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DEVELOPING METHODS FOR VISUALIZING THE LAWS OF MECHANICAL MOTION THROUGH 2D ANIMATION

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Abstract. This article develops a method for translating mechanical motion laws into accurate and instructionally useful two-dimensional animations. Because motion is temporal, learners must interpret force, acceleration, coordinate systems, and mathematical relations that are not directly visible. A design-oriented synthesis connects Newtonian mechanics, model-based instruction, multiple representations, and multimedia learning. The resulting five-stage framework defines the learning objective and physical model; specifies variables, assumptions, and coordinate conventions; maps the model to visual elements; synchronizes animation with equations, graphs, and learner controls; and evaluates physical fidelity and usability. Examples address inertia, acceleration, action–reaction, projectile motion, and friction. The framework treats vectors, trails, timing, and scale as encodings of defined physical quantities and recommends prediction prompts, replay, and purposeful interactivity. No learner experiment is reported. Instead, the article offers a reproducible design method and evaluation plan for later classroom validation.

Keywords: Newton's laws; mechanical motion; 2D animation; physics education; multiple representations; instructional design.

1. Introduction

Mechanical motion is foundational to describing, predicting, and testing physical systems, yet learners may treat equations, diagrams, graphs, and observed movement as separate forms. A student can calculate acceleration while still assuming that continued motion requires a continuing force. Newton's laws instead relate an object's motion to the net force and change in momentum [1].

Two-dimensional animation can help connect these ideas because it represents change over time and allows the designer to coordinate a moving body with force vectors, velocity indicators, coordinate axes, and graphs. A ball moving along a curved path, for example, can be shown together with its changing velocity vector and a constant downward gravitational force. The visual sequence may make clear that acceleration concerns a change in velocity, not necessarily an increase in speed. However, animation alone does not guarantee understanding. Reviews of animation research show that dynamic displays can be difficult to inspect, may direct attention away from relevant relations, and often work best when learners are prompted to interpret them [2, 3]. The educational value therefore depends on how physical meaning is mapped to visual change and how the learner is guided through that mapping.

The purpose of this article is to develop a systematic method for visualizing the laws of mechanical motion through 2D animation. It addresses three questions: (1) how should a physical

law be translated into visible elements and temporal changes; (2) how can animation be coordinated with equations, graphs, and learner interaction; and (3) what criteria can be used to evaluate the physical and instructional quality of the resulting animation? The contribution is a design framework with reusable procedures and examples. The intended audience includes physics teachers, researchers in science education, and developers of digital learning resources.

2. Methods

The study used a design-oriented conceptual synthesis rather than a classroom intervention. It combined four strands of work: the formal structure of Newtonian mechanics; model-based approaches to physics instruction; research on learning from animation and multiple representations; and established multimedia and simulation design principles. This choice is appropriate to the article's objective, which is to specify a method for creating animations rather than to estimate an effect size for a particular product. The literature was used to derive design requirements, while mechanics equations served as constraints on the visual representation. The synthesis follows the principle that a teaching model should preserve the key structure of the physical system and make its assumptions explicit [4].

Each animation is treated as a visual model with three layers: a physical layer defining the system and governing relations; a representational layer assigning visual forms to quantities; and an instructional layer specifying what learners should notice, predict, or explain. These layers are fixed before storyboarding to prevent decorative effects from being mistaken for physical evidence.

Five steps were used to formulate the proposed method. First, an observable learning objective was selected, such as distinguishing velocity from acceleration or identifying the net force in a system. Second, the physical model was bounded: the object, environment, reference frame, idealizations, and time interval were stated. Third, a visual grammar was defined, including scale, color, symbols, vector conventions, and rules for showing time. Fourth, the animation was paired with at least one complementary representation, such as a position–time graph, velocity–time graph, or equation. Fifth, review criteria were specified for model accuracy, readability, synchronization, accessibility, and learner control. Multiple representations should complement and constrain interpretation rather than duplicate information without purpose [5].

A reproducibility record should list the target law, system boundary, equations, parameters, frame rate, time scale, visual legend, and limitations. Under constant one-dimensional acceleration, position follows $x(t + \Delta t) = x(t) + v(t)\Delta t + \frac{1}{2}a(\Delta t)^2$ and velocity follows $v(t + \Delta t) = v(t) + a\Delta t$. Frames must be generated from simulated time; rendering intervals must not change the physical time scale.

