

Unpacking Measurement Devices: Transduction And Multimodality For Blending Mathematics And Physics In Teacher Education

Giancarlo Artiano

University of Naples Federico II, Italy

This exploratory study investigates how the analysis of measurement processes and transduction mechanisms can support the integration of mathematics and physics in teacher education. Framed within a socio-semiotic perspective on multimodality, we conceptualise teaching and learning as the result of cognitively and affectively motivated choices among available meaning-making resources. Building on work by Duval, Bezemer and Kress, Airey and colleagues, and others, we distinguish between semiotic and non-semiotic representations and between intra-modal transformations (treatments) and inter-modal transformations (transductions). We then use these constructs to examine how mathematical and physical reasoning can be blended rather than separated. The empirical context is a teacher training course (February–June 2023) within the Multidisciplinary Laboratory Teaching project at INDIRE, involving a working group of researchers and eight secondary school mathematics and physics teachers. The group collaboratively designed and analysed experimental activities centred on motion and measurement, with particular attention to the functioning of motion detectors as paradigmatic “black-box” instruments. By progressively unpacking the internal mechanisms of such devices—analogue and digital, continuous and discrete—the teachers explored transductive chains linking bodily action, sensor signals, graphs, and formal mathematical expressions. Video-recorded and transcribed meetings were cross-analysed to identify key epistemological and didactical themes. Two transversal foci emerged: (1) the role of transduction and measurement in mediating between continuous physical magnitudes and discrete numerical structures; and (2) the interplay between analogue and digital representations in contemporary measuring instruments. The findings suggest that treating transduction and measurement as central scientific practices offers a promising educational alliance for overcoming the perceived gap between formal mathematical entities and the modelling of physical phenomena, while also fostering teachers’ critical engagement with technology and multimodal classroom design.

Keywords: Transduction and transformations, measurement, physics, mathematics, socio-semiotic, treatment and conversion

Theoretical Background

Teaching mathematics and physics presents challenges due to the perceived disconnect between the two disciplines (Osborne, 2023). Blending these two disciplines involves more than merely introducing mathematical concepts through physical examples. Instead, the focus should be on recognising the unity of cognitive processes that underpin the understanding of interconnected concepts and structures in both disciplines. In recent studies, Kapodistrias and Airey (2024, 2025) examine mathematical functions in physics and how they, in turn, shape physics education. It begins by emphasising that mathematics has historically been regarded as central to physics, with influential figures such as Feynman, Einstein, and Hertz arguing that meaningful physical laws and even nature itself are deeply mathematical. Mathematics is thus often described as the language of physics. This central role of mathematics has important consequences for education. A recurring issue in the literature is the tension between mathematics as a technical, computational tool and mathematics as a means for conceptual, physical reasoning. Many studies show that students can successfully perform calculations, such as solving quantum mechanics

problems or computing the curl of an electric field, without truly understanding the underlying physical concepts (Johansson et al., 2018; Airey & Linder, 2017). Educators, in turn, often struggle to design problems that promote conceptual meaning-making instead of pure computation. These difficulties motivated the development of Conceptual Physics (Hewitt & Baird, 2014), an instructional approach that treats mathematics as a potential barrier to understanding. In this view, instruction should begin with building a strong conceptual model of the physical situation, and only once this understanding is established should mathematical formalism be introduced. However, other researchers argue that sharply separating conceptual understanding from mathematics is not always appropriate (Uhden et al., 2012; Redish & Kuo, 2015). Rather than treating mathematics and conceptual reasoning as distinct phases, they investigate how mathematics itself can serve as a vehicle for conceptual thinking. Some of this work describes students' mathematical problem solving in terms of scientific thinking strategies, or epistemic games, that they engage with when using mathematics in physics. Others focus on what students mean when they say they "understand" a physics equation, examining this from an epistemological standpoint. Building on these ideas, several models have been proposed that integrate mathematical and physical reasoning instead of keeping them apart. Uhden and colleagues (2011) claim that physical (conceptual) and mathematical (quantitative) models should not be separated in physics education and instead propose a model in which the two co-exist as part of a unified physical-mathematical reasoning process. Redish (2006) offers a related framework in which using mathematics in science involves mapping physical quantities to mathematical expressions, processing those expressions, interpreting the mathematical results back into the physical world, and finally evaluating whether the results are adequate.

