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Constructing a precursor model of friction through ontological analysis, learners' ideas, and modeling theory: towards an embodied inquiry framework

PANAGIOTIS PANTIDOS, STELLA FOTIADI

Department of Early Childhood Education
National & Kapodistrian University of Athens
Greece
ppantidos@ecd.uoa.gr
stellaf@ecd.uoa.gr

ABSTRACT

This paper proposes a precursor model of friction constructed through the articulation of three complementary perspectives: an ontological analysis of friction as an interfacial phenomenon, research on learners' alternative conceptions, and the modelling framework developed by Lemeignan and Weil-Barais. The model is designed to support conceptual transitions toward a relational and interaction-based understanding of friction by foregrounding system interaction, reciprocity, interface dynamics, and the identification of variables with genuine predictive value for motion under frictional conditions. Particular emphasis is placed on the distinction between variables that participate in the frictional mechanism and variables that function as predictors of stopping distance. The paper concludes by proposing embodied inquiry as a coherent pedagogical extension of the precursor model, since bodily investigations of coupling, uncoupling, resistance, and sliding can support learners in progressively reconstructing friction as an emergent phenomenon of system interaction and interface dynamics.

KEYWORDS

Friction, precursor model, modeling, ontology of friction, learners' ideas, embodied inquiry

RÉSUMÉ

Cette contribution propose un modèle précurseur du frottement construit à partir de l'articulation de trois perspectives complémentaires : une analyse ontologique du frottement en tant que phénomène interfacial, les recherches sur les conceptions alternatives des apprenants et le cadre théorique de la modélisation développé par Lemeignan et Weil-Barais. Le modèle vise à soutenir les transitions conceptuelles vers une compréhension relationnelle et interactionnelle du frottement, en mettant l'accent sur l'interaction entre systèmes, la réciprocité, la dynamique de l'interface et l'identification des variables possédant une véritable valeur prédictive dans les situations de mouvement soumises au frottement. Une attention particulière est accordée à la distinction entre les variables qui participent au mécanisme du frottement et celles qui permettent de prédire la distance d'arrêt. L'article se conclut par la proposition d'une démarche d'investigation incarnée (embodied inquiry) comme prolongement pédagogique cohérent du modèle précurseur, dans la mesure où l'exploration corporelle des processus de couplage, de découplage, de résistance et de glissement peut aider les apprenants à reconstruire progressivement le frottement comme un phénomène émergent résultant de l'interaction entre systèmes et de la dynamique des interfaces.

MOTS-CLÉS
Frottement, modèle précurseur, modélisation scientifique, ontologie du frottement, conceptions des apprenants, investigation incarnée

INTRODUCTION

Despite its central place in science curricula, friction is often presented in school science merely as a resistive force, overlooking the complex dynamics of the *interface* and its role in energy dissipation. Research has shown that students frequently adopt forms of linear causal reasoning according to which motion is sustained by an internal force and ceases when this force is gradually 'used up' or eventually 'overcome' by the weight of the object (Hammer, 1996). Within such forms of reasoning, mass tends to be construed as the dominant regulator of motion, leading students to predict that heavier objects stop more quickly because they experience a greater frictional force and therefore encounter greater resistance to motion. Yet, under idealized dry-friction conditions, this prediction is incorrect, since the increase in friction associated with greater mass is accompanied by a proportional increase in inertia, leaving both deceleration and stopping distance unchanged (Driver et al., 1994).

To address such conceptual obstacles, research in science education has proposed the construction of *precursor models*. These models should not be understood as simplified or incomplete versions of scientific knowledge, but rather as autonomous intermediate cognitive structures designed to bridge the gap between learners' personal conceptions and scientific models (Lemeignan & Weil-Barais, 1993). In this perspective, precursor models function as transitional cognitive tools embedded in teaching processes that provide a framework for their construction and refinement through meaningful engagement with physical phenomena (Ravanis & Boilevin, 2022; Ravanis & Pantidos, 2008).

The present study proposes a precursor model of friction grounded in an ontological analysis of the phenomenon. Central to this perspective is the concept of the *interface*, understood not simply as the geometric contact region between two bodies, but as the interactional zone in which interfacial processes and electromagnetic interactions emerge. Furthermore, because the precursor model places particular emphasis on the qualitative characteristics of the interface, it appears that an embodied inquiry approach may provide a particularly appropriate pedagogical framework. The kinesiology of the human body naturally incorporates features such as relative motion, coupling, resistance, release, and gradual sliding, which can create and support the exploration of interfacial relations. More broadly, embodiment has been identified as a fundamental dimension of human cognition and conceptual development, highlighting the central role of bodily experience in the construction of meaning and understanding (Shapiro, 2019).

