The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 15.7
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.15.7

Automated Railway Interlocking Plan Verification Using Petri Nets

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Abstract

The efficiency and safety of rail transport are ensured by interlocking systems. In the areas controlled by interlocking systems, trains can only run on locked routes. Route control tables made by plan engineers include all the routes and the related safety conditions for a given station layout. The preparation process of railway interlocking plans is still mostly done manually, but it is supported by several tools. For the verification of completed plans, there is no established, systematic methodology yet. In our paper, we define the planning process steps. The first step is route identification, for which we developed a Petri net based method. The solution can be derived from the structural properties of a specially crafted Petri net, in particular its T-invariants. The station topology can be decomposed into elementary objects, each of which can be modelled by corresponding Petri net fragments. We demonstrate our method for the identification of routes in a case study. The paper describes the models of objects defined for track elements and the Petri net constructed from them. The results can be used to prepare the route control tables (conflicting routes, point positions, and occupancy detection).

Keywords: railway interlocking, railway topology modelling, route control table, formal methods, Petri nets, T-invariants.

1 Introduction

In stations, trains run mainly on locked routes. Route control tables are the tabular forms of interlocking plans. These include all the routes that can be set on a given layout and the related safety conditions. The plan preparation of railway interlocking is supported by a number of currently available tools (e.g. FEDIT in Hungary or ProSig in Germany [1]). The final verification of the plans is typically still performed manually.

The planning steps for railway interlocking systems can be performed using a well-defined process. In the planning process, the following steps can be distinguished:

1. route identification,
2. search for flank protection,
3. handling overlaps,
4. determination of possible signalling aspects of the entrance signal,
5. route-related optimizations for efficient traffic management.

The aim of our research is to develop a systematic plan verification methodology. The methodology we propose helps to create a possibility to fully check the prepared plans, taking into account the necessary restrictions and constraints. One of our goals is to make each step of the process available in an automated form to facilitate more efficient plan verification. In this paper, we present one of the basic steps, the identification of the routes. In addition, we describe how the results can be used in the preparation of route control tables. Throughout the paper, we use the terminology by [2].

In this paper, the solution of the first step is obtained using formal methods. Route identification is a path finding problem that current algorithms used in the planning process are already capable of solving. However, these algorithms are not proven, they can contain errors. By mapping the problem to a formal method and solving it with a qualified tool, the results can be accepted as correct.

Numerous researches deal with the mathematical methods of describing the internal logic of interlocking devices. In our previous research, we modelled the route setting and releasing processes using Petri nets and timed automata [3].

Research [4] uses finite automata and NuSMV, researches [5] and [6] use coloured Petri nets to verify interlocking plans. The locking conditions of the routes are checked by modelling train traffic. In our research the verification was done in a static way, we did not deal with train movements.

In [7] a practical tool for verifying interlocking plans is presented. By formalizing CAD-based plans, the tool statically verifies the compliance of the plans with industry requirements.

2 Methods

Formal methods are discrete mathematics and mathematical logic based methods that allow the modelling and analysis of the discrete-event and hybrid systems. Petri nets are a graphical formalism composed of places and transitions, with the state expressed as a distribution of tokens. Suitable for modelling distributed systems in a compact but expressive way. For a more detailed description, see [8].

T-invariants are sets of transitions whose firing returns the net to the same state. In a net with source and sink transitions, T-invariants will correspond to paths between them. Portinale used this feature to propose an answer to diagnostic problems [9]. Recognizing that route identification is a similar problem, we developed a solution using T-invariants. For the modelling we used PetriDotNet, which is a framework for editing, simulating, and analysing Petri nets [10].

Every station topology can be composed of a set of standardised objects (similarly to geographical interlocking [3]). We decided to model these object types each, see Figure 1. The boundaries of the objects are marked by places. The internal structure of each object corresponds to transitions, they achieve the possible movements through the given object.

