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Exploration and Practice on Experimental Integration of Computer Hardware-Oriented Courses for System-Oriented Competence Cultivation

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***Abstract*—*Against the background of Emerging Engineering Education construction, this paper proposes innovative ideas for constructing an experimental teaching system of computer hardware-oriented courses targeting system-oriented competence cultivation. Taking Digital Electronic Technology and Computer Organization Principles as examples, a unified experimental teaching system is established. In terms of experimental content, a three-level progressive system of "basic verification—comprehensive integration—innovation expansion" is constructed to realize the deep connection between digital logic device design and computer system integration. From the perspective of teaching methods, a practical mode of "virtual-real combination plus project-driven learning" is introduced to break the constraints of traditional experimental platforms and venues, so as to cultivate students' capabilities in system design and innovation. For assessment methods, a four-dimensional and eight-element evaluation model is built, which takes both thinking in experimental procedures and outputs of innovative competence into consideration. The reform and practice of integrated curriculum experiments have expanded the scale and difficulty of experiments, cultivated students' abilities in hardware design and solving complex engineering problems, and improved students' computer system-level competence.*

***Keywords*—*Computer Hardware-Oriented Courses; Virtual-Real Combination; System-Oriented Competence Cultivation; Integrated and Connected Experiments.*

I. INTRODUCTION

With the growing complexity and networking-driven development of the computer industry, higher requirements have been placed on the cultivation of system-oriented competence. System-oriented competence serves as the foundation for the development of big-data industry, the core strength of artificial intelligence, and a critical capability for addressing bottleneck technologies and implementing high-end engineering projects [1]. The essential connotation of system-oriented competence cultivation lies in mastering the software-hardware coordination within computing systems as well as the logical relationships among internal system components, understanding external system characteristics and human-computer interaction modes, and emphasizing comprehensive approaches to realizing system functions from the perspective of system architecture. Featuring prominent engineering attributes, system-oriented competence constitutes the fundamental capability and direct manifestation of solving complex engineering problems. Therefore, strengthening the cultivation of students' system-oriented competence is not only a requirement for cultivating innovative computer-talented personnel, but also an imperative for the strategic development of the computer industry.

Practice plays a vital role in the cultivation of students' computer system-oriented competence and serves as a critical measure to evaluate the effectiveness of theoretical teaching. The objectives of system-oriented competence cultivation place greater emphasis on system-level design, which highlights engineering scale and complexity [2-4]. As an important component of computer-related curricula, computer hardware-oriented courses feature prominent practicality and strong engineering applicability. Within the talent-training system for computer majors, Digital Electronic Technology and Computer Organization Principles act as core introductory and professional courses for computer hardware, and are critical for cultivating students' understanding of underlying hardware as well as system-architecture design competence. The former focuses on the analysis and design of digital logic circuits, serving as the "cornerstone" of computer hardware systems; the latter focuses on the overall architecture and working principles of computer hardware, serving as a "bridge" for the transition from digital-logic knowledge to system-level applications [5-7]. Nevertheless, the traditional experimental mode for Digital Electronic Technology and Computer Organization Principles in our university has long adopted separate experimental boxes. Experiments based on discrete components suffer from low reliability, difficult debugging, complicated assessment, high cost and large space occupation. Furthermore, the experimental contents of the two courses are fragmented and isolated from each other with insufficient knowledge connection. Most experiments are confined to basic-level verification operations. Little attention has been paid to effectively integrating those experimental outcomes into a complete computer system. The absence of unified system-level planning prevents students from forming a holistic concept of a complete computer, making it difficult for them to truly understand computers from the perspective of an entire system.

To address the above-mentioned problems, we have carried out reform and practice on experimental integration for computer hardware-oriented courses. Following the system-design philosophy of "hierarchical progression and system synthesis", we decompose experimental contents with complete-machine design as the teaching objective. Specific

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experimental contents and projects for Digital Electronic Technology and Computer Organization Principles are defined, so as to form a complete experimental teaching system. The integrated and connected experimental teaching of the two courses is realized, which helps students establish a sound knowledge system of hardware systems and develop their computer system-oriented competence.

