Physics, smartphones and 3D-print technology : a digital-transition case study in science education

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Abstract
We describe the stages of technological development in a 4-year project designed to adapt college-level physics education to the realities of the digital era. Leveraging multiple complementary innovations, it is used as a case study in understanding more generally how technological transitions take place in an educational setting and, in particular, in the education of students in science and engineering fields.

The complete lifecycle of technological-change projects is examined including an evaluation of longer-term challenges that include the development of new competencies in teachers and support staff, and the need for investments in equipment in participating educational institutions. Québec`s recent Digital Action Plan is used both as a reference funding framework for discussion, and as an example of how individual technology-based projects can indirectly benefit from broader government investments that target the college network as a whole.

Introduction

Science education in a digital landscape
Today's students are increasingly immersed in a digital landscape. Their primary source of experience is now mediated through mobile screens and laptop monitors instead of direct interactions with the physical world[1], [3]. This new reality has important implications for science pedagogy and, in particular, for physics education[4]–[7].

A cornerstone of science education is the establishment of links between general theories and the application of those theories to specific phenomena in the everyday world. To ensure science students continue to be engaged, educators must renew their repertoire of classical examples with digital-era ones that are more relevant to the new world in which students now live.

For today's students, the everyday world of physics is no longer the experience of sliding down a ramp or throwing a baseball: it is more noticing how their smartphone screen automatically transitions from portrait to landscape mode. Indeed, smartphone behaviours of this type are the starting point for the kind of digital-transition project we will be describing in this paper.

Transformation of content vs. transformation of content delivery
The digital revolution has produced a vast array of information-technology (IT) tools that are transforming the way we communicate with and deliver content to students, independent of the subject matter. This type of transformation has been and will continue to be widely discussed in the education-research literature [8], [9],[10] but is orthogonal to the digital transition we discuss here: The former transformation changes the manner in which content is delivered, whereas the latter involves a change in the content itself. The former involves an adaptation and then an exploitation of tools made possible by technology; the latter, as we shall presently explain, incorporates into the curriculum itself an understanding of digital technology itself and its associated data-processing paradigms.

Classical physics meets the digital world
A major impediment to the latter transformation is the fact that curriculum content is a zero-sum game, to borrow a term from game theory: If we add new content related to digital technologies, we usually have to remove some traditional content to make room for it. The strategy is to conceive of examples of

digital-world behaviours that illustrate traditional scientific concepts. In this manner, we keep the traditional content intact, replacing only traditional *examples* with digital-era ones.

Our challenge, then, is to find, within the ideas and concepts of digital technology, examples that illustrate classical physics concepts. The project in our case study does exactly that by carefully designing activities in which students examine modern smartphone behaviours that illustrate fundamental physical principles.

The general potential for smartphones to enhance the classroom experience has been discussed widely, [11]–[13], including in the present journal [14]. This has been investigated for some time within the physics education research community: earlier attempts examined handheld devices such as the Nintendo Wiimote [15], with the much more versatile smartphone devices [16]–[19] including tablets [20] quickly becoming of greater interest.

The project we will discuss here builds on these initiatives and has itself been described in various international journals [21]–[24]. It has also been extensively promoted locally[25]–[29] and in some cases [30], [31], published in both official languages. It provides a series of laboratory activities that rely on the accelerometer motion sensors found in current-generation smartphones. An additional digital-era component is found in the laboratory apparatus used for each activity, as they are built using 3D-print technology.

Quebec's Digital Action Plan

The Quebec government has long recognized the need for stimulating and supporting systemic change in its educational system. At the collegial level specifically, it administers a number of programs[1] which have been increasingly geared towards digital literacy. Our case study, for example, is in its 4th year of funding through such programs[32]–[34].

The Quebec government recently deployed its Digital Action Plan[35], an ambitious multi-year project for carrying out a digital transition across the entire Quebec educational system. It recognises three broad categories of activities and investments as listed in Table 1.

