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PROBLEM-BASED SIMULATION OF PHYSICAL EXPERIMENTS: COGNITIVE MOTIVATION, HYPOTHESIS FORMATION, AND THE STRUCTURE OF MODELLING TASKS

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Abstract. Problem-based learning (PBL) and physical experiment simulation are two of the most widely recommended pedagogical approaches in science education, yet their integration in instructional practice remains theoretically underdeveloped. This paper examines the conditions under which problem-based organisation of learning activity generates the cognitive motivation necessary for productive physical experiment simulation, and proposes a structured framework for the design of problem-based simulation tasks.

Keywords: problem-based learning, physical experiment simulation, cognitive motivation, hypothesis formation, problem situation, digital modelling, Makhmutov, thinking paradox, science education.

Introduction. The case for problem-based learning in science education rests on a well-established empirical and theoretical foundation: students who engage with genuine problems - situations in which available knowledge is insufficient to produce a resolution - develop deeper conceptual understanding, stronger transfer performance, and more durable cognitive engagement than students who receive the same content through expository instruction. The case for physical experiment simulation rests on a complementary body of evidence: virtual and computational simulation environments allow students to investigate physical phenomena at scales, speeds, and levels of parametric control that physical laboratories cannot provide, and to develop the modelling competencies that professional scientific practice requires.

What remains comparatively underdeveloped is the principled integration of the two approaches. Problem-based learning requires a problem situation - a genuine cognitive impasse - as its motivational engine. Physical experiment simulation provides a modelling environment. The question is: under what conditions does a simulation environment generate problem situations powerful enough to sustain genuine problem-based inquiry, rather than degenerating into exploratory play or algorithmic parameter scanning?

This paper addresses this question by examining the structure of thinking in problem-solving contexts (Brushlinsky), the conditions for generating and sustaining cognitive motivation in learning (Leontiev, Davydov), and the typology of problem situations applicable to physical phenomena (Malafeyev). From this analysis, a classification of problem-based simulation task types is derived, together with design guidelines for each type and a characterisation of the teacher’s instructional role.

In the context of physical experiment simulation, problem situations arise most naturally from three sources, following Malafeyev’s typology. Contradiction-based situations occur when simulation outputs conflict with students' existing physical intuitions or previously acquired theoretical knowledge - for example, when a simulation of air resistance on a falling body produces counter-intuitive velocity-time curves. Hypothesis-based situations occur when the teacher presents an explanatory conjecture (with no stated basis for it) and challenges students to test it using a simulation model. Absence-of-method situations occur when students are given a physical question and a simulation environment but no prescribed procedure, and must independently discover an investigative strategy.

Each of these situation types generates a different motivational structure, and consequently a different cognitive engagement profile. Contradiction-based situations produce the highest initial motivational intensity - the «surprise» response documented in cognitive psychology as a trigger for deep processing. Hypothesis-based situations are particularly effective for developing the ability to formulate and operationalise scientific conjectures. Absence-of-method situations are most demanding and most suitable for students with a prior foundation in simulation methodology.

The Thinking Paradox and Its Pedagogical Management. Brushlinsky's analysis of productive thinking identifies what he terms the «paradox of thinking»: the solver must seek a solution that is simultaneously already known (in the sense that the problem statement contains implicit constraints that guide the search) and genuinely unknown (in the sense that the specific solution has not been encountered before). This paradox is not a defect in the structure of problem-solving; it is its defining feature. It means that the solver must simultaneously use available knowledge as a search guide while remaining genuinely open to the possibility that the solution will require revising that knowledge.

For physical experiment simulation, this paradox manifests in the following way: the student approaches a simulation task with a physical model (explicit or tacit) of the phenomenon, uses this model to generate initial hypotheses and guide parameter choices, and must then remain genuinely responsive to simulation outputs that contradict the model. The pedagogical management of this paradox requires that two conditions be maintained simultaneously: the student must have sufficient physical knowledge to formulate hypotheses and interpret outputs (if they have no prior model, the paradox collapses into random exploration), and the simulation task must be designed so that the initial physical model is systematically inadequate to account for the full simulation behaviour (otherwise the paradox collapses into confirmation of existing knowledge).