II. Inherent Correlations and Existing Problems of Experiments for Computer Hardware-Oriented Courses

Experiments of Digital Electronic Technology take "logic gates—combinational logic circuits—sequential logic circuits" as the core thread to cultivate students' ability to analyze and design basic logic units. For instance, experiments such as full-adders, decoders and data selectors lay the foundation for understanding the Arithmetic Logic Unit (ALU) of computers. Experiments on flip-flops, registers and counters provide prerequisites for mastering computer storage systems and controller timing. On this basis, experiments of Computer Organization Principles are upgraded toward "module integration—system collaboration". Typical experiments include ALU design, CPU (Central Processing Unit) design, memory expansion and interface experiments, which require students to apply digital-logic knowledge to solve system-level problems. Essentially, the two sets of experiments present a progressive relationship between "device-level design" and "system-level construction". The former provides technical support for the latter, while the latter serves as the application extension of the former. Digital Electronic Technology focuses on the verification of underlying gate circuits as well as combinational and sequential logic, emphasizing the cognition of basic devices; Computer Organization Principles is oriented toward system integration.

Although there are close correlations between the experiments of the two courses, a widespread phenomenon of "three-emphases and three-neglects" exists in practical teaching. (1) Emphasis on isolated verification while neglecting correlated design. Most experiments aim to verify individual knowledge points. In Digital Electronic Technology, students are only required to design conventional functional modules such as 4-bit adders, encoders and decoders. In Computer Organization Principles, students merely verify standard functional components including arithmetic units and memories. Students are not guided to think about cross-course questions such as "how an adder is integrated into a CPU". (2) Emphasis on hardware wiring while neglecting software collaboration. Under the traditional experimental-box mode, especially for Computer Organization Principles experiments, functional components are pre-integrated. Students finish experiments merely by wiring connections, so they cannot gain in-depth insight into the internal working mechanism of functional components. They also lack sufficient understanding of "interaction logic between hardware circuits and control programs", which makes it difficult for them to adapt to the development trend of "hardware-software co-design" in modern computers. (3) Emphasis on result-oriented assessment while neglecting process-oriented thinking. Traditional experimental assessment relies merely on experimental results and lab reports, ignoring the evaluation of core competencies formed during the experimental process. It cannot identify whether students think independently and finish experiments on their own, nor can it assess their capabilities to analyze and troubleshoot circuit faults and logical errors. Consequently, many students develop a perfunctory learning attitude of "valuing reports over practical operations".

III. Integration and Connection of Experimental Teaching for Computer Hardware-Oriented Courses

To realize the integration and connection of curriculum experiments, it is necessary to break down curriculum barriers. We carry out the work from three dimensions: "content reconstruction, method innovation, and evaluation upgrading". Following the system-design philosophy of "hierarchical progression and system synthesis", we decompose experimental contents with complete-machine design as the ultimate objective. The specific experimental contents and projects for Digital Electronic Technology and Computer Organization Principles are defined. Experimental platforms and assessment modes are unified to construct a complete experimental system and achieve the goal of integrated experimental teaching.

A. Integrated Design of Experimental Contents for Computer Hardware-Oriented Courses

Experiments of Digital Electronic Technology mainly focus on constructing various functional components required inside the CPU. They specifically cover combinational logic circuits (decoders, data selectors, adders, encoders, etc.) and sequential logic circuits (flip-flops, registers, counters, memories, etc.). These functional components lay the groundwork for the subsequent experiments in Computer Organization Principles.

TABLE 1. Experimental Projects of Digital Electronic Technology

No.	Experimental Project
Experiment 1	Design of Simple Combinational Logic Circuits (1 week) (Design-oriented experiment; design of full-adders and adders)
Experiment 2	Design of Combinational Logic Circuits (1 week) (Design-oriented experiment; encoder verification, ward priority control circuit)
Experiment 3	Design and Application of Decoders (1 week) (Design-oriented experiment; 2-to-4 decoder, 3-to-8 decoder, traffic-light fault-alarm circuit)
Experiment 4	Design and Application of Multiplexers (1 week) (Design-oriented experiment; 4-to-1 multiplexer, 8-to-1 multiplexer, multi-directional control switch circuit)
Experiment 5	Design of Latches and Flip-Flops (1 week) (Design-oriented experiment; RS latch, D flip-flop, JK flip-flop)
Experiment 6	Design and Application of Registers (1 week) (Design-oriented experiment; 4-bit shift register, memory)
Experiment 7	Design and Application of Counters (1 week) (Design-oriented experiment; arbitrary-radix counter, digital clock)
Experiment 8	Design and Application of Finite State Machines (1 week) (Comprehensive experiment; intelligent vending-machine system)

Meanwhile, we have added the course Comprehensive Training for Digital System Design following the experiments of Digital Electronic Technology, where Verilog hardware

