Learning motion concepts using real-time microcomputer-based laboratory tools

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Microcomputer-based laboratory (MBL) tools have been developed which interface to Apple II and Macintosh computers. Students use these tools to collect physical data that are graphed in real time and then can be manipulated and analyzed. The MBL tools have made possible discovery-based laboratory curricula that embody results from educational research. These curricula allow students to take an active role in their learning and encourage them to construct physical knowledge from observation of the physical world. The curricula encourage collaborative learning by taking advantage of the fact that MBL tools present data in an immediately understandable graphical form. This article describes one of the tools—the motion detector (hardware and software)—and the kinematics curriculum. The effectiveness of this curriculum compared to traditional college and university methods for helping students learn basic kinematics concepts has been evaluated by pre- and post-testing and by observation. There is strong evidence for significantly improved learning and retention by students who used the MBL materials, compared to those taught in lecture.

I. INTRODUCTION

Results from research in cognitive science and education substantiate the importance of basing development of scientific concepts and skills on concrete experience. 1,2 The "Tools for Scientific Thinking" project3,5 at the Center for Science and Mathematics Teaching at Tufts University has developed microcomputer-based laboratory (MBL) tools and curricula that can help students make connections between the physical world and the underlying principles that constitute scientific knowledge. These materials, which are intended for use in introductory courses in high school and college, provide a convenient and effective means for collecting and displaying physical data in a form that students can remember, manipulate, and think about.

MBL tools, of the style described in this article, were first developed at the Technical Education Research Centers (TERC)6 and are readily available.7 They make use of inexpensive probes, connected to an Apple II +, IIe, or II GS computer through an interface box (the "Red Box"), to measure such physical quantities as temperature, position, velocity, acceleration, and sound pressure. Additional Apple II MBL tools that are able to measure force and motion simultaneously, current and voltage, and light intensity, have been developed at the Center for Science and Mathematics Teaching at Tufts University. For the Macintosh computer, MBL tools able to measure these physical properties and others (such as ionizing radiation) have been developed at Tufts University and Dickinson College.8

Students are not required to know anything about computers to use the MBL tools. Menu-driven, self-explanatory software is friendly, even for first-time users, and encourages underprepared and anxious students. With these tools, students are in control of their learning since they
select the measurements to be made and the way the data are displayed. Data are displayed in digital and graphical form on the computer monitor as the measurements are taken. Students can transform and analyze the data, print graphs or tables, or save data to disks for later analysis. The tools do not simulate physical phenomena, but instead are a means of changing inexpensive computers into instruments for student-directed exploration of the physical world.

The following characteristics of these tools are important to student learning.

1. The tools allow student-directed exploration but free students from most of the time-consuming drudgery associated with data collection and display.

2. The data are plotted in graphical form in real time, so that students get immediate feedback and see the data in an understandable form.

3. Because data are quickly taken and displayed, students can easily examine the consequences of a large number of changes in experimental conditions during a single laboratory period. The students spend a large portion of their laboratory time observing physical phenomena and interpreting, discussing, and analyzing data.

4. The hardware and software tools are general—independent of the experiments. The variety of probes use the same interface box and the same software format. Students are able to focus on the investigation of many different physical phenomena without spending a large amount of time learning to use complicated tools.

5. The tools dictate neither the phenomena to be investigated, the steps of the investigation, nor the level or sophistication of the curriculum. Thus a wide range of students from elementary school to university level are able to use this same set of tools to investigate the physical world.

II. THE MOTION DETECTOR

The motion detector (hardware and software) is able to measure, display, and record the position, velocity, and acceleration of an object. The original motion detector was developed by TERC using a sonic transducer designed for Polaroid cameras. The motion probe (essentially a SONAR unit) transmits short pulses of high-frequency sound (50 kHz), then amplifies and detects the echo (much as a bat is able to do). The computer is programmed to measure the time between the transmitted and received pulses, and to calculate the position, velocity, and acceleration of the object causing the reflection. Any one of these quantities may be graphed on the screen as data are taken, and any one or more are available for display immediately after the measurements are completed. The motion detector can accurately detect objects between 0.5 and 6 m away. It detects the closest object in a roughly 15° cone.

