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Forms of productive complexity as criteria for educational reconstruction: the design of a teaching proposal on thermodynamics

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Abstract

The paper discusses teaching materials on thermodynamics, designed and implemented in 5 classes of scientifically-oriented secondary schools in Italy (grade 12).

The materials are designed to: i) foster conceptual understanding; ii) create a learning environment rich enough to enable each student to find a personal way for appropriating content knowledge.

In order to achieve the first aim, the design takes into account the main results of literature about students' difficulties in thermodynamics. In order to achieve the second aim, forms of "productive complexities" are implemented.

The paper presents the design criteria and shows why they have the potential to create an inclusive and creative learning environment.

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1. Introduction

Within Physics Education Research, great attention has been paid to students' difficulties in understanding the concepts and laws of thermodynamics.

Recently, the need of problematizing a linear model of curriculum design has been strongly highlighted within the *Design Studies* perspective. In particular the need of pointing out new criteria for guiding the design and the implementation of teaching/learning materials able to foster the resonance between the growth of intellectual autonomy of each student and the development of the classroom as a whole has been stressed (diSessa & Cobb, 2004; Confrey, 2006). The issue of cultural diversities and the growing number of multi-cultural classes is amplifying the relevance of studying how learning environments and content reconstructions can make learning *of* and *in* the disciplines more and more inclusive for all (Nasir *et al.* 2006).

The goal of the paper is to present teaching materials on thermodynamics designed to achieve two different aims: i) foster conceptual understanding; ii) create a learning environment rich enough to enable each student to find a

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personal way for appropriating content knowledge.

In the following sections, the design criteria (§2) and the conceptual structure of the materials (§3) are presented. The materials are the result of a circular process of design/implementation carried out throughout 5 teaching experiments in different classes of scientifically-oriented secondary schools in Italy (grade 12).

2. Methods: design criteria

A long tradition exists in investigating students' difficulties in learning thermodynamics. In particular several studies addressed the problem of understanding the concepts of temperature and heat (Erickson & Tiberghien, 1985; Kesidou & Duit, 1993; Viennot, 1997), heat and work, their relationship and their character of being process variables (Loverude *et al.*, 2002; Meltzer, 2004). Further studies highlight students' difficulties in managing the variables involved in the thermodynamic description/explanation and, in particular, in relating the first principle and the perfect gas law (Rozier & Viennot, 1991; Kautz *et al.*, 2005a; 2005b; Pollock *et al.*, 2007). Most of the learning problems are interpreted either in terms of difficulties in considering more than two variables at a time, or in terms of confusion between macroscopic and microscopic levels of description (Loverude *et al.*, 2002; Rozier & Viennot, 1991; Kautz *et al.*, 2005a; 2005b; Lijnse *et al.*, 1990). As far as the second law is concerned, the existing studies point out students' difficulties in: i) understanding the meaning of irreversibility in the second law (Kesidou & Duit, 1993); ii) managing the relationship between entropy, second law and spontaneous physics processes (Christensen *et al.*, 2009); iii) recognizing the relevance of the second law in solving problems about cyclic devices (heat engines and refrigerators) (Cochran & Heron, 2006); iv) understanding basic probability concepts needed to comprehend the microscopic view of the second law (Loverude, 2009).

All these results have been taken into account in order to achieve the first aim of our study. In particular, the research results have been analysed so as to point out the “critical details” to be stressed and problematized throughout the teaching activities. Extra-materials on such critical details have been produced and, for example, activities were organized to involve students to cope with the exercises suggested by the research literature.

In order to achieve the second aim, the whole structure of content presentation was *reconstructed* (Kattman *et al.* 1996) so as to implement some forms of “productive complexities”:

A. *multi-perspectiveness*: the same physical contents are analyzed from two different perspectives, each one characterized by a specific approach to the contents - the macroscopic and the microscopic approach;

B. *multi-dimensionality*: the two approaches are analyzed and compared at different levels, i.e. for their conceptual, experimental and formal implications, but also for their philosophical-epistemological peculiarities;

C. *longitudinality*: the “game of modeling” which characterizes the thermodynamic systems and processes is explored by a systematical comparison with the models previously studied by the students (in optics, classical mechanics and special relativity).