3. Results

The synthesis produced a five-stage framework for developing instructional animations: (1) define the learning problem and target concept; (2) formalize the physical model; (3) create a visual mapping and storyboard; (4) implement synchronized motion and representations; and (5) review and evaluate the product. Each stage has a decision rule and a deliverable, making the framework suitable for repeated development and peer review.

3.1. Define the concept and physical model

The first deliverable is a concise learning statement expressed in terms of what a learner should be able to explain or predict. For Newton's first law, a suitable objective is: explain why a body

continues at constant velocity when the net external force is zero. The system boundary must identify the body and distinguish forces acting on it from forces it exerts on other bodies. This distinction is essential when visualizing Newton's third law: the two interaction forces are equal and opposite but act on different objects, so they should be drawn on separate bodies rather than as arrows that cancel on one body [1]. A prompt asking learners to predict the motion before playback can reveal whether they are attending to the law or merely watching the sequence.

The model statement should identify assumptions such as negligible air resistance, a point-mass approximation, or a uniform gravitational field. Such assumptions determine what the animation can legitimately show. If air resistance is omitted, a projectile's horizontal velocity should remain constant; if drag is included, its effect should be represented and named. When simplification is necessary, it should be disclosed in a brief caption or opening panel. Modeling instruction regards the construction, testing, and revision of models as central activity, rather than presenting equations as detached rules [4].

3.2. Translate quantities into a visual grammar

The second deliverable is a visual specification. Position can be shown by an object marker against fixed axes; velocity by a tangent vector; acceleration by the change in velocity over a defined interval; and force by labeled vectors acting on the selected body. A consistent legend should distinguish these quantities through labels and shape as well as color, so that meaning does not depend on color perception alone. Vector arrow length may encode magnitude only when a scale is stated. If arrows are enlarged solely for visibility, the display should identify them as schematic. Otherwise learners may infer a quantitative relation that the graphic does not support.

Time must also be encoded carefully. Equally spaced animation frames do not necessarily imply equal spatial steps. For constant velocity, an object should cover equal distances during equal time intervals; for constant acceleration, the distance between successive equal-time markers should change systematically. A motion trail or series of ghosted positions can make these intervals inspectable. It is useful to provide an adjustable playback speed while keeping a visible time counter, because slow motion changes the viewing experience but not the model's time variable. Text and graphics should be coordinated spatially and temporally, and decorative elements that compete with the target relation should be removed [6].

3.3. Build law-specific animation patterns

For inertia, the animation can show a cart moving at constant velocity on an ideal frictionless track after a brief push. The applied force is shown only during the push; afterward the net-force indicator becomes zero while the velocity vector remains unchanged. A short comparison with a frictional track clarifies that stopping is associated with an unbalanced resistive force, not with the absence of a forward force. The graph panel can pair constant velocity with a straight, sloping position–time line and a horizontal velocity–time line.

For Newton's second law, a body can be shown under a net force whose magnitude or mass is varied through a slider. The visual sequence should preserve the relation $a = F_{net}/m$: at constant mass, a larger net force produces a proportionally larger acceleration; at constant force, a larger mass produces a smaller acceleration. Learners should be able to pause and compare trials while the display records the selected values. The slider should change one variable at a time in an initial exploration, then permit combined changes in a later task. Interactive simulations are most

productive when controls support inquiry and feedback while keeping the relation between an action and its consequence visible [7].

For Newton's third law, two interacting bodies should appear together. During a push or collision, equal-length opposite force arrows are attached to different bodies and labeled as an interaction pair. The bodies' accelerations may differ when their masses differ, which helps prevent the misconception that equal forces require equal motion. A split-screen or selectable-body view can maintain visual clarity while preserving the shared interaction. For projectile motion, the path is represented in two dimensions, but horizontal and vertical components are also shown separately. With air resistance neglected, horizontal velocity remains constant while vertical velocity changes under gravity; the resultant trajectory follows from the combination of these component motions. These examples reflect the value of connecting motion, force diagrams, and graphs within a coordinated representational environment [8].