The present work constitutes an introductory, exploratory study within a broader research project. The goal is to study the impact of unpacking and repacking a measurement mechanism (i.e. a motion detector) to foster its pedagogical and disciplinary affordances (Kapodistrias & Airey, 2025) in a teacher-training context. The study is framed within socio-semiotic theory (Bezemer & Kress, 2008) and the multimodal activities that arise from transduction and transformation (or conversion and treatment) in mathematics and physics classrooms. Key concepts such as socio-semiotic theory, multimodality, transduction and affordance will be briefly outlined.

Socio-Semiotic In Math And Science Education

Following Copley (2001), semiotics can be understood as follows: "In a general sense, a culture can be seen as a typical configuration of choices derived from various semiotic resources. Semiotics itself is the study of semiosis, which is the process of producing signs". In other words, it is possible to study a specific community—such as science classrooms—through the meanings of the signs it produces. Michael Halliday, through his theory of Systemic Functional Linguistics, was the first to introduce a distinctly social orientation into semiotic theory. Halliday (1978) argues that the meanings of signs, or semiotic choices, are shaped by social context and negotiated within social and cultural environments (Halliday, 1978). Since the 1990s, scholars have further extended socio-semiotic studies to a variety of subfields, including popular culture, multimedia, and disciplinary domains such as science and mathematics. In this perspective, the volume *Multimodal Teaching and Learning: The Rhetorics of Science Classrooms* (Ogborn et al., 2001) has made a substantial contribution to science education. The authors conceptualize multimodality in teaching and learning science as the coordinated use of multiple semiotic modes—language, gesture, visual representations, and bodily movement—through which scientific activity in the classroom is conducted and can be observed. Social-semiotic theory has significantly reshaped how learning and teaching processes in science and mathematics education are conceptualised. In line with Kress et al. (2001), we adopt the following view: teaching and

learning in the mathematics and science classroom are the “evidence” of the cognitively and affectively motivated choices of teachers and students from among the meaning-making resources available in a particular situation (the classroom) at a given moment. In mathematics education, Luis Radford has devoted numerous studies to the meanings of signs in mathematical activity (see Radford, 2002; Radford et al., 2003). In (Radford, 2002), he introduces the notion of the semiotic node to describe the coordination of different semiotic modes (e.g., action, gesture, word, drawing) in students’ activity. To identify these nodes empirically, Radford and his colleagues (2003) designed an experimental study in which students represented the spatiotemporal graph of a body’s motion. Their data showed that this context was particularly suitable for observing the emergence of semiotic nodes (Radford, 2002).

Transduction And Conversion

Semiotically, two types of change have been noted: transformation and transduction (Bezemer and Kress, 2008). Transformation involves changes to the object of learning within the same semiotic system (mode), and transduction involves moving semiotic material from one mode (or semiotic system) to another. This transfer can significantly alter the potential meaning of the material (Volkwyn et al., 2019).

In physics education, Airey and colleagues discussed transduction in physics education extensively while Tuminaro and Redish (2007), for example, describe how students often resort to “plug and chug” strategies, where “plug” denotes substituting numerical values into equations and “chug” denotes carrying out algorithmic transformations to obtain a result. Instead, Arcà and Guidoni (1987) define it differently: transduction is the conversion of an input signal into another type of signal via a specific interface. In this context, transduction reveals the functional relationship between two interacting variables and thus represents a specific instance of the broader socio-semiotic framework.

In mathematics education research, Duval (2006) identified the same definitions under different names, distinguishing two aspects of mathematical activity: conversion and treatment. Conversions are transformations of representation that consist of changing a register without changing the objects being denoted. Treatments, by contrast, are transformations of representations that happen within the same register: Duval (2006) argues that “passing from one register to another [makes] explicit other properties or aspects of the same mathematical object.” When the object of learning is moved across different representational modes—word problems, graphs, equations, and so on—different facets of mathematical knowledge are made explicit; in meaning-making terms, different meaning potentials are unlocked (Airey & Linder, 2017).