D. *transversality*: a special emphasis is given to the process of interaction between electromagnetic radiation and matter in order to relate the thermal, optical and electromagnetic description of complex phenomena.

More operatively, the teaching path has been structured in an introduction, about the primitive concept of equilibrium, the zero principle and the concept of temperature, and in two parts about, respectively, the first and the second principle, both addressed from a macro and a micro approach.

The structure allows the two approaches to be *analyzed separately*, so as to show the inner consistency of each approach, and *systematically compared*, so as to show their peculiarities (multi-perspectiveness)[†].

Multi-dimensionality is introduced by framing the comparison between the macroscopic and microscopic

[†] The main references for the teaching proposal design have been: C. Tarsitani and M. Vicentini. *Calore, energia, entropia*, Franco Angeli, Roma (1991); M. Vicentini Missoni. *Dal calore all'entropia*, La Nuova Italia Scientifica (1992); C. Tarsitani and D. Busini. Macroscopic vs. Microscopic: a problem of History, Epistemology and Teaching of Physics, in *Proceedings of the GIREP-ICPE '95*, Michelini M et al. (eds.), FORUM, Udine, 281-286 (1996).

These references contain precious suggestions for: i) addressing coherently thermodynamics from both a macroscopic and a microscopic approach; ii) pointing out epistemological criteria for comparing the two approaches by tracing their roots back to history.

approach within the epistemological debate on possible ways of knowledge organization (theories). In particular, specific activities were planned (questionnaires and collective discussions) to reflect on the two approaches in the light of Einstein's paper about the "theories of principles" and "constructive theories" (Einstein, 1919).

As far as longitudinality is concerned, it is implemented by the choice of making conceptual knowledge progress, along the thermodynamics curriculum, according to the following leading question: *How does the game of modeling change from mechanics to thermodynamics?*

At least, transversality is introduced by applying the acquired concepts to the study of global warming, by stressing its inter-disciplinary and intra-disciplinary character (Tasquier *et al.* 2013).

These forms of complexity are supposed to support the teacher in realizing an inclusive and "psychologically safe" learning environment (Nasir *et al.* 2006) for the following reasons: 1) they challenge in depth the authoritative and exclusive image of science where a unique point of view is legitimate (and possible) and where only students "naturally" interested in it can have an acknowledged role; 2) the legitimacy of a variety of perspectives opens a faceted access to physics which can resonate with multiple cultural interests and cognitive styles and it can stimulate classroom discussions where the personal points of view can emerge, be verbalized and exploited; 3) the usual rigid notion of "scientific explanation", instead of closing discussions in the name of a naïve idea of absolute truth and objectivity, becomes itself a topic of discussion and the crucial question for deep understanding "what a physics explanation explains to me" finds legitimacy and room for discussion.[‡]

The whole structure, moreover, is supposed to provide a further substantial contribution to enable the students to address the known conceptual difficulties in understanding thermodynamics. Our hypothesis is indeed that the difficulties can be only partially addressed by making the single concepts clearer and clearer and by avoiding confusion between macroscopic and microscopic levels of description. To solve such difficulties also implies explicitly facing the "strangeness" of the modelling game implicit in the macroscopic approach to thermodynamics. The implementations of multi-perspectiveness, multi-dimensionality and longitudinality enforced us to make the effort of making the macroscopic approach strongly self-consistent and open to comparison with the mechanistic way of modelling systems and interaction. In the next section this point will be described in detail (§3.1): it is in fact the main key for following the brief presentation of the conceptual skeleton of disciplinary reconstruction. Figures 1 and 2 show, on a time line, the activities implemented by the teachers. The figures represent an attempt to visualize the back-and-forth dynamics needed to play out the forms of productive complexity and to guide the collective reasoning to stop, look back-around-over and go on.