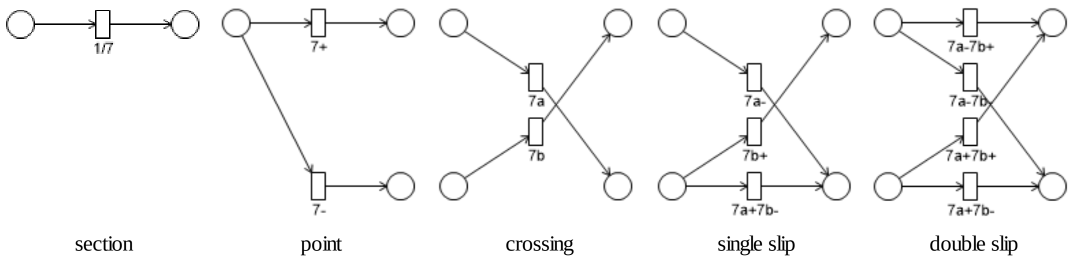

Figure 1: Petri net patterns of the object types

The signals also appear as separate objects in the model because they represent the start and end points of the routes. An entrance signal is a source transition and an exit signal is a sink. If a signal can be both, then source and sink transitions are both used (see Figure 2).

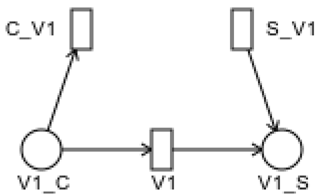

Figure 2: Signal model

Routes can have two orientations according to the two directions of traffic. Therefore, two direction-dependent models need to be generated and analysed for each station layout. Executing structural analysis, the possible routes are listed as T-invariants. Our approach provides all the following types of routes:

- *simple routes* between two sequential signals;
- *alternative routes* that have the same entrance and exit signals but lead through another path;
- *combined routes* where the exit signal of the prior route is the entrance signal of the following one. If a combined route leads through the whole station, it is called pass through route.

To illustrate the practical application of our method we present a case study of a four-track station (see Figure 3).

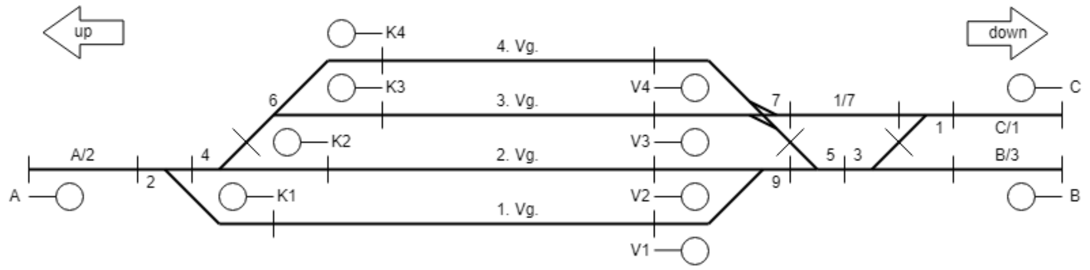

Figure 3: Topology plan of the station

Using the presented net patterns, we constructed the two opposing direction models of the station (see Figures 4 and 5). Both models were subjected to the T-invariant analysis.