THE ONTOLOGICAL CONTENT OF FRICTION

The problem of stopping distance

A central claim advanced in this study is that, under the idealized conditions of Coulomb dry friction, the stopping distance of a moving object is determined by its initial velocity and by the nature of the interface, as expressed through the coefficient of friction, rather than by its mass, momentum, or kinetic energy. Although this conclusion follows straightforwardly from classical mechanics, it raises a significant conceptual and didactical problem, since mass appears to play a crucial role in the generation of friction while simultaneously having no effect on stopping distance.

Consider an object of mass m released from an inclined plane of height h and length x. Upon reaching the bottom of the incline, the object enters a horizontal surface with an initial velocity v_0. Depending on whether friction is present on the incline, this velocity is given by $v_0 = \sqrt{2gx(sin\theta - \mu_1 cos\theta)}$ or $v_0 = \sqrt{2gh}$ in the frictionless case. In both cases, the resulting velocity is independent of mass. The object subsequently moves along a horizontal surface characterized by a coefficient of friction μ_2. Applying Newton's second law yields:
$T = ma \Longrightarrow -\mu_2 mg = ma \Longrightarrow a = -\mu_2 g$ (1). The deceleration is therefore independent of mass. Combining this result with the kinematic equations for uniformly accelerated motion:

$$v = v_0 - at \Longrightarrow 0 = v_0 - at \Longrightarrow t = \frac{v_0}{a} \ (2)$$

$$d = v_0\, t - \frac{1}{2}\alpha t^2 \overset{(2)}{\Longrightarrow} d = v_0 \frac{v_0}{a} - \frac{1}{2} a \frac{{v_0}^2}{a^2} \Rightarrow d = \frac{{v_0}^2}{a} - \frac{1}{2}\frac{{v_0}^2}{a} \Rightarrow d = \frac{{v_0}^2}{2a} \overset{(1)}{\Longrightarrow} d = \frac{{v_0}^2}{2\mu_2 g} \ (3)$$

Where d denotes the stopping distance. Equation (3) shows that stopping distance depends exclusively on the initial velocity and the coefficient of friction and is therefore independent of mass. This result remains unchanged for objects of different masses. Two objects entering the horizontal surface with the same initial velocity, but different masses, will travel the same stopping distance despite possessing different kinetic energies and momenta. For example, objects of mass m and $2m$ have different kinetic energies, $K_m = \frac{1}{2} m{v_0}^2$, $K_{2m} = \frac{1}{2}(2m){v_0}^2$ and different momenta $p_m = mv_0$ και $p_{2m} = 2mv_0$, yet they come to rest after the same distance.

From an educational perspective, this outcome reveals an important explanatory tension. Mass appears to contribute directly to friction through the normal force and therefore seems causally implicated in the stopping process. Nevertheless, variations in mass do not alter the stopping distance. The challenge is therefore not to explain the absence of mass from the mathematical solution, but to construct an explanatory framework capable of accounting for why mass participates in the interfacial processes associated with friction while simultaneously failing to function as a predictive variable for stopping distance. Addressing this tension constitutes a central requirement for the construction of a precursor model of friction suitable for educational purposes.

Interfacial interactions and the coefficient of friction (μ)

According to the seminal work of Bowden and Tabor (2001/1950), friction is determined by the nature of the interactions that develop within the regions of real contact between two surfaces. The coefficient of friction, μ, may be expressed as μ = s/p where *p* (*yield pressure*) corresponds to the pressure required to deform surface asperities and increase the real area of contact. In tribology, *p* is closely related to the hardness of the softer material and can be understood as a measure of its resistance to plastic deformation. Because no surface is perfectly smooth, contact initially occurs only at the summits of microscopic asperities. Under the action of the normal force, these asperities deform, progressively increasing the real area of contact and enabling the development of interfacial interactions at the atomic scale. Similarly, *s* (*shear strength*) expresses the shear resistance of the regions of real contact. It corresponds to the tangential stress required to shear or disrupt the microscopic junctions formed between the two surfaces. In other words, *s* characterizes the resistance of interfacial interactions to the relative sliding of the contacting materials.

The values of both *s* and *p* ultimately arise from the structure of the materials and the electromagnetic interactions occurring between their surface molecules. Consequently, the coefficient of friction does not constitute a property of an individual material but rather a characteristic of the interface established by a particular pair of materials under specific contact conditions. As Hutchings and Shipway (2017) emphasize, friction emerges from the interaction between surfaces rather than from either material considered in isolation.

