ilmiy-amaliy jurnal · ISSN 3093-8694

UDK 372.854:159.955

Kokhkharov Mirzokhid,
Namangan State Technical University,
Doctor of Chemical Sciences, Associate Professor

Asfandiyorov Marufjon,
Tashkent University of Information Technologies named after Muhammad al-Khwarizmi,
Senior Lecturer

DEVELOPING ANALYTICAL AND CRITICAL THINKING IN CHEMISTRY PROBLEM SOLVING THROUGH THE "FIND X" METHODOLOGY

Abstract. This methodological study develops and theoretically validates a structured "Find X" approach to chemistry problem solving aimed at strengthening analytical and critical thinking. Chemistry-education research on metacognitive scaffolding, inquiry-based learning, open-ended problem solving, higher-order cognitive skills and critical-thinking assessment was synthesised for this purpose. In the resulting framework X is treated not as an algebraic unknown but as any chemically meaningful target that must be inferred from evidence: an amount of substance, a formula coefficient, a concentration, an equilibrium quantity, a reaction pathway, the identity of an unknown species, or the explanation that best fits the data. The framework comprises six recursive phases — Frame X, Extract, Connect, Solve, Challenge and Explain — each aligned with observable indicators of reasoning and with prompts suitable for classroom, laboratory and assessment use. Three worked chemistry cases show how attention shifts from algorithm reproduction towards model selection, assumption checking, dimensional analysis and argumentation. A four-level analytic rubric with six dimensions and a quasi-experimental validation protocol are proposed for future testing. Because no student dataset was available, the article reports the products of methodological synthesis rather than learning gains.

Keywords: *chemistry education; problem solving; critical thinking; analytical thinking; metacognition; scaffolding; Find X methodology; higher-order cognitive skills; assessment rubric; prompt fading; reasoning trace; evidence-based argumentation.*

KIMYO O‘QITISHDA "X NI IZLASH" METODIKASI ASOSIDA MASALALAR YECHISH ORQALI ANALITIK VA TANQIDIY FIKRLASHNI RIVOJLANTIRISH

Annotatsiya. Ushbu metodik tadqiqotda kimyodan masala yechishda analitik va tanqidiy fikrlashni rivojlantirishga qaratilgan "X ni izlash" yondashuvi ishlab chiqilgan va nazariy jihatdan asoslangan. Metakognitiv tayanch, izlanishga asoslangan o‘qitish, ochiq tipdagi masalalar, yuqori tartibli kognitiv ko‘nikmalar va tanqidiy fikrlashni baholash bo‘yicha kimyo ta’limi tadqiqotlari maqsadli sintez qilindi. Taklif etilgan modelda X algebraik noma’lum emas, balki dalillar asosida aniqlanishi lozim bo‘lgan kimyoviy maqsad kattalik sifatida talqin etiladi: modda miqdori, formula koeffitsienti,

konsentratsiya, muvozanat kattaligi, reaksiya yo‘li, noma’lum zarrachaning tabiati yoki ma’lumotlarga eng mos izoh. Model oltita takrorlanuvchi bosqichdan iborat: X ni aniqlash, dalillarni ajratish, bog‘lanishlarni qurish, asoslangan yechim, natijani tanqidiy tekshirish va izohlash. Har bir bosqich kuzatiladigan indikatorlar va savol-tayanchlar bilan bog‘langan. Uchta ishlangan misol diqqat markazining algoritmni takrorlashdan model tanlash, taxminlarni tekshirish va dalilga asoslangan argumentatsiyaga siljishini ko‘rsatadi. Olti o‘lchovli, to‘rt darajali baholash rubrikasi va kelgusi kvazieksperimental sinov dasturi taklif qilinadi. Talabalar bo‘yicha real ma’lumotlar bo‘lmagani sababli maqolada o‘quv natijalari emas, metodik sintez natijalari yoritilgan.