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description language is adopted for digital system design. Students are required to model and implement all logic devices involved in Digital Electronic Technology experiments with Verilog. Besides, tasks for designing and implementing complex digital systems of moderate scale are arranged, such as traffic-light systems, intelligent vending-machine systems, electronic clock systems, festival color-light systems, kitchen timer systems, sequence generators and sequence detectors. The comprehensive-design tasks raise academic challenge, stimulate students' learning motivation and professional interest, and bring them a strong sense of achievement. Meanwhile, considering that sophomore students are new to hardware knowledge, the difficulty level should not be excessively high so as not to dampen their enthusiasm for hardware-oriented courses. By appropriately increasing the scale and difficulty of design tasks, students' comprehensive knowledge application ability, innovative design competence and capability of solving complex engineering problems can be enhanced.

Previous experimental outcomes are extended and applied to the experimental projects of Computer Organization Principles, so as to realize the connection from logic gates to CPU and achieve the teaching objective of CPU design. In Computer Organization Principles experiments, students mainly finish the Verilog-based design of a 32-bit ALU (Arithmetic Logic Unit), memory, controller and I/O interfaces. They develop a single-cycle CPU supporting 8 instructions with Logisim, as well as single-cycle CPU and multi-cycle CPU supporting 12 instructions with Verilog-HDL. Students integrate previous experimental achievements to accomplish the design of a complete hardware system, which realizes the integration and connection of experiments for computer hardware-oriented courses.

B. Unified Experimental Platform for Computer Hardware-Oriented Courses

In the experiments of Digital Electronic Technology, we adopt a two-track intersecting strategy with virtual-real combination. The first track uses experimental boxes, enabling students to directly access chips and integrated circuits to gain perceptual understanding. The second track employs the virtual simulation software Logisim, which breaks the time-space constraints of experimental boxes regarding venues and hardware platforms, and realizes a blended teaching mode combining in-class and extra-curricular activities, as well as online and offline learning. Logisim supports schematic-based design with the merits of easy-to-learn, convenient debugging and zero experimental cost. It effectively extends available experimental time and supports sub-circuit encapsulation. It avoids the excessive abstraction and programming-oriented nature of hardware description languages, which is conducive to cultivating students' hardware-design thinking. The visualized experimental results of Logisim can greatly stimulate students' experimental interest and enthusiasm and improve the effectiveness of course experiments.

Furthermore, the experimental class hours for Digital Electronic Technology in our university are merely 18 credit hours, which leads to insufficient hardware practice and inadequate cultivation of students' hardware-design and innovation capabilities. We make full use of after-school time to increase the scale and difficulty of experiments with the help of Logisim virtual simulation software. In-class time is mainly used for completing basic verification-oriented experiments and simple design-oriented experiments via experimental boxes. After class, students are required to design complex digital circuits of specified scale with Logisim, and submit their designs to the Educoder online virtual training platform for automatic evaluation of experimental results. For sophomore students, to reduce experimental difficulty, complex problems are decomposed into several sub-problems on the Educoder platform. Similar to passing levels in video games, students move on to the next task upon finishing the current one and obtain instant feedback just like game level-clearing. Such an experimental mode greatly arouses students' interest in experiments and their spirit of continuous exploration.

Fig. 1. Two-Track Intersecting Experimental Mode with Virtual-Real Combination

Fig. 2. Game-Like Level-Passing Experimental Mode n the Educoder Platform

In the course Comprehensive Training for Digital System Design, we adopt the Vivado integrated simulation environment from Xilinx to model digital logic devices and digital systems with the Verilog hardware description language. Experimental results can be verified on the Xilinx FPGA board Nexys 4 DDR (as shown in Fig. 3), and can also be validated via the simulation-test function of Vivado (as shown in Fig. 4). This experimental mode is free from venue and time restrictions. The compact Nexys 4 DDR development board is easy to carry, enabling students to conduct experiments anytime and anywhere. Meanwhile, we provide a large number of instructional videos for practical cases on the Xuexitong platform for students' learning and reference.