An increase in the normal force generally leads to an increase in the real area of contact. As a result, a greater number of interfacial junctions are formed, increasing both the resistance to sliding (s) and the resistance of the material to further deformation (p). Since these quantities tend to vary proportionally, their ratio—and therefore the coefficient of friction—remains approximately constant for a given pair of materials. Under these conditions, increasing mass, or more generally the normal force, does not necessarily alter the coefficient of friction itself. Rather, it modifies the extent and intensity of the interfacial interaction while preserving, to a first approximation, the proportional relationship between s and p.

This analysis highlights an important distinction between the mechanisms through which friction is constituted and the variables that govern the prediction of motion. Although normal loading influences interfacial interactions and the formation of the real area of contact, the macroscopic description of dry friction leads to a mass-independent deceleration for a given pair of surfaces. The coexistence of simple macroscopic regularities with complex microscopic mechanisms is a defining feature of contemporary friction physics (Persson, 2013; Urbakh et al., 2004). For the purposes of the present study, this distinction is particularly significant because it provides the ontological foundation for a precursor model in which mass participates in the constitution of frictional interactions without functioning as a predictive variable for stopping distance.

LEARNERS' IDEAS ABOUT FRICTION

Research in science education has consistently shown that learners construct mental representations of physical phenomena that often differ from scientifically accepted models, a pattern documented across a wide range of domains, such as mechanics (Chachlioutaki & Pantidos, 2024), magnetism (Ravanis et al., 2010), thermal phenomena (Kaliampos et al., 2024) and astronomy (Neofotistos et al., 2024). Research specifically focusing on friction has likewise revealed significant difficulties in conceptualising it as an interactional phenomenon. One of the most common ideas is that friction exists only when visible motion occurs. Consequently, static friction is often not recognised as an active force that can prevent relative motion, maintain equilibrium, or enable locomotion, since learners tend to associate friction exclusively with situations involving visible sliding (McDermott, 1984). In the same vein, friction is commonly conceived as a force whose sole function is to oppose motion. As a result, learners often fail to recognise its productive role in situations such as walking, running, or wheel motion, where friction enables rather than inhibits movement (Driver et al., 1994). A second recurring tendency concerns the attribution of friction to individual objects rather than to the interaction between surfaces. Learners frequently describe friction as a property possessed by a particular object or material (e.g., "the carpet has more friction" or "the tyres have friction"), rather than as a phenomenon emerging at the interface between interacting systems (Viennot, 1979).

Research has also documented difficulties in distinguishing friction from other forms of motion resistance. Learners frequently group together frictional forces and fluid resistance under a single explanatory category, focusing on their common effect of slowing motion while overlooking the different physical mechanisms involved (Driver et al., 1994; Viennot, 1979). Such reasoning reflects a broader tendency to treat resistance forces as homogeneous causal agents rather than as phenomena arising from distinct forms of interaction.

Another robust finding concerns learners' assumptions about the variables that determine frictional effects. Many students believe that increasing the apparent contact area necessarily increases friction, while others assume that larger masses inevitably produce stronger frictional effects and therefore shorter stopping distances (Driver et al., 1985). These ideas are often associated with difficulties in coordinating interacting variables and reasoning proportionally. In particular, learners tend to focus on the increase of frictional force with mass while neglecting the simultaneous increase of inertia. Consequently, force and resistance are treated as independent quantities rather than as quantities embedded in the proportional relationships that characterise Newtonian mechanics (Clement, 1982; McCloskey, 1983).

Taken together, these findings suggest that learners frequently conceptualise friction as a property of individual objects, as an exclusively resistive force, or as a phenomenon determined by isolated variables such as mass or contact area. Such patterns contrast with contemporary physical accounts of friction and reveal persistent difficulties in coordinating the entities, interactions, and variables involved in frictional phenomena. These difficulties constitute an important point of departure for the construction of a precursor model and motivate the need for a modelling framework capable of reorganising learners' interpretations of friction.

BASIC PRINCIPLES OF MODELLING ACCORDING TO LEMEIGNAN AND WEIL-BARAIS

For the construction of a precursor model of friction, independently of any particular educational level, the present study draws on the theoretical and methodological framework developed by Lemeignan and Weil-Barais (1993). Within their approach to *modélisation*, learning physics is associated with the progressive construction of explanatory models that enable learners to organise phenomena, identify relevant variables, and predict the behaviour of physical systems. From this perspective, modelling does not consist merely in simplifying reality but in reorganising it into systems, interactions, and transformations that support scientific reasoning.

Identification of systems

A fundamental modelling operation is the partitioning of reality into systems (*partition en systèmes*). Depending on the phenomenon under investigation, objects may be grouped into distinct systems, giving rise to internal relations within systems and external interactions between systems. The identification of systems therefore determines both the entities that will be considered relevant and the interactions through which the phenomenon will be interpreted.

