

Interdisciplinary Research and Integration in Social Robotics

Erik Weber

Ghent University, Belgium

Julie Mennes

Ghent University, Belgium

In this paper, we analyse what interdisciplinary integration looks like in a research project aimed at developing Probo, a social robot that can be used as an interface by therapists working with autistic children. With our analysis, we contribute to a piecemeal approach to theorizing about integration, which is sensitive to the diversity of goals of integration. We first perform a case study of the interdisciplinary research underlying the development of Probo. The case study shows how interdisciplinary integration was achieved by means of disciplines interlocking and iterative research steps triggered by feedback. Next, using function concepts from philosophy of technology, we frame the Probo case as a paradigmatic example of a type of interdisciplinary research that is aimed at producing new technical artefacts. We elaborate on the type of interdisciplinarity and show how it points to limitations of established characterizations of interdisciplinarity.

Keywords: interdisciplinary integration, philosophy of interdisciplinarity, social robots, technical artefacts, technical functions.

1. Introduction

This paper is structured in three parts: The first part contextualizes our research and outlines our approach (Sections 2 and 3), the second part contains a case study (Sections 4 and 5), and the third part discusses lessons learned from the case study (Sections 6 and 7). The case study focuses on *Probo*, a social robot with an elephant-like appearance, developed by a team of researchers at the Free University of Brussels (VUB). Probo is a robot that can reason about tasks and their execution by linking perception to action. As a *social* robot, it also has the ability to communicate non-verbally through facial expressions and gestures. Probo's development required collaboration among team members with various disciplinary backgrounds and integration of their contributions.

In Section 2, we provide background from the philosophical literature on interdisciplinary research and explain how our paper relates to it. Section 3 outlines our approach by clarifying how we intend to draw lessons about certain types of interdisciplinary integration from our case study of Probo.

The paper then moves to the case study. In Section 4, we analyse the interdisciplinary research that contributed to Probo's development: We identify the disciplines that were involved and describe their contributions. Section 5 details how these contributions were integrated throughout the development process. More specifically, we describe (i) how research from different disciplines interlocks (i.e. how findings from one discipline are used as input for research in another discipline), and (ii) how this interlocking led to iterations, (e.g., how the results of interlocking research are fed back to the contributing disciplines, leading to new research).

In the final part of the paper, we investigate what general lessons on interdisciplinary integration can be drawn from the case study. In Section 6, we point to some practice-related "typical features" that are present in the case and are also common in other, similar cases of interdisciplinary integration. In Section 7 we reflect on how the case study may contribute to the development of an overall philosophical account of "interdisciplinary integration." Section 8 summarises our results and outlines possible directions for future research.¹

2. Interdisciplinarity and Integration: Knowns and Unknowns

Following Michael O'Rourke and Stephen Crowley (2013, p. 1938) we use the term "cross-disciplinary research" (CDR) as an umbrella term covering all research that crosses the boundaries of scientific disciplines. As is common in the literature (see e.g., Holbrook, 2013; Crowley et al., 2014; Klein, 2014; and Menken & Keestra, 2016) we use the terms "interdisciplinary research" (IDR), "multi-disciplinary research" (MDR), and "transdisciplinary research" (TDR) to refer to specific subtypes of cross-disciplinary research. These subtypes are typically distinguished based on the types of fields of expertise involved and the way in which (elements of) these fields are combined. While IDR and MDR only involve (elements from) academic disciplines, TDR draws both from academic and extra-academic fields; additionally, in IDR and TDR, elements from different fields are integrated, whereas in MDR, disciplines are combined by juxtaposition.

Integration plays a key role in defining IDR and its relation with MDR and TDR, but the concept remains little understood. This is widely acknowledged.

¹ This paper is written from a philosophy of science perspective. As philosophers of science-in-practice we are—in general—interested in philosophical analysis of how scientists proceed. This paper fits into general research interests.

For instance, Uskali Mäki (2016, p. 338) points out that the concept of integration is desperately in need of analysis. According to Allen Repko (2007, p. 7) the lack of conceptual clarity about integration constitutes the “Achilles’ heel of interdisciplinarity.” However, developing a better understanding of integration is challenging because integration can take many different forms (e.g. Klein, 2012; Kestra, 2019). One important factor contributing to this variety are the goals of integration. Building on a Finnish study, Julie Thompson Klein notes that these goals are typically epistemic, consisting in “the development of new and broad knowledge of a particular phenomenon,” but can also consist in “sharing knowledge, skills or resources” as well as “the development of technical equipment or products such as information technology protocols, medicines, and measuring devices” (Klein, 2008, p. S118).

There is no *prima facie* reason to assume that integration will be the same thing in all cases. While there may not be a universal, comprehensive definition of integration, a general definition can be formulated that captures only the essential features, which are present in all cases of integration. Michael O’Rourke and colleagues developed such a general definition on the basis of a review of literature on integration in studies of cross-disciplinarity and philosophy of biology. According to their definition, which is contained in the so-called “Input-Process-Output model” (IPO model), integration is “an input/output process, where a series of changes to the inputs results in a “bringing together” or combination of inputs, producing an output” (O’Rourke et al., 2016, p. 67).

This “bringing together” consists in establishing integrative relations between the inputs. The IPO model is a schematic model, which includes parameters related to the inputs, process and outputs that can be specified when applied to a case. Some of these parameters are qualitative (e.g. concerning the nature of in- and outputs or of integrative relations) or quantitative (e.g. the number of changes made to the inputs, or the number of relations being established). Additional parameters concern the scale of integration, the commensurability of the inputs and the comprehensiveness of the outputs.

