

## VISUALISING CHANGE PROPAGATION

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### Abstract

Reliable change propagation is the key for successful change management. However, only a small number of support tools exist for the analysis of change propagation information. As change propagation data has many different facets, a set of different visualisation techniques is needed to assist designers in predicting change in complex products.

In this paper we introduce different views on change propagation data. We show how this can be visualised using the CPM (Change Prediction Method) tool, a software tool currently under development for predicting change propagation. On the basis of an example case study at a UK diesel engine manufacturer, we show how different graphs can benefit design change management and which graphs are suitable for displaying which aspects of change propagation data.

*Keywords: change propagation, risk management, design process improvement, design structure matrix, detail and context visualisations*

### 1. Introduction

Component connectivity in complex products has a major impact on design change management. Changes to one component can propagate through a product in various ways, affecting components that are not directly connected to the initiating component. Understanding these direct and indirect links is vital for accurate change risk assessment and successful change management. Identifying these links is typically dependent on experienced designers remembering and recognising them during the analysis of particular change cases. An overlooked link can lead to very costly changes later on. In one example an engine company missed a direct link when they replaced a metal temperature sensor with a cheaper plastic one, and found that the engine did not work properly, because one part was no longer earthed. Indirect links can be more problematic to spot, for example when a helicopter is customised additional sensors are often added to the outside of the craft. If the weight exceeds the margin of the fuselage, the fuselage has to be reinforced, leading to many other costly changes due to the balance distribution of a helicopter. Both cases could have been avoided if there had been proper visual representations of the change data available to the responsible designer that would have predicted the risk associated with their decisions.

The Change Prediction Method (CPM) [1] is a technique for calculating the combined risk that a change in one component affects another and for analysing indirect changes. The key for the success of such a method is the availability of effective and intuitive visualisations to assist decision-making. Current visual representations of change propagation data, however, do not allow designers to explore direct and indirect connectivity sufficiently. In this paper we will introduce new visualisation techniques for displaying change propagation data. The emphasis will be on which aspects of current change propagation data can be displayed with different representations.

## 1.1 CPM tool

The EDC Change Tool is a software tool developed at the Engineering Design Centre in Cambridge (see Clarkson *et al.* [2] and Jarratt *et al.* [1]). The core representation of the CPM tool is the Design Structure Matrix (DSM) (see Browning [3]). The DSM interfaces have been refined using feedback from designers in two leading UK engineering companies. This *User Centred Design* approach (see Brown [4]) of interviewing potential users to gather functional requirements promotes the development of optimised interfaces and visualisation techniques for the CPM tool. The interviews showed that designers are overwhelmed by the amount of information provided by a DSM. For efficient decision-making, they require a balance between detailed information and a global overview. The software tool supports risk assessment by drawing designers' attention to components that are highly connected to other components and where changing any of these components would result in major rework on other, not necessarily directly connected components. We argue that proper visual representations and user interfaces are the key for industrial acceptance of this software tool (for the impact of interfaces on design see Ligetti *et al.* [5]).

Currently the CPM tool supports the design change process in two different ways. On the one hand it supports abstract product-model building. Systematically populating the corresponding product model with a multidisciplinary team increases awareness of all the participants. It helps the individual designers as well as team leaders to understand how the components in their area of responsibility are connected to other parts of the products and where possible interfaces with other teams exist. With the software tool, information such as different linkage types and direct change impact and likelihood can be captured. The model building was carried out successfully in several different companies throughout the UK, such as a diesel engine manufacturer and a gas turbine company.

The second benefit the CPM tool provides is a platform to analyse change propagation data, based on combined component connections. For that purpose, algorithms for calculating combined risk from direct impact and likelihood values were developed and integrated into the tool [6]. This allows designers to quickly assess the probability of change propagating from one component to other components as well as the overall risk associated with a component change. The visualisation techniques described in this paper are designed to support this second case.

## 2. Diesel engine example

The example discussed in this paper is the model of a diesel engine elicited at a local diesel engine manufacturer. Starting with negotiations over a suitable component breakdown, a primed matrix was generated by a senior engineer. In a group meeting a DSM of 41 components connected through 8 different linkage types including likelihood and impact values associated with each direct component connection (see Jarratt *et al.* [7]) was populated. From these 41 components we identified 22 core components. The sub-system of these 22 components will be used throughout this paper to show the different visualisation approaches. An evaluation of historic product change data for the diesel engine by Jarratt *et al.* [1] revealed that this model would have captured 74% of all product changes.