Kalit so‘zlar: *kimyo ta’limi; masala yechish; tanqidiy fikrlash; analitik fikrlash; metakognitsiya; metodik tayanch; "X ni izlash" metodikasi; yuqori tartibli kognitiv ko‘nikmalar; baholash rubrikasi; tayanchni asta olib tashlash; fikrlash izi; dalilga asoslangan argumentatsiya.*

РАЗВИТИЕ АНАЛИТИЧЕСКОГО И КРИТИЧЕСКОГО МЫШЛЕНИЯ ПРИ РЕШЕНИИ ХИМИЧЕСКИХ ЗАДАЧ НА ОСНОВЕ МЕТОДИКИ «ПОИСК X»

Аннотация. В методической статье разработан и теоретически обоснован структурированный подход «Поиск X» к решению химических задач, ориентированный на развитие аналитического и критического мышления. Проведён целевой синтез исследований по метакогнитивному сопровождению, исследовательскому обучению, задачам открытого типа, навыкам мышления высокого порядка и оцениванию критического мышления. В предложенной модели X трактуется шире алгебраической неизвестной: это химически значимая целевая величина или вывод, который необходимо установить на основе данных, моделей и ограничений, — количество вещества, коэффициент в формуле, концентрация, равновесная величина, путь реакции, природа неизвестной частицы либо наиболее обоснованное объяснение наблюдений. Модель включает шесть рекурсивных этапов: определить X, выделить доказательства, установить связи, получить обоснованное решение, критически проверить результат и объяснить его. Каждый этап соотнесён с наблюдаемыми индикаторами мышления и вопросами-подсказками. Три разобранных примера показывают смещение внимания от воспроизведения алгоритма к выбору модели, проверке допущений и аргументации. Предложены четырёхуровневая рубрика по шести измерениям и схема квазиэкспериментальной проверки. Поскольку эмпирические данные учащихся отсутствовали, количественные эффекты не моделируются.

Ключевые слова: *химическое образование; решение задач; критическое мышление; аналитическое мышление; метакогниция; педагогический скаффолдинг; методика «Поиск X»; навыки мышления высокого порядка; рубрика оценивания; постепенное снятие опор; след рассуждения; доказательная аргументация.*

INTRODUCTION

Problem solving is a defining practice of chemistry, because chemical knowledge becomes useful only when a learner can turn observations, symbols and data into defensible conclusions. Yet success in routine exercises often coexists with fragile reasoning: students reproduce worked-example procedures without de-

ciding why a relation applies or whether an answer is plausible. Chemistry-education research therefore increasingly treats problem solving as a metacognitive and epistemic activity rather than a sequence of calculations. Structured workflows and metacognitive scaffolding make planning, monitoring and evaluation explicit, guiding novices out of dead ends [7; 10–12].

Critical thinking is equally central and harder to operationalise. Chemistry undergraduates, teaching staff and employers associate it with analysis, critique, objectivity and evaluation, yet shared definitions remain limited [6]. The construct has even been called amorphous in students' own accounts [9], so a teaching method should specify what students actually do: separate evidence from assumptions, compare models, justify choices, detect inconsistency and revise conclusions when warranted.

This article uses "Find X" as a deliberately broad label. It does not claim an established pedagogy standardised under that name, and searching identified no recognised method formally so titled. The closest traditions are problem-solving scaffolds, metacognitive prompting, inquiry learning, open-ended problems and higher-order cognitive skills; the framework synthesises them transparently. Its novelty lies in organising established principles around the recurring act of identifying an unknown target and defending how it was found. In chemistry that target varies widely, from a limiting reagent or concentration to the identity of an ion or the best explanation of a laboratory anomaly.

Three recurring weaknesses motivate the approach. Students calculate before defining the target and its constraints. They choose equations by surface similarity rather than chemical principle. Having obtained a number, they stop without checking units, magnitude or assumptions. The aim is a chemistry-specific framework that operationalises analytical and critical thinking through teachable prompts. Four questions guide the study: (RQ1) which reasoning functions recur across the relevant research; (RQ2) how they can be organised into a workflow; (RQ3) which behaviours indicate each phase; and (RQ4) how reasoning can be assessed without reducing it to answer accuracy.

