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Development of Cognitive Products via Interpretation of System Boundaries

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Abstract: Cognitive products use cognitive functions to work autonomously and reduce the amount of interaction necessary from the user. However, to date no method exists to support the integration of cognitive functions in common products. This paper presents a method that supports designers when exploring ideas for new cognitive products. The method is based on functions/actions that humans perform while using a product, as well as functions/actions performed by the product itself, all of which can be consistently modelled in an activity diagram. Initially, the system boundary of the product is drawn around the functions/actions performed by the product. Cognitive functions are then identified that are currently performed by the user, and can possibly be integrated into a new cognitive concept. The resulting concept is specified systematically by interpreting the system boundary of the product to include cognitive functions. This method has been verified via design projects performed by interdisciplinary student design teams, and an example of this work is presented.

Keyword: Cognitive Products, Functional Modelling, Activity Diagrams

Introduction

Cognitive products are tangible and durable things with cognitive capabilities that improve robustness, reliability, flexibility and autonomy [1]. They meet and exceed customer expectations by using cognitive functions e.g. *to perceive*, *to learn*, *to plan*, etc., to reduce the need for human input, for example when such input is difficult or repetitive. However, no method exists to support the integration of cognitive functions into common products. This paper presents such a method, with the intention of supporting designers as they explore ideas for new cognitive products.

The research presented here is concerned with identifying how cognitive functions can be included in the functional modelling process. Functional modelling is core to many product development activities, and numerous methods have been introduced that result in a holistic representation of a product according to its functional structure [2]. The resulting functional models are often represented as flow diagrams with functions described according to some taxonomy, e.g. [3], and linked according to the material flows between them e.g. [4]. In the method presented here, the functions of a product are represented as actions in an activity diagram. The diagram is then extended to include the actions of the user during product use, with the system boundary of the product surrounding the actions performed by the product. The user actions are compared to a taxonomy of cognitive function and flows [5] to identify those that could be integrated into the functionality of the product. Finally, the system boundary of the product is interpreted to include those cognitive functions that are identified and have the potential to improve the product as a cognitive product. This systematic variation of the system boundary results in gaining a holistic perspective which can support the design of cognitive products, and the method has been validated via design projects conducted by interdisciplinary student design teams, as described in [6].

The next section provides an overview of the role of functional modelling in product development, and an overview of modelling with cognitive functions. In Section 3, the problem of using cognitive functions in product development is presented, and in Section 4 a method is introduced which seeks to overcome this problem. The method is illustrated with reference to a cognitive washing machine which was developed by a student design team. The paper concludes with a discussion exploring the potential of the method to support cognitive product development, and an outlook towards future research.

Background

Functional Modelling in Product Development

Functional modelling is central to many product development activities, particularly conceptual design [4]. It supports a systematic, top-down approach to product definition, starting from a description of the required core functionalities of the product. These can then be sequentially decomposed into lower-level sub-functions, resulting in an abstract specification of the product that describes how the required functionalities can be realised by sub-functions and the relations between them, e.g. [7]. There are various approaches to formally representing the resulting functional models, a review of which are provided by Erden et al. [2]. A common approach, and the one that is employed in this paper, is to represent functions according to a flow-oriented model [4]. In particular, functions can be defined as a general input/output relation that is used to perform a task, and can be described by verb-noun pairs, e.g. *mix water and detergent*. The relations between these functions can then be defined as flows characterised according to types e.g. *material*, *energy* or *signal*, and the resulting functional models are represented as flow diagrams, as illustrated in Figure 1. Here, the functionality of a washing machine is presented as a system of functions and sub-functions, and the flows of material, energy and signal between them.

Functional models are well suited for supporting modern design processes, in which multi-disciplinary teams collaborate to develop complex products [2]. They provide a common representational framework for defining a product as a system of functions and sub-functions, which is accessible to all members of the team, regardless of engineering discipline. A functional model provides an abstract but holistic view of the system which allows designers to better understand the complex products with which they are working, individually and in collaboration with team members [8]. If a functional model is constructed based on an accepted language of functional descriptions then this reduces potential ambiguity in the model, increases uniformity and increases the potential to reuse the model either manually or in an AI-based system. For example, the NIST Reconciled Functional Basis is a taxonomy in which functions are input/output relations connected via flows and represented in flow-oriented models [3].