Moreover, Duval distinguishes representations between:

1. Semiotic representations: produced through systems of signs (natural language, mathematical symbols, codified diagrams, graphs with conventions, etc.). Here the relation between object and representation is conventional and governed by the rules of a system of representation.
2. Non-semiotic representations: produced by physical devices (mirror, camera, microscope...) or by sensory and brain organizations. Here the relation between object and representation resembles a causal relation: the object (or phenomenon) produces, so to speak, an “effect” on the device or on the senses. In other words, on-semiotic representations produced by physical devices may be regarded as a particular mode of access to the object, in which the “sense” is strongly constrained by physical causality (for example, an image in a mirror, a trace on a screen, a photograph of the phenomenon, an instrumental measurement, etc.).

This work discusses how the same phenomenon, such as motion, can be represented through various senses: some are semiotic, like equations, graphs, natural language, and diagrams, while

others are non-semiotic in Duval's sense, such as experimental traces, instrumental measurement, and sensor readings, which are linked to the object through causal relations. Blending mathematics and physics involves connecting these two types of representations within a multimodal teaching and learning environment. In this sense, the connection between mathematics and physics is evident in the transduction processes.

Therefore, analysing the internal workings of physical mechanisms is an excellent opportunity to clarify the relationship between theoretical entities and measurement processes. Depending on the nature of the transducers (e.g., analogue, digital, mechanical, electrical), learners may observe straightforward correlation patterns or discern a more pronounced cause-and-effect relationship that informs their understanding of the phenomenon's operating principles. Measurement intrinsically implies the concepts of numbers and countability, which emphasise the psychological underpinnings of mathematical concepts. This link suggests a profound connection between understanding and perceiving mathematical abstractions and the ability to measure and quantify physical properties.

Furthermore, the examination of transduction highlights the crucial role of technology from an engineering viewpoint. The accuracy of the conversion between magnitudes (e.g., linear, quadratic, cubic) is closely linked to geometric constraints. Understanding the apparatus's geometry allows one to grasp the benefits and key steps of a particular conversion process. In physics, exploring the internal mechanisms of machines and measurement devices provides a significant opportunity to clarify the relationship between theoretical concepts and measurement practices. During the modelling process, familiarity with both historical and modern machines, as well as transducers, is of considerable cognitive value. The mechanical metaphor is foundational for all cause-and-effect reasoning and is essential in physics. In mathematics, mechanical drawing machines serve as valuable tools for dynamically studying notable curves. Analysing geometric and motion transformations (e.g., linear versus circular) alongside transduction processes enables students to understand fundamental concepts in mathematics and physics while developing advanced technological skills.

Materials And Methods

This contribution outlines the activities and outcomes of a teacher training course that utilised experimentation to explore the limitations and potential of introducing the analysis of measurement instruments and their functioning mechanisms in educational practice.

The course, held between February and June 2023, is part of the Multidisciplinary Laboratory Teaching project at the National Institute for Documentation, Innovation, and Educational Research (INDIRE). The Working Group (WG) comprised two researchers in math and physics education and one researcher from INDIRE, and eight secondary school mathematics and physics teachers. The group met monthly for 2-hour session meetings over 4 months.

Regarding teacher education, research increasingly underscores that teachers' attitudes and beliefs influence how science subjects are taught. Numerous studies have demonstrated a strong correlation between teachers' attitudes and beliefs regarding teaching methods and subject content and their success or failure in teaching practices (Jones & Carter, 2006; Bryan, 2012; Jones & Legon, 2014; Wallace, 2014). In this area, the proposed training model (Amabile et al., 2022) connects teaching practice with scientific research. This approach enables the transformation of field-based experimental results into valuable suggestions for teacher training and the reassessment of teaching practices. Such an approach can lead to didactic proposals that resonate with classroom practice, promoting a bottom-up rather than a top-down approach.

The proposal seeks to incorporate a carefully crafted analysis, along with a series of practical

field experiments conducted over the years, which are well documented on the research group's website (www.les.unina.it). The aim is to examine the processes of transduction and measurement as exemplary educational practices and transversal cognitive frameworks within both disciplines, and to assess their effectiveness in bridging the apparent gap between the teaching and learning of mathematics and physics.