A general definition like the one contained in the IPO model provides only high-level insights into integration. More detailed definitions, which are necessarily partial, can be developed through a piecemeal approach. By this, we mean an approach in which examples of different types of integrative CDR are analysed to understand what integration looks like *for each specific type*. In later stages, the findings can be compared to identify recurring elements or family resemblances. This article can be seen as a small but substantial contribution to such a piecemeal strategy.

3. Our Approach

We start this section with more information about Probo (3.1). Next, we explain that our choice for Probo as a case study implies that we focus on a specific type of interdisciplinarity, which Jan Cornelius Schmidt (2022) calls “object-oriented” (3.2). More specifically, it implies a focus on the production of what we call “interdisciplinary technical artefacts” (3.3). These clarifications allow us to explain clearly how we will proceed in the second and third parts of the paper (3.4).

3.1 *Probo*

Probo is a social robot with an elephant-like appearance.² In robotics research, several generations of robots are distinguished. Robots of the 3rd generation and beyond fit the following characterization:

[A robot] operates in the three-dimensional world as a machine endowed with the capacity to interpret and to reason about a task and about its execution by intelligently relating perception to action. (Giralt, 2016, p. xi)

Probo is a robot in this sense.³ What it means for a robot to be “social” is clarified in the following quote:

The overall trend in robotics is that robots will work more frequently with humans. For a good collaboration a good communication between the robot and human is necessary. To communicate in a proper manner the robots can be equipped with some human-like traits, for instance, facial expressions and gestures. . . . Most of our communication goes over non-verbal means, like facial expression and gestures. When a robot has these capabilities as well, one can speak of social robots. (Goris et al., 2011, p. 490)

Probo is able to communicate verbally by means of a touch screen in its abdomen and a voice with a lip-syncing mechanism. It can also communicate non-verbally by producing human facial expressions (see Section 4.1 for details).

As mentioned before, developing Probo required collaboration between team members with different disciplinary backgrounds and the integration of their contributions. The team built the robot to serve as a platform for studying human-robot interaction and to be used in robot-assisted therapy (Goris et al., 2009b). Regarding therapeutic applications, the team saw potential in

² Pictures and videos are available on http://probo.vub.ac.be/Pics_Video/

³ Robots from the 3rd generation onwards have sensors and reprogrammable software. They are also called “intelligent robots.” Robots of the 2nd generation lack the latter property. Robots of the 1st generation (usually called “robot manipulators”) do not have sensors either. Many industrial robots (e.g. many robotics arms) belong to the 1st generation.

using Probo as a companion for hospitalized children, but prioritized its use as an interface for therapists working with autistic children (Goris et al., 2009a; Vanderborght et al., 2012).

3.2 Object-Oriented Interdisciplinary Research

Schmidt (2022) distinguishes four types of interdisciplinarity: object-oriented, theory-oriented, method-oriented and problem-oriented. Object-oriented interdisciplinarity leads to interdisciplinary human-constructed objects. He gives several examples:

New interdisciplinary objects are constructed and created through the massive spread of technologies or are cognitively constructed by the sciences themselves. Examples include the hole in the ozone layer, high-frequency trading on the stock exchange, or virtual objects in computer science. (p. 27)

Furthermore, socio-technical objects, such as the water supply system, the internet, or the hole in the ozone layer, are further examples of interdisciplinary objects that are representative of object-oriented interdisciplinarity. (p. 33)

Probo clearly is an example of an interdisciplinary human-constructed object. Hence, by having Probo as protagonist in our case study we focus on object-oriented interdisciplinary research as conceptualised by Schmidt.

3.3 Interdisciplinary Technical Artefacts

Probo is not only an interdisciplinary human-constructed object but also a “technical artefact” as defined by Yoshinobu Kitamura and Riichiro Mizoguchi:

A technical artifact α is a physical object created by an intentionally performed production process. The process is intentionally performed by one or more agents with the goal of producing the object α which is expected to realize intended behavior in some given generic technical situation, and the object α can realize to some extent that intended behavior and/or has a property which supports that behavior. (Borgo et al. 2014, p. 221)⁴

According to this definition, “technical artefacts” are a subclass of “human-constructed objects”: they are *physical objects* that are deliberately designed and constructed by researchers.

⁴ This definition was originally put forward in a conference paper (Kitamura & Mizoguchi 2010). We cite it from a more recent paper of which Kitamura and Mizoguchi are co-authors. In the 2014 paper, three compatible definitions of “technical artefact” are given, each one emphasizing aspects that are important from a certain perspective. The definition above represents the “engineering design” perspective (the other perspectives in the paper are “applied ontology” and “philosophy of technology”).

We define the class of “interdisciplinary technical artefacts” as the intersection of the class of “technical artefacts” and that of “interdisciplinary human-constructed objects.” Under this definition, Probo clearly qualifies as an example of an interdisciplinary technical artefact. Each type of interdisciplinary technical artefact is characterised by a specific combination of properties they should have. The goal of the developers fits the following generic format:

To create a new technical artefact with properties $X_1, \dots, X_n$.

What makes a technical artefact *interdisciplinary* is that ensuring that it has all the desired properties requires integrated contributions from several scientific disciplines.

3.4 The Way We Proceed

The specifications in 3.1–3.3 allow us to spell out our “methodology” in the rest of this paper. After analysing the development process of Probo, we plan to draw lessons about integration in IDR that aims at the production of *interdisciplinary technical artefacts*. This represents the ambition of this paper (we want to provide insights that go beyond the case study) but also its inherent limitations (the nature of the case study implies that we cannot draw lessons about *other types* of IDR). As mentioned before, Sections 4 and 5 contain our analysis of the development of Probo. In Sections 6 and 7 we draw practical and philosophical lessons from the case.

4. How Probo was Developed

In Section 4.1 we describe the goals of the Probo team in more detail. Next, we explain how the research underlying the development of Probo was grounded in three established academic disciplines: mechanical engineering (Section 4.2), psychology and computer science (Section 4.3). In this way, we clarify how Probo was developed. Later on, in Section 5, we explain how interdisciplinary integration functioned in the case of Probo.

