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Enlightening Interdisciplinarity in STEM for Teaching

DISCIPLINES AND INTERDISCIPLINARITY IN STEM EDUCATION TO FOSTER SCIENTIFIC AUTHENTICITY AND DEVELOP EPISTEMIC SKILLS

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Integrate Disciplines to Elaborate Novel Teaching approaches to InTerdisciplinarity and Innovate pre-service teacher Education for STEM challenges

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INTER-DISCIPLINARITY vs. A-DISCIPLINARITY, TRANS-DISCIPLINARITY or MULTI-DISCIPLINARITY

"Multidisciplinarity involves encyclopaedic, additive juxtaposition or, at most, some kind of coordination, but it lacks intercommunication and disciplines remain separate: it is, in fact, a pseudo-interdisciplinarity. True interdisciplinarity is integrating, interacting, linking, and focusing. […]. Transdisciplinarity is transcending, transgressing, and transforming, it is theoretical, critical, integrative, and restructuring but, as a consequence of that, it is also broader and more exogenous" (Thompson Klein, 2010

How can disciplines integrate, interact, be linked each other in perspective teacher education, in disciplinary-based institutional contexts?

INTER-Disciplinarity implies to start from «disciplines» and their «identities»

The term “discipline” contains the Latin root “discere”, whose meaning is to learn. Disciplines are re-organizations of the knowledge with the scope of teaching it.

Students, whilst building their knowledge, should also develop epistemic skills, like problem solving, modelling, representing, arguing, explaining, testing, sharing, evaluating the correctness of a reasoning/an argument.

From this perspective, disciplines can still play a relevant educational role, provided that they are explicitly pointed out as forms of knowledge organization historically developed and grounded on specific epistemologies

The challenging questions related to ..INTER-Disciplinarity between Mathematics and Physics (from a curricular point of view)

- What characterizes physics and mathematics *as disciplines*?
- Does school science give back the sense of physics and mathematics as disciplines?
- What is the relation between the «disciplinary identities» and the added value of their «integration»?

FRA "wheel" (Family Resemblance Approach; Erduran & Dagher, 2014)

Disciplines and school science

School science often do not reflect both the nature of contemporary scientific endeavor and the history of science

Disciplinary authenticity should be pursued developing epistemic skills "by emphasizing the practices of doing science and generating scientific knowledge, while other, more historical-philosophical–oriented settings may emphasize critical reflection on the epistemological and historical processes of the development of scientific knowledge."
(Kapon et al., 2018)

Interdisciplinarity and disciplinary authenticity: a virtuous circle?

Interdisciplinarity ⟷ Disciplinary authenticity

1. an interdisciplinary approach could help in understanding better a discipline (ex. blackbody radiation, parabola and parabolic motion)

2. disciplinary knowledge could help in learning new disciplines or in dealing with new problems that are not yet organized in a discipline (ex. artificial intelligence)

History-pedagogy-mathematics/physics (HPM/Ph): an innermost relationship (Tzanakis, 2016)

Intertwined and bi-directional co-evolution, interdisciplinarity as the essence of the historical evolution of the two disciplines.

Historical cases can mirror both disciplinary authenticity and interdisciplinarity

Maths → Physics

mathematics is the language of physics, not only as a **tool for expressing** ... but also as an indispensable, formative characteristic that shapes the physical concepts, by **deepening, sharpening, and extending their meaning**, or even endowing them with meaning.

Physics→ Maths

physics constitutes a natural framework for **testing, applying and elaborating mathematical theories,** methods and concepts, or even motivating, stimulating, **instigating and creating all kinds of mathematical innovations.**

Blackbody radiation

One of the most interesting historical case studies:
the breakthrough that led to Quantum Physics

What contribution can this **historical case** provide to the debate on the **interplay of physics and mathematics**? What are the specific roles of mathematics in this case?

How can the case be **reconstructed for an educational purpose**?

