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Discriminability Analysis of Supervision Patterns by Net Unfoldings

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Abstract: In this paper, we are interested in the discriminability of supervision patterns, in discrete event systems (DES). Discriminability — as opposed to diagnosability — is the possibility to detect the exclusive occurrence of a particular behavior of interest — called the supervision pattern. To this end, we propose to adapt the classical twin-plant approach to Petri nets unfolding. The usage of unfoldings permits us to avoid the combinatorial explosion associated with marking graphs. The method can also be used to solve the classical problem of discrete event systems’ diagnosability.

Keywords: discriminability, diagnosability, supervision patterns, labeled Petri nets, Petri nets unfolding.

1. INTRODUCTION

In the context of discrete-event systems (DES), the supervision task consists in analyzing the sequence of observed events and determining whether an abnormal/faulty situation has occurred before deciding what kind of actions to perform in order to recover the optimal performance of the system. By the intrinsic nature of DES, an abnormal situation is characterized by a partial order of observable/non-observable events called an event pattern or a supervision pattern as introduced in Jéron et al. (2006).

In this paper, we address the problem of analysing the discriminability of a set of supervision patterns. Two supervision patterns R₁ and R₂ are discriminable if it is always possible to assert from the observed events that if R₁ has occurred then R₂ has not occurred and will not occur.

The notion of pattern discriminability is obviously related to the notion of pattern diagnosability and their respective analyses (Jiang et al. (2003), Jéron et al. (2006), Yoo and Garcia (2008), Gougam et al. (2013)), however the point of view is different. The result of a diagnosability analysis states whether any considered pattern is always detectable or not. If such a property holds then it is possible to design a diagnoser that will always be able to determine which patterns have occurred in a finite amount of time. However there is a pitfall: underlying real-world systems are not and cannot be diagnosable as the diagnosability property is very restrictive (Pencolé (2005)) and requires an observability level that cannot be implemented as a set of sensors on the underlying system (physical and/or cost constraints). The classical diagnosability analyses will then conclude such a real-world system is not diagnosable, so what is next?

To cope with this problem, we propose to develop a more constructive analysis by checking the discriminability of the occurrence of a set of patterns with respect to another disjoint set of patterns. The analysis is constructive in the sense that any partial discriminability result has an outcome that can impact the design of a diagnoser for the analysed system even if the underlying system is not globally diagnosable. And finally, once the proposed discriminability analysis is completed, checking the classical diagnosability analysis is straightforward and for free.

In our proposal, the development of the discriminability analysis relies on two original choices. The first one is the use of Petri net — which were shown to be more appropriate to solve diagnosis problems Lai et al. (2008) — to model patterns as well as the system (Basile et al. (2009), Dotoli et al. (2009)) so that we benefit of the natural way to represent event concurrency. The second one is the use of net unfoldings (McMillan (1995), Esparza et al. (2002), Benveniste et al. (2003)) in order to benefit of a representation as a partial order of events. unfoldings avoid the explicit enumeration of event sequences that is performed by techniques based on marking graphs like in Cabasino et al. (2012). Our proposed approach allows us to have some interesting properties. First, genericsness, meaning that we do not impose particular patterns, we rather define a generic framework for supervision pattern, and every pattern falling in this framework can be used for supervision. Second, the supervision patterns are compact, i.e. only relevant events are included leading to more concise patterns. Finally, reusability, which is a direct consequence of the compactness, the exclusive use of relevant events yields supervision patterns which are independent from the system.

The paper is organized as follows. Section 2 introduces the problem, Section 3 presents Petri nets and their use to model the system and the patterns. The proposed analysis method is detailed in Sections 4 and 5. An example of
or words — over "exclusively Cachan, France. May 14-16, 2014
WODES 2014
discriminable

We can now define the discriminability of a set of supervi-
sion patterns.

We make the assumption that the system is

The observable events are represented by the set

which are also languages with specific properties. More for-

mation patterns.

