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ACTIVITY-BASED MODELLING OF PHYSICAL EXPERIMENTS: THEORETICAL FOUNDATIONS AND PEDAGOGICAL DESIGN

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Abstract

Physical experimentation is a cornerstone of science education, yet the transition from hands-on laboratory work to digital simulation environments raises fundamental pedagogical questions about how students construct understanding through modelling activity. This paper argues that Activity Theory - as developed by Vygotsky, Leontiev, and Davydov within the cultural-historical tradition - provides the most coherent theoretical foundation for the pedagogical design of physical experiment modelling.

The paper identifies three activity-theoretic principles that are especially consequential for modelling instruction: the primacy of joint (collective) activity over individual activity in the formation of higher mental functions; the mediating role of signs and symbolic tools in the development of scientific reasoning; and the necessity of reflective activity as the condition for genuine appropriation of modelling skills.

Keywords: physical experiment modelling, activity theory, Vygotsky, zone of proximal development, reflective learning, digital simulation, science education, collective activity, motivational structure.

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Introduction

The modelling of physical experiments occupies an increasingly central position in contemporary science education. As digital simulation environments - MATLAB/Simulink, PhET Interactive Simulations, Wolfram Demonstrations, and virtual laboratory platforms - become standard instructional resources, the pedagogical challenge is no longer one of access but of design: how should modelling activities be structured so that students genuinely develop the capacity for scientific reasoning, rather than merely producing correct outputs by navigating unfamiliar interfaces?

This question has theoretical depth. The answer depends substantially on what one believes constitutes learning in a scientific discipline and what role activity - as opposed to passive reception of information - plays in that process. The Russian cultural-historical school of psychology, founded by Vygotsky and systematically developed by Leontiev, Davydov, and their colleagues, offers an unusually well-developed theoretical response. Their core insight - that human cognitive development is inseparable from participation in culturally organised, purposeful activity - applies with particular force to the learning of scientific modelling, which is itself a form of culturally transmitted, normatively structured activity.

This paper is structured as follows. Section 2 extracts the three activity-theoretic principles most directly relevant to physical experiment modelling. Section 3 develops a pedagogical design framework grounded in these principles. Section 4 maps the framework onto specific modelling task types. Section 5 draws conclusions.

Activity theory and physical experiment modelling. Primacy of Joint Activity. Vygotsky's foundational claim is that all higher mental functions appear first between people (interpsychologically) and only subsequently within the individual (intrapsychologically). For physical experiment modelling, this principle has a direct instructional implication: modelling competency does not develop optimally when students work in isolation with a simulation interface. It develops through joint modelling activity - shared hypothesis formation, collaborative parameter manipulation, and collective interpretation of simulation results - in which the student's individual modelling reasoning is scaffolded by the reasoning of more competent peers and the instructor.

Leontiev's structural analysis of activity further specifies the conditions under which joint activity generates development. The motivational structure of any activity is constituted by the relationship between need, motive, and goal. In physical experiment modelling, cognitive motivation - the genuine desire to understand the physical phenomenon being modelled - arises when the modelling task poses a problem that cannot be resolved by previously available knowledge or procedures. The collective nature of the activity is important here: in a group setting, the student is exposed to the reasoning strategies of others, creating the «collisions of understanding» that Vygotsky identified as the primary driver of conceptual development.

Signs and Symbolic Tools as Mediators. The second foundational principle concerns the role of signs and symbolic tools in the development of scientific reasoning. Vygotsky argued that artificial thinking tools - written language, mathematical notation, diagrams, models - function as mediators between the human mind and the objects of its activity. A physical simulation environment is, in this sense, a complex semiotic tool: it represents the physical phenomenon through mathematical equations, graphical outputs, and parametric interfaces, each of which carries symbolic content that must be interpreted within the conventions of the relevant scientific discourse.

