Le Leggi della Natura @ MSN

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Laws of nature as educational tools: a research on History and Philosophy of Science relevance for Science Education and Communication

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M's thesis for the programme in **History and Philosophy of Science**

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Acknowledgements

During the drafting of the following thesis, I worked as educational operator at Venice Natural History Museum, where I designed and delivered a guided intellectual itinerary, titled *Le Leggi della Natura,* which is also the main theme of the thesis. However, dealing simultaneously with a job and a M's thesis was not easy. Thus, I am extremely grateful to my supervisors, Hieke and David, for their comprehension of the situation and their patience. I want to further thank them for the trust they put on my project and for our pleasant conversations, that allowed me to considerably improve both the thesis and the itinerary.

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The project *Le Leggi della Natura* started from a previous collaboration with MUVE, Fondazioni Musei Civici di Venezia. Once I completed the exams of the History and Philosophy of Science Master's programme, I looked for a part-time job that would require to use the skills and capacities I acquired during university years. I found the perfect match in a MUVE museum, Palazzo Fortuny, that hosted a temporary artistic exhibition, PROPORTIO, inquiring the presence of universal proportions in artistic production. I was really surprised by the terrific response to my HPS-in-action methodology of presentation, and eventually some months later I received a proposal to extend this approach to another MUVE museum. *Le Leggi della Natura* design process thus began. So, I am grateful to all MUVE employees, and especially to Monica, that allowed for this process to actually take place.

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Dedico questa tesi a mio nonno Sergio, che la sta aspettando da un bel po'.

ABSTRACT

How can the discipline of history and philosophy of science improve science teaching? The present thesis tries to answer this question pragmatically, describing the design process and the disciplinary content of *Le Leggi della Natura*, a guided itinerary active at Venice Natural History Museum. *Le Leggi della Natura* employs the laws of nature as educational tools, and aims at inquiring different laws pertaining to the realm of mathematics, physics and biology. The concept of laws of nature is inherently transdisciplinary and allows for a coherent infusion of technical and socio-cultural contents: it is therefore an instance of HPS knowledge used in science education. In fact, I will show how this particular concept can map knowledge about the Nature of Science (NOS), a major theme discussed in publications concerning HPS and science education. Furthermore, analyzing audiences' degree of satisfaction after attending the itinerary, I can quantify whether the itinerary was successful and, consequently, whether laws of nature are a powerful conceptual device for science education.

Keywords: Laws of nature – Scientific laws – Science Education and Communication – Nature of Science – Natural History Museum – Interdisciplinarity – Mathematics, physics and biology intercommunication

SUMMARY OF CONTENTS

Note on the references: I have used a footnotes-based referencing system - e.g. E. Zilsel, "The genesis of the concept of physical law", 1942. *The Philosophical Review* 51 : 3. If I refer to a publication more than once, from the second time onwards I am using a reduced reference, as: E. Zilsel, "The genesis of the concept of physical law" (1942).

1. INTRODUCTION

History and philosophy of science (HPS) aims at studying the foundational principles and the socio-cultural context of scientific theories and discoveries; consequently, is able to offer an accurate and detailed image of work-in-progress science and its evolution. Thus, HPS turns out primarily important to understand and evaluate every aspect of our lives that includes a reference to scientific and technological issues. In this thesis, I investigate why and how much history and philosophy of science discipline is necessary for science education and communication. Thus, I focus on how HPS feature of offering a realistic description of science proceedings is applicable in the specific context of science teaching. This is a research on the pragmatic virtues of HPS, and I looked for a pragmatic answer. Hence, I took my collaboration with Venice Natural History Museum (MSN) as the starting point of my analysis. Here, I designed a guided itinerary, titled *Le Leggi della Natura*, inquiring the intercommunication between mathematics, physics and biology, this intercommunication being mediated by the laws of nature. Through an overview of *Le Leggi della Natura* main contents, design process and methodology of presentation, and showing that the concept of laws of nature is inherently transdisciplinary and complex to define, I demonstrate that developing a Science Education and Communication (SCE) product based on this concept allows for a comprehensive transmission of scientific technical and cultural contents, at the same time blurring this conceptual distinction. In fact, the laws of nature helps to realistically describe science as the result of humans endeavor, and not just as a set of immutable, objectively-defined nude facts. Hence, with the following thesis, I inquire what are the main characteristics of the concept of the laws of nature, allowing for such a characterization of science proceedings and, therefore, for an efficacious science teaching through a coherent transmission of HPS contents.

Under the point of view of science didactic, *Le Leggi della Natura* is quite peculiar, since it raises numerous questions, for which a clear-cut answer is not always present. With the guided itinerary, I introduce audiences to questions of the kind: “How can natural phenomena obey theoretical laws? Are those laws immanently present into nature or are they just useful tools scientists use to describe natural recurrences? Is there difference between scientific laws and laws of nature?” Throughout the whole guided itinerary, lasting around 2 hours, I investigate these questions using various objects and specimens of the museum collection. I start with a short description of the object in exam, for then proceeding to an analysis of the corresponding scientific law I want to present audiences with. Each law, depending on its characteristics (e.g. exact or statistical, a priori or inferred) entails different conceptual problems, that rarely have a clear-cut resolution. Therefore, through an historical survey, I present some tenable positions on the issue, through the works of past scientists and scholars. After this, the itinerary acquires a more interactive character, since I ask students – when they look interested in the discussion – to express their opinion over the subject matter.[1] Interestingly, during *Le Leggi della Natura* first sample visit, which occurred with a second-year art high school class, after I explained how I conceived my interactive, interdisciplinary and multidirectional HPS-based itinerary, a student raised his hand, asking: “I don’t care about science, why should I care about its history?” In that precise (and quite funny) moment, I found my thesis’ main theme. The student raised an issue of primary importance for nowadays science teaching and, indeed, I believe that HPS has a pivotal role not only for working and scientists, but also for wannabe scientists; I thus try to pragmatically establish how much HPS allows students to approach science with a more fruitful and interested attitude. More specifically, since the milestones of the itinerary are the laws of nature, the main scope of the following thesis is thus inquiring what is the added value of a Science Education and Communication (SCE) product based on this transdisciplinary concept.

To introduce *Le Leggi della Natura* to the reader, before dwelling more in deep on its educational value, in the next section I present some major themes that are necessary to have a general overview of the itinerary content and methodology of presentation. First, I introduce my starting hypotheses over the definition of the concept, to illustrate the discrepancies that are inherent to the definition(s) of the laws of nature intended as a philosophical category, for then inquiring to what extent an historical analysis could clarify these discrepancies. The issue at stake is rather complex and has been subjected of extensive treatments, all of them pointing in different directions. However, the scope of my analysis is demonstrating

[1] Three detailed examples of this iterative process can be found in chapter 3, dealing specifically with classical mechanics, mathematical modeling of natural forms and fluid dynamics. The scientific content of these examples will be introduced earlier, in section 1.2.2.

that, despite all philosophical and historical problems arising in defining such an elusive idea, laws of nature are anyway of inestimable importance for describing science in the making. Furthermore, they are primarily important for science education and communication since several typologies of audiences are already familiar with it, for instance due to their massive use in 'pop science' publications.[2] After the presentation of the concept under exam, in section 1.2 I will return to the actual itinerary, quickly describing how it is set within the museum environment, and its main scientific contents. Then, in chapter 2, I focus more in deep on the academic value of the present research for science teaching, first inquiring the importance of using an HPS-based approach in SCE, for then specifically study the role of laws of nature for SCE. I want to present the laws of nature as a concept naturally grounded on HPS and, as such, essential for science teaching. Furthermore, through an overview of up-to-date literature on the subject, I also show that very little attention has been given to the laws of nature as educational tools and, accordingly, with the itinerary *Le Leggi della Natura,* I tried to fill this gap. Later, in chapter 3, I investigate whether experience matches theory: at the end of every itinerary delivery, I handed students and teachers a survey form to be filled, asking their opinion over different features of the itinerary. Through a statistical analysis of these surveys, I can formally evaluate whether *Le Leggi della Natura* was a successful itinerary, and thus whether focusing this specific SCE product on the laws of nature implied an efficacious science teaching.

Summing up this introductory section, the broader context of analysis is the efficacy of history and philosophy of science for science teaching, and I am basing the following research on the results obtained from *Le Leggi della Natura*. Therefore, my research is twofold, and the main questions it investigates can be summarized as follows:

RQ1. *Are the laws of nature a suitable tool for science education and communication?*

RQ2. *Was* Le Leggi della Natura *@ MSN a successful interdisciplinary itinerary?*

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[2] See, for example: G. Musser "Deep in thought: What is a "law of physics," anyway?", 2010. *Scientific American.* R. Allain "I'm so totally over Newton's Laws of Motion", 2016. *Wired*.

1.1. LAWS OF NATURE AS PHILOSOPHICAL AND HISTORICAL CATEGORIES

To answer the previous questions it is first necessary to introduce the background knowledge I used in designing *Le Leggi della Natura* content. In this subchapter, I am offering some hints on how science philosophers and historians dealt with the problem of defining the laws of nature and their historical evolution. So, I now inquire what are the laws of nature (or, what are not), and whether there is consensus on when and why they entered the scientific discourse. This is an overview chapter, but it is indeed necessary to formally define the conceptual context of the analysis. I do not use this content, as presented now, during the pragmatic deliveries of the itinerary because I focus more on the interaction existing between the laws of nature and the museum objects; still the following analysis is primarily important to outline the main characteristics of the laws of nature.

1.1.1. Philosophical quest: what is a law of nature?

To investigate the use science (and accordingly, scientists, science communicators, science teachers, …) makes of the laws of nature, it is necessary to give a pertinent definition of the concept itself: what is a law of nature, and what are the properties defining it? As we shall see, finding an answer to these questions leads to several conceptual difficulties: in fact, dealing with the philosophical intending of the laws of nature means to deal with some core themes of metaphysical debates, as causation, reductionism, and the realism vs. antirealism debate. However, complex this analysis may be, it will allow us to shed some light not only on our starting problem, but also on the role that philosophy has in inquiring the problems of science unfolding.

In science textbooks there are several examples of laws, with a slight predominance of physical laws. As a matter of fact, the most famous laws in science are Newton’s laws of motion, and almost any science student is familiar with them. Similarly, there are Coulomb’s law, Avogadro’s law and Snell’s law, and the list does not stop here. In fact, there are several examples also of non-eponymous laws: even fewer in number, it seems there is no need to exclude from this list the law of reflection, the laws of thermodynamics, the combined gas law, the law of supply and demand. On the other hand, looking at the same science textbooks, we also encounter several (eponymous and not) principles, rules, equations and theories that seems to bare no difference in meaning, application or scope with the admittedly-labelled laws. Where is the difference to be found? Why no electromagnetism compendium has a chapter titled "Maxwell's Laws", but they always refer to Maxwell's equations? To make sense of this situation, we thus need to define analytically which characteristics a law of nature must have.

The recent literature on the subject is quite extensive, and even though we can infer a restricted number of principal thought lines, there is little or no consensus on the specific features of laws of nature. Hence, I tried to isolate the common features discussed in every approach. The first important characteristic concerns the range of application of the laws of nature. What does it mean that a law can be applied universally or, similarly, that is universally valid? Laws of nature, logically, should be valid for nature as a whole, so here on Earth and equally on Mars, as well as on distant galaxies.[3] This request for universal validity leads to the second characteristics of the laws of nature, i.e. their truth value: do laws of nature need to be literally true? And, subsequently, what does it mean for a law to be *true*? In the case laws of nature are considered just mere artefacts, would they still be considered true? These questions can be answered from two radically different points of view on the subject: Humeans' positions (holding laws to be just useful descriptions of natural phenomena), in parallel with Necessitarian views arguing that these laws are literally true.[4] The philosopher of science Ronald Giere's book *Science without Laws* supports Humeans' positions, even vindicating for a lawless science,[5] whereas another philosopher of science, John Robert, in his reinterpretation of Lewis' best-system account, strongly supports the necessity of laws of nature in scientific enterprise, being them the literal truths science aims for.[6]

Despite the differences between the two approaches, both scholars agree over the fact that the laws of nature should inherently be nomic truths, not just accidental ones. To explain further the issue, it is useful to consider an example that the famous philosopher Baas van Fraassen described in his book *Laws*

[3] J. Roberts, "Laws of Nature as an indexical term: a reinterpretation of Lewis's best-system analysis", 1999. *Philosophy of Science,* 66.Pg. 503.
[4] J. W. Carroll, "Laws of Nature", 2016. *The Stanford Encyclopedia of Philosophy.*
[5] R. N. Giere, *Science without laws*, 1999.
[6] J. Roberts, "Laws of Nature as an indexical term: a reinterpretation of Lewis's best-system analysis", 1999. Pg. 504.

and Symmetry.[7] The two sentences “there are no gold spheres with a diameter of over one mile” and “there are no uranium spheres with a diameter of over mile”, are both evidently true - for our present knowledge. On the other hand, the first sentence is not a law of nature, whereas the second could be argued to be: there is no physical law whose content limits the dimensions of gold spheres, being gold a pretty stable transition metal, whereas nuclear physics laws rule out the possibility of an uranium sphere with such dimension, since it would decay much before reaching the one mile diameter.

From the truth-value problem, another issue arises, namely the approximated character of scientific laws. For example, Newton’s law can be considered real if theory and experience perfectly matches, and this is rarely the case. On the other hand, the discrepancies from the ‘ideal’ situation could also be formalized mathematically and entailed in the definition of the specific law. However, there is the risk to end up with tautological laws of the kind “F = ma, given that F = ma”.[8] Furthermore, idealized physical systems, in which laws apply perfectly, could eventually describe unphysical situations; thus, a law of nature could give rise to an unnatural situation. For example, Norton’s dome demonstrates that a mathematically described mechanical system undergoes to an unphysical evolution, since the two solutions to the equation regulating the motion of a ball set on top of a dome (of a peculiar shape) are in contrast with each other; moreover, one of these solutions describes a typology of spontaneous motion that is ruled out by basic physical principles.[9]

It is manifest even from this quick review that each characteristic presented brings about several problems to be tackled. Strong definitions of the laws of nature imply that they should be universally and literally true, but verifying this claim is almost impossible; the approximated character of our in-use laws just makes the situation even worse. Moreover, it is equally evident that there is no definite, completely satisfactory and unanimous answer to the question “what is a law of nature?”. Turning the attention to the

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[7] B. Van Fraassen, *Laws and Symmetry*, 1989. Pg 27.
[8] M. Lange, “Natural Laws and the Problem of Provisos”, 1993. *Erkenntnis*, 38. Pg. 235. Lange provides an example using the law of thermal expansion, but the arguments can be easily extended to Newton’s laws of motion – e.g. taking in consideration inertial and non-inertial frameworks.
[9] J. D. Norton, “The Dome: an unexpectedly simple failure of determinism”, 2008. *Philosophy of Science 75*.

history of the concepts, how it was first used and how it evolved in accord to science progress, could help in clarifying the issue.

1.1.2. Historical survey: an origin to the laws of nature?

In this section, I am questioning whether there are some continuities in the use of the term in the history of science. My aim is to illustrate that indeed this concept underwent to an historical evolution, and thus is not an immutable, self-evident and self-explaining feature of scientific knowledge, independently from their actual existence or their usage by scientific communities. I am focusing on the works on the subject by the science historians Edgar Zilsel, Jane E. Ruby, John R. Milton and John Henry[10], inquiring the possible origins of the term. Also in this case, there is no unanimous agreement over the subject matter, and each of them, trying to identify an exact period in which laws of nature entered natural sciences, at the end points to a different solution. On the other hand, all scholars tend to agree on the pivotal role of Descartes in shaping and spreading the modern intending of laws of nature, bus still they disagree over the priority of Descartes' use of the term. Indeed he admittedly based his mechanist philosophy upon eternal laws that all pieces of matter obey; these laws describing how these pieces of matter actively interact in terms of their velocity and linear momentum. He was able to build a coherent account of the physical world events, and thus of natural phenomena, just using matter and motion obeying specific and mathematically defined laws of nature. So, it is interesting to inquire whether Descartes' use of the term was essentially a novelty or a direct consequence of previous (proto-)scientific accounts.

Zilsel claims that the term first appeared in the seventeenth century, thanks to Descartes and the development of absolute monarchies that entailed the idea of absolute laws. He dismisses all the ancient uses of the term as irrelevant, and considers the medieval use of the term as the accidental result of theologians' thinking about the impenetrable providence of God, and therefore unrelated with laws of nature as components of natural philosophies and, consequently, unrelated with the contemporary

[10] E. Zilsel, "The genesis of the concept of physical law", 1942. *The Philosophical Review* 51 : 3.
J. E. Ruby, "The origin of scientific law", 1986. *Journal of the History of Ideas* 47 : 3.
J. R. Milton, "Laws of Nature", 2000. *The Cambridge History of Seventeenth Century Philosophy*.
J. Henry, "Metaphysics and the origins of modern science: Descartes and the importance of laws of nature", 2004. *Early Science and Medicine* 9 : 2.

concept of laws of nature as related to scientific laws.[11] On the other hand, Ruby sees an explicable continuity between the first uses of the term "law" in Euclid's *Geometry* and the concept Descartes developed. Euclidean axiomatic methodology of inquire strongly influenced the development of mathematical sciences and, accordingly, she argues that laws of nature entered the scientific discourse way much before Descartes, and gives Kepler's leges motuum and Bacon's optical laws as supporting instances. Still, she agrees with Zilsel that the concept of divine providence played no role in shaping the concept of laws of nature.[12] Milton, on the other hand, agrees with Zilsel that the laws of nature entered scientific discourses mainly through Descartes work; however, he strongly disagrees on the reasons and the context behind this historical fact. He states that the fourteenth century richness of discussion over natural laws in the fields of nominalist theology was quickly assimilated by seventeenth century natural philosophy, for example with Descartes, Boyle, Leibniz and Newton. So, he argues that the main source of the appearing of laws of nature is the theological realm, but interestingly sets the actual origin of laws of nature as inherent components of natural sciences even after Descartes, stressing Newton's *Principia mathematica* primary importance in defining the modern conception of a scientific law.[13] Finally, Henry still agrees that our modern conception of laws of nature strongly relies on Descartes' definition, but he grounds it in the correlations between Descartes' mathematical background and his 'metaphysical turn'. Descartes started to consider God-given laws of nature when in need of a causal justification, and thus a foundational basis, for his mechanist philosophy. Henry thus agrees with Zilsel and Milton on the period in which the concept was fully developed, but also agrees with Ruby that it was due to philosophical considerations.[14]

So, it is evident that there is no commonly shared opinion on setting a historically well-defined origin to the laws of nature as a feature of natural philosophy research. Thus, this analysis is not really helpful if we aim to a material definition of the concept; on the other hand, it shows that laws of nature were, implicitly or explicitly, almost always present in the realm of philosophy. Moreover, laws of nature - whatever definition we decide to take as valid - underwent to an historical evolution, thus it would be

[11] E. Zilsel, "The genesis of the concept of physical law"(1942)
[12] J. E. Ruby, "The origin of scientific law" (1986)
[13] J. R. Milton, "Laws of Nature" (2000)
[14] J. Henry, "Metaphysics and the origins of modern science" (2004). Pg. 99

wrong to consider them as immutable and objective characteristics of scientific quests. Still, all scholars tend to agree on two main points: Descartes has been a major personality that allowed laws of nature to enter scientific discourses, and Newton's laws of motion were essential to spread this concept within scientific communities. So, if focusing on the origin of the term did not help in finding a clear-cut definition, trying to describe how later scientists began to use the term could shine some light on the issue.

The historian of natural sciences F. van Lunteren tackles this problem in a recent article published in the online blog Shells & Pebbles.[15] He gives an overview of how scientific communities started to refer to specific scientific results as 'laws', describing for example the genesis of Buys Ballot's law and Mendel's law. He claims that laws in science began to flourish for reasons that are not scientific at all; for example, Buys Ballot's law as a scientific justification to unscientific practices of weather forecasting, and Mendel's law as the result of a debate between two rival scientists, Correns and de Vries. Van Lunteren finds an interesting pattern that could generalize these developments, i.e. laws possession as a mean of authentication of mature sciences. This fact is thus strictly connected with the justification of new disciplines creations, e.g. Mendelians willing to isolate the study of heredity from the broader context of biology. On the light of the previous analysis, establishing laws of nature as the result of disciplinary characterizations is also related to Newton's laws of motion impact on his contemporary scientific communities: Newton's *Principia mathematica* revolutionized natural sciences methodology and is often considered the hallmark identifying the birth of modern physics[16]; his account strongly relies on specific laws, as the laws of motion and the law of gravitation. Consequently, disciplines aiming at receiving the label of 'exact sciences' by their contemporary communities, needed to confront with Newton and with physics, and thus found themselves in necessity to establish clear-cut mathematical principles defining the specific discipline. Furthermore, still focusing on the discipline of physics, van Lunteren finds another interesting pattern concerning the use of laws in science, namely the disappearance of eponymous laws during the twentieth century in favor of, for instance, equations, principles, equalities. He offers some possible reasons to this fact, as the culmination

[15] F. van Lunteren, "The missing history of the laws of nature", 2016. Published on Shells & Pebbles.
[16] The fact that 'Newtonian mechanics' and 'classical mechanics' are freely used as synonyms offers an example of this claim.

of the continuous shift from natural philosophy based on theological considerations, to a fully secular physics or, even more interestingly, to "the realization that even the hardest scientific laws – Newton's laws […] – were at best approximations"[17]. So, Newtonian mechanics – or, at least, its foundational principles, appears to play a role also in this conceptual shift, as a sort of term of paragon which new developments have to confront with.

