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Model-based On-Board Diagnosis and Tools for the Developer of On-Board Systems -VMBD and IDD: Two Projects of the European Car Industries

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Abstract

The growing importance of on-board diagnosis for automobiles demands for new diagnostic methodologies and techniques and for a close integration of diagnostic tasks in the entire design process. This report describes work carried out within two European projects. In the "Vehicle Model based Diagnosis" (VMBD) project, demonstrator vehicles with built-in faults provided a serious challenge to model-based diagnosis techniques and a real-life test-bed for their evaluation. One of the guiding applications within VMBD was model-based on-board diagnosis of faults in a turbo diesel engine system with a focus on potential origins of increased carbon emissions. The second, still on-going, project, „Integrated Design Process for onboard Diagnosis„ (IDD) developed a model of a new design process which allows for a better integration of diagnosis related tasks, such as diagnosability analysis, failure-modes-and-effects analysis (FMEA), on-board diagnosis design, in the overall design process of mechatronic subsystems.

Introduction

Research on model-based diagnosis (e.g. [Hamscher et al. 92], [Dressler and Struss 96]) has generated a number of well-founded theories and sophisticated prototypes of implemented diagnosis engines. However, many of these diagnosis systems have only been applied to toy examples or to problems that ignored the practical context of industrial applications. As a result, the transfer of the technology into practice is well behind the expectations, despite the fact that it promises to meet some crucial requirements of automated diagnosis for industrial needs.

Car industries provides a good example of such industrial needs. It is estimated that European passenger cars have an average yearly down-time of 16 working hours due to malfunctions and maintenance. This figure is even greater for commercial vehicles. For the European Community alone, this amounts to a total of over one billion hours for diagnosis and repair. At the same time, with increased environmental awareness, stricter constraints are imposed on the car manufacturers to develop clean cars, and also to keep them clean during their life cycle (see, for example, [OBD 93]). These growing constraints are reflected in increased requirements on on-board diagnostics development. For engine management control units, currently about one half of the software is dedicated to diagnosis, and this share is still growing.

This contribution presents work on transferring model-based systems technology to industrial practice in order to provide a new methodology and new software solutions that are required to address the needs for both reliable and efficient diagnostics of vehicles and systematic and economic processes for generating them.

We first describe the realization of a prototype of a model-based on-board diagnosis system within the Brite-EuRam project VMBD (Vehicle Model Based Diagnosis) and its theoretical and technical foundations. Next, we present the objectives and intermediate results of the ongoing European Fifth Framework project „Integrated Design Process for onboard Diagnosis" (IDD) which aims at developing tools for the designers of on-board systems.

The VMBD Project

The Brite-EuRam joined several car manufacturers and suppliers project VMBD (Vehicle Model Based Diagnosis) with the intention to promote the transfer of model-based diagnosis technology by the challenge of applying it to on-board and off-board diagnosis of passenger cars. The results and system performance were evaluated on real demonstrator vehicles. Within this project, Volvo Car Corporation, Robert Bosch GmbH, and OCC'M Software GmbH produced a model-based system that diagnoses problems related to increased carbon emissions of diesel engines, a problem of significant importance w.r.t. environmental impact and compliance with legal requirements. The system transforms the sensor signals that are available to the standard electronic control unit (ECU) on-board to a qualitative level and exploits them for detecting and localizing faults based on a model of the turbo control system. It has been installed on a Volvo demonstrator vehicle with a number of built-in faults.

Figure 1 shows the part of the system which is responsible for supplying air to the diesel engine. It can be decomposed into the exhaust gas recirculation (EGR) subsystem (upper part of **Figure 1**) and the turbo control subsystem (lower part of **Figure 1**).

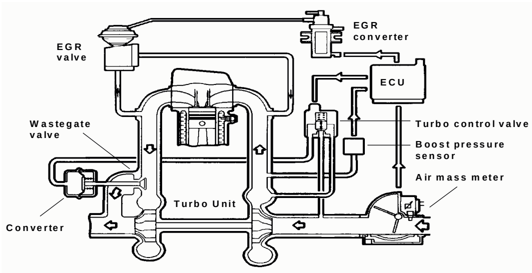

Figure 1: Turbo control and exhaust gas recirculation subsystem of the DTI

The purpose of the exhaust gas re-circulation system is to return a certain amount of the exhaust gas to the intake air to decrease the oxygen rate of the intake air and thus to reduce emission levels of the fuel combustion. Depending on driving conditions, the ECU governs the EGR converter to achieve a certain air pressure in a control pipe, which in turn sets the position of the exhaust gas re-circulation valve. The position of this re-circulation valve then determines how much of the exhaust gas is fed back to the air intake pipe.