LITERATURE REVIEW

Four clusters informed the synthesis. The largest concerns problem-solving scaffolds and metacognitive support, where explicit planning, monitoring and evaluation prompts reshape how novices approach chemistry tasks [7; 10–12]. The second comprises chemistry-specific conceptualisations of critical thinking, which supply operational definitions and warn against unexamined use of the term [6; 9].

The third cluster covers inquiry-based and writing-intensive instruction. Guided inquiry with a writing and reflection emphasis has been associated with gains on critical-thinking measures [2], and the Science Writing Heuristic links argumentation to laboratory evidence [5]. An inquiry-based synthetic organic course developed analysis skills [4], and writing assignments have strengthened acid–base

skills [8]. The fourth cluster concerns open-ended and higher-order tasks. Expert–novice comparisons show that expertise rests on purposeful interpretation rather than faster calculation [3], while higher-order cognitive-skills approaches tie laboratory practice to declared cognitive goals [1].

Recent work confirms that these directions remain active. Laboratory manuals carrying cognitive prompts have been tested for their effect on critical-thinking skills and dispositions [13]. Analyses of science practices in the general chemistry laboratory document hits, misses and near misses [15], and a systematic review ties problem-based learning to critical thinking and motivation [14]. What this literature lacks is a compact, chemistry-facing cycle uniting target definition, evidence evaluation, model selection and obligatory critical appraisal in a form printable on a worksheet.

METHODOLOGY

A methodological development design was used. The unit of analysis was a reasoning function reported in peer-reviewed chemistry-education literature and its translation into a teachable action. Four stages were followed: targeted literature identification, extraction of recurring reasoning functions, synthesis into the framework, and analytic testing through worked cases. The procedure resembles theory-informed instructional design rather than a systematic review, so no PRISMA claim is made. Priority went to studies in Chemistry Education Research and Practice and the Journal of Chemical Education.

Statements about learner actions, instructor prompts, assessment and reasoning processes were coded into functional categories covering problem definition, planning, information selection, representation, principle selection, execution, monitoring, evidence evaluation, plausibility checking, alternatives and justification. Similar functions were merged only where their instructional purpose overlapped. Five criteria then governed the synthesis. Each phase had to be interpretable without specialist vocabulary. The phases together had to cover analytical decomposition and critical evaluation. The sequence had to serve quantitative, conceptual and experimental problems alike. Each phase had to yield observable evidence, and a recursive loop was required, because authentic problem solving is rarely linear.

Three problem families tested transferability: (A) identification of an unknown element from molar-mass evidence, (B) determination of a limiting reagent and product yield, and (C) evaluation of an unexpected laboratory result. Each was solved twice, as a minimal answer-oriented route and through the six phases, so the comparison showed the reasoning made visible rather than invented scores. A four-level analytic rubric was then built across six dimensions, shown in Table 1.

Table 1. Proposed four-level analytic rubric for reasoning

Dimension	0 – Absent	1 – Emerging	2 – Analytical	3 – Analytical + critical

Target (X)	No clear target	Target copied but not interpreted	Target defined with units and meaning	Target defined with criteria for a valid answer
Evidence	Data listed randomly	Some relevant data selected	Relevant data and constraints organ-ised	Relevance, uncer-tainty and missing evidence evaluated
Connections	Formula guessed	Rule named without justification	Principle or repre-sentation correctly linked	Alternative models considered and choice defended
Execution	No viable path	Procedural steps with gaps	Coherent, traceable solution	Solution monitored and revised when needed
Evaluation	No check	Arithmetic or unit check only	Units and plausibility checked	Assumptions, al-ternatives, uncer-tainty and evidence challenged
Explanation	Answer only	Brief statement	Reasoned explanation	Evidence-based argument plus transfer and limita-tions

Being proposed rather than psychometrically validated, the rubric needs reliability and construct-validity testing before high-stakes use.