To conclude this introductory section, it is necessary to link the themes presented above and *Le Leggi della Natura*. This content, i.e. the analysis of laws of nature as philosophical and historical categories, is not the main issue at stake in the itinerary, and thus there is almost no explicit reference to this analysis. I do not refer to Zilsel or van Lunteren directly; however, the results presented worked as starting hypotheses for designing the itinerary content. These results represents some core themes I want to make students reflect upon, in order for them to elaborate a personal opinion on whether laws of nature are the results of scientific inquire or just a conceptual framework to set scientific results within, or whether they do play no active role whatsoever in science. The results can be formalized as follows:

(1) Laws of nature, despite an extensive use of the term in science and philosophy of science, do not have a unique and objective definition.

(2) The conceptual characteristics (being mathematical, universal, true, ...) a law of nature should have actually depends upon metaphysical considerations.

(3) Laws of nature do not have an historically well-defined origin, even though Descartes and Newton played an important role in popularizing them.

(4) The reasons behind the formalization of a certain scientific result as a 'law' strongly relies on extra-scientific matters too - this being demonstrated by the flourishing and successive disappearance of laws in scientific publications.

[17] F. van Lunteren, "The missing history of the laws of nature", 2016. Pg.4

1.2. INTRODUCTION TO THE GUIDED ITINERARY

In the previous section I quickly presented how the laws of nature can describe the nature and the evolution of science, summarized by points (1) to (4). However, laws of nature prove useful also in connecting the museum, its collection and educational agenda, with the subject areas the itinerary focuses on: mathematics, physics and biology. To guide students and teachers through the museum halls and, at the same time, to expose and explain scientific concepts, I present audiences with different laws, each of which with its peculiar characteristics. Indeed, a mathematical law is different from a biological one which, at the same time, is different from a physical law. Interestingly, even laws pertaining to the same realm could strongly differ and, to some extent, appear irreconcilable (e.g. in physics, with statistical mechanics and thermodynamics[18]). To see whether a reconciliation of these differences is possible, I will focus on laws set at the borders of these disciplines: I will look at mathematical and physical laws, confronting them in their application to biological problems.

The itinerary analysis of the laws of nature thus entails a great degree of transdisciplinary arguments, touching both scientific and extra-scientific issues, both technical and contextual knowledge, coherently presented by the use of history and philosophy of science. For example, whereas philosophy of science can describe how different disciplines intercommunicate when ‘using’ the same laws, an historical analysis of such laws explains the reasons behind the intercommunication, offering the specific socio-cultural background. Thus, HPS ultimately shows that a definition of laws of nature, detached from its range of application, historical context and also region of formulation, is inherently empty. Starting from this fact, I want to make students realistically reflect on the evolution and on the actual content of science, offering a view on scientific practices detached from immutable and completely unquestionable knowledge, where exact definition corresponds to unique laws.

However, in order for the reader to fully comprehend how *Le Leggi della Natura* conveys this kind of content, it is necessary to introduce how the itinerary is pragmatically delivered within the museum halls (section 1.2.1), and the main mathematics, physics and biology issues at stake (section 1.2.2). The content

[18] J. Uffink, *Compendium of the Foundations of Classical Statistical Physics*, 2006.

of this last two sections concludes the Introduction chapter, after which I will focus with much greater detail on the didactical use of the laws of nature in a SCE product.

1.2.1. *Le Leggi della Natura* @ MSN

To contextualize the itinerary, it is necessary to introduce the museum itself. Venice Natural History Museum MSN is institutionally part of MUVE, the main regulatory organ of Venice civic museums, which comprehends also Palazzo Grassi, Palazzo Ducale, Ca' Pesaro, Palazzo Fortuny and other seven museums. Unity makes strength and, accordingly, since MUVE foundation, all the museums involved in the project underwent to a radical innovation in their expositive features, inner architecture and even in the collection objects, that reflected into an overall increased public affluence. MUVE is a unique and comprehensive organization capable to manage a great portion of Venice artistic, scientific and technical culture, regulating all the aspects of the museums, curing temporary expositions, organizing fund raising events and museum-specific educational agendas. On the other hand, MUVE results in a heterogeneous organization, especially due to the variety of the museums involved in the project. The most known ones are probably Palazzo Ducale, which deals with the history of the Republic of Venice, and Palazzo Grassi, exposing Venetian art. Therefore, they are both historical-artistic museums; the same is valid, for instance, for Correr Museum, Ca' Rezzonico and Palazzo Fortuny. At the same time, MUVE manages also a museum that combines the commonly-shared historical attitude with sciences. This is the Museum of Natural History (MSN), and it collects different objects and specimens from different ages, pertaining to the realms of biology, ethology, anthropology and paleontology. MSN is rather different from other MUVE museums, since it focuses explicitly on naturalistic content. Moreover, other MUVE museums quite often hosts temporary exhibitions, whereas MSN bases its educational agenda mainly on its permanent collection, due to the recent restructuration and requalification of numerous halls, and to the huge extension of the collection per se. Temporary exhibitions are still present, but organized with an attitude more directed to academic research in the field of natural history and biology, than to science teaching and pop communication.

The content differences between MSN and other MUVE museums reflect in a rather different attitude towards guided tours and educational activities, despite these activities being regulated by the same norms and prescriptions and, more generally, by MUVE educational agenda. Natural History Museum offers a wide range of different activities, such as frontal guided tours within specific museum areas, and workshops in which students and teachers are involved in first person in practical activities. I wanted to design an itinerary set in between these two types of visit, to preserve their advantages and at the same to compensate for the disadvantages of both. In fact, in recent literature, frontal lessons are often described as rather surpassed, due to the inevitable gap that forms between the operator and students; thus educational operators must prefer interactive activities to connect audiences with the museum collection.[19] The risk of frontal lessons is audiences' perception of knowledge as given from above, whereas first-hand work on a specific problem allows students to pragmatically learn the methodological foundations of a problem, over obliging them to independently think about a resolution. On the other hand, frontal lessons still are the easiest way for the operator to present the content of a didactical itinerary in a structured way. During the itinerary, I deal with concepts that could appear rather complex for high-school students; therefore, some typical elements of frontal lessons were extremely useful to introduce these concepts. Moreover, I wanted to cover a vast portion of the museum – about half of the halls, and this that can be made only through a guided type of visit, with an educator explaining briefly the different object the tour encounters. However, I still believe that through workshops students learn better and can truly become familiar with new concepts. Thus, I maintained also some workshops aspects, such as a great degree of interaction between students, teachers and operator, the use of multimedia images and videos, and the first-hand manipulation of different objects of the museum collection. So, *Le Leggi della Natura*, after some sample deliveries, reached a stable presentation methodology, that can be described as an itinerant theoretical workshop, since I am still frontally presenting content, but just to offer a basis from which students can independently elaborate different concepts.

However, designing an educational itinerary is a complex task with many variables coming into play. Pertinence with the other guided tours offered by the museum, the necessity to deal with a specific number of objects already set in a specific order, the need to base the presentation on the audience's

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[19] A. Barry, "On interactivity. Consumers, citizens and culture", 1998. *The politics of display. Museums, science, culture*. Pg 85-87

background knowledge (thus, also trying to guess on the moment what subjects are too difficult or too easy), how to fit twenty students in a $20m^2$ hall: those are some instances of the various problems the didactical operator must take care of. I tried to accommodate for all the various issues arising structuring the itinerary in the following way.

The itinerary is divided in two parts: first, I introduce some philosophical issues in a didactical laboratory; these issues will be further developed during the second part that consists on the actual tour through some halls of the museum. However, in the introduction, I exhibit and make students play with some objects that I cannot bring with me during the guided tour due to their weight or fragility, and I use them to introduce several mathematics and physics concepts, such as fractals, spirals, different types of forces, energy, optimization. In the second part of the itinerary I guide students through the museum halls, starting in the Wunderkammer, an octagonal hall designed to resemble a sixteenth century museum hall, for then passing into the Scientific Museology hall, that is designed in resemblance of a nineteenth century museum hall. After that, I enter the newest halls of the museum, dedicated to the strategies of life and, more specifically, nutrition and motion. I focus more in deep in the halls relative to motion that inquire different types of animal and vegetal movements (specifically, no-motion, motion on surfaces and 3-dimensional motion). I now turn to present the specific technical contents I used in *Le Leggi della Natura.*

1.2.2. *Le Leggi della Natura* content: mathematics, physics, biology issues

During the guided tours, I present students different laws of nature that, to be conceptualized, can be divided in laws concerning the relations between mathematics and biology, and laws set at the borders of physics and biology. To start analyzing the main features of laws of nature, we first should consider the language in which these laws are formulated and, as Galilei said, the book of nature is written in mathematical language, and thus must be described using geometric forms and numbers. Accordingly, the first feature I inquire is relative to the role that mathematics occupies in scientific enterprise. Mathematics is for sure a useful tool, since it aims at reaching objective and exact results; however, using different examples, I will try to see if mathematics can be considered just a useful descriptive tool, or if it entails some stronger qualities in its application to real-world phenomena. I introduce the everlasting philosophical debate starting from the question: "To which extent is mathematics present in nature and, accordingly, to which extent is it a product of human mind? Did mathematics 'exist' before humans learnt to count and measure?" Trying to answer these questions allows students to think about the role that laws have for working scientists.

Indeed nature is rich of geometric forms, and through mathematical considerations scientists are able to explain the formation of minerals, the shapes of coasts, clouds, rivers, flowers and leaves, and ultimately animal physiology. Though different these natural objects are, the mathematical considerations used to describe them are quite similar one another. In fact, the same mathematical object is used to describe very different phenomena pertaining to very different realms: for example, fractals are mathematical objects whose quite recent formulation has been presented by the mathematician Mandelbrot to determine the length of a coastal shore. However, since his publication, scientists used fractal forms to explain a huge variety of natural phenomena, as the physical growth of corals or the structure of leaves and trees.[20] The first step of the itinerary is introducing students to this analytical methodology, namely comparing abstract mathematical forms to actual biological structures. Depending on the biological structure under consideration, the depth of the analysis can be set on different levels. Fractals are probably the most complex mathematical structures to explain to students, due both to their great degree of visual intricateness, and to their conceptual and geometrical complexity based on internal homothety. In order for students to fully understand why fractals are important for biology – and ultimately to connect them to prime examples of a natural laws – first it is useful to introduce them to simpler geometrical forms that we can find in nature and, most important, to explain the reason and the utility of these specific forms.

I usually start with a theme students are more familiar with, namely polygons, for then extend the considerations to new forms and relations. To introduce polygons, I make them look to a beehive. Students are usually familiar with regular polygons, and due to this fact, they can already interact and participate in first person in the discussion. When asked to define a regular hexagon, students are usually capable to

[20] See C. Genzo.,A. Logar *Margherite e Spirali, Cavolfiori e Frattali*, 2014. Quaderni dell'Orto Botanico di Trieste, 13. Burns A. M. "Recursion in Nature, Mathematics and Art" 2005. *Proceedings of Bridges Renaissance Banff*

answer quite correctly, pointing at the equality of angles and sides. Here I present students the first extrapolation of mathematics from nature. However, to try to formulate a correct natural law it is not sufficient to stop at this consideration, since it merely is a descriptive proposition, and laws of nature must entail also explanation and causality. ‘Beehives cells are hexagonal’ is not a natural law, since it merely describes a natural recurrence. In a completely frontal itinerary, the educational operator would be the main source for the explanation of this particular form. On the other hand, with *Le Leggi della Natura*, I like students to try to look for a resolution, and I usually use their responses (correcting them with a positive criticism when needed) to guide the discussion to the final answer. Accordingly, this final answer allows me to introduce an issue of primary importance for the itinerary: optimization. The reason behind the hexagonal form of beehive cells lies in the mathematical procedure of surface tessellation: it is mathematically demonstrable that filling a surface with hexagons optimizes the available area in relation to the sum of sides lengths. Bees and wasps, using the same amount of material to build the same number of cells, using hexagonal forms increase the total available volume,[21] and whether this is a law of nature is the first discussion point of the introduction. For example, from bees’ behavior it seems that the hexagonal form is accidental, caused by the way bees connect different cells together.[22] However, the geometrical consideration about optimizing the available space in relation to the surfaces, still remains true.

After these considerations, I present students another form they should be familiar with - although from my personal experience, it seems that they are not used to think about it in a mathematical way, using numerical considerations and geometrical devices. This form is the spiral. I introduce students to the analytical construction of spirals, referring to polar coordinates and the functional relation between radius length and rotation angle; furthermore, using fossil findings and present-day specimens of mollusks (as nautiluses and ammonites), I explain the differences between Archimedean and logarithmic spirals and how these differences are primarily important for biologists to recognize different species.[23] I focus

[21] L. Wahl et al. “Shear stresses in honeycomb sandwich plates: Analytical solution, finite element method and experimental verification”, 2012. *Journal of Sandwich Structures & Materials* 14 : 4.
[22] F. Nazzi “The hexagonal shape of the honeycomb cells depends on the construction behavior of bees”, 2016. *Scientific Reports* 6:28341.
[23] L. Bonometto, L.Mizzan *Forme e Significati. Osservazioni e riflessioni sugli animali del nostro mare*, 1989. Quaderni del Museo Civico di Storia Naturale di Venezia, 2.

especially on the nautilus for its peculiar proportions: its shell respects the golden spiral canon derived from Fibonacci succession. The analysis is twofold: I deal with the mathematics behind the golden spiral and, at the same time, I analyze more in deep the 'mathematics in nature' concept. This is done by a brief historical analysis of how the golden ratio was used by pre-modern scholars (e.g. Pacioli, Leonardo) as a justification for their (pre-)scientific results. However, recalling beehives' example, "nautilus shells are golden spirals" is not a law of nature (and, as we shall see later in chapter 2, not even completely true), because it lacks the causal explanation of the natural recurrence. Whereas students arrive to the causal explanation for beehives' form quite easily, completing the sentence "nautilus shell has the golden spiral proportions because …" usually turns onto a guessing match. This is reasonable, since the answer entails an interdisciplinary approach and some higher-level concepts that I tried to simplify to audiences. The commonly accepted resolution of the problem lies in a mathematical model, whose growth is regulated by mechanical considerations.[24]

I then return to deal with fractal geometries, which are the last mathematical issue of the didactical laboratory introduction, to explain how they result from an iteration process where the same figure repeats equal to itself at different scales. To explain these geometrical figures, I focus on corals, whose structure can be described using a simple fractal iteration. The reason behind corals' fractal structure lies on arguments I already presented to students, i.e. the concept of optimization of external surface in relation to the overall volume of the animal.[25] My main aim is showing that different structures can serve the same adaptation scope: corals use this modular growth to optimize the surface that is in contact with the water, still occupying a limited volume, which is also the same reason behind sponges' holed structures. On the other hand, several corals species, instead of following a fractal growth, evolve according to non-Euclidean geometries.[26] To display how curved geometries can optimize the external surface in relation to the overall volume occupied in the ecosystem, I use a pragmatic example – that is not completely accurate, but nevertheless capable to transmit immediately the specific concept I wanted the students to reflect upon. I

[24] D. Moulton et al. "The morpho-mechanical basis of ammonite form", 2014. *Journal of Theoretical Biology* 364.
[25] S. J. Purkis et al. "Fractal patterns of coral communities: evidence from remote sensing", 2006. *Proceedings of the 10th International Coral Reef Symposium*. 1753-1762.
[26] Wertheim M. "The beautiful math of corals", 2012. TED.Ed lessons.

use a simple paper sheet: it has a surface S=x*y and occupies an extension given by V=x*y*z, where the variables x, y and z represent the sides of the sheet. The sheet is very thin, therefore V can be approximated to S. However, we should take into consideration the characteristics of the external ambient, which in this case is quite peculiar, namely water. Considering the sheet to represent our coral, the actual volume needed to survive is bigger than V, since the sheet will not be motionless, but will move as the result of currents and waves, fishes passing nearby, and so on. Therefore, the total volume the coral needs to freely move will be bigger and, in first approximation, represented by the half disc with an extension equal to $V' \approx 2\pi*x*S$. After explaining these starting hypotheses, I hand students a paper sheet and ask them to crumple it, for then reflecting on the volume that such an object would occupy in water. The folded sheet represents the actual shape of corals and the new volume needed is smaller than V'; however, being the sheet the same, the surface exposed to water remains also the same. In the crumpled situation, the overall structure is more intricate but, since water is a fluid and therefore covers all the volume available, it can reach even the most hidden folding.

In accord with the previous example, I then proceed to explain other natural shapes but, instead of mathematically describe the specific forms, I start to extensively deal with the physical justification behind the presence of specific shapes. Thus, physics replace mathematics in analyzing different natural phenomena to see whether a conceptual difference arises, but still with the ultimate scope of defining different laws of nature. For this purpose, I consider again marine animals, retaking shells in hands: I compare two bivalve shells, pectens' and clams', to point out their structural difference. Their shells are structurally not much different; however, considering two shells of a comparable size, pecten's one are much thinner. The reason for this lies in their different behavior: whereas clams live under the sand bottom of the sea, pectens use their shells to swim, rapidly opening and closing them to create a propulsion mechanism. So, the situation seems rather strange: pectens' propulsion should require a more resistant shell, since it is subjected to more intense and more frequent stresses than clams. How is it possible, then, that their shells seem more fragile? The explanation for this strange phenomenon lies in the peculiar structure of pectens' shells: their surface is folded several times to form an undulated structure and, through a physical analysis based on rigid-bodies considerations, it is possible to demonstrate that using the same amount of material, an undulated structure increases the resistance of the structure.[27] Students can reflect over this fact in first person through another simple example involving paper sheets. Right after the display of the two exemplars, I hand them a paper sheet, and ask to reproduce the pecten's shell folding the sheet six-to-ten times. After this operation, I ask to balance a pen over it, holding the paper by the two vertexes of a side perpendicular to the foldings. At the same time, I try to do the same with the unfolded sheet, which is obviously impossible. I use this example to make students realize that the folded paper can support a weight – and therefore a force – that the other sheet is not able to support.

To inquire another natural phenomena through physical considerations, I then proceed to present audiences a natural 'superpower', namely geckos' capacity of climbing any vertical wall. This example serves the scope of introducing the concept of balance of forces and more specifically static friction force, which is what allows geckos to defy gravity. However, I do not immediately explain the origin of the friction force, and students' answers usually involves suction pads structures that should be present in the animal's feet. However, this is not the case: geckos use a phenomenon known as dry adherence, based on contact electrification and van der Waals forces.[28] The adherence mechanisms is due to geckos' adapted toe pads: microscopic hair-like structures cover each pad, and further subdivide into smaller tips. Each one of these tips contributes only for a small attraction, but summing all these adherence forces we obtain an overall force of about 10 N per foot, which is quite impressive considering geckos' dimensions. Later, the conclusive part of the tour develops within the museum halls dedicated to motion. I use the halls inquiring three-dimensional motion (flying, swimming) to introduce students to the discipline of fluid dynamics and, accordingly, to Navier-Stokes equations, starting from the question: "How is it possible, then, that the laws regulating the motion of a bird is the same as the laws regulating the motion of a fish but, at the same, it is different from the laws regulating the overall motion of fifty birds?" To inquire more in detail this question, and to better comprehend the relations between the previous examples and the laws of nature, it is first necessary to focus on the relations between HPS and the laws of nature, and HPS and SCE.

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[27] L. Bonometto, L. Mizzan *Forme e Significati. Osservazioni e riflessioni sugli animali del nostro mare* (1989). Pg. 68.
[28] K. Autumn "How Gecko Toes Stick", 2006. *American Scientist* 94.

2. THE LAWS OF NATURE AND SCIENCE TEACHING

All the content presented earlier, as it appears, is strictly scientific, since I am just describing mathematical or physical considerations to explain natural recurrences. To understand the primarily important role of HPS for this type of content, it is necessary to analyze how the laws of nature enters the realm of science teaching. With some specific examples from *Le Leggi della Natura*, I now demonstrate how HPS content is naturally embedded in these technical considerations. The following chapter deals with the laws of nature as educational tools: I will start from a literature review of how history and philosophy of science help science teaching, for then focus more in detail on the concept of laws of nature.

2.1 HPS AND SCIENCE EDUCATION

M. R. Matthews, philosopher of science specialized in science education, in his article "Science Teaching: the role of history and philosophy of science", states that education and culture are strongly and indissolubly interwoven: "Education systems have the responsibility to identify and transmit the best of our cultural heritage".[29] In the case of science, the specific cultural heritage comprehends not only scientific contents, but also its working proceedings. Moreover, due to the primarily important role that science has in our present-day society, it is essential to form future scientists and science teachers not only in scientific contents, but also on its more cultural features, that can be inquired only through the use of history and philosophy. Accordingly, the learning *of* science, of its theories, models and laws, needs to be accompanied by the learning *about* science, such as how scientific knowledge is produced by scientists, which ultimately are individuals with their own human idiosyncrasies, working within a society. The inclusion of what Matthews titled 'liberal scientific knowledge' in science curricula aims at giving a human face to science, to connect more technical results with ethical, cultural and political concerns, placing science in a broader intellectual and social context.