Branchetti, L., Cattabriga, A., Levrini, O. (2019). Interplay between mathematics and physics to catch the nature of a scientific breakthrough: the case of the blackbody, *Phys. Rev. Phys. Educ. Res.*

A possible framework and some steps forward

Akkerman S.F., Bakker A. (2011)
Boundary crossing and boundary objects.
Review of educational research, 81(2), 132-169

Thompson Klein J. (2010)
A taxonomy of interdisciplinarity.
The Oxford handbook of interdisciplinarity, 15, 15-30

Kapon, S., Erduran, S. (in press). Crossing boundaries – Examining and problematizing interdisciplinarity in science education. *Engaging with Contemporary Challenges through Science Education Research: Selected papers from the ESERA 2019 Conference*

Akkerman, S. F., & Bakker, A. (2011).
Boundary crossing and boundary objects.
Review of educational research, 81(2), 132-169.

Boundary people

Boundary objects

Boundary crossing (learning mechanisms)

- *Coordination*
- *Identification*
- *Reflection*
- *Transformation*

Akkerman & Bakker, 2011

Boundary Objects

Boundary Objects -
An ambiguous nature

Both – and: Objects that **enact the boundary** by addressing and articulating meanings and perspectives (multivoicedness) of various intersecting worlds.

Neither – nor: objects that **move beyond the boundary** in that they have an unspecified quality of their own.

This ambiguity creates a **need for dialogue**, in which meanings have to be negotiated and from which something new may emerge → if made explicit, the **ambiguous character can be turned into learning opportunities**

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Identification

Recognition and enhancement of differences, through a dialogic process, in terms of:

- practices and methods
- values
- disciplinary knowledge

which have uncertain demarcation lines.

Coordination

Communicative connection that is established by tools that belong to the different "areas", like boundary objects necessary to find new translation / clarification criteria in order to find a new balance and share new meanings.

Reflection

In the interaction between the different "areas", recognition of one's identity in terms of:

- practices and methods,
- values,
- disciplinary knowledge.

opportunity to see through the eyes of other

Transformation

Profound changes, in one or both disciplines, in terms of:

- practices
- values
- knowledge

potentially allowing the *creation of a new border practice*

Akkerman-Bakker learning mechanisms to design ID activities

In crossing the disciplines’ boundaries, **it is not taken for granted that such learnings will take place** (“learning potentials”).

- Each learning mechanism has its own interdisciplinary processes that must be properly activated.

If we consider:

- an **interdisciplinary topic** as a boundary object between disciplines
- an **activity** on that topic as a boundary crossing

it could be essential to ask **which learning potentials** are enabled.

Parabola and parabolic motion at the boundary between Maths and Physics

Module structure

0. Preliminary activity and intro to IDENTITIES

1. «Living at the boundary: framing interdisciplinarity»

2. Parabolic motion and the establishment of physics as a discipline

3. History of conics and the birth of projective geometry

4. The concepts of symmetry and proof as boundary objects

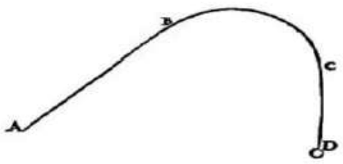
5. Linguistic text analysis

6. Wrapping up

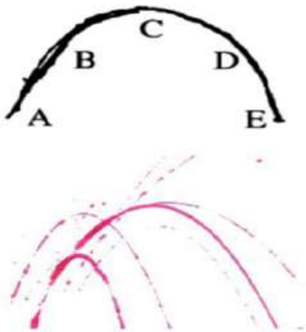
Symmetry and proof as key epistemological boundary objects

Reconstruction of some excerpts from:

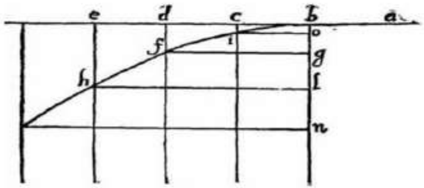
a) Hunting the White Elephant: When and How did Galileo Discover the Law of Fall? (Renn et al., 2000);
b) Guidobaldo Del Monte's Notebook (ca. 1587-1592);
c) Discourses and Mathematical Demonstrations Relating to Two New Sciences (Galilei, 1638).