Definition 2. A supervision pattern is said to be faulty if:

\[ R \subseteq \Sigma \text{ faulty if: } \exists w \in \Sigma^* \text{ such that } \forall z \in S \cup \Sigma^* \exists w \in S \cup \Sigma^* \]

A supervision pattern is modeled by the prefix-closed language

Let \( R \) be a subset of \( \Sigma \). A supervision pattern

The context mean characterizing the performances of the
diagnosis algorithm. A diagnosis algorithm, given an

an observable sequence produced by the system, is responsible

of returning its state, i.e., is the system in a normal state or a faulty state, and in the latter case, which —
faulty — behavior yielded this state. If such algorithm

exists, and can determine with certainty after a bounded

number of observations that only a particular combination

of behaviors occurred, this combination is said to be
discriminable. On the other hand, if the algorithm can
detect the occurrence of a behavior with no information

about the possible occurrence of other faulty behaviors,

the former is said to be detectable.

In this paper, we consider a system modeled by a language,

faulty behaviors are recognized by supervision patterns

which are also languages with specific properties. More for-
mally, the problem of supervision pattern discriminability

in discrete event systems is then defined in the following

context.

Let \( \Sigma = \{a, b, \ldots\} \) be a finite set called an alphabet. The

Kleene closure of \( \Sigma \) denoted \( \Sigma^* \) is the set of finite sequences —

or words — over \( \Sigma \) — including the empty sequence, denoted in the following by \( \lambda \). \( \Sigma^* = \Sigma^* \setminus \{\lambda\} \) is the set of

non-empty finite sequences. A subset \( \Sigma \subseteq \Sigma^* \) is called a

language over \( \Sigma \). The continuation \( z \) of a sequence \( w \) in \( \Sigma \) is a sequence such that \( wz \in \Sigma \). So, the set of \( w \)’s continuations in \( \Sigma \) is defined as \( S/w = \{z \in \Sigma^* : wz \in \Sigma\} \).

The classical projection of a sequence \( w \in \Sigma \) on a subset \( \Sigma_p \) of \( \Sigma \) is denoted \( \mathcal{P}_{\Sigma_p}(w) \). Finally, \( ||w|| \) denotes the

length of the sequence \( w \). The behavior of the system is

modeled by the prefix-closed language \( \Sigma \) over an alphabet

\( \Sigma \) representing the set of events generated by the system.

Some of these events are observable, while others are not.

The observable events are represented by the set \( \Sigma_o \) and the

set of non-observable events is called \( \Sigma_u \). \( \Sigma = \Sigma_o \cup \Sigma_u \).

We make the assumption that the system is \( \Sigma_o \)-alive, meaning:

\( \forall w \in \Sigma, \exists z \in \Sigma \cup \Sigma^* : \mathcal{P}_{\Sigma_o}(z) \neq \lambda \); this hypothesis

ensures that the system produces observations with some

regularity. A supervision pattern \( \mathcal{R} \) is a language over

\( \Sigma_R \subseteq \Sigma \) that recognizes \( \mathcal{R} \)-faulty sequences.

Definition 1. Let \( \mathcal{R} = \{R_1, R_2, \ldots, R_n\} \) be a set of supervision patterns.

A sequence \( w \in \Sigma^* \) is said to be \( \mathcal{R} \)-faulty if:

\( \mathcal{P}_{\Sigma_{\mathcal{R}_i}}(w) \in R_i \). A sequence \( w \in \Sigma^* \) is said to be

\( \mathcal{R} \)-faulty if: \( \forall R \in \mathcal{R} : w \in \mathcal{R} \)-faulty. A sequence \( w \in \Sigma^* \) is said to be faulty if: \( \exists R \in \mathcal{R} : w \in \mathcal{R} \)-faulty.

Definition 2. Let \( \mathcal{R} = \{R_1, R_2, \ldots, R_n\} \) be a set of supervision patterns.

A sequence \( w \in \Sigma^* \) is said to be exclusively \( \mathcal{R} \)-faulty in \( \mathcal{R} \) if:

\[ \forall R \in \mathcal{R}^*: w \in \mathcal{R} \)-faulty \]

\[ \forall R \notin \mathcal{R} : w \text{ is not } \mathcal{R} \)-faulty

We will simply use “exclusively \( \mathcal{R} \)-faulty” rather than “exclusively \( \mathcal{R} \)-faulty in \( \mathcal{R} \)” when there is no ambiguity.

We can now define the discriminability of a set of supervi-
sion patterns.