The turbo control subsystem consists of a turbo-charger turbine, which is driven by the engine's exhaust gas, for compressing (and thereby increasing the mass of) the air taken into the engine. The ECU controls the boost pressure (i.e. the pressure in the engine intake pipe) admitted in a certain driving situation by opening or closing the turbo control valve, which determines the position of a so-called waste-gate valve. The position of this valve determines how much of the exhaust gas drives the exhaust turbine of the turbo-charger.

The ECU not only issues commands to the actuators, but also monitors and checks the sensor values it receives from these systems. The goal of this so-called on-board diagnosis is to signal alarms to warn the driver in case of a failure and to generate fault codes that can be further used in the service bays to track down a failure.

In accordance with the overall thrust of the project, our goal thus was

- to produce a prototypical model-based diagnosis system that is capable of diagnosing faults in the diesel engine based on the sensor signals that are available to the ordinary ECU,
- to this end, generate a library of models of the relevant components, and
- to perform this task in a systematic way as a contribution to a general methodology for producing on-board diagnostics.

In the following, we briefly outline the key idea of the approach to diagnosis and summarize the result of the experiments. For more details, we refer to [Sachenbacher-Struss-Weber 00].

Consistency-based Diagnosis Techniques

In a nutshell, the standard, so-called consistency-based approach to diagnosis ([de Kleer-Mackworth-Reiter 92], [Dressler-Struss 96]) can be described as follows (see Figure 2):

- Observations of the actual behavior of the system are entered.
- Based on the device model, conclusions are computed about system parameters and variables (observed and unobserved). For each derived prediction, the set of component models involved in it is recorded. This information can be determined by the diagnosis system because the device model has a structure that reflects the device constituents.
- If a contradiction is detected, i.e. conflicting conclusions for a variable occur (fault detection), the set of components involved in it indicates which components possibly deviate from their intended behavior.
- Diagnosis hypotheses are generated, i.e. sets of faulty components that account for all detected contradictions (fault localization).
- In case models of faulty behavior are provided, the same approach (checking consistency of a model with the observations) can be used to discard particular faults (fault identification) or to conclude correctness of certain components if the set of modeled faults is considered complete.

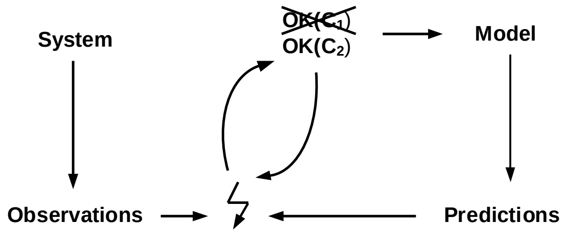

Figure 2 Consistency-based approach to diagnosis

This diagnosis framework has the desired property to systematically exploit the analytic redundancy among the available sensor signals. The model-based approach alone provides one answer to the methodological challenge, because its underlying principles (and the implementation) are independent of the particular subsystem and enable the re-use of the involved software components. Generating a specific diagnostic system is thus reduced to generating an appropriate model of the system to be diagnosed.

As stated above, component-oriented modeling is a natural approach in our application domain. Beyond this, it is the key to solving the variant problem, because the model of a subsystem is derived as the aggregation of standard building blocks. This is another element of a general methodology and enables the automated generation of a device model and, hence, of a tailored diagnosis system based on a structural description of the device only (which should be the natural output of a CAD system). A way of creating diagnostics for all variants of vehicle subsystems is thus obtained that is systematic as well as efficiently supported by computer tools. **Figure 3** illustrates this idea.

For diagnostic purposes, faults can be described as certain component failures, and fault models associated with the respective components. This provides a principled way of capturing knowledge about faults in a modular way which contrasts other approaches in AI (based on storing associations between symptoms and faults for each device in terms of rules or cases) or engineering (trying to identify parameter deviations in a closed mathematical model of the entire device).

