Soft physics: healing the body/mind split in physics education

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A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Arts
in
The Faculty of Graduate Studies
(Curriculum studies)

The University of British Columbia
(Vancouver)
September 2012

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Abstract

Physics education is facing a crisis of meaning: students can “plug” numbers into formulas, but research shows they do not give much meaning to physical concepts. This thesis explores how the cultural context of physics education, in particular the mind/body cartesian split, contributes to a loss of meaning. Drawing from sensory scholarship, cognitive linguistics, feminist critiques of science, her own teaching experience and education research on student misconceptions and intuitive knowledge, the author challenges the mind/body dichotomy by exploring how the body can make sense of the physical world through the senses. Physical concepts can be more-than-representational, exist beyond mathematical symbols and signifiers, but nevertheless be perceived through touch. In her quest for a mind/body truce, the author has created provocative stories for the physics classroom that welcome the body and its physical knowledge, and that reconcile intuition and Newtonian physics. This subtle change of perspective leads her to replace the alleged mind/body war with a respectful quest for compromise and fine tuning, and to analyze the dominant patriarchal narratives of the physics community. The author advocates for an intuition-based, sensory, student-centred pedagogy that redefines traditional power relationships in the physics classroom and challenges indoctrinating scientific discourses, hoping it will contribute to improving the inclusiveness of the physics community. Such a paradigm shift requires a re-storying of collective narratives. Physics is not about dominating nature but about learning from nature; it is time to abandon the myth of the detached observer and study nature from inside, at the confluence of everything that make us humans.
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Acknowledgements

I want to thank all my inspiring teachers: nature, my students, Susan Gerofsky and Pat O'Riley who gave me a new voice, my children and my husband for challenging my certitudes, my colleagues for our fruitful discussions, my family for their love and support, and all the physicists, philosophers, artists and educators I came in contact with through my readings.
“Knowledge in general, and scientific knowledge in particular, serves two gods: power and transcendence. It aspires alternately to mastery over and union with nature.”

Keller (1982)

1 Introduction

In the physics classroom, students learn to “plug” numbers into equations while their teacher hope they do well on the upcoming test. Students can calculate according to prescribed rules, but when asked conceptual questions, or to relate their physics knowledge to objects that surround them, it is surprising how little meaning they give to mathematical symbols (Mazur, 1998).

As a post-secondary instructor, my primary goal is to provide students with a space/time in which they can socially and individually co-create meaning(s) by having them collaborate in manipulating simple objects like strings, boxes and water jars, discussing their findings and reflecting on the physics of everyday life. Through careful observations and listening to my students while they engage in manipulations and discuss with their peers, I discovered there is a plethora of physics narratives that never find their way to physics textbooks. I am in search of physics tales rooted in everyday life, with a focus on stories that welcome embodied knowledges, sensorial experiments, intuition and relationships with the environment. There is a collective narrative in the physics community that the senses are deceptive, that students' intuitions are suspicious and that an educator's role is to fight students' misconceptions: a pure mind is required to access superior knowledge. For my research project, I explored my everyday
life in search of stories that merge physics, my body and my environment, in order to replace reductionist narratives by tales of truce and symbiosis.

1.1 Purpose

My long term goal is to disrupt the Western masculine, reductionist, disembodied and utilitarian discourse that dominates the subculture of the physics community (Keller, 1992; Wertheim, 1997) because it disempowers students with different worldviews and discourages students with a need for more encompassing epistemologies (Tobias, 1990). For knowledge to count as genuine, the community must be adequately diverse (Longino, 1993). Science education is a contributor to declining participation of both women and minorities (Seymour & Hewitt, 1994) because science is “hegemonic and androcentric” (Lederman, 2003); the masculine symbolism informs curriculum discourses and practices which in turn reproduce and legitimize gender divisions (Hughes, 2001). Educators should integrate everyday experiences and interests that are relevant to both genders into the content and context of instruction (Labudde et al., 2000) and apply physics to a broader world-view (Stadler et al., 2000).

The human species is facing environmental challenges that call for a more inclusive demography in the scientific community. To effect a paradigm shift, we need to hear the voices of meaning-cravers, divergent visionaries, non-Westerners, women, Indigenous Peoples, ethicists, philosophers. It is time to work with nature, instead of against it. A physics textbook, instead of presenting nature as primitive and its description/re-design by humans as advanced, could define nature as being the supreme engineer (Benyus, 1997), i.e. a gigantic lab that has
been operating through trial and error for more than 3 billion years and has become a master in an unmatched type of technology that is 100% recyclable and sustainable. The novelty of biomimicry is to reclaim the gerund “engineering” from the dominant discourse and reverse the man-nature power relationship. The hidden curriculum of a physics class can also go through a paradigm shift, and honour nature's beauty, diversity and ingenuity by using new examples, exercises, images and vocabulary. A question about a military submarine can be replaced by a question about a foetus in her mother's womb.

Disturbances into the dominant discourse can be triggered by a choir of dissonant voices. I can play a role by painting a less monolithic picture of physics, by opening spaces where Deleuzian rhizomes can grow (Deleuze and Guattari, 1987), by softening the rigidity of the scientific discourse, so that other ways of talking/doing science are heard and respected.

1.2 Focus of inquiry

A frequent complaint from students is that physics is disconnected from real life, even though they use cells phones and motorized vehicles that would not exist without discoveries in electronics and thermodynamics. Physics teaching suffers from a crisis of meaning. Students often manage to score perfectly on standard problems without understanding any of the underlying basics (Mazur, 1998). As a physics student, I thrived in the web of mathematical truths, but it is only after several years of teaching that I started to create meaning, by stitching equations into the fabric of the physical world.

My research goal is to investigate whether sensorial explorations can lead to making sense
of physical quantities, so that pedagogy welcomes common sense and becomes rooted in everyday life experience. I decided to focus on my own sensual perception of places I visit frequently, like a kitchen, a bathroom, or a bus. I wanted to engage in physical dialogues with objects and textures, attempt to describe felt physical\textsuperscript{1} qualities, and explore the following questions:

- Where can physical quantities be found and felt? How frequently do we encounter them?
- Can I reconcile physics with the sensuous stories told by the world around me?
- Is ocularcentrism the only sensible way of learning physics?
- Is there a more-than-representational dimension to physical quantities and qualities?
- Can we make the body porous to a new “sensory semiology” (Stoller, 1997)? Does it require developing somatic modes of attention?

I aim to trouble the dominant sensory order of my culture, design a phenomenological physics curriculum and question the relationship between senses and knowledge that prevails in the physics community.

1.3 Review of Literature

“In the wake of mechanistic thinking … hymns to nature disappeared.”

Le Breton (1990, p. 84).

\textsuperscript{1} Physical insists on the double meaning of the world physical (as in physical quantity and physical exercise).
1.3.1 Historical context

The subculture of physics bears artifacts of the history of Western science. According to Francis Bacon, one of the fathers of modern science, nature is a (female) object to be exploited and dissected by man (Merchant, 1980). Physics textbooks abound in examples of civil engineering accomplishments, machinery and weaponry. The British Royal Society was first known as “The Invisible College”; scientific knowledge was the well kept secret of an educated elite (Haraway, 2004). Today, physics teaching focuses excessively on form (i.e. the manipulation of mathematical symbols); the mastery of that secret language can be viewed as a rite of passage and physics introductory courses are used by some university programs as a skimming filter. Physical quantities are abstracted, decontextualized and disembodied, even if we experience them on a daily basis (e.g. in the simple acts of walking or pushing a wheelchair). Physics has played a significant political role in its use in developing powerful weaponry; consequently, politics influenced physics education. Since the invention of the atomic bomb, the emphasis of physics teaching has been on educating “doers” (physicists that can make something) instead of “seers” (physicists that see beyond the dominant paradigms of their time) (Smolin, 2006).

The new generations of physicists and engineers must play a role in preventing climate change by participating in the I.P.C.C.\(^2\), but also by inventing sustainable ways of consuming and producing energy. Today's challenges require a grasp of context, complexity and consequences. The British Royal Society recently published an article on the possibility of

\(^2\) International Panel on Climate Change
sending sulfate aerosols in the stratosphere to shelter our planet from our sun (Rasch et al., 2008). Such an approach, which treats the symptoms rather than the causes of climate change, is rooted in old paradigms of nature's domination. It would mean running a planet-wide experiment for which there will be only one trial and that could impact trillions of mammals, reptiles, invertebrates, trees, fungus and bacteria. In a time of information technology, the scientific community has the means to listen to those who claim there are other ways of doing science (Haraway, 1988, Harding, 1996, Cajete, 1999, Shiva, 2001).

1.3.2 A crisis of meaning

Halloun & Hestenes (1985a) talk of the “legendary incomprehensibility of introductory physics.” To illustrate the crisis of meaning in physics education, I will use the example of the energy concept. Driver & Warrington (1985) asked conceptual energy questions to teenager students: only 10% referred to energy concepts in their answer. Duit's study of Grade 10 students (1984) showed that instruction had not been successful at generating meanings differing from colloquial language. Students who are good at solving energy problems often revert to their intuitive ideas when presented with a real-life problem (McDermott, 1984) and despite instruction, they hold firmly onto their alternative conceptions (Rankhumise & Lemmer, 2008). How could students make sense of the sentence “energy is always conserved” when our society is facing a crisis of energy consumption?

At the post-secondary level, students also show a poor conceptual understanding of energy. Loverude (1994) studied both non-science majors and science/engineering majors. “The simplest questions about potential energy proved difficult .... Even at the end of a course, many
students do not understand that gravitational potential energy depends only on the mass and height of an object...” Singh and Rosengrant (2001) surveyed several hundred students in calculus and algebra-based courses: they found students have difficulties in qualitatively interpreting basic principles related to energy. There are also serious discrepancies between preservice physics teachers' understanding of energy and the accepted scientific concepts (Trumper, 1998).

1.3.3 Inert knowledge

The knowledge acquired in a traditional physics course stays confined to its instructional context, which is what Whitehead (1929) qualifies as inert knowledge. Renkl, Heinz and Gruber (1996) propose several explanations for inert knowledge, some of which are relevant to physics teaching:

1. Lack of conceptual knowledge and deep-level understanding;
2. Storage of information acquired in different contexts in separate memory parts that lack connections;
3. Students do not connect subject matter with their everyday experience (they feel they are learning the arbitrary rules of a game);
4. Learning situations differ too widely from out-of-school situations;
5. Students' lack of motivation.

To address the problem, the authors recommend adopting a situated cognition perspective called cognitive apprenticeship, which I will discuss now.
1.4 My pedagogical worldview

1.4.1 Situated cognition and cognitive apprenticeship

The current dominant frameworks in science education are based on individual and social constructivism (see Staver, 1998). Knowledge is not acquired in an abstract, decontextualized way but in the context of immediate application (see, for example, Renkl, Mandl and Gruber, 1996). Circumstances provide essential parts of the structure and meaning of knowledge, situations co-produce knowledge through activity (Brown, Collins and Duguid, 1989). A concept like energy is situation dependent and therefore “always under construction”: it is not an abstract, self-contained entity. Learning a concept is like learning how to use a tool, and “involves far more than can be accounted for in any set of explicit rules.... The culture and the use of a tool act together to determine the way practitioners see the world” (Brown, Collins and Duguid, 1989). A student is an apprentice entering the physics community. Her/his personal strategies for intuitive reasoning and negotiating meaning should be welcomed and confronted by peers in collective problem solving.

1.4.2 Active learning

The teaching method that best describes my practice is active learning, i.e. engaging students in meaningful activities and having them think about what they are doing (Bonwell and Eison, 1991) through cooperative learning, i.e. a “structured form of group work where students pursue common goals while being assessed individually” (Prince, 2004). According to
Grabinger and Dunlap (1995), active learning aims at providing realistic, meaningful, relevant, complex contexts. It encourages the growth of student responsibility and initiative, it cultivates an atmosphere of learning communities. It utilizes dynamic activities that promote high level thinking processes: analysis, synthesis, problem solving, experimentation, creativity and examination of topics from multiple perspectives.

In my classes, activities are organized around experiential learning principles as described by Gentry (1990): the instructor sets the stage, the experience is structured and closely monitored, participants are given frequent feedback and the freedom to fail. Subsidiary effects of experiential learning are a development of interpersonal skills and an appreciation of the messiness and ambiguity of real-world situations. Hands-on activities are performed in small groups since, according to Driver at al. (1994), “developments in learners' cognitive structures come about through interaction with an external physical reality while meaning-making is stimulated by peer interaction.”

Listening to my students taught me that learning physics is challenging at both the verbal and the conceptual level:

• Many physical quantities do not have the same meaning in the “life-world” and in the “world of physics.” Students must be given time to explore the meanings used by the physics community, so that they can “distinguish between meanings in the two domains” (Driver & Warrington, 1985).

• Conceptually, students must re-arrange their pre-conceptions into a coherent set of beliefs validated by the physics teacher (see Brown & Ryoo, 2008).
1.4.3 Physics stories

Learning to *talk science* is like learning a foreign language (Vygotsky, 1962; Rincke, 2011). Some everyday words are given a twisted meaning (e.g. *weight* is called *mass*). Every physical quantity is represented both by a word and a symbol; unfortunately sometimes the symbol is not the initial of the word in the language of instruction (for example: speed is *v*, wavelength is *λ*, density is *ρ*). Like other languages, *physics talk* involves homonyms, ambiguities and exceptions. Gee says that “one does not know what a social language means in any sense useful for action unless one can situate the meanings of the social language's words and phrases in terms of embodied experience” (2005, p. 23). Class time must be devoted to teaching the language of physics, constantly going back and forth between lived experience, words and equations. Following investigations by math educators (Gerofsky, 2009), we also develop gestures for physical quantities and graphs that students can appropriate in peer-to-peer communication.

A scientist is before anything else a person who “tells stories” (Medawar, 1967). One way to welcome students into a community of practice is to act as a story teller. Terms like *force* or *energy* can identify protagonists capable of doing something with other protagonists (Rincke, 2010). Anthropomorphizing physical quantities is not part of my practice; however physical objects can be seen as being active and analogies performed on the human body can make abstract concepts more accessible. For example, we can say: “When a box is placed on a table, the table exerts a normal force on the box.” We can also say: “If a friend presses with her hand on the top of your head, the muscles in your neck need to react for your head to stay still. If she
presses with her hand on the table, the molecules of the table react so that her hand does not break the table.” From there, we can use “the table reacts” or “the table's reaction.” Learning environments must allow narratives to circulate and stories to be added to the collective wisdom of the community (Browns, Collins & Duguid, 1989).

A teacher's role is to make the scientific story available and to support the students in making sense of the story (Mortimer and Scott, 2000, p. 25). Such meaning making does not need to be universal and can involve weaving in personal cultural narratives. For example, an educator can welcome energy stories inspired by ancient concepts like Manito, Qi or Shakti3. Some physics narratives could follow Doll's recommendation:

To bring curriculum to life – to recapture the creative energy of all life, the aesthetic-ness that exists in being – we might well consider a curriculum which combines the rigorousness of science, with the imagination of story, with the vitality and creativity of spirit (Doll, 2002, p. 48).

1.4.4 Non violent conceptual change

The stories teachers bring to the classroom were written by generations of scientists who explored and questioned nature for centuries. Making meaning of them requires awareness, imagination and reflection. It can trigger cognitive conflicts that might lead to conceptual changes. Such cognitive conflicts need to be subtle and non violent. Conceptual changes should not be seen as a medicine that cures intuitive knowledge and pre-conceptions. Attempting to isolate students from their lived world is reductionist and manipulative (Cobern, 1996).

3 Manito (Algonquian), Qi (Chinese) and Shakti (Hindi) are related to the concept of a universal flowing energy.
Cognitive conflicts do not need to be resolved by a forced choice between two worldviews: Learners should be allowed to build “parallel constructions relating to specific contexts” (Solomon, 1983). In an introductory course, it is acceptable that a student builds her own narrative around an observation of the world, as long as that narrative allows her to develop a meaningful physics discourse.

1.4.5 *Embodied knowledges*

Since Descartes, the mind has been seen as the site of knowledge production. For him, only those grounds available to a single, unattached, disembodied mind are acceptable principles for the construction of system of beliefs (Longino, 1993). Today, physicists attached to the Cartesian tradition are very suspicious about embodied and intuitive knowledge. During my PhD in astrophysics, I noticed that intuition was crucial to creative scientific research, but taboo in scientific talk and absent from learning objectives. According to Poincaré (1902/1968, p. 52), instead of reconciling intuition and analysis, we just sacrificed one of the two, and since analysis must be impeccable, intuition was doomed wrong.

In an introductory physics course, the archetype of intuitive *misconception* is that a force is required to keep an object moving. To a physicist, this is nonsense: if a constant net force acts on an object, the object accelerates. I claim, however, that trapping this issue into a dichotomous scheme of right or wrong, of common sense versus enlightened knowledge, is a cultural artifact of Descartes' dualism and I agree with Cobern (1996): “To suggest that students break with everyday thinking is to suggest that they break with that which is meaningful.” Our bodies are capable of a prowess unmatched by modern technology: they carry an amazing
knowledge of classical mechanics that cannot be labelled as *misconceptions*. Since bodies and physics are embedded in the same world, I postulate there is always a possibility to find a *physic-al consensus*. In the above example, making students aware of the omnipresence of the friction force can be an effective way to reconcile the physicists' and the embodied worldviews.

Le Breton (1990) explains in detail how the modern view of the body developed with Cartesianism. Man [sic] became disconnected from the world, from others, and from himself (p.47). The body was deemed unable to provide reliable data about the environment (p.88) and the universe as felt had no value compared to the world of concepts (p.91). Despite the advance of psychoanalysis and phenomenology, the opposition between the senses and reality is still a foundation of Western epistemology (p. 93). Le Breton also makes an interesting parallel between the mind/body split and the historical scission between the educated elite and popular culture. In physics teaching, few references are made to the practices and tools of carpentry, even if it deals with forces and trigonometry. I once entered an engineering course where students were struggling with a 3D hinge problem; few of them had ever repaired or played with a hinge. There were several cupboards in the classroom, but no one thought of opening a door to make sense of the textbook problem.

Le Breton argues that the body is a site of meaning making: “Emetteur ou récepteur, le corps produit continuellement du sens...” (1990, p. 18). Sensorimotor simulations are widely implicated in human cognition (Wilson, 2002) : the body serves the mind (e.g. kinesthetic

4 The mind/body conflict is non existent in quantum mechanics or nuclear physics since the body has no lived experience of particles. Pre-conceptions are not a major issue to educators in such areas. However, there are cognitive metaphors at work here too, some of which relate to embodied experience.

5 “Emitter or receptor, the body continuously produces meaning.”
imagery, working/episodic/implicit memory, reasoning through the use of spatial mental models). Convincing evidence of the body as a site of meaning-making is provided by research in cognitive linguistics. According to Johnson (2007):

Meaning is a big, messy, multidimensional concept ... It grows from our visceral connections to life and the bodily conditions of life. We are born into the world as creatures of the flesh, and it is through our bodily perceptions, movements, emotions, and feelings that meaning becomes possible (p. ix)

For Lakoff and Johnson (1999), the building blocks of human thinking are embodied metaphors constructed at an early age through interactions with the physical world: metaphors in the flesh. When such metaphors contradict the physics discourse, expecting students to undergo a conceptual change is a drastic as removing a bit of their brain. As a physics teacher, I must welcome such embodied metaphors as building blocks of physical meaning. I advocate for a form of cognitive apprenticeship that acknowledges human bodily experience, and aims at a “fine tuning of phenomenological primitives” (diSessa, 1993).

**2. Biographical context, positionality**

As a teenager, I was attracted to physics after marvelling at the wonders of nature. I was seeking a holistic, spiritual, even poetic exploration/explanation of the universe: knowledge as a communion with nature. After ten years of physics learning, I reached emotional exhaustion, and had lost part of my identity. I had been confronted by overwhelming power struggles, misogynist remarks, symbolic violence, isolation, rote memorization, patriarchal values, excessive
competition and stressful exams. My research work is a process of recovery: of meaning and identity. It is not intended to silence the patriarchal solo, but to empower silent voices to join the choir.

2.1 Sensorial background

I was brought up in a large city until the age of six, then in the countryside of South West France, where my sensual education and my relation to the environment took a completely new dimension when I started interacting with animals and was allowed to roam freely for hours in the fields, with my dog. I grew up in a hippie community where bodies were open topics of discussion. The Cartesian French school system forced me to restrict my sensuous self and label it as childish in order to walk the glorious path to enlightened reason. A long term practice of yoga and meditation, and frequent stays in the wilderness of British Columbia taught me to listen again to my body and my environment. My history shaped my sensorium. It impacts and limits the scope of my research.

2.2 Being a female physicist

In the country where I grew up, France, women are more welcomed into the hard sciences than in the United States, but nevertheless represent a minority: 26% of female astronomy faculty against 18% in the U.S., and 18% of female physics faculty against 12% in the U.S. ("Les femmes dans l'histoire du CNRS," 2005; Ivie, Ephraim & White, 2009). 50% of high school physics students are female but this number decreases at every subsequent level, with the largest drop occurring between high school and college (Hazari, Sadler and Tai, 2008).
Physics makes a heavy use of mathematics and the identification of math skills with maleness runs very deep (Lee Smolin, 2006, p. 336). I once suggested to a physics professor that in order to attract more women, physics education could be more rooted in everyday life, for example by connecting sound waves to music; he answered: “If women cannot do physics, they had better leave. There is no way physics can be changed.” I agree with O'Riley (2003) that “survival in this male dominated terrain ... is taken up in a variety of complex ways. Some females ... feel that for their own sanity they need to become 'one of the boys'” (p. 84).

The status of women in physics has its roots in the history of the field and the discourse of its champions. Francis Bacon (1561-1626) is often referred as the inventor of the inductive method. In his imagery, science is disconnected from the female realm. Bacon lived in a time when male scientists were studying alchemy while witches were burnt by the inquisition. According to Merchant (2001), language from witches trials and torture methods permeated Bacon's literary style: nature was a female to be tortured through mechanical inventions. Science was a means of power. In The New Atlantis, Bacon proposed an utopian society led by male scientists, “for they alone possess the secrets of nature” and have “the power to absolve all human misery through science”. Seventeenth century scientists saw “nature as a dull affair, soundless, scentless, colourless; merely the hurrying of material, endlessly, meaninglessly” (Whitehead, 1933). By claiming “cogito ergo sum,” Descartes (1596-1650) negated the embodied component of the mind and expelled the feminine from thoughts: He underwent “a masculinization of thoughts” (Bordo, 2001, p.93). The more intuitive and emphatic elements were exorcised from science and philosophy. The result is a super masculinized model of
knowledge in which detachment, clarity, and transcendence of the body are all key elements. The popular narratives about Newton (1642 – 1727) reinforce the stereotypes of the white-middle-class-straight-solitary-laboratory-oriented man. Today, modern science still crystallizes masculinist modes of thinking (Hardin, 2001a; Stern, 1965; Jillman, 1972). Western society does not have a model of female intellectual transcendence (Wertheim, 1997). Science has again and again been reconstructed by a set of interests and values – distinctively Western, bourgeois, and patriarchal (Harding, 2001b). None of the physics champions is a woman, except Marie Curie, who, because she was a female, had to leave her country, Poland, to study physics. Emily Noether (1882-1935), known for her breakthroughs in mathematics and theoretical physics, had to fight to be finally awarded in 1922 a position with no salary.

Physics is particular among the sciences has being a religiously inspired activity, which could explain the exclusion of women in the physics world: “Women were cast on the side of the material, the bodily, the 'earthy', while men were cast on the side of the spiritual, the intellectual, and the ‘heavenly’” (Wertheim, 1997). Newton's chastity evokes priesthood. Leiss (2008) says that “the Large Hadron Collider is a secular cathedral where physicists wait in meditation and prayer to detect the God particle (the Higgs boson).” It was commonplace in the late nineteenth century and early twentieth century to say that science was the new religion, or, at least, that it had succeeded to the cultural authority that religion once enjoyed (Shapin, 2010). The narrative that science was leading to a bright future, elevating man and unifying the human race was still vivid during my youth, despite the destructive power of modern weapons. After the Second World War, U.S. congressmen perceived scientists as being in touch with the a
supernatural world of mysterious forces whose power they alone could control; scientists were the new prophets (Hall, 1956). As a student, I evolved in regimes of single truth. Non-scientific knowledge had lower status:

In a sense, all science aspires to be like physics, and physics aspires to be like mathematics... But [what] hope is there for sociology acquiring a physics-like lustre? (Wolpert, 1993, p. 121).

I joined a skeptics group and became an anti-pseudoscience crusader.

2.3 Physics and common sense

I received implicit messages that my intuition of physical phenomena was inherently wrong and that the body can teach us no better than Aristotelian mechanics. Yet, my 20th century flesh had created physical knowledge in cars, planes, elevators, playgrounds and amusement parks. I had watched images of astronauts, felt the vibrations of a loud speaker and heated food in a microwave. I was not living in an Aristotelian body! I agree with Galileo that “...we do have in our age new events and observations such that if Aristotle were now alive, I have no doubt he would change his opinion” (Galileo, 1632/1962). Why was my embodied knowledge negated when it could have been the foundation of physical abstractions?

I adopted a culture popularized by authors like Lewis Wolpert6, an eminent British biologist. In the The Unnatural Nature of Science, he undervalues the role played by unconscious thoughts and intuition. He explains that science is misunderstood and feared by the

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6 Wolpert has been a Fellow of the Royal Society for thirty years, was the President of the British Society for Cell Biology (1987-1992), is Commander of the Most Excellent Order of the British Empire (1990), was the chairman of the Committee on the Public Understanding of Science (1993-1998) and won a prize for education (2003).
general public because scientists do not resort on common sense:

The world is not constructed on a common-sensical basis. This means 'natural' thinking – ordinary, day-to-day common sense – will never give an understanding about the nature of science. Scientific ideas are, with rare exceptions, counter-intuitive: they cannot be acquired by simple inspection of phenomena and are often outside everyday experience... Common sense is prone to errors when applied to problems requiring rigorous and quantitative thinking (p. xi).

Wolpert truly discouraged me from using my senses to study the world around me:

...we think that grass is green, that stones are hard and snow is cold. But physics teaches us that the greenness of grass, the hardness of stones and the coldness of snow are not the greenness, hardness and coldness that we know in our experience, but something very different (p. 6).