Table 1: High-level orientations of the Digital Action Plan

Orientation	Description
1	Support the development of the digital skills of young people and adults
2	Make use of digital technologies to enhance teaching and learning practices
3	Create an environment conducive to the development of digital technologies in the education system

[1] Programme de recherche et d'experimentation pédagogiques (PREP) ; Programme d'aide à la recherche sur l'enseignement et l'apprentissage (PAREA); Entente Canada-Québec relative à l'enseignement dans la langue de la minorité et à l'enseignement des langues secondes (ECQ); College researcher programme of the Fonds de Recherche du Québec (FRQNT); Persévérance et réussite en sciences à l'enseignement supérieur (PRPRS).

The framework as a whole is quite comprehensive. Indeed, it can for this reason serve as checklist even for stakeholders evaluating projects that are not directly funded by it, such as the one we describe here. The last orientation in the table, accounting for 70% of the budget, pertains to infrastructure investments, some of which, as we shall explain below, would be particularly conducive to the digital-technology development goals of the project that we shall be examining here.

Digital-era laboratory activities

In our case study, the project's initial goals were to develop a new set of laboratory activities involving devices and phenomena that are specific to the digital age. Such activities have to meet the condition that they reinforce student learning and integration of the classical physics principles identified in the existing college-level physics curriculum. Trials would be carried out with individual students iteratively until the activities were considered ready for use in a full-classroom setting.

Accelerometers and smartphones

Accelerometer sensors were quickly identified as a promising category of device for students to explore. The concept of acceleration is ubiquitous in physics, but students often have difficulty with it, and most laboratory activities only obtain acceleration values by performing calculations on data related to the position of objects. Accelerometers are devices that can measure accelerations directly, potentially making the concept of acceleration more accessible to students. They are widely used for mobile motion sensing, including smartphones, sleep-monitoring and fitness-monitoring devices.

Recent advances in micro-electromechanical (MEMS) sensors[36] have made these devices small, inexpensive and accurate enough to produce reliable results. A wide variety of stand-alone accelerometer devices were acquired and tested for reliability, configuration options and workflow usability.

Smartphones also host accelerometer sensors, and there are an increasing number of apps available that enable students to view and collect the data from them. By the end of the first year of trials, it was clear that smartphone apps, on both Android and iOS platforms, were reliable and supported a simple data workflow. Smartphones quickly became the device of choice for laboratory activities. An additional element of student engagement was gained through the pride and fascination students experienced in using their very own familiar smartphone devices for an entirely new purpose.

Portrait-landscape transitions

The first promising activity involved an exploitation of the familiar portrait-landscape transition that automatically occurs when changing the orientation of a smartphone. This takes place typically when using photo-viewing or texting apps. Students are instructed to carefully measure the critical angle at which this transition takes place, and to interpret the corresponding output of the actual accelerometer sensor which the smartphone uses to track such orientations. By examining the accelerometre data, students deduce the critical angle that they had originally measured by other means.

The activity is a digital-age replacement for the classical example widely known as ``the inclined plane``. The same fundamental physics concept is covered: the decomposition of the gravitational vector into components along the axes of an inclined frame of reference; in this case, the frame of reference of the smartphone. Additional skills include understanding the difference between global and local coordinate systems, and the determination of the angle of a component-form vector as summarised in Table 2.

Spinning smartphones

A second successful laboratory activity involved spinning the students` smartphones and examining the resulting acceleration output. Student engagement was elicited, this time, by the vague sense of danger produced in seeing their beloved phones spinning quickly. The accelerometer output, in this case, demonstrates the principle of centripetal acceleration, a quantity that exists even when an object is rotating at a uniform rate.

A particular insight arises in the students when they are able to conclude that, regardless of where they place the phone on the rotating surface, the acceleration vector always points towards the center of rotation. In addition, they can carry out some *bona fide* digital-era reverse engineering: By putting together the results from multiple positions, they are able to conclude where exactly the accelerometer sensor is located within the body of the phone. They can then obtain circuit diagrams of their own model of smartphone to obtain visual confirmation of the result they obtained.