Definition 3. Given a system \( S \) and a set of supervision patterns \( \mathcal{R} = \{R_1, R_2, \ldots, R_n\} \). A subset \( \mathcal{R}^* \) of \( \mathcal{R} \) is said to be discriminable if:

\[ \exists n \in \mathbb{N}, \forall w \text{ an exclusively } \mathcal{R}^* \text{-faulty word of } S, \forall z \in S/w : \]

\[ ||\mathcal{P}_{\Sigma_o}(z)|| \geq n \implies D \]

where the discriminability condition \( D \) is:

\[ \forall w \in \mathcal{P}_{\Sigma_o}(\mathcal{P}_{\Sigma_o}(wz)) : w^o \text{ is exclusively } \mathcal{R}^* \text{-faulty} \]

This property insures that one can detect with certainty

that only a particular combination of patterns — namely \( \mathcal{R}^* \) — occurred.

Similarly, we define the \( \mathcal{R} \)-diagnosability of a system.

Definition 4. Let \( \mathcal{R} = \{R_1, R_2, \ldots, R_n\} \) be a set of supervision patterns. A language \( S \) is \( \mathcal{R} \)-diagnosable if:

\[ \forall R \in \mathcal{R}(\exists n \in \mathbb{N}), \forall w \text{ an } \mathcal{R} \text{-faulty word of } S, \forall z \in S/w : \]

\[ ||\mathcal{P}_{\Sigma_o}(z)|| \geq n \implies D \]

where the diagnosability condition \( D \) is:

\[ \forall w \in \mathcal{P}_{\Sigma_o}(\mathcal{P}_{\Sigma_o}(wz)) : w^o \text{ is } \mathcal{R} \text{-faulty} \]

More intuitively, a language \( S \) is \( \mathcal{R} \)-diagnosable if it does not contain two arbitrary long sequences, the first \( \mathcal{R} \)-faulty, the second non \( \mathcal{R} \)-faulty, which have the same observable behavior.

3. ON MODELING ASPECTS

To tackle the problem of discriminability, we propose to use

labeled Petri nets to model the system and the patterns.

3.1 Labeled Petri nets

Definition 5. A labeled Petri net is a tuple \( (P, T, A, \ell, L, \Sigma) \) where:

- \( P \): a set of places;
- \( T \): a set of transitions with \( P \cap T = \emptyset \);
- \( A \subseteq (P \times T) \cup (T \times P) \): a binary relation representing arcs between nodes;
- \( \ell \colon P \cup T \rightarrow L \cup \Sigma \cup \{\lambda\} \): a labeling function where \( L \) is the set of place labels, \( \Sigma \) is the set of transition labels and \( \lambda \) denotes the empty sequence.
- \( \ell \) is naturally extended to markings and sequences of nodes. Let \( M \) be a marking: \( \ell(M) = \{\ell(p) : p \in M\} \).

A marking \( M \) is a map from \( P \) to \( \mathbb{N} \) which maps any place \( p \) to the number of tokens \( M(p) \) contained in it. For the sake of simplicity, a marking may sometimes be denoted as a multiset. For instance, let \( P = \{p_1, p_2, p_3\} \), the marking \( M \) such that \( M(p_1) = 2, M(p_2) = 0 \) and \( M(p_3) = 1 \) can be represented as \( M = \{p_1, p_2, p_3\} \). A marked

labeled Petri net is a tuple \( \theta = (P, T, A, \ell, L, \Sigma, M_0) \) where \( (P, T, A, \ell, L, \Sigma) \) is a labeled Petri net and \( M_0 \) an initial marking.

The current state of a Petri net is defined by its current marking. The set \( \bullet = \{p \in P : (p, \ell, L, \Sigma, M_0) \} \) is the preset of \( t \) and \( \bullet = \{p \in P : (p, \ell, L, \Sigma) \} \) is its postset (the preset \( \bullet \) and postset \( \bullet \) of a place \( p \) are similarly defined). The transition \( t \) is firing from a given marking \( M \) iff: \( \forall p \in \bullet(M) : M(p) > 0 \). Firing \( t \) leads to a new marking \( M' \) such that \( M' = (M \setminus \bullet) \cup \bullet \) and which is denoted by \( M \xrightarrow{\cdot} M' \). A marking \( M \) is reachable if there exists a firing
sequence $s = t_0 t_1 \ldots t_n$ such that $M_0 \xrightarrow{t_0} M_1 \xrightarrow{t_2} \ldots \xrightarrow{t_n} M$, we can also write $M_0 \xrightarrow{} M$. Given a marked and labeled Petri net $\Theta$ and a set of final markings $Q$, the G-type language (see Peterson (1977)) generated by $\Theta$ is given by:

$$L(\Theta) = \{ \ell(s) : s \in T^* \land M_0 \xrightarrow{} M \land \exists M' \in Q, M' \subseteq M \}.$$ 