2.4 Science is Western

The scientific stories of my youth were populated by white males geniuses from European empires: Galileo, Kepler, Boyle, Newton, Faraday, Maxwell, Bohr, Pauli, Heisenberg, Schrodinger, Einstein. Units were named after them: I was measuring quantities in Ampere, Volt, Watt, Pascal, Newton, Joule. It seemed nature was speaking a European language. The Système International d'unités (S.I.) is French and the Bureau International des Poids et Mesures is in France. Non-European science, as well as empirical manual knowledge were disqualified as real science (Wolpert, 1993, p. xii, p. 29; Cromer, 1995, viii-ix). I felt lucky I was born in the cradle of modern science: I belonged to the chosen people.
3. Methodology

3.1 A path toward sensuous scholarship

In the course of my Masters' Degree, I became aware that scientists and engineers make choices that are value-laden: Western science is framed by capitalism, is mono-cultural (Harding, 2001b) and gendered (Bordo, 2001; Keller, 1992; Harding, 2001a; Merchant, 2001; Wenners and Wold 2001). Physics education presents the same traits. The mandatory courses taken by the large cohorts of students who won't become physicists focus essentially on mechanics, and to a lesser extent on electromagnetism. Is this because society needs engineers? Is this what students need as scientific literacy to become informed citizens? Why don't we teach more about heat and cold since we frequently turn the knobs of heaters and fridges? What about physics for the life sciences? What happened to astronomy so that, despite Newton's and Galileo's work, it disappeared from physics textbooks? We could explain why the sky is blue and sunsets are red instead of the technicalities of thin lenses. We could open spaces for Indigenous knowledges. In the chapter on pulleys, where is the African mother pulling water from a well? A problem about a cannon ball could be replaced by a story of a vulture\(^7\) throwing a bone to break it on a rock. Where is the critical reflection on hydroelectric dams? Where is the Earth? A new theory of knowledge is possible in which attachment to nature acquires a positive epistemological value.

My Masters' Degree course work and readings included a deconstruction of physics

\(^7\) The Lammergeyer vulture can through objects with great precision.
education practices and narratives. I revisited the history of science from a feminist perspective, and investigated new ways of relating to the lived world through cognitive linguistic, perception, phenomenology. Meanwhile, I was given the chance to teach\(^8\) an introductory physics course (equivalent to a grade 11 level) eleven times in a row. I was constantly going back and forth between my readings, classroom observations and implementation of new teaching material: I wrote a short textbook that approaches physics from a more intuitive and nature friendly angle, created labs that involve touch, and developed tactile classroom activities (see appendices). I learned about the educational potential of touch while manipulating objects with my students, from listening to their group discussions and from reflecting on my teaching method with my colleagues. I gave room for students to approach physics with their own physic-al knowledge and language, and witnessed how it can impact a teacher-student power relationship. These reflexions and observations about my professional practice informed the present research work.

My course work challenged my certitudes about rational thought; I now agree with Merleau-Ponty (1960) that rationalism is based on two myths: the *laws of nature* according to which the world is constructed, and the *scientific explanation*, as if knowledge of relations could transform the existence of the world into an analytic proposition. A knowledge of causes and conditions does not answer *all* questions about essence and origin. I gradually understood there is more to physics than what I could find in textbooks: my interest in physics also takes root in perception and sensuality. It has been a long and troubling deconstructing journey; fear had often to be overcome. I finally accepted that, against everything I was taught and believed, my approach to physics was not simply analytical and detached. I experimented with unfolding the

\(^8\) I teach at Langara College, Vancouver, B.C.
tales hidden inside equations and interweaving them with natural phenomena, without seeking a single story that summarizes everyone's sensual relationship to the physical world. In this thesis, I wish to share my sensuous stories to assert that such tales can and do exist, and can be scientifically valid.

I chose to tell stories, and deconstruct existing stories, rather than a scientific study of people's intuitive knowledge through observation/analysis/generalization, because I did not see an analytical approach as an appropriate language to speak of intuitive knowledge. I refuse to consider the body as a text that can be read, analyzed, and be eventually re-written through physics education. It would have being contradictory to use the notion of embodiment to critique the Western phallocratic predisposition of scholarly thought, in order to develop theories of cognition that are themselves Western and phallocratic. Moreover, I encountered more-than-representational physical quantities/qualities for which textual interpretation seemed inappropriate. Story telling gave me freedom of expression and access to a sensuous and metaphoric language that is banned from physics texts.

3.2 Sensuous scholarship

My investigations were inspired by sensuous scholarship which attempts to reassert the validity of non-visual experiences of space and place (Paterson, 2009) and reawaken the scholar's body by demonstrating how the fusion of the intelligible and the sensible can be applied to scholarly practices and representations (Stoller, 1997). My instrument of research was my own body (Crang, 2003).

In his foundational book (Sensuous Scholarship, 1997), Stoller explains that rational
myths remain intact in scholarship activity (i.e. disembodied observations transformed into disembodied representations), however a growing number of scholars are using the body as a new site for analysis and are reformulating the place, and significance, of the body in social thought. His main proposition is to move away from an embodied discourse that uses the body as a text that can be read and analyzed because “this analytical tack strips the body of its ... sensuousness.” He wants to avoid a writing on the body that is articulated in a disembodied language like, for example, the abstract models and metaphors constructed by Foucault: they powerfully deconstruct the Cartesian edifice but use a language that reinforces the principles they critique. He therefore advocates for a sensuous scholarship in which “writers tack between the analytical and the sensible, in which embodied form as well as disembodied logic constitute scholarly argument.”

Sensuous scholarship aims at exploring localized non-dominant epistemologies: scholars must fine tune to local wavelengths that depends on the way the body orders one's experience of the world, to learn about one's epistemology (Stoller, 1997). I explored my own physical epistemology under the premises that it could be at peace with Newtonian mechanics and that vision is not the singular sense that orders my experience of the world.

### 3.3 Senses or sensors?

I once presented to a group of educators a project about teaching physics through dance and touch; someone in the audience said: “This is behind the times. You are doing a disservice to your students by not introducing modern technology in the classroom.” Inspired by Haraway's cyborg manifesto (1991), I want to challenge the opposition between senses and sensors.
Manmade sensors like telescopes, microscopes, mass spectrometer and ultrasounds provide an allegedly objective insight into the hidden secrets of nature. Galileo's first observations with a telescope are a milestone for modern science, even if his telescope had very poor lenses compare to his organic eye, even if he was drawing moon craters with his fleshy hand. Our sense of touch includes pressure and temperature sensors, our eardrums are high-tech sound waves analyzers. Nowadays, haptic\(^9\) technology makes it possible to feel and touch the nano-world: Haptic interfaces were developed because multi-sensory rendering enhance the nano-scientists' cognition (Marliere et al., 2004). We are biological creatures who evolved into cyborgs. There is no need to dichotomize between electronic and organic senses: they both have attributes and limitations. I welcome any sense/sensor in the classroom, and when dealing with imperceptible quantities, I welcome virtual reality softwares. However, we must keep in mind that the senses do not measure nor order the world the way sensors do. Our organs are not instruments; on the contrary, our instruments are added on organs (Merleau-Ponty, 1961/1993).

4. Method

There are two ways of knowing a thing: by moving around the object and by entering it (Bergson, 1955). In physics education, three dimensional objects are flattened on blackboards and in textbooks: Usually students have no way to enter objects, nor to move around them. Laboratory practice is often under valued, even if there is evidence that Renaissance artisans contributed to the scientific revolution because their bodily immersion afforded them a privileged insight into the nature of substances (Smith, 2004). Phenomena are decontextualized

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\(^9\) Haptic: relative to the sense of touch.
through a reductionist approach that isolates events in space and time, so that the connection to haptic\textsuperscript{10} knowledge is lost. I investigated a haptic re-engagement with the physical world.

4.1 Mode of investigation

My principal means of investigation was touch, however since senses work in synergy more than in isolation, other senses were also involved. In the Western tradition, touch has been identified as the lowest sense, the most animal, servile, and unconscious of the resources of the human sensorium (Chidester, 2005). It is associated - with smell and taste - with subordinate groups like women, workers and non-Westerners (Howes, 2005, p. 10). Touch is debased and ignored (Jay, 1994). In the academic world, it has been taken for granted, a medium for the production of meaningful acts, rather than meaningful in itself (Classen, 2005, p. 2).

The importance of touch is often overlooked in the physics classroom, even in physics labs where there is more emphasis on measuring instruments than on perceived sensations. However, touch precedes, informs and overwhelms language (Classen, 2005, p 13). It simultaneously opens up other imaginative and emotional ways of knowing material objects. It provides an understanding of texture, weight, shape, number, composition, distance, capacity and immensity. Solidity cannot be learned by any other sense. Touch is undeceiving, associated with verification, is necessary to measure and compare and is more consistent than vision: the hand is the extension of the mind and at the forefront of calibration (Paterson, 2007).

Teaching beyond \textit{inert knowledge} might require a bodily engagement with matter.

Touching an object brings it alive (Candlin, 2008) and fosters \textit{situational thinking} (Pallasmaa,

\begin{footnotesize}10\end{footnotesize} Haptic means relating to the sense of touch in all its forms, including proprioception, the vestibular system, kineasthesia and tactility.\end{footnotesize}
2005). The whole body is involved in perceiving the *thickness of the world* (Merleau-Ponty, 1992). We live and evolve in somatic spatial contexts; not in transcendent/geometric/abstracted spaces, but in immanent/situational/phenomenal spaces (Paterson, 2007, p. 74). The intimate relation between sight and touch allows a sense of immersion in the world; through touch, the world is with us (Merleau-Ponty, 1964b). As for motility, it helps bind and cohere sensory experience, and to disclose the world to us (Merleau-ponty, 1945/1992, pp. 137, 234).

### 4.2 Felt phenomenology

Paterson showed that a suitable mode of analysis of the senses of touch is felt *phenomenology* (Paterson, 2007, p.7). I made use of my five senses, but most of all of my somatic senses, i.e. the complex synergy between kinaesthesia (the sense of movement), proprioception (felt muscular position) and the vestibular system (sense of balance). I now agree with Paterson that touch, rather than vision, is prime (Paterson, 2007) and that touch functions in rational terms, indeed it may be the basis of rational thought (Candlin, 2008). During my investigations, I was aware of the limitations of sensuous inquiry: it is composed of both sensations (i.e. information routed via the nerves) and sensuous dispositions (i.e. the sociocultural construction of the sensorium and its possible alterations). There is no immediacy of sensory experience, it is always mediated (Paterson, 2009). I have ostensibly been searching for narratives that mediate felt sensations into a classical physics description of the world.

### 4.3 Choosing sites for investigation

Cavendish considered that women's experience in the kitchen gave them a sound basis for
conducting experimental inquiries into nature (Classen, 2005, p. 79). I revisited places of remarkable insignificance (Lorimer, 2005) like my kitchen, my bathroom, a bus ride, an elevator, a car, a bicycle ride, a tennis court, while bringing my awareness to my senses, trying to make my body aware of my environment. One of my main challenges was to translate felt sensations into written words, since our language is lacking terms to communicate haptic sensations (Paterson, 2009). This lack of vocabulary could be a consequence of the Western tendency to focus on vision, especially since the Enlightenment has condemned other senses as “subjective.”

4.4 Choosing a subject

Pink (2009) reminds us that sensory ethnographers cannot access directly people's intimate sensations and Paterson says that reporting on the haptic experience of others is inescapably mediated through the haptic experience of the researcher. Considering the available timeframe of my research project, I decided to limit my investigations to an exploration of the everyday physical world through my own senses, with no intention to generalize. Finding consensual expressions of interpersonal knowing (Rowles, 1980) through sensuous ethnography could be the subject of further research.

4.5 Opening doors

My search for truce between embodied knowledge and classical mechanics was informed by the zones of tensions between students and teaching content I felt in the classroom; they led me to develop stories that challenge the ontological premises that order physics knowledge and
physical knowledges.

I felt the need to juxtapose my sensuous stories with the narratives of my community. I revisited education research articles and popular physics tales assuming that, whenever there is an apparent clash with students' intuition, it must be possible to find stories that compromise with students' experience of the lived world. It led me to critique the methods used to integrate learners into the physics community. My haptic explorations increased my awareness of practices that ignore, or negate, embodied knowledge: Context, language, diagrams and metaphors can all be improved to reconnect physics education with physical knowledge.

My research was an exploration that did not lead to a single conclusion, nor to a single teaching method that can “cure” students of their misconceptions. This is not a linear academic text, nor an ordered progression of theoretical ideas that leads to a coherent conclusion: such concepts are problematic when trying to overcome binary polarizations, when looking for points of intersection and convergences (Honan & Sellers, 2008). I weaved my own concept/sensation resonances with “aha” moments observed in the classroom, stories found in physics textbooks and the narratives heard in my community, chasing away zones of friction and searching for overlaps. I want to open doors to less violent and more engaging/empowering ways of communicating with learners.

5. Students' misconceptions

When I started my research, I was troubled by an inner conflict: fifteen years of experience in the classroom and forty years of physical experiments in this world had
convinced me that teaching physics with the help of the senses is feasible. However “misconceptions” are a prevalent meme in my educator's community: students hold robust and erroneous common sensical views of the physical world that hinder their learning. I became unable to fully engage in my explorations without doing first an annotated literature review of misconceptions. My comments are in *italics*.

**5.1 What is a misconception?**

A common view in my community is that in order to improve students' conceptual understanding, an educator needs to investigate students' misconceptions and induce a “conceptual change.” I even heard that “students are infested with misconceptions.” Lists of misconceptions are shared by educators, mostly coming from classroom observations. Here are a few examples:

- **Kinematics**: Two objects side by side must have the same speed; Acceleration and velocity are always in the same direction; Velocity is a force; If velocity is zero, then acceleration must be zero too.

- **Falling bodies**: Heavier objects fall faster than light ones; Freely falling bodies can only move downward; There is no gravity in a vacuum; Gravity only acts on things when they are falling.

- **Newton's Laws**: Action-reaction forces act on the same body; The product of mass and acceleration, \( ma \), is a force; Friction can't act in the direction of motion; The normal force on an object always equals the weight of the object; Equilibrium means that all the forces on an object are equal; Only animate things (people, animals) exert forces, passive ones (tables, floors) do not exert
forces; A force applied by, say a hand, still acts on an object after the object leaves the hand. Momentum is the same as force.

- **Circular motion**: Circular motion does not require a force; Centrifugal forces are real; An object moving in circle with constant speed has no acceleration; An object moving in a circle will continue in circular motion when released; An object is circular motion will fly out radially when released.

Such lists do not tell the proportion of students holding those misconceptions, nor if there are other student views: they look like a shopping list and give the impression that the typical student holds those typical common sensical views.

In the literature, a misconception is a student conception that produces a systematic pattern of errors (Smith, di Sessa and Roschelle, 1993), a belief that does not match what is known to be scientifically correct (Alwan, 2011) and that constitutes an obstacle to learning (Hammer, 1996). This is a wide definition that includes intuitive knowledge but also misconceptions arising from prior classroom learning, and erroneous overgeneralization. In my research, I focused on student intuitive knowledge.

The term misconception is closely related to *preconception*, *preconceived notions*, *alternative conception*, *alternative framework*, *naive physic*, *naive belief*, *non-scientific models*, *conceptual misunderstanding* or *intuitive model*. Misconceptions are even sometimes confused with *student difficulties*. Hereafter, I will be using the word *misconception* because it best captures how student preconceptions are perceived in my community of practice, i.e. a “wrong mindset about how the physical world works” (Martin-Blas et al., 2010).
Research on misconceptions is carried in psychology and education departments as well as by the Physics Education Research community (PER), i.e. physics and astronomy faculty working in physics and astronomy departments who want to improve teaching methods. Conferences for physics teachers like AAPT\textsuperscript{11} meetings present mostly research work by the PER community, which is therefore of special interest to my research. Today, the research on misconceptions includes light, heat and electricity, but for the purpose of this thesis, I will limit my explorations to classical mechanics.

\textbf{5.2 Early works}

In 1976, Shanon asked fundamental questions that would later be explored in depth: Are people's cognitive models of the physical world:

\begin{itemize}
\item congruent with their perceptions?
\item congruent with Newtonian theories?
\end{itemize}

She examined more specifically if people's models of falling objects are Aristotelian (i.e. objects fall at a constant speed) or Newtonian (i.e. the free fall model). \textit{According to Newtonian physics, objects fall at a constant acceleration in vacuum: we cannot expect people to have any lived experience in the absence of air. In air, objects' motions are described by a variety of physical models of aerodynamic drag (that include compressibility, induced drag, boundary layer separation, etc) and that depend on several parameters (the shape, size, texture and speed of the object). For example, a raindrop falls at a constant speed of 9 to 13 m/s and snowflakes at 1 to

\textsuperscript{11} American Association of Physics Teachers
2 m/s\(^2\). Also, when a person drops a penny, the coin takes half a second to reach the ground, so the person's senses cannot appreciate if this motion is at a constant speed or accelerated unless they watch a slow motion movie.

The first question asked to participants was “given that a ball dropped from a window reaches the ground in four seconds, how long will it take for it to get halfway to the ground?” 67% of the respondents chose the Newtonian answer and only 20% chose the Aristotelian one. Assuming the ball is in free fall, the window would be 80 meters high. It is really hard for a person to perceive the changes in speed over such a drop. Besides, a basket ball dropped from such a height would reach a constant velocity before hitting the ground (closer to the Aristotelian view). In a follow up experiment, participants were presented with slow motion movies of objects falling at a constant speed or accelerating and asked to describe these motions as “natural.” All the responses were Newtonian. Nevertheless, Shanon concludes that “there is a discrepancy between scientific theories and the layman's model of the world.”

Trowbridge and McDermott explored students' understanding of velocity (1980a) and acceleration (1980b). They noticed that some students rely on perception and intuition to answer the questions. Students have a “repertoire of procedures, vocabulary, associations, and analogies” that may be considered as a set of “protoconcepts”. Clement (1982) introduced the concept of difficult “conceptual primitives” rooted in intuitive preconceptions. For example, students hold the preconception motion-implies-a-force, which is a major stumbling block in the

\[\text{12 http://physics.info/drag/}\]
physics curriculum. Physics instruction has little impact on students' preconceptions: students are unlikely to abandon a preconception by being exposed to the standard view in their physics course. More likely, they memorize formulae disconnected from concepts. *My main concern with this study is that Clement assumed students were able to verbally articulate their felt knowledge of physics. We must keep in mind that our language is poor in vocabulary to express somatic knowledge, and that the language of physicists is hard to master. Moreover, even educators use frequently preconceptions like motion-implies-a-force because they are at the core of the language we speak.*

Halloun and Hestenes (1985a) showed that college students use their common sense theory of the physical world to interpret what they hear in the physics class. The failure of educators to take these beliefs into account is largely responsible for the legendary incomprehensibility of introductory physics. They conclude that common sense beliefs about motion are generally incompatible with Newtonian theory and confirm that conventional physics instruction does little to change them. *In this article, I noticed an appeal to generalization that does not seem supported by evidence: do students systematically misinterpret all material? The authors want to design the ultimate quantitative measuring instrument for assessing the “knowledge state” of beginners. Since misconceptions are a complex and loose assemblage of clusters and sub-clusters of ideas, wouldn't a qualitative analysis be necessary for their mapping?* In a follow up article Halloun and Hestenes (1985b) show students use the language of physics in a confusing manner (for example, they confuse force, speed, energy, momentum, inertia and acceleration).
Students' common sense about motion is in fact not Aristotelian, but medieval. They conclude by giving a long list of mistaken common sense beliefs hold by students. Halloun and Hestenes' way of calculating their results (1985b) was over-inflating a negative picture of students. They mostly reported students' failure, when they could have focused on students' success. For example, they say that 66% of the respondents held, at least once, that under a constant force an object moves at a constant speed. How many of the respondents gave, at least once, a correct answer, knowing that only 2% held their mistaken belief consistently? 84% of the respondents believed that a free particle follows a linear trajectory, which is a good Newtonian intuition to build upon. The authors attribute all misconceptions to a pre-Newtonian understanding of the world. Did the authors rule out all other possible explanations for students' wrong answers? For example, an alleged misconceptions is that in circular motion, there is a centrifugal force acting on the object. I recently followed a discussion on a physics teachers' forum and noticed this view is accepted by some educators. Envisioning students' preconceptions as a chance or as an hindrance is, before all, an epistemological choice.

5.3 A few well studied cases
I found an abundant literature on four well studied cases. There are articles studying other misconceptions about mechanics, but I discarded them because they dealt with student difficulties not related to intuitive or embodied knowledge.

5.3.1 The breaking pendulum
Caramazza, McCloskey and Green (1981) asked undergraduate students to consider a
moving pendulum and to draw the path the ball would follow if the string were cut (See Fig. 1). Only 25% of the students produced an answer in agreement with the real observed motion. The authors concluded that students hold the pre-Galilean notion of impetus and that simple real-world experience with moving objects does not lead to the abstraction of principles consistent with Newton's laws.

Fig. 1: Predicted trajectories followed by the ball after cutting the string at the top and at the bottom position (from Kaiser et al. 1992). Answers #1 and #2 are correct.

*The question is not really about people's intuitive knowledge of a pendulum, but about*
making a prediction about a phenomena participants might have never witnessed (i.e. the string breaks). To make sense of the first diagram, they needed to know that when the pendulum is exactly at the top of its trajectory, its velocity is zero. This is not an observation that most people make, unless they are asked to pay special attention to that very point. Even then, it is hard to perceive an instantaneous velocity of zero, unless watching the phenomenon in slow motion. It would be interesting to ask the same question for a swing, to see if respondents rely on a different embodied knowledge.

5.3.2 Throwing an object

McCloskey (1983a) asked respondents to imagine they hold a stone at shoulder height while walking forward at a brisk pace. They were asked: “What will happen if the person drops the stone? What kind of path will the stone follow in its fall?” Most people answered that the stone would fall straight down. According to Newton's laws, the stone follows a parabola and falls ahead of the initial position of the thrower. When watching a person dropping a stone, it is possible that the observer uses the moving person as a frame of reference, and therefore predicts the stone will fall straight down. For our senses to be able to notice that the stone's velocity has a horizontal component, the thrower must run really fast, something we usually do not do when carrying or throwing objects. We cannot expect people to have an intuition of a situation they never experienced.

When a study asks respondents to choose the “most natural” path of the projectile, or the one that best predicts the real motion of a thrown object, the wording of the question is problematic, since we have no guarantee that participants and researchers share the same
meaning of “natural.” To a lay person, the “most natural” motion could be the one that predicts the landing point of the projectile with the best accuracy, not the one that follows a parabolic path. Air drag can squeeze a parabolic trajectory, or push a tennis ball sideways (Magnus effect). For example, Aidar says: “the physics of baseball is not the clean, well-defined physics of fundamental matters but the ill-defined physics of the complex world in which we live, where elements are not ideally simple and the physicist must make best judgments on matters that are not simply calculable” (Adair, 1995). If we draw the collection of all the possible paths of tennis, basket and baseball balls observed in real life, it will include a wide variety of curves and arcs seen from all possible angles, not just the generic textbook parabola. Is it, for example, “natural” to use a parabola to describe the path of a squash ball or is it more “natural” to approximate this path with a straight line? What about the path of a bullet fired by a rifle? Even physicists find the straight line model is sometimes more convenient. For example, in The Cosmic Perspective13 (Bennett et al., 2009, p.412) a man is shown throwing a ball that follows a straight line path when in free fall (see Fig. 2).

In further studies about intuitive knowledge of motion, it would be interesting to move away from multiple choice questionnaires and ask respondents to draw the path of the ball with a finger in 3D.

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13 A first year astronomy textbook, in the chapter about Einstein's special relativity.
Fig. 2: A man throws a ball in a train. The ball follows a straight line path despite being in free fall. From Bennet et al., 2009, p. 412.

Hecht and Bertamini (2000) carried a detailed study of projectile motion using the example of a person throwing a ball at another person. They conclude that people observing a motion are usually not good at detecting and judging vertical acceleration, even if they implicitly use this information to predict the landing point of the projectile. In their experiment, participants characterized as “natural” projectile trajectories shaped like circular, sinusoidal and parabolic shapes, either symmetrical or deformed towards the catcher, as if participants were taking air resistance into account (*Is this a misconception?*). 22% of the respondents said the speed of the ball is maximum around the middle/top of the trajectory, and only 6% thought the speed is maximum just after throwing or before catching it. 45% said the ball first speeds up and then slows down. When shown 3D animated trajectories, however, observers judged as natural the Newtonian trajectories. The authors propose that participants projected muscle activity (throwing/catching) onto the ball itself, after it had left the hand. Another possibility is that participants do not slice the history of the projectile into a throw, a free fall phase, and a catch. Therefore they have a correct intuition that the ball receives energy when thrown, and loses it when caught. This is an observation I frequently make in the classroom: if I ask students to draw
a dot diagram of a tossed coin, many include the acceleration of the coin while it is thrown and caught: we do not share the same definition of “the motion of the coin.” A major issue with Hecht and Bertamini’s work is that they presented participants with static diagrams of moving objects that might not trigger intuitive knowledge about motion.

5.3.3 The C-shape experiment

Kaiser, Proffitt and Anderson (1985) presented participants with a C-shape tube laying on a table; a marble was thrown into the tube. Participants were asked to predict the motion of the ball. They answered in two different ways: by choosing between six videos of simulated motions or by looking at diagrams (See Fig. 3).

![Diagrams of C-shape experiments]

Fig.3 : Examples of predicted path for a ball exiting a C-shaped tube.

From Kaiser, Proffitt and Anderson (1985). Answer #3 is correct.

Participants answered better in motion conditions: 75.6% of men and 31.7% of women found the correct answer against 48.6% of men and 23.3% of the women in static conditions. The gender difference could not be attributed to former physics training. A troubling observation was that the children group did not show any gender effect, but the authors offer no explanation for
the discrepancy. It would be interesting to know if respondents knew they were doing an experiment about physics and test if some women had already constructed an epistemology of physics as being counter-intuitive.

Catrambone et al. (1995) revisited this experiment using a transparent spiralling tube. One group was told that this tube is a “hose” and the other group that it is a “tube.” Surprisingly, roughly 70% of the people in the first group made a correct prediction, but only 30% in the second group, as if the word “hose” was guiding their search for analogies.

Fig. 4. Possible paths of a ball exiting a spiral maze. From Kaiser, McCloskey and Proffitt (1986).

In a C-shape tube experiment, the body needs to deal with a disturbing discontinuity when the marble exits the tube: the marble was trapped in the tube, and it suddenly becomes free. Half way through the problem, the conditions are changing: the normal force responsible for the curvilinear motion suddenly stops to exist, creating a discontinuity that is not easy to negotiate somatically, especially since the normal force is itself not somatically understood by an important number of students. It is possible that, for some people, somatic intuition of angular momentum takes precedent over their ability to predict the path of the marble. In everyday life, angular momentum does not vanish instantaneously, but dissipates, for example when a wheel
stops because someone puts on the brakes. In the physics classroom too we only study gradual changes, and solve problems with differentiable functions. The spiral maze experiment is not a trivial physics problem: it reaches beyond first year level.