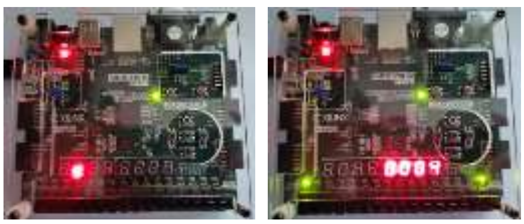

Fig. 3. Demonstration of experiment results using Nexys 4 DDR Board


Fig. 4. Demonstration of simulation results using Vivado

For experiments of Computer Organization Principles, we adopt the aforementioned unified experimental platform. An integrated experimental platform allows students to devote more energy to experimental contents rather than getting familiar with the platform itself. Moreover, as system-oriented courses progress, students can deepen their understanding and achieve knowledge connection across course contents. In Computer Organization Principles experiments, students are required to implement basic functional components and finite-state machines, as well as single-cycle CPU and multi-cycle CPU designs using the Verilog hardware description language. Supporting parallel description, Verilog helps students better understand and implement concurrent systems, which is critical for learning computer organization principles. As one of the leading vendors in the FPGA industry, Xilinx provides the Vivado virtual simulation environment. Practices based on Vivado and Verilog hardware description language comply with industrial standards. Such practices enable students to adapt to and integrate into relevant industries more easily. This practical session not only facilitates students' in-depth comprehension of course knowledge of computer organization principles, but also cultivates their skills consistent with industrial standards and practical applications.

Guided by the philosophy of PBL (Problem-Based Learning), we elaborately design each experimental project in a problem-oriented manner. Complex digital systems are decomposed and tackled step-by-step in a progressive way to gradually foster students' system-oriented competence. Scores are reasonably assigned for each experimental checkpoint, and experimental tasks are deployed on the Educoder platform for students to complete in a game-like level-passing mode. To support students in accomplishing tasks smoothly, detailed experimental manuals and essential instructional videos are provided on the Educoder platform for students' reference and self-study.

C. Reform of Experimental Assessment Methods

We reform the traditional single-mode experimental assessment and construct a four-dimensional eight-element evaluation model. It integrates theory with practice, online learning with offline practice, individual work with teamwork, and process assessment with result assessment. Evaluation rules and criteria are designed for every learning activity of students, so that students can compare their performance against the criteria in real time and adjust their learning strategies accordingly. The experimental assessment for Digital Electronic Technology and Computer Organization Principles consists of online experiments, offline experiments and lab reports, accounting for 20 %, 40 % and 40 % respectively.

(1)Online Experiments: Completed on the Educoder platform. Students finish predefined tasks on the online experimental platform, and their design proficiency is examined via online automatic evaluation. Instructors can create teaching classes and select experimental projects on this platform. Students enter the virtualized experimental environment through the course experiment page, complete the assigned levels, and submit their work online. The system performs automatic evaluation based on test sets and feeds back results in real time. Students may also register platform accounts independently to join practical-course classes. They can study via experimental handouts and instructional videos, or directly enter the training environment to finish levels and submit assignments for instant system feedback. With Educoder, instructors can collect statistics such as completion time, completion rate, compliance rate and timeliness for each assessment checkpoint of every experimental project. These statistics help further analyze the rationality of experimental settings, the effectiveness of course learning, and whether competency cultivation meets expected standards.

(2)Offline Experiments: This refers to in-class hands-on practice performed in groups, mostly with two students per group. Instructors and teaching assistants inspect and verify students' experimental work. One representative from each group demonstrates and explains the completed experiment and presents the design ideas. Instructors and teaching assistants may question any group member at any time to examine their mastery of circuit working principles, as well as to verify the functionality of designed circuits and the correctness of operation procedures. If experimental requirements are not satisfied, group members shall revise their design scheme, retest circuit functions and re-validate operation outcomes. Students are required to analyze and troubleshoot circuit faults and logical errors that occur during experiments.

(3)Lab Reports: A lab report shall include the experimental design scheme, schematic diagrams of functional modules and circuit diagrams drawn in Logisim, simulation test plots of experimental data, as well as analysis and troubleshooting methods for circuit faults and logical problems encountered in experiments. Each student also needs to write reflections and summaries for the experiment. Submitted lab reports are reviewed according to requirements for completeness and standardization. Review scores are mainly determined by students' described design ideas, structures of implemented sub-components and corresponding simulation test plots, reported problems encountered in experiments and their solutions. In addition, reviewers check whether answers to thought-provoking questions are correct, and whether improvements or innovations exist in experimental design schemes.

IV. IMPLEMENTATION EFFECTS OF EXPERIMENTAL REFORM

We retain the traditional experimental-box mode in Digital Electronic Technology experiments, allowing students to get access to hardware devices and gain perceptual understanding.