3. Findings: the materials

3.1. The macroscopic approach and the problem of its inner consistency

The macroscopic parts of the conceptual structure is the result of a detailed reconstruction aimed at facing explicitly three kinds of apparent paradoxes that the modelling game of the macroscopic approach intrinsically has:

- a. *Familiarity and abstractness* – in spite of the feeling of familiarity suggested by words like temperature, heat and energy, the access to their scientific meanings requires a deep reflection on the specific epistemological way of accounting for phenomena. For example, the definition of temperature in a consistent macroscopic way which avoids tautologies (temperature is what is measured by a thermometer and a thermometer is what measures temperature) requires a long process where the inner consistency of argumentation must be made explicit (see §3.2, Introduction). To achieve this goal the epistemological status of the various steps in the argumentation is stressed by the distinction between "assumptions" (the equilibrium as a primitive concept), "elevation of a fact to the rank of principle" (the transitive property of being in equilibrium), "implications of a definition on modelling objects/systems". Such a distinction draws an epistemological scaffolding which provides a relevant contribution

[‡] The progressive implementation of the materials in different classes, with different teachers, showed indeed to be a sound basis for enabling teachers to support the students to appropriate thermodynamics according to personal approaches (Levrini *et al.* 2011).

to reach two aims: i) to help students to understand the physical concept of temperature, and ii) to enable students to face explicitly why *that* type of abstractness is needed to account for phenomena whose perception is commonly described by familiar words.

- b. *Processes and steady states* – in spite of the name thermo-“dynamics”, the dynamical explanation of the systems’ evolution disappears behind the weird choice of modelling processes as sequences of equilibrium states in the pV diagram. Traces of the dynamical processes are only recognisable in the distinction between process and state variables. In order to make the dynamical model of thermodynamics explicit, an epistemological reflection is needed to stress how the ideal, quasi-static, transformations implement a mechanistic view of interaction. The system is assumed to have, at any time, well-defined properties whose change is interpreted in terms of “inter-actions” with an external causal agent that controls, deterministically and step by step, the whole process (See §3.2, Part I).
- c. *Reversibility and irreversibility* – even though the second principle aims at finding out a quantity (entropy) for describing the intrinsic irreversibility of phenomena, such a quantity is defined on reversible transformations. A system which evolves in an irreversible way *forgets* the initial conditions and it does not come back spontaneously to its initial state; a system which evolves in a reversible way *remembers* the initial conditions and it can come back and go on. In order to address this seeming paradox, an epistemological reflection about the various meanings of entropy is needed as they emerge from the game between models and reality (See §3.2, Part II).

3.2. The conceptual skeleton

Leading question: How does the game of modeling change from mechanics to thermodynamics?

Introduction – Zero Principle

- a) The problematic definition of the apparently trivial concept of temperature: reflections on the difficulties of defining the concept of temperature in a non-tautological operational way.
- b) First assumption: it exists, in nature, an universal tendency of the “bodies” toward reaching a steady state with regard to possible external and internal changes (the assumption of equilibrium as a primitive concept).
- c) A fact elevated to a principle: systems in equilibrium in the same environment, when placed in contact with each other, do not change any of their properties. From the Zero Principle of thermodynamics to the definition of temperature.
- d) Implications of the concept of temperature on modeling objects/systems: the inadequacy of the mechanical models of point mass and/or rigid body to account for the thermal properties influenced by the environment and the need to introduce further variables for describing the internal state of a body.
- e) Reflections on the meaning of measuring an intensive quantity by means of the “transduction” into an extensive one (like length, volume, electric resistance).