This model building exercise was followed by a number of interviews and meetings with responsible design engineers. The aim of these meetings were to verify the findings of the analysis of the data as well as to get feedback on the user interfaces of the CPM tool, ongoing work looks at the introduction of the tool to the wider organisation.

## 3. Functionality of the tool

The data currently used in the CPM tool reflect several aspects of change propagation. The list below shows a subset of currently supported aspects of change in the CPM tool. Other aspects of change, such as design freezes, logical component connections and component hierarchies are under development but not part of this paper. However, the following four aspects of change propagation data form the basis of current change research.

- **Direct linkages** show direct connections between components. As changes propagate through links between components it is vital for design engineers to know direct links in order to manage change propagation and assess risk associated with component change. It is important to know the magnitude of the likelihood and impact as well as the type of a link. Adequate representations for direct connectivity in a product should provide means to show these aspects of change propagation in order to really support design engineers.
- **Indirect linkages** can occur even when components are not directly linked together. An indirect link between two components exists, if these two components are linked via one or several other components. Displaying indirect linkages between components and associated risk values is a challenge for visualisations but crucial for the understanding of change propagation in complex products. However, in these indirect linkages can easily be forgotten and not considered when it comes to assessing costs of a change as recent case studies showed (see Jattatt *et al.* [1] and the diesel engine example from the introduction).
- **Component connectivity** means the overall connectivity of a component in a product. A component can have very much incoming links and only few outgoing links, meaning that changes to other components highly affect this component. On the other hand, components can have very few incoming but lots of outgoing links, making it a source of change propagation. Knowing such attributes of

components can greatly improve change management as it can give hints to which components should be frozen early in the design process in order to avoid propagation.

- **Propagation paths** are the chains of changes that result from changes distant from the initiating component. The possibility to assess all propagation paths between two components (the set of all direct and indirect links) can give valuable information about the entire product as well as a hint, how to prevent unwanted change propagation in the future. The problem is that designers – as all human – struggle to explore search spaces completely and systematically. They either jump to a result based on past experience or drill deep in a few routes systematically. A visualisation that supports assessing all propagation paths can thus highly benefit design.

## 4. Visualising change propagation

Four important aspects of product change were discussed in the previous section. In this section we will introduce several visualisation techniques and discuss their value for visualising these aspects of change propagation. The diesel engine design introduced earlier in this paper will serve as an example for showing the advantages and disadvantages of the different representations for visualising change propagation data. We are particularly interested in the component *Fuel Injection Assembly*, a component that was identified as one of the problematic components by a senior design manager.

### 4.1 DSMs

Matrix-based techniques are used frequently in assessments in design processes and Design Structure Matrices (DSMs) are reputed to be “*a simple, compact, and visual representation*” [3]. However, matrices have limitations when used to display large and complex products and indirect linkages (see Ghoniem *et al.* [8]). An experienced designer said during a model building exercise: “*Lets face it, a DSM is not a representation designers like using*”. Nevertheless, a DSM is a very popular representation for displaying linkages between components and is the basic representation implemented in the CPM tool. DSMs also proved to have advantages over network representations for showing direct connections [8].

Figure 1 shows the DSM of the diesel engine. It is easy to see whether components are directly connected or not. However, only binary information about the existence of a link is provided. It is not clear through which linkage types the components are connected or how likely changes propagate through this link. Querying (e.g. interactive presentation of additional information), such as provided in the CPM tool, allows further investigations. Colour coding to represent different linkage types can draw attention to specific types of links (in Figure 1, all *Mechanical Static* connections are highlighted). The Direct Risk Plot shows the direct change impact and likelihood values similar to the Change Risk Plot with colour coding of large risk values.

