An Agent-Oriented Architecture for Holonic Manufacturing Control

Stefan Bussmann
Daimler-Benz AG
Research and Technology
Alt-Moabit 96a, D-10559 Berlin
email: Stefan.Bussmann@dbag.bln.daimlerbenz.com

Abstract

Many manufacturing paradigms promise to meet the challenges of the next century much better than present approaches do. Two of these paradigms, holonic and agent-oriented manufacturing, have received a lot of attention in academia and industry lately. Their visions, however, have many concepts in common, such as autonomy, cooperation, and self-organization. In order to assess the difference between both paradigms, this paper compares the ideas and concepts of holonic and agent-oriented manufacturing. It will show that both paradigms have different, but compatible views on manufacturing control and that a combination is beneficial to both paradigms. To support this thesis, the use of agent technology to design and implement the information processing in a holonic manufacturing system is discussed.

1 Introduction

On the edge of the 21st century, manufacturing companies are facing market conditions that will very soon change manufacturing control fundamentally. The current market is characterized by a growing industrial supply which, if it continues to grow, will shift the dominant role from the vendor to the customer. The customer already demands better quality and service, low-cost customization, and constant product innovation. This increasing market pressure forces the industry to shorten product life cycles, to reduce time to market, to decrease product lot sizes, and to improve product quality. The consequences for the manufacturing process are manifold: Mass production environments move towards smaller series while manufacturing costs must be reduced and process quality improved. Manufacturing equipment must be reused in order to assure the agility of the company in the face of changing markets. Process productivity has to be improved despite a decreasing labor force and reduced inventories. And finally, manufacturing disturbances and process perturbations must be limited in their impact in order to keep resource utilization at a high level. Only manufacturing companies that are able to meet these challenges will stay or become a key player in an increasingly competitive market.

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In response to these trends, radically new manufacturing paradigms were proposed that promise to meet the challenges of the future much better than present approaches do. Making use of modern information and control technology, these approaches claim to offer the necessary flexibility and robustness. Because of their radicality, however, these paradigms require companies to completely change the manufacturing process, involving a high investment and also a high risk. For the industry, it is therefore imperative to assess the benefits and the risks of the new paradigms before they are implemented in the factory.

Two of these new paradigms, holonic manufacturing [1] and agent-oriented manufacturing [2], have received a lot of attention in academia and industry lately. Their visions are appealing, their ideas and concepts seem both powerful and appropriate. The study of their concepts, however, reveals many similarities. Both approaches use terms like autonomy, cooperation, or self-organization. The apparent similarities give rise to the question whether the approaches are identical or at least equivalent. If they are not equivalent, then in what respect do they differ? Does one paradigm subsume the other? Or do they have different advantages and disadvantages? Given this uncertainty, the first step in assessing the two paradigms must therefore be to clarify their relation.

The aim of this paper is to compare holonic and agent-oriented manufacturing and to identify substantial differences. To this end, we will give an overview of concepts and state of the art for holonic as well as for agent-oriented manufacturing in section 2 and 3 respectively. The comparison of both paradigms is then performed in section 4. We will show that holonic and agent-oriented manufacturing are different, but compatible views on an autonomous and cooperative manufacturing process. The benefits of both paradigms can be combined in one manufacturing system. To support this thesis, section 5 will discuss an agent-oriented design for the information processing in a holonic manufacturing system.

2 Holonic Manufacturing

Holonic Manufacturing was first proposed as a new manufacturing paradigm in the beginning of the 1990s and has since then received a lot of attention in academic and industrial research.[1] The holonic concept was developed by the philosopher Arthur Koestler in order to explain the evolution of biological and social systems [4]. On the one hand, these systems develop stable intermediate forms during evolution that are self-reliant. On the other hand, it is difficult in living and organizational systems to distinguish between ’wholes’ and ’parts’: almost everything is part and whole at once. These observations led Koestler to propose the word “holon” which is a combination of the Greek word ’holos’ meaning whole and the Greek suffix ’on’ meaning particle or part as in proton or neutron [5].