Tartaglia



Guidobaldo



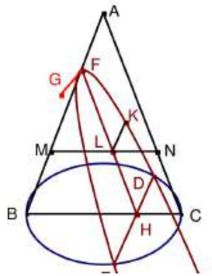
Galileo

On the **left**, motion's representation of Tartaglia (1537); in the **middle**, the trajectory drawing in Guidobaldo's notebook and the reproduction of his ink experiment, done by Cerreta (2019); on the **right**, the figure supporting Galileo's demonstration of the parabolic trajectory.

Parabola in the History of Mathematics and Physics

- <u>Contextualization of Galileo's proof</u> in the framework of history of argumentation and proof and conics in Ancient times (Euclid, Apollonius)

- <u>Conics in the history of mathematics</u> and contribution of physical studies in Optics to their evolution (Kepler, projective geometry)



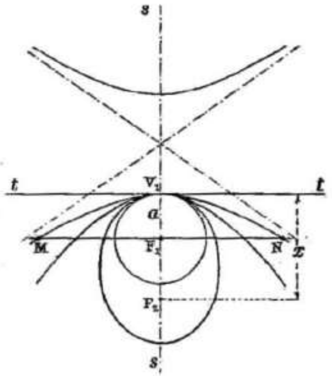


Fig. 1

Two examples to show in a concrete case the paradigm of co-evolution of mathematics and physics (Tzanakis, 2016)

Schvartzer, M., Elazar, M. & Kapon, S. Guiding Physics Teachers by Following in Galileo's Footsteps. *Sci & Educ* 30, 165–179 (2021).

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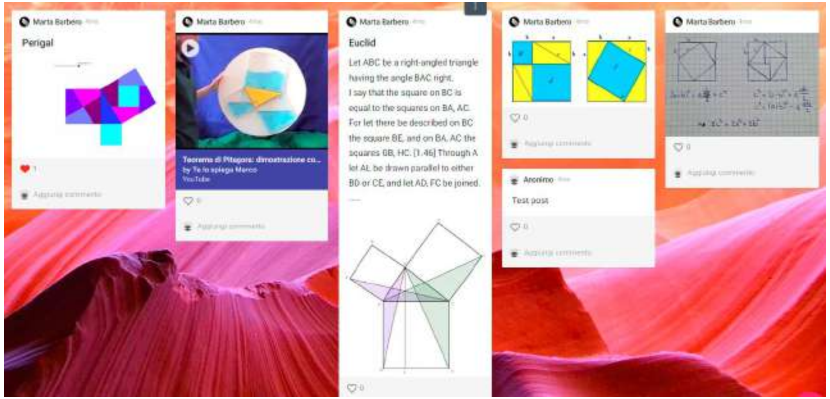
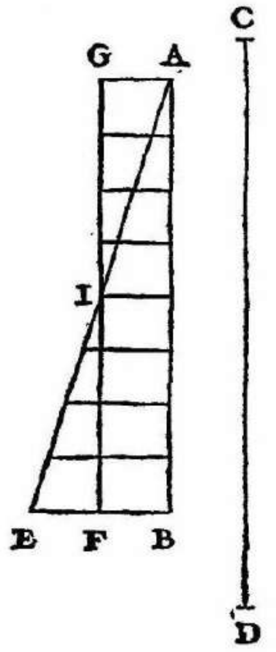
How to make Galileo's proof a boundary objects?

