A Hybrid Pedagogy through Topical Guide Objective to Enhance Student Learning in MIPS Instruction Set Design

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Abstract
Computer Architecture course can be a particularly challenging and intimidating subject for computer science, electrical and computer engineering students in engineering and computer science disciplines. It mainly addresses structures in modern microprocessor and computer system architecture design. Among them, MIPS instruction set design is a challenging portion in the learning curve. In this paper, our recent experiences in applying an integrated pedagogy are discussed. Our methodology utilizes a hybrid combination of techniques including Topical Guide Objectives (TGO) method, on-going assignments method and classroom demonstration method, while assessment of ABET criteria in our course structuring is addressed. This paper focuses on the use of educational exercises for computer architecture students in order to enhance their understanding of instruction set design and principles. Results of self-assessment, course evaluation, ABET-enabled assessment, and exams validate that this integrated pedagogy can promote motivation of students and improve capability to learn computer architecture with satisfactory results for both instructor and students.

1 Introduction

All our effort in engineering education is centered on training or educating our engineering students to prepare for their professionals. To reach this learning and teaching outcome, a variety of pedagogical techniques have been implemented and considered [1, 2]. Computer architecture course mainly addresses structures in modern microprocessor and computer system architecture design [3]. Among them, MIPS instruction set design is a challenging portion in the learning curve. Computer science and computer engineering education requires an understanding of both hardware and software, as the interaction between the two offers a framework for mastering the fundamentals of computer architecture. This course aims to cultivate an understanding of modern computing technology through an in-depth exploration of the interface between hardware and software including MIPS instruction sets, datapath, processor design, pipelining, memory management, storage, and other interfacing topics. In this paper, some of our recent experiences in applying an integrated pedagogy are discussed. Our methodology utilizes a hybrid combination of techniques including Topical Guide Objectives (TGO) method, on-going assignments method and classroom demonstration method, while assessment of ABET criteria in our course structuring is presented. TGO method was initially proposed by Dr. Mattew Morrison at the University of South Florida [4].

Within the educational setting, a variety of pedagogies are always adapting, modifying, and improving techniques to ensure that students learning can perform effectively in a professional setting [5, 6]. Due to this factor, there have been several methods designed to aid in student learning especially in engineering education, such as active learning [7–11], project-based learning [12, 12–16], inquiry-based learning [17].

Active learning has been aware of improvement of students' affect toward engineering education in support of meaningful engagement with computer engineering concepts and practices [7]. Compeau *et al.* [8] developed an active learning pedagogy in engineering electromagnetics course, in which engineering students are actively engaged in learning through specially designed activities, followed by reflection upon. A teaching plan is elaborated in [9], which introduces some active programming teaching methods. Portela employed four approaches to develop the instructional plan, namely: BYOD, flipped classroom, gamification, and using the skills of individual students to solve posed problems. Tewolde presented a method for improving student motivation in a microcontroller-based embedded systems course to enhance students' role in active learning [10]. The method consists of three tools, namely: laboratory assignments for practical hands-on activities, "peer teaching" techniques, and self-proposal, which enables individual creativity. For some complex and difficult to understand courses such as programming algorithms-related subjects, Garcia *et al.* [11] proposed a method in the form of active methodologies to promote students' learning and fully develop programming-related skills and abilities. Through active-based learning procedure, this provides increased interaction among students in addition to providing more self-directed learning.

Project-based learning approach is one of the most effective methods used to promote engineering education [12, 15]. Banerjee *et al.* [13] developed and taught a project-based learning method for the principles of thermodynamics for undergraduate students. The projects are designed with the purpose of testing real life problems in thermodynamics and evaluating its effectiveness to enhance student learning experiences. The projects are evaluated through a written report and a short presentation by each group. The overall methods are verified through two mechanisms. Wang *et al.* [12] implemented a project-based pedagogy in a graduate engineering course. In their method, one of creative aspects is to pay particular attention to students' self-assessments and meta-cognitive ability as a protocol of the self-regulation on the trajectory from sub-tasks to the ultimate project.

Inquiry-based learning considers learners as a subject of learning and teaching. Students act as to discover the core of the material, whereas educators act as motivators and facilitators, to learners as a participant in the learning and teaching cycle [17]. Wahyuni *et al.* [18] suggested an effective inquiry-based learning method in an engineering course to teach outliers with the K-means method using Minkowski-Chebyshev distance. In [16], an instructional program is elaborated that introduces project-based learning using logistic regression design methods in engineering education. The authors analyze the excellent results of project-based learning in interdisciplinary fields through logistic regression analysis of a general framework for processing and building models.