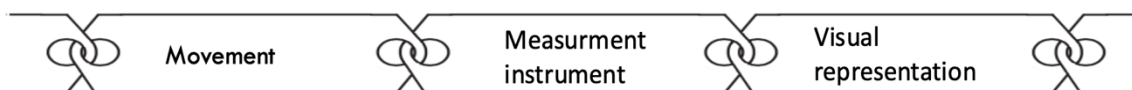
A valuable theoretical tool for designing educational activities that integrate mathematics and physics is the transductive link (Svensson & Eriksson, 2020). This link is any semiotic system that facilitates the transduction process between two different semiotic systems. It can be a single link or part of a short chain, or it can comprise multiple links forming a longer chain. For example, a lengthy transductive chain might be a physics project in class, where the properties of the chain depend on its context and purpose. According to Svensson and Eriksson, this concept can be a useful design and evaluation tool, helping to focus on the consistency of semiotic material flow between different modes.

Experimental Activities

As first activity, a video is presented in which a group of children moves their bodies back and forth, in a wave-like motion. To support temporal coordination, the children are instructed to clap when their bodies reach the forward position. Simultaneously, a motion detector records only the first child's movement, positioned at the head of the row, and displays it on a screen. While observing the screen, the children continue their movements.

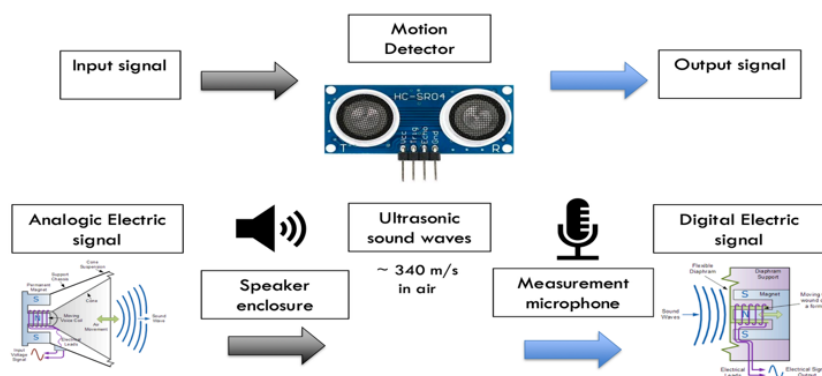
The video illustrates a multimodal activity that represents a specific motion in a collective and real-time manner. The measurement process plays a fundamental role, as it relies on a motion detector that, at present, functions as a black box. It is hypothesised that this activity could be repeated multiple times to support children who experience difficulties coordinating their bodily movements, especially in relation to others' movements. The transductive chain of the activity is showed in figure 1.

Figure 1. Transduction chain associated with the activity shown in the video.



Successively, it appears essential, on the one hand, that teachers acquire the ability to design experimental activities that exploit the potential of technology to activate multiple learning modalities, and, on the other hand, that they become aware of the implications of using black-box instruments, which can empower them and foster critical thinking. One possible approach is to develop an unpacked model of such black-box instruments.

Figure 2. Transduction processes and unpacked motion detector scheme.



Several experiments were designed to measure the velocity of ultrasound waves during an object test. The functional mechanism was discussed, and a representative diagram highlighting the differences between analogue and digital equipment was created as shown in Figure 2. The operation of the motion detector sensor is then examined, focusing on the transduction processes involved. Thanks to advances in microelectronics and programmable sensors, it is now possible to explore the sensor's internal structure, effectively unpacking the black box and revealing its internal mechanisms (see Artiano et al., 2025). This understanding helps teachers familiarize themselves with the technology and recognize its pedagogical and disciplinary affordances in educational settings.

Results

During the meetings, the WG highlighted several key concepts that were both broad and transversal. The topics addressed by the study group included investigating the phenomenological aspects of motion through two main subthemes:

1. The transduction and measurement process between continuous and discrete;
2. The transduction and measurement process between analogue and digital.

The meetings were recorded on video and transcribed. The resulting content was then cross-analysed. The analysis's findings are presented below as a report on the activities undertaken.