Figures 1 and 2 are examples of motion graphs produced by the detector interfaced to an Apple II computer, while Figs. 3 and 4 show Macintosh displays. The software enables students to change the scales of the vertical and time axes before or after the data are collected. Students who in the past plotted graphs in the corner of a large sheet of graph paper soon learn to make readable graphs—a general purpose skill, useful in many disciplines. The software allows one set of data to be displayed on the screen while a new set of data are collected and graphed (perhaps after a slight change in experimental conditions). Numerical data are available in tabular form or can be read directly from the graph using the analysis software feature which presents digital values corresponding to the position of a movable cursor on the graph.

One of the most exciting features of the motion detector is its ability to detect and display graphs of the motion of any object. Thus, instead of using complex apparatus like nearly frictionless air tracks, which are not common to students' everyday experiences, the motion probe may be used to measure the motion of simple, common objects such as toy cars and even the motion of the students themselves. There is no other way of accurately displaying such graphs, certainly not in real time.

III. THE MOTION CURRICULUM

These tools have made possible the Tools for Scientific Thinking curricula for university and secondary school students developed by the Center for Science and Mathematics Teaching at Tufts University. These discovery-based laboratory curricula allow students to take an active role in their learning and encourage them to construct physical knowledge from actual observation. This article will discuss only the kinematics curriculum. This curricu-
Fig. 3. Macintosh screen display of velocity and acceleration graphs for a cart (with friction) given a push away from the motion detector and then released. The surface is horizontal.

lum, in common with the others, makes substantial use of the results of educational research.10–13 The curriculum uses a guided discovery approach and is intended for student groups of two to four. It supports the peer learning that is possible when data are immediately presented in an understandable form. It also uses predictions to engage the student and provide a vehicle for discussion. It pays attention to student alternative understandings that have been documented in the research literature, and encourages students to construct knowledge for themselves. The introductory parts of the curriculum make substantial use of the students' own body motions to teach kinematic concepts.

The kinematics curriculum is divided into two pieces: Introduction to Motion, which covers concepts of position (distance from the motion detector) and constant velocities, and Introduction to Motion—Changing Motion, which covers changing velocities and acceleration. Figure 5 shows excerpts from the first page of Investigation 2—the velocity section of Introduction to Motion. (Investigation 1 contains a number of exercises with distance graphs.) Students are asked to graph their velocities as they walk quickly and slowly away from the motion detector. They are then asked questions about the graphical representations of fast, slow, away from, and toward. Figure 1 shows typical distance and velocity graphs for moving away from the detector slowly and then moving toward it more quickly. Many students—including university physics students—are surprised, after viewing inclined distance graphs, to see roughly horizontal lines on the velocity graphs. These simple and quick exercises are designed to relate velocity graphs to various motions of real objects. Specifically, the exercises clarify the sign convention for velocities and firmly establish the relationship between an object's actual velocity and the displacement of the velocity graph from the time axis. Experience has shown that these simple exercises are necessary even for the majority of university students in calculus-based physics courses.

After being asked to produce a velocity graph for a more complicated motion involving walking away, stopping for a few seconds, and then walking toward, the students are asked to walk so as to duplicate a velocity graph that appears on the screen. (A similar exercise with a distance graph is included in Investigation 1.) Figure 2 shows the velocity graph to be matched (stored in the alternate display, so that it remains on the screen), and a student's third attempt to duplicate it with her own motion. The velocity graph is deliberately "unrealistic" (it shows several infinite accelerations) to provoke discussion. In addition, since the motion toward the detector is of longer duration than the
Introduction to Motion—Changing Motion begins with a series of exercises designed to relate the sign of the acceleration to actual changing motions. Students are first asked to walk so as to produce graphs of distance, velocity, and acceleration for moving away from the detector while speeding up. After storing these in the alternate display, they produce graphs walking toward the detector quickly at first and then slowing down. Then, they are asked to predict what the graphs will look like for walking toward the detector, speeding up, and for walking away, slowing down. The students then move in the appropriate manner and compare their results to the predictions. Next they graph the motions of a cart, under various conditions. Figure 7 shows an activity where students observe the acceleration and velocity of the cart slowing down and coming to rest from friction. Figure 3 shows the corresponding graphs.