1. Write a proof of Pythagoras' theorem
2. Proof in Euclid's *Elements* and in analytical geometry
3. The characterization of theorems, theory and metatheory
4. Proof by Galileo about parabolic motion: an epistemological analysis





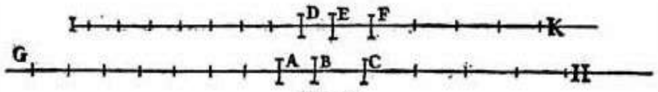


Fig. 40

From the above definition, four axioms follow, namely:

Axiom I ↩

In the case of one and the same uniform motion, the distance traversed during a longer interval of time is greater than the distance traversed during a shorter interval of time.

Axiom II ↩

In the case of one and the same uniform motion, the time required to traverse a greater distance is longer than the time required for a less distance.

Axiom III ↩

In one and the same interval of time, the distance traversed at a greater speed is larger than the distance traversed at a less speed.

Axiom IV[192] ↩

The speed required to traverse a longer distance is greater than that required to traverse a shorter distance during the same time-interval.

Theorem I, Proposition I ↩

If a moving particle, carried uniformly at a constant speed, traverses two distances the time-intervals required are to each other in the ratio of these distances.

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FOURTH DAY ↩

SALVIATI. Once more, Simplicio is here on time; so let us without delay take up the question of motion. The text of our Author is as follows:

THE MOTION OF PROJECTILES ↩

In the preceding pages we have discussed the properties of uniform motion and of motion naturally accelerated along planes of all inclinations. I now propose to set forth those properties which belong to a body whose motion is compounded of two other motions, namely, one uniform and one naturally accelerated; these properties, well worth knowing, I propose to demonstrate in a rigid manner. This is the kind of motion seen in a moving projectile; its origin I conceive to be as follows:

Imagine any particle projected along a horizontal plane without friction; then we know, from what has been more fully explained in the preceding pages, that this particle will move along this same plane with a motion which is uniform and perpetual, provided the plane has no limits. But if the plane is limited and elevated, then the moving particle, which we imagine to be a heavy one, will on passing over the edge of the plane acquire, in addition to its previous uniform and perpetual motion, a downward propensity due to its own weight; so that the resulting motion which I call projection [*projectio*], is compounded of one which is uniform and horizontal and of another which is vertical and naturally accelerated. We now proceed to [245] demonstrate some of its properties, the first of which is as follows:

THEOREM I, PROPOSITION I[269] ↩

A projectile which is carried by a uniform horizontal motion compounded with a naturally accelerated vertical motion describes a path which is a semi-parabola.

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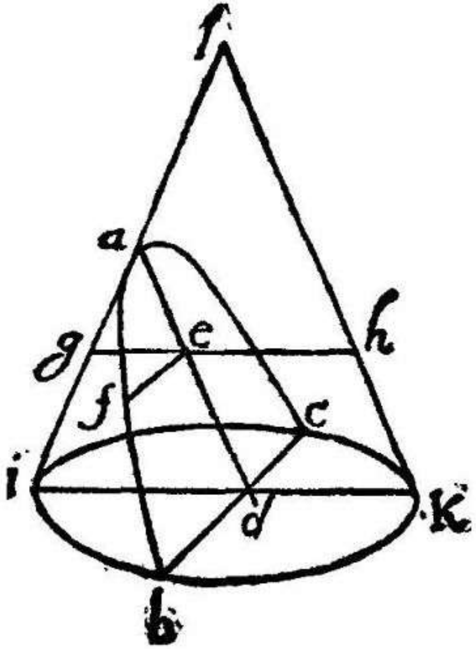

Fig. 106

SAGR. Here, Salviati, it will be necessary to stop a little while for my sake and, I believe, also for the benefit of Simplicio; for it so happens that I have not gone very far in my study of Apollonius and am merely aware of the fact that he treats of the parabola and other conic sections, without an understanding of which I hardly think one will be able to follow the proof of other propositions depending upon them. Since even in this first beautiful theorem the author finds it necessary to prove that the path of a projectile is a parabola, and since, as I imagine, we shall have to deal with only this kind of curves, it will be absolutely necessary to have a thorough acquaintance, if not with all the properties which Apollonius has demonstrated for these figures, at least with those which are needed for the present treatment.