With a DSM it is also easy to identify the overall connectivity of a component. In the DSM of the diesel engine one can see that there are several components with a large

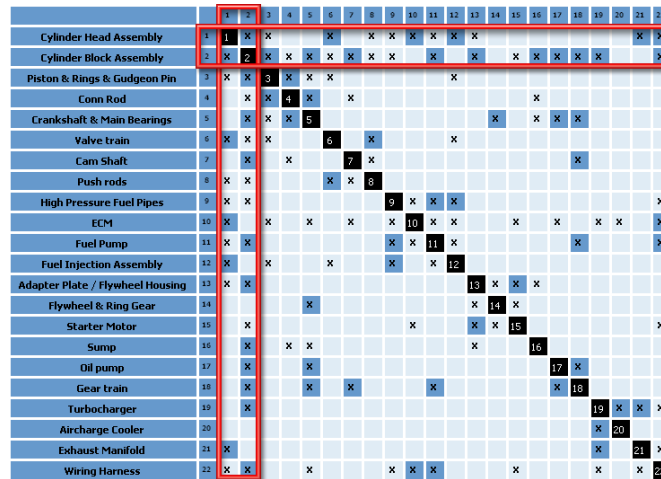


Figure 1. A DSM of a diesel engine; *Mechanical Static* Links are highlighted; *Cylinder Block* and *Cylinder Head* are highly connected to other Components

number of connections to other components. These are *Cylinder Block Assembly*, *Cylinder Head Assembly*, the *Wiring Harness* and the *ECM*. The component *Fuel Injection Assembly* does not seem special in any way.

#### 4.2 Change risk plot

The Change Risk Plot (see Figure 2 and Jarratt *et al.* [9]) is similar to a DSM described in the previous section. Instead of visualising direct linkages between components, it shows the combined risk of a change to one component, given another component is changed. The width of each rectangle represents the likelihood of a change and its height is proportional to the impact [6]. The area of the corresponding rectangles thus represents the risks and colour coding draws attention to high-risk connections. The Case Risk Plot is not able to show any information about direct links at all, all data shown represent combined values and thus, no information about propagation paths is shown as well.

The Change Risk plot identifies high-risk component connections. In the case of the diesel engine, it can be seen easily that there are two such high-risk connections, both resulting from a change of the *Fuel Injection Assembly*. The components that have a high risk of change given a change to the *Fuel Injection Assembly* are the *ECM* and the *Wiring Harness*. Especially the link to the *Wiring Harness* is interesting, as there is no direct connection to the *Wiring Harness* (there is no corresponding mark in Figure 1), but still a high change risk. Additionally it can be seen that the *Fuel Injection Assembly* is generally a source of direct and indirect change propagation to other components (see selected column in Figure 2 with lots of yellow and red rectangles) while it is quite resistant to changes propagating from other components (see selected row in Figure 2 with only green rectangles). A reordering of the Change Risk plot reveals that the *Fuel Injection Assembly* is the largest source for propagating changes and only the 9<sup>th</sup> largest recipient change of propagation. The biggest recipients of change propagation are *Wiring Harness* and *ECM*.

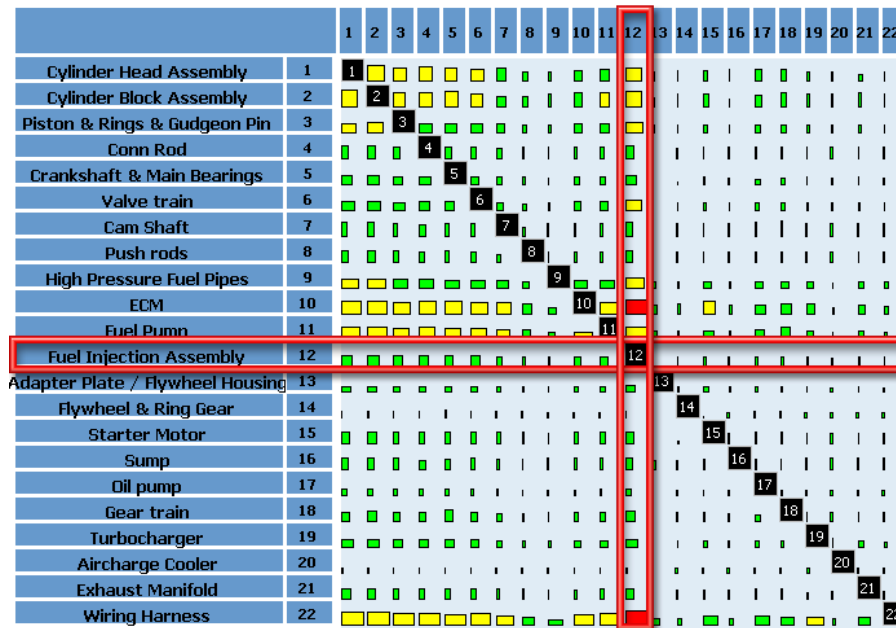


Figure 2. Change Risk Plot of the diesel engine; the *Fuel Injection Assembly* is a source of change propagation