Part I – First Principle

Macroscopic Approach

- a) From mechanics to thermodynamics: the friction and the “invention” of the concept of internal energy to save the principle of conservation of energy.
- b) The cryptic concept of heat: reflections on the process of interaction that can be indirectly deduced from the observation and measurement of other quantities, that is mass and difference of temperature (the law of calorimetry re-examined).
- c) The concepts of work and heat as fundamental variables for describing those interactions “system–environment” and/or “system–system” that can change the internal state of a system.
- d) Internal energy, heat, work and the crucial distinction between state variables and process variables.

Discussion on the meaning of expressions like “heat transfer”, “providing heat”, “absorbing heat”, i.e. expressions affected by the historical meaning of heat as a fluid exchanged from a body to another.

e) The relation between internal energy, work and heat elevated to a principle: the First Principle of thermodynamics.

f) The strategic choice of a special thermodynamic system: the perfect gas and its phenomenological, macroscopic definition/modeling as the system satisfying the empirical law $PV=nRT$ (“State Equation”).

g) Ideal transformations: useful inventions that allow the changes in a system from an equilibrium state to another to be ideally, step by step, followed and graphed; reflections on the graphic representations in order to stress the distinction between state variables and process variables and to make the thermodynamic model of interaction explicit.

Microscopic Approach

a) Re-examining the model of perfect gas in the light of the epistemological goal of reducing thermal properties to mechanical ones: introduction of specific hypotheses about the microscopic constituents of a gas.

b) Kinetic theory of gases: the microscopic interpretation of the perfect gas law and the relationship between the internal energy and temperature.

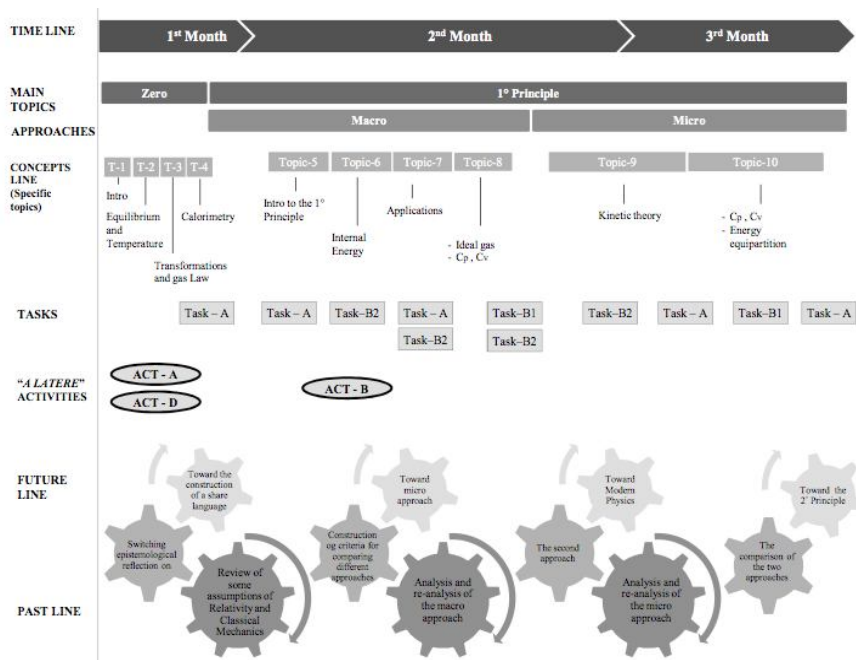


Figure 1- First parts of the conceptual skeleton on a time-line (See Figure 3 for the legend)

Part II – Second Principle

Macroscopic Approach

a) The irreversibility of real processes and the inadequacy of First Principle to describing it: focus on emblematic types of spontaneous and irreversible transformations (free expansion of a gas, heat transfer from a body at a higher temperature to a body at lower temperature, dissipation of mechanical - electric - energy by friction).

b) The spontaneous evolution of natural processes as a “fact of nature” elevated to a principle: the Second Principle of thermodynamics and its different statements as special cases of a general principle “If a system spontaneously evolves from an equilibrium state to another, such transformation is irreversible: there is no

transformation that can produce the only result of bringing the system back to its initial conditions”.