SALV. Indeed, all real mathematicians assume on the part of the reader perfect familiarity with at least the elements of Euclid; and here it is necessary in your case only to recall a proposition of the Second Book in which he proves that when a line is cut into equal and also into two unequal parts, the rectangle formed on the unequal parts is less than that formed on the equal (i. e., less than the square on half the line), by an amount which is the square of the difference between the equal and unequal segments. From this it is clear that the square of the whole line which is equal to four times the square of the half is greater than four times the rectangle of the unequal parts. In order to understand the following portions of this treatise it will be necessary to keep in mind the two elemental theorems from conic sections which we have just demonstrated; and these two theorems are indeed the only ones which the Author uses. We can now resume the text and see how he demonstrates his first proposition in which he shows that a body falling with a motion compounded of a uniform horizontal and a naturally accelerated [*naturale descendente*] one describes a semi-parabola.

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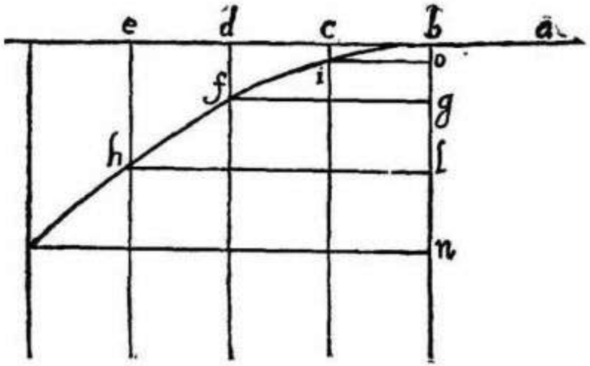


Fig. 108

Let us imagine an elevated horizontal line or plane *ab* along which a body moves with uniform speed from *a* to *b*. Suppose [249] this plane to end abruptly at *b;* then at this point the body will, on account of its weight, acquire also a natural motion downwards along the perpendicular *bn*. Draw the line *be* along the plane *ba* to represent the flow, or measure, of time; divide this line into a number of segments, *bc, cd, de,* representing equal intervals of time; from the points *b, c, d, e,* let fall lines which are parallel to the perpendicular *bn*. On the first of these lay off any distance *ci*, on the second a distance four times as long, *df;* on [273] the third, one nine times as long, *eh;* and so on, in proportion to the squares of *cb, db, eb*, or, we may say, in the squared ratio of these same lines. Accordingly we see that while the body moves from *b* to *c* with uniform speed, it also falls perpendicularly through the distance *ci*, and at the end of the time-interval *bc* finds itself at the point *i*. In like manner at the end of the time-interval *bd*, which is the double of *bc*, the vertical fall will be four times the first distance *ci;* for it has been shown in a previous discussion that the distance traversed by a freely falling body varies as the square of the time; in like manner the space *eh* traversed during the time *be* will be nine times *ci;* thus it is evident that the distances *eh, df, ci* will be to one another as the squares of the lines *be, bd, bc*. Now from the points *i, f, h* draw the straight lines *io, fg, hl* parallel to *be;* these lines *hl, fg, io* are equal to *eb, db* and *cb* respectively; so also are the lines *bo, bg, bl* respectively equal to *ci, df,* and *eh*. The square of *hl* is to that of *fg* as the line *lb* is to *bg;* and the square of *fg* is to that of *io* as *gb* is to *bo;* therefore the points *i, f, h,* lie on one and the same parabola. In like manner it may be shown that, if we take equal time-intervals of any size whatever, and if we imagine the particle to be carried by a similar compound motion, [250] the positions of this particle, at the ends of these time-intervals, will lie on one and the same parabola.