Kaiser, Jonides and Alexander (1986) also found that participants produced significantly more correct prediction for the trajectory of water emerging from a curved hose (66%) than for a ball emerging from a curved tube (39%). Catrambone et al. (1995) hypothesize students used their former experience of holding a garden hose, while for a marble, participants could not rely on any memorized lived experience, and therefore searched for an analogy that might have mislead them.

The path predicted by many participants in the spiral maze experiment is surprising: they believed the marble will continue in the air on a circular trajectory, because of a bizarre circular momentum. Surprisingly, those respondents could be lead to believe they are correct by reading The Cosmic Perspective (Bennett et al., p. 123), a textbook for first year astronomy university students:

Perhaps you've wondered how Earth manages to keep rotating and going around the Sun...The answer comes from … the law of conservation of angular momentum...The Earth needs no fuel or push of any kind to keep orbiting the Sun – it will keep orbiting as long as nothing comes along to take angular momentum away.

Could a marble, like the Earth, continue orbiting around a C-shape tube for ever? Or are Bennett et al. making implicit assumptions that are hidden to the reader?
A marble is a solid object undergoing rotational motion. It has two angular momenta, one because it follows the spiral tube and another one because of its rolling motion. These two momenta are conserved. This could create a conflict between two different preconceptions, and explain why participants attribute a short lived angular momentum to the exiting marble.

There are positive ways to look at the spiral maze experiment that are often overlooked:

1) The respondents have an intuition of angular momentum and of linear momentum.

2) The respondents have an intuition that there is a transition phase between two different physical set ups when the marble exits the tube; they just overestimate the time taken by the marble to transition between the two.

Those experiments show the difficulty of finding the causes of a misconception: the answer is not as a simplistic as “students hold a medieval belief system.”

5.3.4 The drifting rocket

Cooke and Breedin (1994) examined people’s judgment of motion. In their study, a rocket is mysteriously drifting sideways in space when it suddenly ignites its thrusters at point P. Participants are asked to predict the motion of the rocket at point P (See Fig. 5). Assuming a constant force is applied to the rocket, the answer should be (e).
Fig. 5: The rocket drifts from N to P. The thrusters are ignited at point P (Item #24 of the FCI).

I see several issues with the drifting rocket question:

- Asking participants to predict the motion of a spaceship using their intuition is problematic, since none of them ever piloted a spaceship, except maybe in a computer simulation. Since respondents are not used to a world without friction and without gravity, they are likely to search for analog situations, for example remembering skating or kicking a soccer ball, which will mislead their intuition. It is also hard to imagine a rocket drifting sideways in space: we rarely see this, even in Sci Fi movies.

- Respondents lack important information. To a physicist, there is only one correct answer, whatever the speed of the rocket: a path shaped like an arc of a parabola. To other people, it might matter to know how fast the rocket was drifting, and how strong the thrust is: depending on those parameters, the path of the rocket will have a variety of
shapes, regardless of the fact that a mathematician can generalize them all as parabolas.

- To a physicist, a crucial data is that the thrust is constant. Participants could overlook this information and refer to their intuition of giving a kick. What we see of the path of the object in real life depends on how long the force is applied; in the case of a hockey sticking kicking a puck, we do not perceive the parabolic path of the puck.

5.4 Experts' misconceptions

When solving a problem, experts too use concrete physical intuition rather than abstract verbal principles or equations (Clement, 1994). Much of thinking and learning involve unconscious processes (May & Semetsky, 2008); some famous scientists think without words, without algebraic symbols; some even abstract the world in made up nonsense words or sounds (Hadamard, 1945, p.69). Some experts use gesture to think, which could mean the motor system is implicated in their thinking processes: gesture could be a way of running simulations to apply knowledge that is not stored as a linguistic description (Clement, 1994). It is possible that the mind extends beyond the brain to the whole nervous system, which could explain Richard Feynman's behaviour:

Those who watched Feynman in moments of intense concentration came away with a strong, even disturbing sense of the physicality of the process, as though his brain did not stop at the gray matter but extended through every muscle of his body (Gleick, 1992, p. 244).
Even if they hold Newtonian beliefs, some scientists exhibit marked deficiencies in conceptual interpretation. (Reif & Allen, 1992). They show the same implicit beliefs as novices when an immediate response is required (Kozhevnikov and Hegarty, 2001). For example, Proffitt and Gilden (1989) found that physics educators develop a formal mathematical understanding of gyroscopes, but not a perceptual one. When asked to predict the behaviour of rolling wheels, almost no one, physicists and naive observers alike, anticipated that mass distribution affects the rate at which a wheel rolls down an inclined plane. When presented with problems involving wheels, physics experts - if not allowed to use equations - did not perform better than naive undergraduates, i.e. with a failure rate up to 80% (Proffitt, Kaiser & Whelan, 1990).

Those observations show instruction had little impact on experts' intuitive knowledge, and challenges the idea that students can be “cured” from their misconceptions, i.e. that conceptual change is a meaningful educational strategy.

It would be interesting to study a different category of “experts”, for example people who work everyday with rolling wheels, and study if they developed a more elaborate intuitive knowledge of rotational motion.

5.5 Conceptual anchors

Smith, diSessa and Roschelle (1993) want to focus on continuities between expert and novice knowledge. They see a need to refine and reorganize misconceptions instead of replacing them by experts' beliefs. If preconceptions are seen as interfering with learning, resisting
instruction and in need of being replaced, they seem incompatible with a constructivist approach to learning. On the contrary, if researchers shift their focus toward productive preconceptions, and acknowledge that preconceptions are strongly context-dependent, they could build a constructive learning strategy upon them. The authors claim that a classroom model based on “confrontation” denies the validity of students' ideas; it is inconsistent with the pedagogical sensitivity and care required to negotiate new understandings.

An anchor is a valuable preconception (in a physics context), a knowledge structure that appears self-evident to many students, needing no explanation to be believed, and that is in rough agreement with accepted physical theory (Clement, Brown & Zietsman, 1989; Clement, 2008). Clement advocates a teaching strategy that taps into kinaesthetic or tactile knowledge in order to create “bridging analogies” between anchors and targets. For example, some students do not believe that a table can exert a force on a book, but they can believe that a spring can exert a force on a hand. The normal force exerted by a table on a book is therefore introduced using the analogy of small springs pushing into the book. A positive preconception is considered an anchor if it is held by at least 70% of the students. Such anchors are tested in the classroom and only the most successful ones are retained.

Let's keep in mind that most studies in intuitive physics show a wide variety of participants' answers so that we are dealing more with a blurry continuum than with categories, and more with a complex variety than with generalities. My concern about Clement's teaching strategy is one of ownership. The educator selects the relevant anchors, and the relevant bridges, based on statistical results. What about the 30% of students who do not share those anchors: what
message do they receive if instruction relies on embodied knowledge that contradict theirs? This strategy is normative, linear and systematic. It is designed to address a generic student. I would rather create a space where we revisit the messages told by the real world, asking students to focus their senses, especially touch, on specific phenomena, and let them build their own representations of the world.

5.6 The Force Concept Inventory

The Force Concept inventory is an instrument for teachers to probe and assess the commonsense beliefs of their students and the quality of instruction. It was developed by Hestenes, Wells and Swackhamer (1992) and is widely used in the physics education community. The FCI is a multiple choice questionnaire, only available online to instructors. It mostly focuses on misconceptions that are identified in the literature: It assesses how many are still hold by students. It does not focus on conceptual anchors: The FCI is a catalog of all that can go wrong, therefore the average score on the test is in the 23%-34% range. Heller and Huffman (1995) warned that the FCI should not be used to make decisions about individual students.

The authors of the FCI claim:

It has been established that commonsense beliefs about motion and force are incompatible with Newtonian concepts in most respects ... [Students] have been forced to cope with the subject by rote memorization of isolated fragments and by carrying meaningless tasks... The [FCI] requires a forced choice between Newtonian concepts
and commonsense alternatives... It is a probe of belief systems. (Hestenes, Wells and Swackhamer, 1992)

They acknowledge the violence of traditional teaching methods, but do not question the ethics of forcing students to change their belief system. They claim that misconceptions are universal (p. 150) however there is no evidence in the literature that all students hold “mistaken” commonsense beliefs. The authors give a taxonomy of misconceptions based on a single article: Halloun & Hestenes (1985b). Since educational researchers unanimously conclude that “the problem is very serious,” one could expect to find a plethora of references about taxonomies of misconceptions. The authors' taxonomy is articulated around a dichotomy between common sense and the Newtonian world, even when this opposition is blurry. For example, the authors say that in the world of common sense, “mass is regarded as a king of resistance, because it 'resists' the efforts of an active agent,” i.e. close to the concept of inertia which, for a motion in a straight line, is mass. Hestenes, Well and Swackhamer overemphasized dichotomy evokes a power struggle: Educators, instead of building on embodied knowledge, should erase it. The authors offer no space for common ground between two belief systems.

The history of the FCI could have been written by engineers. First, the research community discovered the existence of misconceptions in some students, which lead to a general statement: “teaching does not work” and a grand narrative: “students hold misconceptions,” therefore the need to replace misconceptions by “correct knowledge.” The problem triggered the invention of a measuring instrument (the FCI) and new teaching strategies operating in the abstract world of paper-and-pen mechanics. The good instructor became the person able to
repair the broken students.

The FCI perpetuates a mechanistic view of students that erases the complexity and variety of their modes of being in the world, of perceiving the world, of analyzing, understanding and abstracting reality. However, it is so widely used, that I carefully looked at what could be the sources of errors done by students. I classified difficulties in eight categories:

- Comprehension: the wording of the question is extremely complicated.
- Definition: the student does not know the definition of a physical quantity.
- Misleading prop: the question triggers the use of intuitive knowledge irrelevant to the context.
- Intuitive blank: the question refers to a context for which the student has no intuitive knowledge at all and s/he cannot recall any analog situation.
- Perceptual bias: for example the student observes a motion from a different view point than a physicist.
- Abstract leap: the student cannot abstract the situation, or abstract the situation according to different criteria than a physicist. For example, the student does not focus on the parabolic shape of a trajectory but on other characteristics of the motion.
- Implicit assumptions: they are obvious to a teacher, but not revealed to the student.
- Misleading mental construct from previous instruction (such misconceptions can even be found in textbooks. A well spread example is the idea that $F_N = -F_g$).

My results are summarized in Table 1. These various difficulties cannot be gathered under a single label of misconceptions, nor can we claim they all find their root in medieval common
sense knowledge. I find it concerning that the FCI is still widely used in 2011 without being further problematized.

<table>
<thead>
<tr>
<th></th>
<th>comprehension</th>
<th>definition</th>
<th>Misleading prop</th>
<th>Intuitive blank</th>
<th>Perceptual bias</th>
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<tr>
<td>Total</td>
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<td>9</td>
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<td>12</td>
<td>12</td>
<td>17</td>
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Table 1: Possible difficulties in answering the Force Concept Inventory

5.7 The mind/body split is overblown

The majority of current PER papers accept the existence of misconceptions as an established and universal fact. For example, Rosenblatt, Sayre and Heckler (2009) introduce their article by stating “students commonly believe that if there is a net force pushing on an object, then the object must be moving in the direction of the push.” What is meant by commonly: 90% or 30% of students? Are the authors addressing the student population as a whole or focusing on students with difficulties? Even if they wrote in 2009, they still refer to studies on misconceptions made by Clement (1982) and Halloun and Hestenes (1985b), and do not include references from the field of psychology: The PER community has built a narrative around misconceptions based on a small collection of foundational articles. Most of the literature characterizes students' knowledge of mechanics as medieval or Aristotelian (diSessa, 1982; Halloun and Hestenes, 1985b). These collective narratives evoke Galileo's fight against Aristotelian followers, which required courage and boldness, but it is surprising to see how they still impact the community.

Research on misconceptions overemphasize the gap between common sense and classical mechanics by focusing on examples of incorrect intuition. Correct performance is
virtually ignored in current research. Cooke and Breedin (1994) showed there is “little evidence naïve impetus theory plays a significant role in subjects's performance; instead, … motion judgment and explanations are constructed on the fly from contextual cues and knowledge that is not necessarily naïve.” They remark that literature on misconceptions paint a “rather bleak picture of people's understanding of motion, in spite of the fact that their everyday interaction with moving objects do not seem to be impaired. Intuitively, people seem to know more about motion than experimental results suggest.” They notice that respondents were giving vague explanations for their choices, even when asked to give more detailed explanations, showing the non-verbal aspect of the knowledge involved in their thinking. People have a perceptual knowledge about motion that is much more accurate than their conscious verbal-cognitive concepts (Kozhevnikov & Hegarty, 2001). Humans are remarkably accurate when it comes to complex motor actions such as catching a baseball or hitting a target. However, that knowledge of the physical world can be poorly represented in the cognitive domain (Bertamini, Spooner & Hecht, 2004).

Research that sees misconceptions as flawed ideas is over-emphasizing the discontinuity between students and experts (Smith, di Sessa & Roschelle, 1993). Studies do not fairly assess the skills of novices since respondents are asked to perform under conditions in which they are incompetent. Can the abstract and unrealistic tasks given to participants really tap knowledge routinely used in real life situations (McCloskey and Kohl, 1983)? In all of the cases in which impetus beliefs are shown, what was tested was not people's somatic knowledge of their lived-world, but their capacity to export intuitive knowledge into different contexts (Kozhevnikov and
tasks is neither a measure of knowledge of the principles of physics nor a reflection of whether
one holds an incorrect intuitive theory.

In the PER community, disagreements between experts and novices are easily labelled as
misconceptions, even when students hold conceptions that are Newtonian in specific contexts:
they are physically correct, but lack the generality of Newton's laws. Here are a few examples:

• **Objects fall at a constant speed**: This is true when objects reach terminal velocity.

• **An object moves in the direction of the force**: This is true for an object starting from rest.

• **Force is a mover**: This is true for objects starting from rest.

• **Speed is proportional to force**: If the net force is constant and the object starts from rest,
then \( v = a.t = F.t/m \).

• If a student draws an arrow in the direction of the motion of an object on a free body
diagram, it can be seen as an erroneous Aristotelian belief, or as a good intuition of
momentum.

### 5.8 Differences between Newtonian and common sense physics

There is however an opposition to be made between Newtonian and intuitive physics: the
order of complexity they are addressing. Expert in artificial intelligence tried to describe the
everyday world using Newtonian equations in order to program mobile robots: they realized that
approach was too complicated. They therefore developed their own theory of everyday life
physics: *qualitative physics* (Forbus, 1988; de Kleer, 1993). Our bodies are constantly receiving
data from countless organic sensors. Processing them all in the same way is not effective nor necessary. The body-mind has a capacity to prioritize data according to their relevance to the context, which becomes a matter of survival in fight or flight situations. Physicists, on the other hand, are looking for patterns in nature that can be modelled using mathematics and seek a high degree of generalization. Their endeavour often requires simplifying hypothesis, i.e. a way of prioritizing data that does not necessarily match the body-mind's hierarchy. Moreover, the limits of a mechanistic description of the world becomes apparent when attempting to predict the behaviour of complex systems like the Earth's climate.

In introductory courses, physics educators seek an over-simplified view of the world, often even removing the force of friction from the picture, so that the calculations become as “simple” as possible. By doing so, they are making classical mechanics more decontextualized and abstract, therefore more disconnected from somatic knowledge. If we accept that there is no possibility to think without having access to our phenomenological metaphors, the scaffolding of the curriculum needs to be reversed: first study real life cases where there is friction, and develop a perceptual awareness of friction; then, in a second stage, ask students to abstract what happens when friction can be neglected. The adjective “simple” needs to be problematized in the context of physical knowledge.

It could be argued that the physics class is a place where to formalize and mathematize a former explicit knowledge of everyday physics. This view assumes that all students bring the same experiential background knowledge to a physics class. However, not every one pays attention to their senses while engaging in manual or physical activities, nor is able to transform
tacit knowledge into an explicit one. People might not develop the same physical knowledge in a kitchen, in a workshop or on a sports field. A child helping his father repair mechanics does not develop the same intuitive knowledge if playing video games. Not every child is provided with construction games or Meccano gears, especially girls. Expecting explicit physics knowledge to be part of a student's background introduces a strong selection bias; the classroom should be a place where every learner is given a chance to develop experiential knowledge of physical quantities.

5.9 Aristotelian, medieval and Newtonian physics

The PER community frequently opposes misconceptions to the Newtonian worldview. Students should therefore undergo a conceptual change, i.e. abandon their misconceptions to adopt Newtonian views (Hestenes, Wells & Swackhamer, 1992). Can we really trap the history of physics in such a dichotomy? Is there really two confrontational worldviews and a need for students to undergo a drastic (eventually painful) conceptual change from one to the other? If, instead, we picture the history of classical mechanics as a continuous evolution and refinement of ideas by thinkers who seek generalization, students can be seen as novices joining the stream at a point of entry that suits their needs. In this section I will explore two question: Is it enough to say that Aristotle was plain wrong? Is it realistic to divide the history of mechanics between pre-Newtonian and post-Newtonian?
5.9.1 *Was Aristotle plain wrong?*

Even though most, if not all, of Aristotle's science was wrong – he can be thought of as the scientist of common sense – he established the basis of a system for explaining the world based on postulates and logical deduction.

(Wolper, 1992, p. xii)

Aristotle is often pictured as the scientist of common sense, the archetype of wrong physics. In this exploration, I deconstruct an anti-Aristotle narrative I was exposed to as a student. My goal is to show how physics teaching and research on misconceptions are informed by the folklore of the physics community.

*René's story*¹⁴

“Today, René will introduce free fall to his grade 12 class. He knows that most of his students hold the Aristotelian misconception that the speed of a falling object is proportional to its weight: heavier objects fall faster than lighter ones. To bring his students’ awareness to this issue, he wants to surprise them, to confront their worldview, create a cognitive conflict, in other words: prove them wrong. He holds a bowling ball in his right hand and a volley ball in his left hand, and asks:

- If I neglect air resistance, which of these two objects will reach the ground first?

As expected, most students answer:

- The bowling ball.

René explains that before Galileo’s discovery, this was the commonly held opinion. But

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¹⁴ René is a fictional teacher inspired from my high-school teachers and university professors.
Galileo's experiments proved otherwise: if one neglects air friction, the two objects will reach
the ground at the same time. René cannot really drop the bowling ball: it could damage the
floor. Besides, the phenomenon is hardly perceptible for objects falling over such a small
height. So René draws the Tower of Pisa on the board, with a man at the top dropping the two
balls, and says:
- Galileo showed that all falling objects fall at the same rate: \( g = 9.81 m/s^2 \). The two balls would
hit the ground at the same time, with the same speed.”

**The Aristotle/Newton split is not clear cut**

According to Halloun and Hestenes (1985), “many students share with Aristotle the
belief that the speed of a falling object is proportional to its weight,” \( W \): the heavier body falls
faster in proportion to its weight\(^\text{15}\). A simple calculation shows that in real life, thanks to air
resistance\(^\text{16}\), falling objects do reach a constant velocity proportional to their weight\(^\text{17}\), i.e. a
terminal speed that is in agreement with the students' common sense. Taylor (2005), a textbook
author, does this calculation and concludes: “For example, if two objects have the same shape
and size …, the heavier object … will have the higher terminal speed, just as you would expect
[emphasis mine]”. In the case of two objects of different size and same density (for example two
iron balls), the more massive object will also fall at a higher rate because the mass increases in
\( R^3 \) and air resistance in \( R^2 \), again in agreement with common sense.

To convince students that Galileo was correct, some educators show videos of well known

\(^{15}\) \( v_1/v_2 = W_1/W_2 \)

\(^{16}\) If we model air resistance as being proportional to the speed of the object: \( f = -b.v \)

\(^{17}\) \( v_{ter} = mg/b \)
free fall experiments:

- Dropping a feather and a hammer in a vacuum chamber.
- Dropping a feather and a hammer on the moon (Apollo mission).

These two examples can add to the students' confusion since it is not uncommon for them to think that:

- There is no gravity in vacuum (because they confuse vacuum with interstellar space and weightlessness).
- There is no gravity on the moon.

These two examples can also give the impression that physics is irrelevant to real life since none of us live in a vacuum chamber nor on the Moon.

**Telling the story of the lived world**

A lived world story could start with the study of falling snow flakes and hail stones, then an exploration of what happens in the special cases where air resistance can be neglected. It could also explore the meaning of *neglected*:

- On the moon and in a vacuum chamber, objects are in free fall because there is no air.
- In real life, if a stone moves slowly enough, air resistance can be neglected: the effect of air resistance becomes apparent only once the stone reaches high speed. For a feather, however, air drag must be taken into account. The shape and size of objects matter.

Deciding when to neglect friction is a time consuming topic that is often omitted. However, it is an essential topic of discussion if we want students to relate physics to everyday life. It is
also a chance to explain what a model is, and how most models require simplifying assumptions. There is a wide epistemological gap between presenting physics theories as truths or as models of the world we live in.

**Teaching is informed by legends**

There is no historical record that Galileo performed the Tower of Pisa experiment. Galileo described the expected outcome in his writings, but it could have been a thought experiment. The Tower of Pisa experiment belongs to the collection of physics legends, like Newton's falling apple. The legend sometimes includes a crowd of Aristotle's followers waiting at the bottom of the tower, convinced the heavier ball will reach the ground first, and then being baffled that the two balls hit the ground simultaneously. On May 31, 2009, physicist Steve Shore of the University of Pisa “re-created” the experiment in front of “Aristotelian skeptics” dressed in period costumes. The show was filmed by Falk (2009), a science journalist. Galileo is presented as “the father of physics.” Falk explains that a bowling ball and a volley ball of the same size dropped from the tower would reach the ground at the same time (which is unlikely since, over a height of 56 meters, the volley ball would reach terminal speed). The experiment is carried by Shore using water bottles. **The heavier bottle reaches the ground slightly faster!** But Falk concludes: “Galileo would have been pleased. He was right. Aristotle was wrong. The two objects reached the ground at the same time.”

Ironically, the Tower of Pisa legend contributes to narratives about the power of the experimental method, allegedly initiated by Galileo. In fact, Galileo carried out experiments on inclined planes, that are now kept at the Museo Galileo in Florence: he studied objects rolling
down at low speeds, along short distances, not falling from high towers, so that air resistance was reduced to a minimum.

The first time I watched Falk's Tower of Pisa video (2009), I thought it was an excellent demonstration of Galileo's work on free falling objects: I was too indoctrinated to notice the heavier object was hitting the ground slightly ahead of the light one. The second time, I felt uneasy. It is only the third time that I noticed the inconsistency with Galileo's model.

**Physicists are biased by mathematical models**

Mazur (2008) presented a very telling example of the use of the free fall model by experts. He created a diagram showing a man dropping a ball while walking. The ball was shown taking three different paths:

- A: hitting the ground behind the point where it was dropped,
- B: hitting the ground right below the point where it was dropped,
- C: hitting the ground several feet ahead of the point where it was dropped.

Mazur asked lay people and physicists to choose between the 3 answers. The preferred answer for lay people was B, while the vast majority of physicists chose C. For a person walking at an average pace, the answer is actually closer to B than to C. Lay people answered according to their life experience while physicists answered according to a model. This an example where neither intuitive physics nor Newtonian physics can be labelled as wrong: they belong to different epistemologies.
5.9.2 Dissolving Newton in the historical continuum

What is meant by “pre-Newtonian?” Did Newton's work really mark a radically new beginning in the history of classical mechanics? Without denying the importance of his discoveries, can the history of mechanics be split between pre-Newtonian and post-Newtonian times? Or could it be seen as succession of refinements and major advances? Let's look at some of the facts recorded by Western history of science.

There is not a single “impetus theory.” Kozhevnikov and Hegarty (2001) track the concept of impetus back to Philoponus (Greek, 6th century). It was then developed further by Avicenna (11th century) and by di Marchia, Buridan, Saxony and Oresme (14th century). In Aristotelian physics, the force responsible for the motion of an object was always external to the object, but the impetus theory assumed the existence of an internal force acquired when the object is set in motion, and that keeps it moving. This force is called impetus (i.e. motive force). According to Buridan, impetus can dissipate due to the resistance of the medium in which the object is moving, or under the action of gravity. He stated that impetus = weight x velocity, bringing impetus even closer to the modern concept of momentum. He extended his definition to curvilinear impetus: the impetus of planets orbiting the sun. Buridan differentiated between the state of rest and the state of motion, while both cases are now described under the general concept of a velocity relative to a frame of reference.

Benedetti (16th century) claimed that a body which moves when an impetus has been impressed on it by any external force, has a natural tendency to move on a rectilinear path. Shortly after, Galileo's work on inclined planes led to the conclusion that a body moving on a
level surface will continue in the same direction at a constant speed unless disturbed.

Newton (1726/1972) stated: “Every body perseveres in its state of resting or of moving uniformly in a straight line, as far as it is not compelled to change that state by impressed forces” but his definition of inertia still needed to be refined. Coelho explains:

In Newton’s Principia there are two kinds of force: *vis insita*, which is inherent to bodies; and *vis impressa*, which is exerted upon a body. From the first kind, there is only one force: the force of inertia. Centrifugal force, pressure, impact are examples of impressed forces. The maintaining of the state of rest or of uniform and rectilinear motion is connected to the first kind of force, the force of inertia; accelerations are connected with the second one. Inherent forces to bodies will be rejected by d’Alembert as ‘metaphysical entities’, in 1743. Euler, in 1750, criticized ‘force of inertia’ as a contradictory expression, which, consequently, should be eliminated from mechanics (Coelho, 2007).

The famous equation \[ \Sigma \vec{F} = m \ddot{a} \], known as Newton's second law, was first written by Euler in his “Mechanica” (1750). In France, it is called the “fundamental equation of dynamics,” or “the theorem of the centre of inertia.” Such denominations erase the split between pre-Newtonian and post-Newtonian physics. It also answers the question “who invented it?” in a different way: the law is a property of matter, not Newton's invention.

The history of the impetus theory, and its slow morphing into the more refined

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18 Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus illud a viribus impressis cogitetur statum suum mutare.
concepts of inertia and momentum, can be seen as a continuum from a collection of everyday life observations to a generalization of concepts assembled in a consistent theory. The causes of impetus dissipation, i.e. the invisible forces of friction and gravity, are now defined as external forces that induce changes in momentum.