Since a component model is meant to be used within the contexts of various devices, it has to capture a behavior description which must not presume a specific context and, particularly, not the correct functioning of the rest of the device. The strict discipline in modeling required to achieve this goal is another important element of the methodology.

It is interesting to note that we need not to build a model of the control unit behavior itself, unless we want to detect faults in the ECU. Due to the fact that the model runs within an on-board environment, all the control unit's signals will be available for observation. Consequently, a behavior model of the control unit could never be part of a diagnostic hypothesis, and would therefore be useless.

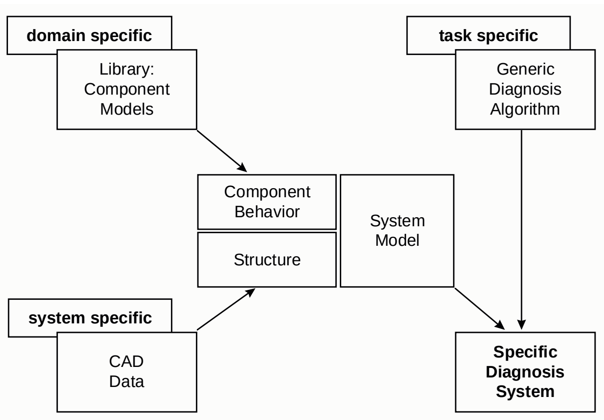

Figure 3: Automated generation of model-based diagnostic systems

Evaluation on the Demonstrator Vehicle

The software for the on-board diagnosis prototype consists of two components:

- a module for the conversion of raw signals into qualitative observations, and
- a model-based run-time system that performs diagnosis on the basis of these observations.

This was based on components of the commercial RAZ'R system of OCC'M Software that offers a development environment for diagnostic models as well as a run-time version of a consistency-based diagnosis engine ([RAZ'R 02]).

In the VMBD project, a Volvo 850 TDI demonstrator car was made available for hands-on experimentation with the DTI application. Failures can be induced in the car during various operational conditions of the engine with the model-based diagnosis system running, and the results can be compared with the conventional diagnostic capabilities of the control unit. The various failures in the demonstrator car can be adjusted by potentiometers and triggered by switchboards from inside the passenger compartment (see **Figure 4**). A pneumatic leakage, for example, is simulated by additional valves opened and closed by electrical switches.

Figure 4: View of the Volvo Demonstrator Car showing the notebook connected to the ECU. The glove compartment (behind) contains the switchboard for controlling the built-in faults.

We were particularly interested in failures that were not captured by existing on-board diagnostics. Since increased legislative and customer demands have lead to new requirements especially for aspects related to emissions and performance of the system in the Volvo car, we concentrated on effects that involve incomplete fuel combustion and increased carbon emissions due to an excessive quantity of fuel injected or insufficient airflow to the engine (called "black smoke" problems). Types of failures which can lead to black smoke symptoms involve leakages in pipes, malfunctions of valves (e.g. stuck-at-open or stuck-at-closed), increased friction in bearings (resulting in a delay of actuators) or signal disturbances due to electrical failures.

One scenario in the demonstrator car consists of a leakage in the air hose between the turbine outlet and the engine intake manifold. The scenario was realized in the car by installing an electric motor which opens a valve to release pressure from the inter-cooler system via a 12mm opening. If the leakage is opened, air (oxygen) mass is lost after having passed the air mass sensor. The fuel quantity calculated by the control unit which is based on this signal will therefore be too high for the actual amount of oxygen in the combustion chamber. This leads to incomplete combustion of the diesel fuel, which causes increased carbon emissions in the exhaust gas (due to non-burnt particles) and reduces the torque of the engine. This effect is, depending on the driving condition, perceivable for the driver as black smoke emerging from the exhaust system.

From the available control unit data, the following subset of signals was fed to the prototype for diagnosing the described scenarios:

- atmospheric pressure sensor signal
- boost pressure sensor signal
- mass airflow sensor signal
- engine speed sensor signal
- duty cycle of the turbo control valve
- current fuel quantity injected.

The on-board diagnosis prototype uses only these control unit signals, and no further signals from additional sensors. The current control unit software in the turbo control system is not able to detect any of the above failures based on the same signals. The frequency at which the control unit reads the signals from the sensors varies with the speed of the engine, therefore the time points at which observations occur are not evenly distributed.