The pedagogical implication is that learning to model physical experiments is not primarily a matter of acquiring software skills. It is a matter of acquiring facility with the symbolic languages in which physical knowledge is encoded - differential equations as representations of dynamic processes, phase diagrams as representations of system states, block diagrams as representations of causal structure. Instruction that treats simulation software as a black box, accepting its outputs without engaging with its symbolic substrate, forecloses precisely the cognitive development that modelling activity is intended to generate. Planning activity - what Vygotsky described as the preliminary construction of action in signs and diagrams - is a prerequisite for productive experimental modelling.

Reflective Activity as the Condition for Appropriation. The third principle, developed most explicitly by Shchedrovitsky and incorporated into Davydov's theory of learning activity, concerns reflection. For modelling activity to be genuinely appropriated - that is, for the student to become capable of independently initiating and executing modelling processes - the activity must include a reflective phase in which the student consciously examines not only the results of their modelling work but the methods and operations through which those results were obtained.

Reflection in this sense is not retrospective recall or summarising; it is the student's capacity to objectify their own activity - to treat their modelling procedure as an object of analysis. In physical experiment modelling, this means that students should, at the conclusion of each modelling task, be able to articulate: what physical assumptions were encoded in the model; what operations were performed and why; where the model succeeded and where it failed; and what would need to change in the model to better represent the physical phenomenon. Without this reflective phase, modelling activity risks becoming mechanical and producing what Davydov called «formal knowledge»

- knowledge that can be reproduced in familiar contexts but cannot be transferred or extended.

Pedagogical design framework. Drawing on the three principles identified above, a pedagogical design framework for physical experiment modelling is proposed. The framework organises modelling instruction around four phases, each with a defined motivational-operational structure and a corresponding instructional role for the teacher.

The critical design features of this framework are three. First, cognitive motivation is generated structurally - through the orientation phase's encounter with an unexplained phenomenon - rather than assumed or externally imposed. Second, joint activity precedes and scaffolds individual activity: students first build models collaboratively before being asked to work independently. Third, reflection is a non-optional structural component, not an optional addition.

Modelling task types and their activity structure. Three principal types of physical experiment modelling task can be distinguished, each with a characteristic activity structure and corresponding learning outcomes.

Simulation tasks present students with a pre-built model of a physical system and ask them to run the simulation, varying one or more parameters systematically to investigate the system's behaviour. The activity structure of simulation tasks is primarily investigative: the student's goal is to discover the functional relationship between parameter values and system behaviour. The cognitive challenge lies in designing a systematic investigation plan - identifying which parameters to vary, in what range, and how to interpret the resulting output patterns. The reflective question at the end of a simulation task is: «What did this model assume, and how would different assumptions change the result?»

Parameter identification tasks ask students to adjust model parameters until the simulation output matches observed experimental data. This task type has a distinctively dual activity structure: the student must simultaneously reason about the physical meaning of the parameters (modelling knowledge) and about the mathematical relationship between parameters and outputs (analytical knowledge). The cognitive challenge is high, and the motivational structure is rich - the task is closed (there is a correct answer) yet genuinely open in the sense that the student must discover the solution path independently.

Predictive modelling tasks ask students to build a model from first principles, use it to generate a prediction, and then test the prediction against physical experiment or authoritative data. This task type most fully instantiates the activity-theoretic framework: it requires all four phases, engages all three symbolic registers (mathematical model, simulation interface, experimental data), and demands genuine reflective articulation of the relationship between model and reality.

Conclusion

Activity Theory, as developed within the cultural-historical tradition of Vygotsky, Leontiev, and Davydov, provides a theoretically rigorous and practically actionable foundation for the pedagogical design of physical experiment modelling. Three principles - the primacy of joint activity, the mediating role of symbolic tools, and the necessity of reflective activity - translate directly into the four-phase instructional framework proposed in this paper.

The framework's central pedagogical contribution is its insistence that the learning objective of physical experiment modelling is not the production of correct simulation outputs but the appropriation of the modelling activity itself - that is, the student's development of the capacity to independently initiate, execute, and reflect on the process of constructing and testing physical models. This objective requires instructional designs in which joint activity, symbolic scaffolding, and structured reflection are permanent structural features, not occasional enrichments.

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