Working scientists and engineers need to have different kinds of knowledge of their discipline to have a complete view of the problems under examination. This knowledge can be itemized as falling within

[29] M. Matthews, *Science Teaching: the Role of History and Philosophy of Science,* 1994. Pg. 213.

three categories, namely ontological, epistemological and ethical. Furthermore, it aims at forming individuals that are prepared in learning, learning about and doing science and technology, with the additive ultimate goal of a sensitive sociopolitical engaging.[30] The discipline of HPS explicitly focuses at inquiring these three types of knowledge and their mutual relations. The biology-trained historian of science J. Maienschein takes the discipline of HPS to include all the work examining science content, context and impact,[31] whereas R. Creath, historian of biology, goes even further, listing features of scientific enterprise that inherently have historical character – e.g. in declaring certain experiments as crucial or a scientific result a novelty in the specific disciplinary field. Therefore, including historical and philosophical knowledge is not only useful, but even necessary to describe accurately science unfolding.[32] An essential character of the inclusion of HPS in SCE entails the explanation of what in literature is referred to as NOS, the Nature of Science, describing the ways in which scientific knowledge is produced and later received and validated by different types of audiences, the conceptual relations between theory and experimentation and, ultimately, the features of scientific method(s).[33] These examples illustrate the widely shared opinion that science teaching benefits from including HPS elements, ultimately forming scientists to be not mere and neutral fact-finders, but as individuals of a society, trained in technical and cultural issues, able to understand the rules of the game in play during work-in-progress science[34].

In the previous paragraph I underlined the reasons behind the HPS-SCE connection, thus *why* HPS and SCE should work together; however, *how* to do it still remains unspecified. With the present thesis, I want to study more in deep how it is possible to integrate efficaciously HPS in a SCE product, taking *Le Leggi della Natura* pragmatic example as starting point. I propose that any SCE product, even the most 'technical' one, inherently includes several transdisciplinary concepts, and exactly focusing on these concepts we can have an effective (and, even more important, interesting) science teaching. My approach

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[30] V. M. Vesterinen, G. Smith. "History, Philosophy, and Sociology of Science and Science-Technology-Society Traditions in Science Education: Continuities and Discontinuities", 2014. *International Handbook of Research in History, Philosophy and Science Teaching [Int. Handbook of HPS&ST]*. Pg. 1915-1916.
[31] J. Maienschein et al., "What Difference does History of Science make, anyway?", 2008. *Isis*, 99 : 2. Pg. 319.
[32] R. Creath, "The Role of History in Science", 2009. *Journal of the History of Biology* 43. Pg. 212-213.
[33] D. Hodson, "Nature of Science in the Science Curriculum: Origin, Development, Implications and Shifting Emphases", 2014. *Int. Handbook of HPS&ST*. Pg. 919-920.
[34] V. M. Vesterinen et al. "History, Philosophy, and Sociology of Science and STS Traditions" (2014). Pg. 1918.

has a quite distinct characteristic: instead of introducing historical and philosophical content in support of specific scientific concepts (e.g. mechanics and fluid dynamics laws), I worked the other way round, focusing on historical and philosophical themes to laterally and implicitly explain more technical issues, such as equations solutions or recurrent geometrical forms in nature. I decided to use the laws of nature as the main theme, due to their inherent characteristics of being an interdisciplinary concept extensively used in scientific literature, but at the same time that cannot be easily defined without incurring in some extra-scientific problems; therefore, I used these characteristics of the laws of nature to map the specific NOS contents I wanted to present students with. Thus, I used the laws of nature as transdisciplinary concept to glue together technical, philosophical, historical and sociological considerations in a comprehensive SCE product. My answer to the previous question concerning *how* should educators embed HPS in SCE, is that through transdisciplinary concepts such as the laws of nature we have a crucial and pragmatic instance. I thus claim that the laws of nature are an essential educational tool for science education and communication.

Surprisingly, although much has been written about the concept of laws of nature, virtually no author explored their didactical import. Neither historians or philosophers, nor researchers in the science education field, dealt with the laws of nature as an educational tool, focusing on other equally important aspects of the laws of nature, intended as a philosophical or historical category. [35] I found just one example where laws are inquired for their didactical value;[36] however, the broader subject area of this article is biology and chemistry teaching, whereas *Le Leggi della Natura* explicitly focuses on mathematics and physics. Moreover, the conceptualization of the laws under examination is quite different too: the authors specifically deal with scientific laws, while I focus on the laws of nature. This represents another important issue for the itinerary delivery, namely the conceptual difference between laws of nature and laws of

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[35] See for example: E. Zilsel " The Genesis of the Concept of Physical Law" (1942), J. Henry "Metaphysics and the Origins of Modern Science: Descartes and the Importance of Laws of Nature" (2004), J. Ruby "The Origins of Scientific Law" (1986), J. Milton "Laws of Nature" (2000), R. Giere *Science without Laws* (1999), J. Roberts "Laws of Nature as an indexical term" (1998), B. Van Fraassen, *Laws and Simmetry* (1989), F. van Lunteren "The missing history of the laws of nature" (2016). J. Henry "Galileo and the Scientific Revolution: The Importance of his Kinematics", 2011. *Galilæana* VIII.

[36] Z. R. Dagher, S. Erduran "Laws and Explanations in Biology and Chemistry: Philosophical Perspectives and Educational Implication". 2014. *Int. Handbook of HPS&ST*.

science. Scientific laws are usually just approximations of the truth, therefore considered as instruments for scientific enquire. However, if scientific laws are just approximated truths, there must be some other more complex law that describes the factual truth. Laws of nature are thus represented by these literally true laws.[37]

Generally, the majority of articles concerning HPS and science education embeds HPS in a technical context, using the history of a discipline to explain its present state on the basis of its past progresses and events, structuring the specific SCE product to follow the 'linear evolution' that led to present conceptions, also clarifying past misconceptions. Some examples of this approach include *Using History to Teach Mechanics* – C. Gauld[38], and *Teaching About Thermal Phenomena and Thermodynamics: The Contribution of the History and Philosophy of Science* - U. Besson[39]. Other approaches include the use of historical experiments to build first-hand knowledge, therefore miming how science was pragmatically done at the time, exhibiting also the educational benefits of re-doing these historical experiments.[40] Similar considerations can be put forward in museums contexts, when dealing with historical collections, with the specific scope of studying of scientific practices.[41]

2.1.1. HPS & SCE: two examples

To describe the main characteristics of the HPS implementation I used in *Le Leggi della Natura*, it is useful to start from two practical examples. The first example has been developed by Matthews, a pioneer in the study of NOS didactical import, and inquires how HPS can be used in explaining the pendulum motion.[42] This is a primary important issue in science education, and through an historical analysis Matthews illustrates how the study and manipulation of pendulum shaped in many ways science evolution. For example, focusing on the technological relevance of the pendulum, he describes how its study

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[37] J. W. Carroll, "Laws of Nature" (2016)
[38] C. Gauld, "Using History to Teach Mechanics", 2014. *Int. Handbook of HPS&ST.*
[39] U. Besson "Teaching About Thermal Phenomena and Thermodynamics: The Contribution of HPS", 2014 *Int. Handbook of HPS&ST.*
[40] Two examples can be found in P. Heering "Science Museums and Science Education", *2017. Isis* 108 : 2
[41] S. Alberti, "Objects and the Museum" 2005. *Isis* 96 : 4. Pg 569. The article's subject is not specifically science education. However, he deals with the public engagement of scientific issues; thus, I consider his claims over the possibility of improving science communication to be valid for, and transportable to, science education.
[42] M. Matthews "Pendulum Motion: A Case Study in How History and Philosophy Can Contribute to Science Education", 2014. *Int. Handbook of HPS&ST.*

established accurate methods of timekeeping. An interesting claim he is putting forward is that Galilei, Newton and Huygens, studying the pendulum motion, demonstrated that fundamental laws are universal in the solar system, and relating this claim to the concept of laws of nature comes straightforwardly. Thus, in this case, though implicit, there is still a reference to the evolution and the conception of the laws of nature, in support of my thesis that laws of nature are almost omnipresent in accurate historical reconstructions of science proceedings, as analytical categories. However, an interesting theme of Matthews' article is a methodological reconstruction of how to improve science curricula: he describes, in the case of pendulum motion, what material to teach and where to place the specific topics and concepts.

The science of pendulum motion connects with important topics in religion, history, philosophy and literature, and Matthews offers the following diagram as a schematic reconstruction of the transdisciplinary connections that must be made clear in including historical and philosophical issues in science education. The columns represent curriculum subjects and the circles the topics within subjects. This diagram displays the inherent transdisciplinary connections that are present in Matthews' SCE product; moreover, the diagram should reveal the integrative function of HPS in science curricula.[43]

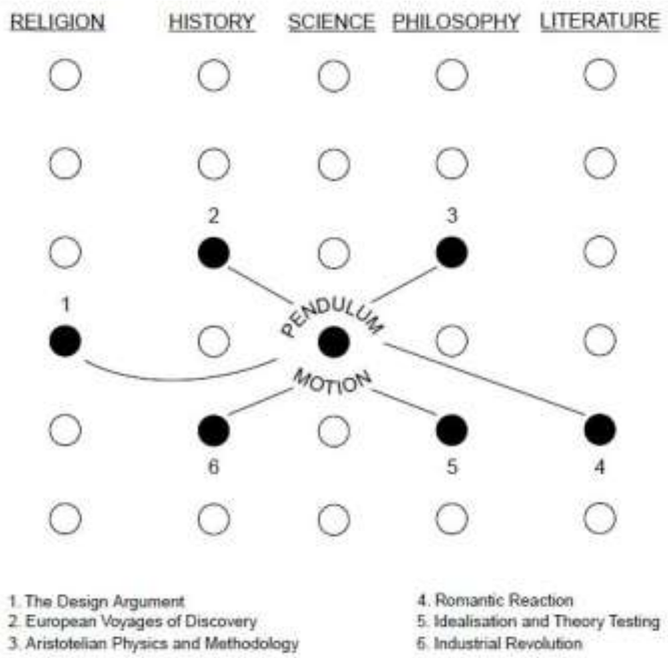

Figure 1: HPS-informed curriculum.

[43] HPS is intended not just as philosophy of science plus history of science, but as an umbrella discipline capable to include themes pertaining to different disciplines, e.g. religion. Thus, in Matthews' example, HPS encompasses all the five different subjects touched by a culturally-informed study of the pendulum motion.

I tried to follow a similar account in *Le Leggi della Natura*, clarifying to audiences the disciplinary interconnections used. However, *Le Leggi della Natura* aimed at offering a novel and broader view of science, where the disciplinary boundaries are just artifacts, useful for pragmatically structuring education, but do not completely represent the actual evolution of science - e.g. describing Einstein's theory of relativity impact on the contemporary scientific communities, it is necessary to rely also on foundations of physics considerations, therefore falling outside strictly defined scientific boundaries to end up within philosophy.

The second example I would like to present comes from a more recent publication on *Isis*, by Peter Heering, professor of physics and its didactic, and I will use it to present another important characteristics that an effective HPS-based SCE product should have. Matthews' example served the scope of describing the necessity of an interdisciplinary approach, whereas now I will focus on the presentation characteristics, to demonstrate how much a dialogic type of itinerary, instead than frontal-lessons, improves my SCE product. Heering describes the use of a solar microscope, an eighteenth century device that uses sunlight to project the image of microscopic specimens on a screen, thus enabling large groups of people to view the image simultaneously, and therefore allowing them to discuss about what they see. This approach transforms audiences in active agents of the specific SCE product, making them capable to reflect not only on the specific scientific issue at stake, but also on their role as observers, formulating insights equally on science and its history, and also on the practical skills necessary to undertake first-hand research. Here, Heering explains the importance of building an SCE product with the specific scope of having an elevate degree of interaction between different agents – for example, between teachers and students, and between students themselves. This dialogic characteristic is easily introduced by virtue of HPS disciplinary features.

I consider these examples to be very effective ways to include HPS into SCE, and indeed I used the previously described characteristics, namely interdisciplinarity and interactivity, as conceptual milestones in designing *Le Leggi della Natura*. On the other hand, as quickly explained earlier, I wanted to use HPS not only as support content to deliver specific scientific issues, but as the main theme of the itinerary itself.

Considering Matthews' image, the core of the scheme would be the laws of nature, that accordingly cannot be easily reduced to be an argument just falling within science or just falling within history or philosophy, but to have a complete overview of the issue at stake, it is necessary to consider the subject as a whole, not divisible in specific themes pertaining to just one disciplinary realm. For example, teachers could explain an historical experiment with no reference to the history behind it, or without any reference to the broader cultural context the experiment was set within. Similarly, pendulum motion can be explained technically with no reference whatsoever to its history, just with equations and mathematical variables. In this way, teachers would present just a truncated – and less interesting - version of the story, but they could convey some technical knowledge anyway. On the other hand, I designed *Le Leggi della Natura* in such a way that, without HPS, it would be lacking a huge portion of the whole content, beside just a bunch of different scientific laws with no apparent connection whatsoever. Thus, without including historical and philosophical considerations in the itinerary, students would leave the museum with no idea of the main issue at stake.[44]

2.1.2. *Le Leggi della Natura* and Newtonian mechanics

During the itinerary, I touch the subject of Newtonian mechanics not through a frontal explanation, just with a set of different laws related to different equations to be resolved, but through an active reflection upon the application of these laws to natural phenomena. I thus try to guide students and teachers to the resolution of a problem from a rather small set of starting hypotheses. The first hypothesis I am conveying actually regards the history of the concept 'laws of nature', specifically used for describing phenomena pertaining to the physical realm. I usually start my analysis from Descartes' natural philosophy, therefore presenting students with an argument deeply rooted in history and philosophy. In *Le Monde* and in the *Principles of Philosophy*, he explicitly used the term, and used immutable laws of nature as the milestone of his mechanical philosophy – he thus was a precursor of the modern-day scientific attitude of expressing laws in rigorous mathematical terms. Descartes' laws of nature concern motions of bodies and

[44] As we will see in the Evaluation chapter, however, it seems that the majority of students, at the end of the itinerary, consider themselves not fully able to recognize a law of nature. On the other hand, this is not in contrast with the itinerary educational objectives, as will become clearer later.

represent a first formalization of what later would become the laws of mechanics, finding a later re-formalization in the work of Newton.

After this short historical review concerning the application to the concept of law to mechanics, I focus my explanations on a specific law: the law of inertia. Aristotle, in his tome *Physics*, already stated that every moving body, had to be put into motion by another body in motion hitting it. Similarly, Descartes' first law of nature asserts that "each thing always remains in the same state, and consequently, when it is once moved, it always continues to move", implying thus that a thing which is at rest, will remain at rest unless it is moved. Similarly, Newton's first law of motion, usually referred to as the law of inertia, is quite similar, stating that "an object at rest stays at rest and an object in motion stays in motion with the same speed and in the same direction unless acted upon by an unbalanced force." Therefore, unless en external force is acting on a resting body, the body would stay still.[45] At this point, I introduce audiences to a problematic situation. Newtonian mechanics, often paired with classical mechanics, is a highly effective tool for scientific research in different fields, and it still is one of the most used theories in scientific enterprise. It is therefore reasonable to assume that the laws of motion are laws of nature, in this case.[46] So, how can a law of nature be counterfactual with nature itself?[47] Newton's first law entails that there should not be any self-acceleration in nature, yet it appears to be: a lioness preying is staying still, hiding in the high grass until, at a certain moment, she springs at high velocity in the direction of the chosen prey. However, no external force acted on the lioness, and thus forced her to move; it appears that the lioness' motion started by itself. Similarly, a kangaroo can jump from a rest position with no problems; moreover, a typical crab of the south Venetian lagoon, called *mołeca* in the period it is changing its carapace, equally stands still and, if touched even with the softest pressure, runs away. However, the touch does not determine direction, velocity or acceleration of the crab, therefore it is definitely not the 'external force'

[45] I usually do not spend too much time in formalizing Newton's and Descartes' laws, even though sometimes students explicitly asked to explain them further, to understand if and where they actually differ. Another point for HPS-based approaches.

[46] Here, I go more in deep in questions concerning the relation between the laws of motion and the laws of nature (as 'hoe does nature *obey* the laws of motion?') only if asked by students or teachers to do so.

[47] This is a question I am always asking during the itinerary in order to introduce the specific problem. I earlier explained concepts in such a way that such a question would resemble a 'plot twist', to make the story I am telling more interesting and, at the end, more theatrical, inducing audiences to contradict themselves.

needed by Newton's law to explain the phenomenon. Equal considerations are valid for Venus flytraps. So, it seems that living beings do not respect the laws of mechanics. But this apparently wrong: they are laws of nature, how could nature not respect them?

There is a simple yet smart solution to the problem, and it entails introducing Newton's third law of motion (action and reaction), while thinking about the process in physical terms, thus using the balance of forces and describing heuristically the transformation between potential energy and kinetic energy. However, the educational operator explains this solution just in 'desperate cases', e.g. classes with no intentions whatsoever to participate in the dialogue. In the case students lack some prior knowledge on Newton's three laws of motion, the ideal situation would entail that the operator stops 'giving hints' after the introduction of inertia law and of action/reaction principle.

The necessity of including the concept of laws of nature in this example is twofold: first of all, laws of nature improve extensively the efficacy of the discourse, allowing for a 'Socratic' approach toward the problem. After inducing audiences to map the notion of laws of nature with the laws of mechanics with historically informed arguments,[48] they are presented with a simple situation that goes against the induced knowledge just presented,[49] and asked to come up with a resolution that makes use of a previous set of notions – in this case, action/reaction and energy conservation laws – which also quite resembles some typologies of physics research. Secondly, *Le Leggi della Natura* surely is a technical itinerary, but the main issue at stake is not a mere description of (a small part of) Newtonian mechanics. Laws of nature become particularly important due to their actual historical evolution, offering also big space for HPS-based inquiring. Did Newton(ians) keep calling the laws of motion laws of nature, even after the realization that they were approximated laws? And, in the case of a negative answer, how is it possible, since scientific communities considered classical mechanics the most accurate way to inquire, discover and describe natural phenomena?

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[48] Interestingly, Descartes himself dealt with the problem of animal self-acceleration in animal, describing a solution that is coherent with his natural philosophy, but still not completely scientific for modern tastes. To further deepen this subject see: R. Hassing, "Animals versus the Law of Inertia", 1992 *Review of Metaphysics* 46:1.

[49] In some cases, since this part of the itinerary takes place in the museum hall dedicated to animal motion on surfaces, students themselves are able to come up with this counterexample to the inertia law

2.2. LAWS OF NATURE AS EDUCATIONAL TOOLS

As introduced in the previous section, in my literature survey I found a lone example of the laws of nature used as didactical means – even though quite implicitly. Two professors of science education, Z. Dagher and S. Erduran, in chapter 37 of the *International Handbook of Research in History, Philosophy and Science Teaching*, deal explicitly with the philosophical perspectives and educational implications of laws and explanation in biology and chemistry. As presented above, I agree with their claim that “explanations, and particularly laws, have been understudied from an epistemological perspective in science education research”.[50] Yet, in literature concerning science and education I find a recurring statement that could partially explain this underestimation, namely that the goal of a science teacher should no longer be just instilling knowledge of scientific laws, theories and models.[51] Whereas I totally agree with this claim, that teaching laws should not be the *only* aim of science teachers, I also argue that the specific concept of the laws of nature is capable to explain scientific laws not only technically but also conceptually. This is due to the conceptual difference that exists between ‘scientific laws’ and ‘laws of nature’, that is also one of the main issues of the itinerary.[52] Moreover, focusing on this difference offers some meaningful insights over the nature of science, allowing to depart from the intending of science as an objective-facts-discovery factory. What I argue is that studying the nature and the characteristics of laws of nature satisfies exactly this scope.

In the itinerary, I use laws with a scope similar to what Z. Dagher and S. Erduran did in their article, namely providing a meta-level type of understanding of how particular domains of science engage with scientific knowledge in the making. On the other hand, there are some important differences between their approach and mine. Over the typology of laws inquired (as explained earlier, they are mostly concerned with the nature of scientific laws, whereas I deal specifically with laws of nature in relation to scientific laws), the most evident difference is in the disciplinary focus of the analysis: whether the article concerns

[50] Z. R. Dagher, S. Erduran. “Laws and Explanations in Biology and Chemistry: Philosophical Perspectives and Educational Implication” (2014). Pg. 1204.

[51] P. Heering “Science Museums and Science Education” (2017). M. Matthews, *Science Teaching: the role of HPS* (1994). Pg. 401.