Inertia is now a property of objects, and momentum a conserved quantity, which can be further mathematically generalized as an invariant through translations in space. *The reality is the same, the felt quantities are the same, but the formalism has become more abstract, and more general.*

The culture of the PER community has its roots in the history of Western science, which places a few heroes like Newton and Galileo on pedestals, without questioning why Persian thinkers like Al Hazen, the father of geometrical optics, are absent. The contribution of tradesmen to scientific discoveries was also erased from the tales of the ruling class. If the dominant narrative about the history of Western science were re-written to include contributions that have been silenced, to explore spaces inside, and outside, the Aristotle/Newton dichotomy, it would be harder to classify students' intuitive knowledge as *pre-Newtonian;* it would change the power relationship between those who are fluent in Newtonian mechanics and those who cannot make sense of it.

**6. Understanding phenomenological primitives**

As I was exploring my environment with my senses, I soon came upon cognitive elements that could be best described as *phenomenological primitives,* also called *p-prims,* as described
by diSessa (1993).

## 6.1 What is a p-prim?

diSessa (1988) argues that intuitive physics is a *Knowledge in Pieces*, i.e. thousands of inarticulate explanatory primitives, abstracted from common situations, intuitive schemata describing “the way things are.” Such phenomenological primitives are what happens naturally in the world: no further explanation is necessary or possible. They are activated as a whole and highly depend on context. They provide a sense of understanding when evoked, but puzzlement when none are available (di Sessa et al., 2004). diSessa could explain a number of physics misconceptions in terms of p-prims (1993).

diSessa's collection of p-prims is a valuable tool for educators. However, some of the questions he used were not, in my view, testing p-prims since they involved some degree of abstraction. For example, he asked respondents to imagine space tracks passing next to the earth and to predict the motion of an harmonic oscillator travelling on the tracks. Such a thought experiment illustrated on paper is unlikely to trigger intuition drawn from an embodied experience of everyday life.
6.2 Searching for p-prims: the mad yo-yo experiment

In order to develop an understanding of p-prims, I decided to explore my own reactions to a puzzling physics problem. Rotational motion is an extremely challenging topic for first year physics students and they often have difficulties predicting the outcome of a classroom demonstration. I chose to explore the mad yo-yo experiment (a situation I had never taught), leave all equations aside, and focus on my intuitive reactions to the problem.

The mad yo-yo experiment is discussed by di Sessa (1993) in his description of the p-prim called force as a spinner (p. 130). He presented students with a figure similar to Fig. 6 and asked them to predict the motion of a rolling yo-yo.

![Diagram of a mad yo-yo](image)

Fig. 6: A mad yo-yo: The string is wrapped around the axle and being pulled horizontally to the right.

Di Sessa concludes:

As is true with most p-prims, context determines whether this or competing p-prims are applied, not articulable applicability conditions or general methods of conflict resolution. In the case of the yo-yo shown in [Fig. 6], most subjects will [...] predict that the yo-yo will spin counterclockwise and, hence, that it will roll of to the left. A few will
admit that, because the object is pulled to the right, it might move to the right […]. Almost no one who senses both possibilities has any way to decide which applies. […] There are, in general, no methods or more reliable knowledge elements [than p-prims] to decide conflicts. Pretending to be a novice proved surprisingly easy: even as a physics instructor, solving that problem using my common sense soon turned into a phenomenological nightmare.

6.2.1 My own exploration of the mad yo-yo

Here I am, facing Fig.6, unable to decide if the spool will go to the right or to the left. I never taught this problem. Being a physics teacher, I could tap into my collection of equations (my safety net!) to solve this problem. But I refuse to go that way. I want to give meaning to Fig. 6 with my senses, find a resonance between my somatic knowledge and the correct answer. I look at Fig. 6 and I feel suspended in a blank space, having to choose between two white doors, with no way of distinguishing between them.

My first reaction is to recall the feeling of holding a yo-yo. When I pull up, the yo-yo rolls down. But am I really pulling or is the yo-yo simply falling? I cannot recall exactly when and how much I pull on the string of a yo-yo. I seem to recall that when the yo-yo reaches its bottom position, I need to pull upward on the string to make the yo-yo move upward. But when the yo-yo is at the bottom, the string is not rolled around the axle any more, so may be this is not relevant to the present problem. I really need a yo-yo to do it, to build my awareness of the forces acting on it! Or do I? A yo-yo moves vertically, while this spool is rolling on a flat surface, so surely there is something different between the two: one is falling and the other one is
touching a table. I never made a yo-yo roll that way. Now the name yo-yo feels very confusing. May be I should search for another example, another life experience that my body can recall. This is my main problem: I cannot relate this mad yo-yo to any familiar context. A yo-yo is NOT a generic rolling object.

What about a carpet roll? It would roll to the left if pulled to the right. Same with a roll of wall paper, which can also stay roughly at the same spot while I am unrolling it. If I remember well, something depends on the angle at which I pull. However the wall paper is touching the ground, while the string in Fig. 6 is not, so may be this is not a good example.

What about a spool of string or a yarn of wool? I am pretty sure they would roll to the left: I chased them so often when my grand-ma was knitting. Damn! I cannot make sense of this mad yo-yo question.

Let's replace the yo-yo by a wheel. The image of a wheel opens three possibilities to my mind: moving to the right (like a carriage), to the left (like a yarn) or rolling at a given spot. It eases the frustration. I start to wonder if the problem has something to do with the friction between the wheel and the ground, or the shape of the spool. Since the question is on paper, I have no way to tell, as I would in real life. I feel deprived. If such information is irrelevant, I need to figure it out by myself, to see it, to feel it.

There is one thing I know for sure in my body: if the string were pinned to a wall and instead of exerting a pull on the string, I was pushing on the spool to the right, the spool would definitely roll to the right and the string would wrap around the axle. At least I can feel the type of rolling that is involved, as if I were the spool myself. Strangely, this brings images of my body being pulled by a ski lift. I can now reconnect with the yo-yo: if the yo-yo were at the end of its rolling course, it would feel the pull of the string that will make it move back to the right. So I can
now feel it is possible for the spool to move to the right, but I still cannot make sense of the present problem.

I try imagining the spool is now a gear and the floor has teeth. But this does not bring me anywhere either. Here I am, in the middle of a confusing landscape of p-prims, not knowing which way to go. I agree with diSessa that I have no way to decide which p-prim applies. The good news is that I realize I have a large collection of p-prims that are meaningful to me. In order to create a meaning full story out of them, I NEED TO PLAY WITH A SPOOL! And maybe build new p-prims.

I grab a spool of sewing thread in a cupboard (see picture 1). I pull on the thread. Well... it rolls to the left! I try different angles for the pull, and when the force is horizontal, as in Fig. 6, the spool does NOT roll! It slightly spins laterally. So there is something about friction happening here. I feel in my flesh that the shape of the object matters. I want to try with an object that has a thin axle.

I dig into my daughter's Meccano chest. There I find two large wheels, with a good grip, and a slim axle, I build the object shown in picture 2. Just by looking at the object, I suddenly find it easy to differentiate between the three options opened earlier by the mental picture of a wheel: this is going to operate like a vehicle. It will move to the right. I feel a deep sense of relief. I can now make sense of the problem, or I should say I can make peace between the physicist's view and my somatic knowledge. So I pull on the string, for the sake of feeling the peace deeper in my flesh, and, as expected, the wheels roll to the right.

But I also feel angry. I have initially been deprived of relevant information, been tricked by the word yo-yo and confused by the lack of context. I feel as if I have been trapped, or grilled. I would have enjoyed the journey if I had been to a real magic show. But here there are
issues of power hidden behind the mastery of knowledge: the scholar is in a position of judging
the learner. The mad yo-yo demo is intriguing and exciting, but it also deprives students from
their ownership of phenomenological knowledge. It is as if the physicists came from a different
universe with different physical laws, to challenge the students' worldview, as magicians do.
Magician create illusions, and most of us do not have the skills to reproduce their tricks. In the
case of the mad yo-yo, there is no illusion, and I could do the experiment myself, therefore I
feel I should be able to predict the outcome. If my predictions are wrong, it means I do not know
my own world, or that, for the time of a physics class, I am transported, and isolated, into a
physicist's universe.

I now go on Youtube to look for other examples. In physics textbooks, there is a
tendency to summarize all possible situations under one generic conceptual diagram, but I
noticed that I understand better by comparing a variety of real life situations. I find a video of
man who is able to make a mad yo-yo roll to the left, or to the right, or slide, depending on the
angle of the pulling force. I can then perceive that all three situations are plausible, and that the
outcome of the mad yo-yo experiment might depends on several parameters. Let's imagine that
instead of Fig.6, an educator would provide photographs like picture 1 and picture 2: the
students could imagine what the textures feel like. It would be interesting to study what
predictions students would make and how the results would differ from diSessa's.

![Picture 1](image1)

![Picture 2](image2)

Fig. 7a: Two mad yo-yos in context.
My children are just back from school and look at my two real life spools (see picture 1 and 2) while I hold the strings. I ask them to make a prediction about the motion of each rolling object. They do not even need to touch the objects to give the same answer simultaneously: the spool will roll to the left and the wheels to the right. Then I present them with Fig. 6. They come to an agreement that this case is “undecided.” A generic drawing does not tell as much as real life pictures.

6.2.2 Physics versus somatic knowledge

The equations of physics show that the motion of the spool depends only on the angle between the string and the table. If that angle is:

- less than a critical angle, the spool rolls to the right (ideally!),
- more than the critical angle, the spool rolls to the left.

The value of the critical angle depends only on the ratio between the radius of the axle and the radius of the spool. For the two objects I used:

- For the spool of sewing thread (picture 1), the critical angle is small, so it was really hard for me to experience a situation where the spool would be moving to the right, since for a small angle the spool was moving sideways.
- For the wheels (picture 2), the critical angle is close to 90 degrees, so the wheels move to the right for a wide varieties of orientations of the string.

In everyday life, the sewing thread has a high probability of rolling to the left and the wheels of rolling to the right. Most of my life experience with pulling on rolling objects is with
spools and yarns that are most likely to roll to the left, for example rolls of toilet paper, paper
towels and kitchen foil. My somatic knowledge was incomplete to predict the behaviour of a
mad yo-yo; before introducing equations, I would need to play with spools of different shapes
and feel where the critical angles are, i.e. focus my senses on fine details I was not initially
aware of.

6.2.3 The “mad yo-yo” magic show

J.C Sprott is an accomplished lecturer who ran a popular physics public show for 25
years. On his webpage about physics demonstrations (Sprott, 2012), his portrait evokes a
performing illusionist. In Physics demonstrations: a sourcebook for teachers of physics, Sprott
(2006) explains how to present this well-known demo to students:

You can effectively introduce this demonstration by asking the audience
whether they have ever had a yo-yo and showing them one. Point out that
your spool is like a yo-yo, and ask them to predict if it will move forward or
backward when you place it on the table and pull the string. Hold the string
at an angle where the result is ambiguous when asking the question.
Whichever way the majority of the audience votes, you can make the spool
go in the opposite direction by pulling the string at the appropriate angle.
[...] A change in angle so small the audience does not notice will reverse the
direction. The behaviour of the spool is quite mysterious, but point out this
is not a magic trick but rather a principle of physics.[...] You should use a
spool whose runners are far apart and have considerable friction. Wooden
spools are usually better [...].

Even though Sprott emphasizes that “this is not a magic trick,” his description could belong to a magician's handbook. By referring to a yo-yo, Sprott initially creates a contextual distortion: while a yo-yo moves vertically, the rolling spool is moving horizontally and is in contact with a table. The spool is definitely not used as a yo-yo in this demo. Sprott starts with an “ambiguous” value of the angle, willingly contradicts the audience's predictions and performs unnoticeable changes of the angle to produce a mysterious behaviour. Notice also the practical tips about the shape and texture of the spool to make the trick work; they describe well the spool we use in our department (See Fig. 7b).

![Spool Image]

Fig. 7b: A typical spool used for the mad yo-yo classroom demonstration.

6.2.4 Hidden messages

Unexpectedly, my sensory exploration of the mad yo-yo experiment made me reflect on the role played by “tricks” in physics education and how they can influence underlying power relationships. Magic is a recurrent theme in physics education. Sprott dresses up as a magician. Walker (1985), author of The Flying Circus of Physics, says that he is always amazed by the motion of gyroscopes: “Such motion is magic.” Magicians are a closed circle surrounded by
secrecy, their tricks are not to be revealed to the public. Is staging physics demonstrations as “tricks” an artifact of the culture of secrecy that initially prevailed in the British Royal Society, and nowadays in military science? Does understanding a physics trick mean one can enter an elite circle? During a classroom demonstration, the educator, like a magician, is the only person that has access to a somatic/sensual knowledge of the equipment. Providing each student with small spools has deep implications in terms of power relationships, knowledge sharing, knowledge ownership and the value given to somatic knowledge.

6.3 Accessing p-prims

The mad yo-yo problem made me aware of how much my thinking process relies on p-prims. I agree with diSessa (1993) that when faced with a new physics question, the body-mind searches in its collection of embodied p-prims to assemble the intuitive blocks that lead to an answer. The process by which those blocks come together is not fully understood:

I am uncertain whether words, symbols, and images of various types are the primary tools of thoughts or whether there are forms of thought antecedent to all of these – forms of thought that are essentially amodal... Vygotsky use to speak of 'thinking in pure meanings' (Sacks, 2005, p. 40).

If no adequate p-prims are available, the mind immediately searches for analog p-prims; however it selects them based on surface features that can be misleading.

Relevant p-prims allow the mind to off load part of the thinking process onto the body, in the same way we scribble on paper or draw forms with our hands when solving a problem. In
order to tap into students' intuitive knowledge of the physical world, it is essential to:

- give students the opportunity to access relevant p-prims,
- engage in activities to create p-prims relevant to physics education,
- create an environment where students develop a sensorial awareness of their p-prims and learn to verbalize them using the language of physics.

Intuitive physical knowledge is not based on a system of beliefs, nor on generalization. Students make theories on the fly (Cooke and Breedin, 1994), misconceptions are not single cognitive units (Hammer, 2000), concepts assemble in complex clusters of related ideas (Smith, di Sessa & Roschelle, 1993). P-prims are context dependent and cannot be generalized into a single theory, nor be easily categorized. They form a complex web, with different scales and layers, that could change over time. An educator cannot obtain a list of the typical p-prims of a generic student, but can provide hands-on activities so that students can enrich their embodied knowledge on an individual basis.

7. Representing the lived world

Physics means “the study of nature,” mechanics has many practical applications, forces and energy are entities in which we are bathed every second of our lives. How is it possible that so many students complain physics is not related to real life? Why is it so hard to understand what physicists are telling us about the world that surrounds us? In this section, I explore several elements that can impair communication because they prevent accessing p-prims: context, implicit assumptions, language, diagrammatic representations, symbolic representations, more-
than-representational physical quantities, metaphors and storyline. But I will first shortly review how equations gradually replaced sentences in the physics language.

### 7.1 The mathematization of nature

Physicists used to be called *philosophers of nature*. Originally, *natural philosophy* was the study of the cycles of nature, e.g. the seasons and the cycle of life. Aristotle$^{19}$ studied physics as well as biology, politics, poetry, music and philosophy; he explained the world using words. A century later, the prolific mathematician and engineer Archimedes studied floating objects in a more numerical fashion: He carried measurements and summarized his observations into a single principle.

In the 1600s, Galileo initiated the *geometrization of nature* by looking for geometrical patterns in the lived world. He thought mathematics gave an insight inaccessible to common sense. In Galileo's time, two major observing instruments were invented: the telescope and the microscope, extending the capacities of the human eye to pierce into the heavens and the microcosm. Quantitative measurements of the natural world acquired more and more credit, even if Galileo's astronomical discoveries were reported in the form of drawings of the Sun and planets. Almost at the same time, Johannes Kepler was interested in the hexagonal shape of snowflakes and envisioned the orbits of the planets as nested solids. It was a time when chemists still characterized compounds by tasting them, a practice that would be abandoned a century later in favour of precision scales: here too, qualities slowly became replaced by quantities.

$^{19}$ Physics textbooks used in North America are silent about the study of the laws of nature made other civilizations.
Isaac Newton belonged to the next generation: he was born the year Galileo died. In his "Mathematical Principles of Natural Philosophy," he introduced the *mechanization of nature*: the universe was God's giant clockwork. Following Newton's footsteps, the French scientist d'Alembert claimed it was time to abandon literary physics. Nevertheless, two hundred years later, Lord Kelvin still considered himself a *natural philosopher* who defined *matter* as “that which can be perceived by the senses...” (Kelvin and Guthrie Tait, 1912, p. 219). Poincaré argued that the invention of Euclidian geometry and cartesian coordinates was informed by our sensual perception of the world (Poincare, 1902/1968, pp. 78-87).

What made numbers so appealing? They allow scientists to make predictions. There is no thrill like predicting the outcome of an experiment, and be later proven correct by novel observations. At that very instant, physics feels like a dialogue with nature, in her secret encoded language: mathematics.

Today, we live in the age of the triumph of form. In mathematics, physics, music, the arts, and the social sciences, human knowledge and its progress seem to have been reduced in startling and powerful ways to a matter of essential formal structures and transformations (Fauconnier & Turner, 2002). The spectacular success of form leads us to see forms as carrying far more meaning than they actually do (p. 7). *Form is not substance.*

### 7.2 Context matters

While reading research articles on misconceptions about parabolic motion, I initially found respondents' answer extremely puzzling, and counter-intuitive for a physics instructor. I
therefore decided to learn tennis and observe what knowledge of free fall I would develop throw this activity. I then imagined what it would look like playing tennis inside a physics textbook.

7.2.1 Playing tennis on a court

I visited a tennis court a dozen times in the course of two months and played with my husband who had only played ping-pong before. Each game lasted about one hour. In order to achieve some progress, I had to prioritize the large quantity of new information I was dealing with: the size of the court, the height of the net, the length and inclination of my racket, the influence of the wind, the sun blinding my eyes now and then, when to catch the ball (just after it rebounds or just before it rebounds for the second time?), how to position my body before hitting the ball, dealing with the slippery texture of the court after a Spring shower, and before all, the psychology of my opponent. In the beginning, there were many parameters I could not master, and therefore had a very poor control of where I was throwing the ball. However, after a few games, things started to fall into place; not one parameter after the other, but all at once, in a synchronized fashion, or so it felt. Every time I threw the ball where I wanted to, I felt a wave of pleasure, and my brain registered this success as something to reproduce, in the form of a single image, and certainly not a as chart of numbers like: $x_0 = 2.55 \, m$, $y_0 = 1.21 \, m$, $v_x = 2.34 \, m/s$, $v_y = 1.23 \, m/s$. I became more and more able to anticipate the motion of my opponent's ball, without relying on equations nor calculations.

The most fascinating part of the learning is that the analysis of the hundreds of trials was happening in my unconscious. I was amazed by the continuous and intense focus required by the game. I was not relying at all on my analytical brain, but instead had to stay in a constant reptilian mode of awareness that I would characterize as “survival mode.” We were not playing
for points, so pleasure came not from scoring, but from forcing my mind to stay in an instinctive mode that relied on the sharpness of my sight and somatic senses. My playing was stunningly clumsy, even after several hours of practice. However, through intense training, some players can train their bodies to reach an incredible level of precision: their mind/body can eventually master the numerous parameters involved in playing tennis, and therefore develop a knowledge of the game too complex to be predicted by a mathematical model.

If I were asked to draw the path of a tennis ball, I would draw a collection of lines, some straight (for smashes and services), some curved like a mountain top, some curved like a highway bend, all as seen from a player's standpoint. Unlike physics textbook, the path of the ball through the air was not my primary focus: what mattered was the position of the ball just before I hit it, and where it fell into my opponent's camp.

### 7.2.2 Playing tennis in a textbook

What stories of tennis are told in physics textbooks? What would a game look like through the lens of the equations we teach our students?

The physicist actually never plays tennis: he is a spectator. He always occupies one of the preferred seats, aligned with the net. The sides of the court are decorated with giant wall papers showing graduated axes called $x$ and $y$. The $y$-axis, that so often lays down on the floor, is now upright.

The physicist sits in the upper row, to get a good overview of the path of the ball. He only watches tennis matches when there is no wind. Even the presence of air is neglected, so players cannot give any sideways effect to the ball. The physicist focuses exclusively on the path
of the ball: his goal is to find the mathematical equation that best describes the observed curve. Physics students are often asked to start studying the motion only \textit{once the ball has left the racket} and stop \textit{just before the ball hits the ground}. The idea is to be able to model reality with a single equation that can describe all the possible paths taken by the ball: a parabola. To a physicist, a smashed ball follows a flatten parabola, and a ball thrown upright follows a squeezed parabola.

\textbf{7.2.3 The vertical cliff experiment}

There are other examples where people's intuitions do not agree with physicists' predictions (McCloskey, 1983b; Cooke & Breedin, 1994). For example, draw a table with a rolling ball on it and ask someone to predict the motion of the ball as it falls off the table. When I do this experiment, many students spontaneously ask “is the ball moving fast or slow?” “is the ball heavy or light?” Depending on my answers, they meaningfully predict the position of the ball's impact on the floor, then carelessly draw a line that joins the table's edge to the point of impact. However, if the question were part of a physics test, students would be expected to draw a portion of a parabola to obtain full mark, even if dealing with a bowling ball rolling very slowly before falling off the table. Students and teachers do not always focus on the same elements of the lived world and can both be correct in their own terms.

\textbf{7.3 Implicit assumptions}

Clement (1982) asked first semester engineering students to draw the forces acting on a coin tossed in the air. These students had all taken high school physics, however 88\% gave the
incorrect answer that there are two forces acting on the coin: the force from the hand and the force of gravity. Clement's conclusion is that the preconception “motion-implies-a-force” was involved. My conclusion about his observations is that the sentences “a coin is tossed in the air” or “a girl throws a ball” exemplify the meaning gap between physics teachers and students. In this exploration, I juxtapose a personal felt story of throwing a ball in a park and a textbook definition of projectile motion.

7.3.1 My story: “Drawing with the Earth.”

Here I am, in the park, standing, with this compact leather ball in my hand, willing to offer it to my planet's gravity. I could let it go, drop it, and it will fall down, hardly showing any imprint of my intentions. Or I could throw it, decide where and how fast it will go. It is up to me. I firmly grab the ball with my right hand, fold my arm so the ball reaches above my right shoulder, then quickly stretch my arm to throw the ball. I feel a slight pain in my muscles as the ball leaves my hand, like a diffuse sting deep inside my arm muscles. After the ball has left my hand, it shows the imprint of my muscles: they/I decide how fast the ball should go, and in which direction.

I now bring my awareness back to my body, and to the park. I can hear a fountain gurgling, to my left, as a parabolic stream of water falls into the basin. The thin aquatic line looks like a sketch drawn by the Earth's gravitational field. As many other mathematical curves, parabolas are elegant, intriguing objects, that can inspire artists (See Fig. 8).

Once I throw the ball, it draws a parabola in space, a collective art piece made by the ball, the Earth, and my body. Among the huge collection of parabolas that we could draw together, I can choose the parabola that suits my purpose. If I want to throw the ball into the
fountain basin, my body will pick up a parabola that works, without my brain having to use the equation
\[ y = x \tan(\theta) - \frac{x^2}{2} \frac{g}{v_0^2 \cos^2 \theta} \]

Fig. 8: Chaotic parabolas,
by H.M. Gale Shapero, a.k.a "Pyracantha."  

7.3.2 A textbook story: “Projectile Motion.”

In physics, throwing an object falls under the umbrella of a chapter called “projectile motion.”

Explanations about projectile motion are often rich in military vocabulary. According to the Merriam-Webster dictionary, a projectile is:

1: a body projected by external force and continuing in motion by its own inertia; especially: a missile for a weapon (as a firearm)

2: a self-propelling weapon (as a rocket)

The website “The Physics Classroom” introduces projectiles as follows:

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20 Source: [http://www.pyracantha.com/cgi-bin/blosxom.cgi/2006/05/24#EB268NewArt934s](http://www.pyracantha.com/cgi-bin/blosxom.cgi/2006/05/24#EB268NewArt934s). With permission from the artist.
22 [www.physicsclassroom.com/class/vectors/u3l2a.cfm](http://www.physicsclassroom.com/class/vectors/u3l2a.cfm)
...A projectile is any object that once projected or dropped continues in motion by its own inertia and is influenced only by the downward force of gravity...

Thus, the free-body diagram of a projectile would show a single force acting downwards and labeled force of gravity.

Beyond the topic of misconceptions, this outdoor exploration of projectile motion made me realize how I became accustomed to a physics language inspired by the needs of the military and to textbook problems about bullets, rockets, cannon balls and arrows. Projectile motion stories found in physics textbooks do not acknowledge the aesthetic of my worldview, my sense of connection with the Earth, nor the presence of my body. Without changing anything to the equations of physics, it must be possible to re-story physics to welcome different voices.

7.3.3 Discussion

According to my felt experience, it is hard to believe the force exerted by my hand has no long lasting effect on the ball that I throw. Despite claiming that a projectile is under the sole influence of gravity, physicists do acknowledge that my hand leaves an imprint on the ball. They call it initial velocity. Initial because physicists start studying the ball after it left my hand: they keep my body out of the picture. Throwing a ball can be decomposed into two separate movies: a very short movie showing my muscles acting on the ball, that could be used by a human kinetics teacher; a second movie starting after the ball has left my hand, that could be used by a physics teacher. My experience in the classroom is that this way of slicing the world is often not meaningful to students. Some students draw the force exerted by the hand not because they have
a misconception but because they are telling the whole physical story. I therefore spend class

time on the transition between the *initial kick* (on a soccer ball), the *initial push* (on a sleigh), the

*initial throw* (of a ball), and *initial velocity*. The transition between a short lived force, expressed

in Newtons, and a speed, expressed in meters per second, is far from being trivial, but is often

overlooked at the introductory level.

In Clement’s study (1982), students could have been misled by the question. They were

asked to draw the forces acting on “a coin tossed in the air.” Such a phrasing can refer to the

tossing itself. In this case, students are completely correct. But Clement makes the implicit

assumption that the coin has already left the hand, which is a common assumption in his

community of practice. For example, in Cutnell and Johnson (2012, figure 2.15, p. 44), the

legend says (see Fig. 9): “...a referee tosses a coin upward with an initial velocity of \( v_0 = +

5.00 \text{ m/s} \)” But the diagram shows the hand *before* it tosses the coin, suggesting the hand is about

to exert an upward force on the coin; nevertheless the authors expect people to assume that only

the force of gravity is acting on the coin. Such a wording can create confusion: An object that

*was once* thrown is a projectile but an object that *is being* thrown is not a projectile.