The application of holonic concepts to manufacturing was initially motivated by the inability of existing manufacturing systems (i) to deal with the evolution of products within an existing production facility and (ii) to maintain a satisfying performance outside normal operation conditions [6]. With respect to the well-established CIM technology, for

1. First experiments with the holonic concept applied to manufacturing were already made by Toshiba and Hitachi in the late 1980s [3].

instance, it was pointed out that manufacturing systems on the basis of CIM are inflexible, fragile, and difficult to maintain [7]:

- CIM systems have a fixed control hierarchy that does not support change.
- Reconfiguration and extension of existing systems is difficult.
- Production performance is not maintained outside normal operation conditions.
- Machine data for diagnosis is difficult to access.
- Control is completely automated and excludes human intervention.

These deficits are mainly caused by a centralized and hierarchical control that creates a rigid communication hierarchy and an authoritarian top-down flow of commands. Holonic manufacturing tries to overcome these deficits with the help of autonomy, cooperation, and self-organization.

2.1 HMS Vision

A holonic manufacturing system (HMS) consists of autonomous, self-reliant manufacturing units, called holons. Any unit like for example a machine, a conveyor belt, a work piece, or an order can be a holon as long as the unit is able to create and control the execution of its own plans and/or strategies (cf. HMS definition of autonomy [8]). A holon always contains an information processing part and optionally a physical processing part. A scheduler is an example of a holon without a physical processing part.

Holons cooperate with other holons during the production process in order to accomplish the production goals. Cooperation, in form of coordination and negotiation, develops wherever and whenever necessary, usually along the material and information flow. The cooperation process, in contrast to CIM, also involves humans. They are viewed as ordinary resources that show autonomous and cooperative, i.e., holonic behavior. However, the integration of humans requires a human machine interface at an artificial holon. For this reason, Christensen [8] provides three major interfaces to an artificial holon: a physical processing interface, an inter-holon interface, and a human interface.

A general architecture of a holon is depicted in figure 1. The physical processing layer is the actual hardware performing the manufacturing operation, like for example milling or assembly. It is controlled by the physical control layer. The decision making represents the kernel of the holon and provides two interfaces: the first for interaction with other holons, and the second for interaction with humans.

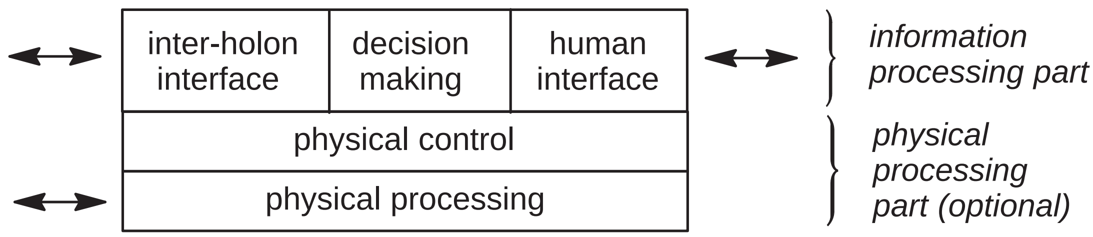

Figure 1: General architecture of a holon.

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A system of holons which can cooperate to achieve a goal or objective, is called a holarchy [8]. Holarchies are recursive in the sense that a holon may itself be an entire holarchy that acts as an autonomous and cooperative unit in the first holarchy. An example is given in figure 2: A workstation is regarded by order holons as a single holon even though it actually consists of two distinct holon types, namely resource allocation and process control holons.

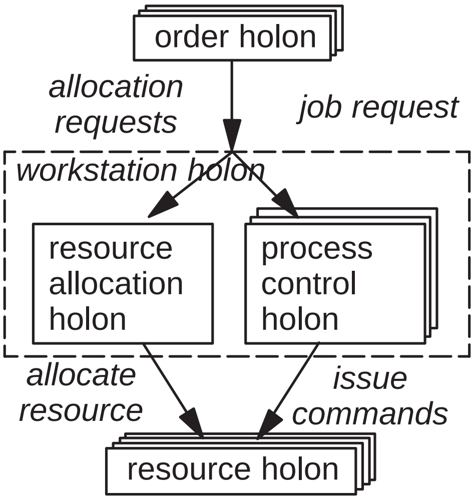

Figure 2: An example holarchy [9].

Holons within a holarchy may dynamically create and change hierarchies. Moreover, holons may engage in multiple hierarchies at the same time. In contrast to hierarchical and heterarchical control systems, HMS creates loose and flexible communication hierarchies which never force a holon to perform a certain task (cf. [10, 11] for a discussion).