An interesting motion is that of a cart rolling up an inclined ramp, coming to rest, and rolling back down. The velocity and acceleration graphs are shown in Fig. 4. These graphs illustrate the advantages of tools that allow students to extend their observations beyond specialized cases such as uniform motion on a nearly frictionless air track. We have in fact used a toy car or a dynamics cart modified with an adjustable friction pad on the bottom, so that motion can be examined with different amounts of friction. The different slopes of the velocity graph on the way up and the way down, combined with the different heights of the acceleration graph, are convincing evidence for a frictional force that changes its direction when the cart reverses direction at the top.

The last investigation is a more quantitative one comparing two ways of measuring the accelerations of the cart rolling down a ramp of different inclinations. Accelerations are read directly from the acceleration graphs and compared to accelerations calculated from the slopes of portions of the velocity graphs.

The MBL curriculum has been designed to be incorporated into traditional introductory physics courses found at most colleges and universities, where laboratory sections are often taught by teaching assistants with varying pedagogical skills, and where lecturers pay little attention to the laboratory. In place of the classroom discussions—which
under the best of circumstances would be used to consolidate the concepts learned in laboratory—each of these laboratories is accompanied by a homework assignment which the students complete after the laboratory session. They are asked to draw and interpret a number of graphs similar to and different from the ones they have produced in the laboratory. It is sometimes possible to have these problems discussed in discussion sessions.

IV. HOW EFFECTIVE IS MBL IN TEACHING KINEMATICS?

A visit to an MBL laboratory illustrates the contrast with a traditional class. Students are actively involved in their learning. They are sketching predictions and discussing them in groups of two or three. They are appealing to features of the graphs they have just plotted to argue their points of view with their peers. They are asking questions and, in many cases, either answering them themselves or finding the answers with the help of fellow students. There is a level of student involvement, success, and understanding that is rare in a physics laboratory.

Enthusiasm is one thing, but are the MBL tools and curriculum really effective in teaching kinematics? Over the past 3 years we have been conducting studies of the effectiveness of the tools and curriculum at a number of college and university campuses that are part of the “Tools for Scientific Thinking” project. It has been particularly valuable to collaborate with Priscilla Laws and the Workshop Physics Program at Dickinson College where the tools and some of the curricular pieces have been adapted into a more ideal learning environment. In more usual environments, we have used pre- and post-testing and other forms of evaluation to examine the kinematics understandings of more than 1500 college and university physics students. We have also collected data for a large sample of secondary school students that will be discussed in another article. There is strong evidence for significantly improved learning and retention by students who used the MBL materials, compared to those taught in lecture. As examples of these results, we discuss data from Tufts University and the University of Oregon below.

The pre- and post-tests that we have used in these studies consist in part of multiple choice questions. From earlier testing of students using free response questions requiring written answers and the drawing of graphs, we have constructed questions that seem to give a reasonable indication of students’ basic knowledge of kinematics concepts and of graphical representation. Student results with these questions correlate well with their written answers on these and earlier tests. We find there are almost no random answers. Almost all students pick choices that we can associate with a small number of student models. Many of the multiple choice questions require students to choose the correct graph from a group of graphs. Testing on smaller samples shows that students who can pick the correct graph under these circumstances are almost equally successful at drawing the graph correctly without being presented with choices. Although a more complete understanding of student learning as gained by an open-ended questioning process, we decided to use short answer questions in order to gather sufficient data at many different institutions to counter the common response that “my students do not have these difficulties you describe.” The difficulties in convincing physics professors to give up course time for testing, our desire to make evaluation less subjective, and the effort involved in analyzing large samples moved us to use short answer questions for these studies.

In the fall of 1987, all of the students in the Introductory Physics Laboratory course (Ph 204) at the University of Oregon were pre- and post-tested on their knowledge of kinematics. This is a standard, introductory laboratory that is offered as a separate course to accompany both the noncalculus and calculus-based General Physics lecture courses. (About 64% of the students were in the noncalculus lecture, Ph 201, while the other 36% were in the calculus-based lecture, Ph 211.) The pretest was given in the weekly lecture that accompanies the laboratory sections. At the time of the pretest, the noncalculus lecture class had heard all of the lectures on one-dimensional kinematics and dynamics, and had been assigned the corresponding text readings and problems. The calculus lecture class also had completed one-dimensional kinematics and a preliminary consideration of dynamics. The pretest was given before the students did the two MBL kinematics laboratories.