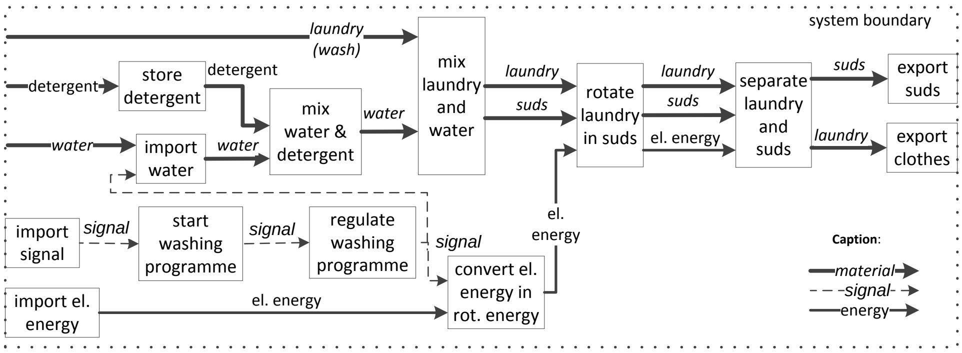

Figure 1 Flow-Oriented Functional Model for a Washing Machine.

In systems engineering, flow-oriented functional models can be represented as activity diagrams. These are flow diagrams representing activities, which are defined according to constituent actions and their inputs/outputs [9]. Activities/actions are an abstract formalism for describing behaviour in the same way that functions/sub-functions are an abstract formalism for describing behaviour [7]. So activity diagrams can be used to model the functions carried out by a system as actions, but with additional capabilities beyond those provided by a flow-oriented model. For example, control nodes such as fork/join nodes or decision nodes can be included in a diagram to represent control logic and provide additional constraints on the timing and order in which actions execute [9]. The combination of object flows with control flows is a powerful formalism for modelling products as systems of functions. Also, the additional capabilities provided by activity diagrams mean that when they are defined formally, using a language such as SysML, they can be mapped to executable constructs which in turn support evaluation, for example through simulation. For these reasons activity diagrams will be used in the remainder of this paper, to represent the functional structure of products and support development of cognitive products via introduction of cognitive functions.

Functional Modelling for Cognitive Products

Cognitive products are tangible and durable things with cognitive capabilities that consist of a physical carrier system with embodied mechanics, electronics, microprocessors and software. The surplus value is created through cognitive capabilities enabled by flexible control loops and cognitive algorithms. Customer needs are satisfied through the intelligent, flexible and robust behaviour of cognitive products that meet and exceed customer expectations. Cognitive products have all or a subset of capabilities of Cognitive Technical Systems (CTSs) and the solid grounding of an everyday product that meets user needs and desires [1].

What makes products cognitive are their special properties stemming from the integration of CTSs. The implementation of cognitive capabilities results in high-level performance. In particular, in contrast to products which have deterministic control methods, cognitive products do not only act autonomously, they do so in an increasingly intelligent and human-like manner. This means that they are more robust than non-cognitive products since they are able to adapt to a dynamic environment, such as human living environments. Cognitive products should be able to maintain multiple goals, conduct context sensitive reasoning, and make appropriate decisions. This results in higher reliability, flexibility, adaptivity and improved performance.

Incorporation of cognitive capabilities in a product concept requires specific descriptions of cognitive functions, as discussed by Metzler and Shea [1]. The term *cognitive function* is used to refer to basic functions that enable cognition, e.g. *learn*, *perceive*, *understand* or *decide*. Such functions perform operations on flows of information, or they process data flows to create information. However, there is no commonly agreed list of cognitive functions that are required for a cognitive system, neither human nor artificial. Typically, researchers in particular areas compile their own list of cognitive functions. Metzler and Shea [5] present a comprehensive set of cognitive functions and flows structured in a taxonomy that incorporates views from engineering and cognitive sciences. The taxonomy of cognitive functions and flows is tailored for mechanical engineers and supports consistent functional modelling through a standardized representation. It can be used to model a wide range of cognitive products and is used throughout this paper. As discussed, functional modelling results in an abstract representation of a product that is useful for multi-disciplinary concept development phase. An example of using the taxonomy of cognitive functions and flows to define flow-oriented functional models is presented in Metzler and Shea [5].

