Part 13 / Strand 13

Pre-service Science Teacher Education

Editors: *Maria Evagorou & María Ruth Jimenez Liso*

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Professional knowledge of teachers, pre-service teacher preparation, instructional methods in pre-service teacher education, programs and policy, field experience, relation of theory with practice, and issues related to pre-service teacher education reform.

Part 13. Pre-service science teacher education

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Introduction

The recent changes around the world, with the COVID-19 pandemic and the war appearing in Europe again after decades, have once more brought our attention to the importance of understanding uncertainty in science, being able to navigate in a changing world and supporting our students, as science educators, to become active and responsible citizens. Becoming active and responsible citizens entails focusing on social justice (Cho, 2017), developing critical consciousness, engaging in dialogue and taking action (Blackmore, 2016) and understanding the uncertainties of science (i.e., Osborne et al., 2022). Further changes in our field include the emphasis on interdisciplinarity, especially as this emerges from the new emphasis on STEM education (Alvargonzález, 2011) and the effort to support integrated STEM teaching. Therefore, as science educators working with pre-service teachers, we are called to support them: in (trans)forming their pedagogical skills, understanding and teaching in interdisciplinary STEM settings, and preparing them to enter the classroom as autonomous educators.

Strand 13 of the ESERA 2021 online conference invited science educators to submit research work focusing on pre-service teacher preparation, instructional methods in pre-service teaching, field experience studies and programs linked to science teacher preparation. This volume of the e-proceedings brings together 12 papers from across the world. The work included in this part of the volume provides an overview of pre-service science teacher education trends. Furthermore, it highlights how research in our Strand has adapted because of the changes in our world during the last two years. The topics are similar to previous years (modelling, argumentation, inquiry), but methods have shifted to accommodate the pandemic. Specifically, papers in this volume for Strand 13 include themes of digital media with an emphasis on COVID-19 as triggers, some of the studies on teacher identities and expectations to be teachers, whilst others focus on scientific competencies (i.e., modelling, argumentation, inquiry) and curriculum effects.

We hope that this group of selected papers will support us as science educators as we continue our conversations about how to assist future teachers in providing their students with the knowledge, skills and dispositions that will enable them to become scientifically literate and responsible citizens.

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DISCIPLINARY IDENTITIES IN INTERDISCIPLINARY TOPICS: CHALLENGES AND OPPORTUNITIES FOR TEACHER EDUCATION

Eleonora Barelli[1], Berta Barquero[2], Oscar Romero[2], Maria Rosa Aguada[2], Joaquim Giménez[2], Carolina Pipitone[2], Gemma Sala-Sebastià[2], Argyris Nipyrakis[3], Athanasia Kokolaki[3], Ioannis Metaxas[3], Emily Michailidi[3], Dimitris Stavrou[3], Michael Lodi[1], Marco Sbaraglia[1], Evmorfia-Iro Bartzia[4], Simon Modeste[4], Simone Martini[1], Viviane Durand-Guerrier[4], Sara Satanassi[1], Paola Fantini[1], Veronica Bagaglini[1], Shulamit Kapon[5], Laura Branchetti[6], Olivia Levrini[1]

[1]Alma Mater Studiorum - University of Bologna, Bologna, Italy

[2]University of Barcelona, Barcelona, Spain

[3]University of Crete, Rethymno, Greece

[4]University of Montpellier, Montpellier, France

[5]Technion - Israel Institute of Technology, Haifa, Israel

[6]University of Milan, Milan, Italy

Interdisciplinarity (ID) represents nowadays a complex, multi-dimensional and timely challenge in STEM and, more in general, in STEAM education. If on one side ID is at the core of the most urgent societal issues, in schools and universities disciplines are almost exclusively taught separately and rigid boundaries are created. After a long period of good practices, researchers are more and more perceiving the need to develop theoretical frameworks to rigorously define what ID is and to recognize if and how interdisciplinary knowledge and skills can be developed in teaching. In this paper, four theoretically-oriented studies are presented as outcomes of the IDENTITIES Erasmus+ project aimed to develop an approach to design interdisciplinary teaching modules for pre-service teacher education.

Keywords: interdisciplinarity, pre-service teacher education, STEM education.