Figure 8 shows a few of the simple, multiple choice velocity questions given on the pretest, and Fig. 9 shows the results. It was surprising to observe error rates as high as 40%–60% on these simple velocity questions after kinematics had been covered in lecture. Most physics professors had predicted that fewer than 10% of their students would miss these questions and felt that students who were unable to answer such simple questions understood very little kinematics. The large error rates on questions 1 and 3 (43% and 62%, respectively) are not simply the result of the wrong choice of sign. The most common error is the choice of the “distance analogs,” graphs A and B. This is consis-
Fig. 9. Comparison of the velocity question error rates before and after MBL for introductory physics laboratory students (in noncalculus- and calculus-based lectures) at the University of Oregon, Fall, 1987. The pre-MBL test was given after lecture instruction and problem assignments in kinematics. The same questions were given as part of the homework for the two MBL laboratories and then again 3 weeks later on a midterm examination.

tent with previous studies,11,13 in which students confused position and velocity graphs. The different error rates on these two questions show that students have significantly more difficulty interpreting negative velocities. (This conclusion is borne out by the results of additional testing.) Neither the results of this pretest nor the correct answers were shared with the students. It should be noted that most students did not miss the questions because they were simply unable to read graphs. More than 90% could answer questions involving distance graphs correctly.

Over the next 2 weeks, the students completed the two MBL kinematics laboratories described above in place of standard experiments. As part of the homework turned in after completion of the first laboratory, the students were asked the same velocity questions. The tabulated error rates for this homework also are shown in Fig. 9. The improvements are dramatic. The homework was graded and returned, but the correct answers were not posted. Three weeks after completing the MBL experiments, the students were given a laboratory midterm examination, administered in the laboratory lecture. The same velocity questions, rearranged, appeared on the midterm. The results on the midterm are also shown in Fig. 9.

Velocity questions 1–4 were included on the final examination for one of the noncalculus lecture sections in order to test the retention of students who seemed to understand velocity concepts and to compare their understanding to students who did not take the MBL laboratory. The order of the questions was again rearranged to minimize any possible effects of memorization. This examination was given 7 weeks after the completion of the motion experiments. Of the 90 students who took this examination, 37 were also enrolled in the laboratory (and were included in the laboratory pretest sample), while the other 53 were enrolled only in the lecture (and therefore did not take the pretest). Figure 10 compares the error rates on the laboratory pretest with the error rates for each of these two groups on the final exam. The MBL lab group retained the significant improvement seen on the midterm, while the lecture only group showed mastery on only one of the questions—question 2, identifying the velocity graph of an object standing still.

In the fall of 1988, students in the introductory physics classes at Tufts University were given the same velocity questions as part of 50-question pre- and post-tests. (At Tufts, the laboratory and lecture courses are tied together, but, as at Oregon, the students in both the noncalculus lecture, Ph I, and the calculus-based lecture, Ph II, do the same experiments.) As at Oregon, the pretest was given after kinematics had been covered in lecture, but immediately before the first MBL motion laboratory. The post-test was given a few weeks after the two motion laboratories had been completed. Both the questions and the choices were shuffled on the post-test. The students turned in homework assignments that did not contain these questions. The results for students in the noncalculus lecture are shown in Fig. 11, while those for the calculus students are shown in Fig. 12. The two sets of results are remarkably similar.

Also in the fall of 1988, three of the same velocity questions (the more difficult ones) were included on tests given to students in the noncalculus lecture sections at the University of Oregon. The post-test was given to all three sections, but it was only possible to give the pretest to two of the lecture sections. Since the populations of these lecture sections were random (the only selection criterion was time of day) the pretests should have been similar for all three. The results showed no significant differences between the two sections that were pretested. Of the total of 294 students in these lectures, 124 also were enrolled in the laboratory. Thus we were able to compare the learning of students who listened to lectures and did problems to the learning of those who also participated in MBL laboratories. All of the lecturers were aware of the testing, and all made a special effort to teach kinematics graphing and concepts in their lectures. For these students the pretest was given in lecture before any lectures on kinematics (unlike 1987) and before the MBL laboratories. The post-test was given either as a quiz or as part of a midterm examination in
Fig. 11. Results for noncalculus-based introductory physics students at Tufts University, Fall, 1988—comparison of student error rates on a few velocity questions given on the pretest (Pre-MBL) and post-test (Post-MBL). The Pre-MBL test was given before lecture instruction and problem assignments in kinematics. The post-test was given a few weeks after two MBL laboratories.