[52] Once, during the introduction of the itinerary, a student immediately asked me whether there is a difference between scientific laws and laws of nature. This indicates that the very nature of the concepts under examination is capable to instill a sort of positive criticism in students, which is a successful feature of an HPS-based itinerary.

the history and philosophy of chemistry and biology, I was explicitly asked at the beginning of the itinerary design process to focus on physics and mathematics – and I found no reference in literature to the laws of nature used in a context of physics and mathematics didactic. However, I think they are particularly suited for this case, since a main characteristic of science (and physics in particular) is aiming at pure objectivity, reached by means of describing natural phenomena through mathematical relations. Discussing the laws of nature in relation to mathematics, the educational operator can introduce major philosophical issues in the foundations of science, as the realist/antirealist debate, discussing instrumentalist and neo-Pythagorean positions, and all the other various tenable positions in this multi-dimensional spectrum. Moreover, physics is often considered as the exact science par excellence, and discussing different physical laws allows students to reflect on the role of approximations in scientific enterprise, to see whether purely exact laws can actually exist in nature.

I offer an example of these considerations during the itinerary introduction, set into a laboratory, where students can manipulate, touch and observe closely different specimens of the museum collection. I use these specimens to introduce the concept of mathematical modeling, i.e. using mathematical tools to describe natural recurrences. As explained earlier in the introduction, through different mollusks shells I am introducing the mathematical construction of spiral forms, where the radius length is a function of the rotation angle. Similarly, I introduce them to the concept of fractal growth with different species of corals skeletons.

However, the example I emphasize the most concerns the nautilus shell, due to its particular form. Nautiluses shells are commonly considered to be golden spirals; these spirals are strictly connected with the Fibonacci numerical succession and the golden ratio. I focuses particularly on the golden ratio, since this number has been used in so many different contexts to model so many different phenomena and, moreover, in every visit there was at least one student capable to identify the golden spiral; it is therefore a commonly-known mathematical concept. The Italian Renaissance mathematician Luca Pacioli published a famous book titled *De Divina Proportione*: the divine proportion under examination is exactly the golden ratio, and this book provides a survey of the various disciplines (from arts and architecture to music and natural philosophy) that uses this proportion to vindicate for its omnipresence in nature.[53] Interestingly, *De Divina Proportione* illustrations are by the hand of Leonardo da Vinci, famous for using the golden ratio in several of his paintings, the Vitruvian man and Mona Lisa as well-known instances. Pop-science articles also often vindicates for the omnipresence of golden spirals and Fibonacci succession in nature: from pineapple to the positions of birds relaxing over wires, to galaxies forms.[54] Nautiluses shells are very frequently quoted as one of the clearest example of this omnipresence. However, through a simple experiment where students overlap a transparent sheet with a drawing of the golden spiral to a paper sheet with a print of the nautilus spiral, it becomes manifest that nautiluses shells do not actually follow the golden spiral evolution: the closer to the starting point of the spiral, the stronger the mismatch between the two mathematical forms becomes. Shall we conclude that pop science publications lie? Or that Pacioli was wrong in considering the golden proportion the ultimate example of nature intelligence, thus a divine entity?

This example serves the scope of making students reflect over the use of mathematical functions to fit natural forms and phenomena, and therefore over the role of approximations in scientific enquire. “In nature, several example of animal physiology respect the golden proportion” can thus be considered a law of nature?

2.3. EDUCATION IN NATURE OF SCIENCE (NOS)

As seen in the previous section, I consider the laws of nature to be a highly suitable instrument for science teaching mainly due to their transdisciplinary characteristics, that covers subjects pertaining to ‘pure’ science as well as religion. Therefore, the content of such concept can be easily mapped to represent knowledge about the nature of science and of scientific knowledge. But how does this mapping actually work? To understand the contribution that the use of laws of nature can bring to education, it is first necessary to have a formal definition of the Nature of Science (NOS) itself, and to describe how it is used in science education, to understand the specific issues and problems the laws of nature serve to clarify.

[53] A. Vervoordt et al, *PROPORTIO* (2015).
[54] See, for example: Boeyens J. “Golden Ratio offers Unity of Science”, 2014. Published in *phys.org*.
J. Marshall “What is the Fibonacci Sequence, and Why is it Famous?”, 2012. Online podcast for *Scientific American.*

D. Höttecke, professor specialized in Nature of Science teaching, defines the learning about NOS as a major objective of didactical HPS-based approach, since it is an umbrella concept capable to include both scientific processes and contexts, and critical reflections on science conditions and constraints as well.[55] Furthermore, he states that it is impossible to discern science education and NOS education: even if teachers restrict themselves to basic technical content transmission, in any case they are sending messages about science proceedings and goals, what matters to scientists and, ultimately, what science is. This is a case of implicit transmission of NOS content, which in science education literature is regarded as potentially dangerous, since it could offer a distorted view of science proceedings, in the case an a-historical approach is used.[56] [57] Focusing a SCE product on the laws of nature is an ideal way out the problem, since they allow for both an effective transmission of technical content, represented by the content of laws itself, and for an explicit treatment of the nature of science, for example offering different philosophical views on the meaning of the term 'law of nature', and the consequences of these different views on actual scientific practice. The laws of nature represent an explicit treatment of NOS issue by their intrinsic transdisciplinary features.

Arguing for the necessity of an explicit teaching of NOS content is further enforced by Matthews. Due to the characteristics of educational systems, mainly based on teacher-students relations, he argues that any student's representation of science is strongly teacher-influenced, since even after they forgot the details of what has been learnt in science class, their teacher's epistemological view still influences their intending of scientific enterprise and scientists' role in society.[58] Therefore, well-prepared teachers, aware of the specific NOS content they are transmitting to students, are primarily important for an efficient and coherent science teaching. Again, if teachers are willingly using laws of nature as a medium for specific content transfer, they must be aware, for instance, of the difference between laws of nature and scientific laws (which is in itself a NOS type of content), or of the historical evolution of the concept (e.g. why, at a

[55] D. Höttecke, C. C. Silva, "Why implementing History and Philosophy in School Science Education is a Challenge: An Analysis of Obstacles", 2011. *Journal of Science and Education* 20. Pg. 300.
[56] P. Heering "Science Museums and Science Education" (2017). Pg. 402.
[57] D. Höttecke, C. C. Silva, "Why implementing History and Philosophy in School Science Education is a Challenge: An Analysis of Obstacles" (2011). Pg. 300-302.
[58] D. Höttecke, C. C. Silva, "Why implementing History and Philosophy in School Science Education is a Challenge: An Analysis of Obstacles" (2011). Pg. 300-302

certain point in modern history, the term started to disappear from scientific literature), therefore offering them the pragmatic possibility of inquiring more in deep personal views on the subject. A teacher who does not have the full control of the whole content transmitted to students (even though just implicitly or laterally) is, at the end, teaching incomplete lessons. [59]

But what is, pragmatically, the nature of science? Even the most elementary analysis of science evolution displays that finding a specific, formal and unique answer to this question is an utopian task. Accordingly, the ultimate aim of *Le Leggi della Natura* is not offering students a specific view to take as granted or as exact, but exactly the opposite, namely guiding them in a personal elaboration of the concepts presented – for example, of what a law of nature is intended to be. Höttecke rightly points out that the history of science does not offer clear-cut sets of scientific facts[60]: the role of teacher thus becomes being a working mediator between multiple different opinions, views and interpretations. I designed my itinerary using this dialogic approach to be the milestone of the pragmatic visit through the museum halls, keeping attention in not just presenting facts and problems as knowledge given from above, but on offering the possibility to students to form their own knowledge through the exchanging of ideas.

2.3.1. Laws of Nature and NOS contents

In literature, different formalizations of NOS contents can be found. D. Hodson, professor of Science Education at the University of Auckland, clarifies the content of such an umbrella term as NOS. He notes that if we turn to literature, we find a slight misusage of the term as referring solely to epistemological issues.[61] He vindicates for broaden this term and, when authors refers solely to epistemological matters, they should specify that they are using Nature of Scientific Knowledge (NOSK) content. Combining NOSK with considerations over the nature of scientific enquire, we obtain a formalized account of NOS approach to science teaching. Such an account explicitly aims at describing to students, for

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[59] M. Matthews "Scheffler Revisited on the Role of History and Philosophy of Science in Science Teacher Education", 1997. *Studies in Philosophy and Education* 16. Pg. 170-171

[60] D. Höttecke, C. C. Silva, "Why implementing History and Philosophy in School Science Education is a Challenge: An Analysis of Obstacles" (2011). Pg. 301.

[61] D. Hodson, "Nature of Science in the Science Curriculum: Origin, Development, Implications and Shifting Emphases". (2014). Pg. 911-912.

example, scientists' reliance on empirical evidences, even though by the nature of scientific enterprise these evidences are theory-laden. Accordingly, another aim of NOS teaching is describing scientific knowledge as reliable but at the same time tentative, since science proceeds by mean of trials and errors.

The laws of nature are a particularly suitable concept for NOS teaching on the light of Hodson's analysis. However, it should be noted that an SCE product can be valid even with no use of the laws of nature as an educational tool. On the other hand, referring to such a concept allows to mediate efficaciously between NOSK and processes of scientific inquire contents. One example is represented by the last major theme I deal with in the itinerary, i.e. fluid dynamics. I touch this subject in two halls of the museum: the one dedicated to marine animals, where I inquire the physical laws regulating swim, and the one dedicated to flight. These two really different phenomena are actually more connected that it may appear: there is a unique physical law regulating both swimming and flying, this law represented by Navier-Stokes equations. Navier-Stokes equations are not much more than Newton's second law applied to the motion of fluids (liquid and gases); however, due to the complexity of the broad-ranged phenomena they describe, they result in nonlinear equations that are mathematically really tricky. For example, scientific community offers 1M dollars to the scholar that will be able to prove that a solution for the equations always exists – or, similarly, offering a counterexample to this claim.[62] Solving the equations can thus be really hard, so they are often found experimentally, collecting numerical data from the actual evolution of the system under consideration. For example, the study of the turbulences forming in the contact between fast winds and tall buildings (e.g. skyscraper) is a typical problem for which scientists use fluid dynamics considerations. However, finding analytical solutions to this system is truly hard due to the high number of variables under considerations, thus scientists need to use experimental data. However, collecting data from a skyscraper can also be extremely difficult – and, most of all, expensive – and, moreover, usually these studies are conducted before the building is actually built, so it seems that it is conceptually impossible to collect first-hand data. How do scientists resolve this situation? It is possible to find the solutions to the equation, i.e. the description of the motion of the air around the building, due to a

[62] https://www.theguardian.com/science/blog/2010/dec/14/million-dollars-maths-navier-stokes. For the official statement of the problem, see: http://www.claymath.org/sites/default/files/navierstokes.pdf

particular feature of the equations themselves, i.e. the fact that they are scalable: changing some parameters in the starting equation (as the dimension of the whole system, wind velocity, air pressure, …) scientists are able to have a small-scale version of the big-scale problem, where the air moves around the small-scale system exactly how it would do around the actual building. What changes between these systems is a dimensionless term to be found within the equations, known as Reynolds number, numerically defined as the ratio between inertial and viscous forces; it describes the typology of flow the fluid undergoes in the system evolution and includes all the information on the system initial conditions.

This is a first case where the same law applies to two different situations. However, the power of Navier-Stokes equations do not stop here. With the same 'scaling' mechanism, based on Reynolds number value, these equations can equally describe the motion of a body in water as the motion of a body in air. The actual motion of the fluid around the body would be different (so, it is a different case in respect to the skyscraper one) but the starting equations describing analytically the motion are the same. So, the same universal law applies to different creatures, that moves in different ways, from dolphins to mosquitoes, from jellyfishes to albatrosses.

So, finally, what is the specific NOS content that can be transmitted by examples coming from fluid dynamics? First of all, focusing on the laws of nature helps in formalizing what is science ultimate goal through pragmatic examples. Does the discovery of such laws represent science goal? Is there a difference between science and scientists' goals? These questions can be addressed with the specific example of Navier-Stokes equations, after having inquired what are the main features that can allow us to define this set of differential partial equations as law of nature. Accordingly, an issue often arises in this part of the itinerary, and can be summarized as: "are laws of nature better represented by equations, or by equations' solutions (e.g. by the laws of motion, or by the trajectories that these laws, once solved, identify)?". Secondly, fluid dynamics allow to tackle the conceptual difference existing between mathematical, computer and experimental models. These issues (Are Navier-Stokes equations laws of nature? Are Navier-Stokes equations solutions laws of nature? What is the conceptual difference between numerical, analytical and experimental solutions?) represent a typology of NOSK knowledge to be discussed together with students and teachers. Moreover, analyzing the discipline of fluid dynamics as an historical process, the mainstream approach describes fluid dynamics through a linear path to success, where all the major contributions have been made by white-skinned males (e.g. Torricelli, Pascal, Newton, Bernoulli, d'Alambert, Euler, …), thus enforcing a naïve conception of the nature of science. As Heering noted, from an educational point of view it is necessary to overcome the ivory-tower genius narrative:[63] first of all, it provides a description of science proceedings that is detached from the actual unfolding of scientific practices; secondly, with this narrative students are less capable to identify with the story told, diminishing the communicative power of the arguments. Focusing on present-day practices, on the other hand, allows to overcome this naïve approach, due to the focus on research groups instead than embellishing the contributions of individuals. The only 'lonely contributor' I usually present to audience in this part of the itinerary is E. Noether, to illustrate her contributions to the field of chaos theory, direct product of fluid dynamics and statistical mechanics.

[63] P. Heering "Science Museums and Science Education" (2017). Pg. 405.

3. EVALUATION OF THE DIDACTICAL ACTIVITY

3.1. EVALUATION SURVEYS: MAIN FEATURES

I received a general positive feedback from teachers and students. Numerous students expressed their interest over the subjects with questions and requests of clarification, whereas teachers seemed interested mostly in the interdisciplinary features of the itinerary and in the exposition methodology. However, to quantify this feedback and the level of satisfaction of the audiences attending *Le Leggi della Natura*, I designed two evaluation surveys to be filled out at the end of the itinerary. One survey is specifically addressed to teachers, the other to students. In these surveys, after some introductory questions to set up the context of analysis, I ask users to evaluate some specific features of the itinerary, grading them from 1 (lowest grade) to 4 (highest). I used these results as my main data pool that, statistically analyzed, will present a more formalized feedback to establish whether this project can be considered successful. Before going more in detail on the analysis of the survey results, it is necessary first to briefly comment the characteristics of the data set to weight the goodness of the statistical pool under examination, then the structure of surveys and finally the methodology of the statistical analysis, to understand also the limitations such an analysis could suffer from.

3.1.1.The data set

In total, I collected 183 survey from students, and 17 from teachers, coming from 12 different classes. The overall number of bookings was higher (21), but the first four bookings arrived so early I was not able to draft the survey yet; moreover I used those itineraries as tests to see what itinerary feature I could immediately improve. Furthermore, even after these sample tours, not every teacher wanted to fill the survey, mainly because of an irresolvable organizational problem: several classes had other activities to attend after mine, and Venice is definitely not the easiest city to travel in as a tourists. On top of that, MSN location is quite peculiar, and even an experienced Venetian can easily get lost in the surrounding areas. Therefore, even though my itinerary ended at 10am and they had another activity booked at 11am, I suggested them to skip the survey part to reach as soon as possible the other museum. This was obviously not positive for my statistical analysis, but considering the fact that two times I received a phone call from the other museum, asking where the class was (they usually arrived there no earlier than 10 minutes late), at the end it was a thoughtful decision. The survey filling usually takes no less than 20 minutes: to make students and teachers familiarize with the survey contents, I found useful to spend few words on the survey items that could result not completely clear, basing my explanation on questions and requests from the users themselves.[64] Therefore, if they also filled the survey, they would be half an hour late. Moreover, I wanted to keep them having positive emotions and memories on regard of my itinerary. If teachers filled the surveys, and arrived late to the other activity, they could have blamed the survey filling for taking too long, and I obviously tried to avoid this.

On the other hand, three teachers (from two different classes) found themselves in this situation but wanted to help me anyway: we agreed that I would email the surveys, and they would emailed me back them filled. This is a slight statistical incoherence: to be completely formal, every survey should have been filled at the same moment, i.e. right after the itinerary delivery. I decided that having two teachers survey more, to increment their number, was more important than maintaining this overall coherence, thus I considered them au pair with the others. Furthermore, two teachers were so satisfied by the itinerary that they came back with another class of students. In this case, I did not make them fill the survey again: even though the itineraries they attended could differ one another, I think their judgment would not substantially change. So, even if they attended the itinerary twice, I considered the answers coming just from the first survey filled.

Beside coherence among different surveys, there is another problem the analysis suffers from. In fact, the overall amount of surveys do not allow for a perfectly sound statistical analysis: indentifying patterns and recurrences to understand, for example, the itinerary features to be preserved and which ones to change, just from just 17 surveys, is quite hard. It is thus necessary to clarify from the very beginning that this is a descriptive analysis, and serves as a comparison between my prefixed objectives

[64] This fact, however, might have influenced the results, since different audiences might understand the instructions differently; I will tackle this issue for sure for future evaluations, maybe preparing a standard text to be read out loud before the survey filling.

and audiences' responses. Students' surveys number is higher, and considering that those represents a way more variegate statistical pool than teachers, these could be used for more complex analysis too, to identify even some correlations between different items. For example, I found that a low grade on question SQ3.7 (I could define a law of nature) often corresponded to a high grade on SQ3.8 (I would attend Le Leggi della Natura again): even though students felt they did not completely grasp the overall meaning of the itinerary, they would be willing to follow it again. My inference is that they were interested in the itinerary, and would attend it again to improve their understanding. Still, the overall number of classes filling the surveys is too low to allow for a truly meaningful analysis of correlations.[65]

The following list comprehends all those classes whose teacher(s) agreed to fill the survey. #3 and #4 represents the first teacher bringing another class to attend *Le Leggi della Natura* again; #6, #7 and #8 are the teacher that came back twice. In both cases, I gained three different surveys (#7 and #8 teachers were the same), since I did not make the same teacher fill the survey more than once. #9 and #12 are the teachers I digitally sent the survey to. This list also demonstrates how much variegate the audiences following *Le Leggi della Natura* have been, spacing from 2nd year art students to 4th year scientific lyceum students. I think this is due to the high level of interdisciplinary subjects touched by the itinerary, that attracted teachers coming from different backgrounds. However, it is also clear that the majority of classes came from a science or applied science background, which is quite appropriate on the light of *Le Leggi della Natura* main educational objective, namely inquiring science from different perspectives. A science/applied science background is perfectly fit for attending the itinerary, since it is reasonable to think followers already have a personal idea on science and mathematics proceedings – independently from how elaborated or hazed this idea could be. The classes that attended the itinerary and filled the surveys are:

1. Liceo Artistico M. Guggenheim (2nd year): 18 students + 1 teacher
2. IIS Benedetti-Tommaseo (4th year, applied science): 18 students + 2 teachers
3. IIS Benedetti-Tommaseo (4th year, applied science): 17 students + 2 teachers (-1)
4. Liceo Scientifico Ugo Morin (2nd year): 25 students + 2 teachers

[65] This is another evaluation problem to be resolved for future evaluations coming from a small statistical pool: a solution would be replacing surveys with interviews.

5. Liceo Scientifico Paleocapa, (3rd year): 19 students + 2 teachers

6. IIS Giuseppe Veronese (4th year, science): 20 students + 2 teachers

7. IIS Giuseppe Veronese (2nd year, science): 17 students + 2 teachers (-1)

8. IIS Giuseppe Veronese (2nd year, applied science): 15 students + 2 teachers (-2)

9. IIS Paolini – 1 teacher

10. IIS Einaudi-Gramsci (2nd year, science): 23 students + 2 teachers

11. Istituto Canossiano (2nd year, applied science): 11 students + 1 teacher

12. IIS G Galilei – 2 teachers

3.1.2. Surveys structure

I designed these two different surveys to quantify the efficacy of the itinerary, on the light of the educational objectives. These can be summarized in two main points: (a) implementing HPS knowledge and methodology into a SCE product - in this case, the HPS knowledge is represented by the concept of the laws of nature; and (b) promote a cultural change within science education activities, stressing the importance of interdisciplinary analyses when approaching scientific problems. Therefore, over audiences' overall degree of satisfaction (thus, whether users enjoyed attending the itinerary), I wanted to have some quantitative feedback on the actual meeting of these two goals. So, I used the surveys to test the efficacy of the content transfer and of the presentation methodology. In this way, I am able to test whether adding HPS content to a scientific itinerary improved both its educational importance, either its communicative power.

To structure the surveys, I conceptually divided them in three parts. Both surveys start with a set of questions related to the filler's background and his familiarity with Venice Natural History Museum. The other two parts are structured similarly: they both require a judgment over specific characteristics of the itinerary, using a scale of satisfaction ranging from 1 (not satisfied) to 4 (completely satisfied). In the second part of the survey the scale represents the degree of accordance with a set of sentences; users have to say if they completely agree with the sentence under consideration (grade 4), or not at all (grade 1). This part inquires specifically the level of satisfaction, with reference to the didactical content of the itinerary. In the third and last part of the survey, users have to rate (1 = negatively, 4 = positively) the main features of the content presentation, therefore I consider this last part to ultimately test the general satisfaction over the design methodology.