RESULTS

The principal result is a six-phase recursive framework. Table 2 pairs each phase with its reasoning function and the prompt a student answers.

Table 2. The six phases of the "Find X" cycle

Phase	Primary reasoning function	Core student prompt
Frame X	Goal definition and problem rep-resentation	What exactly must be found, ex-plained, identified or justified?
Extract	Evidence and constraint analysis	What is given, relevant, missing, uncertain or constrained?
Connect	Model and representation selection	Which chemical principle links the evidence to X, and why?
Solve	Execution with explicit reasoning	What sequence of justified steps produces a candidate X?
Challenge	Critical evaluation	Do units, magnitude, assump-tions, alternatives and evidence support X?
Explain	Argumentation and transfer	Can I defend X and state when this strategy would or would not work?

The order is deliberate. The target precedes evidence, because relevance cannot be judged without a known endpoint. Solve follows model selection, which prevents premature formula choice. Challenge makes evaluation obligatory, and the loop permits return to an earlier phase when a check fails.

Metacognition is embedded in ordinary chemistry language. "What am I finding?" functions as planning, "does this relation actually apply?" as monitoring, and "does the answer make chemical sense?" as evaluation [7; 10–12]. Analytical and critical thinking proved better treated as overlapping processes than as separate objectives. Frame X and Extract are predominantly analytical. Connect adds judgement, because several principles may appear plausible. Solve stays analytical only while reasoning remains traceable. Challenge is the strongest critical phase, and Explain integrates both.

Worked case A concerns an acid of formula HXO_3. A sample of 0.0133 mol has a mass of 1.123 g, and X must be determined. Extract records m = 1.123 g, n = 0.0133 mol and one H, one X and three O per formula unit, and Connect joins M = m/n to $M(HXO_3) = Ar(H) + Ar(X) + 3Ar(O)$. Solve gives $M = 1.123/0.0133 = 84.44$ g mol^{-1} and $Ar(X) \approx 84.44 - 1.008 - 3(15.999) \approx 35.44$. Challenge notes that the value lies close to the standard atomic weight of chlorine, about 35.45, the small deviation arising from rounding of the given data. Explain concludes that X is Cl and the acid is $HClO_3$, chloric acid; a result such as 34.5 or 45.3 would instead demand re-examination.

Worked case B uses the reaction $2H_2 + O_2 \rightarrow 2H_2O$ with 5.00 mol H_2 and 2.00 mol O_2 mixed. Frame X identifies two linked targets, the limiting reagent and $n(H_2O)$, while Extract separates actual mole amounts from stoichiometric coefficients. Connect treats the balanced equation as a ratio model: 2.00 mol O_2 requires 4.00 mol H_2, of which 5.00 mol are available, so O_2 is limiting. Solve gives 4.00 mol H_2O. Challenge asks whether product can exceed the capacity of the limiting reactant and whether the residual 1.00 mol H_2 is consistent. Explain states the causal logic: oxygen limits product formation because it is exhausted first.

In worked case C a student determines acetic-acid concentration by titration and obtains a value 18% above the labelled concentration. A conventional exercise would ask only for recalculation; here X is reframed as the most defensible explanation of the discrepancy. Extract distinguishes observations from hypotheses, and Connect maps procedural events to directional effects. Residual water dilutes the titrant and, if the nominal concentration is still used, biases the calculated analyte concentration; overshooting an endpoint inflates the recorded volume and the result with it. Challenge requires ranking explanations against the evidence, so the answer stays conditional: concordant but consistently high titres with a visibly overshot endpoint point to endpoint bias.

DISCUSSION

Analytical thinking in chemistry depends on representation. Learners must move among macroscopic observations, submicroscopic entities, symbols and words, and a formula-first habit bypasses this work. Requiring students to define X, inventory evidence and state the connecting principle delays calculation until a

problem model exists, which is compatible with findings that expertise in open-ended problems rests on interpretation rather than speed [3].