![Diagram](image)

**Fig. 9:** In this diagram, the force exerted by the hand on the coin is replaced by its consequence: the initial velocity of the coin *after* it is thrown. (From Cutnell and Johnson, 2012, figure 2.15, p. 44).
In physics textbooks, text often works under implicit assumptions depending on the chapter in which it is found. For example, in Tipler and Mosca (2007), on p. 497 we can read that: “...The speed of a sound from a car horn depends only on the properties of air and not on the motion of the car,” however in the paragraph about the Doppler Effect, we read: “The sound you hear from a car horn is different if the car is moving toward or way from you.” Usually, in a static equilibrium chapter, “at rest” means “not moving and not about to move,” however in the Newton's Second Law chapter, it means “not moving and about to move.”

Word problems also involve implicit assumptions. Here is an example: “A boy who is standing at the top of a well drops a stone into the well. The stone hits the surface of the water 1.80 s after the stone is dropped. What is the position of the surface of the water from the top of the well?” The question assumes that the stone is compact, not flat, and therefore air drag can be neglected. It also makes assumptions about the shape of the well, since the only thing that one can calculate is the distance between the water and the hand. Is this a shallow well? Is the boy laying down on the grass? Is this taking place in France where wells have a brick rim? Or is the hand a meter above the top of the well?

A successful student is the one who adopts the practices of the community, including all its implicit assumptions, not necessarily someone who gives meaning to physical principles.

7.4 Language

Today, scientific knowledge is shrouded in highly technical language (Merchant, 2001). New vocabulary can be overwhelming. For example, Tipler and Mosca (2007) open chapter one
with two short paragraphs in which the following twelve words are being used without having been previously defined or illustrated: motion, position, direction, descriptor, displacement, velocity, acceleration, force, mass, mechanics, kinematics and dynamics. A typical introduction to electricity include 18 new words: electric current, voltage, voltmeter, volts, potential difference, resistors, resistance, equivalent resistance, electro-motive-force, amps, ammeter, associations in series and in parallel, ohms, ohm's law, load, terminal, cells of battery. In the college where I teach, we expect students to give meaning to those words in one week (six hours of instruction).

Language can be problematic when dealing with felt quantities/qualities for which we have a poor vocabulary: the language we use in the physics classroom abstracts, “makes the things of the world insubstantial, it alienates us from sensation” (Connor, 2005). For example, we can feel moment of inertia with our hands, but the meaning conveyed by the flesh is very different than a definition in words (“rotational inertia describes the relationship between angular momentum and angular velocity”) or in symbols (\[ I = \int_0^M r^2 \, dm \]).

Finally, words and symbols can have several meanings:

- A "scale" is: a balance to weigh an object; a tool to measure the magnitude of a force; a ratio used to draw a diagram.
- \( W \) stands for work, weight and Watts.
- "Gravity" can be: the force of gravity; the acceleration due to gravity; the field of gravity; the gravitational constant; Newton's theory.
• Even the “=” sign can have various meanings. \( \vec{F} = m \vec{a} \) looks very much like
\[ \vec{F}_g = m \vec{g}, \]
however we expect students to perceive them as fundamentally different.

### 7.5 Diagrams and p-prims

Diagrams represent a generic situation, a generalized and decontextualized version of the real world. When exploring the mad yo-yo, the drawing of a generic spool with a middle size axle forbade me from accessing relevant p-prims, while real life examples of a thin axle and a thick axle led me to the answer: the relative size of the axle was the key variable. The repeated use of block in physics textbooks is a form of decontextualization. They should be replaced by real life objects: Humans rarely deal with “blocks sliding on inclined planes,” unless they work for a moving company.

Paterson (2007, p 68) claims that by representing the world in diagrams, we collapse the multi-sensory and multidimensional experience into a two dimensional abstracted form (p. 68), which leads to a sense of detachment from the world (p. 76). P-prims are highly context dependent. Representing a physical situation on a diagram removes a large part of the context, and can therefore lead students to pick inadequate p-prims. Surface, volume, density and weight are not optical phenomena. Man first learned about them between his finger and the hollow of his palm; he does not measure space with his eyes but with his hands and feet (p. 76). A diagram is a 2-D version of reality that removes information about shapes and volumes. It suppresses access to felt texture and distribution of mass. In a 2D diagram drawn in a textbook, the process of choosing which quantities and qualities of the real world are relevant to solving a problem,
and how they should be graphically abstracted, is made by teachers, when it could be done by the learner.

Abstract or unrealistic tasks may fail to tap knowledge and reasoning abilities that are routinely used in realistic situations (McCloskey & Kohl, 1983). Here are examples of meaningless diagrams found in a textbook. Fig. 10 shows a man standing on a scale placed on a skateboard, itself rolling down an inclined plane. How can a student rely on her/his intuition when, in real life, the man should be falling off? Fig. 11 shows a cube on a curved slope. The teacher expects students to study the sliding motion of the cube, however this cube should be rolling down the slope.

Fig. 10: From Tipler & Mosca (2007). Fig. 11: From Tipler & Mosca (2007).

Some diagrams are meaningless because they represent a useless apparatus, as for example the two blocks sliding on each other in Fig. 12. What is the point of calculating their acceleration since the upper block will soon fall off? What is the use of that machine? Moreover, the text says that all surfaces are frictionless and the pulley is both frictionless and massless. How can a
student's intuitive knowledge of the physical world be welcome in a context of unrealistic surfaces and pulleys?

![Figure 4-68 Problem 80](image)

Fig. 12: From Tipler & Mosca (2007).

A horse can even be abstracted into a point, because horses, humans and galaxies can all be considered to be “particles:”

In a horse race, the winner is the horse whose nose first crosses the finish line. One could argue that all that really matters during the race is the motion of that single point on the horse, and that the size, shape, and motion of the rest of the horse is unimportant. […] An object that can be represented in this idealized manner is called a particle. […] For example, we can consider car, trains, and rockets particles. Earth and other planets can also be thought of a particle as they move around the Sun. Even people and galaxies can be treated as particles (Tipler & Mosca, 2007).

How easy it is for a student to accept that the size, shape and motion of a racing horse do not matter or that they exist in this world as mere particles? There might be room here to discuss the limitations of physical models.
Static diagrams are especially problematic when trying to represent motion. People may
demonstrate a greater level of sophistication when judging on-going events than in paper-and-
pencil activities (Shanon, 1976). Kaiser and Proffitt (1984) found that respondents performed
much more poorly when asked to make judgment about static images and suggest people may
possess a perceptual sensitivity to natural dynamism. A drawing of a moving car is, in itself, an
abstraction. With the multimedia equipments available to us, we can represent moving objects
using movies shot by students, and let the students replay them at will. By relying on 2D
diagrams, we are favoring a population of students that is comfortable with a
flat/fossilized/visual representation of the world. This was a necessary skill when teaching was
happening solely on blackboards and notebooks. Today, we can play with simulations, replay
movies, draw on them, collect data from them.

7.6 Disembodied symbols

In its written form, physics abstracts the lived world by means of mathematical symbols,
but the correspondence between symbols and reality can be questioned. Lakoff and Johnson
write that a “symbol-system realism maximizes the chasm between mind and world, since the
abstract entity of the symbol shares nothing with anything in the world, not even physical
reality...In symbol-system realism, the mind-world gap is not only maximal, but maximally
arbitrary...” (1999, p. 95). In physics, symbols carry stories that extend beyond the scope of a
single letter. For example, $P$ stands for pressure, but might have a different meaning for a sperm
whale diving 1000 meters deep, a pioneer digging a shallow well, a doctor measuring blood
pressure and a breastfeeding mother. The symbol $P$ cannot bloom without a context. Diderot (1746/1961, p. 216) complained that “the mathematization of physics tends to strip concepts of all that is tangible.”

Physics teaching often focuses on the manipulation of symbols, as if they were intrinsically meaningful, however physics is primarily about natural phenomena. Faraday defined himself as a philosopher of nature who had no mathematical training and had never written an equation to carry or interpret experiments (Mowus, 1992), but he nevertheless made breakthroughs in electromagnetism and electrochemistry and was arguably one of the best experimentalists in the history of science.

Mathematical symbols can be manipulated without being given any meaning. We could rewrite Searle's famous *Chinese room experiment* (1980) with a physics student in mind: Consider a student in a room containing baskets full of physics symbols that he does not understand. He is also given a rule book in English for matching mathematical symbols with other mathematical symbols. The rules identify the symbols by their shape. A teacher outside the classroom hands in small bunches of symbols to the student, who manipulates them according to the rules, then hands back an "answer". Even if all the student's answers are correct, it does not guarantee cognition, perception or understanding.

Mathematical symbols are only a partial, and biased, representation of the lived world; the mathematization of nature is a form of subjectivity. Physics education should refocus on the complex and messy stories told by the world we live in.
7.7 More-than-representational quantities/qualities

Perceptual-motor knowledge is distinct from verbal-cognitive concepts and follows different development courses (Krist, Fieberg & Wilkening, 1993); this implicit knowledge may be cognitively impenetrable. For example, Kozhevnikov and Hegarty (2001) showed that people develop a perceptual knowledge about motion that is much more accurate than their conscious verbal-cognitive concepts. In the course of my explorations, I came across physical quantities and/or qualities that were better expressed without sentences, as if their meaning was brimming over words. Here are two examples.

**Tension in a string**

I taught the tension force to a nine year old using elastic bands. She first could not tell if the tension in the middle of a taut string is zero or the sum of the tension forces at the two ends. When I added elastic bands at the ends of the string, she could find the answer spontaneously, before observing the phenomenon: the tension is the same at each point of the string. An answer that would have initially been counterintuitive became sensical. As I was holding the equipment myself, there was a felt quality to the tension force that I am unable to describe in words, and that was not encompassed by the symbol \( \vec{T} \) found in textbooks. The elastic bands had brought the string into another domain where the string was no more a solid object, but a field of tiny elastic elements.

**Electric circuits**

When I was a student, I was taught electricity in a very formal and mathematical fashion and never developed a felt meaning for voltage, resistance or capacitors. By playing several
times with computer simulations of electric circuits, I developed my own felt stories, beyond words. For the purpose of this thesis, I could however try to give a remote image of what they now feel like. If I look closely at a resistor, I am an electron and *resistance* means thick bushes through which I make my way with a machete: The larger the ohms, the denser the shrubs. If I look at the overall electrical circuit, current is a flow and electrons are cars driving backward on a looping highway. Voltage across a resistor feels like a person dragging steel balls in thick sticky mud. Associations of light bulbs are protagonists living together with communal rules:

- In series, the bulbs must share the voltage, with the larger resistance getting the larger share, therefore being brighter.

- In parallel, the bulbs must share the current, with the one offering the least resistance getting the larger share, therefore being brighter.

Assembling those felt stories like building blocks allows me to solve problems more intuitively, and in some cases, even without any calculations. I cannot tell how the assemblage operates. The diagram of the electrical circuit becomes animated, with different regions developing a different behaviour, until the whole circuit feels coherent. Playing with simulations was like learning the rules of a role playing game, immersing in a foreign world. After several hours of play, the rules translated into felt stories by anchoring onto existing p-prims like *walking in bushes and dragging balls* or reviving memories (e.g. *cars on a highway*).

### 7.8 We need shared metaphors

Martin-Blas et al. (2010) claim that the common sense misconceptions the most difficult
to overcome have a strong metaphorical basis. Which metaphors should be banned from the classroom? What are the consequences of such decisions in terms of students' ability to verbalize their understanding? Let's take the example of the concept of energy. One could expect that, in physics, every quantity is unequivocally defined, however a careful look shows no strong consensus between scientists, educators and students.

The concept of energy underwent several mutations in the last two hundred years; even today experts disagree about its nature. In the 18th century, energy was related to the vitalist concept of life force (vis viva). In 1807, Thomas Young made the first scientific use of energy to refer to what we now call kinetic energy (Trumper, 1990). The concept only became meaningful in the middle of the 19th century through the establishment of the principle of conservation of energy by Mayer and Joule (Arons, 1999). In special relativity, energy can be transformed into matter \(E = mc^2\). In thermodynamics, there is a distinction between energy per se and modes of energy transfer (heat and work). In quantum mechanics, energy cannot be viewed as a substance since it is not localized, therefore Kaper and Goedhart (2002) propose to “speak of classical mechanics and quantum mechanics as two different languages”, i.e. they accept that in physics, the meaning of a word can be context dependent. To others, energy is not even a fundamental concept: conservation of energy is simply a consequence of the principle of least action (Van Waerbeke, 2012). Moreover, a biologist or a chemist's definition of energy is unlikely to agree with that of a physicist.

Some educators teach that energy cannot be created nor destroyed, but it can be transformed from one form to another, however Warren (1986) argues that energy should not be
introduced to students as a tangible object because it is a mathematical abstraction which *can only be experienced by disciplined thinking*. The verb “transform” has even been banned by some curriculum authorities (Kaper & Goedhart, 2002). This controversy between *materialists* and *conceptualists* educators underlines the split between giving priority to meaning or to orthodoxy. *Materialists* (Duit, 1981, 1987; Kaper & Goedhart, 2002) are satisfied with a quasi-material conception of energy because it suits classical mechanics and *it is meaningful* to many students. While *conceptualists* (Warren, 1982) view *energy* as an abstract and advanced concept that “should be taught correctly to those students who are able to understand it” (Warren, 1983).

Hewitt (2002, p. 104) claims *energy* “is very difficult to define satisfactorily.” Duit (1984) speaks of a very abstract quantity balancing processes, in nature and in technology while Raphoto (2008) avoids the issue by saying “it is more important to understand how energy behaves than to state what it is.” In a study of 12 high school textbooks, Lehrman (1973) found that 4 did not offer any definition of *energy* and the other 8 defined *energy* “as the ability to do work.” Hicks (1983) found that same definition in 17 of 30 college textbooks, but this definition is criticized by Duit (1984) because it does not describe heat and light.

The meanings and conceptions of *energy* of school age students is well documented. Socially acquired meanings of *energy* are situation bound (“exercise builds up energy” and “exercise uses up your energy”) (Solomon, 1983). Since motion eventually stops and living things eventually die, students do not see *energy* as being conserved. In everyday language, *conservation of energy* means being careful not to waste energy while in physics it means that the energy of a close system is constant. Watts (1983) interviewed grade 10 to 12 students and
summarized his findings into seven frameworks:

1. Energy is something human beings have (e.g. a person pushing a box).
2. Energy is a source of force stored in certain objects (e.g. a battery).
3. Energy is a dormant ingredient that needs a trigger to be released (e.g. eating food).
4. Energy is identified by an overt display of activity (people running, telephone ringing).
5. Energy is a short lived byproduct.
6. Energy is a kind of fuel and is associated with technical appliances.
7. Energy flows, it can be stored, transported, transferred.

A study by Kruger (1990) amongst primary teachers showed that they hold energy conceptions similar to students.

The example of the energy concept underlines the need to develop shared meanings in the classroom. If we follow conceptualists like Warren, we are at risk of forbidding the use of all meaningful metaphors because of their lack of scientific rigour: the only language left are abstract mathematical symbols isolated from the real world. Using mostly equation means communicating with a very limited number of students, i.e. adopting an elitist approach to teaching. At the introductory level, I advocate for a more encompassing acceptance of students' cultural and embodied metaphors, followed by a refinement of definitions at a higher level. For example, substance based models are powerful intuitive representations for heat, electricity and light among novices. Surprisingly, they are also used by experts: They know this model to be remote from current physics knowledge, but they use it as a good approximation in informal contexts to maintain an intuitive grasp on the topic, and abandon it when the need arises (Riener
et al., 2000). I agree with Riener et al. that representing physics concepts through nonmaterialistic representations from the start might strip students of all the tools and experience patterns they have constructed to make sense of things.

7.9 Story line

Through my investigations, I realized that textbooks problems present disjointed slices of real life. When I use a salad spinner, the basket goes through four phases: it starts from rest, goes through a short acceleration phase, then a long phase at a constant speed, and then decelerates. The exact same four stages are present when I use my washing machine, when I walk, when I push a cardboard box on the floor, when I am in a car on the highway, when I take an elevator, when I paddle in a canoe. However in a physics textbook, static equilibrium, Newton's first law and Newton's second law are hardly ever part of the same problem, not even the same chapter. We need to rewrite physics stories according to their real life dynamical context in order to restore their phenomenological consistency.

The misconception “force-is-a-mover” is one of the most documented, as well as a well known issue for teachers. When students are presented with a diagram of a moving object, let's say a bowling ball, many of them draw an arrow in the direction of the motion: the “force of motion.” After discussing with them, I realized that many assumed the ball started from rest, and therefore a force initiated the motion: they wanted to tell the whole story, while I expected them to slice the story into set-in-motion/rolling/hitting the pins. I decided that before introducing dynamics, students should learn how to slice real life examples the physics way (see appendices: Newton's Second law worksheet). Since then, I have never seen the “force of motion”
misconception in any of the assessments I marked.

8. A softer approach to physics storytelling

After reviewing the literature about my community's view on misconceptions, and exploring how physics texts can fail to speak to the body, I was ready to write physics stories that welcome my physical epistemology. In this section, I explore what I call soft physics stories, in opposition to the expression hard science. Part of the language I use was developed by communities of learners: I share the ownership of this work with several generations of high school and university students, with my children, and with visitors of the Cité de l'Espace where I worked in science outreach. Those stories are not meant to replace but to complement traditional textbooks. I explore a few topics of the curriculum: forces, Newton's Laws of motion, rotational motion and fictitious forces.

8.1 The quality of forces

In a physics class, forces are symbolized by a vector arrow, and much emphasis is put on their collective properties: direction, magnitude, components. For this first story, I went for a walk in Spirit Park (Vancouver, B.C.) to search for the felt qualities of forces.

The rain forest's presence whispers the silent stories of the past, tales of ubiquitous growth and impermanence. A message of hope and trust permeates the moisture, gently cooling down my skin. Several light rays pierce through the leaves, warming up my left cheek; a gift from the Sun's nuclear fusion. Once, primordial hydrogen atoms collided in its core, forming
tiny pockets of energy. It took those photons a million year to find their way out of the dense plasma, emerging from the Sun only eight minutes ago. They travelled a hundred and fifty million kilometres across the vacuum of the solar system to reach my body, the surrounding ferns, and the tiny spider crawling on my shoulder.

We are all made of ashes from stars that died more than five billion years ago; our decomposed bodies will be recycled into new life forms. After Earth was born, and gifted with liquid water, nature experimented with chemistry and biology for several billion years. Everyday, I feel blessed she gave me bio-tech devices that are highly sensitive, non-polluting, long lasting: my skin, my eyes, my ears, my tongue, my nose, my sense of balance, so that I can survive as well as appreciate her beauty. As the forest breathes out, I breath in. In every rain paddle standing in the peat, there are molecules of water from a dinosaur's bladder, which circled the skies and rivers for seventy million years, and might one day journey inside a spinach leave through my gut. What does it feels like living in a space station? I would fear cracks in the windows, and breakdowns of the water system. Would I enjoy floating around like a foetus deprived of amniotic liquid, my bones and muscles weakening every day? I could watch Earth floating in the deaf coldness of space, imagine her vulnerability, but I would rather admire her from within, with all my senses, and feel her strength.

**Gravity**

I grew as a two-legged being thanks to the earth's invisible, everywhere felt gravity. All my knowledge of balance I learned through her teachings. I can hold a heavy object in each hand and transform myself into a scale. Gravity guides raindrops towards the plants; she holds the Moon close to the Earth, providing rhythm to intertidal ecosystems. Newton described my "heaviness" as a pull from the Earth. The further away I move from the Earth's core, the less I
feel her pull; when I hike up a mountain, the interaction with Earth weakens, but the change is too small to be noticed by my senses. If I could take a walk on planet Mars, the pull would be 2.5 times weaker, and on the Moon, six time weaker. I might enjoy feeling so light, but those are scary places: no air, running water nor food, nothing of the unbelievably complex and sturdy ecosystem we enjoy of Earth, only millions of square kilometres of dead rock and dust. Some dream of settling on Mars, of engineering the planet to make it habitable: they call this terraforming. They believe that with hundreds of thousands of years of efforts, they could recreate an ecosystem that would be a pale copy of the one that was given to us. Meanwhile, millions of humans spoil their own land, or the land down the river.

Normal forces

As I stand on the rainforest's topsoil, I wonder if it can feel my weight. How do the bacteria, fungi, protozoa, insects, spiders, mites, centipedes, earthworms, react to my presence? As I step onto a wooden stick, I hear it cracking, and feel it breaking under my sole: its fibres were not strong enough to hold my weight. Sorry! I climb on a low branch, wet and mossy. It goes down with a shriek, then finds a balance point where it can hold my body. Our contact feels top-down, elastic. I feel the wood fibres reacting to my presence, stretching, bending; I could play trampoline if I wasn't afraid of breaking the living branch. In physics, the force exerted by the wood fibres on my feet is called the normal force, normal meaning that the force is acting perpendicular to the branch. In my grand-mother's living room, there was an old oak buffet that hold a massive earthen vase from Morocco. How is it that the wood fibres never wore out over a hundred years of use? However, not all surfaces could hold my weight as strongly as wood. I once walked on thin ice on Pyramid lake, in Jasper National Park. Had I carried a heavy backpack, the ice could have cracked, or so I feared. I could never trust frozen
water. I would never dared to jump on it.

_Friction_

Walking in greasy mud feels different from walking on dry rocks, or river gravel; my body knows how to adapt to changes in grip, and even how to transition from hiking boots to flip-flops. My hands do not seem to know as much, they are more into enjoying the softness of velvet, the warmth of my cat's fur or the crispy roughness of a French baguette. The soles of my hiking boots have teeth ready to bite into the peat, so that my feet can create a sturdy contact with the ground and push me forward. Is this what friction is about? Is this why the anti-skid strips on the stairs of my deck look like sand paper? I search the forest floor for a heavy coarse stone. I find one, clean the dead leaves, and place it on the tender part of my forearm, then I slowly tilt my arm, up to a point where the stone is about to slide. It clings to my skin, it feels like tiny piercing stings. A physicist would label this feeling as _static friction_. Static because the stone does not move. I now rub the stone against my skin with my other hand: it burns because of _kinetic friction_ (from the Greek _kinema_, meaning motion). It reminds me of the day I salvaged an abandoned night stand: as I was sanding the top to remove old paint, the sand paper became so hot that it literary burnt the skin of my index finger.

A squirrel grunts in the cedar tree besides me. As soon as I look at him, he runs away, and hides below a branch. How can he hold onto the bark? Nature gave me twenty-six bones and one hundred ligaments to make my foot able to take advantage of any type of ground. Geckos and snails can hold upside down, even on smooth surfaces. A gecko's feet produce an adhesive that disengages easily without leaving any sticky residue on the surface. It inspired the invention of Geckskin. The size of an index card of this material can hold a force of about 300kg while adhering to glass! Burrs have seed-sacs that cling to your clothes thanks to tiny
hooks; they inspired the invention of Velcro. The silk of the Darwin’s bark spider is ten times stronger than Kevlar, its web is strong enough to catch a bird. Could a physics class insist more on nature’s creativity, and present her as the root of human inspiration?

Tension

As I walk close to home, moving layers of moisture bring to my nostrils the smell of birch logs burning in the fireplace. I hang my coat in the corridor and call nine-year-old Anna to ask her if she wants to experiment with strings and elastic bands. She likes playing with “stuff,” breaking and mixing “stuff.” She seems excited, and fetches the elastic bands we collect from the broccoli bunches we buy at the local grocery store. They are all identical. The only string we have is a roll of purple sewing thread. I ask Anna to cut a thread two-hands long, then to pull on each end. The thread must be taut, but not moving. I ask Anna if she feels she is pulling stronger on the right or the left side, or equally. She immediately answers “as much on each side.” While she keeps pulling, I ask her to focus on a point in the middle of the thread and ask “how much are you pulling on this point?” She frowns, and says: “Nothing at all, you see, I am pulling on it to the right and to the left at the same time, so it cancels out. It feels the same as if Milo and Lucas were pulling on my arms. No, wait... I pull twice more in the middle than on one end. It adds up. Well, I am confused now...”

I stretch an elastic band, while explaining to Anna it can be used to measure how strong forces are. I tie one elastic band to each end of the sewing thread, and ask Anna to explore different ways of pulling on them. As she correctly forecast, the stretch is always identical on each two sides: everything looks symmetrical and balanced. I then repeat my previous question: “How much are you pulling on the middle of the thread?” With a flash of inspiration, she whispers: “I think I know now!” But she won’t be convinced until she has seen it, so she
cuts the thread in two halves and ties an elastic band in the middle of the thread. She now has a series of bands and strings that looks like jewellery. She pulls on the ends. The three elastic bands stretch the exact same amount. At that instant, a sort of intuitive coherence releases my inner tension; there is something meaningful about the pattern unfolding in front of our eyes, a meaning beyond words, that can so easily be seen, and felt.

I discovered that a sensorial approach to physical quantities made me appreciate their qualities. Before, all forces looked the same: they were all vectors, with a direction and a magnitude, an arrow on a clean diagram, a symbol in a numerical algorithm. In the course of my sensuous explorations, I learned about the qualities of those forces, I grew a context around each of them. They grew roots into the flesh of the world at the same time as they were taking roots in my flesh. To me, now, no two forces are qualitatively alike and textbook diagrams do not tell the whole story: they are schematized/impoverished representations of real life quantities, without their multiple attributes. For example, I became aware that some forces are smart (Doerr, 2001): if I place a book on a table and slant the table, the normal and static friction forces will adjust their magnitude instantaneously to a change in the table's angle. I would go as far as claiming that I developed a relationship with those forces, to a point that they now come to my mind when I engage in the daily routine of my life, like sitting, walking, scraping, carrying, using water and containers: I now spontaneously pay somatic attention to them.

8.2 Newton's tales

Newton's second law is the element of the curriculum I teach that was, at the beginning of
my research, the most likely to forbid any reconciliation with the felt lived world. I paid
attention to my living room, played with a mug and a string in my kitchen, swept the floor,
played with soap in my bathtub, tried ice skating, observed my environment, took several buses,
rode my bicycle, and recalled everyday life feelings to tell stories of Newton's laws that welcome
the body.

Here, I introduce Newton's second law using concepts that are intuitive (forces and
momentum), and the metaphor “an imbalance can trigger a change.” I present Newton's third
law as interactions with our environment and I describe Newton's first law in terms of balance
and continuity.