Problem Identification

There are many factors that are driving the introduction of cognitive functionality in today's consumer products, i.e. functionality that introduces cognitive capabilities so that products can operate with robustness, reliability, flexibility and autonomy. The need for companies to differentiate themselves from the competition means that they are constantly looking for opportunities to develop their products in innovative ways and they often want to be seen to be on the cutting-edge of technological development. Also, consumers expect more functionality from their products and want the user experience to be as enjoyable as possible. AI algorithms and methods have reached a high-level of maturity which means that they can be reliably incorporated into cognitive products. And, the steady reduction in the cost of components necessary to utilise these algorithms, such as CPUs, digital cameras, actuators, etc. means that they are cost effective. Cognitive products use cognitive functions to enable products to work more autonomously so that they can reduce the amount of interaction necessary from the user, while exceeding their expectations. For example, iRobot's Roomba is an autonomous robot vacuum cleaner that uses cognitive functions to map, navigate and plan routes and significantly reduces the need for human interaction [10].

Although there is a drive to incorporate cognitive functions in consumer products it is not always obvious how to include such functions in a design. As discussed in the previous section, functional modelling is central to many product development activities, but cognitive functions are rarely considered. The taxonomy of cognitive functions and flows (as described in Section 2.2) defines a language for describing the required cognitive functionality of a product in the same way that the NIST Reconciled Functional Basis defines a language for describing non-cognitive functions. Despite this, it is not obvious how to incorporate the taxonomy when introducing cognitive functions to an existing product concept.

The difficulty that arises with respect to developing cognitive products was observed during a series of student projects, as described by Metzler and Shea [6]. Since 2007, 6 projects have been set in which 16 teams of students were tasked with inventing or adapting household products that address user needs by using cognitive functions. The students who participated were from varied backgrounds including mechanical engineering, electrical engineering or computer science, and worked in multi-disciplinary teams of 3 to 5. They were tasked with developing cognitive products that address a general problem, e.g. *saving energy* or *recycling,* by incorporating cognitive functions into existing products. For example, the washing machine design that is used throughout this paper was developed by one student team in response to a project where they were asked to introduce cognition into a household product so that it can be more easily used.

Before starting the projects, the students were introduced to a user-centred process that supports early phases of development of new products that are useful and usable [11]. The process was adapted to the context of cognitive product development to assist in the identification of user needs; to aid in the development of a product concept; and to support the building of a functional prototype. The students were also encouraged to use functional modelling to support the development of a product concept and were presented with the taxonomy of cognitive functions and flows to aid in the specification of cognitive functions.

During the projects the performance of the students was observed, and it was found that the teams were able to identify product market opportunities and needs, and they constructed functional prototypes of adequate quality. However, it was also observed that many of the teams had difficulties incorporating cognitive functions into a product concept. The major difficulty for the students was on the one hand translating the user needs into cognitive functions and on the other hand identifying and incorporating functions related to or required by the cognitive functions in the new product concept. Most teams did not use a systematic approach that could assist in the integration of cognitive functions into product concepts. The result was product concepts that had to be adapted in the following development phases, resulting in additional iterations of the design process and delayed development of the cognitive product.

A Method for Incorporating Cognitive Functions

The method described in this section addresses the incorporation of meaningful cognitive functions into existing product concepts. The goal is to turn existing product concepts into cognitive product concepts by identifying and incorporating cognitive functions that are currently carried out by the user. To achieve this goal four steps have to be carried out, as described in Figure 2. These steps are explained in the following sub-sections.

Model a Product Concept as an Activity Diagram

Step 1 of the method is concerned with creating an activity diagram as a model of the product concept into which cognitive functions will be incorporated. The model can be derived from a product already existing in the physical world or from a product concept under development. This makes the method applicable to new product development as well as incremental product development. As discussed in Section 2, activity diagrams are an abstract formalism to describe behaviour. They represent activities as flow diagrams, defined according to constituent actions and their inputs/outputs. When applied to product modelling they are used to represent the product according to object flows which represent the input/output of functions represented as actions, and control flows which represent the chronology of the actions. If a functional model of a product concept already exists, such as the flow-oriented functional model of the washing machine illustrated in Figure 1, then it is a trivial task to translate this into an activity diagram. In Figure 1, the functionality of the internal operations of the washing machine is described with active verbs and objects from the NIST Reconciled Functional Basis. In the translated model, these functions are represented by actions, and the functionality of the product is represented as a system of actions and the flows between them.