Some notes on the choice of the scale are necessary to justify why the ‘1 to 4’ (1t4) scale is the best choice for the evaluation I am aiming at. Other sample scales I could have used are, for example, 1t3, 1t5, 1t10. I can already dismiss the first and the last one on the basis of simple considerations. Let’s start considering the 1t10 scale: if one has to judge, for example, the length of the itinerary, choosing between 10 different grades could be quite redundant: what would the difference be between a 7 or a 8? Or a 3 and a 4? I think there is actually none. Therefore, the solution is reducing the number of choices. The minimum scale is 1t2, but it represents a binary evaluation, that would be quite meaningless for a statistical analysis. Moreover, there is not a huge difference between 1t2 and 1t3: the three grades for the 1t3 scale would mean: positive, undecided, negative - so, it is not different from a binary evaluation. In this two cases, fillers are presented with too few possibilities. So, in line of principle, we are left with two possibilities: 1t4 and 1t5. Also this two scales are quite similar one another: both comprehends two possible choice in the opposite side of the spectrum: two negative judgments (completely negative, slightly negative) and two positive judgments. So, this is the first benefit that comes out from choosing one of these two scale: we have not a ‘black-or-white’ judgment over their degree of satisfaction concerning the itinerary, but fillers can indicate how much they liked (or disliked) it, without redundancy. Moreover, the 1t5 scale has one more element, that is the medium grade 3. Therefore, 1t5 is in line of principle more accurate and able to cover a biggest range of possibilities, allowing for a better sensitivity. On the other hand, I knew from the beginning that the overall number of surveys would not be elevate and thus I needed to have clear and defined results. 1t4 scale obliges the filler to take a stance over the matter, deciding whether they considered the item under judgment to be more positive or more negative. Using a 1t5 scale could have implied many 3s as answers: in this case, the interpretation of the results could be quite difficult since, for a specific question, a mean answer of 3 would not tell me if the specific item should be considered positively or negatively. In fact, 3 on a 1t5 scale is quite a neutral grade that could represent indecision over the actual judgment. I have chosen the 1t4 scale over the 1t5 to have specific and well-defined answers, where the filler is obliged to evaluate a certain item positively or negatively, with no mid-term. Moreover, the 1t4 scale is used also in the standard museum surveys too, and I decided to align my evaluation schemes to theirs. But a question immediately rises: what if the student really is undecided and do not have an opinion on the subject matter? Analyzing the results a posteriori, I noted there were some surveys with non-filled answers, that can indicate that or the students did not understand the issue at stake in the question, or that they were undecided over the subject matter, and instead than taking a stance over positive or negative evaluations, they preferred to leave the question blank.

3.1.3. Statistical analysis

I will now explain how I structured the statistical analysis to visualize and interpret the survey results. I use mainly descriptive statistics: first of all, I visually provide the whole population result through graphs; more specifically, pie charts for the introductory questions and bar charts for the survey items based on the 1t4 scale. These charts meaningfully show and summarize the results obtained and, more specifically, the frequency distributions for each question' answers. Moreover, I calculated the main statistical variables for each item, i.e. mean, median, mode and variance, allowing me to confront the result obtained with my starting hypotheses. Therefore, I use measures of central tendency and measures of variance to describe the patterns in the answers of teachers.

I will take the mean of the grades received for a specific survey item as the index of whether the feature described in the item was successful or not. However, the mean (from now on *Ag*) can assume any value in the continuous interval [1,4]. It is therefore a continuous variable, despite coming from a discrete scale formed by the set of integers {1,2,3,4}. Therefore, there is a modification of the nature of the evaluation scale and it is needed to connect logically the discrete scale and the continuous interval. The simplest way to make manifest this connection is approximating the value of *Ag* to the closest integer, therefore maintaining, at the end, the same starting discrete evaluation scale. However, I think this is nothing more than an easy way out of the problem and, more importantly, it would imply a not-negligible loss of sensible information, since I think there is difference from an average value of 2.7 and 3.2. I proceeded as follows. I maintained the interval continuous - accordingly, no approximation for the average grade value is needed, over deciding to use numbers with two decimals - and I divided the whole interval in several sub-intervals with similar extension, each of which representing a different level of satisfaction / judgment. Depending on the sub-interval *Ag* falls within, I have a more detailed evaluation of the specific item. This categorization of the evaluation scale serves to have a general structure to evaluate the results, on the light of my expectations: in fact, before analyzing the results, I already had a personal opinion on whether the specific item was really positive, positive, mediocre, negative or very negative. Thus, I decided to use these categories. This must not be intended as strictly limiting the average value interpretation: these categories boundaries are just representative, since they offer a conceptual framework to set my results within.

- $3.5 \leq Ag \leq 4$. This is the highest range possible. I reasonably suppose that if an item has an average grade higher than 3.5, it means that the itinerary users considered that specific itinerary feature extremely successfully delivered.
- $3 \leq Ag < 3.5$. This interval represents an overall positive judgment towards the item under consideration. If the mean value falls within this interval, in line of principle, no improvement for the described characteristic should be needed.
- $2.5 \leq Ag < 3$. This interval represents a mild satisfaction level. An average lower than 3 means that the majority of grades were on the negative side of the discrete scale. If the mean value for an item falls within this interval, it means that it has some slightly negative features, implying that they need a reassessment, or a form of improvement, but with a rather low priority.
- $2 \leq Ag < 2.5$. If the item judgment falls within this interval, it means it received a negative evaluation. I will comment on the possible reasons behind the quite negative evaluation and, accordingly, I will put forward some ideas on how to improve the feature under consideration.
- $1 \leq Ag < 2$. I decided to do not divide this interval with half grades, because I think that it is useless to formalize a difference between an average of 1 and 1.9: in both cases, the item was considered negatively delivered, and therefore the itinerary feature it describes needs to be improved (or even

deleted) with the highest priority. Luckily, a posteriori, no *Ag* fell within this range, signifying that no itinerary feature was totally negatively received by users.

The evaluation scale I just described can be visualized as follows:

1	2		3		4
VERY NEGATIVE	**NEGATIVE**	**MEDIOCRE**	**POSITIVE**	**VERY POSITIVE**	

Evidently, it is not a ‘linear’ scale, since 2/3 of the intervals represent more negative than positive judgments. Thus, there is a slight change between the punctual evaluation scale I presented students and teachers with, and the scale I use for the results evaluation. This is the first and most important difference between my methodology of analysis and the approximation case I described earlier. In the approximation case, an average value of 2.7 would automatically turn into a positive judgment, since *Ag* would become 3, and in the discrete scale 3 corresponds to “pretty positive” or to “I agree”, depending on the question. With my continuous interval, an average of 2.7 would correspond to a ‘mediocre’ evaluation, even if set very close to the positive intervals of evaluation.

Moreover, every question could have its own way of weighting the average value, based on my specific expectations. For instance, on Q3.7 of students surveys, asking them whether they would be able to recognize or describe the characteristics of a law of nature, I am already expecting an average value that is lower than the other means, therefore also the scale should be reset. The content I presented admittedly had not a unique definition or characterization of laws of nature: first, it was one of my aims presenting students the concept following a pluralist account; secondly, I wanted them to reflect on their own definition of natural law. Therefore, I can expect that not every students formulated its own view on this subject just after the itinerary or, even if they had, they could feel insecure that it was not the ‘right’ answer, even though I tried to convey to them that even among eminent scholars there is almost no agreement on the actual ‘right’ definition of a law of nature. It could have been interesting to ask students the same question some time after they attend the itinerary, to see whether the value of *Ag* increases.

Optimizing the evaluation of the transfer of this specific content, is one of my future objectives for improving the itinerary. However, a general scale to discuss on the same ground the results obtained is useful to have a context to set the analysis within. I will reset the scale just when needed, i.e. for the questions I already knew for sure I could not aim at the highest grade.

Furthermore, the mean value is not sufficient to draw some meaningful conclusions over the data set: this is where the population variance comes into play, offering an index of data dispersion. Through the analysis of the value of the variance, I am able to formalize numerically if, and how much, the judgment for the specific item was unanimous. I will use the value of the variance *V* to have a first glance on the confidence level of the survey items results. As for the mean, also the variance can assume any value in a continuous interval; accordingly, I decided to use the following evaluation scale:

- $V < 0.3$. The data are very close to the mean, therefore there was a commonly shared judgment among different classes.
- $0.3 < V < 0.6$. The data still are pretty close to the mean value, meaning that also in this case I can consider the result to be reliable.
- $0.6 < V < 0.9$. The data set tends to spread out, therefore the judgment over the specific item was not unanimous, and this fact has to be taken into consideration when commenting the mean value.
- $V > 0.9$. The data set hugely spreads out, and therefore the result is not completely reliable.

The average value and relative dispersion are the most meaningful variables that allows a rather qualitative, but still formal, descriptive analysis. For example, supposing that for a specific item of a survey, after the numerical calculation, I found Ag = 3.2 and V = 0.5, the complete numerical value to consider is *Ag* = 3.2 ± 0.5, and spreads over the interval [2.7, 3.7]. The mean value falls within the ‘positive evaluation’ interval, but introducing the variance it is evident that this results spans over three different intervals, entailing the ‘positive’ interval wholly, and falling within the ‘mediocre’ interval for a length of 0.3 and within the ‘very positive’ interval with a length of 0.2. In this case, considering variance value, the result is quite reliable, and I consider such a judgment to be quite unanimous, and thus the data to be quite reliable. This result can be visualized as follows:

1	2		3		4
VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE	

Ag = 3.2 ± 0.5

The second example I would like to describe, entails an high-valued variance: I suppose *Ag* = 3.2 ± 0.8, implying a confidence interval given by [2.4,4.0]. The variance falls within the third interval of the ones described above and indicate that the data tends to spread out, since the confidence intervals spans within four different evaluation intervals (mediocre, positive and very positive wholly, and 0.1 within the negative interval). Focusing just on the average value, the item should be considered quite successful; however, the fact that this judgment was not unanimous implies that the feature under examination needs to be improved.

1	2		3		4
VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE	

Ag = 3.2 ± 0.8

I have chosen the values 0.3, 0.6 and 0.9 as the limits of the confidence intervals as the result of analyzing the extension of the result in relation to the extension of the whole evaluation spectrum. The length of the spectrum is 3; if a specific item results to have V = 0.3, it means it covers an overall extension of 0.6, i.e. 20% of the whole spectrum. Similarly, a result with V = 0.9 implies the covering of 60% of the whole spectrum and at least three evaluation intervals wholly. Due to the rather small number of data, which are also composed by just four possibilities for their numerical value, aiming at the classic 95% confidence level, used almost always in scientific literature, would be quite utopian; that is why I decided to take the ‘extension of the result’ as the major index of the reliability of the result obtained.

I will now proceed with the detailed analysis of the answers received. I will start analyzing the teachers surveys, for then passing to students surveys. I will analyze the frequency of the answers received, question per question, commenting and comparing the results with my expectations. Whereas all the teachers surveys were valid, and therefore analyzable, I deleted some students surveys because I considered them not reliable; for instance, one student answered ‘1’ to every item, but ‘4’ as general grade for the itinerary. I considered this survey to be not coherent neither sensible. Luckily, the amount of invalid surveys was limited – the one described above was the only one I had to wholly delete from my analysis. Other surveys had some questions left blank: this explains why, in the analysis of students surveys, the overall number of answers may slightly vary from question to question.

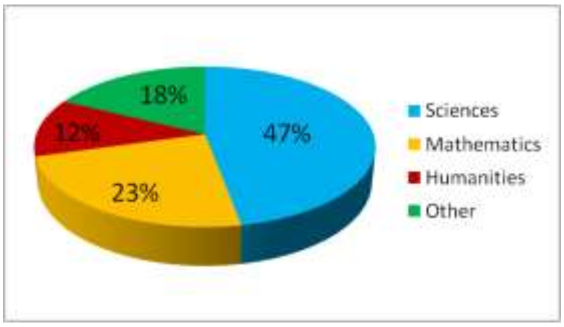
3.2. TEACHERS SURVEYS

The surveys results are primarily important for defining the success of *Le Leggi della Natura*, since the cultural change of methodological framework for SCE product I am promoting aims at increasing students’ interest in scientific issues, but it should start from teachers’ attitude. I will start my analysis from teachers’ surveys, trying to infer whether *Le Leggi della Natura* was able to make them reflect upon the power of transdisciplinary presentation methodology. For example, most teachers have much more experience in the educational environment than I have. So, knowing whether they will use some of the content presented during their lessons already gives me an index of interest.

The first four questions work as introduction to the actual evaluation, inquiring teachers’ background knowledge (Q1, Q2) and familiarity with the context (Q4). Moreover, I will already ask for a preliminary evaluation of the itinerary, since Q3 asks whether the filler will test students on the content presented. I will use the information conveyed in this introductory part to contextualize the results obtained in the second part of the survey (Q5, Q6).

3.2.1 Introductory questions - Q1. What is your area of expertise?

Subject	# teachers
Sciences	8
Mathematics	4
Humanities	2
Other	3

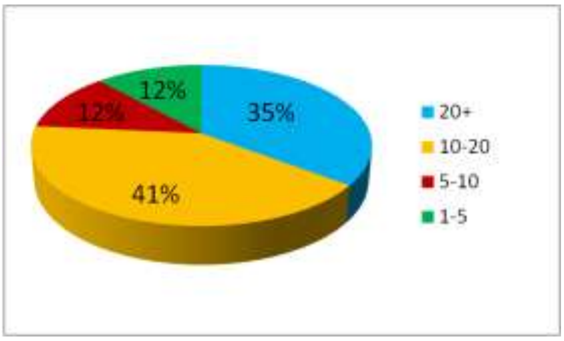


I decided to use the general nomenclature 'Sciences' to include physics, biology, natural sciences, chemistry. The reason behind this lies in the nature of the content I present: I built the itinerary trying to blur disciplinary borders. For the same reason, I included in the 'Humanities' item both history and philosophy.[66] However, an heterogeneous set of teachers attended the itinerary, spacing from biology to religion. Anyway, as one could expect from a group leader deciding to book a science itinerary at a natural history museum, almost half of the teachers had a science background. Adding science and mathematics trained teachers, we obtain the 70% of the whole set of teachers. This is reasonable, since mathematics and science teachers were the target of the itinerary, focusing it on mathematics, physics and biology. The other teachers had different backgrounds, and I think it is interesting to narrate why two different classes of IIS Benedetti-Tommaseo attended the itinerary: the group leader was a philosophy teacher that, at the time of the itinerary booking, was dealing with Descartes' philosophy with her students. I consider this to represent a first example of success, namely attracting users from different backgrounds, each of which can find interesting themes to discuss. Moreover, to consider the itinerary successful, teachers do not have just to book it, but they also have to like it, and the fact that the Benedetti-Tommaseo philosophy teacher came back to MSN to make another class attend the itinerary, bringing with her a physics teacher, is an index of a successful content transfer. Another teacher (teaching mathematics and physics, but with a specific mathematics background) came back twice: the first time an art teacher accompanied her, the other two times a religion teacher – with whom we had, at the end of the itinerary, truly interesting final discussions, with numerous students expressing their opinion on the role of the laws of nature for scientific enterprise.

[66] Interestingly, the two teachers answering 'Humanities', teach both history and philosophy

Q2. How long have you been working in education? Check the relative box

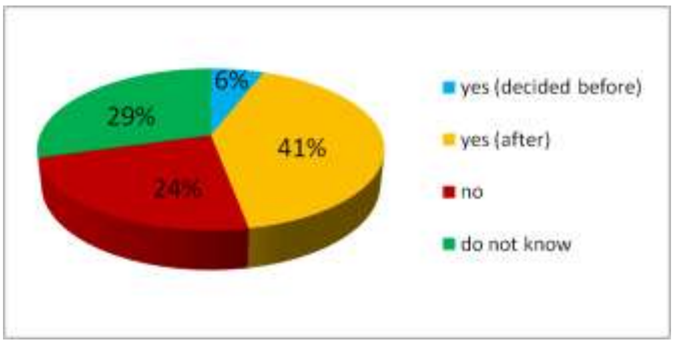
Years	# teachers
20+	6
10-20	7
5-10	2
1-5	2



Whereas the previous question helped me formalizing the general background of the itinerary users, I was equally interested in knowing teachers' years of experience in the field, to see whether the itinerary was appealing to different generations of teachers, used to different teaching methodology – e.g. I can reasonably suppose that young teachers, working in schools for less than five years and thus probably born within the digital era, would not be very impressed by the use of digital tools, but indeed they can evaluate their use based on their previous experience. Moreover, I suppose a direct correlation between having several years of experience in the education field, and having attended other SCE activities – so, they can base their judgment confronting my itinerary with others they attended previously. The results of the analysis show that more than 3/4 of teachers have 10+ years of experience in the education field and just four teachers have less than 10 years of experience in the field. So, the statistical pool is quite reliable and on its basis I can already state that *Le Leggi della Natura*, as presented in MSN website, attracted different generations of teachers and, therefore, laws of nature is a concept appealing to teachers with different years of experience.

Q3. Are you planning to test the students on the themes discussed in the itinerary?

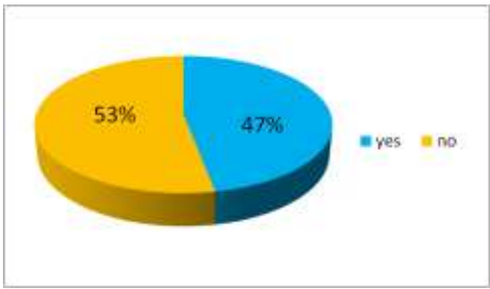
Doing a test?	# teachers
Yes (decided *before*)	1
Yes (decided *after*)	7
No	4
Do not know	5



This question can already offer some hints over teachers' general interest on the themes discussed. As briefly explained earlier, I assume that teachers designing some classroom activities following the itinerary means they were interested in the itinerary content and satisfied by the presentation level to the extent they decided to study the arguments more in deep by themselves. Data show more than half of the teachers (53%) answering with 'no' or 'do not know'. However, to justify this result, it is necessary to note that the scholastic year ends on 10th June, and usually at the beginning of May teachers already have all the grades they need for the final judgment. Many bookings (specifically, nine) arrived in the scholastic year period ranging from the end of April to June; thus teachers would not have the necessity, or even the material time, to further test their students. Still, the statistical mode are teachers that decided to take a test on issues dealt by *Le Leggi della* Natura, and I strongly believe this is symptomatic of a great interest. I specifically asked whether they would do a test because I think it is a stronger index of interest than asking if they would do some general classroom activity on the itinerary content. With tests, teachers are pragmatically inquiring students' understanding of the subject matter; moreover, setting up a test requires that teachers already prepared a classroom activity to test, may it be in the form of frontal lessons or in the form of workshops.

Q4. Have you ever visited Venice natural history museum before?

Been to MSN before	# teachers
Yes	8
No	9



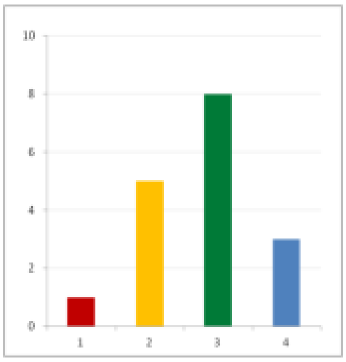
This introductory section ends inquiring whether teachers already visited the museum before, and interestingly the majority of them did not. Accordingly, they cannot compare *Le Leggi della Natura* with any other itinerary or guided tour offered in the museum. On the other hand, they have chosen the laws of nature as their first thematic approach to MSN, which is rather positive on the light of my educational objectives. Moreover, 8 over 17 teachers have already been to MSN and can thus evaluate better the novelty of the approach to the museum collection. Also in this case, I consider the data pool to be reliable.

3.2.2. Content transfer & methodology

In this second part of the survey, I want to evaluate the general usefulness of *Le Leggi della Natura* as an educational mean. The questions presented are in the form of one line sentences and the teachers can completely agree with them, judging '4' the specific item, or, in the opposite side of the spectrum, completely disagree, judging the item with a '1'.

Q5.1- I was familiar with the contents of the itinerary

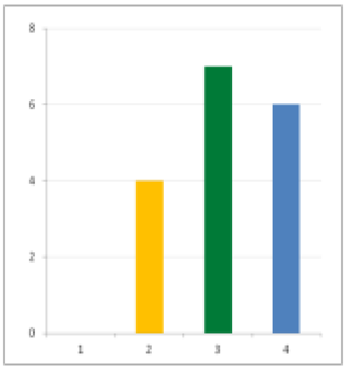
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# teachers	1	5	8	3		2.77 ± 0.65	3	3



The average level of familiarity with the itinerary content is 2.77 and on the light of the evaluation spectrum previously described, it corresponds to a mediocre familiarity. The variance falls within the third interval, and therefore indicates that the data set tends to spread. However, the mode is 3, thus the majority of teachers considered their background knowledge adequate to follow the itinerary in its entirety. This result represents a positive feature of the content design: I designed the itinerary to focus on classroom material, either on extra-scholastic content - for example, almost no mathematics teacher, during five years of high school deals with fractal geometries. Moreover, being *Le Leggi della Natura* highly interdisciplinary, it is reasonable to assume that science teachers were not really familiar with the HPS content and, accordingly, it is probable that a religion teacher is not really familiar with Navier-Stokes equations. For this reason several themes could result completely new to audiences, lowering the overall index of familiarity.