2.2 Research activities

Holonic Manufacturing was one of the six test cases in the Intelligent Manufacturing Systems (IMS) feasibility study program [12] that was set up in 1992. The holonic manufacturing test case was a one-year feasibility study and consisted of five benchmark testbeds that were used to achieve a better understanding of the requirements of the 21st century manufacturing systems and to develop an approach to build future manufacturing systems based on these requirements ([6], see also [10,13,14]). The success of the benchmark tests led to the endorsement of Holonic Manufacturing as an international IMS project in 1994. Over 30 academic and industrial partners from the IMS regions Australia, Canada, Europe, Japan, and the United States participate in this international collaboration.

The goal of the HMS project is to develop the generic aspects of holonic technologies and to demonstrate their appropriateness and benefits with the help of several prototypical industrial applications. Its extensive research effort, as well as parallel research activities in many regions, are still on-going.

3 Multi-Agent Systems

Multi-agent systems are a growing field that has established itself after more than a decade of intensive research as a major field of computer science and artificial intelligence in particular. Recently, its growth is accompanied by a hype in fields that are also based on the notion of an agent: mobile agents, user agents, software agents, etc. (cf. [15]). Multi-agent systems, however, are quite distinct from these fields, even though there are commonalities and a clear distinction is somewhat difficult because the term agent is still not well-defined. Nevertheless, multi-agent systems as a distinct field has developed its own theories, architectures, techniques, and methodologies.

Multi-agent systems (MAS) can be best characterized as a software technology that is able to model and implement individual and social behavior in distributed systems. It investigates on the one hand notions like autonomy, reactivity, and goal-directed reasoning in order to model and implement individual behavior (cf. e.g. [16,17,18]). On the other hand, it examines aspects of cooperation, coordination, negotiation, coalition formation, role assignment, and self-organization in order to create social behavior (cf. e.g. [16]). Multi-agent systems provide theories for social and individual behavior, agent architectures, communication and cooperation techniques, and also new programming languages and environments [19]. These theories and techniques can be applied to a wide range of domains, like for instance concurrent engineering, electronic commerce, telecommunication, traffic, and in particular manufacturing control.

3.1 Agent-Oriented Manufacturing

In contrast to HMS, agent-oriented manufacturing is not a field of research with a single vision. It is rather a collection of work that proposes to improve the control of existing manufacturing infrastructure with the help of agent-oriented techniques. Most work, for instance, is focussing on the control of a flexible manufacturing system as it was developed within the CIM initiative.

One of the very first applications of agent-oriented modelling and coordination techniques to manufacturing control was the prototype factory control system YAMS [20, 21,2]. In YAMS, the manufacturing enterprise is modelled as a hierarchy of production units, called workstations or workcells. An engine plant, for instance, consists of a block, an oil pump, a head, and an assembly flexible manufacturing system (FMS). The hierarchy, however, records only composition, not control. Task distribution down the hierarchy is done by negotiation. A node announces a task; units capable of performing the task reply with a bid; and the node assigns the task to the node with the best bid (cf. figure 3). This negotiation phase enables YAMS to flexibly assign the production load to the available units, even if some machinery has broken down. A similar approach was taken by Shaw & Whinston [22]. An approach that controls an FMS with the help of team formation is described in [23].

Some work in agent-oriented manufacturing concentrated on one aspect of manufacturing control. Bussmann [24], for example, presented a coordination algorithm for the scheduling of transportation tasks. Like in YAMS, tasks are announced to the transport units. In contrast to YAMS, these units perform only a local analysis of the task and return the result of the analysis to a coordinator. The coordinator then synthezises the results into a global schedule. Hahndel et al. [25] have developed a completely decentralized approach to planning manufacturing jobs that consist of several steps. A machine agent responsible for the execution of a manufacturing step of a specific job determines via negotiation another machine agent that is able to execute the next step. This agent then takes over the responsibility for this job and continues the planning process. The approach proposed in [26] uses a market mechanism for assigning jobs.