INTRODUCTION

The confrontation of the most urgent problems we face today, such as the pandemic and global warming, requires deep collaboration and integration between STEM disciplines. The emergence of new interdisciplinary fields like biomedical engineering, materials engineering, and artificial intelligence reflects this point as well. However, even though the increasing predominance of interdisciplinary discourses not only in professional and academic realms but also at the societal level, STEM education has been criticised for the disconnected teaching in schools and universities that perpetuates sharp separations between disciplines.

To face this challenge, one of the primary actions that need to be undertaken is a profound re-thinking of pre-service teacher education. Indeed, teachers and teacher educators have a disciplinary background and, usually, they are not educated to a fruitful interdisciplinary dialogue that is required to enter the recent emerging societal challenges. That is why innovating the path through which university students are prepared to become teachers deserves specific attention, first of all from the research community. This is the goal of the IDENTITIES

Erasmus+ Project (www.identitiesproject.eu) that has developed innovative and transferable teaching modules and courses to be used in contexts of pre-service teacher education. The modules' main objective is unpacking interdisciplinarity (ID) in STEM fields, illuminating the links and interweaving between physics, mathematics, and computer science.

Philosophers of science have discussed a lot on what ID is and how it can be characterised with respect to other forms of interplay among disciplines. The IDENTITIES theoretical approach considers the following definitions of inter-, multi-, and trans-disciplinarity: "Multidisciplinarity involves encyclopedic, additive juxtaposition or, at most, some kind of coordination, but it lacks intercommunication and disciplines remain separate [...]. True interdisciplinarity is integrating, interacting, linking, and focusing. […]. Transdisciplinarity is transcending, transgressing, and transforming, it is theoretical, critical, integrative, and restructuring but, as a consequence of that, it is also broader and more exogenous" (Thompson Klein, 2010 in Alvarogonzález, 2011). In the IDENTITIES' conceptualization of ID, it is crucial the metaphor of *boundary*, borrowed from the metatheory by Akkerman and Bakker (2011). It introduces two crucial terms in our framework: *boundary objects*, i.e., "objects that enact the boundary by addressing and articulating meanings and perspectives of various intersecting worlds" (p. 150) and *boundary-crossing mechanisms*, i.e. types of interaction between disciplines (collaboration, identification, reflection, and transformation) that lead to a scale of interdisciplinary learning potential.

In this paper, we present four research contributions that refer to modules developed within the IDENTITIES project and already implemented in local and international contexts. They differ and complement each other for several aspects. First of all, they focus on themes that deal with different types of ID. Two studies focus on advanced, intrinsically interdisciplinary, STEM topics that are societally relevant but difficult to include in official curricula: coronavirus evolution and nanotechnologies. Other two focus on curricular themes that curricula and teaching tend to separate in different fields: cryptography and parabola and parabolic motion. In the former cases, the studies discuss the role of S-T-E-M disciplines to unpack and exploit the complexity of the STEM themes. In the latter cases, ID is used as a *lever* to uncover the epistemological cores of the disciplines by confronting them on a common *boundary theme*. The four studies complement each other also for their research approach to didactics. The studies on coronavirus and cryptography implement research approaches elaborated within the didactics of mathematics: the Anthropological Theory to the Didactic and the Theory of Didactical Situation. The studies on nanotechnologies and parabola are, instead, influenced by approaches developed in science education: the Model of Education Reconstruction or the Family Resemblance Approach.

INTERDISCIPLINARITY IN ADVANCED STEM TOPICS

Design of an interdisciplinary module about modelling coronavirus evolution

The topic of modelling the evolution of coronavirus was chosen in part due to its intrusion into our daily lives at the beginning of 2020. We recognized in it an authentic example of STEM advanced ID, i.e., a major issue for the society that required the collective effort of putting different disciplines to react in front of unexpected questions. Indeed, the COVID-19 pandemic has shown more than ever that students and, more in general, citizens need to understand how mathematics and scientific advances contribute to the understanding of societal phenomena. In addition, "the pandemic illustrates perfectly how the operation of science changes when questions of urgency, stakes, values, and uncertainty collide" (Saltelli et al., 2020). Specifically, it has emerged the need to explore what kind of knowledge can models and modelling provide, how we may interpret their predictions, and more in general, what contribution they provide to the understanding of such a complex issue.