What makes an object speed up, slow down, or turn? How do interactions with the
external world impact its movement? Such questions spontaneously plague me with modern
images of race cars, airliners and other symbols of our current carbon dioxide orgy. But what
did it mean to Galileo or Al Hazan? What does it mean to me? As I open my eyes to my
surroundings, away from the computer screen, I notice two sparrows playfully swirling in the air.
I let my mind wind between islands in Desolation Sound, I hear the hushing rhythms of orcas'
dorsal fins piercing the dark waters. I picture an alert cheetah, perfectly still, her eyes on a prey.
She springs; after a few strides, she runs at 100 km/hr, then suddenly veers to the left, with
amazing ease, her body slanted at 45°, her paws hardly touching the ground. I remember
images of a peregrine falcon, diving straight down toward a pigeon a kilometre below, reaching
a speed of 500km/hr in only 16 seconds. Just before reaching his prey, he pulls out with an
acceleration of 18g! What do all these animals have in common? How do they make use of
nature's ways to survive in their environment? Isaac Newton attempted to describe the
geometry of the motions that surround us, from whales to eagles, critters to clouds, bacteria to ocean waves, into three simple statements. His laws are too simple to account for phenomena we observe in particle accelerators or the far away cosmos, but they are sufficient to talk about the middle world, the one we experience with our senses.

*Interactions, Interconnections*\(^{23}\)

As I am sitting on the living room sofa, I am interacting with the Earth's gravity, with the soft fabric of the cushion, with the air that surrounds my flesh and penetrates my lungs. There is sunlight reaching my skin, and eyes. Each square centimetre of my skin is crossed by 100 billion neutrinos from the sun, every single second. Countless waves travel through my flesh, from my wireless router, cellphone antennas in the neighbourhood, radio-waves broadcasted by TV channels, by exploded stars, by the super massive black hole at the centre of our galaxy, not to mention the after glow of the big bang. A raven and my neighbour's piano trigger air vibrations which engage my eardrums. The rain dripping from the roof waters the daffodils. I am a biological entity interacting with our ecosystem by rejecting carbon dioxide (my lungs, the electric dish washer), digesting food, burning wood in the fireplace, living in a home made of logs. I am hosting a massive microbiome: 100 trillion bacteria live in my gut alone, which is ten times the total number of cells in my entire body! The metal of my desk lamp and my laptop were extracted from the Earth's entrails after scrapping of top soil and life forms to dig in. Interactions are omnipresent. In the physics class, we focus on mechanical interactions, mostly contact forces (objects pressing against each other, friction, pulls and pushes) and the Earth's gravity.

Newton's law of "reciprocal actions" tells a story of a world where bodies\(^{24}\) are

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\(^{23}\) Newton's Third Law
\(^{24}\) In physics a “body” can be an object, or an actual body. It is the object studied by the physicist.
interconnected. It claims forces cannot exist in isolation: they always belong to a pair, an interaction. When I was a little girl, I loved leaning my head against my grandmother's shoulder. I could feel her bones supporting me, she could feel my head pressing onto her skin: we created a pair of forces, an interaction. The Sun is pulling on Earth, keeping it in orbit. Earth is also pulling on the Sun, by the same amount, but it is not enough to affect the Sun which is 300,000 times more massive than Earth. If the Earth had been much heavier, it could have forced the Sun to dance along a small orbit. At school, I used to ask my best friend, Mary, to hold my hands, arms crossed, and we would spin as fast as we could, pulling on each other's bodies. When I walk my mother's dog, he pulls on me as much as I pull on him.

In my living room, interactions are everywhere: a lamp is pressing into the wood of the buffet, and the buffet is proving support to the lamp; the coffee table and the floor; the books and the shelves; the flower pot and the window seal; the cat and the couch. At the microscopic level, these interactions can be pictured as the interplay of atoms and molecules: the molecules of my cat's coat cannot pass through the molecules of the couch fabric. Contact interactions can also result in deformation, for example when I knead pie dough or work a piece of clay on the pottery wheel. When I sit onto my daughter's bed, the springs of the mattress become compressed by my presence and provide me support. The interaction of atoms and molecules can manifest in the form of friction forces, for example when I rub my hands to warm them in winter, when I strike a match, when I aggressively scrape burnt food in a frying pan with a sponge. When I grate gruyere cheese, the rubbing can even be destructive.

What fascinates me about contact forces is how they can adjust to each other in front of our eyes. Some teachers call them smart forces25. Take a heavy object like a book. For your

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25 See, for example, Doerr (2001).
fingers to give tangible meaning to the word friction, wrap the book in sand paper. Tape another sheet of sand paper onto a cutting board. Place the book on the cutting board and slant the board until the book is about to slide. Then tilt the board back and forth and imagine the forces felt by the wrapped book. The book is attracted by our Earth, but the board and the sand paper react and engage in a game against gravity. The molecules of the board form a sturdy network that prevent the book from deforming the board, from sinking. Do they provide more support when the board is horizontal or slanted? The molecules of the sand paper prevent the book from sliding. For which angle is friction the largest? Which of the two forces plays the larger part against the Earth's gravity? Which one gives way to gravity when, for a large angle, the book starts sliding?

If you are comfortable experimenting on yourself, you can even replace the book with your own body. Lie down on a warm slanted rock, after swimming in a cold lake. The interaction between you and the rock extends over a large surface, at every point of contact between your flesh and the stone. A physicist could describe this situation as two pairs of forces: one for the rubbing between the rock and your skin, and one for the pressing of the stone and your body against each other. He could also use a single pair of forces: your action on the rock, and the reaction of the rock. Physics is before all a language that attempts to describe nature, with often more than one way of speaking of her.

Laziness

Newton's laws of motion are founded on the concept of inertia. Inertia means laziness. It is both an elusive concept that took centuries to be defined and an everyday sensation well known to our senses. This morning, I was carrying a mug of tea to my office. It was full to the

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26 This paragraph is about inertia.
rim. When I suddenly stopped to avoid bumping into a student, it slightly spilled over. Inertia is a property of objects that no one has really explained: objects resist changes in their state of motion. You can feel inertia if you start a wheelbarrow loaded with dirt, or a shopping cart full of groceries. You can give inertia a felt meaning when a bowling ball rolls by your side and you attempt to change its direction by pushing or pulling on it with your hand.

We often feel our own inertia: the laziness of our own body. I am sitting at the rear of a car; the vehicles takes a left bend. I close my eyes and feel how my flesh is resisting this change in direction: my body would rather continue moving in a straight line. It takes a strong push from the window against my shoulder and a pull of the seat fabric onto my trousers to force me to stick to the path of the car. Inertia can be meaningful understood by the flesh, provided we pay attention to it.

*The motion of lost asteroids*\(^{27}\)

Galileo understood that, in an ideal world where friction is totally negligible, a bowling ball would roll for ever on a flat track. Try it for yourself: slant a cutting board, place a marble at the top of the slope and let it roll down: it speeds up. Now throw the marble straight up from the base of the board. The marble moves up while slowing down. Galileo concluded that in the case in between, i.e. a horizontal board, the marble should neither speed up nor slow down: it should move for ever at a constant speed.

The next step for physicists was to imagine the behaviour of an object subject to no force at all. This can only be a thought experiment, since there is no object in the universe that does not interact with other objects. They pictured that such an imaginary object never changes its state of motion. If it is still, it will not start moving spontaneously. If it is already moving, it will

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\(^{27}\) This paragraph is about Newton's First Law, also know as the Principle of Inertia.
continue moving in the same direction, with the same speed, forever. I could use the example of an asteroid lost in space, that was kicked by a giant boulder five billion years ago, when the solar system was a busy and chaotic mess. The asteroid has now left the solar system and the Sun's influence. So it moves in a straight line, at a constant speed, forever. But again, this is a view of the mind; in the real world, asteroids travel through a mixture of molecules and dust, are under the influence of the gravity field of our galaxy; they can even crash on planets.

What is the point of making a statement that does not apply to real life, that cannot be tested through experiments? It is a way of defining inertia, to picture what is left when all external influences are removed. Newton envisioned inertia as an inner force (vis insita) of matter. Today we see inertia as a property of objects: It cannot be a force because it misses its twin sister to form a pair, an interaction.

_Balance_28

On my window seal, there is a magnificent amaryllis opening its petals to the shy April sun. Four heavy corollas hang to the sides, while three closed ones aim straight up at the sky. The stem is slightly bending to the left under the weight of the white flowers; it does not collapse, there is enough strength in its fibres to hold the weight. In my early years, my body too learned to deal with everyday balance challenges, like standing up in a bus or cycling. However, when I try to find balance on a single leg, I become suddenly aware of the distribution of mass in my body.

Many people picture balance as requiring a left/right symmetry: let's see if they are correct. Tie the middle of a string to the handle of a mug, tie a knot around the handle, so that you now have two strings to hold onto. Hold the mug by the strings. Keep holding while moving

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28 Static equilibrium
the strings in all possible ways. Explore this situation by paying attention to the tension in each string:

- Do the strings need to be symmetrical?
- Do the lengths of the strings influence how much the strings pull on the mug?
- What do we feel in our hands as we open the angle between the strings?
- Is it possible to hold both strings horizontally?

The strings do not need to be symmetrical. When I stand up on one leg, I am not symmetrical, however I can feel that there is something symmetrical about the distribution of mass on each side of my body. As soon as I break this balance, I fall. In order to hold the mug, the left and right pulls by the strings must balance out. The total upward pull by the two strings must also balance the downward weight of the mug. Physicists say the mug is in equilibrium. Since the mug does not move, they say it is in static equilibrium.

All objects around us that are not moving and not about to move are in static equilibrium: mountains, houses, shelves, fridges, bathtubs, hanging lamps, trees, totem poles. However equilibrium is an illusion, a transitory state: if we could play the movie of the universe fast forward, the mountains could eventually be shaken by earthquakes, the house would collapse and the trees would fall. We live in a world of perpetual changes.

**Balance and motion**

On my way to work, there is a street with a slight downward slope where I can drive my bike without pedalling nor breaking. Why does my bike keep moving at a constant speed at that particular spot? I could answer “gravity,” however if I stop, the slope is not steep enough to make my bike start again: I need to give a little push on the pedals. Besides, there are also

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29 This paragraph is about understanding Newton's First Law in terms of balance.
other forces acting on me and the bike: we interact with the road, with the air. The answer is:
we keep moving at the same speed thanks to our inertia. The two of us feel as if there were no
force acting on us because all the forces acting on us balance out. We feel as free as an
hypothetical asteroid travelling endlessly across the universe. Air drag and other mild friction
forces should slow us down, but the earth is pulling slightly on us, just enough to balance
friction.

When I drive on a flat road, the effort I make to keep my bike going at 8 km/hr is used
only to balance the friction forces hindering my forward motion. I enjoy pedalling with that
perspective in mind, it makes me feel more intensely the texture of the road, the pressure in my
tires, the deformations of the rubber, the insufficient grease in the gears and, some days, my
interaction with a head wind. Once, I remember getting help from a tail wind that provided the
exact amount of force required to balance friction. I stopped pedalling and felt like myself and
the wind were talking physics together.

This is where the invention of the wheel comes into the picture. A horse pulling a cart at
a steady speed on a flat road must provide the right amount of force to balance the strong
forces of friction that hinder the motion. A horse pulling a loaded sleigh on a dirt road would
soon be exhausted. But put the sleigh on wheels, and the horse will feel there is much less
friction to work against.

Can we imagine an object that has such mild friction acting on it that we could, at least
for a while, pretend that no force is required to keep it sliding on a flat surface? Such objects,
however unusual in our world flooded with friction forces, do exist. Just after emptying my bath
tub, I placed a wet piece of soap on the bottom of the tub, and gave it a little push to see how
long it would keep going: it crossed the tub without any noticeable slow down.
I am a very poor skater who has not yet learned to turn. When I desperately try to stop, I sometimes wish I had less inertia. How could I lose some? My inertia is simply my mass: sixty kilograms. To decrease my inertia, I would need to lose some body fat.

In summary, when an object moves, and all the external forces acting on it balance out, the object, thanks to its inertia, forever continues moving in a straight line, at a constant speed. It is as if the object possessed a certain “quantity of motion”, and refused to give it away. For example, it is hard to change the direction of a rolling bowling ball or a fast train. “Quantity of motion” is now called momentum. If a big truck and a car are driving side by side on the highway, the truck has more momentum because it has more inertia. The truck is harder to stop. Your car has more momentum when you drive at 150 km/hr than at 50 km/hr, and it requires a longer distance to stop it. Momentum describes the inertia of an object, how fast it is going, and the direction it is moving. When all forces acting on an object balance out, momentum stays the same.

Changes

Our world is in a perpetual state of evolution. It experiences cycles of balance and imbalance. It is not uncommon to see an imbalance trigger a change. The same is true about momentum: if the forces acting on an object do not balance out, if one of them overcomes the others, momentum will change. For example, if I pull the brakes on my bike, the friction force decreases my momentum. When I kick a ball, momentum is transferred from my foot to the ball. When I push my daughter on her bicycle, I increase her momentum. When I hit a tennis ball with a racket, I change the direction of its motion, so I change its momentum. What matters here are not the individual forces acting on an object, but the net result of all these forces acting

30 Newton's Second Law
together, also called the net force.

We often do not pay much attention to changes in momentum because they are short lived, like for example starting to walk, getting of a chair, setting a heavy box in motion, diverting a ball directed at us or throwing a stone. When I sweep the floor, I change the momentum of the brush several times per second. In other situations, changing a momentum takes time, for example when a heavy truck brakes, or a ferry boat veers around an island. It can even be strongly felt. Imagine you are standing in a bus. When the bus brakes, your momentum tends to stay the same and could make you crash into the windshield; you need to hold onto something to make you momentum decrease faster. Imagine you sit in the bus by a window. When the bus turns to the left, you momentum resists the change in direction, you feel squeezed against the window on the right: you need a push from the window to force your momentum to align with the momentum of the bus.

What are the factors that influence a change in momentum? It depends on how strong the net force is and for how long it is acting: If I want to stop my bike, I can brake hard for a short time, or brake less over a longer time.

All the above concepts can be summarized into a few mathematical symbols. Physicists chose the Greek letter \( \Delta \) to say change. Momentum is called \( \vec{p} \) and the net force is \( F_{net} \).

\( \Delta t \) tells for how long the net force is acting on the object. All the above stories, for objects at rest or in motion, for cheetahs, falcons, viruses, satellites, basket balls, elevators, subways or hanging lamps can be told using either words or mathematical symbols, however, for those who understand them, symbols can be used to make calculations and predictions. Newton's second law states that “the rate of change in momentum is equal to the net force applied to the object”:

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\[ \frac{\Delta \vec{p}}{\Delta t} = F_{\text{net}}. \]

The world as a lab, the body as a tool

Before Newton, scientists separated the world in two categories: moving and non-moving objects. Newton summarized these two cases under one concept: an object's state of motion, which can be either rest or movement. Generalization is valued in physics because it allows to develop a description of nature reduced to a few grand principles. But to some people, generalization means losing track of context. If context matters to your learning, do not hesitate to create your own meaning of physical concepts in kitchens, workshops, gymnasiums, forests, beaches, etc. I made sense of the Doppler effect by walking back and forth in ocean waves. Many scientists transformed their home into a laboratory and learned physics from manipulating home equipment. Some even made their own body part of the experiment: Newton pocked underneath his own eye with a blunt needle in his effort to understand vision and Archimedes allegedly understood buoyancy as he stepped into his bathtub and bursted his famous “Eureka!”

8.3 Tales of the inner ear

This third story explores first year university physics. It is an attempt at teaching rotational and circular motion, and introducing mathematical formalism, using the vestibular system. In order to write this story, I explored my sensations in an elevator, experimented with several spinning objects in my home (a salad spinner, a lazy Suzan, observed a washing machine), recalled experience of being a mother at the playground, of taking a plane. I also rode several buses (again!), and danced in my living room.
To tell our position, we use sight and objects of reference, like the side of the road when we drive. To know we are moving, we rely on touch (for example feeling the wind on our skin, the bumps of a rough sea, or the effort in our legs while walking) and sight (for example, the apparent motion of roadside trees). However, according to Galileo, if we set up a physics experiment in a moving vehicle with no window (and no vibrations), we cannot detect our velocity, only our acceleration. Acceleration can be detected by a 3-D accelerometer present in each of our inner ears. Whenever the vehicle’s motion changes, fluids move in small canals, making us aware of the slightest variations of our velocity.

*Mysterious forces and felt acceleration*31

If you sit on a merry-go-round, you feel like flying off, and thanks to your senses, you know you should better hold onto the rail. Physicists developed two ways of describing the motion of objects: from the point of view of the person sitting on the merry-go-round, and from the point of view of someone observing the merry-go-round from afar. To feel acceleration, you must be sitting on the merry-go-round.

Another great place to study acceleration is a bus ride. Imagine you sit on the bus, and watch the handles hanging from the top rails.

- If the handles hang vertically, it means the bus is moving at a constant speed in a straight line. People are not impacted by the motion of the bus, they can stand up without holding onto the rail, a stroller is safe without its brakes on, a coffee cup would stay upright on the luggage platform. Someone could even pour water in a cup. You are observing the passengers and their ordeals in an *inertial* frame of reference. Notice we only drink hot beverages in a moving vehicle when it is moving at a constant speed, i.e.

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31 Introduction to inertial forces
when it behaves as an inertial frame.

- When the bus brakes, the handles are tilted toward the front, people feel projected forward, the stroller rolls towards the front, the cup topples over. When the bus speeds up, the handles hang toward the back, a mandarin lost on the floor rolls to the back of the bus; when the bus turns, the handles hang sideways and passengers feel pushed to the side. Nothing is actually pushing nor pulling objects, nor even touching them that could explain their behaviour. They seem under the influence of a mysterious force, that physicists call a fictitious force. Fictitious forces are strongly felt by our bodies. Whenever you feel acted upon by a force with no apparent cause other then the motion of a vehicle, you know you are in a non inertial frame of reference. In a bus, you notice passengers reacting to fictitious forces, for example by holding onto their suitcase, or blocking their stroller. If such forces are so strongly felt, why do we call them fictitious? Because our vestibular system is not measuring those forces per se, but our own acceleration. What we detect is a change in our state of motion (i.e. a change of speed or a change of direction).

We can make use of our body to draw the direction of our acceleration. You now stand up in a bus in order to use your body as a drawing device. Every time you feel a fictitious force, your sense of balance instinctively counterbalance it, i.e. bends in the opposite direction: your body draws the direction of your acceleration. When the bus speeds up, your body bends forward. When the bus brakes, your body bends backward. When the bus turns, your body tilts towards the centre of the bend.

What does acceleration look like from afar? Let's follow a physicist who goes to the playground with her son. The six-year-old chooses to sit on the merry-go-round. He
experiences a fictitious force that makes him fly off: the centrifugal force (which means fleeing the centre). To stay put on the merry-go-round, the little boy instinctively holds onto the rail, creating a centripetal force (i.e. toward the centre) to balance the centrifugal force. As seen from the mother's point of view, the child is sitting on a spinning platform and his arms indicate the direction of his acceleration: toward the centre of the merry-go-round.

If you feel ready for more advanced physics, observe that, in the above merry-go-round example, the platform was assumed to be spinning at a constant speed. What if the mother were setting the merry-go-round in motion? Which way would the little boy need to pull on the rail? What would be the direction of his acceleration? Imagine now the merry-go-round is spinning too fast, the child is scarred and crying, and the mother attempts to stop the merry-go-round as fast as possible. What would be the direction of the boy's acceleration? The answers will be found in a playground near you.

**Gaining and losing weight**

Another place to do physics with our vestibular system is an elevator. Take a fast elevator from the ground floor to the top of a very tall building. When the elevator starts, and speeds up, you feel heavier, as if the Earth's gravity had increased. However it did not: you are feeling a downward fictitious force. If you were holding a slinky with a ball attached at the bottom, you would see the slinky being stretched. If this fictitious force were so strong that it became uncomfortable, you could extend you arm to grab something on the elevator ceiling, to try to balance the pretend downward pull. The direction of your acceleration is given by the direction of your hand: upward. When the elevator approaches destination, you feel lighter, as if pulled upward. Similarly, when a plane is landing, there is a short instant when I feel like flying and I am glad my seat belt is keeping me on my seat.
Now let's look at an elevator from outside. At the beginning, the floor of the cabin is pressing harder on the sole of a passenger's feet to set the passenger in motion. When the elevator reaches destination, the elevator floor gives way to the force of gravity, so that the earth's pull can slow down the motion of the passenger. Next time you take an elevator, try to alternatively feel the two points of view in your body.

**Vestibular system and math symbols**

The vestibular system is an amazing device that can detect acceleration in a straight line in three dimensions, as well as a three types of rotational motion, i.e. three different ways of spinning. In order to explore physics as well as your own body, you can undergo the following experiment. Stand up, with your neck straight. The direction of your neck is what physicists call the z-axis. Draw an x on your right hand. Extend you right arm to the right: this is the x-axis. Draw a y on your left hand, and extend your left arm in front of you: this is the y-axis. Close your eyes. Walk to the right, then walk to the front, then jump: you just experienced three types of *linear* motion, i.e. motion in a straight line, and three types of accelerations: \( a_x \), \( a_y \), and \( a_z \). Keep your eyes closed. Spin your body to the right, then to the left. This is a *rotational* motion about the z-axis. Your neck is called the *rotation axis*. Your vestibular system experience a rotational acceleration \( \alpha_z \). Bend your shoulders forward: your vestibular system is perceiving a motion about the x-axis. Now, find your own way to experience a rotation about the y-axis.

**Dancing circular motion**

In the middle of a routine activity, I close my eyes, and feel our planet under the sole of my feet. I grew so used to its pull that I hardly notice it anymore: I learned to balance the weights of my limbs, a long time ago, when my navel was only 50 centimetres above the ground. I imagine the soil below the house, with its crawling mammals, worms and bacteria; the
gurgles of underground water; the mysterious life forms leaving inside the crust of our planet; the rumbles of the crimson lava searching for a way out into the open air; the geothermal heat flowing from the core; and the massive rotation of our planet about its axis that creates magnetism for migrating birds to find their way across continents; the dance of the Moon around the Earth, like a child holding hands with her mother; the whirling dance of Earth around the Sun, itself spinning and spurting tangled magnetic lines. Memories of pottery making awaken in my fingers. When I was nine years old, the potter of my village used to lend me his wheel and a handful of clay on Saturday mornings.

The speed at which an object spins is called *angular* speed by physicists. Stand up, extend your arms sideways and spin. Notice that your speed cannot be expressed in meters per second, nor in kilometres per hour, since your hands move faster than your elbows. Your spine, on the other hand, hardly travels any distance. What all the parts of your body have in common is the angle they sweep every second. Play a tune with a tempo of one beat per second, or go online, find a metronome, and set it to 60 beats per minutes. Even better: go outside in the sunlight with a drummer friend and ask her to drum her heart beat. On the ground, draw a circle with a piece of chalk and cut it in six equal slices. Each of them is called a radian\(^{32}\). Extend your arms and spin like a Rajasthani dancer.

If you want to know your angular speed, count the number of slices swept by your right arm every second. For example, it takes me 10 beats to cover 18 slices: my angular speed is approximately 1.8 radian per second. A physicist would do almost everything the same way, except she would graduate the circle on the floor using the transcendental number \(\pi\) (pi): Half a circle is an angle of \(\pi\) radian, a slice measures \(\pi/3\) radian.

\(^{32}\) A radian is roughly 0.16 of a full circle while a sixth is roughly 0.17. This is close enough for the purpose of this activity.
If you keep spinning at a constant speed, a physicist would say your body is undergoing *uniform rotational motion*, like Earth every 24 hours. If you are holding a ball in your right hand while dancing, the ball will describe a circle: the ball is undergoing *uniform circular motion*, like the Moon on its orbit around the Earth.

I love eating arugula, and I dry it in a salad spinner. When I get hold of the spinner’s handle, I must fight its inertia, and the friction and wobbling in the cheap gear, to set it in motion; it takes several seconds to reach full speed. The rate at which the plastic basket gains angular speed is called *angular acceleration*. In order to calculate it, I would need to measure angular speed at different instants, which I have no way to do in my kitchen, but I could do with a motion detector. A good physical exercise would be to go back to the dancing circle, and try to accelerate from an angular speed of 1 radian/second to 2 radian/second, then decelerate to 0.

*In this exploration, I realized that using the vestibular system implies introducing fictitious forces and inertial frames of reference at the beginning of the chapter, because they play a primordial role when our bodies experience acceleration. However, in traditional teaching, fictitious forces are usually introduced in second year physics. Welcoming embodied knowledge might require a re-storying of physics texts.*
8.4 Revisiting “Galileo's ship” tale

Galileo's tale of the moving ship is well known in the physics education community, for example when teaching Galilean relativity, i.e. the idea that when we are in a reference frame moving at a constant velocity, objects behave as if the frame was at rest. The tale even made its way into the movie Agora\textsuperscript{33} (Bovaira, 2009) as a illustration of the power of scientific reasoning.

I will describe how I used to introduce the tale to students, following the tradition of my own teachers. I will then show how the tale is confusing people's intuition. Finally, I will look at Galileo's own words to show that educators can create physics stories that seek truce between the mind and the body.

8.4.1 The story I used to tell

Today I am introducing Galilean relativity to my students using the following problem:

“A sail boat is moving at a constant speed on a flat sea. Neglect air friction. A boy climbs to the top of the mast, and drops a heavy bag that lands on the deck. I would like you to predict if the bag will fall:
A - at the bottom of the mast,
B - toward the prow,
C - toward the stern.”

Most students choose answer C. I am convinced that students forget to take into account the horizontal velocity of the bag: this is what I want to teach today. On the board, I draw the final position of the ship and the bag, to explain why the correct answer is A: the bag follows a

\textsuperscript{33}A biography of Hypatia of Alexandria, directed by Amenabar, that shows how she was murdered by the Christian mob for her scientific beliefs.
parabolic path and lands at the bottom of the mast. To an observer on the boat, the bag falls as if the boat were at rest.

Fig. 13: The parabolic path of a bag thrown from the top of the mast.\textsuperscript{34}

\textbf{8.4.2 Playing tricks with students' intuition}

What if we make the assumption that students' common sense must be correct, at least partly? Then the above story appears problematic. The context makes the problem look like it refers to lived experience. The problem is observed from the shore, however it is very unlikely that someone ever observed such an event from the land: boats are often too far out, the sea is not flat, there is air drag. Galleons on which one can climb the mast are pretty rare those days. It is also hard to imagine a sailing ship moving at a brisk pace, and at the same time neglect the influence of the wind. The respondent needs therefore to search for analogous p-prims, which are at risk of being misleading. The respondent can imagine the boy dropping the ball, but there is a chance that, in this image, the mast will be used as a reference, in which case no forward speed will be attributed to the bag. If the respondent confuses the two reference frames (the shore and the boat), s/he is likely give a wrong answer. Also many students relying on their

\textsuperscript{34}Source: physics 101 online. \url{http://www.physics101online.com/physics101/mechanics/motion-in-2d/relative-motion-text-1} With permission.
intuition would factor in air friction or the action of the wind.