Table 2: Properties of two sample lab activities

Title	Classical concept	Competencies	3D-printed apparatus
"Investigation of the inclined plane using smartphones and the TiltTray"	the inclined plane	gravity; normal forces; vectors; local and global coordinate systems; data processing;	the "TiltTray"
"Rotational motion using smartphones and the SpinFrame"	centripetal acceleration	vectors; centripetal acceleration; local and global coordinate systems; data processing;	the "SpinFrame"

3D-printed equipment

Each laboratory activity comes with its own apparatus requirements. The design and choice of building materials are themselves important considerations that are often overlooked in the development of laboratory activities. 3D-print technology is becoming an increasingly attractive option: the total cost of ownership for 3D printers is decreasing regularly, and the printed objects themselves cost very little in materials[37]. It also allows prototypes to be designed, used and improved upon in an iterative manner. This has important implications for the long-term project survival which we will discuss presently. Finally, apparatus that can be printed from an electronic file is attractive and easy to share with colleagues at other colleges

For the portrait-landscape experiment, an apparatus dubbed the “TiltTray” was developed, a set of which is depicted in Fig. 1. It holds smartphones of a variety of shapes on an inclined place that can be set to any desired angle. It has a built-in protractor for accurate direct measurement of the angle of incline.

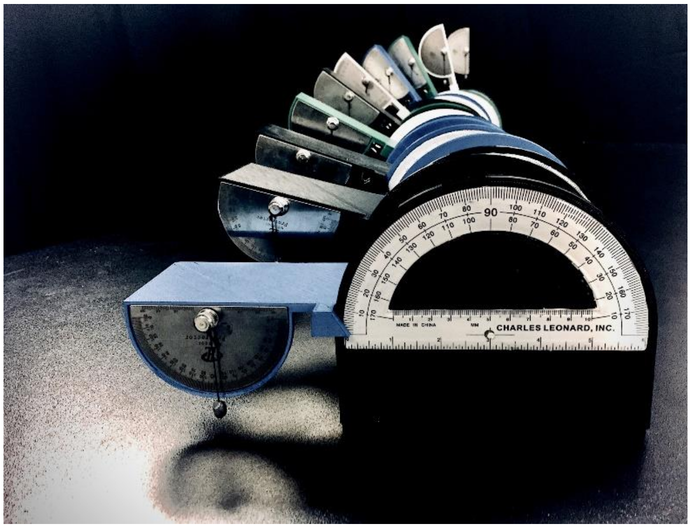

Fig. 1 A set of 3D-printed TiltTray apparatuses

For the spinning smartphone, another apparatus, dubbed the “SpinFrame”, was developed. It consists of an 8-1/2-by-11-inch rectangular frame that perfectly admits a standard piece of paper, and on top of which is placed the smartphone. The frame prevents the phone from slipping off of the rotating surface and provides reference positions to measure from. The frame sits on top of a record player adapted to the purpose.

Both of these apparatus are in fact “mixed media” objects: The TiltTray requires a conventional protractor to be glued into place on the 3D-printed surface; The SpinFrame has a motorized base that is bought off-the-shelf in the form of an inexpensive record player. One of the consequences is that there is some assembly required and, therefore, the necessity of documenting parts, materials and assembly instructions.

Project evolution

The technology-adoption process

Each lab activity is refined in an iterative manner by running pilot projects with individual students and adjusting the written lab instructions accordingly. Additional iterations take place with full classrooms of students, at which point the activity is made available to other teachers for adoption. The first early adopters were colleagues in the same Physics department as the project initiator. The next ones were teachers in the Engineering Technologies program of the same college.

As the instructions matured, they began to be made available to teachers at other colleges for extramural adoption. As usage grows, variations and improvements on the original lab activity occur. These become new resources to share within the network of participating colleges, contributing to the overall collective benefit. Table 3 summarises the to-date historical usage[2] of the two sample labs described above.

