

Dynamic Cognitive Profiling: A Systematic Approach to Diagnose Strategic Knowledge Gaps in Problem-Based Programming

Pemprofilan Kognitif Dinamik: Satu Pendekatan Sistematis untuk Mendiagnosis Jurang Pengetahuan Strategik dalam Pengaturcaraan Berasaskan Masalah

Siti Sarah Izhan Khalib*, Siti Fadzilah Mat Noor, Tengku Siti Meriam Tengku Wook, Kauthar Mohd Daud

Center for Software Technology and Management (SOFTAM), Fakulti Teknologi dan Sains Maklumat (FTSM), Universiti Kebangsaan Malaysia (UKM)

Center for Artificial Intelligence Technology (CAIT), Fakulti Teknologi dan Sains Maklumat (FTSM), Universiti Kebangsaan Malaysia (UKM)

*Corresponding author: Siti Sarah Izhan Khalib (e-mail: p166765@siswa.ukm.edu.my)

ABSTRACT

Introductory programming courses continue to report failure rates exceeding 50% due to students' struggle in applying strategic knowledge. While Problem-Based Programming (PBP) encourages active learning, existing models remain fundamentally static and provide "one-size-fits-all" paths that ignore individual cognitive variations. This paper proposes a conceptual Dynamic Cognitive Profiling Model derived through a systematic literature review and thematic synthesis. The model evaluates diagnostic mastery across six core strategic knowledge components: problem analysis, input, process and output (IPO) identification, algorithm planning, coding, testing or tracing and debugging. External performance alone is an insufficient diagnostic indicator, the model integrates internal metacognitive traits such as self-monitoring, self-evaluation, planning and reflection, which act as the foundational elements. This comprehensive model establishes the blueprint for a dynamic analysis pipeline driven by Large Language Models (LLMs) for multi-dimensional artifact extraction and Latent Profile Analysis (LPA) for student classification. This systematic approach isolates precise points of confusion, offering a dynamic diagnostic tool for future learning interventions with the aim to reduce programming failure rates.

Keywords: problem-based programming, cognitive profiling, strategic knowledge, large language models, dynamic diagnostics

ABSTRAK

Kursus asas pengaturcaraan terus melaporkan kadar kegagalan melebihi 50% disebabkan oleh kesukaran pelajar untuk mengaplikasikan pengetahuan strategik. Walaupun Pengaturcaraan Berasaskan Masalah (PBM) menggalakkan pembelajaran aktif, model sedia ada kebanyakannya bersifat statik dan menawarkan laluan "satu saiz untuk semua" tanpa mengambil kira variasi kognitif individu. Kajian ini mencadangkan satu Model Pemprofilan Kognitif Dinamik secara konseptual yang dihasilkan melalui kajian literatur sistematik dan sintesis tematik. Model ini menilai tahap penguasaan diagnostik merentasi enam komponen pengetahuan strategik utama yang dikenal pasti: analisis masalah, mengenal pasti input, proses dan output (IPO), perancangan algoritma, pengkodan, pengujian/penjejakan dan penyahpejatan. Prestasi luaran sahaja tidak mencukupi sebagai penunjuk diagnostik, model ini mengintegrasikan ciri metakognitif dalaman seperti pemantauan sendiri, penilaian sendiri, perancangan dan refleksi sebagai elemen asas. Model komprehensif ini membina rangka bagi saluran analisis dinamik yang digerakkan oleh Model Bahasa Besar (LLM) untuk pengekstrakan artifak berdimensi tinggi dan Analisis Profil Terpendam (LPA) bagi mengklasifikasikan pelajar. Pendekatan sistematik ini menyasarkan titik kekeliruan spesifik, dan menawarkan alat diagnostik dinamik untuk intervensi pembelajaran masa hadapan demi mengurangkan kadar kegagalan pengaturcaraan.