Critical thinking enters most strongly when a candidate solution is treated as a hypothesis to be tested. The Challenge phase formalises dimensional consistency, order of magnitude, boundary conditions, conservation laws, chemical plausibility and alternative explanations. These checks turn "check your answer" from an arithmetic instruction into an epistemic practice. That is in line with research using inquiry, writing and reflection to develop critical-thinking behaviours [2; 5], and it answers the concern that the term is invoked without shared operational meaning [9].

The method is closely related to metacognitive scaffolding but uses a compact architecture, translating the core logic of that research into six chemistry-facing questions printable on worksheets or laboratory manuals [7; 10–12]. Implementation can begin with teacher modelling. The instructor solves one problem aloud, labels each phase and deliberately voices a correction, so that revision is normalised. Students then complete partially scaffolded templates, after which prompts are faded, because a scaffold that stays permanently detailed becomes another algorithm. Early worksheets may carry six boxes with sentence starters, later tasks only the phase names, and finally a bare reasoning trace.

The cycle adapts across topics, as Table 3 sets out: the form of X changes, but each row carries its own obligatory challenge question.

Table 3. Integration of the cycle into different chemistry topics

Topic	Possible X	Critical challenge question
Stoichiometry	limiting reagent, yield, empirical formula	Does the answer satisfy conservation and mole-ratio constraints?
Solutions / acid–base	concentration, pH, equivalence point	Are approximations and significant figures justified?
Equilibrium	K, equilibrium composition, direction of shift	Is the equilibrium model applied to the correct state?
Thermochemistry	ΔH, heat, calorimeter constant	Are sign convention, system boundary and heat losses considered?
Kinetics	rate law, order, k	Does the proposed model fit the pattern across multiple experiments?
Electrochemistry	Ecell, spontaneous direction, unknown ion	Are half-reactions, signs and conditions internally consistent?
Organic / spectroscopy	structure or pathway	Does one structure account for all available evidence better than alternatives?
Laboratory inquiry	cause of anomaly or best model	Which explanation is supported, contradicted or unresolved by the data?

Assessment should award reasoning independently of final accuracy. One student may slip arithmetically after selecting the right model, while another reaches the correct number by an unjustified shortcut. For research use, raters need anchor responses and reported reliability. A feasible quasi-experimental validation design would place two comparable classes on the same content for four to six weeks, the intervention group using the scaffold with prompt fading and the comparison group conventional worked examples matched for content and time.

Several limitations follow. "Find X" is a newly synthesised label whose components are grounded in prior research but whose integrated form has not been validated as a distinct intervention. The literature identification was targeted rather than exhaustive, and the worked cases demonstrate conceptual applicability rather than learning gains. The framework may overload novices if all prompts arrive at once, which is why staged modelling and fading are recommended. Critical thinking is also context-sensitive, so assessment should sample several chemistry domains.

CONCLUSION

The study developed a six-phase "Find X" methodology for chemistry problem solving by synthesising research on metacognitive scaffolding, inquiry learning, open-ended problems and critical thinking. It reframes X as any chemically meaningful target that must be established and defended from evidence, and its phases make problem representation, model selection, monitoring, evaluation and argumentation visible. Its value is not a new route to correct answers but a structure that slows unexamined procedural behaviour and makes reasoning inspectable.

Four recommendations follow for instructors. Model the framework explicitly with think-aloud reasoning before expecting independent use. Choose problems in which the unknown varies in form, so that X is not equated with algebra. Score reasoning dimensions separately from final-answer correctness. Fade prompts gradually, but preserve the Challenge phase even after other supports are withdrawn, because evaluation is the element most likely to disappear under time pressure.