c) From reality to idealization: the introduction of the model of reversible transformations as those quasi-static transformations that can occur in both directions, given that no irreversible processes, like the emblematic ones, are supposed to occur. A seeming paradox: how can reversible transformations explain the irreversibility of natural phenomena?

d) The specific and crucial role of reversible transformations when applied to ideal thermal engines: i) pointing out an “intrinsic” (not removable) asymmetry between heat and work (the engine’s efficiency is less than 1, even in absence of irreversible processes); ii) highlighting the need of introducing a new state variable - entropy - able to differentiate between work and heat in ideal cases (in ideal transformations interaction via work transfers only energy whereas interaction via heat transfers both energy and entropy).

f) From idealization to reality: the production of entropy due to the presence of unavoidable spontaneous processes and the meaning of entropy as the entity able to quantify the irreversible change in real transformations.

g) A new insight on the First and Second Principle of thermodynamics in order to identify the two possible faces of the cryptic concept of heat: $Q = \Delta U + L$ (the energetic face), $Q = T\Delta S$ (the entropic face).

Microscopic Approach

a) The evolution of the epistemological project of reducing physics to mechanics: introducing the breaking choice of accepting statistics as part of physical explanations and the historical roles played by Maxwell and Boltzmann in achieving a microscopic interpretation of entropy.

b) Focus on Maxwell’s project: from the aim of investigating “the motion called heat” to the statistical interpretation of an equilibrium state by means of the distribution of the velocities of the molecules of an ideal gas.

c) The notion of “a-priori probability”: reflections on the problematic compatibility between the microscopic mechanical model (intrinsically reversible) and the irreversibility introduced by the Second Principle.

d) Focus on Boltzmann’s project and on its decisive steps: the development of Maxwell’s project within the theoretical framework based on the concept of “a-priori probability” and the interpretation of the equilibrium state (i.e. the macroscopic state towards which a system evolves) as the most probable state (i.e. the state corresponding to the highest number of microscopic states).

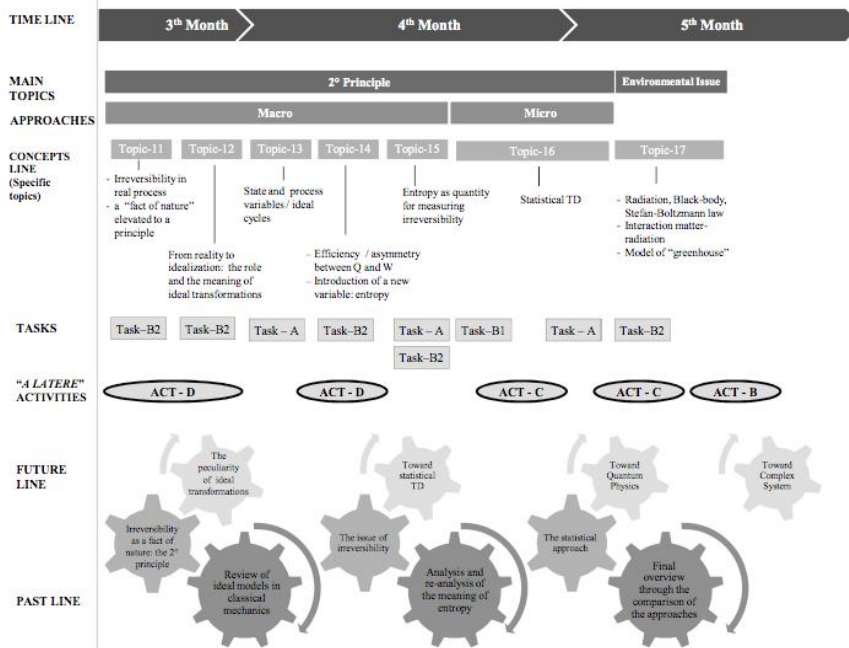


Figure 2- Second part of the conceptual skeleton on a time-line (See Figure 3 for the legend)