### 8.4.3 Galileo’s own words

In *Dialogues Concerning the Two Chief World Systems* (Galileo, 1632/1962), Salviati and Sagredus discuss a very different ship tale, in a style that deeply contrasts with today’s textbooks. It is so moving and meaningful that it deserves to be cited in full:

> SALVATI: Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though doubtless when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. In jumping, you will pass on the floor the same spaces as before, nor will you make larger jumps toward the stern than toward
the prow even though the ship is moving quite rapidly, despite the fact that
during the time that you are in the air the floor under you will be going in a
direction opposite to your jump. In throwing something to your companion,
you will need no more force to get it to him whether he is in the direction of
the bow or the stern, with yourself situated opposite. The droplets will fall as
before into the vessel beneath without dropping toward the stern, although
while the drops are in the air the ship runs many spans. The fish in their water
will swim toward the front of their bowl with no more effort than toward the
back, and will go with equal ease to bait placed anywhere around the edges of
the bowl. Finally the butterflies and flies will continue their flights
indifferently toward every side, nor will it ever happen that they are
concentrated toward the stern, as if tired out from keeping up with the course
of the ship, from which they will have been separated during long intervals by
keeping themselves in the air. And if smoke is made by burning some incense,
it will be seen going up in the form of a little cloud, remaining still and
moving no more toward one side than the other. The cause of all these
correspondences of effects is the fact that the ship's motion is common to all
the things contained in it, and to the air also. That is why I said you should be
below decks; for if this took place above in the open air, which would not
follow the course of the ship, more or less noticeable differences would be
seen in some of the effects noted...
SAGREDUS: Although it did not occur to me to put these observations to the test when I was voyaging, I am sure that they would take place in the way you describe. Indeed, I remember having often found myself in my cabin wondering whether the ship was moving or standing still; and sometimes at a whim, I have supposed it going one way when its motion was the opposite....(Galileo, 1632/1962)

The issue of wind and air drag have been taken care of. Galileo appeals to the reader's lived experience of the world, to the reader's somatic knowledge (jumping, pouring water) and even the somatic knowledge of the fish (catching a bait). He welcomes the reader's sensorial perception of the world.

8.4.4 Dropping bombs

An application of Galileo's ship often found in textbooks reads like: “A plane flying at a speed of 275 m/s drops a series of bombs. Draw the path of the bombs as seen by an observer on the ground.” To move away from the war lexicon, the bombs are sometimes replaced by boxes, or bowling balls. If the plane is moving at a constant velocity, in the reference frame of the plane, the bombs seem they are falling straight down, but for an observer on the ground, the bombs have a forward component to their motion and therefore follow a parabolic path, as shown in Fig. 14. Many students draw a straight down path, or even a backward trajectory (because they have an intuition of air resistance), which are considered wrong answers. However, even textbooks sometimes show object falling straight down from planes (Fig. 15). How does this problem relate to felt experience? Hopefully, most students never observed
falling bombs while they were standing on the ground below a plane.

Fig. 14: A moving plane dropping an object (Cutnell & Johnson, 2012, p. 63).

Most images we have about planes dropping objects are from movies (bombs, sky divers, etc). In such movies, the camera is attached to the plane, or following the plane, therefore objects are seen falling in the reference frame of the plane, i.e. straight down, or even backward if air drag is taken into account. The wording of the question places students in between two different reference frames, like in Galileo's ship tale. In real life, it is extremely hard to observe a
parabolic path:

- because the plane is so high in the sky that we do not get a good perspective on the path of falling objects (they might not even be visible);
- because the observer could be too much below the plane, therefore the parabola would be seen at an angle;
- in British Columbia, planes drop water on forest fire: the water is definitely not falling forward.

Many physics tales are meant to trigger cognitive conflict, in the hope to move students from their intuitive concepts to the scientific framework (Rowlands, 2007). Galileo's tale of the moving ship and the question about falling bombs, however, are not about conflicting worldviews but about positioning students in ill defined contexts. The same situation happens when a teacher ask students to perform thought experiments in a world with neither friction nor air drag. What is anomalous is not the students' intuition but the ecology of the situation studied. Educators could put extra effort to work with the ecology of the world we live in, as in Galileo's own writing.

**8.4.5 Indoctrination**

After revisiting the conflict-based stories that marked my professional life, and exploring the softer physics stories told by my environment, I wondered if the use of repeated cognitive conflicts has something in common with methods of indoctrination.

Indoctrination involves denouncing someone's old belief systems and creating a sense of
righteousness by pointing to the wrongness of alternate ways of thinking. These are important narratives in the PER community (see for example Hestenes, Wells, & Swackhamer, 1992).

Indoctrination can involve group pressure. When I was a student, the intense competition often engendered a clique of nerds who felt superior and were praised by the teacher. They had their own humour, their own value system, and formed the hard core of the community. I know many graduate students, including myself, who renounced a career in physics partly because the pressure to conform made them feel inadequate.

Indoctrination can also mean inducing a loss of self-confidence. The counter intuitive stories of the physics repertoire, including those providing confusing cues, made me feel I was born wrong. Fortunately, the teacher was there to elevate me to the higher spheres of the intellect. He would soon tell me the secret code that would make me belong to a closed circle of knowers. I surely paid close attention to his version of the story, and felt relieved when the conflict eased of. Was it a cognitive conflict between my old belief system and modern scientific beliefs? Surely not, since I did not have a system of belief. I only had me, my body, and my experience of the world, mostly trapped in my unconscious, that could not be retrieved in the form of words or principles, but rather as puffs of stuff, a shapeless mix of foggy images, impressions, emotions and memories.

The portraits of famous (old white male) physicists were hanging on the walls of the classroom, all of them blindly revered by the community. Einstein was venerated, even though he treated his wives in despicable ways and he did not take care of his children: Physics could absolve one's sins. The conflict resolution I was made to go through had more to do with my
self-esteem, and my desire to belong. As I was making sense of my teacher's story, warmth and joy infiltrated my chest: he had given me one more key to understand the true essence of the world. The physics story was now part of my own narratives, I could carry it around the world, and share it with others, spreading the good words of truth.

Physics instruction never made me drop my embodied knowledge of the world: That would have meant ceasing to exist. Instead, it opened a beautiful piece of real estate in my mind, a place where order and simplification brought peace, where everything fell into place, logically, bathed in the light of truth, sanctified by generations of superior thinkers. This was the world as it should be, with no ambiguities, no hidden sublayers, no accidents. That place had a sense of harmony as powerful as a symphonic orchestra playing Bach's *Gloria in Excelsis Deo* in a cathedral. Meanwhile, the bombardment of counterintuitive examples and the competitive environment were nourishing my feelings of inadequacy and my anxieties. As I was becoming addicted to harmony, I was losing my self-esteem and my roots in the lived world.

Reading Galileo's own explanation of the ship experiment was a revelation. Until then, physics had felt like a white sanitized room with cartesian coordinate axes painted on the walls and square blocks sliding on surreal frictionless inclines. “A place of mind” where no-one can breathe because free fall only happens in vacuum. An immaculate floating paradise, with right angles. On the contrary, Galileo's words resonate with the presence of water, fish and butterflies. It is aware of air and flesh, people and play. It appeals to the senses. It does not contain the slightest hint of power struggle. In the midst of his contemplative awe, Galileo teaches me something very profound, and long lasting.
9 Re-storying curriculum

Perception does not give me truth like geometry but presences.

Merleau-Ponty (1964a, p.15)

9.1 Defending the purity of physics

Mazur (2008) warns us that spherical cows can endanger physics: too much generalization and models can make physics teaching lose credibility. But other educators favour an abstract approach to physics education. In Mechanics as the logical point of entry for the enculturation into scientific thinking, Carson and Rowlands (2005) advocate teaching a meta-discourse on the nature of mechanics, and the relationship between mathematics, the theoretical objects of science and the way science speaks of the world. They claim mechanics should always open the door to any physics curriculum because:

• the scientific revolution began with mechanics in the 17th century,

• children can enter the abstract world of the thought experiment without having to have a prior knowledge of physics,

• it imposes the rules of the game.

They despise textbooks that offer an empiricist treatment of mechanics, in which the laws of mechanics are presented as mere summaries of what is given in sense perception. They cite Lombardi (1999, p. 222): the semantic reference of physical theories is not constituted by the object perceived by direct observation, but by ideal objects which form the so called “physical models”. For Carson and Rowlands, students should be inducted with the role that idealization plays in physical theories, else they will form common sense notions of force that will
undermine their understanding of science. Teaching mechanics through axiomatic structure will help students understand fundamentally what science is. Not all physicists share such an axiomatic worldview. Poincaré showed that it is almost impossible to define the concept of force: “Force is primitive, irreducible, undefined; we all know what it is, we have a direct intuitive perception of it” (Poincaré, 1902/1968, p. 124).

Physics education and the practice of physics do not need to reach the same level of rigour and abstraction. The vast majority of students will never become physics practitioners. I see an urgency for the science curriculum to reconnect with the organic, messy, complex, hard-to-model world that we live in. Today’s challenges are not about the refinements of pure thoughts but about the survival of our species. Every era has its milestones; our physics textbooks are still celebrating the knowledge that mattered to the industrial revolution. Curriculum is not about redefining science, but contributes to redefining our relation to science, and to the world.

9.2 A physics photo essay

I explored my home and my neighbourhood with a digital camera in search for physics questions, in order to compare the physics that matters to me to the curriculum I teach. Since I have no interest in cars (I do not drive), the images I collected had very few in common with those found in introductory physics textbooks.

The first salient theme was light. In a corridor of the shopping mall, I noticed strange patterns of light on the floor, convex mirrors, plastic signs acting as plane mirrors, automatic doors and taps, a rainbow on the stairs. While walking in the streets, I wondered why the reflection of the sun on a car travelled across the windshield as I walk by, why a black statue
standing in the sun exhibited white patches, and why the white clouds crowding Grouse Mountain were the same colour as the snow. Can I read time using the length of my shadow? At home, I wanted to know why hot plates become bright and why I could see my face reflected in the window of my living room. I was puzzled by sound: Why do I hear the subway coming long before it shows at the end of the tunnel? Why do my rubber soles squeak on the shiny floor of the shopping mall? What are all the transformations undergone by a song from the throat of a singer to my eardrum via a wireless connection?

**Physics in my home**

![Images of various household items](imageURL)

Fig. 16: Pictures of physics taken in my home. Rotational motion and lever arms are very present: electric fan, washing machine, coffee grinder, salad spinner, hinges, faucets, coffee maker, paper towel roll, metronome.
Another prevalent theme was heat and temperature. I sat down on a public bench with metal arms; strangely, the black arm was feeling much warmer than the light grey one. Why do metal spoons feel cold when I take them out of the drawer, even if they are at room temperature? Why can I hurt my skin if I cook with one of them? During a hot summer, can I cool my kitchen by living the fridge door open? Would a frozen meal defrost faster in air or in water? What is the most effective way of saving energy: taking a shorter shower or switching off ten light bulbs?

Fluids are present in my home, in the streets and in the shopping mall. I observed a fountain with a regular oscillating motion next to a fountain that spurted water pockets in a random fashion: could they both be described by a physics model? What is the optimal inclination angle of a gutter? Why does water spurt out of my garden hose in a straight line if I block the hose mouth with my thumb? How does water climb from my hot water tank to my second floor faucet? Why does oil float in the water when I cook pasta?

Most of the mechanics I found was in my home: handles, hinges, coffee grinder, salad spinner, washer, dryer, hanging lamps, rocking chair, wind in the curtains, oscillations of a metronome. I wondered how the gears of my bike work, and how to build a stable stroller.

Very few of the above examples are explained in traditional textbooks. I spend most of my time teaching about blocks sliding along inclined planes, pulleys, banked curved and projectile. This photo essay questions the relevance of the traditional physics textbooks content, in terms of reader’s interest as well as adequacy to the needs of our times.
Fig. 17: Pictures leading to physics interrogations, taken in my neighbourhood. For example: How does a tree find its balance? Why is the slide gently curved? How to choose a safe coil for the duck? What directions of the wind make the little mill spin? Can a swing work with uneven ropes? Where does the pressure come from in a fire hydrant?

9.3 Aesthetic criteria

Aesthetic criteria of order and simplicity, often equated with harmony, are prevalent in the scientific community. Occam's Razor, i.e. the claim that the simplest theory need not be most accurate, is a scientific “rule-of-thumb” that finds its origin in the epistemological belief that nature itself is simple. It was an argument in favour of Copernicus' heliocentric model and played a role in Einstein's theory of relativity, however it is nothing more than a heuristic preference.
The same aesthetic criteria inform the science curriculum; order and simplicity can become synonym of a form of reductionism that distance the teaching material from common sense knowledge. In their study on misconceptions, Proffitt and Gilden (1989) claim that “the unity and elegance that characterize a mathematical description of natural motions do not characterize commonsense understanding.”

I propose to re-story the physic curriculum under an aesthetic that values tangled networks, rhizomatic thoughts and trans-disciplinary connections, where complexity and randomness are considered beautiful while idealized/unified/generalized statements are seen as simplistic; a heuristic of messiness in which common sense knowledge is praised for its capacity to deal with the complexity of the organic and chaotic qualities of the world.

10 Making sense of physical quantities/qualities

It is essential for physics education to re-contextualize highly abstracted material and break away from dichotomized regimes of truth and an elitist epistemology that scares away capable, creative students. I will now describe applications of my research to the classroom.

10. 1 Democratizing access to touch

In the mad yo-yo exploration, I showed how class demonstrations can deprive students of sensual context by reducing interactions with the physical world to visual perception. Demonstrations are even worse since the educator has access to the full sensorial experience of the apparatus in front of his students, therefore being the holder of both physical and physics knowledge. Crouch et al. (2004) showed that class demo are not an effective way of teaching,
even when asking students to predict the outcome. Educators can find hands-on activities involving low cost or recycled every day objects so that every student has a chance to manipulate the equipment.

10.2 Decontextualization, simplification and generalization

Abstracting physical concepts can unroot students from their p-prims. For example, Newton's first law makes a statement about objects moving in a straight line at a constant speed. One can always find a reference frame in which the motion of such an object is at rest. Therefore, to a physicist, rest is simply a special case of motion that does not deserve special attention. In real life, we do not travel in idealized hypothetical cars. Most often we can tell we are moving, because of the vibrations of the vehicles, the road bumps, the moving scenery, the speedometer, the gauge of the gas tank and the awareness required to prevent potential accidents. In order to not feel the motion of a vehicle, we would need to lose vision, smell, hearing and touch, in which case we could not perform any physics experiment to verify Galileo's relativity. The equivalence of rest and motion is not intuitive. Every leap of abstraction through generalization, simplification or decontextualization, is at risk of unrooting students from their p-prims: It must be negotiated and scaffolded. As educators, we should develop an awareness of abstract leaps triggered by language, mathematical symbols, diagrams and/or reductionist stories. We need to welcome shared metaphoric representation of more-than-representational physical quantities. Teaching physics can be seen as taking students on journey from the intuitive to the symbolic domain, hoping one day they will be able to move back and forth between the two.
Fig. 18: Physical embodied knowledge and physics textbook knowledge differ and complement each other.

10.3 Soft physics studio
During the three years of my Masters' degree, I constantly went back and forth between my course work and my classroom practice, testing and implementing teaching units inspired by my theoretical readings. I gradually developed and introduced a teaching method that I call the soft physics studio.
The name *Studio* refers to a teaching environment introduced at MIT that is centered on an active learning approach: a highly collaborative, hands-on environment (Belcher, 2001). In the MIT model, students make an extensive use of networked laptops and desktop experiments.

The *soft physics studio* is not a revolutionary way of teaching, but a form of apprenticeship. In the *soft physics studio*, students make as much as possible use of their senses and manipulate objects from everyday life, like for example a salad spinner, a plastic container floating in water, or a piece of string attached to a weight. Students should be able, as much as possible, to reproduce the experiment outside school, so that physics does not appear like a topic trapped into high tech laboratories. Another goal is to create teaching material that can be used in school with minimal funding, and can even be used by home schoolers. Soft physics hands-on activities complements lecture, they do not replace them.

### 10.4 The guiding principles of the soft physics studio

In *The Crisis of European Sciences and Transcendental Phenomenology*, Husserl claims that:

> Through Galileo's mathematization of nature, ... nature itself becomes... a mathematical manifold (p. 23)...Everyday induction grew into induction according to scientific method, but that changes nothing of the essential meaning of the pre-given world as the horizon of all meaningful induction. It is this world that we find to be the world of all known and unknown realities.... It is in this world that we ourselves live, in accord with our bodily, personal way
of being. ... This world is [not changed by] the geometrical and Galilean
technique which is called physics. (Husserl, 1970, p. 50).

A soft physics studio is a space of re-contextualization where physical quantities recover
their qualities, their texture, without which their are not fully meaningful. The workshop is
before all a landscape, a playground, where students can be set free to explore, feel and
verbalize without value judgment. They recover their trust in their ability to discover, reflect,
and theorize. Knowledge is not just light coming from above, it is osmosed from the roots. The
studio resonates with May and Semetsky's educational views:

We must recognize that learning is not simply cognitive: it is also corporeal. Our
bodies learn outside our conscious awareness ... The corporeal affects and
perceptions are complementary to intellectual concepts and they make, that is, the
unconscious thought , immanent to rational thinking (May & Semetsky, 2008).

The soft physics studio tries to transcend the boundaries of normative physics teaching:
the educator does not engineer a conceptual change in students, does not attempt to
control students' metaphors and unconscious thought according to an optimal
prescribed method and inflexible definitions. S/he moves away from all three elements
of the traditional model (the teacher who knows, the student who doesn't, and the
material to be known) to substitute a new structure: the teacher who learns, the student
who investigates, and the material that appears (May & Semetsky, 2008).

Learning cannot take place only by means of representation: this would be the
reproduction of the same. For learning to occur, a meaningful relation between a sign and a
response must be established through experiential and experimental encounter with the other
(May & Semetsky, 2008). In a soft physics studio, the others are material objects and physical
quantities as well as the perceptions verbalized by peers: meaning is co-constructed. The
distribution of knowledge becomes a function of the shared experience rather than of a centrally
administered curriculum. The body of knowledge is being held together not by some abstract
end but by the immanent production of meanings, including not only the sense and worth of
production of [physics] but first and foremost, the sense and worth of self (May & Semetsky,
2008). It demands a “novel understanding of collective experiences, that is, creating or inventing
a set of … meanings as a means for re-valutation of experience, therefore constructing one's
identity in practice” (Semetsky & Lovat, 2008). The studio creates context, i.e. a dynamic
kinesthetic framework “that includes the motile body but also instruments, tools, or spatial
measuring equipment” (Merleau- Ponty. 1945/1992, p. 143). Activities attempt to “make
perceptible the imperceptible forces that populate the world, affect us, and make us become”
(Deleuze & Guattari, 1994).

The soft physics studio follows Cajete's recommendations that science learning should be
highly kinesthetic and activity oriented, using a variety of sensory modalities in creative
combination (1999, p. 36). Students explore the space between the body and the mind through
touch and movement in the margins of logocentrism. Through their senses, learners generate
novel representations of non-explicit knowledge and collectively “create metaphoric and
symbolic communication system that allows access and retrieval of tacit knowledge” (Riener,
2009). They mess around with science in order to refine their common sense knowledge
(Hammer, 2000) instead of being force-fed inert symbolic knowledge.

10.5 Feel-it activities

Some of the group activities carried in the soft physics studio are feel-it activities: students are asked to pay attention to non-verbal knowledge, to discuss it and to relate it to symbolic representations. They follow a worksheet that guides their somatic attention (some examples are provided in the appendices). I will describe here four examples: potential energy, forces, linear momentum and angular momentum.

10.5.1 Felling potential energy

Potential energy can be a very abstract concept for students. They memorize the equation, and solve the textbook problems, but are unable to transpose what they know to new contexts, which is characteristic of inert knowledge confined to memory.

To define potential energy, I ask students to work in groups of three. Each student holds a heavy object above his/her foot (slightly on the side for safety). The student is asked to engage in a conversation with his/her foot about the energy stored in the heavy object. As a group, students find that potential energy depends on mass and height. I then lead them to discuss the influence of $g$ by imagining what it would feel like on the moon. They conclude that $U$ depends on $m$, $g$ and $y$. I then introduce the definition: $U_g = m g y$.

When I teach elastic potential energy, I provide students with springs of various stiffness, and ask them to hold a compressed spring close to their chest or forearm. Without them releasing the springs, they can guess that the energy stored in the spring depends on its compression, $x$, and its stiffness, $k$.  

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Of course, sensorial perception is far from being enough to describe all the physics knowledge contained in \( U_g = mg \) and \( U_e = \frac{1}{2} k x^2 \). The goal of a *feel-it* activity is not to tell the whole physics story, but to give an embodied meaning to each of the symbols in the equation.

### 10.5.2 Feeling forces

In my classes, I witnessed occurrences of *feel-it* activities giving meaning to a force concept. Here are three examples:

- Many students cannot make sense of the buoyancy force: they cannot recall embodied feelings of swimming or being in a boat that give substance to the vector arrow drawn on the blackboard. I ask them to push an empty plastic container into water. They often cry “I did not know water could be *that* strong!” or “oh, this is water producing its own normal force.” I even heard: “Look, the more I make it sink, the more the water pushes back”: they could get a feeling of Archimedes’ principle.

- I had a student who could not make sense of the friction force between a wooden block and his hand. But when the block was wrapped in very coarse sand paper, he exclaimed: “Oh! I get it now!”

- I once had a student who would draw tension force vectors, but could not make sense of them. For example, she would confuse the magnitude of the force with the length of the string. I asked her to create a static equilibrium of her own design using heavy objects of her choice, as well as strings and pulleys. Even after assembling these elements, she still asked: “But what is
meant by tension? I don't get it!” I told her to feel the fibers of the string. She placed her fingers on the fibers and said: “Oh, this is what tension is about!” *Feel-it* activities can help operating a transfer from the perceptual domain to the verbal-cognitive domain.

### 10.5.3 Feeling linear momentum

In my college, we have a rolling chair with room to store a bag (see Fig. 19). A student can sit on the chair and set it in motion with her feet, in an open space like a hall or a gymnasium. She can then attempt to change the linear momentum of the system student+chair, in all possible ways, and feel that linear momentum stays constant. She can then add a heavy object to the system, like a heavy backpack, and feel how much harder it is to set the chair in motion or to stop it: she can then feel the importance of inertia.

![Fig. 19: A rolling chair that can be used to teach many physics concepts.](http://upload.wikimedia.org/wikipedia/commons/4/4b/Desk_chair.jpg)

### 10.5.4 Feeling angular momentum

Here are examples of feel-it activities related to angular momentum:

Ask a student to hold a bicycle wheel and to attempt to change the direction of the axle: the resistance to a change in direction gives a strong feel of the angular momentum. Repeating the experiment for various speeds of the wheel gives an appreciation of the dependance on angular speed.

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Ask students to create two rotating objects by wrapping two chop sticks in identical amounts of plasticine. Tell them to design an object that will be easy to spin, and one that will be hard to spin. They intuitively create a mass distribution close to the axis of rotation, and another further away from the axis. While spinning their creations, they can get a feel for why moments of inertia are important to describe rotational motion.

A traditional activity to make students aware of the conservation of angular momentum is to ask them to sit on a spinning stool while holding heavy weights in each hand. The stools is set in motion and the student can change the angular speed of the stool by extending or folding his arms.

10.6 A map of embodied knowledge

In order to design material for the soft physics studio, educators need to know what intuitive knowledge students bring to class. Fig. 20 maps the distribution of physical quantities according to results found in the literature. In the top left corner are quantities highly likely to be embodied, like momentum, that can be used as starting points. On the bottom right corners are quantities that needs to be revisited in the classroom to develop shared understandings of what they represent. It is essential to keep in mind that:

- some students have a very different map, for example a student playing basket ball could have a more acute knowledge of “throwing while moving” than her peers,
- each individual's map can change with context,
- learning can reshape the map,
• this map does not say anything about the capacity to verbalize p-prims.

Energy is in the top right corner because it is not an embodied concept per se, but students bring a variety of strong energy-like concepts and metaphors that need to be narrowed down to the meanings relevant to a physics context.

Fig. 20: Distribution of some intuitive physical concepts from very likely to be intuitive (top left) to unlikely to be intuitive (bottom right).

Designing feel-it activities requires to develop a good understanding of body sensors. For example, I now know that one cannot compare the weights of two objects by using one's hands
as a two-pan balance: What is felt by the hollow of a hand is pressure, it depends on the density and size (i.e. height) of the object. A physical response to the force of gravity is felt when holding a suitcase by the handle, i.e. feeling tension in the muscles and holding heavy objects. Experiencing with my own body can only give me clues since people have different relation to their body and various thresholds of sensitivity. Classroom adjustments are always necessary to adapt the teaching material to individual needs.

10.7 A critic of the soft physics studio

The soft physics studio can be an epistemological storm for students coming from traditional physics classes. The focus is new, the expectations are different, the freedom is not necessarily comfortable. I introduce the philosophical principles of the studio at length on the first day of class. I model new attitudes in the classroom by frequently referring to what I feel. I show examples of embodied physical knowledge: videos of acrobats, street dancers or urban bicycle free rides. But I cannot expect every student to feel at home in this new learning environment.

Do I have the right to expect my students to trust their body? How does this expectation plays in their cultural framework and personal lived experience? The soft physics studio imposes a view of physics that might discourage students willing to escape everyday life into the abstract spheres of the intellect. I once observed a student's reaction that lead me to think he felt insulted to be asked to manipulate tools. Since touch is considered a lower sense in some cultures, sensorial explorations and manual work can be seen as degrading. It can also be inaccessible: How can I adapt my discourse to students with special needs?
Is embodied experience something universally and unproblematically shared? Bodies should not be seen as anonymous because this would omit the particularities provided by gender, sexuality, class, race, age, culture, individual experience and upbringing. In the Western philosophical tradition, sexual neutrality means implicit masculinity (Irigaray, 1981). In the *soft physics studio*, I do not make claims about what things “should feel like;” I can only speak of my own experience, and remind students that individual experiences of the physical world are, thankfully, diverse.

I am aware that my project is informed by Western dichotomies, sensory values, and traditions of craftsmanship. What is worth knowing is still defined by Western norms and habits. By teaching physics, I make the choice to value a mathematization of nature: I take pleasure in talking about nature using mathematical symbols and incarnating idealized shapes. My hope is that by welcoming students' experience in the classroom, I open the door to cultural, historical, social and political forces that will enrich the scientific community. I recognize it is delicate to welcome individual metaphors while leading students to construct concepts meaningful in a physics context.