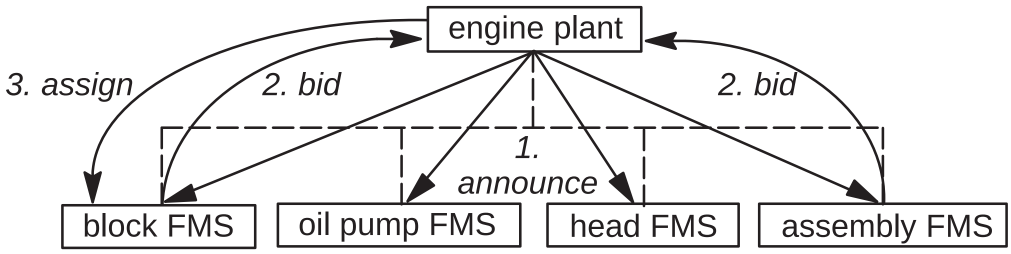

Figure 3: An example factory hierarchy in YAMS [20].

3.2 Research Activities

Most work in agent-oriented manufacturing has focussed on developing innovative solutions for the information processing part of an existing infrastructure, like flexible manufacturing systems. However, the greatest potential for concepts like MAS does not lie within the information processing alone, but in a completely new approach to manufacturing in general, as it is undertaken in holonic manufacturing systems. On the other hand, multi-agent systems as a very active and vibrating field of research has produced a vast amount of approaches for modeling individual and social behavior. This technology can be of use to holonic manufacturing or other manufacturing specific paradigms.

4 Comparison

It is obvious from the previous sections that holonic and agent-oriented manufacturing systems have many concepts in common, although there are some conceptual differences. Both paradigms have a similar vision of future manufacturing systems which should consist – according to their point of view – of autonomous and cooperative manufacturing units. Concerning the basic unit (holon vs. agent) and the organization of the system (holarchy vs. hierarchy), however, there are different views, not necessarily incompatible, but at least non-equivalent.

HMS was motivated by the deficits of current manufacturing systems and has developed a vision of how manufacturing systems should be organized and controlled in order to meet the challenges of the future. In doing so, it focussed on the whole manufacturing system, i.e., (i) on the overall organization of the production process, and (ii) on the equipment, control, and human integration. On the other hand, its vision is strictly motivated by trends in manufacturing and is thus very specific to the manufacturing domain. And it started as a vision with only few work so far describing how HMS can be implemented.

MAS is a general software technology that was motivated by fundamental research questions concerning aspects like autonomy, cooperation, team formation, etc. It focussed on what can be done and how it can be done, and is applicable to a wide range of domains. Agent-oriented manufacturing, on the other hand, adopted mainly the ideas of CIM and introduced more flexibility with the help of coordination along given hierarchies. The software technology itself, however, does not favor a specific solution, but offers a set of concepts and techniques for implementing the information processing part of domain specific solutions. In particular, multi-agent systems allow to create any kind of organization, from rigid hierarchies to multiple holarchies. Furthermore, the concepts and techniques of multi-agent systems are described algorithmically and are ready to be implemented.

Put together, HMS and MAS are similar approaches with different, but complementary foci. HMS deals with the overall structure of the manufacturing process and in particular with the integration of equipment, control, and workers, whereas MAS concentrate on the design of the information processing in a control system and its implementation (cf. figure 4). Given the strong similarities of concepts, it seems advantageous to combine both paradigms and to use multi-agent systems as an enabling technology for the information processing in HMS [7]. Starting with the holonic vision, multi-agent systems can supply the reasoning techniques necessary to implement the information processing architecture of a holon and the cooperation techniques necessary for holons to interact with other holons and to build holarchies.