### 4.3 Propagation networks

The visualisation techniques described so far were good in assessing direct linkages (DSM) or combined linkages (Change Risk Plot), but have limitations showing both simultaneously. Common was that both techniques used a matrix representation to visualise connectivity data. Another possible representation for relational data is a network. The question is, whether networks views can also benefit designers when assessing component connections.

The main difference between network and matrix representations showing the same relational data is that there are many more degrees of freedom laying out a network. In a DSM there is only the possibility to change the vertical and horizontal component order. In a network each node can be drawn individually in the 2-dimensional (or even 3-dimensional) space and the links can be drawn in various ways (for a discussion of different possible layout algorithms for networks see Battista *et al.* [10]). Another advantage of network representations are that it is easier to assess indirect linkages or propagation paths between components (see Ghoniem *et al.* [8]) which was very difficult with the previously introduced matrix-based visualisation techniques.

In the CPM tool, two different layouts for visualising component connectivity with networks are implemented. One is based on the number of links between two components, the other is based on combined change risk. Both are radial layouts (see Lamping & Rao [11]) that share the following properties:

- Each layout has a root component. This root component serves as the central point of the network (see *Fuel Injection Assembly* in Figure 3); all other components are laid out with respect to this component. The central component is either the source

of a change propagating (the initiating component) or the recipient of changes from other components.

- The shortest spanning tree with its root on the root component is calculated and used to determine the initial radial layout. A radial layout is a layout where all nodes of a tree are arranged “around” the root (for a detailed description of distorted radial tree-layouts, see Lamping & Rao [11]).
- The distance between each component and the root component is calculated based on combined risk or level-distance values.
- The layout has a focus component that serves as an additional point of interest additional to the root component (in Figure 3, the focus component is the *Wiring Harness*). The focus component and closely connected components are displayed with a higher level of detail than other components (in our approach this means that the node is drawn larger). This is based on a “fisheye” presentation approach of effectively showing detail and context data on one screen (see Furnas [12] and Apperly *et al.* [13]). This is achieved by calculating a “Degree of Interest” value based on the shortest spanning tree that determines the level of detail shown for each component. Additionally, the initial radial layout is distorted to allow more space for displaying the focus component.
- The layout is then improved with a spring layout algorithm (see Huang *et al.* [14]) in order to avoid overlapping nodes and to improve the appearance of the network.

The difference between the two layouts is how the distance between each component and the root component is calculated. The first approach as seen in Figure 3 sets the distance of each component to the root component proportional to the length of the shortest change path between these two components. A component that is directly connected to the root component has a distance proportional to one. The second layout sets the distance anti-proportional to the combined risk of a change in the component resulting from a change in the root component (see Figure 4 for a similar approach for visualising propagation trees). The less the risk of a change propagating, the further apart is a component from the root component. The background of both layouts is used to display level or risk information depending on which kind of data is currently displayed.

In the case of the diesel engine, we identified the *Fuel Injection Assembly* as a component that has a huge effect on other components. Let this be the root component for further analysis. Figure 3 (with the focus on the *Wiring Harness*) shows the resulting Component Connection Network of the change resulting from the *Fuel Injection Assembly*. The Component Connection Network does not accommodate risk data in the layout, all the data shown is based on level distance. From this plot we can confirm that there is no direct connection from the *Fuel Injection Assembly* to the *Wiring Harness*. In this display we can see easily that there is a path of length two from *Fuel Injection Assembly* to *Wiring Harness* via the *Cylinder Head Assembly*. It is still difficult to identify all propagation paths, but interactive controls, such as highlighting all connected components, show that there are more such propagation paths of length two.