Table 3: Usage history of lab activities

year	semester	lab activity	department	college	# classes	# students
2017	Fall	TiltTray	Physics	John Abbott	0	4
		TiltTray	Physics	John Abbott	1	40
2018	Winter	SpinFrame	Physics	John Abbott	0	3
		TiltTray	Physics	John Abbott	4	160
		SpinFrame	Engineering Technologies	John Abbott	1	25
		TiltTray	Engineering Technologies	John Abbott	1	25
2018	Fall	SpinFrame	Physics	John Abbott	0	1
		SpinFrame	Physics	John Abbott	4	160
		SpinFrame	Physics	Marianopolis	0	1
		SpinFrame	Physics	Marianopolis	1	30
		TiltTray	Physics	John Abbott	0	1
		TiltTray	Physics	Marianopolis	1	30
		TiltTray	Physics	John Abbott	7	280
2019	Winter	SpinFrame	Physics	Marianopolis	11	330
		SpinFrame	Engineering Technologies	John Abbott	1	25
		TiltTray	Engineering Technologies	John Abbott	1	25
		TiltTray	Physics	Marianopolis	3	90
		TIltTray	Physics	John Abbott	4	160
2019	Fall	SpinFrame	Physics	Vieux-Montréal	1	30
		TiltTray	Physics	John Abbott	4	160
		SpinFrame	Physics	Marianopolis	8	240
		SpinFrame	Physics	John Abbott	4	160
2020	Winter	SpinFrame	Engineering Technologies	John Abbott	1	25
		TiltTray	Engineering Technologies	John Abbott	1	25
		TiltTray	Physics	John Abbott	1	40
		TiltTray	Physics	Vieux-Montréal	2	41
		SpinFrame	Physics	Vieux-Montréal	2	41
		TiltTray	Mechanical Engineering	Vieux-Montréal	1	15
		SpinFrame	Mechanical Engineering	Vieux-Montréal	1	15
		SpinFrame	Physics	Marianopolis	11	*340
				Totals	77	2135

Enlarging the reportoire of lab activities

The two activities described above cover the classical topics of inclined planes and circular motion. Additional lab activities continue to be developed using the same digital-era tools. These include experiments that explore oscillations; that develop 3D spatial reasoning for the purpose of understanding magnetic phenomena; and that identify hand-drawn alphabet symbols from accelerometer signals.

[2] The last usage item with the asterisk was cancelled due to the COVID-19 pandemic. It is excluded in the grand total sum.

3D-print capability in the college network

The use of 3D-print technology to design and produce the supporting equipment for the lab activities opens up an exciting new category of sharing and collaboration between colleges. Adopting colleges can now not only download and print the (paper) instructions for the lab activities, but also the (3D-printed) equipment that the students will be manipulating during that very activity. A freely-available resource package contains all the necessary documents described in Table 4.

Table 4: Elements of the open-source educational resource package

Category	Item
Lab activities	Instructions for students
	App instructions (installation, usage)
	Teacher notes (duration, competencies, strategies)
	Presentation material for accelerometres
3D-printable equipment	3D-modeling source files
	Universal 3D format files (.STL)
	3D-printing guide
	Construction guide (parts, materials, assembly instructions)

Such a forward-looking vision was made possible only because of the technological lead of the college[3] hosting the project: It had already invested in a dozen 3D printers for its Engineering Technologies program, including a large-volume printer; and had acquired the not-to-be-overlooked skills of lab technicians in calibrating and maintaining the equipment, and in assisting students and faculty members in their use.

Indeed, this novel delivery model (paper-printed instructions plus 3D-printed equipment) assumes a certain level of *3D-print capability* in adopting colleges, which includes investments in both 3D-print equipment and in the training of personnel for its effective operation. Such capability is only beginning to emerge within the college network. Four years into the project, all equipment is still being produced using the 3D-print farm at the hosting college and lent on a temporary basis to the external early-adoption colleges. Initial 3D-print trials have taken place at three other colleges[4] in the network, but none are yet at the capability level of producing a full-classroom set for their exclusive internal use.