The system is modeled by a Petri net $\Theta$. As the language of the system is prefix-closed, it can be represented as the G-type language of a bounded Petri net ($\exists n \in N, \forall p \in P : M(p) \leq n$) associated with the set of final markings $Q = \{ \emptyset \}$ (any reachable marking being a superset of $\emptyset$).

### 3.2 Supervision Patterns

The classical framework of DES diagnosis (Sampanth et al. (1995)) relies on detecting the simple occurrence of particular — faulty — events. The supervision patterns framework, as proposed in Jiang et al. (2003) and in Jérôme et al. (2006), extend this analysis to more complex models, enabling us to express more interesting behaviors, possibly involving several events. We propose to represent a supervision pattern as a labeled Petri net.

**Definition 6.** A supervision pattern is a marked labeled Petri net $(P, T, A, \ell, L, \Sigma, M_0)$ such that:

1. (labeling) $L = \{ N, F \}$;
2. (initialization) $\forall p \in P : M_0(p) > 0 \Rightarrow \ell(p) = N$;
3. (exclusivity) $\forall p_1, p_2 \in P : \ell(p_1) = N \land \ell(p_2) = F \Rightarrow M(p_1) \times M(p_2) = 0$;
4. (stability) for each reachable marking $M$, $\exists p \in P, M(p) > 0$ and $\ell(p) = F$ implies that for each successor marking $M' : \exists p' \in P, M'(p') > 0$ and $\ell(p') = F$.
5. (completeness) for each reachable marking $M$, $\forall c \in \Sigma, \exists t \in T : (\ell(t) = c \land \forall p \in \bullet t, M(p) > 0)$;

The first condition ensures that every place is either labeled by $N$ or $F$. Condition 2 states that in the initial state, each marked place is labeled by $N$. Condition 3 states that a place labeled $N$ and another one labeled $F$ cannot be marked at the same time in a reachable marking, meaning that the pattern cannot be recognized and not recognized at the same time. Condition 4 ensures that once the pattern is recognized — the place labeled $F$ is marked — it cannot return to a non-faulty marking. Condition 5 is the completeness condition: from any reachable marking, the supervision pattern can fire a transition labeled by any event in its alphabet, this condition ensures compact independent pattern (the pattern does not include other events than those relevant to faulty behavior).

Any supervision patterns is associated to the set of final markings $Q$ that contain only one marking $Q = \{ p \in P : \ell(p) = F \}$.

**Example: event concurrency** Let $E = \{ e_1, e_2, \ldots \}$ be a set of events. The pattern describing the concurrent occurrence of these events is the labeled Petri net depicted in Figure 1, with the final marking $Q = \{ \{ p_0 \} \}$. Transition $t_0$, as it is labeled with $\lambda$, is firable as soon as every event of $E$ has occurred.

![Figure 1. A set of concurrent events.](image-url)
This product can be constructed simply by taking the union of the two nets, removing transitions with labels in $\Sigma_1 \cap \Sigma_2$, and for each $(t_1,t_2) \in T_1 \times T_2$ where $t_1 = t_2$ or they do not reach the appropriate transition. The completeness condition imposed on the supervision patterns ensures that this situation cannot happen in our context — the completeness condition states that in any marking, the pattern can fire a transition with any label. So, applying this product to two supervision patterns can model all the possible combinations of their evolution — only one of them evolves, the two evolve in the same time, etc.

**Final Markings: Product of Patterns**

Let $Q_i$ be the set of final markings of $\Omega_i, i = 1, 2$. We define the set of final markings of the product $\Omega = \Omega_1 \parallel \Omega_2, Q = Q_1 \cup Q_2$.