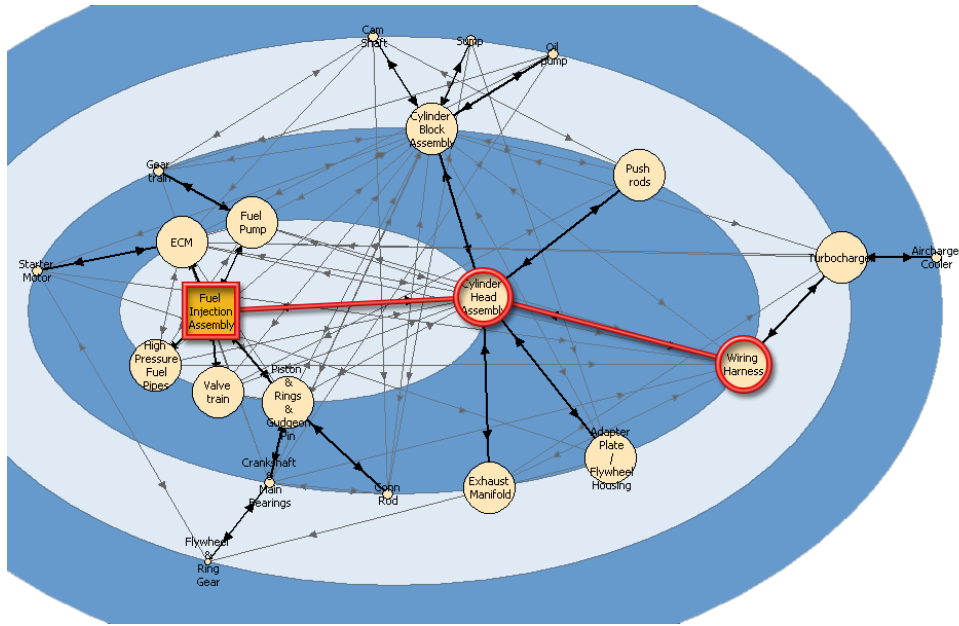


Figure 3. Network of the diesel engine components; one propagation path from the *Fuel Injection Assembly* to the *Wiring Harness* selected

#### 4.4 Propagation trees

The networks described in the previous section had the advantage that they provided a better representation of indirect linkages (at least some indirect links could be identified). Still, not every propagation path could be seen and analysed easily. A different representation especially designed to show different propagation paths is the propagation tree.

The construction of the tree starts with a root component, similar to the root component in the network. All components that are directly connected to this component are drawn as children of this component. For all these children, this is repeated until the probability of each particular branch falls under a certain user specified threshold (in Figure 4 this threshold is 5%). The difference to the networks introduced in the previous section is that each component except the root component is likely to appear multiple times in the diagram. For instance if a component A is connected to the root component R directly and there is an indirect link through another component V as well, then component A will appear as a child of R as well as a child of V (see multiple appearance of *Wiring Harness* in Figure 4).

The tree is laid out in one of the two radial layouts as the networks described in the previous section, having a root and focus component. One sets the distance of a component to the root proportional to the level distance to the root component (similar to the network in Figure 3); the other one is based on the likelihood of a change propagating from the root component (see Figure 4).

A Propagation Likelihood Tree that takes likelihood values into account is shown in Figure 4 for the diesel engine. With the interactive possibilities offered by the diagram, we can find that there are 7 different links from the *Fuel Injection Assembly* to the *Wiring Harness* with a probability of 5% or higher and none of them is direct.



In Figure 4 it then can be seen clearly that there are especially two paths from the *Fuel Injection Assembly* to the *Wiring Harness* that have a very high likelihood of change propagating: one via the *Fuel Pump* and one via the *ECM*, another high risk component.