4.1 Probo Development Goals

The central goal of the team behind Probo was to create a new technical artefact, that is, a robot. The team had a clear idea of the properties the artefact should have. In a paper describing the design process the developers write:

The mechanical design process of Probo aimed to develop a *social* robot with a *huggable* and *safe* behavior. (Goris et al., 2011, p. 500; italics added)

What a robot is, and what it means for a robot to be social was already clarified in Section 3.1. The Probo team had specific ideas about *how* their robot had to be social: it had to be able to adopt six *standard facial positions* (defined as a combination of position of head, eyes, ears, mouth and trunk) that can be recognised by children and adults as *expressing the six basic emotions*, namely, joy, sadness, disgust, anger, surprise and fear.

Moreover, they wanted Probo to be huggable. While this target is frequently mentioned in key sections of their papers (such as in titles and keywords), the authors do not clarify what they mean by “huggable.” However, they do provide clues: For instance, they write that they want to create a robot that “looks and feels like a stuffed animal” (Saldien et al. 2010, p. 378). Thus, Probo was to have an animal-like appearance and a “soft touch.” The latter property is explicitly discussed in the publications (Saldien et al., 2010, p. 378; and Goris et al., 2011, pp. 491–492).

Safety was another key objective. In general, the safety of social robots has two aspects: an internal and an external one. To ensure Probo’s internal safety, its internal hardware had to be shielded and protected (Saldien et al., 2010, p. 379; Goris et al., 2011, p. 498). For external safety, Probo’s “behaviour” had to be safe, that is, its interactions had to be safe for the children involved (Saldien et al., 2010, p. 379; Goris et al., 2011, pp. 499–500).

We have discussed the development goals because they guide what the researchers do. In the remainder of this section and in Section 5 we focus on how the researchers proceeded.

4.2 Contributions From Mechanical Engineering

The Probo team summarises the main technical innovations as follows:

To give Probo a huggable and safe behavior a new set of actuators is developed together with a triple layered protection cover which is presented in this paper. (Goris et al., 2011, p. 490)

First, we will discuss the (new) actuators and the associated engineering research, followed by a brief description of the “triple layered protection cover.”

An *actuator* is a machine component that makes certain parts of the machine move (see e.g., Van Ham et al., 2009). It converts pneumatic, hydraulic or electric energy into mechanical motion, and can either be stiff or compliant. *Stiff* actuators maintain a fixed position unless directed to move by the machine’s control system, while compliant actuators allow for deviation from their set position when external force is applied.

Probo contains two types of compliant actuators that were newly developed by the team and are called “CBSDAs” and “NBDs.” The design process, comparative experiments, and the advantages of using the new actuators in

Probo are discussed in detail by Goris et al. (2011). In this paper, the authors argue that stiff actuators decrease the safety of a robot:

The high stiffness can lead to undesirable and possible dangerous situations. For instance, during operation, high contact forces can occur between human and robot, and consequently human can get hurt and/or the robot can break down. During a collision, the complete inertia of the robot is felt. (Goris et al., 2011, p. 491)

While stiff actuators increase the likelihood of robot damage (affecting internal safety) and are less safe for human interaction (affecting external safety), compliant actuators enhance both internal and external safety.

The authors also highlight an additional safety benefit of the CBSDAs they developed. The CBSDAs allow for “remote control” because the actuators that move Probo’s head are located in the belly (p. 492). This means the head can be kept light-weighted, resulting in a safer design for users.

Moreover, compliant actuators enhance Probo’s huggability by creating an “inherent” or “intrinsic” soft touch, as they absorb the impact of collisions (p. 491–492). The accuracy, repeatability and durability of the (novel) mechanical design of Probo is established based on actuator experiments showing that, Probo’s capacity to adopt the six designated facial positions remains stable after repeated use.

Let us now look at the three-layered cover of Probo, which is described as follows:

In order to obtain Probo’s final shape and appearance, the internal robotic hardware is covered. The covering exists of different layers. Hard ABS covers shield and protect Probo’s internal hardware. These covers are fixated to the head- and body-frames at the different points. The covers roughly define the shape of Probo. These are manufactured by use of rapid prototyping techniques, which means that the parts are built layer by layer. These covers are encapsulated in a PUR foam layer, that is covered with a removable fur-jacket. (Goris et al. 2011, p. 498)

This quote describes a number of important features of the triple coverage. First, there is the cover as a whole (i.e. the three layers together), which determines the “final shape” of Probo. It consists of a hard ABS cover, mounted on the aluminium frame of the robot that protects the internal hardware (a.k.a. mechatronics) of Probo; a polyurethane foam layer that covers the hard ABS cover; and the fur-jacket. While the ABS cover increases internal safety, the foam layer and the fur-jacket contribute to external safety by ensuring safe interaction and soft touch.

4.3 Contributions from Psychology and Computer Science

Psychologists played an important role in establishing the social capacities of Probo, specifically in ensuring that its six facial positions would be recognized

as expressing, respectively, joy, sadness, disgust, anger, surprise and fear. To do so, they performed “recognition tests”:

It is important that people who interact with the robot recognize the correct emotion behind these facial expressions. To evaluate this recognition, different tests were taken. (Saldien et al., 2010, p.383)

In total, seven recognition tests (T₁–T₇) were performed, some with children only, some with both children and adults. Early tests (T₁ till T₅) used computer-generated images of Probo’s head. These images were produced based on a virtual model of Probo’s head that was developed before the physical robot was built (see Saldien et al., 2010, p. 387 (Fig. 12)). Here, the role of the third discipline, computer science, becomes evident.