Discussion

Infrastructure investments: a symbiotic relationship

As discussed previously, the advancement of the 3D-print component of the project, and thus of the project as a whole, depends on the degree of 3D-print capability within the college network. Although no systematic evaluation of this capability has been undertaken, current project experience suggests

[3] John Abbott College, St-Anne-de-Bellevue, Quebec
[4] Marianopolis College (Physics), CÉGEP Vieux-Montréal (Industrial Design) and Dawson College (Physics).

that it has been generally lacking; and that, in this sense, the project appears to be lamentably ahead of its time.

With the recent deployment of the Digital Action Plan, however, the situation looks altogether different. Section 3 of the Plan (see Table 1), representing the bulk of the funding, concerns network-wide investments in infrastructure, wisely combined with a freedom granted to individual institutions in making strategic choices in equipment purchases. One of the possible investments colleges may choose is in building up their 3D-print capability.

This has the potential of producing a valuable symbiotic relationship. For the project at hand, it reduces the barrier to adopting the lab activities: It becomes attractive and inexpensive when both lab instructions and lab equipment can be printed locally. For the architects behind the Digital Action Plan, it ensures investment choices that contribute to visible and world-class uses of technology in a classroom setting, all the while ensuring equal accessbility for even the most remote 3D-print-capable locations within its geographical territory.

From the point of view of college administrators, the project is a seldom and welcome example in which some of their infrastructure investment is being used for a purpose that is both tangible and visible: There is a concrete image of their own locally-printed laboratory equipment being used for the benefit of engaged students learning physics through the use of their own smartphone sensors.

3D-print capability: New competencies for teachers and support staff

3D-print capability involves much more than just the acquisition of equipment. Both teachers and support staff need to develop skills with 3D modeling software that is used to specify the shapes to be printed, and become familiar with the workflow from 3D modeling file formats to the final printed object. A key element is the training of support staff for the calibration and maintenance of the equipment, as well as for the management of the various print requests and of the supply of 3D filament.

Administrators need to ensure that their investment can benefit multiple stakeholders effectively; and, hopefully, find ways to make it foster collaborations between departments and between categories of employees. Indeed, in our case study three of the currently-participating colleges have teachers collaborating closely with lab technicians in the development of their 3D-print capability. The project has also stimulated significant collaborations between the departments of Physics and Engineering Technologies at one college[5], and between the departments of Physics and Industrial Design in another[6].

The project, therefore, can serve i) as a stimulus for adapting and integrating personnel into the new workflow implied by 3D-print technology, ii) as a concrete example of a comprehensive 3D-print project that is purposeful and pedagogically oriented iii) as a model and creative stimulant for future projects within such educational institutions.

The Digital Action Plan: a reference framework

In this case study, we have a interesting situation in which one type of innovation (3D-printed equipment) is co-developed in support of another innovation (lab activities using smartphone sensors).

[5] John Abbott College
[6] CÉGEP Vieux-Montréal

Although there are significant interactions between their parallel and inter-dependent development, they nevertheless follow two broad phases characteristic of most educational-innovation projects.

In the establishment phase, they begin with ideas and sketches; are elaborated as prototypes; are iteratively tested and improved through pilot programs with individual students, and then with individual teachers in a classroom setting. In the elaboration phase, they are shared with more practitioners, usually in the same department or college as the project initiator. An important milestone is the adoption of the innovation by practitioners outside of the initiating college. The extramural adoptions (see Table 3), in turn, bear witness to the value of the innovations, and signal a level of project maturity in which a plan for broader deployment within the college network can be considered.

Each phase of development involves new priorities for the further development of the project. In the first phase, the emphasis is in providing to teachers the resources needed for carrying out the laboratory activity itself. In the second phase, a bottleneck to further elaboration is the need to support the development of 3D-print competencies in teachers and support staff. These two concerns correspond to the two categories of resources identified in Table 4. In the broader deployment phase, the bottleneck lies, as discussed, in the availability of 3D-print equipment in the adopting colleges.