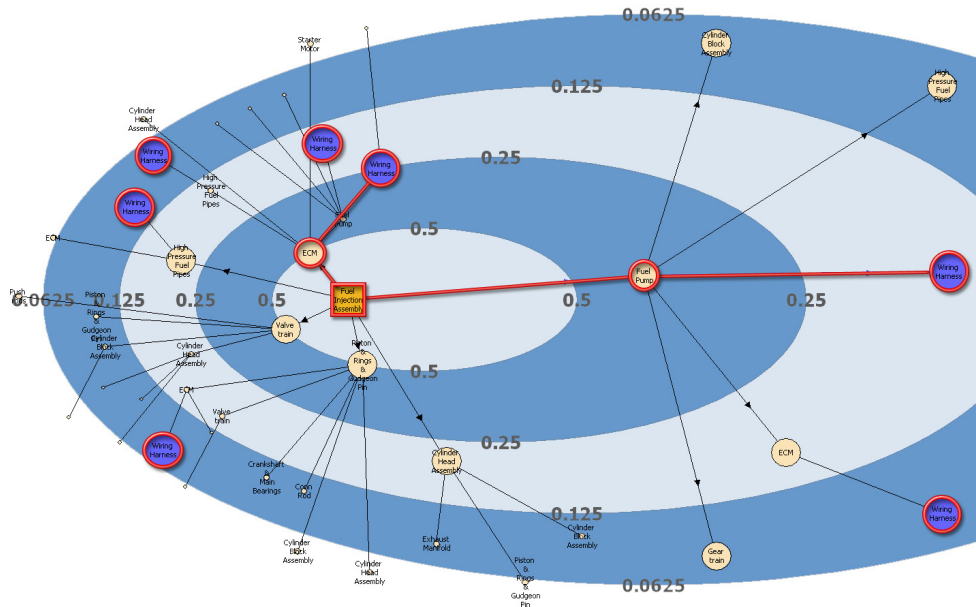


Figure 4. Propagation Tree with the *Fuel Injection Assembly* as the initiating Component; seven high-risk paths to *Wiring Harness* can be identified

## 5. Discussion

Using all different plots introduced in the previous sections the findings for the component *Fuel Injection Assembly* are as follows:

- With the standard DSM, no complex high-risk connections could be found.
- The Change Risk Plot revealed that changing the *Fuel Injection Assembly* is very risky as knock-on effects to other components are likely and a high risk of change to the only indirectly connected component *Wiring Harness* could be identified.
- The Propagation Network showed that one likely propagation path to the *Wiring Harness* propagates through the *Cylinder Head Assembly*. It was also confirmed that there is no direct link to the *Wiring Harness*.
- In the Propagation Tree it could be seen that there are seven distinct propagation paths from the *Fuel Injection Assembly* to the *Wiring Harness* with a probability greater than 5%.

We see that different graphical displays are necessary to fully analyse the role of the *Fuel Injection Assembly*. Table 1 summarises the different findings that can be provided by the different displays. Based on this table, it can be seen that there is no “best” representation that is able to display all different aspects of change propagation properly and no one representation technique seems to be superior to others.

As there is no “best” visualisation approach for change propagation data, and different plots can help to solve different problems, we propagate a visualisation approach that makes use of different representations and lets users make the final decision which plot is most useful for a specific problem. Such an approach of providing users with several, possibly linked, graphics is very popular in several fields outside the Engineering Design community, such as Exploratory Data Analysis (see Unwin [15]) and Information Visualisation (see Baldonado *et al.* [16]). However, this approach has high requirements on the software, because otherwise users can get lost in the amount of different information offered by a various number of linked plots. Techniques such as selection and linking & highlighting are all included in the current implementation of the CPM tool and increase user’s ability to quickly search through an entire plot to find the desired information.

The feedback we got from our industrial partners so far has been very positive. The visualisations were presented to the two engineering companies mentioned earlier. One such meeting was with a panel of experts criticising different aspects of the interfaces. More such meetings will be carried out in order to find flaws that then can be removed in order to create a user-friendly software solution. One identified flaw is the labelling of nodes that often results in labels overlapping with other elements of graphs.

Table 1. Summary of the visual abilities of the introduced visualisation techniques to show important aspects of change propagation.

	<b>Direct Linkages</b>	<b>Indirect Linkages</b>	<b>Component Connectivity</b>	<b>Propagation Paths</b>
DSMs	+	-	+/-	-
Change Risk Plot	-	+	+/-	-
Propagation Networks	+	+/-	+	+/-
Propagation Trees	+/-	+/-	+/-	+

## 6. Conclusion

Visualisation of change propagation is of particular interest to industry. This paper introduced several ways of displaying change propagation data utilizing sophisticated information visualisation techniques. The displays presented in this paper allow more thorough analyses of change propagation because it displays connections that are not currently displayed by standard visualisations.

Future research will focus on the development of additional visualisation techniques for displaying product connectivity. Finding good representations for the attributes that were not discussed in this paper, such as design freezes, logical component connections and hierarchies will also be an issue for further research.

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