Figure 5 shows the diagnostic results for a slowly opening leakage during stalling the engine. The upper part of the window shows the control unit signals listed above. The measurement runs for 9.75 seconds and yields 1064 quantitative observation vectors. The signal transformation module reduces them to only 12 qualitative observation vectors (indicated by the small "peaks" at the base of the signal window).

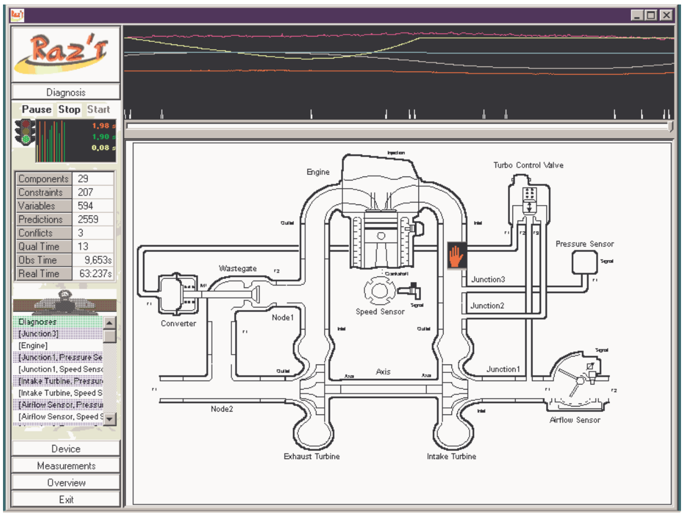

Figure 5: Screenshot of the model-based run-time diagnosis prototype for the DTI turbo control subsystem

The two single fault hypotheses generated by the system contain the component where the failure was actually induced ("Junction3", see mark in **Figure 5** within the window depicting the system structure).

The runtime for the example (on a Windows/Pentium PC) is 25,85 seconds without using temporal caching, and 2,87 seconds if temporal caching is activated. This means that, for this example, the performance of the on-board system is in the order of magnitude of real-time.

In summary, this demonstrator, like two others produced in VMBD (see [Cascio et al. 99], [Bidian et al. 99]), successfully proved the feasibility of model-based techniques for on-board diagnostics of vehicles.

The IDD Project

The results of the VMBD project triggered the interest of the European car industry in further steps towards the introduction of the technology into industrial practice. This requires to refer to the actual industrial work processes related to the design and implementation of on-board diagnostics.

At present, there is no correspondence between the important role of diagnosis in onboard systems and a similar role that diagnosis should play in the design process chain.

The European Fifth Framework project „Integrated Design Process for onboard Diagnosis“ (IDD) pursues the goal to formalize and standardize the diagnostic design process, and to enable the introduction of diagnosis early in the chain. This methodological goal has to be combined with another important objective: *giving to the designers a set of model-based tools that can help them in evaluating and understanding the effects of each choice* *on the system being designed*. The IDD project was started February 2000 with a duration of three years and involves both industrial and academic partners: Fiat CRF (Torino), Magneti-Marelli SpA (Torino), PSA, Peugeot Citroen (Paris), Renault (Paris), DaimlerChrysler AG (Stuttgart), OCC'M Software GmbH (München), Universita di Torino, Université de Paris Nord, XIII, and Technische Universität München.

Analysis of the Current Process of Design and Generation of Diagnostics

The project started with an analysis of the current processes of each industrial partners with a focus on the integration of the diagnostic process and diagnosis-related processes into the whole design process of mechatronic subsystems.

Based on this analysis, a „merged process" has been developed that is based on the similarities recognized, ignoring details and small differences. The abstraction of this process is used as a comprehensive reference for the current design processes. This analysis and its consequences are presented in more detail in [Brignolo et. al. 01].

The core process the project is focused on is the **"inner design loop**" which is concerned with the design of the ECU-based control system and components. Each iteration involves the design of the control algorithms, failure-modes-and-effects analysis (FMEA), diagnostic development, implementation of the ECU (hardware and software) and verification of the algorithms, as shown in Figure 6. The verification step at the end of the first iterations is performed using models (software/ hardware in the loop), whereas, later, the physical system is used. Depending on the achieved results, there are several iterations, each one of them producing an advanced prototype.