For friction, a sequence can vary surface conditions while holding other variables fixed. It should distinguish static from kinetic friction and show that friction opposes relative slipping or its tendency at the contact surface, rather than always opposing an object's motion. A force diagram and force–time trace can clarify the transition from rest to sliding.

3.4. Synchronize animation, mathematics, and interaction

The third and fourth framework stages require the animation to stay synchronized with equations and graphs. A synchronized cursor can mark the current time on a graph while the object moves; the displayed numerical values can update from the same model state. This shared data source is important: independently authored motion and graphs may drift out of agreement. The learner should be able to pause, step frame by frame, replay a short interval, and reset initial conditions. Prediction questions should precede playback, and brief explanation prompts should follow it. Ainsworth's framework suggests that representations may constrain interpretation, support complementary information, or help learners construct deeper understanding, but these functions require explicit task design [5].

Controls should correspond to meaningful parameters; excess controls obscure the objective. Labels need units, vectors need a consistent coordinate convention, and narration should explain rather than repeat visible text. Captions and keyboard access broaden usability. Multimedia principles advise reducing extraneous processing [6], while replay and user-paced inspection help learners examine transient events [2, 3].

3.5. Evaluate quality before classroom use

The fifth stage is a structured review. A physics reviewer checks whether the object, forces, directions, scales, units, and time evolution agree with the stated model. An instructional reviewer checks whether learners can identify the target relation and whether prompts elicit prediction and explanation. A usability reviewer checks legibility, navigation, playback controls, and the cognitive load imposed by simultaneous representations. A small think-aloud review with representative learners can reveal unexpected interpretations before broader use; simulation projects such as PhET describe iterative design research and student interviews as part of development [7]. These reviews assess design quality, but they are not substitutes for a controlled learning study.

A practical rubric can use four dimensions scored on a four-point scale: physical fidelity; representational coherence; learner control and feedback; and accessibility/readability. Each score

should be supported by a specific observation rather than a general impression. For example, a low fidelity score might record that arrow length changes without a stated scale, while a low coherence score might identify a graph whose slope contradicts the animated displacement. The rubric should also record intended level, prerequisites, and conditions of use. This makes later classroom evaluation interpretable and allows developers to compare revisions.

4. Discussion

The proposed framework treats 2D animation as a model-based representation whose instructional value depends on precise correspondence among physical quantities, visual encodings, and learner activity. Its central implication is that the animator should begin with the law and its assumptions, then decide what should move, change, remain invariant, or be compared. This ordering supports physical accuracy and reduces the chance that a visually attractive sequence will teach an unintended rule. It is consistent with the broader view that physics learning involves building and using models to explain phenomena [4].

A second implication concerns multiple representations. Animation shows temporal change, while equations and graphs make quantitative structure easier to inspect. The sequence should coordinate them and ask learners to translate between forms instead of assuming that motion explains itself. Ainsworth's DeFT framework and Mayer's multimedia principles underscore the importance of representation choice, timing, and instructional prompting [5, 6].

Third, interactivity should be purposeful. Parameter controls support learning when learners predict, change one variable, observe, explain, and compare with a mathematical representation. Feedback should be tied to the model and support rather than replace reasoning [7].

The framework is conceptual and has not been validated in a comparative classroom study. Its examples should be adapted to prior knowledge, curriculum, language, and device access. Two-dimensional displays simplify three-dimensional processes, while vectors and graphs require explicit teaching. Future studies should compare framework-based animation with static diagrams or unstructured video, measuring conceptual explanations, graph interpretation, transfer, and delayed outcomes. Reports should describe participants, instructional duration, and assessment validity. Existing animation-media studies suggest feasibility and positive responses, but effectiveness claims remain specific to their contexts and measures [9, 10].

5. Conclusion

This article proposed a five-stage method for developing 2D animations of mechanical motion: define the learning objective; formalize the physical model; specify visual encodings; synchronize animation with equations, graphs, and learner controls; and evaluate accuracy, coherence, usability, and accessibility. The method is applicable to inertia, force and acceleration, action–reaction, projectile motion, and friction. Its practical rule is straightforward: every visible movement, vector, trail, label, and graph should have a defined physical meaning and should agree with the same underlying model. Animation becomes an effective instructional representation when learners can inspect, predict, manipulate, and explain the relations it displays. The framework now requires classroom validation across age groups and topics, using learning measures that test both conceptual understanding and transfer.

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