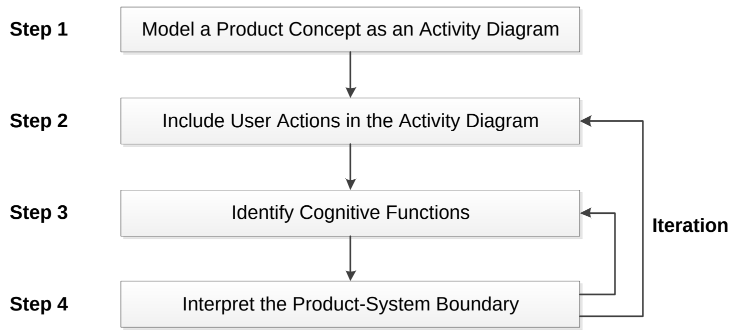

Figure 2 Procedural Model of the Method.

Include the User Actions in the Activity Diagram

In Step 2, the user's interaction with the product (during intended use) is considered, and the system of actions represented in the activity diagram is extended to include the actions of the user. To achieve this, the user experience is considered chronologically. First, start and end nodes are included; these indicate the beginning and the end of product use. Next, all possible (within the limits of the design) user actions are added to the activity diagram. Finally, these are connected by flows, which are either object flows, such as those commonly used in flow-oriented functional modelling, i.e. material, energy, signal, etc., or control flows that model the chronology of actions by specifying when and in which order actions are executed [9]. The authors recommend using the taxonomy of cognitive functions and flows and the NIST Reconciled Functional Basis to model the user actions. For example, Figure 3 shows an extended activity diagram of the washing machine that includes, in addition to the functionality of the washing machine, illustrated in Figure 1, the user's pre-wash actions. The post-wash actions of the user are not included due to space limitations, and the activity diagram ends when the wash cycle terminates. The functionality of the washing machine was presented in Figure 1, and in Figure 3 is enclosed in one block as a subsystem. The actions included describe the user's process of planning and executing a washing programming, for example deciding the type of laundry to wash, separating the laundry, putting the laundry in the machine, choosing appropriate detergent, etc. The flow between these actions describe the materials that are needed for input/output, and also structure the actions chronologically.