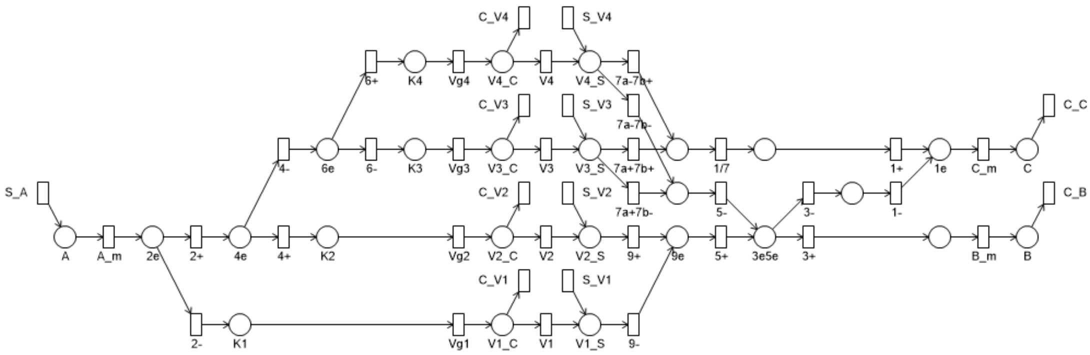

Figure 4: Down direction model

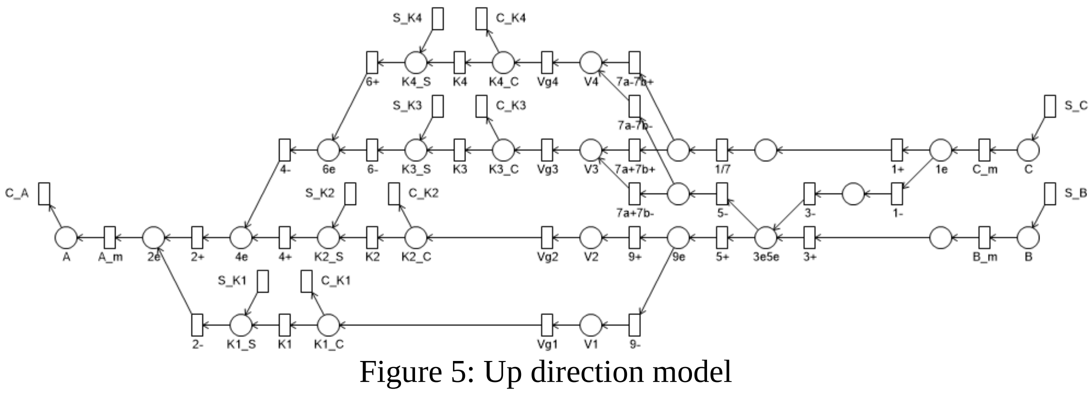

Figure 5: Up direction model

3 Results

Since there are no loops in the model, each T-invariant must contain a source and a sink transition. As the source and sink transitions represent the entrance and exit signals, the firing sequences correspond to the possible paths among them. The models in both directions of the example topology contain 26 locations and 41 transitions. A total amount of 24 T-invariants were identified for each direction (see Figure 6).

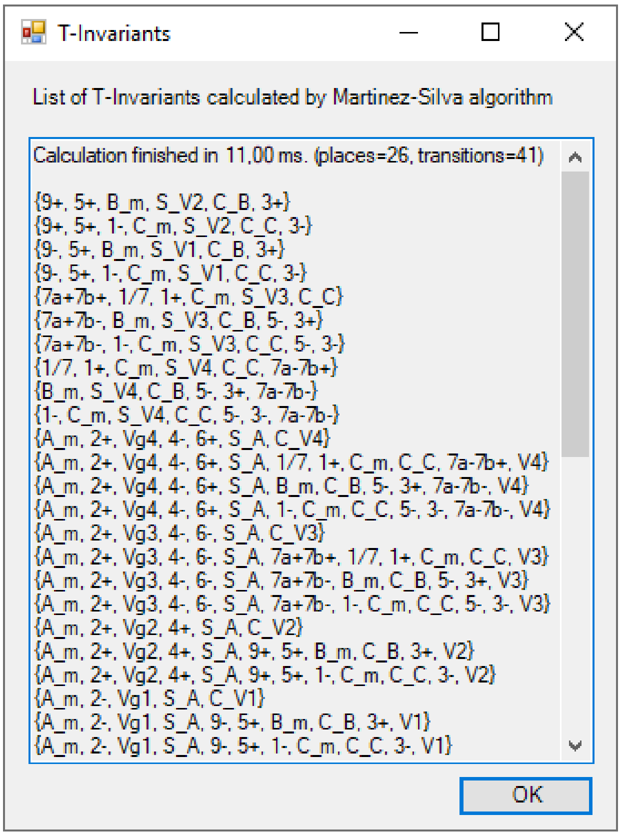

Figure 6: List of T-invariants of the down direction model

By determining the routes, we obtain input for the preparation of the route control tables. There are three tables (see Figures 8, 9, and 10) that can be partially filled out using the results. The dependencies identified during the plan preparation steps are independent of each other, they complement rather than modify the previously found ones. The cells that can be completed based on route identification are marked blue in the tables. Every cell that remains empty can be overwritten during the following steps (that will determine flank protection and overlaps).