For researchers, the framework should now be tested with transparently reported designs, authentic student work and genuine transfer tasks, asking whether the integrated cycle adds value beyond existing metacognitive scaffolds. No numerical improvement, effect size or statistical significance is claimed here, because no authentic participant dataset was provided. The limitation is deliberate: a methodology meant to promote critical thinking should itself model evidence-responsible scholarship.

Foydalanilgan adabiyotlar:

1. Zoller U., Pushkin D. Matching Higher-Order Cognitive Skills (HOCS) promotion goals with problem-based laboratory practice in a freshman organic chemistry course // Chemistry Education Research and Practice. – 2007. – Vol. 8, No. 2. – P. 153–171. DOI: 10.1039/B6RP90028C.

2. Gupta T., Burke K. A., Mehta A., Greenbowe T. J. Impact of Guided-Inquiry-Based Instruction with a Writing and Reflection Emphasis on Chemistry Students' Critical Thinking Abilities // Journal of Chemical Education. – 2015. – Vol. 92, No. 1. – P. 32–38. DOI: 10.1021/ed500059r.

3. Randles C. A., Overton T. L. Expert vs. novice: approaches used by chemists when solving open-ended problems // Chemistry Education Research and Practice. – 2015. – Vol. 16, No. 4. – P. 811–823. DOI: 10.1039/C5RP00114E.

4. Ghanem E., et al. Developing Students' Critical Thinking, Problem Solving, and Analysis Skills in an Inquiry-Based Synthetic Organic Laboratory Course // Journal of Chemical Education. – 2016. – Vol. 93, No. 5. – P. 847–851. DOI: 10.1021/acs.jchemed.5b00678.

5. Stephenson N. S., Sadler-McKnight N. P. Developing critical thinking skills using the Science Writing Heuristic in the chemistry laboratory // Chemistry Education Research and Practice. – 2016. – Vol. 17, No. 1. – P. 72–79. DOI: 10.1039/C5RP00102A.

6. Danczak S. M., Thompson C. D., Overton T. L. "What does the term Critical Thinking mean to you?" A qualitative analysis of chemistry undergraduate, teaching staff and employers' views of critical thinking // Chemistry Education Research and Practice. – 2017. – Vol. 18, No. 3. – P. 420–434. DOI: 10.1039/C6RP00249H.

7. Yuriev E., Naidu S., Schembri L. S., Short J. L. Scaffolding the development of problem-solving skills in chemistry: guiding novice students out of dead ends and false starts // Chemistry Education Research and Practice. – 2017. – Vol. 18, No. 3. – P. 486–504. DOI: 10.1039/C7RP00009J.

8. Cox C. T. Jr. Using Writing Assignments as an Intervention to Strengthen Acid–Base Skills // Journal of Chemical Education. – 2018. – Vol. 95, No. 8. – P. 1276–1283. DOI: 10.1021/acs.jchemed.8b00018.

9. Bowen R. S. Student perceptions of "critical thinking": insights into clarifying an amorphous construct // Chemistry Education Research and Practice. – 2022. – Vol. 23, No. 3. – P. 725–741. DOI: 10.1039/D2RP00097K.

10. Vo K., Sarkar M., White P. J., Yuriev E. Problem solving in chemistry supported by metacognitive scaffolding: teaching associates' perspectives and practices // Chemistry Education Research and Practice. – 2022. – Vol. 23, No. 2. – P. 436–451. DOI: 10.1039/D1RP00242B.

11. Vo K., Sarkar M., White P. J., Yuriev E. Development of problem-solving skills supported by metacognitive scaffolding: insights from students' written work // Chemistry Education Research and Practice. – 2024. – Vol. 25, No. 9. – P. 1197–1209. DOI: 10.1039/D3RP00284E.

12. Vo K., Sarkar M., White P. J., Yuriev E. Metacognitive problem solving: exploration of students' perspectives through the lens of multi-dimensional engagement // Chemistry Education Research and Practice. – 2025. – Vol. 26, No. 1. – P. 141–157. DOI: 10.1039/D4RP00096J.