Q5.2- The level of the itinerary content was adequate to students' background knowledge

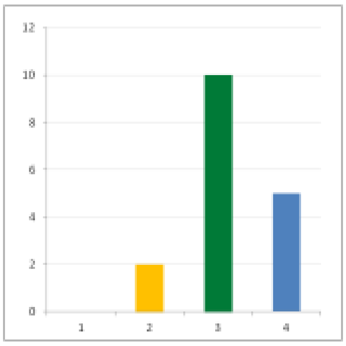
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# teachers	0	4	7	6		3.12 ± 0.57	3	3



With this question, I am inquiring how much teachers thought their students had the necessary background knowledge to fully follow and understand *Le Leggi della Natura.* I asked the same question directly to students in the other survey form, and will later compare the two results. Here, the mean falls within the positive evaluation interval, with a rather small variance: interestingly, no teacher completely disagree ('1'). I was quite surprised by this result: I expected a lower grade due to the extra-scholastic themes, as explained in the previous question. However, this result indicates that teachers considered the level of the content adequate - not too difficult, nor too simplistic - for the classes attending *Le Leggi della Natura*.

Q5.3- During the itinerary, students were interested in the themes presented to them

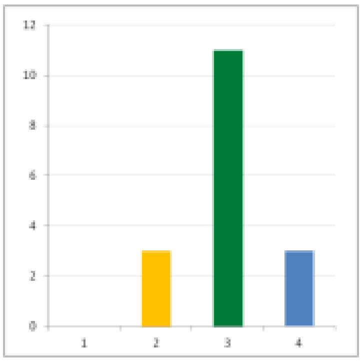
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# teachers	0	2	10	5		3.18 ± 0.38	3	3



Here I am asking teachers to evaluate students' interest, in relation to the interest for scientific themes that they usually show during everyday classroom lessons. The results are very encouraging. The majority of teachers agreed with this sentence, and almost 30% of them completely agreed ('4'). The mean still falls within the positive range of evaluation, and the variance is pretty satisfactory: the data set does not spread out and no teacher completely disagreed ('1') with the sentence presented. Also in this case, I asked the same question directly to students, and I will later compare the results of these two questions.

Q5.4- Students, after the itinerary, seem more interested in scientific issues

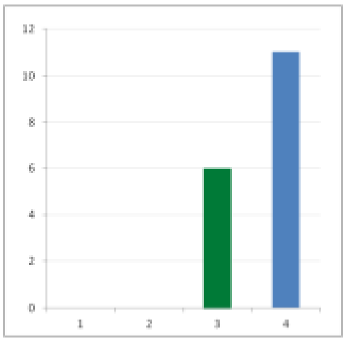
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# teachers	0	3	11	3		3.00 ± 0.35	3	3



This question suffers of a minor complication: knowing if my itinerary has changed students' attitude towards the sciences would require a latent period before they could answer this question. However, due to logistic reasons, I could not pragmatically do it; moreover, I did not want to hand two different surveys to be filled out. On the other hand, I suppose that teachers' familiarity with their students' way of expressing feelings and emotions, can suffice to preliminary evaluate their attitude also just right after the itinerary. The mean is exactly 3 (thus, positive) and the data do not spread out too much; therefore, theoretically, I should consider this item to represent a successful feature of the itinerary – still to be confronted with the same question asked to students themselves. On the other hand, I also think that some teachers answered '3' by default, in accordance with what they answered in the previous question.

Q5.5- I found useful to explain physics and biology concepts, starting from an analysis of the laws of nature and their conceptual features

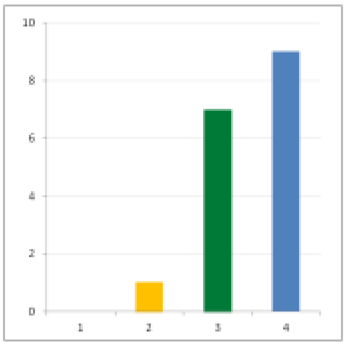
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# teachers	0	0	6	11		3.65 ± 0.23	4	4



This is the first question directly asking to teachers to evaluate an important feature of the itinerary content, i.e. the value laws of nature didactically used to explain specific scientific issues. I was very surprised, and ultimately very satisfied, by these results: 65% of the teachers firmly agreed with this statement, and no teachers disagreed, even slightly (there are no '1' or '2' grades). Moreover, the mean falls within the 'very positive' interval, and the variance within the $V < 0.3$ interval, which is the highest confidence level my statistical analysis aims at. I was not expecting such a high evaluation: I feared that teachers expected a standard scientific itinerary, composed just by a series of equations and facts, and thus considered the transdisciplinary approach to be off-topic. Evidently, this was not the case, and teachers considered the laws of nature a suitable tool to explain scientific issues.

Q5.6- An interdisciplinary approach can make the hard sciences more accessible to students

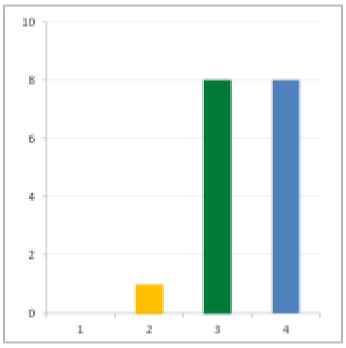
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)	Mean± Var	Median	Mode
# teachers	0	1	7	9	3.47 ± 0.37	4	4



This question is rather similar to the previous one but, whereas in Q5.5 I inquired the adequateness of laws of nature as a didactical mean, here I wanted to have an index of their usefulness, represented by their capacity of tying together technical and socio-cultural contents. Furthermore, I am specifically inquiring the usefulness of such a content mediation. The average value is lower than the previous question (formally falling within the 'positive' interval), the variance is quite good (though higher than previously), but median and mode still are 4s, indexes of a successful item. Thus, I can conclude that teachers appreciated the interdisciplinary approach and considered it useful in a science didactic context.

Q5.7- I would attend again *Le Leggi della Natura,* if extended to other museum halls or other themes

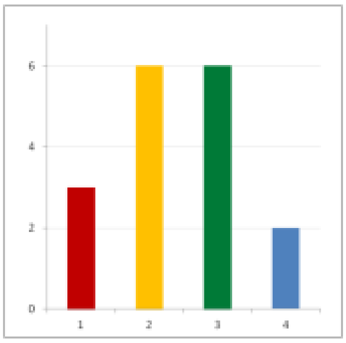
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)	Mean ± Var	Median	Mode
# teachers	0	1	8	8	3.35 ± 0.36	3	3, 4



I elaborated this question for two main reasons. First of all, there is a materialistic reason, namely convincing teachers to come back and attend again the itinerary next year. To do so I already explained them that *Le Leggi della Natura* can be extended to other halls or thematically modified (for instance, focusing on other laws of nature) and, therefore, they could visit again the museum even with the same class. The second reason is related to my didactical objectives: I reasonably argue that if teachers would come back to attend *Le Leggi della Natura* 2.0, they considered it an efficacious science education product. Therefore, with this question allows me to already have a preliminary index of teachers' interest. Both mean and variance are positive: both falls in the interval just below the maximal one, and 16 over 17 teachers expressed their willingness to come back, as the bi-valued mode shows. This result quite matches my expectations based on face-to-face reactions and feedbacks at the end of the itinerary. Obviously, I did never explicitly ask them to come back, since it would be rather unprofessional, but when I explained them that probably *Le Leggi della Natura* would be slightly modified, almost all of them expressed their interest in being updated with the novelties.

Q5.8- I would attend again *Le Leggi della Natura,* if offered in English

	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# teachers	3	6	6	2		2.41 ± 0.83	2	2, 3



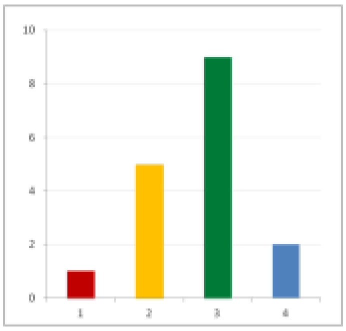
The reasons behind this question are quite the same as the previous ones, namely having a preliminary index of interest, and inquiring whether teachers would attend a similar itinerary. Moreover, a recent reform of Italian secondary education system, that is not completely active yet, entails that students have to follow a technical subject (as mathematics or physics) for an entire academic year wholly taught in English. Therefore, I thought that teachers could be interested in following an itinerary held in English. However, mean and variance values are not really satisfying: the mean falls within the negative evaluation interval, data are quite spread out (almost reaching the value V = 0.9) and the median is 2, representing a slight disagreement with the presented sentence. However, it must also be noted that almost half of the teachers expressed a positive opinion regarding the possibility of attending the English version of *Le Leggi della Natura*. In any case, I consider myself slightly unsatisfied by this result: I designed *Le Leggi della Natura* to be a bi-lingual itinerary from the very beginning, where users can choose their preferred language during the booking process. I consider this result to be indicative of the fact that I was not able to transmit that the English version of *Le Leggi della Natura* could be a great opportunity to make students approach the English language used in a peculiar educational context. I will inquire more in deep the reasons behind this fact during the design process of *Le Leggi della Natura 2.0*.

3.2.3. Itinerary features

The third and last part of the survey aims at inquiring teachers' degree of satisfaction over specific features of the itinerary; it thus represents a direct evaluation of the itinerary success. The scale used is the same as the previous one, ranging 1 to 4: '1' represents a negative judgment, '2' more negative than positive, '3' more positive than negative and '4' a completely positive judgment.

Q6.1 - Use of digital images and videos, tablet

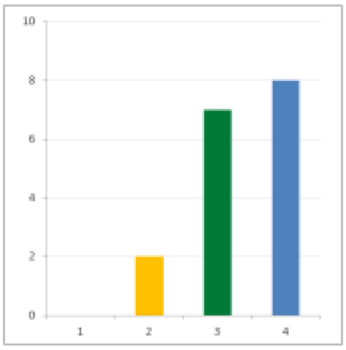
	Negative (1)	**More neg than pos (2)**	**More pos than neg (3)**	**Positive (4)**	**Mean ± Var**	**Median**	**Mode**
# teachers	1	5	9	2	2.71 ± 0.56	3	3



I wanted *Le Leggi della Natura* to be technological in respect to the other offered by MSN. So, during the itinerary deliveries, I used a tablet to display several digital images and videos, to be integrated with the museum exposition. I was expecting to receive a quite low grade for this item, due to a series of issues that arose during the actual deliveries of the itinerary. For example, especially for numerous classes, a tablet screen is actually too small to allow all students to adequately see the images. Moreover, using a digital device implies another set of problems deriving from the nature of the device itself, as files that mysteriously do not open or apps that need to be updated with the worst possible timing. These expectations are met by the results: the mean falls within the 'mediocre' evaluation, and the variance shows that the data set is reliable, even though being near the third evaluation interval. Still, the mode and the median are '3', indicating that averagely teachers liked to attend an itinerary that used extra images and videos.

Q6.2- Possibility of manipulating museum objects and specimens

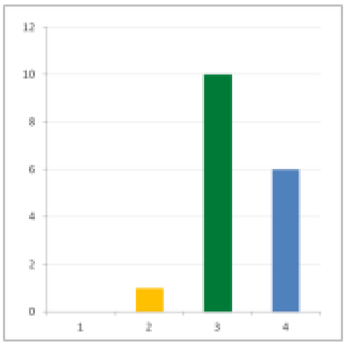
	Negative (1)	**More neg than pos (2)**	**More pos than neg (3)**	**Positive (4)**	**Mean ± Var**	**Median**	**Mode**
# teachers	0	2	7	8	3.35 ± 0.46	3	4



During the itinerary, students and teachers can observe closely and play with some objects of the museum collection. This is the first characteristic of the itinerary reflecting the interactive approach used. With these objects I introduce students different kinds of mathematical forms we can find in nature; and having that specific examples both behind a glass either in their hands can result in a higher capacity of directly elaborating the theoretical concepts. The result of this question agrees with my starting expectations: teacher enjoyed this characteristic of the itinerary , even though during my presentations I was much more interested in students' reaction – being them also much more explicit and, to some extent, 'explosive'. However, almost half of the teachers graded this itinerary feature with a '4'; the mean is quite high (3.35), indicating a positive judgment, and the variance reveals that the data set is well-distributed around the mean value, being V = 0.46.

Q6.3- Coherence between the themes discussed and the didactic environment of MSN

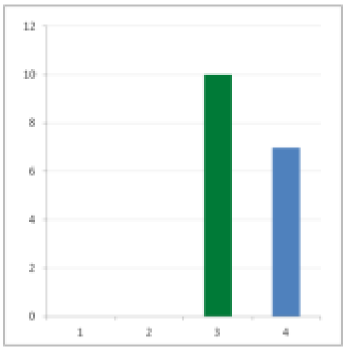
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# teachers	0	1	10	6	3.29 ± 0.33	3	3



This question entails a judgment over a rather peculiar issue: comparing *Le Leggi della Natura* with the museum didactic environment, in line of principle, implies a prior implicit knowledge of the museum itself, thus having attended another itinerary/workshop/activity there. Moreover, teachers coming from the first time to MSN to attend *Le Leggi della Natura* will not even see all the museum halls, being the itinerary restricted to a portion of the museum. However, this portion is sufficient to have a first glance of MSN educational agenda and, accordingly, even first-time visitors can actually judge whether content and themes presented, rightly align with the museum collection. Almost all teachers evaluated positively this item: the mean is quite high (3.3), with a really good value for the variance (slightly bigger than 0.3), implying that I can consider to have a coherent match between itinerary content and museum environment.

Q6.4- Depth of the analysis of the specific themes discussed (e.g. mechanics, fluid dynamics, fractals, …)

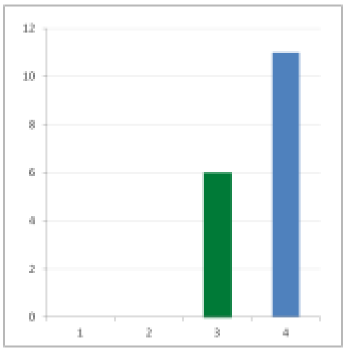
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# teachers	0	0	10	7	3.41 ± 0.24	3	3



This question allows for an index of the degree of satisfaction over the pragmatic explanation of contents, and specifically over the content level. I had not a specific expectation value in mind, also because I had no exact in-depth level of presentation, since I based it on the specific background of the audience. Thus, I consider myself highly satisfied by the result: all teachers' answers were within the positive, and the mean almost falls in the 'very positive' evaluation interval. The value of the variance is low, falling within the $V < 0.3$ interval, underlying a general and shared agreement over the result.

Q6.5- Use of the laws of nature as mediator subject between different disciplines

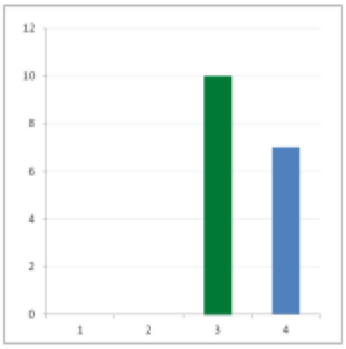
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# teachers	0	0	6	11	3.65 ± 0.23	4	4



This question allows me to judge whether teachers liked the HPS-based approach to SCE, and more specifically the laws of nature to represent NOS content, and as starting point of the analysis equally touching technical issues either cultural and contextual knowledge. Furthermore, this question investigates whether the laws of nature are a suitable tools for mathematics, physics and biology education. The results are, in my opinion, quite astonishing: 11 over 17 teachers rated this item as completely positive, and both mean and variance falls within the respective maximum evaluation interval. The result is represented by the interval [3.42, 3.88], thus covers almost completely all the 'really positive' interval.

Q6.6- Transmission of mathematics, physics, biology, philosophy and history concepts

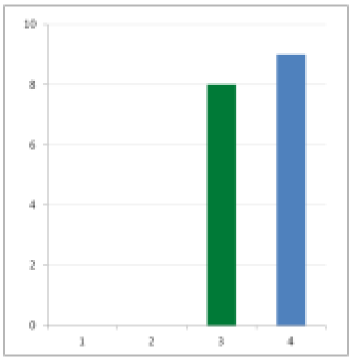
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# teachers	0	0	10	7	3.41 ± 0.24	3	3



In the previous question I focused on whether the laws of nature were a suitable mathematics, physics and biology education mean. Here, I wanted to weight more specifically if teachers thought that the specific technical content was conveyed adequately. In fact, dealing simultaneously with several subject could imply that, at the end, none of them is explained satisfactorily; moreover, there is also the risk for such an analysis to result somewhat chaotic. Evidently, teachers thought that it was not the case: the mean value is in the 'positive' range, and the interval of the evaluation spectrum that this result span, considering the value of the variance V = 0.24, comprehends also a small portion of the 'very positive' interval. Thus, I can conclude that teachers were really satisfied both by the interdisciplinary approach and by the interdisciplinary content. Since teachers came from different backgrounds, they were able to judge the different disciplinary contents. Thus, I consider this result to be indicative of the educational success of *Le Leggi della Natura*.

Q6.7- Real-world application of physics and mathematics concepts

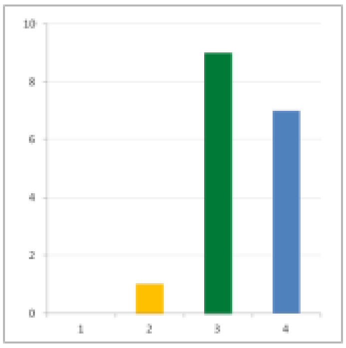
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# teachers	0	0	8	9	3.53 ± 0.25	4	4



With this question I am inquiring whether I was able to explain abstract concepts through material instances – as the construction of spirals through a functional relation between radius and angle, using shells of different mollusks. The main issue at stake is, therefore, the application of physics and mathematics methodologies to biology problems. The results are very positive: median and mode are both 4s, the average is higher than 3.5 and, since V = 0.25, this judgment was unanimous. I can conclude, combining this question with the two previous ones, that teachers were satisfied by the itinerary contents.

Q6.8- Survey design and filling

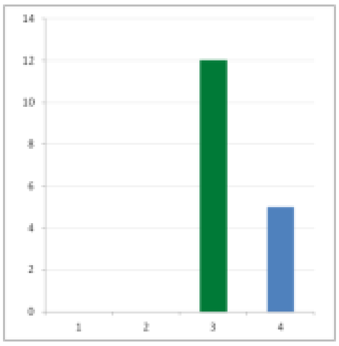
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# teachers	0	1	9	7	3.35 ± 0.35	3	3



An index of satisfaction for the survey is helpful to formalize whether teachers thought the questions were clear and concise. The evaluation is 'positive', since the result interval is [3.0, 3.7], so I can consider myself rather satisfied. This is manifest from the fact that just one teacher was not completely satisfied by the survey filling.

Q6.9- Itinerary overall evaluation

	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# teachers	0	0	12	5	3.29 ± 0.21	3	3



I decided to conclude the survey with a summary question, asking teachers to indicate their general degree of satisfaction over the itinerary considered as a whole, thus over the content presented and over the methodology of presentation. I am satisfied by this result: *Le Leggi della Natura* had a degree of satisfaction of 3.3/4, this result covering all the 'positive' interval of the spectrum, being the confidence interval [3.1, 3.5]. Still, I think there is room for improvement, and such an interesting guided itinerary as *Le Leggi della Natura* could aim at having a 'very positive' evaluation. I will now proceed to similarly analyze students' surveys, to see whether their judgment aligns with their teachers'.

3.3. STUDENTS SURVEYS

As explained previously, students' data set is better-suited for a statistical analysis than teachers', since the overall number of students' surveys is 183. However, the number of answers for each item is sometimes lower. This is due to two reasons: first, I had to fully delete a low, but still present, number of students surveys (0.6%), because they were not reliable at all, in the sense that they did not represent a judgment over the itinerary, but just that the students were tired, bored or disinterested. For example, one student skipped the introduction part, for then completely filling the survey just with 4s, apart from the overall evaluation question, that was a 1. I considered this survey au pair with a statistical offset, since I reasonably assume this student did not even read the questions before filling the survey. The second reason behind the lower number of answers relies on the nature of the evaluation scale itself. In several surveys, some questions were left blank. There could be many reasons behind this fact; for instance, a student that did not know what to answer to a specific question (despite my introductory explanations), would probably leave it blank. In this case, I consider the survey still to be valid, but in the case of unanswered questions, the statistical pool for that specific questions will be smaller. However, it is also important to remember this fact future survey designs: the numerical scale should be improved adding a 'Do not know' box.[67] However, considering that the smallest statistical pool counts 168 answers (Q4.4, concerning the use of digital images), and that all other questions have a statistical pool with a number of answers bigger than 180, I consider this statistical set to be valid and ultimately analyzable.

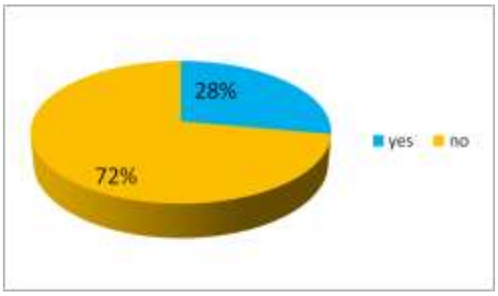
3.3.1. Introductory questions

The two introductory questions are not mutually independent: in fact, if someone answers 'yes' to the first question ('have you ever been to MSN before?), the second answer will be 'yes' too ('have you ever visited a science museum?). With these questions, I wanted to have a general overview of students' familiarity with science museum activities.