A theorem consists of

- a statement
- the proof
- the theoretical framework of reference

\+ metatheory (i.e., the set of formal rules that allow to derive theorems from the starting group of axioms and definitions)

The aims of a proof can be

- **Argumentative**: to convince, give theoretical foundation and rigorous structure to reasoning to persuade the truth of a statement
- “**Relational**”: to show from what assumptions and results precedents depends on a theorem, to understand in which models it holds; decide how much weaken the assumptions, if possible, and what to assume
- **Generative**: to generate new knowledge

Parabolic Path

RWP Just what is the shape of the curved path followed by a projectile launched horizontally? This can be found by combining $x = v_0 t$ and $y = h - \frac{1}{2}gt^2$, which allows us to express y in terms of x. First, solve for time using the x equation. This gives

$$t = \frac{x}{v_0}$$

Next, substitute this result into the y equation to eliminate t:

$$y = h - \frac{1}{2}g\left(\frac{x}{v_0}\right)^2 = h - \left(\frac{g}{2{v_0}^2}\right)x^2 \qquad \text{4-8}$$

It follows that y has the form

$$y = a + bx^2$$

Theorem I, Proposition I

A projectile which is carried by a uniform horizontal motion compounded with a naturally accelerated vertical motion describes a path which is a semi-parabola.

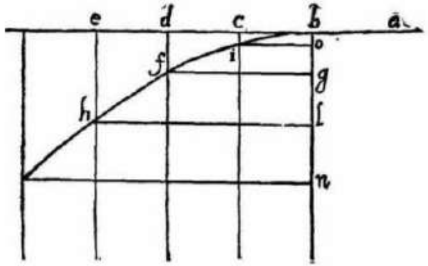


Fig. 108

15. Il moto dei corpi lanciati in aria

Un corpo lanciato in aria si muove, in generale, lungo una traiettoria curva: la figura 30 è stata copiata da una fotografia multiflash di una palla lanciata in aria in direzione obliqua. Cerchiamo di capire come si svolge il moto facendo alcune misurazioni sulla figura.

Innanzitutto: il moto della palla può essere considerato come se fosse composto dalla *sovrapposizione* di due moti: *un moto verticale* ed *un moto orizzontale*. Disegnando sulla figura con una matita a punta fine un reticolato

Un'ulteriore analisi della traiettoria della palla mostra che la sua forma è parabolica. Questo fatto può essere da te verificato riferendo la curva che rappresenta la traiettoria ad una coppia di coordinate spaziali cartesiane aventi l'origine nel suo punto più alto e l'asse verticale che punta verso il basso, coincidente con l'asse di simmetria della curva. La curva è una parabola se, chiamando x le ascisse (orizzontali) dei punti della traiettoria e y le loro ordinate (verticali), risulta che i valori di y sono direttamente proporzionali ai quadrati dei valori di x.

Traiettorie paraboliche come quella della figura 30 si ottengono ogni volta che un moto uniforme si combina con un moto uniformemente accelerato, ad angolo retto tra loro. Ciò avviene anche quando una biglia rotola obliquamente su un piano inclinato, se l'attrito è trascurabile. Un semplice esperimento ti permetterà di verificare questo fatto.

Registra le traiettorie paraboliche di una sferetta d'acciaio che farai rotolare obliquamente su una tavoletta di legno inclinata, su cui avrai fissato un foglio di carta copiativa con la parte inchiostrata verso l'alto, con sopra un foglio di carta bianca. Puoi lanciare la sferetta sul piano facendola rotolare giù da una guida ottenuta piegando una striscia di cartone nel senso della lunghezza (fig. 31).

Tracciando opportunamente degli assi cartesiani sulle traiettorie registrate, verifica che si tratta di parabole.

Nota. Forse sei curioso di sapere per quale ragione queste traiettorie sono proprio delle parabole. Eccola.