The computer scientists developed two virtual models. The first, which was used in recognitions tests T₁–T₄, did not include a trunk. After poor recognition rates for “disgust” (43%) and “fear” (51%) in T₄, a second model with a trunk was created. The second virtual model was used in T₅, which involved an online multiple-choice questionnaire, taken by 143 children. Each question featured an image of Probo with a specific facial position, and the task to indicate which of the following statements best described the image:

- Probo is happy.
- Probo is sad.
- Probo is disgusted.
- Probo is angry.
- Probo is surprised.
- Probo is scared.

The average recognition rate was 88%.

The final two recognition tests, T₆ and T₇, were live tests with 23 children, also involving multiple-choice questionnaires. In T₆, photographs were used of an uncovered prototype of Probo. Also in T₇, photos were used, but of the final, fur-covered version (p. 387, Fig. 13 and 14). The average recognition rate was 83% for T₆ and 84% for T₇. Full details of the results can be found in the tables in Saldien et al. (2010, pp. 386–387). Table 1 below provides an overview of the results of the three last tests. The numbers in the cells represent recognition rates.

Table 1. Overview of Recognition Rates

Test	Joy	Sadness	Disgust	Anger	Surprise	Fear
T ₅	92	97	81	97	82	82
T ₆	79	96	88	100	69	70
T ₇	100	87	87	96	70	65

5. Integration by Means of Interlocking and Iteration

5.1 *Analysing Integration*

As explained in Section 4, the development of Probo involved three disciplines: mechanical engineering, psychology and computer science. In this section, we analyse how research in these disciplines was integrated, highlighting two key mechanisms:

- *Interlocking* of research, where results from one discipline are used as input for research in another, and
- *Iterative loops*, where the results of interlocked research feed back into the originating discipline, prompting new research.

As part of our analysis of interdisciplinary integration in Probo's development, we distinguish between a virtual and a physical design phase. In the virtual design phase, which took place before the physical robot was built, the Probo team developed virtual models of the robot's head and used them in the first five recognition tests. The physical design phase involved constructing the actual robot. To facilitate our analysis, we refer to these phases using the following labels: VP1 (virtual Probo 1, the first virtual model), VP2 (virtual Probo 2) and Physical Probo (the physical robot).

5.2 *The Virtual Design Phase*

The targets in the virtual design phase can be schematically represented as follows:

Target V.1: VP1 can adopt six designated facial positions.

Target V.2: The designated facial positions of VP1 are recognised by children as expressing the six intended emotions.

Target V.3: VP2 can adopt six designated facial positions (partially different from those in V.1).

Target V.4: The designated facial positions of VP2 are recognised by children as expressing the six intended emotions.

These targets are desired properties of the virtual model. Each one is a success criterion.

Achieving target V.1 required computer science research, while V.2 required psychological research (recognition tests T1 till T4) that interlocks with the results of the research connected to V.1. The interlocking happened by using the computer science results, associated with V.1, as input in the psychological research aimed at reaching V.2. More specifically, the computer science

results became the cause variable in the interdisciplinary causal hypothesis about the relation between facial positions and perception by the onlookers; “recognising as” is the effect variable (with 6 values) in this hypothesis. Despite V.2 not being reached in the first four tests (cf. the unsatisfactory recognition rates), integration occurred through the attempt to establish an “interdisciplinary” causal relation.

Because of the low recognition rates, a trunk was added to the design of Probo, leading to new targets V.3 and V.4. Achieving V.3 again required computer science research to produce images of Probo’s head, and V.4 again required psychological research based on the outputs of V.3. This marks an iterative loop: V.3 and V.4 were formulated in response to the failure with respect to V.2, and the new targets required additional research. In the second iteration, more IDR was performed, and this time, it was successful in achieving the target (V.4).

5.3 *The Physical Design Phase*

The first set of targets in the physical design phase can be schematically represented as follows:

Target P.1: Physical Probo is able to accurately reproduce the designated facial positions of VP2.

Target P.2: Physical Probo is internally safe.

Target P.3: Physical Probo is externally safe.

Let us examine how these targets were achieved and how their fulfilment was argued for. With respect to P.1, extensive research engineering was done (see Section 4.2). For P.2, internal safety is argued for based on general engineering knowledge: The ABS covers are strong enough to protect the internal hardware of the robot against damage from outside. External safety (P.3) is also argued for on the basis of general physical and engineering knowledge, more specifically about the effect of concentrating mass in the main body of the robot and of the energy absorbing effect of compliant actuators, foam layers and fur.

In sum, P.1, P.2 and P.3 were met through original engineering research and background knowledge from engineering science. No cross-disciplinary research (CDR) was performed to meet the first set of targets in the physical design phase. This changes when we consider the next target:

Target P.4: Physical Probo is huggable.

The claim that Probo is huggable—meaning that it has a “soft touch”—is supported by the same general engineering knowledge related to external safety plus some common-sense knowledge, namely, that fur feels soft. Two additional arguments, pertaining to the colour and appearance of Probo, are drawn

from psychology and robotics. Psychological research showed that the colour green evokes positive emotions (Kaya et al., 2004). Hence, Probo's green fur can be considered to increase its huggability. In the field of robotics, the "uncanny valley" phenomenon describes the sense of uneasiness, or even disgust people experience when robots closely, yet imperfectly resemble humans (Mori, 1970). By designing Probo to look like an imaginary, elephant-like creature, the team avoided this issue, avoiding the huggability of the robot to be compromised.

In sum, the claim that Probo is a huggable robot is backed up by findings from different disciplines. While it did involve CDR, the research was not interdisciplinary as the team did not conduct any experiments to establish the huggability in a more integrated way.

Finally, let us look at the last, crucial target:

Target P.5: The designated facial expressions of Physical Probo are recognised by children as expressing the six intended emotions.