[67] This scale would still be conceptually different from the 1t5 scale, since it would entail a numerical scale of evaluation 1t4, with the addition of the 'do not know' box.

Q1. Have you ever been to MSN before?

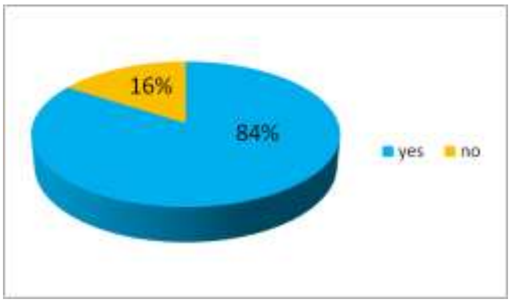
Been to MSN before	# students
Yes	51
No	132



Just a quarter of the students have already been to MSN. This means that the majority of students visited the museum for the very first time on the occasion of my itinerary: this is both an advantage, since I can see whether *Le Leggi della Natura* was able to create enthusiasm for the museum collection, but could also be a disadvantage, because they have no term of paragon with previous activities held at the MSN. However, I consider the statistical pool to be reliable for a descriptive statistical analysis.

Q2. Have you ever been to a science museum before?

Been to a science museum before	# students
Yes	154
No	29



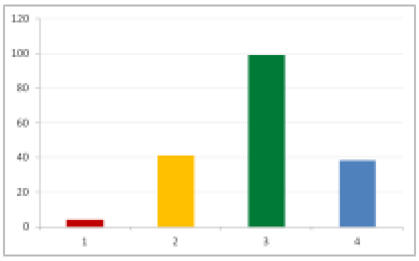
As said in the previous section, students that have already visited the MSN, have automatically already seen a science museum, and therefore should answer positively to this question too. As it can be seen from the results, the majority of students – more than 80% – have been to a science museum before. This result is not really surprising: the majority of students were following a scholastic science curriculum, so it is reasonable to assume they have some paragon term to fairly evaluate the itinerary.

3.3.2. Content transfer & methodology

For the actual numerical evaluation part of the survey, I will use the same statistical variables introduced in the teachers' section, coming from the same evaluation scale. This section is subdivided within two questions (Q3, Q4), inquiring first the degree of students' satisfaction over the content, investigating for example their general interest and whether they felt to have learnt new concepts, and then over the presentation methodology thus on the main itinerary features. The evaluation spectrum is also the same as the one used for teachers'.

Q3.1- My background knowledge was sufficient to fully understand the itinerary

	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# students	4	41	99	38		2.94 ± 0.55	3	3

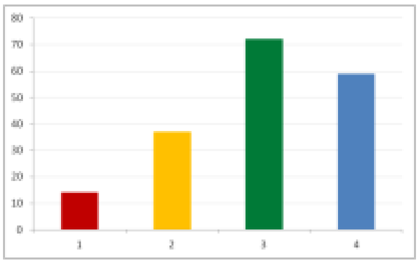


Despite falling within the 'mediocre' evaluation range, even though just for a small value of .06, I was quite surprised by this question results, mainly because I was thinking to introduce students to completely new concepts and themes. However, this result reveals that students were actually capable to meaningfully follow the guided tour. I realized it also from the tour themselves, since I assisted to a satisfying level of participation. I am satisfied by this result for another reason: I was expecting from the very beginning a wide-ranged variety of audiences, with different interests and coming from different backgrounds; I thus maintained the content level settable, since 2nd year art students and 4th year science students should be equally able to attend *Le Leggi della Natura*. Therefore, I consider this result to be representative of the success of this objective of mine. This results is also quite in accord with the result of TQ5.2, even though it seems teachers were optimistic regarding students prior knowledge (the average for TQ5.2 is 3.12)

Q3.2- Before attending the itinerary, I was already interested in scientific issues

	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# students	14	37	72	59		2.97 ± 0.83	3	3

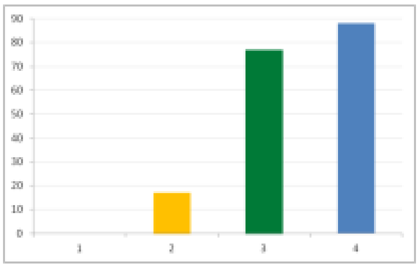
For students, I designed a set of three correlated questions, investigating their interest before, during and after attending the itinerary. I use this set of three question to have a qualitative index of whether I was able to change students' mindset concerning scientific issues. These three questions could have been



subjected to a statistical analysis of correlation; however, the statistical pool is too limited to allow formal and meaningful conclusions; moreover, it should also entails a class-by-class analysis, which at the moment lies outside the aims of my analysis. Furthermore, this question entails another conceptual problem: is it actually possible to quantify an abstract concept such as 'interest' with numbers? Conscious of these issues, I decided to keep these questions anyway in the survey, considering them to represent more qualitative than quantitative characteristics. The results of this question are quite satisfactory: the average is practically 3, but the variance is quite high, indicating that there was no unanimous judgment, as it can be seen from the bar chart and as it can be expected from such a typology of question.

Q3.3- During the itinerary, I was interested in the themes discussed

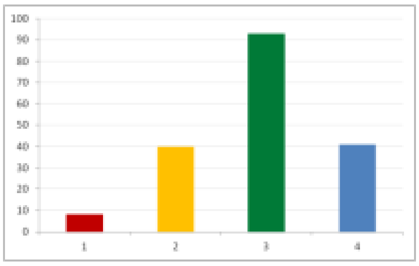
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)	Mean ± Var	Median	Mode
# students	0	17	77	88	3.39 ± 0.42	3	4



With this question, I wanted to have an index of how much students were interested in the themes discussed during the itinerary, to be later confronted with the result of the previous and of the following questions. Moreover, this question also allows me to understand whether I efficaciously presented the content, assuming that students' interest is directly correlated to the quality of the presentation. More than satisfied, I am happy of this question result: no students judged himself totally disinterested in the contents presented, and the most frequent answers (almost half of the students) has been 4, indicating a great degree of interest. The variance is also quite good, since less than 10% of students answered non-positively; the interest was thus rather unanimous.

Q3.4- After the itinerary, I feel I am more interested than before in science and technology

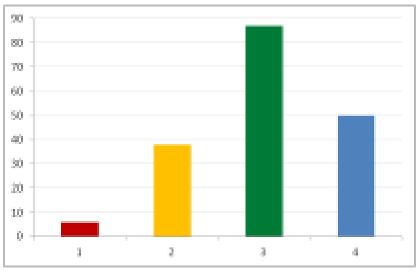
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)	Mean ± Var	Median	Mode
# students	8	40	93	41	2.92 ± 0.61	3	3



The average value of this question is smaller than Q3.2 one, even though just for half decimal. I suppose that it is rather improbable that, a student, after attending the itinerary, is less interested than before in scientific issues – considering also the fact that the negative answers (1s and 2s) dropped from 51 to 48. However, analyzing the semantic of the question, I have a preliminary justification for this fact: faced with a question of the kind 'Are you *more* interested than before …', if students feel that the magnitude of their interest did not change, they could actually disagree with the sentence, resulting in a negative answer. However, almost 75% of students answered positively: despite the mean falling within the 'mediocre' interval, and the variance covering 40% of the whole spectrum, I consider this question to represent a successful feature. So, considering the last three questions, we are faced with a situation where students were interested in the scientific themes proposed during the itinerary: this can be due to the itinerary communicative power, and equally to the fact that students were averagely already interested in scientific issues (Q3.2).

Q3.5- I learnt new mathematics, physics and biology concepts

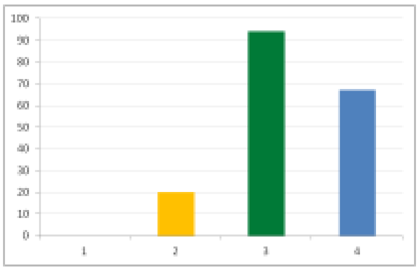
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)	Mean ± Var	Median	Mode
# students	6	38	87	50	3.00 ± 0.62	3	3



This question inquires the index of content transfer, namely whether students felt to have learnt something new. However, this is a quite general question: to effectively test the content transfer level, I should have asked specific questions. However, this would have been too similar to a classroom test, and I wanted to differentiate *Le Leggi della Natura* from classic classroom activities. Moreover, I wanted to test the index of interdisciplinary content transfer, thus inquiring if I was able to transmit discipline-specific issues and equally how these issues intercommunicate. The average is 3, indicating a positive reception, but the variance value is practically at the border between the second and the third interval of confidence. The result is reliable, but the variance indicates that it was not unanimous.

Q3.6- It was useful to explaining scientific issues starting from different laws of nature

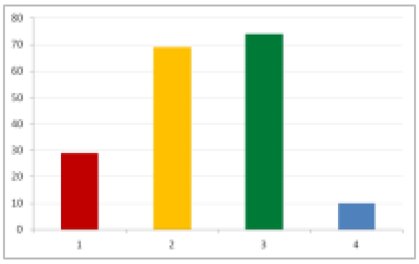
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# students	0	20	94	67		3.26 ± 0.41	3	3



I designed Q3.6 to be a ‘disguised’ version of Q3.5, focusing on the HPS content: If a student found useful to explain scientific issues starting from the laws of nature, it means also that he liked the HPS-based approach. The question thus inquires both the usefulness of the HPS-based approach, either the HPS content transfer. The result is satisfactory, falling wholly within the positive range of evaluation. Moreover, no student completely disagreed with the presented sentence, and this reflects in a quite good value for the variance, covering 26% of the available range.

Q3.7- I would be able to recognize a law of nature, or to describe the main features characterizing it

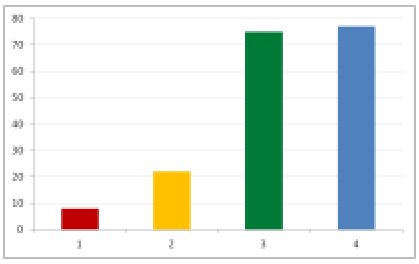
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)		Mean ± Var	Median	Mode
# students	29	69	74	10		2.36 ± 0.66	2	3



I expected contrasting opinions for this question; even though the most common answer has been an agreement (the mode is 3), the median value is 2 and, furthermore, this question has the most elevate number of students grading the sentence ‘1’, thus completely disagreeing with it. The mean is quite low, falling in the ‘negative’ side of the spectrum, and the variance is within the third confidence interval, indicating that the judgment was not unanimous. I think this is due to the characteristic of the question, in relation to my educational objectives and to how I structured the visit. An aim of *Le Leggi della Natura* was allowing students to reflect on their own on the role of laws of nature for scientific enterprise, and indeed I presented them contrasting ideas on the issue, instead than some absolute knowledge formed by right answers. Therefore, that some students do not consider themselves capable of recognizing or describing a law of nature, is not in contrast with the itinerary objectives, since they had not yet elaborated a personal view on the subject. The low grade is also due to the characteristics of the question itself, that probably would have received a higher evaluation if put in a form as "I have a personal idea of what a law of nature is". However, I was aiming not to always-positive results, but to honest ones. Being the result for this question not wholly negative, there is for sure room for improvement, but I am also satisfied by the fact that most students say they would be able to describe, with their own word, their own conception of a natural law.

Q3.8- I would attend LDN again, if extended to other museum halls or to other themes

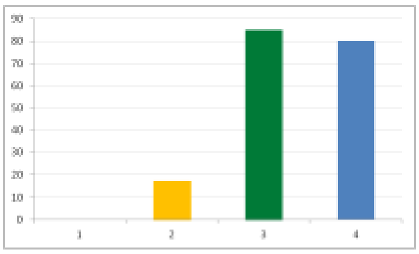
	Completely disagree (1)	Disagree (2)	Agree (3)	Completely agree (4)	Mean ± Var	Median	Mode
# students	8	22	75	77	3.21 ± 0.67	3	4



If students want to come back to MSN, to attend another itinerary similar to *Le Leggi della Natura*, is representative of the fact that they spend an interesting time at the museum, learning and at the same time having fun. Most students completely agreed with the presented sentence (the mode is 4), and the result falls within the positive evaluation range. The variance, V ≈ 0.7, indicates that the data quite spread out but, considering that only 30 of them expressed a negative evaluation, I am still satisfied by this result.

3.3.3. Itinerary features - Q4.1- Possibility of interaction and participation

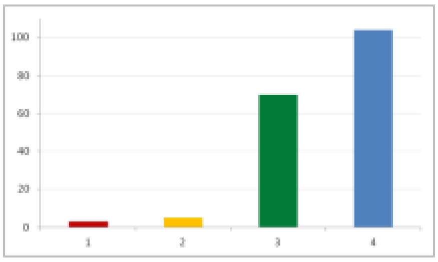
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	0	17	85	80	3.35 ± 0.41	3	3



Students were satisfied by this feature: 90% of them expressed a positive judgment and no student graded it as completely negative. The average falls within the positive interval; the variance reveals a not completely unanimous judgment, but still there is an overall general agreement.

Q4.2- Clarity of the exposition

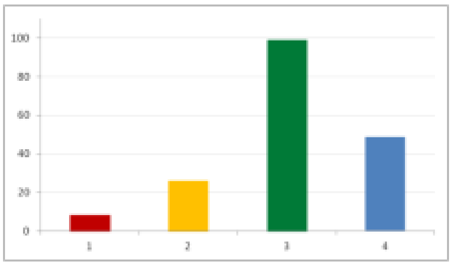
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	3	5	70	104	3.49 ± 0.40	4	4



Each student has its own standards to judge a specific issue as presented clearly. Thus, I was not expecting such satisfactory results: just 8 students thought that the content was not exposed clearly and, on the other hand, both median and mode are 4s. The mean is quite high, almost 3.5. The variance, V = 0.4, is also quite good, therefore I can consider this data pool to be reliable enough to represent a realistic result.

Q4.3- Length of the itinerary

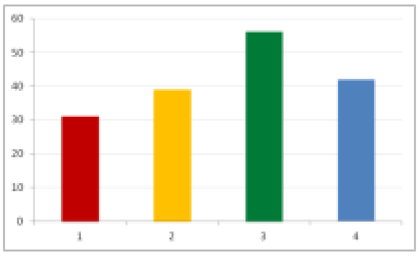
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	8	26	99	49	3.04 ± 0.59	3	3



The result of this question reveals that students found adequate the length of the itinerary, being the average value slightly bigger than 3, with a variance slightly smaller than 0.6. Interestingly, some students that answered ‘1’ or ‘2’ commented their choice, as “too long” (or, just in one case, ‘too short’). From this result, I can reasonably say that a length of about 2h, comprehending the introduction in the didactical laboratory and the actual guided tour, is adequate to fully explain the concepts, without bore or tire the students too much.

Q4.4 - Use of digital images and videos, tablet

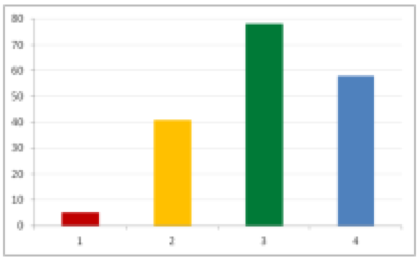
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	31	39	56	42	2.65 ± 1.10	3	3



As explained in teachers' survey, I was expecting a quite low grade for this item, and these expectations are met by the results: the average value, 2.65, indicates a 'mediocre' evaluation, whereas the variance has an high value, falling in the lowest reliability interval V > 0.9. As the bar chart shows, students' answer are divided quite equally among the four different possibilities (the difference between the most frequent answer, 3, and the less frequent one, 1, is just of 25 students). However, considering this result and teachers' one, I can argue that using a tablet during the itinerary is useful and ultimately recommendable for classes that are not too numerous. From this experience, I would consider a class not too numerous if the number of students is lower than 18.

Q4.5- Possibility of manipulating objects and specimens from the museum collection

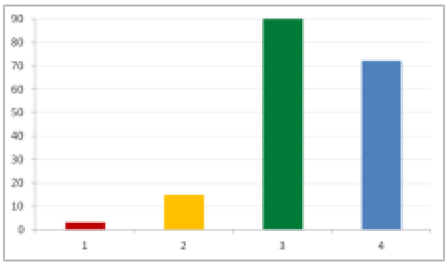
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	5	41	78	58	3.04 ± 0.65	3	3



I expected a higher satisfaction level for this question, since students seemed to really like playing with the various museum objects. However, the results are still satisfactory, with a 'positive' average value; on the other hand, the variance displays that the result extends for a length of 1.30, covering almost half of the possible spectrum. Thus, this result was not completely unanimous, but still satisfactory. The reasons behind the 46 non-positive grades could be the same as the previous question ones, i.e. that in the case of numerous classes, not everyone will have the same amount of time to manipulate the objects.

Q4.6- Multidisciplinarity of the itinerary

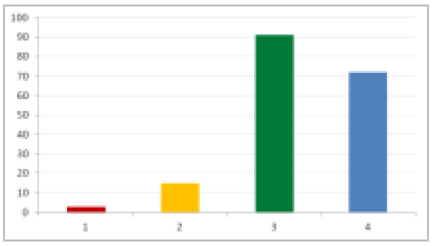
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	3	15	90	72	3.28 ± 0.47	3	3



Here, I tried to inquire whether students liked the multidisciplinary content, therefore passing from mathematics to biology to physics and back to biology. Together with questions Q3.5, Q3.6 and the following Q4.7, they allow me to have a comprehensive index of whether the interdisciplinary approach was appreciated, but most of all useful for in a museum context. Both mean and variance are quite satisfying, thus I consider this item to represent a successful feature.

Q4.7- Mathematical and physical analysis of biology problems

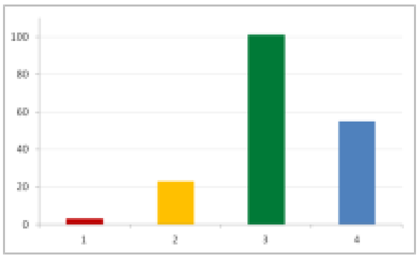
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	3	15	91	72	3.28 ± 0.47	3	3



This question, as it can be seen from the table, has almost the same frequencies as Q4.6. I think this indicates that students answered equally to both these questions, probably because they did not completely understand their conceptual difference: here, I am focusing specifically on technical contents, whereas the previous question entailed HPS knowledge too. In future surveys, I will formalize better this difference.

Q4.8- Survey filling

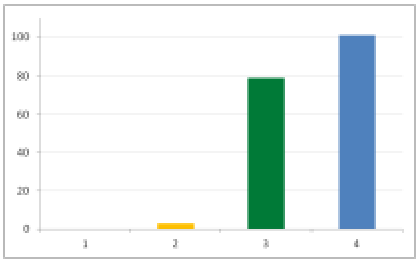
	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	3	23	101	55	3.14 ± 0.47	3	3



As I did for teachers, I wanted to have an index of whether students actually enjoyed filling the survey. I tried to explain them that it was a possibility to express an honest opinion over the itinerary they just attended, and therefore they should not have considered it as a test; so, I reminded them that the surveys is completely anonymous. The results are valid, as the variance value shows, and I can conclude that students actually considered the survey filling positively. Therefore, I will maintain the survey filling part as a feature of the itinerary.

Q4.9- Overall evaluation of the itinerary

	Negative (1)	More neg than pos (2)	More pos than neg (3)	Positive (4)	Mean ± Var	Median	Mode
# students	0	3	79	101	3.54 ± 0.28	4	4



I asked both teachers and students for a comprehensive evaluation of the whole itinerary, on the content presented together with the presentation methodology. Students' results are even more satisfactory than teachers': less than 2% of the whole ensemble answered non-positively and the most frequent answer was 4, which is also the calculated median value. I am really satisfied by this question result: students unanimously graded the itinerary as completely positive ($Ag > 3.5$, $V < 0.3$).

3.4. MUSEUM STANDARD SURVEYS RESULTS

The results coming from the standard surveys proposed by the museum are quite in agreement with mine. However, these surveys were directed just to the teachers that booked the itinerary, not to all teachers actually attending *Le Leggi della Natura*. So, the teachers that were not able to answer my survey, could actually have answered this one, since it is delivered and collected digitally some days after the activity. Furthermore, these surveys are more impersonal than mine: there is no educational operator explaining the questions, thus the object of the evaluation is not present at the time of the filling, as it is recommendable for an objective evaluation. Here, I present the standard surveys results that I consider useful for my analysis: I did not consider the questions concerning the quality of the booking process, but just the survey items relative to the activity evaluation/degree of satisfaction. The redemption index, i.e. the number of filled surveys to the number of surveys sent, is 85%, which is a rather satisfying statistical pool. I here present the result concerning mainly two variables coming from the standard surveys: the net promoter score NPS, and the calculated index of general satisfaction. The NPS is calculated from the question “How much is it probable that you will suggest your relatives or friends to attend the activity?”, and the answers follow a 0t10 scale. Answers are then catalogued based on three categories: *promoters* (answering 9 or 10), *neutral* (7 or 8) and *detractors* (all the others, from 0 to 6). For the itinerary *Le Leggi della Natura*, I have the following result:

Promoters	Neutral	Detractors
72.7%	18.1%	9.2%

More than 90% of teachers that booked the activity, few days after attending it, graded with an ‘8’ when facing a question concerning whether they would suggest to attend the itinerary. I think this result confirm my previous analysis, revealing an elevate general level of satisfaction.