It is instructive to interpret these development challeges in terms of the framework provided by the aforementioned Digital Action Plan. Indeed, as summarised in Table 5, it is clear that the Plan is comprehensive enough to account for all the categories of support identified in this Discussion.

Table 5: Sections of the Digital Action Plan relevant to the case study

General topic	Specific measure	Reference			
		Orientation	Area of intervention	Objective	Measure
Pedagogical project development					
	Promote innovative pedagogical practices and the potential of digital technologies in education	1	2	1.3	08
	Support the acquisition and development of digital educational resources	2	3	2.1	11
	Encourage innovative projects involving digital technologies	2	3	2.1	12
Acquisition of equipment					
	Support educational institutions in their acquisition of digital equipment for pedagogical purposes	3	8	3.3	29
Development of competencies in teachers and support staff					
	Develop a new competency framework for the teaching profession to foster the integration of digital technologies into the educational practices of future teachers	1	2	1.2	4
	Foster the continuing education of teachers, non-teaching professionals and support staff in digital pedagogy	1	2	1.2	5
	Offer technical support in educational institutions to help learners and staff use digital devices for pedagogical purposes	3	8	3.3	31

A promising spin-off: AI sensor research

Small low-cost MEMS accelerometer sensors are still a relatively new technology. Four project years have resulted in many explorations of their use in the analysis of a wide variety of motions. Only a small subset of those opportunities have been selected as appropriate for introducing fundamental physics concepts at the collegial level.

The accumulation of more advanced motion-analysis ideas has resulted in a new spin-off project [38] that defines a promising new area of fundamental research. It involves machine-learning techniques for interpreting accelerometer data and is funded independently of the present project [39]. It benefits students not in a classroom setting but rather through their individual participation in research tasks. Some additional contributions to digital-era pedagogy are likely to arise from it, in the form of educational activities involving computational techniques and the use of machine-learning frameworks [40].

Conclusion

The twin challenges of innovation in the educational sector are *accessibility* and *longevity*. If a new approach requires too many resources to implement or acquire, then it is effectively inaccessible, and will not be adopted very widely. At the same time, if it cannot evolve along with its community of users, then it will eventually die out, in the survival-of-the-fittest sense. The educational innovation at stake in our case study is, of course, the set of smartphone-based physics experiments; and the most promising response to the twin challenges is, as discussed, the full exploitation of 3D-print technology.

Quebec's ministry of education has recognized the importance of these challenges through their direct support of both the innovation itself [32] and its safeguarding mechanism [33], [34]. The recent deployment of its broad Digital Action Plan is expected to bring additional indirect benefit to the project at exactly the time in which it is becoming ready for broader adoption within the college network. Such synergies are the direct result of both the comprehensiveness of the Plan's framework and its emphasis on a flexible and collaborative governance that grants considerable autonomy to individual colleges in responding to opportunities as they emerge.

Our case study demonstrates the potential for 3D-print technology as a tool of empowerment for the college community as whole, and especially for both students and teachers who can have the control to create the apparatus that best contribute to their learning. Open-source licensing encourages a healthy culture of collaboration and innovation that the entire college network can benefit from; and the project as a whole can serve as a model to inspire similar innovations at the high school and university levels.

Regarding digital-transition initiatives, it is in the education of science students in particular that we have a double challenge: We require a transition not only in the learning and communication tools that are used to present the curriculum material, but also in the transformation of the curriculum content itself. This latter transformation is vital if we want to prepare these students to face the challenges of tomorrow's world, in which they are not only users of technology, but also scientists who understand how such technologies work and who are therefore capable of conceiving of new innovations.

Acknowledgements

This work was funded by a grant from the *Entente Canada-Québec relative à l'enseignement dans la langue de la minorité et à l'enseignement des langues secondes.*

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