Discussing Continuous And Discrete

The WG discussed the continuous nature of physical quantities relevant to describing phenomena, whether extensive or intensive. However, it has become evident that a measurement criterion must be established to measure a continuous structure by prescribing *discretisation operations* that impose on the acknowledged continuous variable a structure isomorphic to that of the integers. In experimental practice, this is equivalent to the apparent fact that any measurement process will assign the same number to values of the variable that, through more refined comparisons, can be recognised as distinct from one another. In any case, the specification of an *extensive variable* in a system can always be approximated as closely as desired with an integer number. On the contrary, an *intensive variable* cannot be measured by comparing it with an integer number of repeatedly taken unit systems. To assign numbers (integer or rational) even to *intensive variables*, it is necessary to resort to transduction processes by which changes in an intensive variable (for example, the temperature of a system) systematically correspond to changes in a particular extensive variable (for example, the volume of liquid enclosed in a thermometer at thermal equilibrium with the system under investigation). From the discussion and manipulation of measuring instruments present during the meetings, it emerged that measurements of *intensive variables* by transduction systems are omnipresent in our daily technology.

Discussing Analogue And Digital

Transduction and measurement also prompted the WG to discuss the relationship between *analogue* and *digital* signals in measuring instruments. Within the study of technological devices, the term 'analogue' refers to a device that operates on physical quantities—whether electrical, mechanical, or of another nature—that, by *analogy*, represent the characteristic quantities of the system under examination. This implies a connection between two physical phenomena of differing natures, allowing identical equations to link the quantities relevant to each; thus, complex phenomena can be studied using models built from simpler phenomena. The key aspect of analogue devices was explored, which analyse the input signal in its original form by

leveraging phenomena and mechanisms within the instrument that correspond to the signal's nature. In other words, an analogue instrument distinguishes itself from a digital instrument by the absence of an additional processing phase of the input signal, known as the digitalisation phase. Once this framework has been clarified and agreed upon, a beneficial exercise is to apply it to the measurement process of a specific machine.

Discussion

Adopting a transduction perspective in physics and mathematics education necessitates rethinking physics's fundamental and epistemological elements to generate new insights for teaching and learning physics and mathematics, as illustrated by two cross-disciplinary discussions on the relationships between analogue-digital and discrete-continuous. Furthermore, the training model implemented appears convincing based on teachers' responses. Specifically, it was observed that teachers who participated in the training tended to question their own teaching models, enhancing them through theoretical reflections and the teaching materials they produced. The report presents the testimony of a teacher who argues for structural interventions to promote synergy among the disciplines.

[...] it seems clear to us that any didactic revolution, in this case of Physics and Mathematics, cannot occur solely within the action of the individual teacher but must necessarily be supported and supported over time by the school institution. This should be translated into a systematic dialogue between the disciplines that contribute to achieving the objective.

The hypothesis is that these two scientific practices, transduction and measurement, form an ideal educational alliance for overcoming the difficulties of separation associated with the formalism of mathematical entities and the modelling of physical phenomena. It was shown that adopting a transduction perspective on phenomena requires rethinking the fundamental and epistemological elements of physics and mathematics. Incorporating daily physical experiences in concept construction is also crucial (Artiano & Balzano, 2024), and using specific measuring instruments for physical quantities, both analogue and digital, as cultural artefacts (Bussi & Mariotti, 2008) can significantly facilitate the meaning-making process, promoting multimodal reasoning and problem-solving activities (Guidoni et al., 2005b; Yeo & Nielsen, 2020).

Acknowledgement

I would like to thank Prof. Balzano, Dr. Minichini, and Dr. Amabile for fostering interest in the content of this article. I also thank all the teachers who participated in the experiment.

References

- Airey, J., & Linder, C. (2017). Social semiotics in university physics education. In *Multiple representations in physics education* (pp. 95-122). Springer International Publishing.
- Amabile, A., Annunziata, A., Artiano, G., & Balzano, E. (2022). Experimentation and research in the physics course for the preparation of primary school teachers in Naples. *Education Sciences*, 12(4), 241 DOI:10.1393/gdf/i2022-10472-6
- Arcà, M., & Guidoni, P. (1987). Guardare per sistemi, guardare per variabili. AIF Editore.
- Artiano, G. & Balzano, E. (2024). Macchine e meccanismi in fisica e in matematica. *Atti del XLIII Convegno annuale SISFA*, 435.
- Artiano, G., Balzano, E., Guida, F. (2025). Studying Thermodynamic Processes with Open-Source Hardware and Software Systems. In: Testa, I., Michelini, M., Esposito, S. (eds) *Connecting Physics Education Research and Practice. Challenges in Physics Education*. Springer, Cham. https://doi.org/10.1007/978-3-031-86609-8_9
- Bezemer, J., & Kress, G. (2008). Writing in multimodal texts: A social semiotic account of designs for learning. *Written Communication*, 25(2), 166–195. DOI: <https://doi.org/10.1177/0741088307313177>