In order to establish this, the team conducted psychological research (viz. recognition tests T5 and T6), using the results of the engineering research as input. This demonstrates another instance of interlocking and IDR, similar to what we saw in the design phase (Section 5.2).

Implementing the generic format of Section 3.3, the goal of the developers in this phase is this:

To create a robot that has properties P.1 till P.5.

As we have seen, ensuring that all these properties are realised requires the cooperation of several disciplines.

5.4 Conclusions and Looking Ahead

We have shown that the development of Probo involved the *interlocking* of research, where results from one discipline are used as input for research in another. We have also shown that there were *iterative loops*, where the results of interlocked research are fed back into the originating discipline, prompting new research.

The type of IDR we described here bears some resemblance to Huuttoniemi et al.'s (2010) notion of "methodological interdisciplinarity." The notion stands for IDR that involves the development and combination of methodological approaches from different disciplines into a harmonious whole that suits the interdisciplinary context (p. 84). The type of IDR we described involves such integration of approaches, with the specific goal of evaluating interdisciplinary causal claims related to capacities of a technical object. This fits with a core idea of Laursen and O'Rourke (2019), an article that elaborates the IPO model: The integration process induces dependencies between the inputs. We see this happening throughout the development of Probo: Methodological

approaches from different disciplines are brought into a dependence-relation, for example when the engineers need to rely on psychological tests to evaluate their results.

As mentioned earlier, we think that it is possible to abstract valuable insights about IDR aimed at the development of interdisciplinary technical artefacts (as defined in Section 3) from the Probo case. This will be done in the last part of this paper.

6. Lessons on Interdisciplinary Integration

We begin by introducing the tools we use in the abstraction process (6.1) and then use them to formulate three generic insights about integration in the type of IDR we are studying (6.2). We use Probo to illustrate the insights.

6.1 Behaviour, Effect and Purpose Function

In the abstraction process, we use different function concepts that have been proposed in the philosophical literature on technical artefacts. In previous work, one of the authors argued for the complementarity of three function concepts in engineering science (see van Eck & Weber 2017, p. 55):

Behaviour function: function as the desired behaviour of a technical artefact.

Effect function: function as the desired effect of behaviour of a technical artefact.

Purpose function: function as the purpose for which a technical artefact is designed.

The distinction builds on work by Pieter Vermaas (2009, 2013). In their paper, van Eck and Weber explain the usefulness of the three concepts in several engineering contexts, such as malfunction explanation, innovative design and redesign. In this paper, we use the second and third concept in a new context, that is the analysis of the development process of interdisciplinary technical artefacts.⁵ Before proceeding, the three concepts have to be clarified.

Consider the example of an electric screwdriver. We can say that its (behaviour) function is “to convert electrical current into torque, noise and heat”; that its (effect) function is “to produce torque” and that its (purpose) function is “to drive in/remove screws.” These claims are compatible because they attribute different types of function to the screwdriver. Similarly, we can say that the (behaviour) function of a hairdryer is “to convert electrical current

⁵ We do not use the first function concept explicitly, but it is present in the background. As we can see in the definition in Section 3.3, each artefact has an intended behaviour, which is caught by its behaviour function.

and air into a draft of hot air, noise and thermal radiation”; we can also say that its (effect) function is “to create a draft of hot air” and that its (purpose) function is “to dry hair.”

The difference between behaviour function ascriptions and effect function ascriptions is that the former are complete: They cover input as well as output (they describe how certain output is generated based on certain inputs) and include side-effects. The latter only cover the desired output; there is no reference to input or side-effects.

The difference between effect function ascriptions and purpose function ascriptions is that the latter presuppose a “use plan” that is properly executed. For instance, if I let my electrical screwdriver spin idly in the air, it still fulfils the effect function, but not the purpose function. The latter requires that I use it in a certain way: I have to put it in a designated relative position relative to a screw. Similarly, a hairdryer only dries hair if it is pointed at the head of someone with wet hair.

6.2 Effect Functions and Purpose Functions in Interdisciplinary Technical Artefact Development

Framing the design and development process of Probo in terms of effect function and purpose function helps to understand what integration looks like in IDR that is aimed at the development of technical artefacts. In what follows, we describe three features of integration in this type of IDR using the function concepts. Each feature is first described at type level, and then illustrated—at token-level—by means of Probo.

First, for many technical artefacts (e.g., electrical screwdrivers and hair-dryers) the following principle holds:

If the effect function is realised, then the purpose function is also realised
if the use plan is respected.

In typical cases, establishing the connection between these functions is unproblematic. However, in the development of interdisciplinary technical artefacts, the step from effect function to purpose function constitutes a substantial challenge: The discipline(s) responsible for bringing about the effect function(s) cannot determine whether the purpose function(s) are fulfilled. Therefore, to ensure that the developed artefact is well-functioning, in technical artefact-oriented IDR, integration takes place between the discipline(s) responsible for establishing the effect and the purpose function(s).

In the case of Probo, the effect function is to adopt the six designated facial positions. The purpose function is that these positions are recognised by children as expressing the six basic emotions. The effect function can be present if there is no audience, but the purpose function requires the execution of a use plan involving an audience of children. Establishing that Probo

fulfils its effect function requires one discipline (mechanical engineering), while showing that it fulfils its purpose function requires another discipline (psychology).

Second, in IDR aimed at developing technical artefacts, integration occurs through interlocking. The interlocking arises because first, an artefact is created that fulfils its effect function(s), and then tests are performed to assess whether it also fulfils its purpose function(s). In the second, crucial phase of the research, interdisciplinary causal hypotheses are investigated.

In the case of Probo, the cause variable “facial position” (with six values) is determined by the effect function, while the purpose function determines the relevant effect variable (recognition of emotions, also with six values).