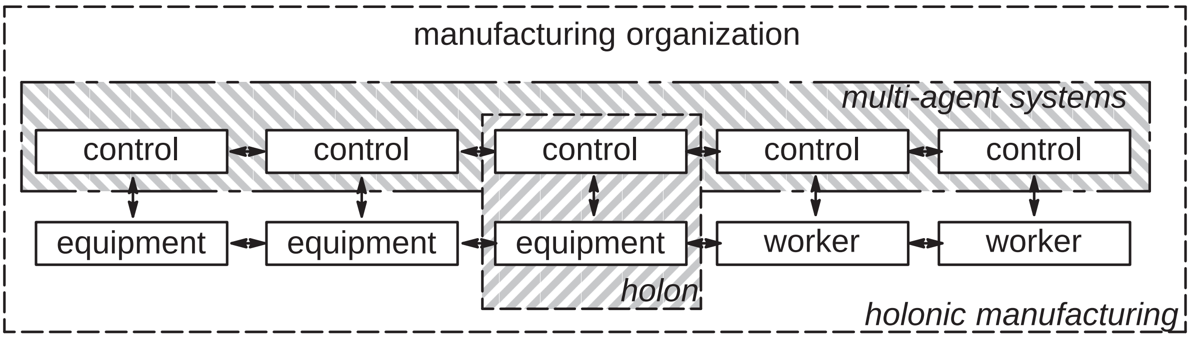

Figure 4: Views of HMS and MAS on manufacturing process.

5 Agent-Oriented Design of a Holon

As argued in the previous section, agent-oriented techniques are an appropriate technology for designing and implementing the information processing part of a holonic manufacturing system. To support this thesis, this section derives an agent-oriented design of a holon from the HMS vision and discusses how this design can be implemented with the help of agent technology.

The holonic vision perceives future manufacturing systems as flexible organizations of autonomous and cooperative units (cf. section 2.1). This vision contains three aspects.

First of all, holons are able to autonomously control the behavior of their associated equipment. They can create and execute their own plans and follow their own strategies within their capabilities. This autonomous behavior implies the existence of some kind of decision making that guides the physical control of the holon.

Second, two or more holons are able to cooperate wherever and whenever necessary. To do so, these holons must be able to identify potential for cooperation, to engage in coordination or negotiation, and finally to execute the agreed cooperation.

Third, holons are able to act within multiple organizations, called holarchies, which are created and changed dynamically. Creating holarchies means to (re-)arrange the manufacturing process or the control process in order to improve productivity. It involves the distribution of work and responsibility, and the fixation of interaction patterns. The creation of holarchies consequently implies that holons are able to identify potential for reorganization, to negotiate reorganizations, and to follow agreed patterns.

All in all, the holonic vision requires a set of properties that must be provided by the manufacturing control system. Assuming that these properties are not hard-wired, nor that the necessary behavior of the holons is prescribed by a central component, each holon must have the following components:

(i) algorithms
for planning, scheduling, and controlling the physical behavior of the holon;

(ii) decision rules
for determining the physical behavior of the holon;

(iii) communication and cooperation techniques
for identifying potential for cooperation, for coordination and negotiation, and for cooperation execution;

(iv) organization techniques
for identifying potential for reorganization, for rearranging organizations, and for pattern-guided behavior;

(v) decision rules
for determining the cooperativeness of the holon.

The incorporation of these components into the general architecture of a holon (cf. figure 1) leads to the agent-oriented architecture of a holon shown in figure 5. In the following, it is discussed how agent technology can be used to implement the components of this architecture (due to space limitations the human-machine interface is omitted from the subsequent discussions).

As argued above, the architecture for information processing of a holon has to support three tasks. The first task is to determine and control the physical behavior of the holon. Depending on the current situation, the holon chooses the plans and strategies that achieve best the long-term goals of the holon (individual decision making). These plans and strategies are provided and executed by the behavioral component. An example of an agent architecture for behavioral decision making is the Procedural Reasoning System (PRS) [27]. Others can be found in [19].