An object can only be involved in one route at a time, so routes that contain the same element cannot be set simultaneously. The flowchart defining the type of conflicts between routes is illustrated in Figure 7. If i = j, these are identical tracks, the number of the station track is added to the main diagonal. If the two routes contain the same element but with a different position, they are called *plain conflicting routes*.

If the same item is included in the same position, it must be indicated in the table as *special conflicting routes*. Otherwise, the two routes are not conflicting. Pass through routes are also indicated in the table. The other cells remain empty.

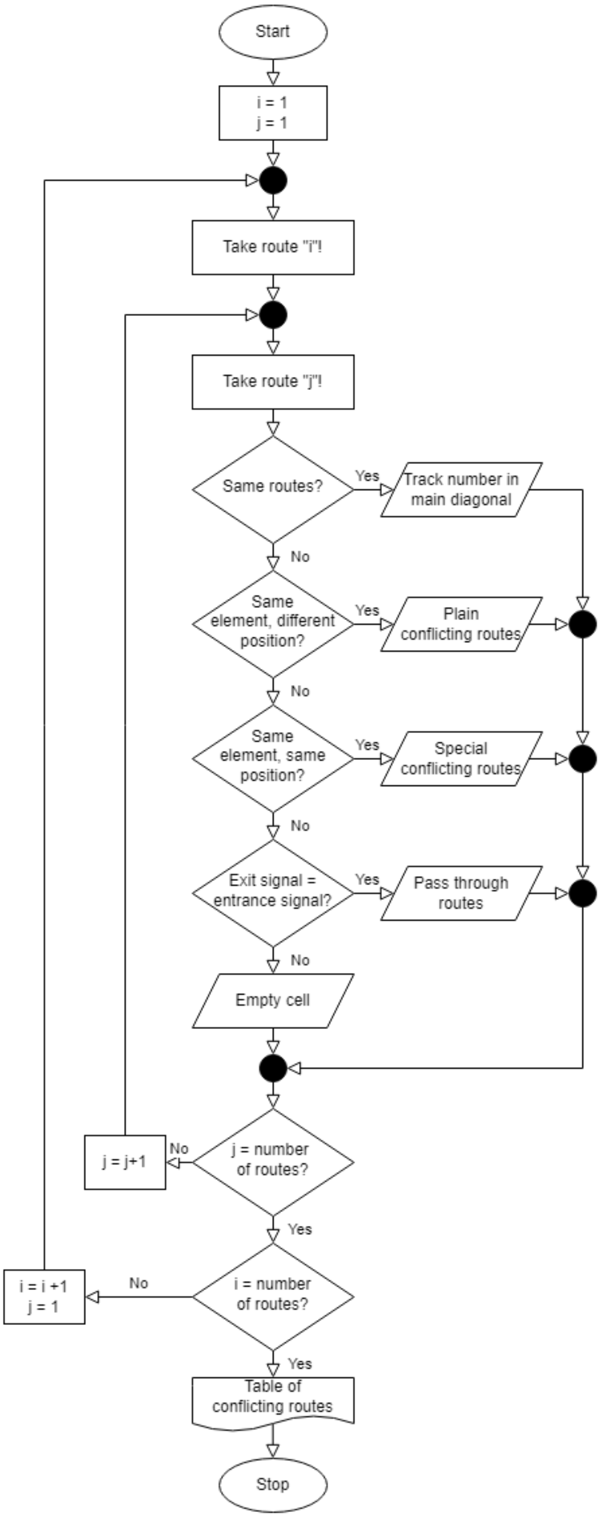

Figure 7: The process of conflicting routes' determination

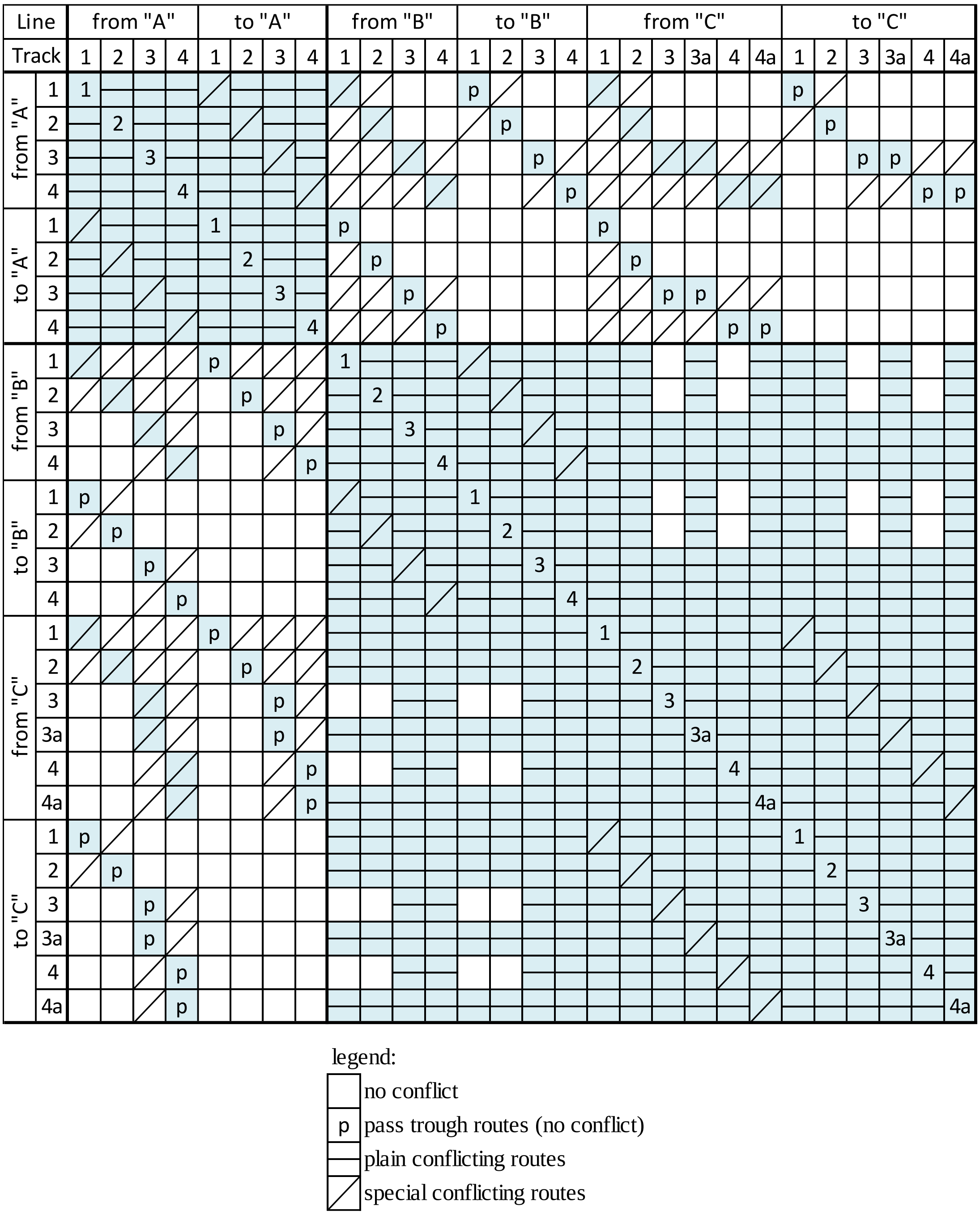

Figure 8: The table on conflicting routes

Since the transitions describe all possible movements on the modelled object, the expected position of the affected elements was also determined for each route.