Finally, in technical artefact-oriented IDR, iteration is triggered when the results of interlocking do not meet the standards and the interdisciplinary causal relation between the cause and effect variable cannot be established. In that case, the “effect function,” which is supposed to produce the cause variable, is reconsidered by the discipline(s) responsible for the effect function(s), building on findings of the discipline(s) responsible for establishing the purpose function(s).

In our case study, the effect function involves the parameters of the six designated facial positions. If the results of the second round of recognition tests with Probo had been disappointing, the team could have introduced new parameters (like they did with the trunk), or they could have removed or adjusted existing parameters.

The concepts of effect function and purpose function can shed light on the purpose of integration (first feature) and on the mechanisms behind integration (second and third feature) in the development process of interdisciplinary technical artefacts.

7. Reflections on Existing Characterisations of Interdisciplinary Integration

7.1 Classical Characterisation

Our case study of IDR aimed at the development of a technical artefact points at limitations of existing characterisations of interdisciplinary integration, as we can find them in for instance in Menken and Kestra (2016):

Interdisciplinary integration can be defined as the synthesis of two or more disciplinary insights—drawn from different perspectives into new knowledge. An important step in integration is to identify which disciplines are necessary for a complete understanding of the problem. Then, one has to uncover which assumptions underlie each discipline. More generally, what are the disciplines’ paradigms? Disciplinary academics are largely unaware

of some of their assumptions, and interdisciplinary dialogue helps to reveal those assumptions (p. 42).

We do not think that there is anything fundamentally wrong with this characterisation. It accurately describes many cases of IDR. However, we do claim that it sidelines IDR aimed at the development of interdisciplinary technical artefacts. In what follows, we elaborate our claim in two steps. In Section 7.2, we elaborate the classical characterisation of IDR and illustrate it with two examples. In Section 7.3, we contrast the presuppositions underlying this characterization with the circumstances present in the development of interdisciplinary technical artefacts.

7.2 Two Illustrative Examples

Menken and Kestra (2016) add the following reflection to their characterisation:

Interdisciplinary integration often forms the basis for a new and more comprehensive understanding of the problem being studied. Integration is primarily a cognitive process enabling scientists to combine different (disciplinary) concepts, methodologies, or theories that, at first glance, have no readily apparent connection or commonality. (p. 43)

They use the case of ADHD research to illustrate their characterization (pp. 41–44). We discuss this example and add a second one: Richard Swedberg's (2003) idea of "economic sociology."

In the ADHD example, the starting point is that there is a phenomenon in the world—ADHD—that is studied by different disciplines in different ways:

Scientists from the fields of biology, psychology, and medicine tend to categorize ADHD as a biological disorder that needs biological intervention in the form of medication, although they realize that it cannot be diagnosed by physical tests alone, like other disorders of biological origin. Academics with a background in sociology, social history, or culture studies, in contrast, think the causes of ADHD are social and cultural, and often reject a physiological explanation of ADHD. Scholars from the field of educational science agree with the first group that ADHD is a medical problem, but also converge with the social causes of ADHD, as some hypothesize that parenting behavior is the main cause of the onset of ADHD, rather than biological factors. (Menken & Kestra, 2016, pp. 41–42)

Interdisciplinary-oriented ADHD researchers view these perspectives as partial and think that "comprehensive understanding" requires an integrated explanatory model that incorporates the causes identified by different disciplines. Developing such an integrated model is not easy:

Interdisciplinary integration begins with communication across disciplinary boundaries, revealing differences but also highlighting similarities

between the insights derived from different disciplines. This can be a challenge. (Menken & Keestra, 2016, p. 43)

The idea of aiming at “more comprehensive understanding” by integrating disciplinary insights is also clearly present in our second example. Swedberg’s view is that in order to understand the dynamics of the different types of economic organizations (e.g., firms) and markets, one needs to look at both self-interest (which is traditionally ignored by sociologists) and social relations (which are traditionally ignored by economists). He writes:

The main theoretical point . . . is that we cannot fully understand the dynamic of the different types of economic organization without realizing that their structures are determined by a combination of *interests* and *social relations* [emphasis added]. (Swedberg, 2003, p. xiii)

In the case of firms (the most important type of economic organisation in contemporary capitalist societies), self-interest translates into the goal of profit-making:

The firm in a capitalist society is oriented toward profit-making. . . . The modern rational firm makes use of capital accounting, which represents a way of establishing exactly how much profit has been made during a specific time period (Swedberg, 2003, p. 90).

Relevant categories of social relations that are traditionally ignored by economists include “competition,” “subordination” and “trust.” Traditional economics relies on the idea of the homo economicus, the isolated all-knowing, and maximising economic agent (2003, p. 3). While another interdisciplinary trend in the social science (behavioural economics) challenges the “all-knowing,” economic sociology challenges the “isolated” by positing that our decisions depend on our relations with other economic agents.

7.3 Contrasting the Examples With IDR in the Development of Probo

When we compare the IDR in the development of Probo with IDR on ADHD, we see two important differences. First, unlike in ADHD research, there is no pre-existing “phenomenon in the world” the researchers of the Probo team try to understand.⁶ Second, while IDR on ADHD involves integrating insights from disciplines such as biology, sociology and psychology, in the case of Probo, there are no clearly distinguished pre-existing “disciplinary insights” that are being combined. Instead, IDR is more accurately described as a joint task, which is defined as the construction of a technical artefacts with properties $X_1, \dots, X_n$, where establishing these properties requires

⁶ Of course, *after* Probo has been created, researchers may try to understand certain aspects of its functioning and study its impact.

collaboration between different scientific disciplines. From the onset, there is a relatively clear division of labour and ordering in which the disciplines become prominent. Moreover, there are clear ideas of how the results of the different disciplines will interlock.