Fig. 13. Results for introductory physics lecture students (noncalculus) at the University of Oregon, Fall, 1988—comparison of student error rates on a few velocity questions given on the pre-test, post-test, and final examination for those who took the MBL laboratory (MBL) and those who did not (No MBL). The “Special” group is a small lecture section where all students took the MBL laboratory (described further in the text).

Fig. 12. Same as Fig. 11 but for calculus-based introductory physics students at Tufts University, Fall, 1988.

Fig. 14. Some of the multiple choice acceleration questions asked on the kinematics pre- and post-tests. Questions 1–5 are the acceleration questions referred to in the following figures. The most common wrong answer is shown in parentheses.
discuss their MBL laboratory results and resolve disagreements and difficulties under teacher guidance. As was done in the previous year, the velocity questions with higher initial error rates (1, 3, and 4) were included on the final examination to check retention. The final was given about 8 weeks after the two MBL kinematics laboratories were completed. The error rates show that most of the students retained their knowledge through the end of the term.

Acceleration questions were also included on the tests given to the same Tufts and Oregon students in 1988. Figure 14 shows some of the acceleration questions. Figure 15 shows the percentage of Tufts students in calculus- and noncalculus-based physics courses who did not get these questions right. The pretest (given after lectures but before MBL) shows a much higher error rate on the acceleration questions than on the velocity questions. The highest error rate is 3.9% on the question about speeding up toward the origin. These results are consistent with other studies[12,17] that show acceleration is considerably more difficult for students.

Tufts students do not understand acceleration as well as they understand velocity after the MBL laboratories, but the improvement is still substantial. The Oregon results are shown in Fig. 16. The different student groups are the same as those in Fig. 13. Again, the results show that the students who only listened to lectures and did problems show no improvement on these concepts, while the students who worked with the MBL curriculum showed considerable improvement. Again, this learning was retained by most students to the end of the semester. (Much better understandings of acceleration have been achieved by high-school students using a very similar curriculum when the work done by the students was also discussed in the classroom.)

V. CONCLUSIONS

The MBL tools give students the opportunity to do real science in the introductory physics course. Thus students can experience the excitement of the process of science—the creative building and testing of models to explain the world around them. These tools give the science learner unprecedented power to explore, measure, and learn from the physical world. Because of their ease of use and pedagogical effectiveness, they make an understanding of physical phenomena more accessible to the naive science learner[16] and expand the investigations that more advanced students can undertake.

The tools, however, are not enough. Preliminary evidence shows that while the use of the MBL tools to do traditional experiments may increase the students' interest, such activities do not necessarily improve student understanding of fundamental physics concepts of the type discussed in this article. These gains in learning physics concepts appear to be produced by the combination of the tools and the appropriate curricular materials. In general, students improve their understanding of the physical concepts when they are guided by a curriculum to examine appropriate phenomena.

This article has presented evidence for substantial, persistent learning of very basic physical concepts by students using MBL tools and curriculum. We believe that the fol-
ollowing five characteristics of the MBL learning environment—made possible by the tools, the curriculum, and the social and physical setting—are primarily responsible for the learning gains. Note that most of the characteristics of this learning environment bear more resemblance to the scientific workplace than to the usual educational environment.

1. **Students focus on the physical world.** Students learn concepts by investigating the physical world rather than only manipulating symbols or discussing abstractions as is common in traditional courses. However, in this learning environment, actions in the physical world are directly linked to useful abstractions. For example, students who see the motion of their own bodies and of other objects displayed graphically in real time learn kinematics effectively.

2. **Immediate feedback is available.** The immediate feedback helps to make the abstract more concrete. The immediate coupling of the graphs to the physical phenomena seems to lead the students not only to understand graphing as a useful scientific symbol system, but also aids understanding of physical concepts when students are guided to examine appropriate phenomena. These observations are consistent with previous studies on a small number of students which suggested that even a short delay in the display of data in graphical form can reduce learning.19

3. **Collaboration is encouraged.** Immediate feedback supports collaborative learning and collaborative work provides immediate feedback. Because data are presented in an understandable way, students can discuss the validity, the meaning, and the implications of the data with their peers. Learning is also enhanced by encouraging students to express their predictions and to discuss unexpected results with their peers. This process appears to be a powerful one in learning about the students’ alternative representations and in making them aware of them. The process of working collaboratively is closer to the way scientists actually work.