To present the design principles at the basis of the module, we use some notions proposed in the framework of Anthropological Theory to the Didactic (ATD). Within the ATD, the step toward a change of paradigm in teacher education in the so-called "paradigm of questioning the world" (Chevallard, 2015) is approached using the "study and research paths for teacher education" (SRP-TE) (Barquero et al., 2018). The SRP-TE is an inquiry-based process combining practical and theoretical questioning of outside- and inside-school scientific activities. The approach is mainly characterised by: i) the formulation of questions that are rich and relevant enough to be placed at the heart of pre-service teacher education programmes; ii) the facilitation, through the questions, of epistemological and didactic analysis tools of disciplinary and interdisciplinary knowledge at stake; iii) the detection of boundary objects and boundary-crossing mechanisms to switch on links between the disciplines and foster the analysis of interdisciplinary knowledge. In the case of the present module, the SRP-TE is structured in four submodules. Each of them asks participants to assume different roles with regard to their interdisciplinary inquiry.

In submodule 1, we start from a professional question related to ID in scientific practices and their conditions for transposition to school. Participants act here as "ID explorers", reading a set of selected pieces of news and discussing questions like: *How have STEM disciplines contributed to the societal understanding of the evolution of COVID-19? How can this interdisciplinary practice be transposed to secondary schools?* From this first analysis, educators guide the participants to delimit possible lines of inquiry involving models and modelling as well as the interaction among different disciplines. These lines are the main object of Submodule 2 that asks participants to experience an interdisciplinary project, under the role of "ID student", about: (1) The complexity of delimiting the system to model: analysing data; (2) The role of the equation-based models: what can we consider a 'good' model? what are models for?; (3) Agent-based models and simulations: Simulating scenarios to help to make decisions about societal restrictions. The main goal of this submodule is to make participants carry out an unfamiliar interdisciplinary activity that could take place also in the classroom. In particular, the participants explore the issue of COVID-19 evolution from three different (but complementary) points of view: the real data processing, selection of variables, and their statistical analysis; the use of equation-based mathematical models for disease diffusion and the interpretation of the models' coefficients, accordingly to the data; and the implementation of an agent-based simulation using methods inspired by statistical physics to evaluate different types of social intervention.

In submodule 3, the participants become "ID analysts" since, in groups, carry out a meta-reflection on the previous activity on three different levels. The first level, using the tool of questions-answers maps (Winsløw et al., 2013), aims to sketch the process followed through the dialectics between the specific questions that the group has faced, and the answers obtained. The second level requires recognizing in the lines of inquiry examples of boundary objects. Finally, participants analyse the kind of interaction among disciplines (i.e. boundary-crossing mechanisms) that happens when boundaries are at stake and eventually overcome. In Submodule 4 some secondary school experiences linked to each line of inquiry are shared with participants. Then, they are expected to use the tools previously developed for interdisciplinary analysis to discuss the conditions to facilitate the implementation of ID in real classrooms, as well as the constraints hindering the chances for ID to happen.

STEM student teachers analysing ID in the field of nanotechnology

Nanoscience-Nanotechnology (NST) is one of the most contemporary and promising research fields in STEM. NST is a wide topic that relates to studying and manipulating matter at the atomic, molecular, and macromolecular levels in order to create materials, devices, systems in the nanoscale (approximately 1-100nm), with fundamentally new properties and functions (Roco, 2001). The rationale for choosing NST for STEM teaching relies on the fact that: a) NST is by nature an interdisciplinary field, in which many disciplines interact, b) NST is related to many contemporary real-world applications and breakthroughs, c) being an ongoing field of research, it gives the opportunity to students to discover new methods and new ways of thinking as well as to cultivate views of Nature of Science and Nature of Technology, and d) it can engage students in relevant socio-scientific issues and issues of responsible citizenship (Kähkönen et al., 2016; Stavrou et al., 2018).

The theoretical framework for designing this module is the Model of Educational Reconstruction for Teacher Education (Van Dijk & Kattmann, 2007), adapted to the needs of the present study. Therefore, studies concerning Pedagogical Content Knowledge and ID interact dynamically with the design and development of educationally reconstructed STEM learning environments from the student teachers in order to develop learning environments for STEM pre-service teacher training. Furthermore, the educational reconstruction of STEM learning environments has been carried out according to the Model of Educational Reconstruction (Duit et al., 2012), in which school students' ideas and attitudes, as well as empirical studies on teaching and learning, are also taken into account. Specifically, studies concerning ID include i) the taxonomy of ID by Thompson Klein (2010) to define ID, as well as ii) the boundary objects framework (Akkerman & Bakker, 2011) as a facilitating means to foster student teachers' views and understandings of ID. The module was divided into four main submodules following the rationale of SRP-TE (Barquero et al., 2018).