Some pedagogies integrate two or three pedagogical methods to take advantage of various features to improve learning quality. For instance, Bailey coupled inquiry-based pedagogy with a peer-teaching method, in which specific experiments are analyzed and performed by a peer-teaching mechanism. Besides, confidence and enthusiasm are increased through guided exploration with inquire-based learning in a physiological signal's lab course [17]. Maseda *et al.* [19] proposed an educational approach that combines project-based learning with specific scenarios that promote active learning for electronics applications. Its purpose is to enable efficient teamwork activities through a project-based learning approach, facilitating the transfer between theory and practical application.

In this paper, some of our recent experiences in applying an integrated pedagogy are discussed. Our methodology utilizes a hybrid combination of methods including Topical Guide Objectives (TGO) method, on-going assignments method and classroom demonstration method, while assessment of ABET criteria in our course structuring is addressed.

It is envisioned that these well-prepared on-going assignments, in-class activities and practice questions improve student attitudes and encourage more active and meaningful student participation in their own learning. Results of self-assessment, course evaluation, ABET-enabled assessment, and exams validate that this integrated pedagogy can promote motivation of students and improve capability to learn computer architecture with satisfactory results for both instructor and students.

2 TOPICAL GUIDE OBJECTIVE PEDAGOGY FUSED WITH ON-GOING ASSIGNMENT LEARNING

Nearly all electrical and computer engineers, regardless of sub-specialty, utilize programming in the course of their job. It is challenging for them to write high performance computer programs, as it needs to understand the underlying hardware and programming in computer architecture. This paper focuses on the use of educational exercises for computer architecture students in order to enhance their understanding of instruction set design and principles. Hybrid method refers to the use of educational models that target both qualitative and quantitative understanding of MIPS instruction set design. A sequence of on-going exercises, in-class activities and homework assignments are designed and incorporated into this hybrid model to provide students with a deeper level of understanding on instruction set design. The assignments are designed explicitly around the TGOs that have been covered in lectures. Every TGO is decomposed of a learning objective, a set of key-points and basic concepts, correlation between them, and one or more exercise problems. The TGO method consists primarily of two components. In view of the TGO method, students are encouraged to complete homework assignments, on-going exercises, and participate in classroom activities, which consist of the two elements of TGO: topical guide objectives for students to study, and example problems for students to solve.

2.1 TGO Pedagogy with On-going Assignments

A sequence of well-prepared in-class exercises, practice questions, homework assignments, review problems and exams are assigned to students to cover a variety of topics in this course. Teaching and learning strategies by the TGO based pedagogy associated with student-centered assignment-based learning are implemented with learning outcomes of this course by analysis of on-going assignments. Satisfactory performance is evaluated by a variety of milestone review sessions, and other activities.

In TGO pedagogy, we prepare for our objectives and implement them as follows:

- an ability to understand fundamental and advanced concepts of computer organization and architecture.
- an ability to analyze and evaluate CPU performance and memory hierarchy performance.
- an ability to analyze and design CPU microprocessor, datapath, and pipelines.
- an ability to understand performance analysis, memory systems, and I/O interfacing.
- an ability to perform alternative design and evaluation of the control unit, pipelines, the arithmetic and logic unit, and hazards for pipelined datapath.

2.2 The Objectives and Topics Connected to Course Materials

According to the TGO pedagogy, besides in-class exercises, practice questions, homework assignments, some well-organized in-class student-centered discussions are performed weekly. These in-class discussions are designed explicitly around the TGOs that have been covered by each lecture. Each TGO comprises of a teaching-learning objective, a series of key-points and intercorrelation among them. Some objectives associated with their tropics as samples are summarized in Table 1. The on-going assignments to coordinate with learning topics and objectives are summarized in this table as well.

In the understanding of CPU performance objective students are given a variety of questions to and sample material to practice their understanding of the objective. Here is an example of one of the questions: A program runs alone on a CPU. The program starts by running for 5 ms. The program then waits for 4 ms while the operating system runs some instructions to access disk. The CPU is then idle for 2 ms while waiting for data from disk. Finally, the program runs another 10 ms and completes. Answer the following question based on the passage above:

- The elapsed time is _____ ms.
- The user CPU time is _____ ms.
- The CPU time is _____ ms.
- The system performance is _____ ms.
- The CPU performance is _____ ms.

Through these kinds of objective questions and sample material, students are able to deepen their understanding of CPU performance in a practical context. By engaging with real-world scenarios like the one described, they learn to analyze and calculate various aspects of CPU usage and performance. For the given example, students can apply their knowledge to determine key metrics such as elapsed time, user CPU time, total CPU time, system performance, and CPU performance. This hands-on approach not only reinforces theoretical concepts but also enhances problem-solving skills, critical thinking, and the ability to apply theoretical knowledge to practical situations. Such exercises are invaluable in bridging the gap between theoretical understanding and real-world application, preparing students for future challenges in the field of computer science and engineering.