4. **Powerful tools reduce unnecessary drudgery.** Instead of the time-consuming drudgery usually associated with data collection and display in the physics laboratory, student time is spent observing physical phenomena and analyzing and interpreting abstract representations of these phenomena (graphs). Students are able to concentrate more on discovering and understanding scientific concepts, and critical thinking skills are more easily developed. Hypothesis development and verification is encouraged by the ease and rapidity of repeating observations with changed experimental conditions. Powerful tools allow students to focus on authentic tasks in ways characteristic of scientists in the workplace. This is not commonly the case in school environments.

5. **Students understand the specific and familiar before moving to the more general and abstract.** The environment guides students to understand a specific, familiar (but often more complex) phenomenon before moving to the consideration of more general and abstract examples. Most students seem better able to understand motion when first considering, for example, their own motion (as complex as it is) as a reference point and then moving on to more idealized, less familiar (and less complex) motions with more general applicability such as frictionless motion or simple harmonic oscillation. Although it is difficult to abstract simple laws of physics from a complex, real process, grounding student understanding in the specific and familiar seems to make the abstract concepts more learnable. Moving from the specific to the general when investigating new concepts may also be more characteristic of the scientific workplace than the usual teaching and learning environment.

The effectiveness of the MBL tools and curriculum in teaching kinematics has encouraged the development of tools and curriculum to teach dynamics. A force probe that makes use of a Hall effect transducer has been developed at Tufts.20 We have developed new software for Apple II and Macintosh computers that uses the force and motion probes to measure simultaneously force and position, velocity, and acceleration. Figure 17 shows graphs of the motion of a weight oscillating on a spring. Preliminary results show that these tools, when used with a guided, discovery-based curriculum produce substantial gains in student understanding of concepts associated with Newton’s laws of motion.

Microcomputer-based laboratory tools and curriculum have the potential to help students develop a solid conceptual basis for understanding the world around them. Through the use of these materials, students’ interactions with the physical world can be connected to the underlying principles that constitute scientific knowledge, thereby helping them to develop a conceptual, qualitative understanding that can be applied both inside and outside of the classroom.

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A plea for a correct translation of Newton's law of inertia

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The formulations of Newton's law of inertia in university-level textbooks usually follow the Motte-Cajori translation of Newton's Principia. The rich content of Newton's law of inertia as a causality principle for mechanics is partly hidden by Motte's mistranslation of the Latin phrase nisi quatenus as unless instead of except insofar as. One effect of this error is a tendency to isolate from the law some of the "Definitions" that precede Newton's statement of the three laws of motion. These definitions, when taken together with the laws, provide the basis for Newton's quantitative and qualitative elaboration of the coupled concepts of mass and force.

A literal translation of Newton's law of inertia, which he designated in the Philosophiae Naturalis Principia Mathematica [Mathematical Principles of Natural Philosophy] (1687) as Law 1, reads:

Every body remains in a state resting or moving uniformly in a straight line except insofar as forces on it compel it to change its state.¹

In college-level calculus-based textbooks written for general physics courses in the United States, the formulations of the law are more or less compatible with the literal translation, but with one principal common exception. Newton's original Latin text contained the phrase nisi quatenus, which is equivalent in this context to except insofar as, but it is invariably translated as unless. I have looked at many comparable texts in French, German, and Russian, and found this to be the general practice in those languages too. In fact, Wolfson and Passachoff, from whose textbook Physics the literal translation given here is taken, employ the word unless when presenting the law in the text on p. 72, but retain except insofar as in presenting the literal translation as a caption to a photographic reproduction of Newton's original Latin text on p. 73.

It is generally recognized that the first law introduces the concept of inertial frames and asserts their equivalence in relation to the changes in momentum. Commentaries on the law, however, invariably fail to recognize its significance as a statement of the basic causality principle for mechanics and as an expression of Newton's successful achievement in establishing the quantitative and qualitative basis of physical force as a cause for the change in momentum. As a result, the significance of the first law is reduced to the role of introducing inertial frames. I shall attempt to show that the first law is an integral part of the quantification of the concept of force.

The use of the term force in the more general sense of cause can be seen in Newton's notes some 20 years before...