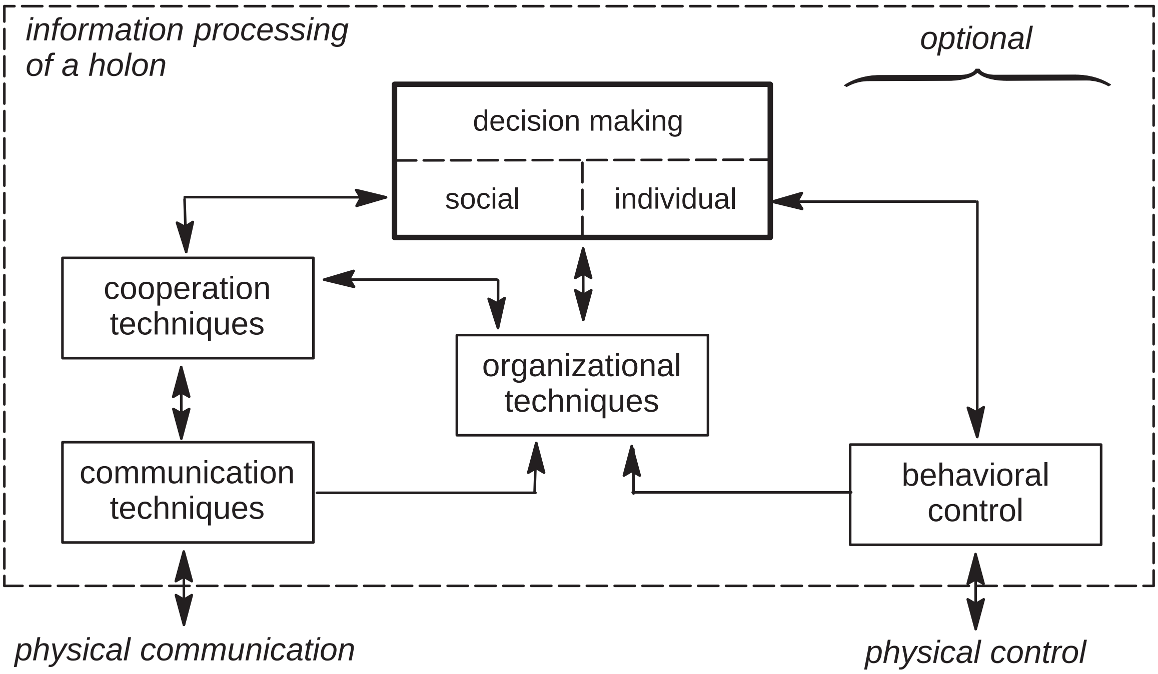

Figure 5: Agent-oriented architecture for a holon.

The second task is to cooperate with other holons wherever and whenever necessary. Possible cooperation is initiated by the decision making and carried out by specific cooperation techniques. These techniques refer back to the decision making whenever a decision becomes necessary. The implications of an agreed cooperation are handed from the cooperation component over the decision making to the behavioral component for execution. An architecture that combines individual and social decision making and thus bridges the gap between the cooperation and the behavioral component has been proposed in [18]. For the cooperation, there exists a vast amount of specific approaches (see [16,17] for an overview). A single cooperation framework, however, has not been developed so far.

A prerequisite for most cooperation between autonomous units is an appropriate form of communication [28]. Burmeister et al. [29], for example, have proposed generic cooperation protocols that are based on speech acts and structure the exchange of message during a cooperation process with the help of dialogue patterns.

Like for cooperation, the holon requires techniques for reorganizing the manufacturing control process. These techniques monitor the actions of the other components, i.e., the physical and the communicative actions, and analyze the control process. They identify potential for improvement and initiate a negotiation process for the reorganization which is carried out by standard cooperation techniques. The implications of the agreed reorganization are again distributed to the other components of the holon. In contrast to cooperation, there exists only few work on the reorganization of multi-agent systems. Some related work has been reported in [31, 30].

In this section, we have shown how holonic manufacturing and agent technology can be combined. We have derived an agent-oriented design of a holon and have discussed where and how agent-oriented techniques can help to implement such an architecture. The design and implementation of a general holon architecture, however, is still a matter of research, in particular because of the state of the art for cooperation and reorganization.

6 Conclusion

Holonic manufacturing and agent-oriented manufacturing are two paradigms with similar visions and concepts. Both use autonomy, cooperation, and self-organization to overcome the deficits of existing manufacturing technology. We have shown in this paper that both paradigms have compatible views on manufacturing control. In particular, we have argued that agent-oriented techniques can be used to design and implement the information processing of a holon. We have supported this thesis by deriving an agent-oriented design of a holon that can be implemented with the help of agent technology.

Given the compatibility of both paradigms, it is desirable to develop a framework for manufacturing control that combines the benefits of both approaches. Such a framework requires a methodology that describes when and how to use the concepts and techniques of the individual approaches. Holonic manufacturing, for instance, should design the overall manufacturing process and derive requirements for the information processing from the intended interactions. Multi-agent systems in turn should provide the basic reasoning and cooperation techniques necessary to meet the control requirements and tailor them to the specific needs of holonic manufacturing. Such a framework for holonic and agent-oriented manufacturing, however, is still a matter of future research.

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