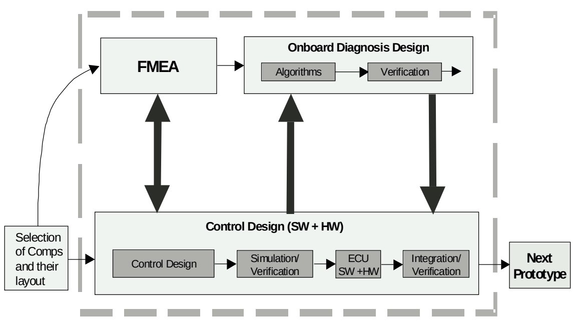

Figure 6 The reference process, one iteration of the inner design loop

A major deficiency of the current practice concerns the interaction between FMEA and the development of diagnostics on the one hand, and the development and design of control algorithms of the system on the other hand. Currently, these are carried out as two substantially separate tasks, despite the fact that there are important interdependencies.

As a consequence, requirements and constraints arising from one of these tasks can be dealt with by the other ones only in the next inner design loop, i.e. changes in the design of control algorithms can have impact on FMEA/ diagnosis only during the next inner design loop and vice versa, thus causing additional iterations and time delay.

Tools for a New Process

Based on the analysis of the reference process and the required improvements, we propose a frame for a new process which is closely connected to a new tool architecture. In summary, the framework for a new process has to satisfy the requirement that the designers (the different experts involved in the design) should be supported in performing the different activities in an interleaved way and in evaluating different designs and in making choices about the best design of a system.

- Such a tight integration of different activities and the aim to perform them concurrently require the fast and reliable exchange of information about any changes in the design introduced by any of the activities. This is why we propose that the **model of the system being designed must play a central role in the new process**.
- The aims to update FMEA, diagnosability analysis and OBD generation quickly after a change and to consider different design alternatives in parallel establishes the requirement that these tasks can be effectively supported or automated by computer tools based on the model, i.e. they have to be **model-based tools**.

These tools rely on model-based systems and will be based on a common set of models and a common model-based diagnostic system core.

The new process and the respective tools should be integrated or combined with the simulation tools, that are currently used for the design of control strategies and typically based on quantitative models. In IDD, this is Matlab/Simulink. This requires software that transforms the models created in these environments into qualitative diagnostic models that form the basis for the model-based tools. The foundations of one of the implementations and a critical discussion of the practical experiences are presented in [Struss 02].

Figure 7 summarizes the overall architecture of the new design support system .

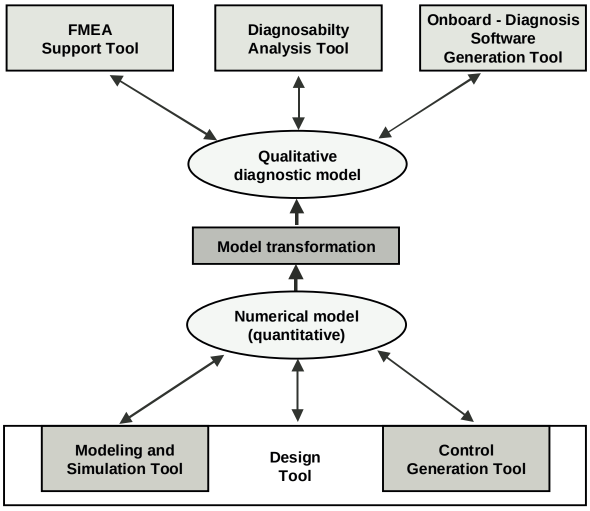

Figure 7 Tools architecture for the new process

Status and Future Work

As of now, two different alternatives have been implemented to generate the qualitative diagnosis models from existing numerical models which both use Matlab itself to compute the tuples of the modeling relation. In addition, a library of qualitative models will be created manually that allows to configure the model based on the structural description only. Based on a use case analysis, the core of the diagnosability analysis tool and the model-based on-board diagnosis engine have been developed.

IDD will use a number of guiding applications with the goal to demonstrate how the diagnostic tasks described can be performed by using the new process and the new tools architecture. Furthermore, we aim to demonstrate how additional advantages of the new method can be achieved, e.g. optimization of sensor placement or deeper diagnostic performance. Thereby, the guiding applications serve, on the one hand, as case studies for the application of the new techniques and, on the other hand, as test cases and demonstrators of the results of the project.