Kata kunci: pengaturcaraan berasaskan masalah, pemprofilan kognitif, pengetahuan strategik, model bahasa besar, diagnostik dinamik.

INTRODUCTION

Programming is a core skill in Computer Science learning, yet its abstract nature poses a significant barrier for novice learners (Shum et al. 2025; Wee et al. 2022). Mastery of programming as a whole involves more than just the programming syntax, it also requires strategic knowledge which refers to the ability of learner to integrate syntactic and conceptual knowledge to solve problems (Qian & Lehman 2017). In a Problem-Based Programming (PBP) environment, students must analyze given problem statements, identify the problem statement requirements which are input, process and output (IPO), plan suitable solution and execute the solution by writing the code and going through the iteration process of testing and debugging (Malik et al. 2022). However, many students struggle with this process, and the current educational technology provide limited diagnostic support (Garcia 2025). This research proposes a dynamic cognitive profiling model, to identify individual strategic knowledge gaps and support students in overcoming programming difficulties.

RELATED WORK

To combat failure rates exceeding 50% caused by syntax-heavy instruction (Malik et al. 2022; Topalli & Cagiltay 2018), Problem-Based Programming (PBP) has emerged as an active, student-centered approach utilizing real-world scenarios (Aksakal & Kucuk 2025). However, its success depends entirely on a student's strategic knowledge. Strategic knowledge refers to the ability to decompose complex tasks and merge syntax into functional solutions (Qian & Lehman 2017). Strategic knowledge misconceptions in problem analysis, IPO identification, algorithm planning and implementing the solution through coding remain the most complex barriers for novice programmers (Malik et al. 2022; Ngadengon et al. 2025).

While existing scaffolding tools like Choice-Based Programming by Oka et al. (2024) and the Problem Analysis Algorithm Model (PAAM) by Malik et al. (2022) provide structural aid, they are fundamentally static. Pre-defined intervention paths ignore critical variation in individual student understanding, metacognitive awareness and cognitive load (Halkiopoulous & Gkintoni 2024). Students with weak metacognitive skills often fail to recognize logic failures, yet existing tools lack the real-time, granular diagnostic capability to identify these specific points of confusion (Casillano & Pajanustan 2025; Garcia 2025; Loksa et al. 2022).

Consequently, a clear research gap exists for a dynamic, individualized diagnostic model. Recent advancements suggest leveraging Large Language Models (LLMs) for multi-dimensional artifact analysis (Theeb et al. 2026) alongside Latent Profile Analysis (LPA) to categorize distinct student behaviours (Wang et al. 2024). Integrating these two approaches into a comprehensive user model allows for profile-based, real-time supports that potential to reduce the strategic knowledge gaps in students.

METHODOLOGY

This study adopts a systematic, qualitative research design, focusing the analysis and conceptual design stages of a new model. The methodology is structured into three progressive phases, establishing the theoretical model for a dynamic cognitive profiling architecture.

Phase 1: Systematic Literature Review (SLR). A systematic review is conducted to ensure a comprehensive baseline across major indexing databases such as Scopus, Web of Science and Springer to obtain the cognitive profiling elements and specific strategic knowledge components that are crucial for PBP.

Phase 2: Thematic Synthesis and Coding. Data extracted from the selected literature underwent the thematic analysis. Initial open coding identified recurring student misconceptions and points of

confusion reported in empirical studies, which were then clustered into their respective themes to define strategic knowledge components.

Phase 3: Model Formulation and Pipeline Mapping. By using the synthesized themes, a conceptual user model is formulated by combining strategic knowledge performance with cognitive and learning traits. The resulting model establishes the blueprint for future automated artifact extraction using LLMs and student classification via LPA.

RESULTS AND DISCUSSION

The thematic analysis identified six core pillars of strategic knowledge essential for success in PBP. Table 1 shows the components of the strategic knowledge with the definition and sources for each component.

TABLE 1. Strategic Knowledge Components.