Comparing IDR in Probo with Swedberg's analysis of IDR in economic sociology yields further insights. Swedberg argues that one important obstacle for developing a comprehensive understanding of the dynamics of economic organizations consists in disciplines claiming to be able to provide sufficient knowledge. A comprehensive, interdisciplinary approach to this phenomenon only becomes possible if groups of scientists admits that their disciplinary insight may not be sufficient for complete understanding of the phenomenon. They then may start the interdisciplinary dialogue Menken and Kestra refer to (cf. the quote in Section 7.1) in order to reveal the assumptions underlying each discipline.

However, in the case of Probo, there is no reason to assume that any of the disciplines at some point claimed "sufficiency." The mechanical engineers knew (and admitted) in advance that recognition tests were required. And of course, the psychologists did not think that they were able to build a well-functioning (in the sense of the effect function) robot.

In sum, IDR aimed at the development of interdisciplinary technical artefacts does not display two features that are considered typical of IDR: It is not aimed at understanding and does not necessarily involve the integration of pre-existing insights from different disciplines. Furthermore, the typical obstacle that Swedberg points to is absent.⁷

8. Summary and Future Research

In this paper, we highlighted a type of interdisciplinary research that has not received much attention in the literature—object-oriented IDR. We characterized the type, which is aimed at the development of interdisciplinary technical artefacts, based on case study of the development of social robot Probo using concepts from the philosophy of engineering.

More specifically, we distinguished between two types of technical functions an artefact can fulfil: effect functions and purpose functions. The first type of function relates to what the artefact should do if it is used according to its use plan when there are no technical defects, the second function relates to the reason why the artefact was designed. Using the case of Probo, we explained that, in IDR aimed at development of interdisciplinary technical

⁷ Of course, there can be other obstacles Challenges for IDR bridging robotics and clinical studies are well-known (e.g., Kim et al., 2012). There are also linguistic barriers to the development of interdisciplinary technical artefacts (e.g. Buckland & Miller, 2017; Cummins et al., 2018).

artefacts, research in different disciplines interlocks and iterations take place. The interlocking is necessary to show that a causal variable, produced when the effect function is fulfilled (e.g., the six facial positions of Probo), causes the states contained in the purpose function (e.g., recognizing the six basic emotions). Iterations take place when the intended causal relation does not obtain.

We also pointed to important differences and similarities between IDR aimed at the development of interdisciplinary technical artefacts and IDR as it is commonly understood. With this article, we aim to contribute to a piecemeal understanding of interdisciplinary integration that is sensitive to the diversity of goals of IDR.

We have focused on IDR aimed at one specific type of goal. The obvious next step would be to look at other types of IDR whose goals are not completely different. The gap between what we have studied and IDR aimed at “better explanation” and/or “better prediction” seems quite large. In order to expand our analysis of interdisciplinary integration, we probably should start with largely *immaterial* tools such as software packages (which have “technical” aspects, but also issues related to user-friendliness), guidelines (e.g. ethical decision procedures, which may incorporate knowledge from philosophy, psychology and other behavioural sciences) and support tools (e.g. the “patient decision aids” that are the crucial tool of patient-centred medicine). Despite the tools being immaterial there is also a significant similarity with object-oriented IDR: Because we are dealing with tools, the vocabulary of (effect and purpose) function makes sense. For this reason, immaterial tools probably are the best next step in developing a bottom-up account of interdisciplinary integration.

The case of object-oriented IDR analysed in this paper closely resembles a type of multidisciplinary research (MDR), previously described by Mennes (2020). In her article, Mennes defends a broad definition of MDR that also includes the option of disciplines working in sequence, where the results of one discipline serve as input for another. The key difference between sequential MDR and object-oriented IDR seems to be that the latter includes feedback loops where the results of one discipline can trigger revisions in another. A more detailed comparison would be useful.

Acknowledgements

We thank the audience at SPSP 2024 (Columbia, South Carolina), the two reviewers and the editors of the special issue for their helpful suggestions. We thank Qianru Wang for checking the final manuscript before submission.

Biographical Notes

Erik Weber, PhD, is senior full professor in philosophy of science and director of the Centre for Logic and Philosophy of Science at Ghent University (Belgium). He is member of the steering committee of the Society for Philosophy of Science in Practice since 2018. Most of his research relates to general theories of causation and scientific explanation or to problems relating to causation and explanation in specific scientific disciplines. Other research interests include cross-disciplinary scientific research, evidence in science and scientific laws. He can be reached at erik.weber@ugent.be.

Julie Mennes, PhD, is a senior postdoctoral researcher at the Centre for Logic and Philosophy of Science at Ghent University (Belgium), supported by funded from the Research Foundation Flanders. She is also a visiting researcher at the Flanders Research Institute for Agriculture, Fisheries, and Food and an active member of the Toolbox Dialogue Initiative Community. Her research focuses on cross-disciplinarity and the relations between science and society. While her work is primarily situated in the philosophy of science, science and technology studies, and epistemology, she frequently collaborates with researchers and practitioners from diverse fields, including computational linguistics, architecture and urban planning, and bioengineering. Julie can be reached at julie.mennes@ugent.be.

References

- Borgo, S., Franssen, M., Garbacz, P., Kitamura, Y., Mizoguchi, R., & Vermaas, P. (2014). Technical artifacts: An integrated perspective, *Applied Ontology*, 9, 217–235.
- Buckland, D., & Miller, S. (2017). Differences in physician, engineer and life scientist training, practice, problem solving and approach to failure. In R. S. Williams, C. R. Doarn, & M. A. Shepanek, (Eds.), *Engineering, life sciences, and health/medicine synergy in aerospace human systems integration: The Rosetta Stone Project* (NASA-SP-2017-633). Washington, DC: NASA.
- Crowley, S., Eigenbrode, S., O'Rourke, M., & Wulfhorst, J.D. (2014). Introduction. In M. O'Rourke, S. Crowley, S. D. Eigenbrode, & J. D. Wulfhorst (Eds.), *Enhancing communication and collaboration in interdisciplinary research* (pp. 1–10). Sage.
- Cummins, G., Cox, B. F., Walker, J. D., Cochran, S., & Desmulliez, M.P. (2018). Challenges in developing collaborative interdisciplinary research between gastroenterologists and engineers. *Journal of Medical Engineering & Technology*, 42(6), 435–442.