When applied to friction, this principle implies that the phenomenon cannot be treated as a property possessed by a moving object or by a surface in isolation. Its interpretation requires the identification of at least two interacting systems (e.g., an object and a supporting surface), which may be considered either as distinct systems or as components of a broader physical system, depending on the level of analysis adopted. Attention is thus shifted from individual objects to the relations established between them, allowing friction to be interpreted through the relations established between interacting systems rather than through the properties of an isolated object (Lemeignan & Weil-Barais, 1993).

Reciprocity

The notion of reciprocity *(réciprocité)*, as introduced by Lemeignan and Weil-Barais (1993), constitutes a central principle for understanding mechanical interactions. In everyday reasoning, friction is often interpreted as a resistive or braking action exerted by a surface on a moving body, thereby attributing an active role to one element and a passive role to the other.

This asymmetrical interpretation reflects a form of linear causality in which action is assigned to a single active agent acting upon a passive recipient (Viennot, 2001).

Within a modelling perspective, reciprocity emphasises that mechanical interaction is not unidirectional but inherently symmetric. The force associated with friction is not located in one of the interacting elements but is defined simultaneously for both, as a manifestation of their coupled interaction. This symmetry challenges explanations based on single-cause reasoning, where motion is determined by one dominant agent acting on an inert object.

From a physical perspective, reciprocity is grounded in the electromagnetic interactions that develop at the interface between the contacting surfaces. These interactions emerge from the mutual coupling of the surface molecules and cannot be assigned exclusively to either body. The frictional force is therefore not the action of one object upon another, but the macroscopic manifestation of a shared electromagnetic interaction field established at the interface.

Functional use

Within the framework of *modélisation* developed by Lemeignan and Weil-Barais (1993), scientific models do not function as mere representations of reality but as cognitive tools that enable the organisation of phenomena, the formulation of explanations, and the generation of predictions. Their epistemic value lies not only in describing states of affairs but in allowing the identification of relevant variables and the systematic exploration of their effects on system behaviour. In this sense, learning physics involves developing the capacity to use models as operational tools for reasoning about and predicting physical processes.

Applied to friction, functional use of the model requires distinguishing between variables that genuinely affect the evolution of motion and those that appear relevant at a phenomenological level but do not independently determine outcomes. The focus therefore shifts from explaining why an object stops to identifying which initial and interfacial conditions lead to different stopping behaviours.

Within the idealised Coulomb model of dry friction, this perspective highlights the initial velocity and the nature of interfacial interaction, expressed through the coefficient of friction, as the primary predictive variables governing motion. Other quantities, such as mass, enter the physical description through the interaction dynamics, but do not constitute independent predictors of deceleration or stopping distance within this modelling framework.

Selectivity and temporal segmentation

The process of modelization in science education necessitates a deliberate transformation of empirical reality. Within the framework of Lemeignan and Weil-Barais (1993), this cognitive operation relies fundamentally on selective abstraction, on the one hand, and the temporal segmentation (découpage temporel) of the phenomenon, on the other. Selectivity entails isolating those entities, relations, and variables deemed essential for explaining and predicting a system’s behavior, while temporarily omitting extraneous elements without rendering them non-existent.

Complementarily, temporal segmentation does not merely constitute a descriptive account of successive stages, but rather a cognitive process that enables the isolation and analysis of systemic changes. Through this segmentation, the continuous flow of experience is reorganized into discrete, comparable states, thereby elucidating the underlying factors that drive each modification.

In the case of friction, where motion and deceleration manifest as an unbroken, evolutionary progression, temporal segmentation becomes particularly crucial. The analysis is structured around an initial state (instantaneous velocity v_1, representing a specific kinematic condition) and a final state (reduced velocity or rest). Comparing these two distinct states facilitates the identification of the variables involved and enables the formulation of causal relationships between the interaction and its outcomes.

CHARACTERISTICS OF A PRECURSOR MODEL OF FRICTION

While previous research has demonstrated the feasibility of developing precursor models for friction within specific developmental stages—such as Ravanis et al.'s (2008) socio-cognitive intervention for rolling friction in preschool education—the present study shifts the focus toward a more generalized framework. Rather than tailoring a model to a restricted age group, this work seeks to delineate the overarching conceptual dimensions required for a universal precursor model of friction. Consequently, instead of building upon learners' scientifically compatible ideas, the proposed framework is intentionally grounded in the persistent alternative conceptions that recur across educational levels (Driver et al., 1994; McDermott, 1984; Viennot, 1979). By synthesizing these stable conceptual obstacles with an ontological analysis of friction (Section 2) and the modeling principles outlined by Lemeignan and Weil-Barais (1993) (Section 4), this study establishes the theoretical foundation for the precursor model presented herein, yielding four core characteristics.