In the first submodule, student teachers are called upon to act as "ID explorers", by engaging in open discussions about contemporary real-world problems that NST research aims to address. Moreover, they are asked to give their initial views on concepts/methods/artifacts in which multiple disciplines are involved, as well as 'linguistic activators', i.e., terms that gain different meanings across different disciplines/communities. Subsequently, in the second submodule, student teachers take the role of "ID students", by engaging in interactive activities which include STEM artifacts related to cutting-edge NST applications, such as smart housing, alternative energy sources, metallic nanoparticles for medical treatment, and NST microscopes. The student teachers are then called upon to design the first draft of their own STEM teaching activities concerning NST, present it to peers in terms of microteaching, discuss, and take feedback.

In the third submodule, student teachers take the "ID analyst" role. The goal in this submodule is twofold: on the one hand, student teachers are called upon to recognise disciplinary knowledge and skills from each S-T-E-M discipline that derive from nanotechnology concepts/phenomena/applications in the STEM activities presented previously. Particularly, student teachers analyse the complex phenomena by using their existing "disciplinary lenses" in order to connect them to their already obtained areas of understanding, and, hence, foster a feeling of *comfort*. On the other hand, student teachers are called upon to recognise several *incidents* where disciplines interact in the STEM activities presented. In order to concretise this process, the module implements indicative concepts/methods/artifacts that were considered to act as boundary objects in NST, such as modelling (Develaki, 2020), instrumentation (Stevens et al., 2009), and biomimicry (Krohs, 2022). Hence, students reflect on how different disciplines coexist, interact, and interconnect through these boundary objects which are used as "interdisciplinary lenses". Subsequently, the module leaves space for student teachers to discuss further incidents of ID regarding their own developed teaching material that can also act as boundary objects. In the last submodule, student teachers are invited to revise their STEM teaching material through a second iteration as "ID designers" in which they reflect from an epistemological point of view on the model of STEM Integration (Ring et al., 2017) that they implemented.

INTERDISCIPLINARITY IN CURRICULAR TOPICS

Teaching cryptography to foster ID between mathematics and computer science

We choose cryptography as an example of a domain at the interface between Mathematics and Computer Science (CS). Both mathematical elements (like proofs, number theory) and CS elements (like computational complexity, systems design, programming) are fundamental to solving the relevant social, technological, and scientific challenges cryptography poses. Moreover, some cryptography elements encompass intertwined aspects of CS and Mathematics (for example, one-way functions are both well-defined mathematical functions and programs that satisfy specific security and efficiency criteria). In the current research, this stimulates a dialectic between the two disciplines, both from CS to Mathematics (e.g., requiring new research in elliptic curves) and in reverse (e.g., using theorem provers to verify cryptographic properties). On the other hand, cryptography allows for "disciplinary projections": inside the field, elements of the two disciplines are still recognisable. Learning about all this is relevant for those secondary teachers who may have to teach some cryptography either in Mathematics, CS, or interdisciplinary courses.

The design of the module relies on two main pillars. First, we consider the need to introduce cryptography as a social issue of contemporary society (ENISA, 2016) following a long-term presence in human history from ancient Greece to nowadays. The development of CS has put forward an increasing number of encryption methods, most of them relying on Mathematics and CS's close intertwining. Second, we choose the didactical engineering methodology relying on the Theory of Didactical Situations. As stressed by Artigue (2014), didactical engineering is structured into four main phases: (i) preliminary analysis; (ii) design and *a priori* analysis; (iii) realisation, observation, and data collection; (iv) *a posteriori* analysis and validation. Validation is internal, based on the contrast between *a priori* and *a posteriori* analysis, not comparing experimental and control groups. In the design of tasks and situations, particular attention is put on: the search for situations that capture the epistemological essence of the mathematics to be learned; the optimisation of the *milieu* to provide relevant retroactions for students' autonomous learning (*a-didactic* potential); the management of *devolution* and *institutionalisation* processes. Following Durand-Guerrier, Meyer, and Modeste (2019), we consider this relevant also for CS and, hence, for designing interdisciplinary teaching modules involving both disciplines. Inspired by the STP-TE (Barquero et al., 2018), the module is structured into five submodules.