In the objective focusing on the understanding of the MIPS instruction set, students are introduced to a range of exercises and sample questions designed to solidify their grasp of this specific architecture. MIPS, as a widely-used instruction set architecture in academic settings, offers a clear and structured way to understand fundamental concepts in computer architecture and assembly language programming. By working through practical examples and solving problems related to MIPS, students gain a hands-on understanding of how instructions are structured, executed, and how they interact with different components of the computer system. Here is an example of one the students practice materials. Please translate the following MIPS to C code. Assume that the variables f, g, h, i, and j are assigned to registers $s0, $s1, $s2, $s3, and $s4, respectively. Assume that the base address of the arrays A and B are in registers $s6 and $s7, respectively.

- lw $t0, 20($s7)
- lw $t1, 16($s7)
- add $t0,$t0, $t1
- sll $t0,$t0,2
- add $t0,$t0,$s6
- lw $t1, 0($t0)
- sub $s0,$s1,$t1
- What is the C code?

Through this exercise, where students are tasked with translating MIPS instructions to C code, they not only reinforce their understanding of the MIPS architecture but also develop a deeper appreciation for the relationship between high-level programming languages and their underlying assembly code counterparts. This practice material vividly illustrates the intricacies of instruction set design and its impact on programming and system performance, rounding out students' knowledge in this critical area of computer science.

Finally in the datapath and microprocessor design objective students are taught the overall flow of a singled data path and how it is formulated, as seen in Figure 1. From the figure the overall memory instruction diagram can be separated into 4 distinct parts. First their is the register file and the ALU sections. The register file, featuring two read ports and one write port, outputs the contents of registers based on the Read register inputs and allows edge-triggered write operations, enabling simultaneous read and write in the same clock cycle. Registers are linked through 5-bit wide lines for register numbers and 32-bit lines for data. The ALU, controlled by a 4-bit wide operation signal, performs the necessary computational and logical tasks. It includes a Zero detection output for branch operations, with the overflow output omitted at this stage. These elements are crucial for the efficient execution of R-format ALU operations in computer systems.

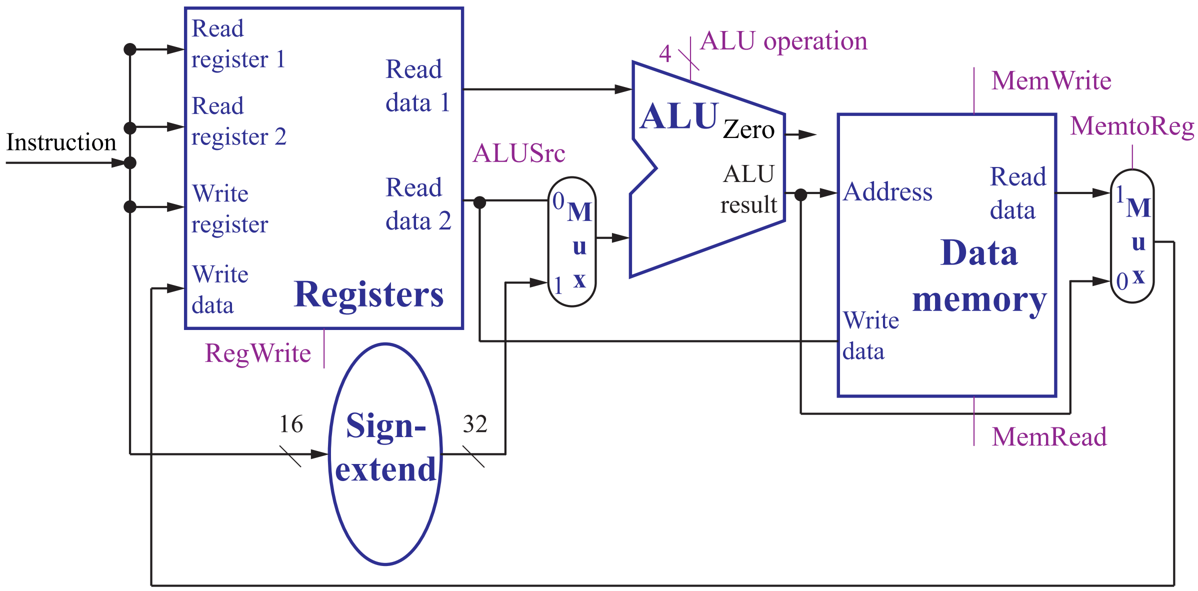

Figure 1: The homework of the processor and datapath. Datapath for the memory instructions and the R-type instructions (redrawn from [20]).