Se ci riferiamo alla palla della figura 30, si trova che essa si sposta orizzontalmente con velocità costante perché la resistenza del mezzo è trascurabile. Chiamiamo questa velocità v_x.

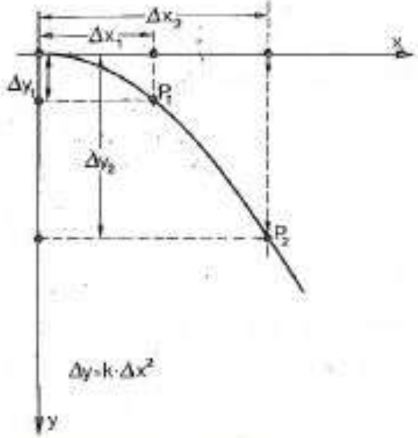
Lo spostamento verticale è invece uniformemente accelerato con accelerazione g.

Dopo un tempo Δt dall'istante in cui il corpo è passato per il punto più alto della sua traiettoria, i suoi spostamenti orizzontale e verticale valgono:

$$\Delta x = v_x \cdot \Delta t \quad e \quad \Delta y = \frac{1}{2} g \, \Delta t^2$$

Se ricavi Δt dalla prima di queste espressioni e lo sostituisci nella seconda, trovi:

$$\Delta y = \frac{1}{2} g \, (\Delta x^2 / v_x^2) = \frac{g}{2v_x^2} \Delta x^2 = \text{costante} \cdot \Delta x^2$$



Dunque lo spostamento verticale risulta proporzionale al quadrato dello spostamento orizzontale, e la traiettoria è proprio una parabola (fig. 32).

3.4.c Il moto dei proiettili

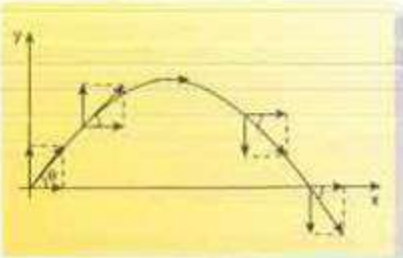


Fig. 3.33 Traiettoria di un proiettile sparato in una direzione formante un angolo θ con l'orizzontale. Si noti che la componente della velocità lungo x si mantiene costante.

Data la complessità della trattazione del moto bidimensionale nella sua espressione più generale possibile, ne proponiamo alcuni esempi iniziando con il moto dei proiettili.
Allo scopo si consideri un proiettile lanciato verso l'alto con velocità **v** in una direzione formante un angolo θ con l'orizzontale. Nell'analisi di questa situazione supporremo trascurabile la presenza dell'aria. Riferiamo il moto e la conseguente traiettoria al solito sistema cartesiano ortogonale Oxy con l'asse y rivolto verso l'alto come in figura 3.33.
In questo caso i valori delle grandezze cinematiche sono:
$a_y = -g$ (l'accelerazione verso il basso è dovuta alla gravità)
$a_x = 0$ (non vi è componente orizzontale dell'accelerazione)
$v_x = v \cdot \cos\theta$
$v_y = v \cdot \text{sen}\,\theta$
Dal momento che l'accelerazione non ha componente lungo l'asse x la componente orizzontale della velocità v_x rimane costante (in quella direzione il moto è rettilineo ed uniforme), mentre la componente verticale della velocità varia secondo le leggi del moto uniformemente accelerato ed il suo valore in un punto P qualsiasi sarà:

$$v_P = v_y - g \cdot t$$

Il moto risultante è dunque dato, istante per istante, dalla composizione (somma) di due moti: uno rettilineo ed uniforme lungo l'asse x, ed uno uniformemente accelerato lungo l'asse y. Le componenti dello spostamento del proiettile all'istante t sono:

$$x = v_x \cdot t \qquad y = v_y \cdot t - \frac{1}{2} \cdot g \cdot t^2$$

Ricavando t dalla prima equazione e sostituendolo nella seconda si ottiene:

$$y = \frac{v_y}{v_x} x - \frac{1}{2} g \frac{x^2}{v_x^2}$$

Essendo v_x, v_y e g valori fissati in maniera univoca una volta definite le condizioni iniziali (si noti tra l'altro che $v_y/v_x = tg\theta$) l'equazione può essere scritta come:

$$y = b \cdot x - a \cdot x^2$$

È immediato riconoscere che questa è l'equazione di una parabola. Dunque la traiettoria del proiettile ha forma parabolica.