Submodule 1 starts from a current social debate (pros and cons of end-to-end encryption in widely used instant messaging services) to make participants (i.e., student teachers) initiate the discussion on cryptography, get in touch with basic principles and terminology, and begin to reflect on ID by analysing a historical piece on the birth of asymmetric cryptography. Submodule 2, designed according to the Theory of Didactical Situations, makes the participants experience as students a didactical situation (a group activity based on the *Dominating Set Perfect Code* cryptosystem (Bell et al., 2003)), with a *milieu* where the students autonomously verify if they have solved a given problem (i.e., deciphering a message). We designed a different organisation of the *milieu* for each participants' group to lead to different perspectives and approaches to the task and help student teachers think about the interdisciplinary objects encountered (graphs, functions, algorithms, complexity). In Submodule 3, participants analyse the previous teaching proposal in light of didactic and epistemological aspects, engaging in interdisciplinary analysis. They make disciplinary projections (recognising CS and Mathematics fundamental concepts in cryptography) and identify interdisciplinary elements (like boundary objects and boundary-crossing mechanisms (Akkerman & Bakker, 2011) or what we call linguistic and epistemological activators - e.g., the different meanings associated with 'function' in CS and Mathematics, or the difference between a non-invertible and a one-way function) to explore the borders between the two. In submodules 4 and 5, participants design, implement and analyse *a posteriori* a new didactical situation on other proposed cryptography concepts.

In the whole module, we designed activities where disciplinary projections can shed light on important disciplinary concepts, like computational complexity for CS and graphs for Mathematics. Disciplinary projections can stimulate exploration and learning of some relevant topics and ideas of each discipline, not only in the specific scope of cryptography but also in other CS and Mathematics areas. Together with the work on boundaries, this can also foster the exploration of other interactions between the two disciplines.

Parabola and parabolic motion to cross boundaries between physics and mathematics

The topic of parabola and parabolic motion was chosen as very prototypical of what happens to ID in school transposition. The two are, of course, intrinsically related. However, school science, through habits, textbooks, and school practices, has consolidated two different disciplinary narratives that separate the two themes into disciplinary enclaves created by artificial barriers. On the contrary, the discovery of parabolic motion represents a crucial step in the historical co-evolution of physics and mathematics, and in the establishment of physics as a discipline (Renn et al., 2011). It led humanity to overcome the medieval distinction of "violent and natural motions" and to admit that mathematics can be applied to the imperfect sublunar world. Vice versa, Kepler and his studies in geometrical optics provided a fundamental contribution to reconceptualize parabola as *locus* and to pave the way for projective geometry. Despite their crucial roles in history, parabola and parabolic motion do not have, in class, a special role in defining the epistemic identity of physics and mathematics.

The module has been designed with the goal to base the search for a theoretical-based model of ID on a concrete example. The model is expected to orient the design of teaching materials able to: a) break down artificial school barriers between disciplines and b) exploit ID as a way to give back mathematics and physics their disciplinary identities. In order to reach these goals, we chose a historical approach that implies the analyses of historical cases through "ID lenses". The interdisciplinary lenses for the analysis have been built as a combination of three main frameworks: the Family Resemblance Approach (FRA) for the NOS by Dagher and Erduran (2016); the Thomson Klein taxonomy of ID (2010); the metatheory developed by Akkerman and Bakker on the metaphor of the boundary (2011). Since the latter have already been introduced, we provide some details about the FRA. It has been used to switch on, in the historical texts by Guidobaldo and Galileo, the dimensions that characterise the epistemic core of a scientific discipline: its aims and values, scientific practices, methods and methodological rules, knowledge (Dagher & Erduran, 2016). The application of the framework to the analysis of the history of parabola and parabolic motion led us to recognize two special cases of boundary objects – symmetry and proof – that, through mechanisms of identification and reflection, activated the appearance of the epistemic cores of the two disciplines. For this reason, the concepts were emphasised as epistemological activators.