For implementing loads and stores operations in a processor, two additional units are essential alongside the register file and ALU: the data memory unit and the sign extension unit. The data memory unit is a critical state element with inputs for the address and the data to be written, and a single output for the read result. It operates with separate read and write controls, but only one control can be active at any given clock cycle. A read signal is crucial for this unit because accessing an invalid address can lead to problems. The data memory unit's design assumes edge-triggered writes, which is slightly different from standard memory chips that typically use a write enable signal. However, this edge-triggered design can be easily adapted for compatibility with real memory chips. The sign extension unit functions to extend data widths. It takes a 16-bit input and sign-extends it to produce a 32-bit output. This unit is particularly important for operations that handle different data sizes, ensuring that smaller data types can be correctly processed in a system primarily operating with larger data sizes. These two units, the data memory and sign extension, play a pivotal role in handling memory operations within a processor, complementing the functions of the register file and ALU in executing a wide range of instructions. In summary, the data memory unit and the sign extension unit are indispensable in a processor's architecture, working in concert with the register file and ALU to seamlessly handle memory operations and data manipulation, thereby ensuring the efficient execution of a wide array of instructions essential for modern computing tasks.

In the TGO learning pedagogy, the topics, and objectives are carefully discovered, organized and analyzed considering their intercorrelations so that we are aware which topics need to be reviewed and pre-reviewed in preparation of the course materials.

3 ASSESSMENT METHODOLOGIES AND RESULTS

This TGO pedagogy with emphasis on on-going assignments is evaluated at the end of semester and during the various milestones. The outcomes of the teaching and learning in engineering

Table 1: Topics, Objectives, and Measurements with Topical Guide

Objectives	**Topics**	**Measurements**
Understanding CPU Performance	☐ Definition of CPU performance ☐ CPU Throughput and Execution Time ☐ Assessing Program Performance ☐ Measuring Computer Performance ☐ CPU Relative Performance ☐ CPU Instruction Performance	☐ In-class exercise 1 ☐ In-class exercise 2 ☐ Homework 1 ☐ Practice questions 1 ☐ In-class discussion 1 ☐ In-class discussion 2
Understanding MIPS Instruction Set	☐ Computer Hardware Operations ☐ MIPS Instructions and Operands ☐ Memory Operand Concepts ☐ MIPS Assembly and Machine Instruction Conversion ☐ High-Level Code to MIPS Translation ☐ MIPS Procedures in Hardware ☐ MIPS Instruction Addressing Modes	☐ In-class exercise 3 ☐ In-class exercise 4 and 5 ☐ Homework 2 ☐ Homework 3, Practice questions 2 ☐ Practice questions 3, In-class discussion 3 ☐ In-class discussions 4 and 5 ☐ Exam 1
Datapath and Microprocessor Design	☐ Datapath Principles ☐ Processor Implementation ☐ Pipelined MIPS Implementation ☐ Constructing a Datapath ☐ Single Cycle Datapath Performance ☐ Pipelined Datapath Performance ☐ Control Unit Design ☐ Instruction Set Design for Pipelining ☐ Data and Control Hazards ☐ Graphical Representation of Pipelines	☐ In-class exercise 6 ☐ In-class exercise 7 ☐ In-class exercise 8 ☐ Homework 4 ☐ Homework 5 ☐ Practice questions 4 ☐ Practice questions 5 ☐ In-class discussion 6 ☐ In-class discussion 7 ☐ In-class discussion 8, Exam 2

Table 2: Three Questionnaires and Improvement using TGO Pedagogy

	Improvement based on Questionnaire 1	Improvement based on Questionnaire 2	Remark
Questionnaire 1	—	—	Stage 1
Questionnaire 2	**8.76%**	—	Stage 2
Questionnaire 3	**11.97%**	3.52%	Stage 3

education are assessed using multiple ways. The self-assessment questionnaire from students was officially gathered by the Department of Electrical and Computer Engineering, whereas the instructor acquired quantitative and qualitative feedbacks from students through survey and some interviews. Students in the course responded to three questionnaires corresponding to the ABET outcomes. The interactive self-assessments are necessary to findings of the strength and weakness

Table 3: The Questionnaire of Students for Assessment of Learning Quality

Questions and ABET Outcomes	Survey				
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Q1-(*b*)	**51.2%**	41.5%	7.3%	0%	0%
Q2-(*c*)	19.9%	26.5%	**38.2%**	12.2%	3.2%
Q3-(*e*)	**43.5%**	27.6%	17.3%	11.6%	0%
Q4-(*g*)	**71.1%**	16.6%	7.3%	3.4%	1.6%

of student learning cycles based on the TGO pedagogy. The self-assessment was collected from students as follows aligned with ABET outcomes.