Instructionally, this means that the simulation task must be pitched precisely in the student's zone of proximal development - Vygotsky's term for the region of cognitive activity that the student can enter with guidance but not yet independently. Tasks that are too simple produce no paradox and no development; tasks that are too complex produce cognitive overload and motivational collapse. The teacher's diagnostic competency - recognising where individual students stand in relation to this zone - is therefore a central determinant of the effectiveness of problem-based simulation instruction.

Classification of problem-based simulation task types. Drawing on the analysis in Section 2, a three-category classification of problem-based simulation task types is proposed, each characterised by its problem situation type, motivational structure, hypothesis format, and primary cognitive challenge.

Contradiction-Based Tasks. The primary design challenge for contradiction-based tasks is selecting a physical phenomenon in which there is a substantial and systematic gap between naive intuition and correct physical description. Strong candidates include: free fall with non-negligible air resistance (intuition: uniform acceleration; reality: terminal velocity); thermal equilibration of objects with different heat capacities (intuition: same temperature equals same thermal sensation; reality: different rates); and resonance phenomena in driven oscillators (intuition: larger driving force produces larger amplitude; reality: amplitude depends critically on frequency proximity to resonance). The simulation must be designed so that students can observe the contradiction directly - not through the teacher's explanation - and so that the parameter space is rich enough to support a meaningful investigation of the underlying physical relationship.

Hypothesis-Testing Tasks. The key design requirement for hypothesis-testing tasks is that the conjecture presented by the teacher must be genuinely uncertain from the students' perspective - neither trivially confirming nor obviously falsifiable with the knowledge the students currently possess. The hypothesis should be formulated in a way that students can operationalise it as a prediction about specific simulation outputs: «If this conjecture is correct, then when we vary parameter X in this range, we should observe output Y to change in the following way.» This operationalisation step is itself a high-value cognitive activity, as it requires students to connect theoretical claims to observable quantities - a core scientific reasoning skill.

Absent-Method Tasks**.** Type III tasks are the most demanding and should be introduced only after students have substantial experience with Types I and II. The teacher poses a physical question - for example, «How does the period of a damped oscillator depend on the damping coefficient?» - and provides access to a simulation environment without specifying an investigation procedure. Students must independently determine what parameters to vary, what measurements to take, how to represent their findings, and how to interpret them in physical terms. The teacher's role is to monitor groups' investigative strategies and provide targeted, minimal interventions when groups become genuinely stuck - not to supply missing procedures but to ask questions that redirect the group's attention to aspects of the problem they have not yet considered.

The teacher's role in problem-based simulation**.** Across all three task types, the teacher's role in problem-based simulation is fundamentally different from the role in expository instruction. Rather than presenting physical knowledge and demonstrating its application, the teacher manages four interrelated processes: creating and maintaining the problem situation; scaffolding hypothesis formulation without foreclosing student reasoning; orchestrating group dialogue to ensure that the paradox of thinking remains generative rather than frustrating; and structuring the reflective phase so that students appropriate not only the specific result but the investigative method.

Makhmutov's typology of levels of student independence in problem-solving is directly applicable here. At the lowest level, the teacher creates the problem situation, formulates the problem, and leads the solution process with student participation. At intermediate levels, the teacher creates the situation but students formulate the problem and participate in the solution. At the highest level, students create the problem situation, formulate the problem, and conduct the investigation, with the teacher providing only organisational oversight. Progress through these levels over a course or academic year constitutes the developmental trajectory of problem-based simulation competency.

Conclusion. The integration of problem-based learning and physical experiment simulation requires more than placing students in front of a simulation environment with an open-ended question.

It requires the deliberate creation of genuine problem situations, the structured scaffolding of hypothesis formulation and simulation-based testing, and the pedagogical management of the paradox of thinking that characterises all productive problem-solving.

The three-category task classification developed in this paper - contradiction-based, hypothesis-testing, and absent-method tasks - provides a practical design tool for instructors seeking to implement problem-based simulation in physics and physical science courses. The progression from Type I through Type III corresponds to an increasing demand for student independence and a decreasing level of teacher scaffolding, constituting a developmental trajectory that can be implemented across a semester or academic year. The teacher's diagnostic competency - the ability to locate students within their zone of proximal development and calibrate task difficulty accordingly - remains the central determinant of the approach's effectiveness.

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