The guiding applications chosen cover on the one hand different mechatronic systems with central ECU-functions, and on the other hand the general application of diagnostic tasks to multiplexed architecture systems. They include

- The **air delivery system** for diesel engines (Figure 8), comprising the exhaust gas turbocharging system and the exhaust gas recirculation system (EGR. and the Common Rail Injection System (Fiat and Magneti-Marelli).

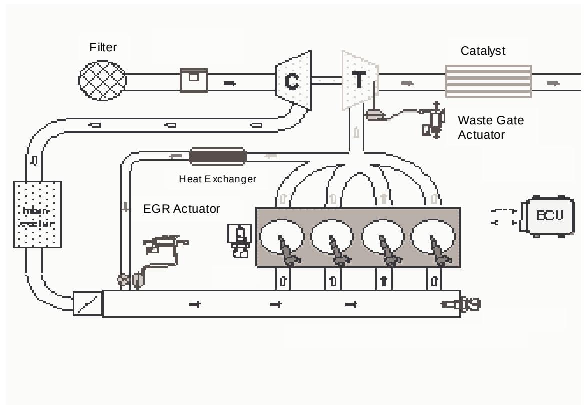

Figure 8 Guiding application: Air delivery system

- The **cooling system** (DaimlerChrysler AG), including an intercooler, which on the one hand increases the efficiency of the engine by cooling the compressed air and, hence, increasing the air charge rate, and on the other hand decreases NOx emissions by keeping the combustion at lower temperature (Figure 9).
- The a**ir conditioning system** (Peugeot Citroën PSA) which consists of two loops that supply a cold heat exchanger and a hot heat exchanger (Figure 10).

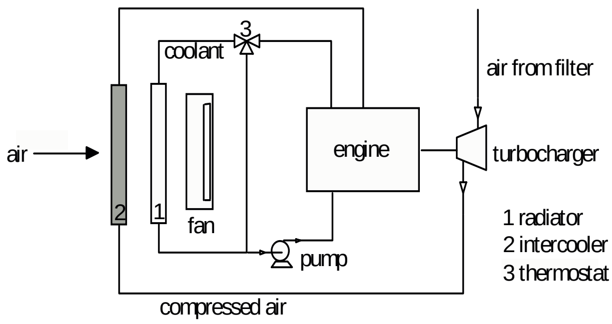

Figure 9 Guiding application: Cooling system

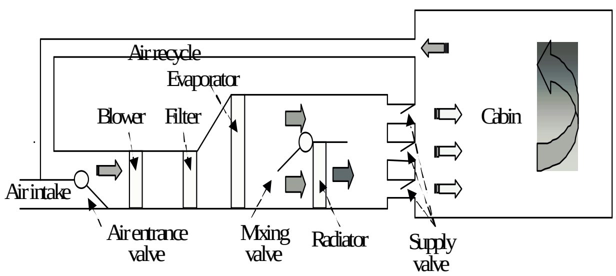

Figure 10 Guiding application: Air conditioning system

- The **multiplexed architecture** (Renault) involving ECUs, sensors, actuators, functions (EF = elementary functions), busses and data frames (Figure 11). The design engineer will be enabled to run a program directly on the representation of a designed architecture and receive the results of an analysis of the interdependency of faults and functions in this architecture.

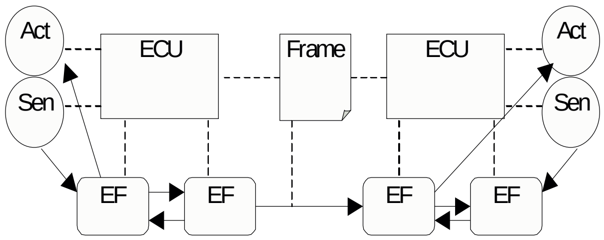

Figure 11 Guiding application: Multiplexed architecture

A first version of models for these guiding applications has been developed and will be used to validate and improve the model abstraction module and to evaluate the tools. By the end of the project in January 2003, we hope to demonstrate the utility of the tools and the benefits of the modified design process based on examples that are close to reality.

Acknowledgements

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