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Are these proofs?

Are they scientific explanations? If so, what kind?

What role does mathematics play?

How do students perceive it?

4 MOTI IN DUE DIMENSIONI: IL MOTO DEL PROIETTILE

Il moto di un punto materiale di massa m, lanciato con una certa velocità iniziale v_0 e soggetto alla sola azione della forza di gravità, è detto **moto del proiettile.**

Scegliamo un sistema di riferimento con l'asse x parallelo al suolo e l'asse y perpendicolare al suolo e diretto verso l'alto. Il principio di composizione dei moti consente di descrivere il moto del proiettile come la composizione di un moto rettilineo uniforme lungo l'asse x e di un moto uniformemente accelerato con accelerazione costante $-g = -9{,}8\ \mathrm{m/s^2}$ lungo l'asse y.

Indichiamo con x_0 e y_0 le componenti della posizione iniziale del proiettile e con v_{0x} e v_{0y} le componenti della sua velocità iniziale; le leggi orarie sono:

$$\vec{s}(t) \rightarrow \begin{cases} x(t) = x_0 + v_{0x} t \\ y(t) = y_0 + v_{0y} t - \dfrac{1}{2} g t^2 \end{cases}$$

$$\vec{v}(t) \rightarrow \begin{cases} v_x(t) = v_{0x} \\ v_y(t) = v_{0y} - g t \end{cases}$$

$$\vec{a}(t) \rightarrow \begin{cases} a_x(t) = 0 \\ a_y(t) = -g \end{cases}$$

Determiniamo l'equazione della traiettoria dalle leggi orarie della posizione, eliminando il parametro tempo; l'equazione cartesiana della traiettoria che si ottiene è quella di una parabola:

$$y = y_0 + \frac{v_{0y}}{v_{0x}} x - \frac{g}{2 v_{0x}^2} x^2$$

Algebraic proof: a contribution from Mathematics education

At secondary schools, **in mathematics, an internal division** emerges that separates it into **the domains algebra, geometry, analysis, statistics** and so on (Boero, Guala & Morselli 2013) → difficulty at the didactic level, but also in building in students (and not only) a vision that, in addition to being **crystallized and sectoral, is also unrealistic.**

Morselli and Boero (2009): adaptation to mathematics teaching concerning the **construct of "rational behavior" for discursive practices,** proposed by Habermas, in particular regarding the **use of algebraic language in proofs.**

How do students perceive it?

Algebraic language in proofs: mainly thought of in secondary school as the domain of synthetic geometry, leading to **a radical change in the forms of explanation when passing from geometry to algebra**.

This trend is found in the mathematics textbooks analyzed and represents the reference knowledge of students in mathematics; they will refer to this knowledge by thinking about the parabola and its equation in physics.

The transposition makes the many opportunities for interdisciplinary reflection disappear….

Conclusions

Epistemological activators (of interdisciplinary learning potential):
objects meaningful within more than one discipline (like argumentation/proof, symmetry, line, …), so good candidates to be boundary objects, but also significant from an "internal" disciplinary epistemological point of view and likely to show the IDENTITIES of the disciplines through a learning mechanism at the boundary between disciplines.

Is this enough to activate the "learning potential" at the boundary?

Is this enough to trigger a fruitful discussion
about disciplinary IDENTITIES and interdisciplinarity?

Necessary but not sufficient…..

IDENTITIES

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