### 10.8 Sensory semiology and somatic modes of attention

Can we translate sensations into signs? Can those signs be structured, articulated and shared? For example, my uncle was a carpenter; when assembling two pieces of wood, he could intuitively tell how they would balance each other, where their centre of gravity was, according to the shape and density he could assess by hand; he could gauge lever arm by touch. As his apprentice, I could have trained my body-mind to create its own felt meanings through my *own*
sensorial experiences, a set of skilled p-prims relevant to carpentry. P-prims are often more-than-representational quantities and are therefore difficult to represent with symbols. The most efficient way to share a p-prim is to tell someone: “Feel-it for yourself.” A good example is angular momentum: I can explain a student what the concept is about, but it is hard to tell what I feel while holding the axle of a spinning wheel; the concept stays in an abstract form until the student holds the axle herself: it is only then that she has access to a felt meaning. In some cases, a student might need to repeat the experiment several times before becoming aware of the existence of momentum. We cannot tell if two persons develop the same felt meaning of angular momentum, we can only hope that they experienced the same physical quantity. P-prims form a complex and changing web, they are not articulated nor structured; they are difficult to describe and classify (see diSessa, 1993) or to organize as a system of signs. They operate like a bridge between signified and signifier. The body does not represent physical quantities in terms of symbols. It is not even good at providing relevant phenomenological analogies. Seeking a sensuous semiology is an artifact of logocentrism, a means to enclose embodied knowledge in text.

We however need a common language in the physics classroom to talk about the complex, more-than-representational quantities the world is affording us. In the soft physics studio, this structured, ordered language is physics. We do not describe our sensations, we try to associate felt quantities with physical quantities. The signified, for example angular momentum, is not only a concept, but also a generalization of a phenomenon observed and quantified by the community. The angular momentum p-pram, which can be built through touching a wheel,
constitute a felt metonym for the phenomenon. The corresponding signifier is two fold: “angular momentum” and “$\vec{L}$”. The role of the educator is to afford students opportunities to learn p-prims that can develop into phenomenological connotations of the signifier, which is essential for quantities like angular momentum, potential energy or buoyancy. On the other hand, some physical quantities are less tacit and only require “fine tuning.” For example, length, speed and time are easily accessible and only need to be refined to meet the requirements of calculus (i.e. length becomes position, speed becomes instantaneous velocity).

Most somatic physi-cal quantities need to be experienced inside the classroom: Relying on memorized somatic knowledge is often not sufficient. Students can only retrieve sensations mediated by their ontology and epistemology. I once sat at my computer to imagine the physics I could teach in a bus. My somatic memories were constrained by the lectures I had received and given. I was not aware that I was abstracting the interior of the bus from the perspective of an observer standing on the sidewalk. The first time I took a bus to test the relevance of my writing, it proved to be disconnected from my felt sensations. I had to take the bus several times, forcing my body to observe the world aside from my traditional physics conditioning, to become aware of the simple fact that my body was always bending in the direction of the bus' acceleration vector. Some students can retrieve felt memories of flying on a merry-go-round, or feeling lighter/heavier in an elevator, but we must be careful not to expect all students to bring the same memorized somatic knowledge to the classroom.

Can I make my body porous to a new sensuous semiology? Using p-prims as an educational tool is not a matter of porosity, but of focus and awareness. Our senses are collecting
a vast amount of information through our nervous system and senses, always ready for a flight or fight reaction or to inform us about our inner organs. The human body prioritizes almost instantaneously vast quantities of information, and re-prioritizes when we change focus. For example, the first time I sat on the rolling chair shown in Fig. 19, I thought: “This is ugly, made of plastic and expansive. We do not need it. We are fine with our old tables and chairs.” When I started exploring my lived world for p-prims, I realized that the very same chair could allow me the feel and play with inertia, linear momentum, lever arm, circular and rotational motion, angular speed and angular acceleration, angular momentum, Newton's laws of motion, and even collision if I added padding on the chair for safety. A soft physic studio aims at developing new modes of somatic awareness rather than making the body porous to a new sensory semiology. Acting onto a student's porosity to the lived world is against my professional ethics.

An educator can create a sensuous play field that conveys the content of the course, but she must also propose somatic guided tours of the material, that trigger a shift in student awareness of their physical environment. The teacher needs to lead students to focus on a single physical quantity at a time, and eventually one or two concomitant quantities (for example, a focus on the friction force can bring an awareness of the normal force). A student develops his own correspondences between his sensorial meanings and signifiers of the physics lexicon. The educator intervenes to help the student articulate his findings using the semiology of the physics community, i.e. language, mathematical symbols and 2D static diagrams.

Sensory values are cultural values; the way a society senses is the way it understands
(Classen, 2005, p. 161). I envision a soft physics studio as a place where to “situate the human intellect back within the sensuous cosmos” (Abram, 2010), to heal the cartesian split, to seek a reconciliation between the culture of the scientific/industrial revolutions and the flesh, a space where the body enriches the mind and the mind speaks to the body.

11. Conclusion

Each generation is the product of its era, and of its history: we carry the teachings of the past. I come from a culture that honours what was created by ancestors. Descartes's philosophy was an emancipation from Church doctrine: man, instead of God, could be the guarantor of truth. Classical mechanics explored the geometric dimension of the world; it developed hand-in-hand with technological inventions that allow us to live in warm homes, conserve food, travel the world, explore the heavens, and study germs. I am not a war with Descartes, Newton, nor my physics peers; I respect them for all they taught me. However, every generation must invent its own stories. The challenges of our times involve making peace with nature and require an expansion of our collective narratives beyond the borders of the Western intellectual landscape. Interlaced in our science stories are issues of power (cultural hegemony, class struggle, gender issues). Whose knowledges are valued? Whose voice is worth being heard? Soft physics is not about fighting the past, but about bringing in new protagonists, welcoming individual modes of meaning-making. The internet is transforming the definition of curriculum and of what should take place in the classroom. A soft physics studio acts as an anti-thesis and a complement to the online world: it is before all a community of the flesh, a sensuous laboratory where time can be spent outside the boundaries of representation, where cyborgs apprentices reconnect with handy
work. Physics is learned like a language, like an art. It becomes a celebration of individual stories of the physical world. Writing physics stories with or against of the body is more than an editorial choice: it tells a worldview. Soft physics aims at healing the body/mind split, it calls for a truce with our own nature.
References


Hicks, N. (1983). Energy is the capacity to do work – or is it? *Physics Teaching*, 21, 529-530.


Appendices

- Feel-it activities for introducing new concepts: forces, energy, mechanical work.
- Re-storying physics worksheet: regrouping Newton's First and Second Laws of motion.
- Feel-it elements in the lab: buoyancy, static equilibrium, tension forces.
## Explore forces

**Equipment:** protractor, spring scale graduated in Newton (N), wooden blocks, masses, sand paper, strings, masking tape.

<table>
<thead>
<tr>
<th>1 - FORCE OF GRAVITY (called $\vec{F}_g$)</th>
<th>2 - TENSION FORCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Take an object and drop it. Draw a diagram showing the object and the force the Earth exerts on it. Forces are represented by an arrow (also called a vector). Label this force $\vec{F}_g$.</td>
<td>A monkey is hanging from a cable. Draw $\vec{F}_g$ and the 2 tension forces, $\vec{T}_1$ and $\vec{T}_2$, acting on a hanging monkey. Such a force diagram is called a free body diagram.</td>
</tr>
<tr>
<td>b) Drop a 1g mass and a 2g mass (or whatever is available). Are they subject to the same gravity? Are they subject to the same force of gravity? Draw a force diagram for each object. Your diagram should show which $\vec{F}_g$ is larger.</td>
<td></td>
</tr>
<tr>
<td>c) Measure the magnitude (in Newtons) of the force of gravity acting on a 200g mass, using a spring scale: Describe the force of gravity (also called weight) of the object: magnitude = _______ (unit: _______) direction: _________</td>
<td></td>
</tr>
<tr>
<td>d) Calculate the magnitude of the force of gravity acting on a 200g mass (= 0.200kg) using the equation $F_g = mg$. Use $g = 9.81 \text{ m/s}^2$. Compare to the magnitude you measured and conclude</td>
<td></td>
</tr>
<tr>
<td>e) In your own words, explain the difference between “mass” and “weight” (also called force of gravity) – You can use the internet or your textbook if you are not sure.</td>
<td>Hang a 1000g cylinder onto a horizontal piece of string. Hold the string with both hands. Reflect on what you feel in your hands (Can you make the string perfectly horizontal? Why or why not?)</td>
</tr>
</tbody>
</table>

Break down each of the two tension forces into its vertical (up/down) and its horizontal
(left/right) components. Which components are used to hold the kitten?

<table>
<thead>
<tr>
<th>3 - NORMAL FORCE (called $F_N$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3.1</strong> Place a 500g object on the back of your hand.</td>
</tr>
<tr>
<td>a) What are the two forces acting on the object? Draw a free body diagram for the object. The length of a vector arrow represents the magnitude of the vector. If two forces have the same magnitude, the arrows must have the same length.</td>
</tr>
<tr>
<td>b) In physics, “normal” means “at a right angle.” Draw the normal force for:</td>
</tr>
<tr>
<td>i) A box resting on the floor:</td>
</tr>
<tr>
<td>ii) A ladder resting on a wall:</td>
</tr>
</tbody>
</table>

| 3.2 a) Draw a free body diagram for yourself standing up on the floor. Close your eyes and try to feel the normal force exerted by the floor on your feet (hard!). |
| b) Draw a free body diagram for yourself sitting on a chair. Close your eyes and try to feel the normal force exerted by the chair on your body. Several possible answers. |

| 6) Assume you just put on 50 kg. Draw the forces acting on your body. Use vectors with the same scale as in a). |
| d) Describe and justify the differences between a) and c) |

| 3.3 a) Hold your hand at shoulder height. Hold a wooden block with the back of your hand. Draw a free body diagram for the block. |
| b) Place a mass on top of the wooden block. Draw a free body diagram for the \{block + mass\}. |
c) Describe all the differences between situations a) and b)

Things will look different if you place the 500g mass on a water surface, on play dough or on a wooden table. The molecules of the table act like tiny springs that hold the mass: the wood is rigid. This capacity to hold is described by the normal force: even passive/inert objects like a table can exert a force on an object.

3.4 Place the wooden block on the table. Draw a free body diagram for the block.

3.5 Place the wooden block on the table and a 500g mass on top of the block. Draw a free body diagram for the block. Show that the 500g mass is pressing onto the block (they are in contact so there is a normal force there too).

3.6 Place a coarse sand paper on your palm, and the wooden block on top of it. Tilt your hand to the maximum possible angle (you don't want the block to start sliding). What would you call the force that prevents the block from sliding?

Draw the 3 forces acting the block. Make sure that the force of gravity is vertical.
## 4 – FRICTION FORCE (called $\vec{f}$)

### 4.1 Direction of the friction force on a block on a horizontal hand

Use a block that is already covered in sand paper.

<table>
<thead>
<tr>
<th>a) Place the block on your horizontal hand palm and pull on the side to make it slide to the right. Draw the direction of the friction force?</th>
<th>b) Now place the block on your horizontal hand (no pull). Quickly move your hand to the right while carrying the block. Draw the direction of the friction force acting on the block?</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Block Diagram" /></td>
<td><img src="image" alt="Block Diagram" /></td>
</tr>
<tr>
<td>c) Some people say “the friction force always acts in the direction opposite to the motion” is wrong. Give an example that proves them wrong.</td>
<td>d) Give a general definition of the direction of the friction force</td>
</tr>
</tbody>
</table>

### 4.2 Magnitude of the friction force (for a static block on a horizontal hand)

Use a block covered in sand paper.

<table>
<thead>
<tr>
<th>a) Place the block on your horizontal hand palm. Draw a free body diagram for a block. This is your reference diagram.</th>
<th>b) Pull very slightly sideways on the block. The block should not be moving. Draw a free body diagram for the block.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>c) Pull harder on the block, but the block should be static (i.e. not moving). Draw a free body diagram for the block. Increase the length of the $\vec{f}$ vector if needed.</td>
<td>d) Describe what happens to the magnitude of the friction force, $f$, as you pull harder on the block?</td>
</tr>
</tbody>
</table>
e) Does the friction force increase in magnitude?

f) Some people call the friction force a “smart” force. From your observations, what could make them think that way?

f) What happens to the block when $f$ reaches its largest possible value?

g) What happens to the block when the pull by the string becomes larger than the maximum possible value for $f$?

h) Place a 0.200 kg mass on top of the block and try to pull on the block so that it is about to slide. Why is the friction force now larger than in question f)?

---

Static and kinetic friction

i) Place the block wrapped in sand paper on a spot where your skin is sensitive, like the palm of your hand. Tilt your hand. How does the friction force feel? Now rub the block against your skin. How does it feel? Write down your feelings for:

<table>
<thead>
<tr>
<th>The static(^{36}) friction force</th>
<th>The kinetic(^{37}) friction force</th>
</tr>
</thead>
</table>

j) Go home and read your textbook (Chapter 1: Forces)

---

36 Static = not moving
37 Kine is the Greek for motion
Block at rest on an inclined plane (i.e. on a board)

Material to be collected before you start: a white board, a block, two pieces of sand paper, protractor, spring scale (optional).

Goal: You will study what happens to the force of gravity, the normal force and the friction force if you place a block on a white board and then tilt the white board until the block starts to slide.

Action 1: Tape sand paper on the block and on the board, to make sure you can observe a large friction force between the two. Position the block on the board, then lift one side of the board. Record the angle for which the block is about to slide. The name of this angle is $\Theta_{\text{max}}$ (say "theta max")

$$\Theta_{\text{max}} = \theta$$

Action 2: The block is at rest on a horizontal board. It is not moving (we say it is "STATIC"). The block is not about to change its state of motion (we say it is in "EQUILIBRIUM"). Draw a free body diagram for this situation, i.e. all the force vectors acting on the block (ask yourself: how many forces are acting on the block? Is there friction?) Don't forget to label the force vectors (with $\vec{F}_g$, $\vec{F}_N$, $\vec{f}$, $\vec{T}$ etc)

Action 3: Tilt the board by an angle of roughly $\frac{1}{2}\Theta_{\text{max}}$. Draw a free body diagram for the block.
Make sure that the three force vectors add up to zero, i.e. that the block is in equilibrium.

Action 4: Tilt the board by an angle $\Theta_{\text{max}}$. The block is about to slide. Draw a free body diagram for the block. Make sure that the three force vectors add up to zero.
Compare situation #4 to situation #3:

a) Did $\vec{F}_g$ change in any way?

b) Describe the changes undergone by $\vec{F}_N$

c) Describe the changes undergone by $\vec{f}$

**Action 5:** Tilt the board an angle larger than $\Theta_{max}$. The block slides.

Is the balance of the forces "broken"? If so, which force component is "winning," i.e. responsible for the sliding of the object? (Be very specific)

**Reflections:**

a) Describe the changes in the magnitude of $\vec{F}_N$ as you increase the tilt from 0 to $\Theta_{max}$ (increasing, decreasing, reaching a maximum value, etc).

b) Describe the changes in the magnitude of $\vec{f}$ as you increase the tilt from 0 to $\Theta_{max}$ (increasing, decreasing, reaching a maximum value, etc).

c) How could you modify the apparatus so that you could increase the tilt of the board even more before that block starts to slide?

d) How would your free body diagram change if the mass of the object was multiplied by 10? (Don't do nay calculation!)
Block sliding on an inclined plane

In this part, you make the block slide from the top of the tilted board by giving it an initial push. You can use any angle for the tilt of the board. **You study the motion of the block after it has lost contact with your hand, so after the initial kick.**

Studying friction in the case of a sliding block is very different from a STATIC block. Here \( \vec{f} \) does not adjust its magnitude to prevent sliding and does not reach a maximum value. Here the magnitude of \( \vec{f} \) only depends on the two types of material in contact (i.e. block and board).

**Action 7:** Choose an inclination for the board that makes the speed of the block increase as it slides down. Draw a diagram describing your apparatus. Tell if you used sand paper or not. Record the angle between the board and the horizontal. Draw a free body diagram for the block. *Hint: which is “winning”, \( F_{gs} \) or \( \vec{f} \)？

**Diagram of the set up diagram**  
(with labels)

**Free body diagram (i.e. force vectors**

**Action 8:** Choose an inclination of the board so that the speed of the block strongly decreases as it slides down the board. Draw a diagram describing your apparatus. Tell if you used sand paper or not. Record the angle between the board and the horizontal. Draw a free body diagram for the block.

**Diagram of the set up**  
(with labels)

**Free body diagram**
**Action 9:** Tilt the board so that the speed of the block is constant as it slides down the board. Draw a large free body diagram for the block. Draw the length of each force vector carefully.

Draw the velocity vector of the block (its magnitude is the speed of the block, its direction is the direction of the block's motion). This vector should be drawn *on the side*, so that it cannot be confused with a force vector.

Are the three forces acting on the block balancing each other?  

| YES | NO |

This situation is called a "DYNAMIC EQUILIBRIUM". We say "DYNAMIC" because the block is moving. Why do you think we call this situation an "EQUILIBRIUM?"
Newton's Laws – Practice sheet

You work as an engineer. For each of the following situations

a) Would you estimate the friction force acting on the object to be negligible, weak or strong?

b) Draw a free body diagram for the object set in motion.

c) Draw a free body diagram for the object moving at a constant velocity.

d) Propose a way to make the object slow down and draw the corresponding free body diagram.

| Situation 1: A soap bar was given an initial push by a baby. The soap bar is now sliding on its
own on the wet smooth horizontal surface of the bathtub at a constant velocity. |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a) friction force:</td>
<td>negligible</td>
<td>weak</td>
<td>strong</td>
</tr>
<tr>
<td>b) Set in motion</td>
<td>c) Constant velocity</td>
<td>d) Slows down</td>
<td></td>
</tr>
</tbody>
</table>

| Situation 2: | A heavy cardboard box received a strong push from a
mover. It is now sliding on a dry wooden floor at a constant velocity because the mover keeps pushing it. Hint: The friction force can
static or kinetic. |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
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</tr>
<tr>
<td>b) Set in motion</td>
<td>c) Constant velocity</td>
<td>d) Slows down</td>
<td></td>
</tr>
</tbody>
</table>
**Situation 3:** A student set her bicycle into motion by pedalling. She is now driving the bike at a constant velocity on a flat road. There is no wind.

<table>
<thead>
<tr>
<th>b) Set in motion</th>
<th>c) Constant velocity</th>
<th>d) Slows down</th>
</tr>
</thead>
</table>

**Situation 4:** A car is driving at a constant velocity.

a) Friction/air drag (compare to the other forces acting on the car. Assume $F_s = 15000N$): negligible weak strong

<table>
<thead>
<tr>
<th>b) Set in motion</th>
<th>c) Constant $\vec{v}$</th>
<th>d) Slows down</th>
</tr>
</thead>
</table>

**Situation 5:** A bowling ball was set in motion by a player. It is now rolling, on its way to strike pins.

a) Friction force/air drag: negligible weak strong

<table>
<thead>
<tr>
<th>b) Set in motion</th>
<th>c) Constant $\vec{v}$</th>
<th>d) Slows down</th>
</tr>
</thead>
</table>
**Situation 6:** A sternwheeler moves at a speed of 10 meters per second on a Canadian lake. The boat was set in motion by a large rotating wheel at the back of the boat. Assume there is a weak drag between the boat and the water.

Reflect on how you can slow down the boat...

<table>
<thead>
<tr>
<th>b) Boat set in motion</th>
<th>c) Constant velocity</th>
<th>d) Boat slows down</th>
</tr>
</thead>
</table>

**Situation 7:** A spaceship is entering the outskirts of the solar system, but is so far away that it hardly feels the force of gravity from the Sun and Jupiter. There is no friction acting on it.

Reflect on how you can slow down the spaceship.

<table>
<thead>
<tr>
<th>b) Set in motion</th>
<th>c) Constant velocity</th>
<th>d) Ship slows down</th>
</tr>
</thead>
</table>

Reflexion: How can you change the direction of the motion of a spaceship?


**Mechanical work**

1 - Defining work

Your shopping cart is full. When you push your shopping cart to set it in motion, you are transferring energy from your muscles to the cart. We say that you transfer work to the cart and that the cart gains energy.

The unit for work is Joule (J), like the unit for energy.

Once your shopping cart is in motion, there is friction between the wheels of the cart and the ground. If you stop pushing, the cart will eventually come to a stop. So you need to keep pushing, i.e. transferring work to the cart. Meanwhile, the friction force is dissipating some of the carts' energy into the environment. If you want your cart to move at a constant velocity, you need to exactly balance the losses due to the friction.

1-1) The amount of work you transfer to the cart depends on several parameters. You have a good intuition of these parameters, so **rank the following situations from least to most work transferred to the cart:**

- You push the cart as shown in the picture with a force of 40N over different displacements:
  \[ \Delta x = 50\text{m} \quad \Delta x = 10\text{m} \quad \Delta x = 20\text{m} \]

- You push the cart as shown in the picture over a displacement \(\Delta x = 10\text{m}\) with a horizontal force \(F\) if:
  \[ F = 20\text{N} \quad F = 100\text{N} \quad F = 40\text{N} \]

- You push the cart with a force of 40N over a displacement \(\Delta x = 10\text{m}\) at various angles. What is the most effective way of transferring energy from your arms to the cart? Rank from least effective to most effective:
1-2) One of my students once said: "OK, so when I try to transfer energy to an object, the push that is not in the direction of the motion is wasted." On the diagrams below, label the component of the push $\vec{F}$ that is used to transfer energy to the shopping cart and the component that is "wasted."

1-3) To define the work done by a force $\vec{F}$ on an object, we first draw an $x$-axis in the direction of the motion (i.e. the direction of $\vec{v}$), then we define the work done by $\vec{F}$, $W_F$, as:

$$W_F = F_x \Delta x$$

Explain why this equation uses $F_x$, the component of $\vec{F}$ in the direction of the motion. **Include a diagram:**

1-4) Why are carts built with a handle at elbow height?

1-5) a) Imagine and describe a situation where your body transfers energy to a ball in the form of kinetic energy.

b) Imagine and describe a situation where your body transfers energy to a ball in the form of potential gravitational energy
2 – Positive and negative work.

- Whenever the work done by a force on the cart “helps” the motion (i.e. the force is in the direction of $\vec{v}$), the energy of the cart increases: $W_F > 0$
- Whenever the work done by a force on the cart “is against” the motion (i.e. the force is opposite to $\vec{v}$), the energy of the cart decreases: $W_F < 0$

Say if the following forces are doing positive or negative work on the carts:

3 – Work done by a force perpendicular to $\vec{v}$

In the following cases, tell if the force is transferring energy to the object (note: these are not free body diagrams, only one force is shown).
Mechanical Energy

Part 1: Kinetic energy, $K$

1) Work in pairs. Sit down on the floor 3 to 5 meters apart. Student #1 rolls balls in the direction of student#2. Student#2 stops these objects with the palm of a hand. Try with objects of different masses and rolling at different speeds. By setting the object in motion, student#1 is transforming muscles energy into energy of motion called kinetic energy, $K$. By stopping the objects, student#2 is absorbing kinetic energy in her/his hand. Do it for 3 different objects for which kinetic energy is markedly different.

Does $K$ depends only on speed? YES NO

2) What does the kinetic energy of an object, $K$, depend on?

3) Rank the following situations in order of increasing $K$.
   A 30-ton truck driving:
   a) at 20 km/hr b) at 110 km/hr c) at 50 km/hr

4) Rank the following situations in order of increasing $K$.
   The following animals all move at a speed of 5 m/s:
   a) A rabbit b) A cheetaah c) A whale

5) Knowing that $K = \frac{1}{2}mv^2$, rank the following by increasing $K$. Show your calculations.
   a) A 70 kg sprinter running at 10.0 m/s
   b) A 12 kg dog running at 8.00 m/s
   c) A 52 kg lion running at 12.0 m/s

7) Imagine and describe a case of an object losing $K$:  

Equipment: heavy and light rolling objects, meter stick, stopwatch, scale, pendulum.
Part 2: Potential energy, $U$

1) Hold a very heavy object one meter above your foot. Ask your foot: “Is there energy stored in this object?” Your foot answer “Ooohh! I bet there is! Don't drop that ball!” This energy is called potential energy, $U$. Define potential energy in your own words:

2) You hold three different objects 1 m above your foot. Rank them by increasing potential energy:
   a) A bowling ball
   b) A calculator
   c) A pencil

3) You hold a bowling ball above your foot. You place a vertical meter stick on the side, so that you can record the position $y$ of the centre of the ball. Rank the following cases by increasing potential energy:
   a) $y = 50$ cm
   b) $y = 1.20$ m
   c) $y = 2.0$ cm

4) Imagine you could hold a bowling ball 1.0 m above your foot in three different locations:
   a) The Moon
   b) The Earth
   c) The international space station (“micro gravity”)

   Rank these three cases in order of increasing potential energy of the ball: __________________

5) What three parameters does $U$ depend on? __________________

6) Propose an equation for $U$: ___________________________ (Check in your book or online!)

7a) Take an object and hold it 1.20 m above the ground. Weigh the object. Calculate its potential energy. Use $g = 9.81$ m/s$^2$.

7b) Hold the same object 1.20 m above the floor, then move it horizontally above your table. Hold a vertical meter stick to symbolize the $y$-axis. Explain why the potential energy of the ball does not change in the process (Hint: origin of the $y$-axis).

8) Imagine and describe a case of an object losing $U$ and gaining $K$:  

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Part 3: Mechanical Energy
Mechanical energy is defined as $E = K + U$. We can represent $E$ by a bar diagram. Notice that $E$ per is not a bar: only $K$ and $U$ are represented:

![Mechanical energy bar diagram]

If there is no non conservative force (i.e. no pull/push/friction force) acting on an object, $E$ is constant. Example of situations where $E$ is constant are: an oscillating pendulum, a ball in free fall, a ball rolling down an inclined plane (assuming air drag is so small compare to other forces, it can be neglected).

1) Make the pendulum (= a bob hanging on a string) swing. For each of the following positions of the bob, draw a $E$-bar diagram.

- Highest position to the left
- Somewhere between highest and lowest
- Lowest position

2) Place the ball at waist height. Throw the ball in the air to give it an initial velocity. *Once the ball as left your hand*, it is in free fall. Draw a $E$-bar diagram for the following positions of the ball:

- Initial
- Highest
- Final (= ball about to hit the ground)

3) **Harder questions.** Roll a ball down an inclined plane. Draw an energy bar diagram for the ball at the top and at the bottom of the plane. *Beware: you need 3 energy bars in your diagram this time because the ball is rolling; it has both a linear (i.e. straight line) and a rotational (i.e. rolling) motion.*

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