Moreover, in the museum standard survey, there is another question asking specifically to rate the degree of satisfaction of the specific activity attended. The scale used is similar to mine. The possibilities are: unsatisfied, not really satisfied, satisfied, very satisfied. In the following table, I present the results that *Le Leggi della Natura* obtained, and I compare them with the results of all other MSN activities.

	Unsatisfied	Not completely satisfied	Satisfied	Very satisfied
LDN	--	--	63.6%	36.4%
MSN	--	3.1%	26.6%	70.3%

This surveys result shows that teachers were satisfied by the itinerary content and methodology. Despite an overall lower number of ‘very satisfied’ users, in respect to the MSN overall evaluation, there were no teachers declaring themselves as being not completely satisfied, whereas the percentage for the whole museum activities is about 3%. Moreover, considering the evaluations coming from other MUVE museums (e.g. for Murano Glass Museum, 2.2% of visitors are unsatisfied and 4.5% are not really satisfied, Goldoni’s

House has 9% of unsatisfied visitors, in Mocenigo Palace 1.8% are unsatisfied and 3.8% not really satisfied), I consider this result satisfactory and in line with the results I obtained from my statistical analysis.

3.5. FINAL COMMENTS

So, what can be inferred just from the statistical analysis? I will confront the comments presented here with the starting educational objectives in the Conclusion chapter of the thesis, to have a complete overview of *Le Leggi della Natura* intended both as an educational activity, therefore with the specific aim of teaching new concepts, either as a pragmatic research over the role and, ultimately, the importance of history and philosophy of science for science education. First of all, it is necessary to confront teachers and students results, to see whether there is agreement over the two surveys results and, thus, to see if the same patterns occur.

The following table summarizes the number of the answers falling within a specific evaluation interval, as a preliminary confrontation between teachers and students' results.

	Very negative [1, 2]	**Negative [2, 2.5]**	**Mediocre [2.5, 3]**	**Positive [3, 3.5]**	**Very Positive [3.5, 4]**
# result (teachers)	--	1	2	11	3
# results (students)	--	1	4	11	1

This table displays an overall shared agreement between students and teachers: in both cases, most questions had an average evaluation higher than 3, representing positive judgments. Moreover, in both cases I have no 'very negative' result and just one negative evaluation; for teachers it comes from the question asking the interest over an English version of *Le Leggi della Natura*, whereas for students it comes from asking them whether they would be able to recognize/describe a natural law. In both cases, however, as I explained in the result description chapter, this negative evaluation must not be taken strictly and can be justified by the nature of the itinerary itself.

Generally, teachers tended to grade the items with higher values: 'mediocre' results are just two and, at the same time, the number of 'very positive' answers is three, therefore quite high. Two of them comes from questions concerning the role of the laws of nature as an educational tool: I can already infer that this characteristics was thus highly appreciated by teachers. On the other hand, the only 'very positive' average for students' surveys comes from the last question, i.e. the itinerary overall evaluation. It must also be noted that teachers are probably more used to grade activities, and indeed from the result summary to be found in the appendix, it appears that teachers' judgments tend to be quite coherent, whereas students' grades tend to polarize. However, the statistical set for students is much larger, leaving more space to statistical fluctuations. From these simple considerations, I can already conclude that, despite small differences and fluctuations, students and teachers mostly agreed, since there is an overall coherent set of results. This agreement entails a generally positive evaluation. I can thus state that both teachers and students left Natural History Museum satisfied by the activity just attended, which is obviously positive for my research, but also for the museum public image.

There are some common patterns in the surveys results: for example, lowest grades correspond to the highest variances. In other words, if Ag falls in the right-hand side of the evaluation spectrum, it is more probable to find a variance lower than 0.6: for higher results, there was a higher level of unanimous judgments. For instance the highest-valued variances for positive evaluations are 0.62, 0.65 and 0.67, whereas the two negatively-evaluated questions variances are 0.83 and 0.66. Finally, the variances of the 'mediocre' questions are 0.65 and 0.56 for teachers, and 0.55, 0.61, 0.83 and 1.10 for students. Interestingly, the lowest variances are: for teachers, 0.21 (positive), and 0.23 two times, in both cases for 'very positive' items; for students, the lowest variance is in the only 'very positive' item ($V = 0.28$).

Summing everything up, due to the concordance of the results between teachers' surveys, students' surveys and museum standard surveys, and due to the fact that higher evaluations correspond to higher concordance between different users, I consider these results to be statistically valid and, more important, to demonstrate that *Le Leggi della Natura* has been a successful didactical activity.

4. CONCLUSIONS

In the present thesis, I investigated why and how much history and philosophy of science are necessary for science education and communication. More specifically, I focused on the import that a transdisciplinary concept such as the laws of nature has within the didactic of physics and mathematics. I decided to test the educational value of the laws of nature in two ways: first, with a conceptual analysis starting from the literature on the subject and then, more importantly, I tested laws of nature import for SCE with a practical example, based on the guided itinerary *Le Leggi della Natura*. This itinerary admittedly aimed at teaching technical issues pertaining to physics and mathematics, focusing on their application to biological problems; however, I used it also to test whether an interdisciplinary approach permits to go beyond a mere presentation of nude and arid technical facts, thus improving the efficacy of the SCE product in interesting a broader type of audiences. These two tests (i.e. studying conceptually the problem with literature study, and testing the pragmatic efficacy of the laws of nature through the museum itinerary) intercommunicate with each other: the literature review helped in designing the itinerary content and, at the same time, through the actual deliveries of the itinerary I made sense of some major concepts pertaining to the realm of science education, such as the Nature of Science. Therefore, I decided to structure the thesis in the following way, that resembles this back-and-forth creative process.

First, I described the starting hypothesis used in designing *Le Leggi della Natura* content, presenting a quick overview of the problems that 'laws of nature' concept suffers from, investigated philosophically and historically. Subsequently, I provide the reader with some core technical themes of the itinerary to set the context of analysis. In chapter 2, embedded in a review of the use of HPS in science education, I described how I presented these technical themes during the itinerary, stressing more in detail the usefulness of the laws of nature to transmit the specific contents. As one would understand, the literature on the laws of nature is extensive, and the same is valid for the application of HPS in SCE. However, it seems that scholars put little attention on the educational role of the laws of nature. I thus tried to fill this conceptual gap with my research. Moreover, I inquired also the pivotal role of laws of nature in finetuning the methodology of presentation. Finally, having offered a comprehensive overview of the itinerary, I analyzed the evaluation surveys I handed in at the end of the itineraries, to base my final considerations on descriptive statistics. These surveys revealed a general agreement between students and teachers over the itinerary evaluation, and are also in accord with the results of the museum standard surveys. There has been a shared general interest for the content presented and for the methodology used and, more importantly, a great degree of satisfaction at the conclusion of the activity. This is the first important final result of my research: audiences left the museum with positive feelings about the itinerary and, most times, they were enthusiastic of the just-attended activity. Therefore, due to this enthusiasm, I can already consider my project to be successful, since I was capable to present the transdisciplinary content I had in mind efficaciously. However, it is useful to formalize more the project results, since enthusiasm surely is an index of success, but it is not sufficient for an explicit judgment over the educational importance of the laws of nature.

I now present the main result that can be inferred from my analysis, namely that indeed laws of nature are an essential educational tool. This result is based on three main arguments: (1) laws of nature are an essential tool for SCE since, when correctly conceptualized and historicized, are able to represent various types of NOS knowledge; (2) focusing a SCE product on the laws of nature allows for an efficacious transmission of both technical either cultural content; (3) laws of nature are a subject that most audiences find interesting.

(1) Laws of Nature and NOS knowledge. As presented in the first two chapters, it is impossible to find a definition of the laws of nature that is, simultaneously, clear, unique and historically coherent. This is the first NOS characteristic that is clarified by using of laws of nature, namely science as detached from the conception of scientists as neutral truths-discoverers that appears to be so common in present-day educational environment. On the other hand, scientific concepts, theories, laws, rules, … are subjected to a historical evolution, that is strongly dependent on the social context. Furthermore, as described in the section 2.3.1., laws of nature are capable to infuse coherently NOSK content with consideration on the nature of scientific inquire, considered as a human process. This leads directly to the second point:

(2) Laws of Nature and content-specific transmission. Due to their inherent transdisciplinary nature, laws of nature help the educational operator in presenting technical content embedded in a broader cultural context, at the same time blurring the strict division between technical and cultural contents, that should have little or no relevance for SCE, as demonstrated in section 2.2. and 2.3. For example, focusing on the distinction between laws of nature and laws of science we are inquiring this division, simultaneously keeping attention to the specific law subject matter. The efficacy of the laws of nature for contents transmission is further enhanced by the evaluation surveys statistical analysis. For example, the average answer for question 5.5 of teachers' survey (TQ5.5 = laws of nature as a tool for mathematics, physics and biology didactic) is 3.65 ± 0.23, which indicates a very positive and unanimous judgment over the fact that laws of nature are apt to transmit technical knowledge. At the same time, combining TQ5.6 (interdisciplinary approach to teach hard sciences), TQ6.5 (laws of nature as mediator between different subjects) and TQ6.6 (transmission of scholastic content), that received, in order, a positive, very positive and again positive judgment, we can infer that teachers were satisfied also by the infusion of extra-scientific content within the itinerary. Similarly, focusing now on students' surveys, SQ3.5 (I learnt new physics, biology and mathematics concepts) and SQ3.6 (I found useful to learn scientific concepts starting from an analysis of the laws of nature) both received positive answers. An interesting case is represented by SQ3.7 (I could recognize a law of nature) that, as explained earlier in the evaluation chapter, despite having received a negative judgment, still represent a successful itinerary feature. Too many high-valued answer would mean that, at the end, I presented them with a unique definition of a law of nature, going against the starting hypotheses I used in the itinerary design.

Combining results *(1)* and *(2)*, we have a decent example of a SCE product built using an approach that P. Heering has quoted with the term 'Whole Science', based on a definition the philosopher of science and science educator D. Allchin introduced. The Whole Science approach "combines together both NOS teaching and the inquire approach by addressing observational, conceptual and socio-cultural dimensions of reliability in science […] Using history as a benchmark, one may well conceive Whole Science in an educational context as a synthesis: teaching scientific concepts while nurturing process-of-science-skills and fostering NOS reflections".[68] As explained above, laws of nature allows for an adequate transmission of technical content, simultanouesly shining light on NOS issues. Moreover, since the itinerary is built dialogically, students are also able to put themselves in scientists' shoes, acquiring theoretical process-of-science-skills, since they are confronted with scientific problems and asked to find a resolution through hypotheses and models. This issue leads us to the last point describing the usefulness of laws of nature as educational tool.

(3) Laws of nature are a subject capable to thrill audiences' curiosity. Two questions results support this claim: TQ5.3 (during the itinerary, students were interested in the themes discussed) and SQ3.3 (during the itinerary, I was interested in the themes discussed) test directly the degree of interest and they both received positive evaluations. Being the laws of nature the main issue at stake during the itinerary, I can reasonably assume that they played a huge role for the itinerary success. Moreover, the result of TQ3 displays that half of teachers decided to test their students on the content discussed on *Le Leggi della Natura*, and the majority of them (41%) decided it after attending the itinerary. Therefore, considering that almost every teacher had at least 4 years of teaching experience more than me, and also that the content presented usually is extra-curricular, I can rightly say that a presentation based on the laws of nature enhanced the interest of teachers, and thus also the communicative power of a scientific itinerary.

In addition, based on the actual itinerary deliveries feedbacks and, for example, on SQ4.1 (possibility of interaction and active participation) that received a positive evaluation, the previous claim can be further strengthen:

(3.1) Basing a SCE product on the laws of nature leads naturally to dialogic lessons .Usually, audiences already have a personal definition of a law of nature and thus can compare the content presented with their previous knowledge. The questions concerning audiences' background adequateness to fully understand the itinerary (TQ5.1 = I was familiar with the itinerary content; TQ5.2 = the content was adequate for students' prior knowledge; SQ3.1 = my background knowledge was sufficient to understand the itinerary) enforce this claim. Most content presented usually do not find space in school curricula;

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[68] P. Heering "Science Museums and Science Education" (2017), p. 402.

moreover, since *Le Leggi della Natura* is a didactical itinerary, my aim was to cope with subjects matters audiences are usually unfamiliar with. Laws of nature glued together all these subjects and the fact that the three previous answers did not receive a negative evaluation implies that audiences already had in mind a personal conception of laws of nature – hazed it might be. Moreover, due to their characteristics presented in point (1), they are particularly apt to exchange different ideas and to raise doubts that the interested user can resolve just by mean of a dialogic confrontation with the operator or, even more important, with the other users.

To conclude, I propose that the laws of nature are indeed an adequate tool for teaching science and for teaching about science. They are capable to effectively and coherently infuse several disciplines, transmitting technical content embedded in its specific socio-cultural context. I presented their effectiveness when dealing with mathematics and physics issues, such as the mathematical modeling of natural forms or the match between classical mechanics laws and animal motion, but I am sure that further research can demonstrate their primary importance also for other disciplines, such as chemistry, ecology or even economics. Furthermore, through the laws of nature, students could approach also problems from higher-level physics, such as quantum mechanics or general relativity. My analysis thus wanted to offer an example of how to include history and philosophy of science in science teaching and communication: I demonstrated that focusing the specific SCE product on the laws of nature makes this inclusion rather easy to do and, even more importantly, highly fruitful. Thus, the laws of nature are a powerful conceptual device for science education and communication and deserve a primarily role in SCE products design.

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6. APPENDIXES

6.1. ITINERARY SURVEY: TEACHERS

Q1: Which is your area of specialization?

♦ Sciences ♦ Humanities ♦ Arts ♦ Other

Q2: How many years of experience do you have in education?

♦ 1-5 ♦ 5-10 ♦ 10-20 ♦ 20+

Q3: Will you do any classroom activities on the themes discussed?

♦ Yes, decided before the tour ♦ Yes, decided after the tour ♦ No ♦ Don't know

Q4: Have you already visited Venice Natural History Museum? ♦ YES ♦ NO

Q5: Do you agree with the following statements? 1 = not at all, 2 = not so much, 3 = quite, 4 = a lot

	1	2	3	4
I was familiar with the themes discussed during the tour				
The level of the analysis was adequate to students' background knowledge				
During the tour, students were interested in the discussed arguments				
After the tour, students are more inclined to study scientific issues independently				
I found useful to learn physics and biology concepts starting from an analysis of the laws of nature and their features				
I think that a multidisciplinary approach could make hard science more accessible to students				
I would follow a "Le Leggi della Natura 2.0" if extended to different museum halls and to different scientific issues				
I would follow a "Le Leggi della Natura 2.0" if offered in English				

Q7: Evaluate the following features of the guided tour (1 = negative; 2 = quite negative; 3 = quite positive; 4 = very positive)

	1	2	3	4
Use of digital images and videos				
Possibility for the students to manipulate some museum objects				
Coherence of the tour content with the educational context of the museum				
Level of the analysis of specific issues (eg mechanics, fractals, …)				
Laws of nature as mediation between different disciplines				
Physics and biology content transfer				
Real-world application of physics and mathematics tools				
Filling of the evaluation survey				
Guided tour final evaluation				

6.2. ITINERARY SURVEY: STUDENTS

Q1: Have you ever visited Venice natural history museum before? | YES | NO |

Q2: Have you ever visited a science museum before? | YES | NO |

Q3: Do you agree with the following statements? 1 = not at all, 2 = not so much, 3 = quite, 4 = a lot

	1	2	3	4
My background knowledge was sufficient to fully understand the itinerary				
Before the visit, I was already interested in science and technology				
During the visit, I was interested in the arguments discussed				
After the visit, I will independently get informed on some scientific issues				
After the visit, I feel I have learnt new mathematics, physics and biology concepts				
I found useful to learn scientific concepts starting from the laws of nature				
I would recognize a natural law used in scientific enterprise				
I would attend again Le Leggi della Natura if extended to different museum halls or to different scientific themes				

Q4: Evaluate the following features of the guided tour (1 = negative; 2 = quite negative; 3 = quite positive; 4 = very positive)

	1	2	3	4
Interaction and participation				
Clarity of the ex position				
Lenght				
Use of digital images and videos				
Possibility of manipulating some museum objects				
Multidisciplinarity				
Usefulness of physics in explaining some biological systems and phenomena				
Evaluation survey filling				
Guided tour final evaluation				

6.3 SUMMARY OF RESULTS

6.3.1. Teachers

Q1. Teachers' expertise area

Sciences	Mathematics	Humanities	Others
47%	23%	12%	18%

Q2. Teachers' years of experience

1-5	5-10	10-20	20+
12%	12%	41%	35%

Q3. Are teachers testing students over Le Leggi della Natura content?

Yes (decided before attending the itinerary)	Yes (decided after)	No	Don't know
6%	41%	24%	29%

Q4. Have teachers already visited MSN?

Yes	No
47%	53%

Q5.1 – I was familiar with the itinerary content

2.77 ± 0.65

VERY NEGATIVE	NEGATIVE	**MEDIOCRE**	POSITIVE	VERY POSITIVE

Q5.2 – The content level was adequate for students' knowledge

3.12 ± 0.57

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q5.3 – During the itinerary, students were interested in the themes discussed

3.18 ± 0.38

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q5.4 – After the itinerary, students are more interested in science

3.00 ± 0.35

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q5.5 – Laws of nature as mean to explain physics, mathematics and biology concepts

3.65 ± 0.23

VERY NEGATIVE	NEGATIVE	MEDIOCRE	POSITIVE	**VERY POSITIVE**

Q5.6 – Interdisciplinary approach to hard sciences

3.47 ± 0.37

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q5.7 – I would attend LDN again, if extended to other museum halls

3.35 ± 0.36

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q5.8 – I would attend LDN again, if offered in English

2.41 ± 0.83

VERY NEGATIVE	**NEGATIVE**	MEDIOCRE	POSITIVE	VERY POSITIVE

Q6.1 – Use of tablet (digital images and videos)

2.71 ± 0.56

VERY NEGATIVE	NEGATIVE	**MEDIOCRE**	POSITIVE	VERY POSITIVE

Q6.2 – Use of museum objects and specimens

3.35 ± 0.46

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q6.3 – Coherence between LDN and MSN environment

3.29 ± 0.33

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q6.4 – Depth of the analysis of the specific subjects

3.41 ± 0.24

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q6.5 – Laws of nature as mediator between different subjects

3.65 ± 0.23

VERY NEGATIVE	NEGATIVE	MEDIOCRE	POSITIVE	**VERY POSITIVE**

Q6.6 – Transmission of scholastic content

3.41 ± 0.24

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q6.7 – Real-world application of physics and mathematics concepts

3.53 ± 0.25

VERY NEGATIVE	NEGATIVE	MEDIOCRE	POSITIVE	**VERY POSITIVE**

Q6.8 – Survey design and filling

3.35 ± 0.35

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q6.9 – Itinerary overall evaluation

3.29 ± 0.21

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

6.3.2. Students

Q1. Have you been to MSN before?

Yes	No
28%	72%

Q2. Have you ever been to a science museum before?

Yes	No
84%	16%

Q3.1 – My background knowledge was sufficient to understand LDN

2.94 ± 0.55

VERY NEGATIVE	NEGATIVE	**MEDIOCRE**	POSITIVE	VERY POSITIVE

Q3.2 – Before the itinerary, I was already interested in science

	2.97 ± 0.83			
VERY NEGATIVE	NEGATIVE	**MEDIOCRE**	POSITIVE	VERY POSITIVE

Q3.3 – During the itinerary, I was interested in the themes discussed

			3.39 ± 0.42	
VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q3.4 – After the itinerary, I am more interested in science

	2.92 ± 0.61			
VERY NEGATIVE	NEGATIVE	**MEDIOCRE**	POSITIVE	VERY POSITIVE

Q3.5 – I learnt new physics, biology and mathematics concepts

	3.00 ± 0.62			
VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q3.6 – Laws of nature as educational tool

		3.26 ± 0.41		
VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q3.7 – I can recognize a law of nature

2.36 ± 0.66				
VERY NEGATIVE	**NEGATIVE**	MEDIOCRE	POSITIVE	VERY POSITIVE

Q3.8 – I would attend LDN again, if extended to other themes

3.21 ± 0.67

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.1 – Active participation and interaction

3.35 ± 0.41

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.2 – Clarity of the exposition

3.49 ± 0.40

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.3 – Length of the itinerary

3.04 ± 0.59

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.4 – Digital images and videos

2.65 ± 1.10

VERY NEGATIVE	NEGATIVE	**MEDIOCRE**	POSITIVE	VERY POSITIVE

Q4.5 – Use of objects and specimens from the museum collection

3.04 ± 0.65

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.6 – Transdisciplinarity

3.28 ± 0.47

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.7 – Mathematics and physics application to biology

3.28 ± 0.47

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.8 – Survey filling

3.14 ± 0.47

VERY NEGATIVE	NEGATIVE	MEDIOCRE	**POSITIVE**	VERY POSITIVE

Q4.9 – Itinerary overall evaluation

3.54 ± 0.28

VERY NEGATIVE	NEGATIVE	MEDIOCRE	POSITIVE	**VERY POSITIVE**