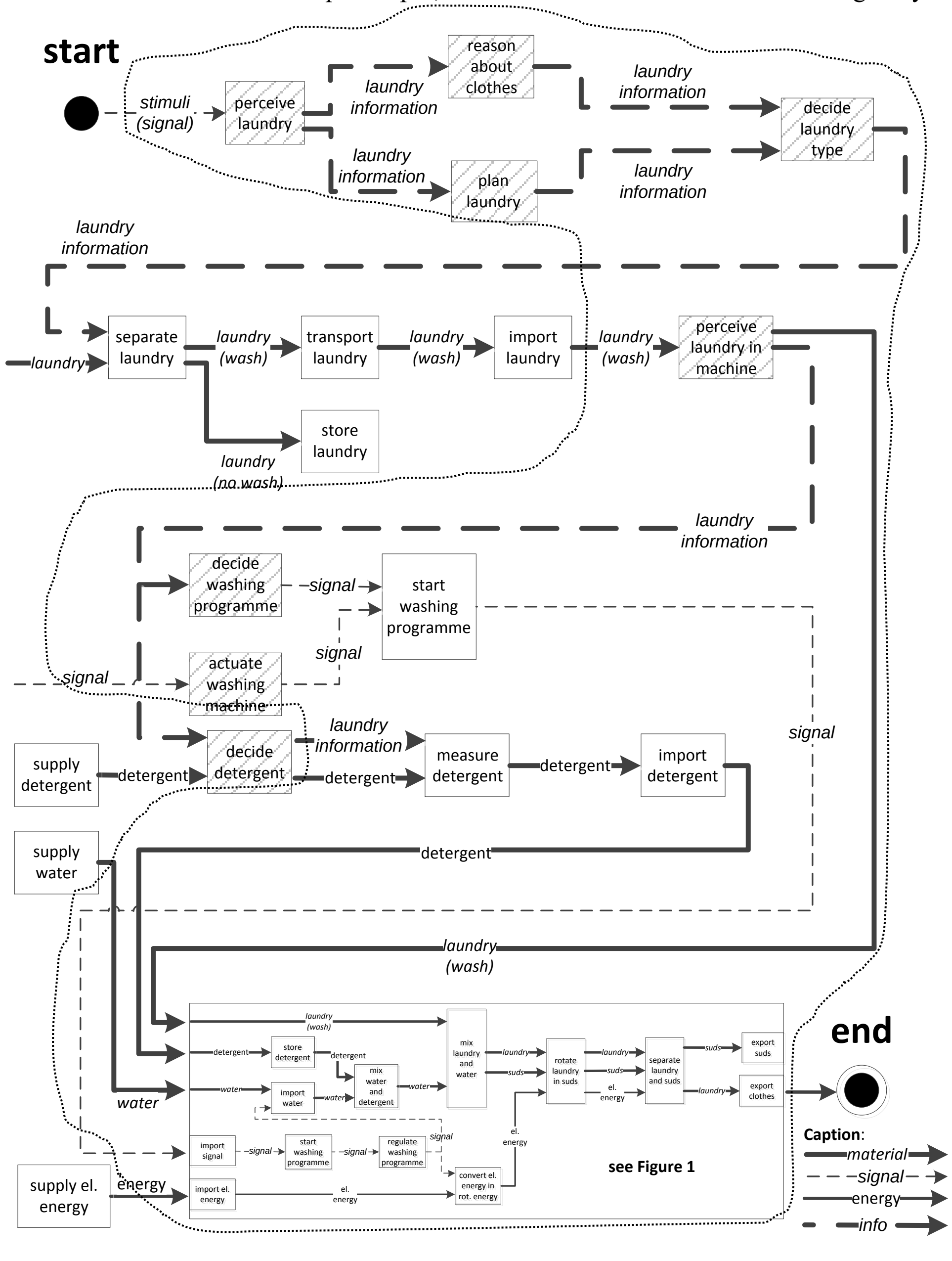

Figure 3 Activity Diagram Including Product Actions and User Actions.

Identify Cognitive Functions

After incorporating the user actions into the activity diagram, Step 3 is concerned with identifying the cognitive functions currently implemented by the user. As discussed in Section 2, these are basic functions that enable cognition by performing operations on flows of information, or by processing data flows to create information. Such functions offer a great potential for innovation by shifting complicated or often repeated tasks from the user to the product. The taxonomy of cognitive functions, defined by Metzler and Shea [5] is an aid to identifying cognitive functions and provides a comprehensive set for comparison. For example, comparison of the user actions specified in the use of the washing machine in Figure 3 with the taxonomy of cognitive functions gives rise to a list of cognitive functions performed by the user during interaction with the product. In Figure 3, these cognitive functions are highlighted as striped blocks, and include *perceive laundry*, *decide laundry type*, *decide washing programme*, etc.

Interpret the Product-System Boundaries

In Step 4, the product's system boundary is interpreted to include some of the cognitive functions that were identified in Step 3. Currently these functions are actions of the user, but can potentially be an action of a new cognitive product concept. Here, the critical decision is to decide *which* of the identified cognitive functions to include in the new product. The following questions could assist in this decision:

1. How close is the cognitive function relative to the product?
2. How many flows link the cognitive function to other functions?
3. How difficult is it to technically realize the cognitive function?
4. How annoying is the cognitive function for the user when carried out?

Question 1 can be addressed by considering the activity diagram defined in Step 2. Here, the distance between functions is measured according to any intermediate functions. In the activity diagram, the cognitive functions closest to the original product concept are likely to be suitable for integration in the product. This is because the closer a function is to the original product, the more likely it is that this function is associated with the product, and would be acceptable as part of the product. Conversely, the more functions that have to be carried out by the user between a cognitive function and the functions carried out by the product, the less it is associated with the product.