On this basis, we further adopt the virtual simulation software Logisim. After comparing the two experimental modes, most students hold the view that Logisim delivers higher experimental efficiency compared with experimental boxes. It supports the implementation of more complex digital-system designs and brings students a strong sense of achievement. Experiments of Computer Organization Principles built upon Logisim and Vivado virtual simulation platforms enable students to further understand the separation between hardware design and physical implementation. Students can verify design principles on virtual simulation platforms before deploying their designs on the Xilinx FPGA board Nexys 4 DDR, which greatly improves design efficiency. Meanwhile, it provides differentiated options for students who are unwilling to learn FPGA development. These practical sessions deepen students' comprehension of theoretical knowledge. The integrated experimental projects realize the connection from logic gates to CPU and help students establish the concept of a complete computer system.

Most students report that these are among the experiments most closely aligned with teaching contents in undergraduate studies. They effectively improve the efficiency and scale of experimental design, foster sound hardware-design thinking, and deepen students' understanding of theoretical course knowledge. The reformed experimental projects are arranged in progressive layers with gradual increase in difficulty, featuring high student completion rates and strong sense of achievement, which contributes to the cultivation of students' computer-system-oriented competence. The game-like level-passing experimental mode and automatic evaluation on the Educoder platform greatly stimulate students' experimental enthusiasm, learning motivation and innovation awareness, and reduce the workload and pressure of instructors.

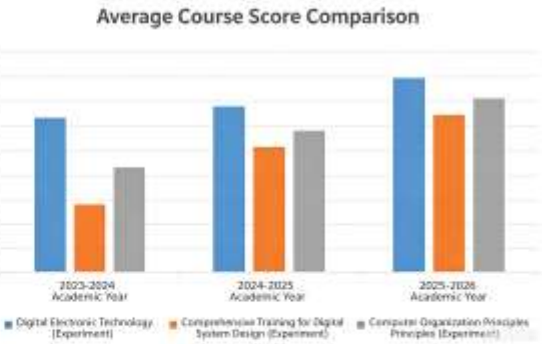

Fig. 5. Comparison of Course Scores between Traditional Experimental Mode and Integrated Experimental Mode

Over the past three years, around 280 students are enrolled in each teaching cycle, who are majors in Computer Science and Technology. The above-mentioned experimental-teaching reform has been implemented for Grade-2023 and Grade-2024 students majoring in Computer Science and Technology in the academic years of 2024-2025 and 2025-2026. We compare the average course scores under the traditional experimental mode in the 2023-2024 academic year with those under the integrated experimental mode in the 2024-2025 and 2025-2026 academic years (as shown in Fig. 5). The comparison indicates that the integrated experimental-teaching reform effectively enhances students' capabilities to design and implement complex digital systems, as well as their system-integration competence.

Questionnaire results show that 91 % of the students believe that "cross-course experiments help them clearly understand the relationship between digital logic and computer hardware". Meanwhile, 87 % of the students state that "practices of hardware-software co-design have improved their system-oriented thinking and engineering-practice capabilities". Many students mentioned in their lab reports that "the whole process from ALU design to CPU integration makes me truly realize that computer hardware is not a simple pile of isolated components, but an organic whole with mutual coordination."

Benefiting from such training on thinking and competence, students have won 38 provincial-ministerial-level and above awards in relevant discipline competitions in the past three years, including multiple national first-class and second-class prizes. In addition, a number of national-level and provincial-level college innovation training projects have been approved. Relying on platform-based training, discipline competitions further promote specialty construction, which realizes the philosophy of promoting teaching and teaching reform through competitions.

V. CONCLUSION

As a provincial-local university, we actively explore teaching reform oriented toward the cultivation of system-oriented competence. Following the systematic design philosophy of "progressive hierarchy for system integration", we have realized the integrated design for experiments of Digital Electronic Technology and Computer Organization Principles, covering integrated experimental objectives, integrated experimental contents and integrated experimental platforms. The integration and connection between experimental teaching of Digital Electronic Technology and Computer Organization Principles serves as a critical path to improve computer-major students' system-oriented competence. By reconstructing the experimental content system of "basic verification-comprehensive integration-innovative expansion", innovating the teaching approach of "virtual-real combination plus project-driven learning", and upgrading the "process-and-competence-oriented" assessment mechanism, we help students build a complete knowledge system of computer systems. In future work, we will actively explore the integration and connection of experiments among Computer Organization Principles, Operating Systems, Compilation Principles and other courses to bridge hardware and software domains. We aim to enhance students' hardware-software co-design capability, cultivate their global and system-oriented perspectives, and truly meet the goals and requirements for the cultivation of computer-system-oriented competence. The cultivation of computer-system-oriented competence is a long-term endeavor. As an old saying goes, "Though the road

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is long, we shall arrive as long as we keep walking; though the task is difficult, we shall succeed as long as we keep acting."

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