Component	Definition	Source
Problem Analysis	Dissecting complex problems into functional sub-tasks	(Boom et al. 2022; Gong et al. 2025)
IPO Identification	Determining required inputs, outputs and their transformations	(Larsson & Stolpe 2023; Malik et al. 2025)
Algorithm Planning	Formulating logical blueprints such as using pseudocode or flowcharts	(Fodouop Kouam 2024; Weeda et al. 2024)
Coding	Active translations of plans into language-specific syntax	(Abdelkader et al. 2026; Charles & Gwilliam 2023)
Testing / Tracing	Verifying logic through mental or mechanical execution of code	(Maryono et al. 2025; Pozzan et al. 2026)
Debugging	Systematic identification, location and correction of logical errors	(Li et al. 2025; Nawahdah et al. 2026; Omeh et al. 2025)

The literature synthesis strongly indicates that evaluating strategic knowledge performance alone is an insufficient diagnostic tool for pinpointing a novice programmer's struggles (Casillano & Pajanustan 2025; Garcia 2025). To construct an accurate diagnostic profile, the model incorporates internal cognitive traits as a foundational element. In this case, metacognitive traits identified as the essential self-regulatory mechanisms governing how a student processes abstract programming problems. These traits encompass the learners' capacity for self-monitoring, self-evaluation, planning and reflection (Loksa et al. 2022). Diagnosing these underlying traits allows the model to capture the learners' internal mental models and variations in cognitive load (Hernández-Herrera et al. 2026). By synthesizing these internal and external diagnostic dimensions, the model moves away from traditional, static “one-size-fits-all” assessments (Halkiopoulous & Gkintoni 2024). Figure 1 depicts the Dynamic Cognitive Profiling Model, combining strategic knowledge performance and metacognitive traits as the main elements for profiling student's PBP cognitive along with the use of LLM and LPA for a dynamic cognitive profiling.

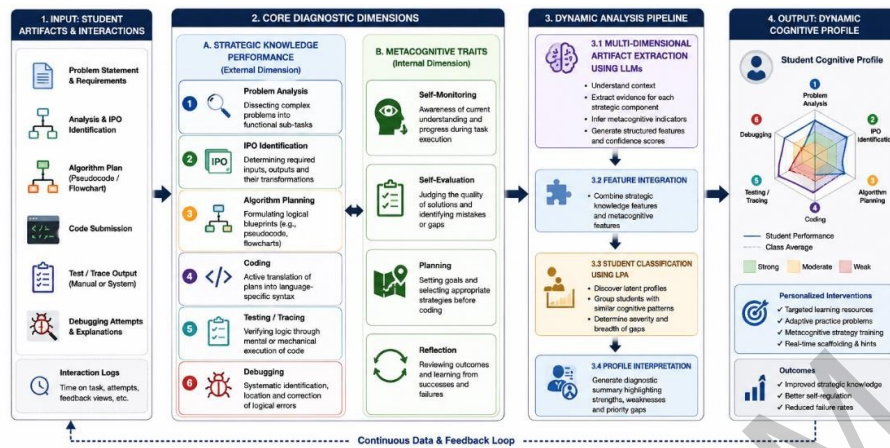


FIGURE 1. Dynamic Cognitive Profiling Model in PBP.

CONCLUSION

This paper presents a theoretically grounded Dynamic Cognitive Profiling Model synthesized from a systematic analysis of current research in programming education. By identifying the six pillars of strategic knowledge and integrating them with metacognitive traits, the model provides a systematic flow for diagnosing student weaknesses in PBP with the use of LLM and LPA as the diagnosing tool. This systematic approach offering a roadmap to reduce the high failure rates in introductory programming by addressing individual strategic knowledge gaps based on their cognitive.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisors, Dr. Siti Fadzilah, Assoc. Prof. Dr. Tengku Siti Meriam and Dr. Kauthar for their invaluable guidance and support throughout this research. Their expertise and dedication have been a source of inspiration and motivation.

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