Question 2 can also be addressed by considering the activity diagram. In the activity diagram, the more a cognitive function is linked to other functions, the more complex the functional model becomes. If there are many flows linking a cognitive function to the original product concept it is expected that many components in the concept will have to be adapted to accommodate the new functionality. Similarly, if there are many flows linking a cognitive function to other cognitive functions outside the original system boundary it is expected that the user has to strongly interact with this cognitive function.

Question 3 relates to the technical feasibility of implementing a cognitive function. Its answer relies on the expertise available to realise such a function in a physical device, and also on the current state of the art, since some cognitive functions may not be realisable using currently available technology.

Question 4 focuses on the user and asks which actions would make the experience of using a product more enjoyable, if they were implemented by the product. A study investigating product market opportunities and user needs is an appropriate method to explore this question.

After answering the questions a pair-wise comparison can help to identify which cognitive function(s) should be integrated into the new cognitive product concept. This results in an interpretation of the product's system boundary to include the identified cognitive functions, as well as other required non-cognitive functions, as part of the product's functional structure. For example, in Figure 3 cognitive functions have been incorporated into the system boundary for a new cognitive washing machine concept, as identified by the new system boundary represented by the dotted line. The new washing machine concept perceives the laundry and, based on how much is available of each type, e.g. colours, whites, delicates, etc., decides which laundry should be washed. The machine suggests to launder the most homogeneous laundry group with the highest capacity utilization first. However, the final choice of which type of laundry to wash is made by the user; this avoids dissatisfaction due to the paternalism of the washing machine. The user then separates this laundry and places it in the machine. The machine perceives which laundry is inserted and adapts its behaviour to the user's decision. For example, the washing machine determines the ideal washing program or which detergent suits best, how much detergent is needed for the current laundry group and if softener is needed. In case the user mixes two different laundry groups accidentally the washing machine can output a warning to inform the user and avoid staining. This new concept improves the experience of clothes washing by carrying out some of the tedious and repetitive actions usually carried out by the user. It was implemented as a physical prototype by the multi-disciplinary team of students who designed it.

Discussion

The method described in the previous section was applied by student teams during the development of cognitive products, including the cognitive washing machine concept represented in Figure 3. These initial applications provide evidence for the usefulness of the method as a way of identifying cognitive functions that are involved in the use of an existing product concept. The method is visual in nature, allowing the system boundary between the user and the product to be interpreted according to identified cognitive functions. This visual nature means that the approach is intuitive for the designer, and easy to communicate to other members of a multi-disciplinary design team. A more thorough evaluation of the method, including comparisons with other approaches and a control group, remains to be conducted.

When applying the method, cognitive functions could easily be identified by following Steps 1 – 3. As discussed, in these steps cognitive functions are identified as user actions modelled in an activity diagram.

However, Step 4 involving the decision of *which* cognitive functions to incorporate is more difficult, and required input from experts with sufficient experience in CTSs to make informed and realistic decisions. The fact that the realisation of cognitive functions in hardware and software is difficult is known and further research is being carried out to improve the decision making process and support implementation of Step 4. This includes the definition of design catalogues that provide patterns of how to realise cognitive functions. Also, analysis of aspects of a generated activity diagram, e.g. according to number, type and direction of flows, may be sufficient to estimate the feasibility of incorporating a cognitive function.

In addition to the difficultly of carrying out Step 4, there are other open issues that remain to be investigated in further research. For example, it is not known if the initial product concept has to be modelled and how detailed this model should ideally be. It may be beneficial to use a black box to represent the initial product concept, with input and output flows indicated. User actions could then be modelled around the black box as illustrated in Figure 3. This may be sufficient to inform and motivate the designers of cognitive products, without having to take the time and effort to model the existing product in detail. This could also avoid issues with design fixation, which may arise through consideration of the original functional structure of the product. However, this approach may be detrimental, since there is no available information about how the flows link to structure and how the structure has to be changed when incorporating a certain cognitive function.

Conclusion

The method described in this paper provides a systematic approach for extending product concepts to include cognitive functions that would otherwise be implemented by the user. This results in products which implement cognitive functions previously carried out by the user and therefore require less interaction and provide a more enjoyable user experience. The approach was illustrated with reference to a cognitive washing machine concept which was developed and built by a multi-disciplinary team of students. This initial use of the method is promising and suggestive of its potential as an aid in cognitive product development.

Acknowledgments

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