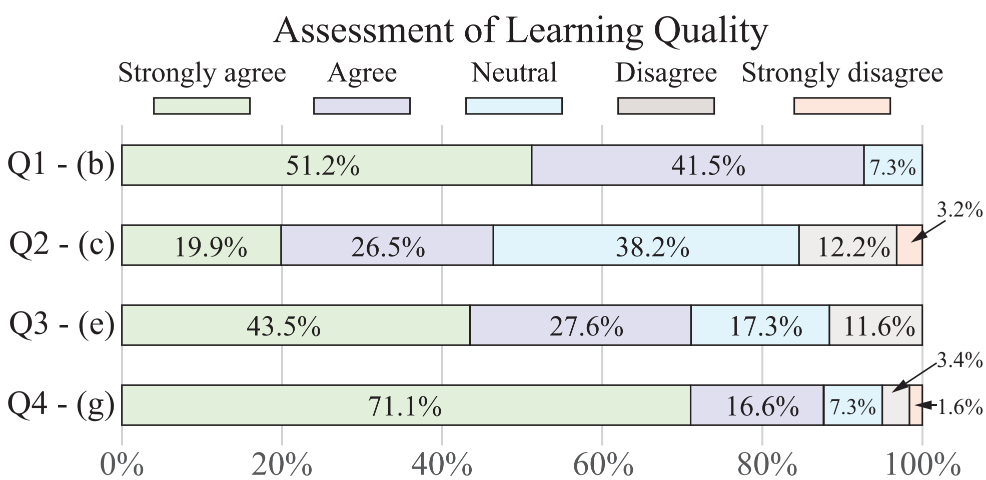

Figure 2: The illustration of the assessment of learning quality results.

- Question 1 - "I can understand how to evaluate and measure computer performance of different computer architectures and understand advances in program performance." (Outcome (*b*): An ability to design and conduct experiments, as well as to analyze and interpret data relating to electrical systems). In this student survey, it shows that 92.7% students strongly agreed and agreed with the statement.
- Question 2 - "I can understand, write and execute MIPS programs. I can understand conversion of MIPS and machine instructions." (Outcome (*c*): An ability to design electrical systems, components, or processes to meet desired needs). This survey reveals that 46.4% students strongly agreed and agreed with the statement, whereas 15.4% students strongly disagreed and disagreed with the statement.
- Question 3 - "I understand construction and implementation of a processor. I can understand and design a datapath, control unit, processor system of computer." (Outcome (*e*): An ability to identify, formulate, and solve electrical engineering problems). This survey reveals that 71.1% students strongly agreed and agreed with the statement. (See Table 3)
- Question 4 - "I have effective interaction and communication ability in the context of a

collaborative, multi-disciplinary class environment". (Outcome (*g*): An ability to communicate effectively). This survey shows that 87.7% students strongly agreed and agreed with the statement, but there are 5% students who strongly disagreed and disagreed with the statement.

Three questionnaires and improvements using the TGO pedagogy are summarized in Table 2. In this table, it is evident that the learning and teaching quality has been improved as the TGO pedagogy is indeed implemented. In Table 2, it reveals that Questionnaire 2 has improved by 8.76% from Questionnaire 1, while Questionnaire 3 is 11.97% better than Questionnaire 1. The average of Questionnaire 3 has improved by 3.52% in comparison with Questionnaire 2. These evaluations demonstrate the positive trend of introduction of this fused pedagogy.

The questionnaire of students for assessment of learning quality corresponding to ABET outcomes is listed in Table 3 and shown in Figure 2. As the course materials targeted by Outcome (*b*) cover computer performance, this material is relatively straightforward. We may find 5% students considered that they have no enough communication skills in a multi-disciplinary environment surveyed by Outcome (*g*). This is because this class has students majored in computer engineering, computer science, electrical engineering, and software engineering. From on-going activities, it demonstrates that performance of students and leaning quality has been improved.

4 CONCLUSION

In this paper, we have presented the rationale, implementation, and assessment findings of the senior-level and graduate level semester-long computer architecture course. A sequence of well-prepared in-class exercises, review problems, in-class discussions, exams, and homework assignments were distributed to students to cover predefined topics to assist in student learning in this course. We have reported the preliminary evidence obtained through the developed TGO pedagogy with on-going assignments that can effectively improve student learning in this course.

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