TASKS	Description (classroom activities implemented along the whole path)
Task - A	Exercises of several kinds: -Standard exercises -Exercises taken from the literature in physics education -Training exercises for the written task
Task – B2	Written tasks
Task – B2	Oral tasks where students are required both to consolidate the concepts and to go through again the conceptual path
“A latere” Activites	Description (particular kind of activities thought in order to implement the forms of productive complexity)
ACT - A	Initial questionnaire
ACT - B	Collective classroom discussions, led by a researcher
ACT - C	Seminar held by a University professors
ACT - D	Readings of passages from critical essays

Figure 3- Legend

4. Conclusions

The paper presents the teaching materials on thermodynamics designed both to foster conceptual understanding, and to support students to find a personal way for appropriating content knowledge. The design shows that a consistent implementation of some forms of complexity implies content knowledge to be clarified for facing apparent paradoxes intrinsic in the thermodynamics game of modeling systems and processes. In the paper, we argue why the solution of such paradoxes requires content analysis to be moved on an epistemological dimension. In this sense, the multi-dimensional structure is argued to provide a substantial contribution to enable students to address deep learning difficulties.

The results of the materials implementations confirm the design hypotheses: the forms of complexity revealed to be productive for supporting students to learn not only the disciplinary contents, but also to situate their learning in wide and personal projects of intellectual and emotional growth (Levrini *et al.*, 2010; 2011; Fantini & Levrini, 2012).

A further corroboration comes from a teaching/learning experiment on quantum physics at upper secondary school (grade 13) where the same forms of complexity oriented the materials design.

Also these results show that the specific structure of the materials allowed unavoidable kinds of difficulty in learning quantum physics to be transformed into real cultural challenges at reach of secondary school students (Levrini & Fantini, 2013, *accepted*).

The future directions of the research is to point out *how*, *when* and *why* the features of the materials trigger and support personal appropriation of physics.

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References

Christensen, W. M., Meltzer, D. E., Ogilvie, C. A. (2009). Student ideas regarding entropy and the second law of thermodynamics in an introductory physics course. *Am. J. Phys.*, **77**, 907-917.