**Proposition 8.** $L(\Omega) = \{w \in (\Sigma_1 \cup \Sigma_2)^* : P_{\Sigma_1}(w) \in L(\Omega_1) \lor P_{\Sigma_2}(w) \in L(\Omega_2)\}$.

**Proposition 9.** $w \in L(\Omega) \iff \exists w_1 \in L(\Omega_1), P_{\Sigma_1 \cap \Sigma_2}(w_1) = P_{\Sigma_1 \cap \Sigma_2}(w) \lor \exists w_2 \in L(\Omega_2), P_{\Sigma_1 \cap \Sigma_2}(w) = P_{\Sigma_1 \cap \Sigma_2}(w_2)$.

**Final Markings: Product of the System and a Pattern**

The recognition of the supervision pattern must be taken into account within the system. This is realized by a slight modification of the product — more precisely, the final markings — which is applied to the pattern and the system. For clarity we will use a different symbol for this product $*$.

Let $Q_i$ be the set of final markings of $\Theta_i, i = 1, 2$. We define the set of final markings of the product $\Theta = \Theta_1 \star \Theta_2, Q = \{q = q_1 \cup q_2 : (q_1, q_2) \in Q_1 \times Q_2\}$.

**Proposition 10.** $L(\Theta) = \{w \in (\Sigma_1 \cup \Sigma_2)^* : P_{\Sigma_1}(w) \in L(\Theta_1) \lor P_{\Sigma_2}(w) \in L(\Theta_2)\}$.

**Proposition 11.** $w \in L(\Theta) \iff \exists w_1 \in L(\Theta_1), P_{\Sigma_1 \cap \Sigma_2}(w_1) = P_{\Sigma_1 \cap \Sigma_2}(w) \lor \exists w_2 \in L(\Theta_2), P_{\Sigma_1 \cap \Sigma_2}(w_2) = P_{\Sigma_1 \cap \Sigma_2}(w) \lor P_{\Sigma_2}(w) \in L(\Theta_2)$.

From these propositions, we can characterize faulty sequences.

**Proposition 12.** Given a system $\Theta$ and a meta-pattern $\Pi$:

$$w \in L(\Theta)$$

is faulty $\iff w \in L(\Theta \star \Pi)$.
(1) modelling the supervision patterns and the system with labeled Petri nets;
(2) compute a meta-pattern and combine it with the system;
(3) construction of a twin-plant;
(4) unfolding the labeled Petri net of the twin-plant;
(5) search for ambiguous cycles in the twin-plant;
(6) conclude on the discriminability of the patterns and consequently on the system diagnosability.

5. FINDING AMBIGUOUS CYCLES

To find cycles in a Petri net, we will use Petri net unfoldings. This technique — introduced by McMillan (1995) — attempts to avoid the combinatorial explosion inherent to the classical usage of marking graphs.

5.1 Petri net unfolding

A Petri net unfolding is another labeled Petri net that is generally infinite.

Definition 22. The unfolding $\Phi = \{P_\phi, T_\phi, A_\phi, \ell_\phi, P, T, M_\phi\}$ of a marked and labeled Petri net $\Theta = \{P, T, A, \ell, \Sigma, M_\theta\}$ is a labeled Petri net such that:

1. \( \forall p \in P_\phi : |p| \leq 1 \).
2. $\Phi$ is acyclic, i.e. for any element $x \in P_\phi \cup T_\phi : -(x < x)$
3. $\Phi$ is finitely preceded, i.e., for every $x \in P_\phi \cup T_\phi$, the set of elements $y \in P_\phi \cup T_\phi$ such that $y < x$ is finite.
4. No $x \in P_\phi \cup T_\phi$ is in self-conflict $\sim (x \neq x)$.
5. $\ell_\phi(P_\phi) \subseteq P, \ell_\phi(T_\phi) \subseteq T$;
6. $\forall t \in T_\phi : \ell_\phi(t)$ is isomorphic to $\ell$;
7. $\forall t \in T_\phi : \ell_\phi(t) \bullet$ is isomorphic to $\ell$;
8. $M_{\phi} = \{x \in P_\phi : \forall y \in T_\phi, y < x \}$.

