ such that $e_1\ V^{\delta}\ e_1'$ and $e_1\ V'^{\delta}\ e_2'$, $e_2'\ V^{\delta}\ e_2$ and $e_1'\ V'^{\delta}\ e_2$, $e_1\ V^{\delta}\ e_2$ and $e_1'\ V'^{\delta}\ e_2'$.

- If $V = \leq$. Let us first remark that if $\exists e_i \in A$, $\exists e''_j \in C : e\ V^{\sigma}\ e''$, then we have $e''_j\ V\ e_i$, since $\forall e'_k \in B : e''_j \ddagger V e'_k$. W.l.o.g. assume $V' = \smile$ and $V'' = \#$. Since S' is not $K_{V'}$-dense, two cases are admissible.

  1. If $(\forall e''_i \in C : e_1\ V\ e''_i)$. If, moreover, $\exists e''_j \in C : e_2\ V\ e''_j$, then we get the contradiction $\neg(e_1\ V^{\delta}\ e_2)$. Otherwise, C is not a V''-section of S'.
  2. If $\neg(\forall e''_i \in C : e_1\ V\ e''_i)$. If, moreover, $\forall e''_i \in C : e''_i\ V\ e_1$, then C is not a V''-section of S'. Otherwise w.l.o.g. assume $\exists e''_i, e''_j \in C : e_1\ V\ e''_i$ and $e_1\ V''\ e''_j$. If $e''_i\ V\ e_2$, then we get the contradiction $\neg(e_1\ V^{\delta}\ e_2)$. Otherwise, S is not ∇-free.

- The remaining cases that $V = \smile$ and $V = \#$ are symmetric. □

3.2. Reducedness and coherence

Now we would like to characterize the reducedness concept for event structures. First, however, we need the following. Let $e \in E$, then $V(e) = \{e' \in E \mid e'\ V^{\epsilon}\ e\}$.

Definition 5. Let $S = (E, \leq, \#)$ be an event structure, let V be a connective of S. Then S is V*-reduced* iff $\forall e, e' \in E : V(e) = V(e') \Rightarrow e = e'$.

For example, the event structure shown in Figure 5(a) is V-reduced for V among $\#$ and $\smile$, whereas the event structure shown in Figure 5(b) is V-reduced for $V = \leq$.

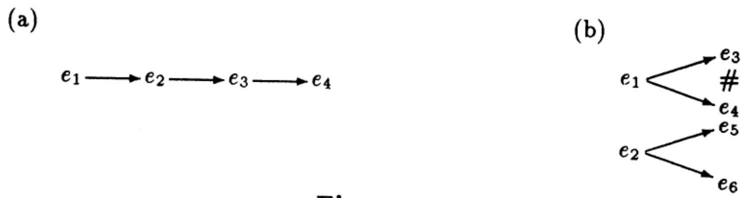

Figure 5

Proposition 4. *Let $S = (E, \leq, \#)$ be an event structure, let V be a connective of S, let S be V-reduced. Then $\forall e, e' \in E$:*
$e\ V^{\mathcal{E}}\ e' \Rightarrow \exists V' \in \ddagger V,\ \exists e'' \in E\ (e \neq e'' \neq e') : e\ V\ e''\ V'\ e'$ *or* $e\ V'\ e''\ V\ e'$.

Proof. We shall prove by contradiction. Then there exist $e, e' \in E$ such that $e\ V^{\delta}\ e'$ and

$$\forall V' \in \ddagger V,\ \forall e'' \in (E \setminus \{e, e'\}) : \neg((e\ V\ e''\ V'\ e')\ \&\ (e\ V'\ e''\ V\ e')).$$

Hence we have $\forall e'' \in E : e\ V\ e'' \Rightarrow e''\ V^{\varepsilon}\ e'$ and $e''\ V\ e' \Rightarrow e''\ V^{\varepsilon}\ e$. Thus $V(e) = V(e')$, contradicting V-reducedness of S. □

Proposition 5. *Let $S = (E, \leq, \#)$ be a $\bigtriangledown$-free event structure and V be a connective of S. Then S is V-reduced iff*
$\forall e, e' \in E : e \neq e' \Rightarrow \exists V' \in \ddagger V : V'(e) \setminus \{e\} \neq V'(e') \setminus \{e'\}$.

Proof.
$(\Rightarrow)$: We suppose a contrary. This means that there exist $e, e' \in E$ $(e \neq e')$ such that for all $V' \in \ddagger V$ we have $V'(e) \setminus \{e\} = V'(e') \setminus \{e'\}$. Hence $V(e) = V(e')$.
$(\Leftarrow)$: Suppose that S is not V-reduced. Then there exist $e, e' \in E$ $(e \neq e')$ such that $V(e) = V(e')$. This means that $e\ V\ e'$ and there is $e'' \in E$ such that $e'\ V'\ e''$ and $e\ V''\ e''$, contradicting $\bigtriangledown$-freeness of S. □

We now come to our definition of the coherence property of event structures.

Definition 6. Let $S = (E, \leq, \#)$ be an event structure, let V be a connective of S. Then S is *V-coherent* iff $(V^{\varepsilon})^* = E \times E$.

Illustrating the concept, the event structure shown in Figure 6(a) is V-coherent for $V = \leq$, when the event structure shown in Figure 6(b) is V-coherent for V among $\#$ and $\smile$.

Figure 6

Proposition 6. *Let $S = (E, \leq, \#)$ be an event structure and V be a connective of S. Then*

(i) *S is V-coherent and* $|\ E\ | > 1 \Rightarrow \forall e \in E : V'^{\varepsilon}(e) \cup V''^{\varepsilon}(e) \neq E$,

(ii) *S is V-coherent* $\Leftarrow \exists e, e' \in E : V(e) \cap V(e') = \emptyset \Rightarrow$
$\exists e'' \in E : ((V(e'') \cap V(e) \neq \emptyset)\ \&\ (V(e'') \cap V(e') \neq \emptyset))$.

Proof. (i) Clearly, for $e \in E$ there exists $e' \in E$ such that $e \neq e'$. By V-coherence, we have $e\ V^{\varepsilon}\ \ldots\ V^{\varepsilon}\ e'$. There is $e'' \in E$ such that $e'' \neq e$ and $e''\ V^{\varepsilon}\ e$. The case (ii) is trivial. □

4. Concluding remarks

In this paper, we have glanced at a variety of density and related properties of flow event structures. The choice of this model was guided by the wish for a unified characterization of the above properties for event structures. Perhaps the most interesting outcome of our work has been the close relationship between different density concepts. We have done so both by proving some new results and by generalizing old ones. An interesting topic for future work would be to investigate the relative strength of the remaining axioms of concurrency (in particular, D-continuity) for the chosen model and to generalize the results to more extended classes of event structures.

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