Locking routes involves checking the occupancy of the various sections. The occupancy of objects determined using T-invariants must be assigned to the dependencies of the investigated routes.

points		2	4	6	1	3	5	7a	7b	9
to/from "A"	1	−								
	2	+	+							
	3	+	−	−						
	4	+	−	+						
to/from "B"	1				⊕	+	+		⊕	−
	2				⊕	+	+		⊕	+
	3				⊕	+	−	+	−	
	4				⊕	+	−	−	−	
to/from "C"	1				−	−	+		⊕	−
	2				−	−	+		⊕	+
	3				+	⊕	⊕	+	+	
	3a				−	−	−	+	−	
	4				+	⊕	⊕	−	+	
	4a				−	−	−	−	−	

legend:

+ point in normal position

− point in reverse position

⊕ point in normal position (flank protection)

⊖ point in reverse position (flank protection)

Figure 9: The table of required point position

Sect.		A/2	2	4	6	Tr1	Tr2	Tr3	Tr4	9	7	1/7	5	3	1	B/3	C/1
from "A"	1	×	×	⊗	⊗	×											
	2	×	×	×	⊗		×										
	3	×	×	×	×			×									
	4	×	×	×	×				×								
to "A"	1	×	×	⊗	⊗												
	2	×	×	×	⊗												
	3	×	×	×	×												
	4	×	×	×	×												
from "B"	1					×				×			×	×		×	
	2						×			×			×	×		×	
	3							×		⊗	×	⊗	×	×		×	
	4								×	⊗	×	⊗	×	×		×	
to "B"	1									×			×	×		×	
	2									×			×	×		×	
	3									⊗	×	⊗	×	×		×	
	4									⊗	×	⊗	×	×		×	
from "C"	1					×				×		⊗	×	×	×		×
	2						×			×		⊗	×	×	×		×
	3							×			×	×			×		×
	3a							×			×	⊗	×	×	×		×
	4								×		×	×			×		×
	4a								×		×	⊗	×	×	×		×
to "C"	1									×		⊗	×	×	×		×
	2									×		⊗	×	×	×		×
	3										×	×			×		×
	3a										×	⊗	×	×	×		×
	4										×	×			×		×
	4a										×	⊗	×	×	×		×

legend:

× section must not be occupied (direct)

⊗ section must not be occupied (flank protection)

Figure 10: The table of occupation sections

4 Conclusions and Contributions

The plan preparation process of station interlocking is primarily aimed at defining the routes and their associated locking conditions. The first step in the process is to determine the routes that trains can travel along, with the involved track elements and their position. In our paper, we have presented an efficient and systematic solution for the initial step of interlocking plan preparation, i.e. the route identification and partial filling of the route control tables.

Although the typical planning process is already supported by tools, inspections are done manually. The focus of our research is to automate and formalize the verification process. Formal methods are mathematical techniques that enable the analysis of the complete state space. Petri nets are an expressive formalism that also have effective solver tools. To address the issue of route identification, we chose Petri nets because one of their structural property, T-invariants, has been shown to be well suited to solve similar problems. The use of simple P-T nets without extensions proved to be sufficient for route identification.

The basic step of the methodology we developed is to map the objects (sections, points, etc.) of the railway network to Petri net patterns, from which any topology model can be built up by automatic composition. The transitions in each pattern describe the possible movements on the corresponding object. Route entrances are source transitions, and route exits are sink transitions. Signals, which can be both start and end points, have an additional transition that will only be part of the corresponding T-invariants for pass through routes. We demonstrated the composition of station models from the patterns defined for the track elements, and the identification of the routes on a case study. The results of route identification can be applied for partially filling out the route control tables (conflicting routes, point positions, and occupancy detection).

Our goal is to realise every step of the plan preparation process in terms of (formal) modelling and model checking, in order to support the work of interlocking plan engineers. In our ongoing researches, we will investigate the identification of flank protection and overlaps. All these steps put together can create an efficient plan verification methodology for station interlocking plans.

Acknowledgements

The project was supported by the EFOP-3.6.3-VEKOP-16-2017-00001: Talent Management in Autonomous Vehicle Control Technologies – The Project is supported by the Hungarian Government and co-financed by the European Social Fund.

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