- Bryan, L. A. (2012). Research on science teacher beliefs. In B. A. Frasier, K. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 477–495). Springer.
- Bussi, M. B., & Mariotti, M. A. (2008). Semiotic mediation in the mathematics classroom: Artifacts and signs after a Vygotskian perspective. *Handbook of international research in mathematics education*, 746.
- Duval, R. (2006). A cognitive analysis of problems of comprehension in a learning of mathematics. *Educational studies in mathematics*, 61(1), 103-131.
- Guidoni, P., Iannece, D., Tortora, R., et al. (2005b). Multimodal language strategies activated by students in understanding and communicating mathematics. *Proceedings of the Fourth Congress of the European Society for Research in Mathematics Education*, Sant Feliu de Guíxols, 841–851.
- Halliday, M. A. (1978). *Language as social semiotic*. Arnold: London.
- Hewitt, P. G., & Baird, D. (2014). *Conceptual physics*. Hoboken, NJ: Pearson.
- Johansson, A., Andersson, S., Salminen-Karlsson, M., & Elmgren, M. (2018). “Shut up and calculate”: The available discursive positions in quantum physics courses. *Cultural Studies of Science Education*, 13(1), 205-226.
- Jones, M. G., & Carter, G. (2006). Science teacher attitudes and beliefs. In S. Abel & N. Lederman (Eds.), *Handbook of research on science teaching*. Lawrence Erlbaum Associates, Publishers.
- Jones, M. G., & Legon, M. (2014). Teacher attitudes and beliefs: Reforming practice. In N. Lederman & S. Abell (Eds.), *Handbook of research on science Teaching* (pp. 830–847). Routledge.
- Kapodistrias, A., & Airey, J. (2024). Rearranging equations to develop physics reasoning. *European journal of physics*, 45(3), 035701.
- Kapodistrias, A., & Airey, J. (2025). Multimodality and disciplinary learning: the case of purposeful transformation in the sciences. *Front. Commun.* 10:1562515. doi: 10.3389/fcomm.2025.1562515
- Kress, G., Jewitt, C., Ogborn, J., & Tsatsarelis, C. (2001). *Multimodal teaching and learning: The rhetorics of the science classroom* (1st ed.). Bloomsbury Publishing.
- Osborne, J. (2023). Science, scientific literacy, and science education. In *Handbook of research on science education* (pp. 785–816). Routledge
- Radford, L. (2002). The seen, the spoken and the written: A semiotic approach to the problem of objectification of mathematical knowledge. *For the learning of mathematics*, 22(2), 14-23.
- Radford, L., Demers, S., Guzmán, J., & Cerulli, M. (2003). Calculators, Graphs, Gestures and the Production of Meaning. *International Group for the Psychology of Mathematics Education*, 4, 55-62.
- Redish, E. F., & Kuo, E. (2015). Language of physics, language of math: Disciplinary culture and dynamic epistemology. *Science & Education*, 24, 561–590. <https://doi.org/10.1007/s11191-015-9749-7>
- Svensson, K., & Eriksson, U. (2020). Concept of a transductive link. *Physical review physics education research*, 16(2), 026101.
- Tuminaro, J., & Redish, E. F. (2007). Elements of a cognitive model of physics problem solving: Epistemic games. *Physical Review Special Topics—Physics Education Research*, 3(2), 020101.
- Uhden, O., Karam, R., Pietrocola, M., & Pospiech, G. (2012). Modelling mathematical reasoning in physics education. *Science & Education*, 21(4), 485-506.
- Volkwyn, T. S., Airey, J., Gregorcic, B., & Heijkskjöld, F. (2019). Transduction and Science Learning: Multimodality in the Physics Laboratory. *Designs for Learning*, 11(1), 16-29.
- Yeo, J., & Nielsen, W. (2020). *Multimodal science teaching and learning*. Learning: Research and Practice, 6(1), 1-4.
- Wallace, C. S. (2014). Overview of the role of teacher beliefs in science education. In R. Evans, J. Luft, C. Czerniak, & C. Pea (Eds.), *The role of science teachers' beliefs in international classrooms* (pp. 17–31). Sense Publishers.