- Giralt, G. (2016). Foreword. In B. Siciliano, & O. Khatib, (Eds.), *Springer handbook of robotics* (2nd ed., pp. xi-xi). Springer Verlag.
- Goris, K., Saldien, J., & Lefeber, D. (2009a). Probo, a testbed for human robot interaction. *Proceedings of the 4th ACM/IEEE International Conference on Human-Robot Interaction, HRI '09* (pp. 253–254). Association for Computing Machinery.
- Goris, K., Saldien, J., Vanderniepen, I., & Lefeber, D. (2009b). The huggable robot Probo, a multi-disciplinary research platform. In A. Gottscheber, S. Enderle, & D. Obdrzalek, (Eds.), *Research and Education in Robotics—EUROBOT 2008* (pp. 29–41). Springer.
- Goris, K., Saldien, J., Vanderborght, B., & Lefeber, D. (2011). How to achieve the huggable behavior of the social robot Probo? A reflection on the actuators, *Mechatronics*, 21, 490–500.
- Holbrook, J. B. (2013). What is interdisciplinary communication? Reflections on the very idea of disciplinary integration, *Synthese*, 190, 1865–1879.
- Huutoniemi, K., Klein, J. T., Bruun, H., & Hukkinen, J. (2010). Analyzing inter-disciplinarity: Typology and indicators. *Research Policy*, 39(1), 79–88.
- Kaya, N., & Epps, H. (2004). Relationship between color and emotion: A study of college students. *College Student Journal*, 38(3), 396–406.
- Keestra, M. (2019). Imagination and actionability: Reflections on the future of interdisciplinarity, inspired by Julie Thompson Klein. *Issues in Interdisciplinary Studies*, 37(2), 110–129.
- Kim, E., Paul, R., Shic, F., & Scassellati, B. (2012). Bridging the research gap: Making HRI useful to individuals with autism. *Journal of Human-Robot Interaction*, 1(1), 26–54.
- Kitamura, Y., & Mizoguchi, R. (2010). Characterizing functions based on ontological models from an engineering point of view. In A. Galton, & R. Mizoguchi (Eds.), *Formal ontology in information systems* (pp. 301–314). IOS Press.
- Klein, J. T. (2008). Evaluation of interdisciplinary and transdisciplinary research. A literature review. *American Journal of Preventive Medicine*, 35, S116–S123.
- Klein, J. T. (2012). Research integration: A comparative knowledge base. In A. F. Repko, W.H. Newell, & R. Szostak (Eds.), *Case studies in interdisciplinary research* (pp. 283–298). Sage.
- Klein, J. T. (2014). Communication and collaboration in interdisciplinary research. In M. O'Rourke, S. Crowley, S. D. Eigenbrode, & J. D. Wulfhorst (Eds.), *Enhancing communication and collaboration in interdisciplinary research* (pp. 11–30). Sage.
- Laursen, B., & O'Rourke, M. (2019). Thinking with Klein about integration. *Issues in Interdisciplinary Studies*, 37(2), 33–61.
- Mäki, U. (2016). Philosophy of interdisciplinarity. What? Why? How? *European Journal for Philosophy of Science*, 6, 327–342.

- Mennes, J. (2020). Putting multidisciplinary (back) on the map. *European Journal for Philosophy of Science*, 10(2), 18.
- Menken, S., & Keestra, M. (2016). *An introduction to interdisciplinary research: Theory and practice*. Amsterdam University Press.
- Mori, M. (1970). The uncanny valley. *Energy*, 7(4), 33–35.
- O'Rourke, M., & Crowley, S. (2013). Philosophical intervention and cross-disciplinary science: The story of the toolbox project. *Synthese*, 190, 1937–1954.
- O'Rourke, M., Crowley, S., & Gonnerman, C. (2016). On the nature of cross-disciplinary integration: A philosophical framework. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences*, 56, 62–70.
- Repko, A. F. (2007). Integrating Interdisciplinarity: How the theories of common ground and cognitive interdisciplinarity are informing the debate on interdisciplinary integration. *Issues in Integrative Studies*, 25, 1–31.
- Saldien, J., Goris, K., Vanderborght, B., Vanderfaeillie, J. & Lefeber, D. (2010). Expressing emotions with the social robot Probo. *International Journal of Social Robotics*, 2, 377–389.
- Schmidt, J. C. (2022). *Philosophy of interdisciplinarity*. Routledge.
- Swedberg, R. (2003). *Principles of economic sociology*. Princeton University Press.
- Vanderborght, B., Simut, R., Saldien, J., Pop, C., Rusu, A., Pineta, S., Lefeber, D., & David, D. (2012). Using the social robot Probo as a social story telling agent for children with ASD. *Interaction Studies*, 13, 348–372.
- Van Eck, D., & Weber, E. (2017). In defense of co-existing engineering meanings of function. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 31, 55–68.
- Van Ham, R., Sugar, T., Vanderborght, B., Hollander, K., & Lefeber, D. (2009). Compliant actuator designs. *IEEE Robotics & Automation Magazine*, 3(16), 81–94.
- Vermaas, P. (2009). The flexible meaning of function in engineering. *Proceedings of ICED 09, the 17th International Conference on Engineering Design* (vol. 2, pp. 113–124). Design Society.
- Vermaas, P. (2013). The coexistence of engineering meanings of function: Four responses and their methodological implications. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 27, 191–202.