Interface as an emergent product of interacting systems

Friction is not attributed to an individual object or surface but is conceptualised as an emergent interfacial effect resulting from the interaction between systems. The focus shifts from object-centred descriptions to relational structures, with the interface constituting the primary locus of explanation. Friction is therefore treated as a systemic outcome rather than a property of matter.

Electromagnetic grounding of interfacial interaction

The interface is understood not as a geometric boundary but as a zone of electromagnetic interactions between surface constituents of the interacting materials. As surfaces approach molecular distances, local bonds and interactions emerge whose nature depends on material properties. At the macroscopic level, these processes are summarised by the coefficient of friction, which functions as a compact descriptor of interfacial dynamics.

System reciprocity and process decomposition

Friction is characterised as a simultaneous and reciprocal interaction between systems, rather than a unilateral action of one body on another. Forces are not transferred but emerge symmetrically from system coupling, challenging linear causal explanations. This reciprocal structure is further clarified through temporal segmentation, which allows frictional interaction to be interpreted as a sequence of progressively changing states. At the macroscopic level, this corresponds to static, limiting, and kinetic friction as phases of a continuous interfacial process, while at the microscopic level it reflects the progressive weakening and rupture of interfacial bonds during the transition from strong coupling to relative motion.

Reconfiguration of predictive variables for stopping distance

To counteract learners' persistent reliance on mass as an independent determinant of motion, the precursor model systematically reconfigures the predictive power of kinematic variables. In alignment with the ideal Coulomb model of dry friction, mass simultaneously influences both frictional force and inertial response, thereby canceling its own effect on deceleration and stopping distance. By exposing this dual role, the proposed model structurally reframes momentum and kinetic energy—which learners typically treat as standalone predictors—shifting predictive power exclusively toward initial velocity and the coefficient of friction as expressions of interfacial coupling.

TOWARDS AN EMBODIED INQUIRY FRAMEWORK FOR FRICTION

By foregrounding friction as an emergent, relational phenomenon that arises at the interface of interacting systems, the proposed precursor model necessitates learning environments that transcend traditional abstract representations (Ioannou et al., 2025; Pantidos & Kaliampos, 2023). In this respect, embodied approaches appear particularly promising; by conceptualizing the learner's own body as an active constituent of the physical interface, embodied inquiry provides an epistemic space where interfacial dynamics are directly experienced through co-constituted contact and sensorimotor engagement.

A possible direction for such an inquiry-oriented approach has recently been proposed by Fotiadi and Pantidos (2025). Rather than using bodily activity to represent scientific concepts, the authors conceptualise bodily interaction itself as a field of investigation. They identify a set of recurrent situations through which learners can explore friction through direct engagement with conditions of stability, transition, and relative motion. At the practical level, these situations are organised around three interactional regimes: anchoring, un-anchoring, and sliding. Anchoring refers to situations in which stability is maintained through strong coupling, either between human bodies or between a human body and an external surface - such as gripping the ground with hands or feet, resisting displacement, or maintaining stable contact under external force. Un-anchoring refers to transitional situations in which this coupling becomes destabilised, for example through coordinated pushing and pulling, off-axis human body holds, or attempts to initiate motion under constrained conditions. Sliding refers to sustained relative motion between coupled systems, such as dragging one's body across a surface or observing progressive deceleration until rest. Through variations of these situations—including different contact configurations, surface materials, and degrees of resistance—learners are invited to investigate how frictional interactions emerge, persist, and change.

The educational significance of this embodied approach lies in its capacity to serve as an epistemic resource for progressive model evolution. Although operating primarily at the macroscopic level without providing direct access to microscopic mechanisms, this somatic engagement enables learners to reason analogically about less directly observable scales. Specifically, the experiential differentiation between anchoring, un-anchoring, and sliding maps onto how surface asperities establish, maintain, and disrupt contact at the intermediate mesoscopic level. Consequently, this mesoscopic interpretation is anticipated to facilitate a smoother conceptual transition toward microscopic accounts, where friction is understood as an emergent property of dynamic electromagnetic interactions at regions of real contact. Embodied inquiry could thus function not as a literal representation of microscopic physics, but as a foundational scaffold holding the potential to link macroscopic lived experience to increasingly sophisticated and abstract explanatory models. However, the empirical validation of these theoretical pathways requires further classroom-based research to explore how learners actually navigate these conceptual shifts.

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