Where $<$ is the transitive closure of the arc relation $A_\phi$ — called the causal relation, and $\leq$ the reflexive closure of $\prec$. The couple of elements $(x, y) \in (P_\phi \cup T_\phi)^2$ is a conflict (denoted $x \neq y$) if there exist two transitions $t_1, t_2 \in T_\phi$ such that $t_1 \neq t_2, t_1 \cup t_2 \neq t$ and $(t_1, x), (t_2, y) \in \prec$.

A configuration $C$ of an unfolding is a set of causally-closed and conflict-free transitions of $T_\phi$, formally: $t \in C \rightarrow \forall t' \prec t, t' \in C \rightarrow \forall t' \prec t, t' \in C : -(t \neq t')$. The cut of a configuration $C$ is the set of places $\text{Cut}(C) = \{M_{\phi}(t) \setminus \bullet C \}$ where $\bullet C = \{p \in \bullet t, t \in C\}$ and $\ell_\phi(\text{Cut}(C))$ characterizes a marking of the net $\Theta$. The local configuration of a transition $t \in T_\phi$ is the set of transitions $t' \in T_\phi$ such that $t' \leq t$.

For any bounded Petri net, McMillan (1995) shows the existence of a fragment of the unfolding $\Phi$ also called the finite complete prefix of $\Phi$ appropriate to analyze a particular property of the Petri net. A partial order which leads to a complete finite prefix appropriate for detecting cycles is the strict set inclusion "$\subseteq$".

5.2 Algorithm

Algorithm 1 looks for ambiguous cycles in the twin-plant $\Gamma$.

Algorithm 1: Search for ambiguous cycles

1: procedure unfold($\Gamma$)
2: \( \Phi \leftarrow \text{unfolding}(\Gamma) \)
3: \( H \leftarrow \text{cut-offs}(\Phi) \)
4: for all $e \in H$ events do
5: \( \text{if } \ell_\phi(H[e]) \) is ambiguous then
6: \( \text{prune}(H[e]) \)
7: end if
8: end for
9: end procedure

The method previously presented was implemented and in order to illustrate it, we present hereafter an example. The system is modeled by $\Theta, \Sigma_{\text{uo}} = \{c, f, g, h, k\}$ represented in bold in Figure 2. There is two patterns $\Omega_1$ and $\Omega_2$, the first models the parallel occurrence of two events $\{b, g\}$, the second models the sequential occurrence of $k$ and $h$.

The table 1 summarizes the size of the Petri nets obtained at each step.

Table 1. Size of intermediary Petri nets of the method

| Method                                      | $|P|$ | $|T|$ |
|---------------------------------------------|------|------|
| System ($\Theta$)                          | 16   | 16   |
| First pattern ($\Omega_1$)                 | 5    | 7    |
| Second pattern ($\Omega_2$)                | 3    | 6    |
| Meta-pattern ($\Pi$)                       | 8    | 13   |
| Product of the system and the meta-pattern ($\Theta_{\Pi}$) | 24   | 27   |
| Twin-plant ($\Gamma$)                      | 48   | 85   |
| Unfolding of the twin-plant ($\Phi$)       | 82   | 38   |

We can see that even though the example is not strongly concurrent, the overhead in places and transitions is
reasonable. Plus, the completeness condition imposed on supervision pattern results in extra transitions that are striped away by the unfolding, whence the reduction of the number of transitions from $\Gamma$ to $\Phi$.

Finally, the remaining markings in $H$ will have the following labels: $\{\neg, N_1, N_2, F_1', N_3\}$ and $\{\neg, N_1', N_2', F_1, N_2\}$. This means that $\Omega_1$ is not discriminable, and consequently that $\Omega_2$ and the combination $\Omega_1 \& \Omega_2$ are discriminable.

7. CONCLUSION AND PERSPECTIVES

In this paper, we introduced the notion of discriminability of supervision patterns and proposed a method to analyse it. The discriminability of a pattern ensures that one can detect the exclusive occurrence of this particular pattern, which differs from its mere recognition without further information about other patterns. We have also shown that once the discriminability analysis is performed, we can conclude about the diagnosability of the system with no extra cost. Our approach relies on the construction of a meta-pattern embedding all interesting behaviors. After combining it with the system, we perform a twin-plant to detect ambiguous sequences by using petri net unfoldings.

An interesting continuation of this work could be the extension of the models to include timed systems and patterns. This would permit us to monitor more complex — and interesting — behaviors that can not be modeled otherwise.

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