- Cochran, M. J., Heron, P. R. L. (2006). Development and assessment of research-based tutorials on heat engines and the second law of thermodynamics. *Am. J. Phys.*, 74(8), 734.
- Confrey, J. (2006). The evolution of design studies as methodology. In Sawyer (eds.), *The Cambridge Handbook of The Learning Sciences*, Cambridge University Press, 135 - 152.
- diSessa, A. A., Cobb, P. (2004). Ontological innovation and the role of theory in design experiments. *The Journal of Learning Sciences*, 13(1), 77-103.
- Einstein, A. (1919). *Time, Space, and Gravitation*. Times (London). 28 November.
- Erickson, G., Tiberghien, A. (1985). Heat and Temperature. In R. Driver, E. Guesne, A. Tiberghien (eds.). *Children's Ideas in Science*. Open University Press, Milton Keynes – Philadelphia, 52-84
- Fantini, P., Levrini, O. (2012). Metacognition in and for appropriating physics knowledge: An empirical study on thermodynamics. Proceedings of the 5th Biennial Meeting of the EARLI Special Interest Group - Metacognition, Milano.
- Kattmann, U., Duit, R., Gropengießer, H., Komorek, M. (1996). Educational Reconstruction -bringing together issues of scientific clarification and students' conceptions. Paper presented at the Annual Meeting of NARST, St. Louis (MI), April 1996.
- Kautz, H., Heron, P. R. L., Loverude, M. E., McDermott, L. C. (2005a). Student understanding of the ideal gas law, Part I: A macroscopic perspective. *Am. J. Phys.* 73, 1055–1063.
- Kautz, H., Heron, P. R. L., Loverude, M. E., McDermott, L. C. (2005b). Student understanding of the ideal gas law, Part II: A microscopic perspective. *Am. J. Phys.* 73, 1064–1071.
- Kesidou, S., Duit, R. (1993). Students' Conceptions of the Second Law of Thermodynamics – An Interpretive Study. *J. Res. Sci. Teach.*, 30(1), 85-106.
- Levrini, O., Fantini, P. (2013). Encountering Productive Forms of Complexity in Learning Modern Physics. *Science & Education*, accepted.
- Levrini, O., Fantini, P., Gagliardi, M., Tasquier, G., Pecori, B. (2011). Toward a theoretical explanation of the interplay between the collective and the individual dynamics in physics learning. In C. Bruguière, A. Tiberghien & P. Clément (Eds.), *E-Book Proceedings of the ESERA 2011 Conference: Science learning and Citizenship. Part 3 (co-ed. Editors of the strand chapter)*, (pp.102-108) Lyon, France: European Science Education Research Association.
- Levrini, O., Fantini, P., Pecori, B., Gagliardi, M., Tasquier, G., Scarongella, MT. (2010). A Longitudinal Approach to Appropriation of Science Ideas: A Study of Students' Trajectories in Thermodynamics. In Gomez, K., Lyons, L., & Radinsky, J. (Eds.) *Learning in the Disciplines: Proceedings of the 9th International Conference of the Learning Sciences (ICLS 2010) - Volume 1, Full Papers*. International Society of the Learning Sciences: Chicago IL, 572-579. (ISBN: 978-0-578-06462-8).
- Levrini, O., Tasquier, G., Pecori, B., Fantini, P., (2011). From heuristics to humble theories in physics education: the case of modelling personal appropriation of thermodynamics in naturalistic settings. Proceedings Twelfth International Symposium, *Frontiers of Fundamentals Physics (FFP12)*, Udine, 21-23 November 2011.
- Lijnse, P., Licht, P., de Vos, W., Waarlo, A. (eds.) (1990), *Relating macroscopic phenomena to microscopic particles*. Utrecht, Holland: CD-β Press.
- Loverude, M. E. (2009). Students understanding of basic probability concepts in an upper-division thermal physics course. *Proceedings PERC 2009*.
- Loverude, M. E., Kautz, C. H., Heron, P. R. L. (2002). Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas. *Am. J. Phys.* 70 137-148.
- Meltzer, D. (2004). Investigation of students' reasoning regarding heat, work, and the first law of thermodynamics in an introductory calculus-based general physics course. *Am. J. Phys.* 72, 1432-1446
- Nasir, N.S., Resebery, A.S., Warren, B., Lee, C.D. (2006). Learning as a Cultural Process. In Sawyer K. (ed.), *The Cambridge Handbook of The Learning Sciences*, Cambridge University Press, 489-504.
- Pollock, E. B., Thompson, J. R., Mountcastle, D. B. (2007), Student Understanding Of The Physics And Mathematics Of Process Variables In P-V Diagrams. Proceedings of the 2007 Physics Education Research Conference, Greensboro, New York, AIP Conf. Proc. 951, 152-155.
- Rozier, S., Viennot, L. (1991). Students' reasoning in thermodynamics. *Int. J. Sci. Educ.* 13, 159-170.
- Tasquier, G., Pongiglione, F., Levrini, O. (2013). Climate change: an educational proposal integrating the physical and social sciences. *Procedia Social and Behavioral Sciences*, 5th World Conference on Educational Sciences, submitted.
- Viennot, L. (1997). Experimental facts and ways of reasoning in thermodynamics: learner's common approach from: *Connecting Research in Physics Education with Teacher Education*. In A. Tiberghien, E. L. Jossem, J. Barojas (eds). *Connecting Research in Physics Education with Teacher Education*. An I.C.P.E. Book © International Commission on Physics Education 1997,1998.