The module is articulated in six submodules. In phase 1 the student teachers are asked to reflect on the metaphor of the *boundary* and on examples of boundary objects to position themselves on the theme of ID. Then the phases 2 and 3 concern both the historical analysis of the discovery of the parabolic motion and a two-pronged analysis of historical texts from Guidobaldo and Galileo: the FRA model is used to recognise the epistemological elements of the discourse; the Akkerman and Bakker's metatheory is used to point out the role of boundary object and epistemological activator played by the symmetry that Guidolbaldo experimentally discovered. Phase 4 regards the analysis of the different meanings of proof in mathematics so as to define criteria to analyse Galileo's proof of the parabolic motion and to exploit the structural role of mathematics in the establishment of physics as a discipline. In phase 5, different definitions of parabola as a mathematical object were given, influenced by the interaction between mathematics and physics over many centuries and to symmetry as a boundary object. In phase

6, a wrapping up lesson was designed to rethink the questions opened in phase 1 after the interdisciplinary activities.

DISCUSSION AND CONCLUSION

The four perspectives presented in the paper allow us to sketch common features of the approach to ID that the IDENTITIES project carries out. The first issue that deserves discussion is related to the importance of grounding an interdisciplinary reflection on the *identities of the disciplines* at stake. While acknowledging the limits of the sharp separation between STEM disciplines in schools and universities, disciplines are still fundamental for interdisciplinary education. A "discipline" is indeed a body of knowledge that has been historically organised to be taught and learned (the very same etymology of the term "discipline" refers to the Latin "discere", whose meaning is "to learn"); moreover, a discipline reflects a didactical organisation of knowledge that supports the development of a particular set of epistemic skills such as modelling, explaining, arguing, which take somewhat different forms in different STEM disciplines. These sets of epistemic skills are the basis of productive collaborations between disciplines in real-life problems, and the generation of productive ID. Hence, learning in the disciplines is crucial for maintaining productive ID. Learning in schools is institutionally organized around separate disciplines. Fostering interdisciplinary learning in this educational context is challenging, since teachers and students often misinterpret the institutionalized separation between classes of different disciplines in school, as an intrinsic feature of the topics they learn in each discipline.

When focused on disciplines, students should be guided to recognize the types of *interactions between disciplines* that occur in interdisciplinary contexts. The shift from separate disciplines to ID in the four modules was afforded by the focus on boundary objects, boundary-crossing mechanisms (Akkerman & Bakker, 2011), and "epistemological activators" i.e., key concepts, methods, or themes that characterise each discipline and invite meaningful reflective comparisons between and across disciplines (Ravaioli, 2020). Additional support for this shift was achieved by supporting students in identifying "linguistic activators" i.e., concepts, categories, or forms of linguistic representations that are used differently in different disciplines. The explicit comparisons of the entailed meanings ascribed in each discipline, help students unpack additional layers of the interaction between disciplines.

The last point that we want to stress is related to the protagonists of the IDENTITIES approach: the *student teachers*. Teachers are the most important agents of change in students' learning. Hence, if we want students to develop interdisciplinary skills, we should start by teaching this in our pre-service teacher education programs. That is why the design process not only includes the reconstruction of disciplinary and interdisciplinary issues in the modules, but also implementations in teacher education that require the preservice teachers to take different roles with respect to what is learned. Student teachers engage in exploring case studies of ID through explicit discussion of boundary crossing, epistemological activators, and linguistic activators, then in instructional design that highlight aspects of ID, in collective reflections on this design, followed by microteaching and further reflections.

Notes

The four sections of the paper have been authored by the team of designers of the four IDENTITIES modules. For the COVID-19 module: B. Barquero, E. Barelli, O. Romero, M. R. Aguada, J. Giménez, C. Pipitone, and G. Sala-Sebastià; for the nanotechnologies module: A. Nipyrakis, A. Kokolaki, I. Metaxas, E. Michailidi, and D. Stavrou; for the cryptography module: M. Lodi, M. Sbaraglia, E. Bartzia, S. Modeste, S. Martini, and V. Durand-Guerrier; for the parabola module: S. Satanassi, L. Branchetti, O. Levrini, P. Fantini, and V. Bagaglini. Kapon's contribution has been included as the discussant at the symposium that was chaired by Levrini and Branchetti.

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