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ProtoSim: Interactive Learning Environment for High School Students to Learn the TCP/IP Protocol Suite in Computer Science Education

Yuki Kitamura, Hiroyasu Ide, Hiroyuki Nagataki, Susumu Kanemune, Shizuka Shirai

Abstract—This study proposes ProtoSim, an interactive learning environment designed to provide experiential learning of network mechanisms with a simulator and autonomous learning support features. The simulator in ProtoSim treats the browsing scene on a webpage on a smartphone, enabling users to observe the flow of information through layers of the TCP/IP protocol suite in a visualized manner. Additionally, it features missions (short-answer questions) that utilize the simulator, with automated correctness evaluation to facilitate autonomous learning. To evaluate the effects of ProtoSim, an educational practice using ProtoSim was conducted with 211 high school students. Analysis of the learning logs revealed that students engaged with the exercises by adjusting the content and methods of their learning according to their individual circumstances. Furthermore, the increase in the correct answer rate from pre- to post-tests indicates that ProtoSim effectively promoted a structural understanding of the mechanisms behind the computer network, particularly those based on the communication protocol layers.

Index Terms—Interactive learning environments, Computer network, TCP/IP protocol suite, Computer science education, Simulator, Visualization, Autonomous learning.

I. INTRODUCTION

In today's society, where computers are widespread and information technology has advanced, it has become commonplace for children to use computers in their daily lives. Consequently, it is crucial for not only CS majors but also novice students, such as high school students, to learn about network mechanisms in order to use networks effectively. In fact, the fundamental mechanisms of networks are included in the high school curricula of several countries [1], such as England [2], South Korea [3], and New Zealand [4].

Even high school students, who use networks daily, should be prepared to select appropriate solutions when issues arise on the network. For example, imagine a scenario where a student is browsing a website on their smartphone, and the webpage suddenly stops loading. A person who understands the mechanisms of networks based on communication protocols organized by multi-layer structures would be able to comprehensively consider various potential causes, such as an issue with the web server's application, packet loss, IP address configuration problems, or physical obstacles like signal interference. This knowledge would enable them to make more appropriate decisions. On the other hand, high school students with no conceptual understanding of how networks operate might only come up with superficial solutions, increasing the

risk of inconvenience or harm. Therefore, it is essential to cultivate a concrete understanding of how information flows within communication networks.

The compulsory subject "Informatics I" in Japanese high schools also includes a unit on the mechanisms of computer networks [5], [6]. Based on their experiences in creating simple peer-to-peer applications in junior high school, students will understand more authentic network mechanisms, including the physical components such as routers and TCP/IP protocol suite with multi-layer structures in high school. The learning objectives explained in the previous paragraph are believed to form the basis for conducting such learning activities in "Informatics I."

However, the concept of networks is difficult to learn because networks are technical, complex, dynamic, abstract, and invisible [7]–[12]. Especially when high school students learn about the mechanisms of networks with the aforementioned goal, the barriers to learning become increasingly significant. First, there are very few learning materials suitable for comprehensively understanding network mechanisms. In courses designed for CS majors, more lesson time is available, allowing for activities focused on individual layers or mechanisms. On the other hand, high school students aim to gain a general understanding of how networks function, not to become network specialists, and therefore require materials tailored to their needs. Second, there are motivational challenges for students who are not necessarily specializing in computer science. Traditional educational approaches, such as lectures based on textbooks, can make students passive. Materials equipped with support to help students learn actively are essential.

To address these challenges, this study proposes "ProtoSim," an interactive learning environment for high school students to experientially learn the TCP/IP protocol suite. The simulator within ProtoSim allows users to visualize the flow of data in a virtual network through hands-on interaction. Additionally, the simulator is also integrated with a set of exercises that include an automated correctness evaluation feature, enabling students to actively learn about network mechanisms by solving problems. To evaluate the effectiveness of ProtoSim, an educational practice was conducted in a Japanese high school. The following sections describe the detailed designs and evaluations of ProtoSim based on an educational practice at a high school.

II. RELATED WORKS

Many researchers have proposed various educational methods for teaching network mechanics [13]. A syllabus analysis

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revealed that many computer network courses in American universities include laboratory exercises [14]. However, with the technological advancements, there is a belief that teaching methods must be revised [15]. Consequently, various new educational approaches have been implemented, such as incorporating collaborative project-based learning [16], conceptualization and summarization techniques [17], blended learning models [18], and IOT devices [19]. In addition, the online learning material “Computer Science Field Guide” [20] was developed following the lineage of CS Unplugged [21].

Furthermore, learning activities that utilize simulators as interactive learning environments have been proposed and their effectiveness has been evaluated from various perspectives. From a learning motivation perspective, Montagud et al. [22] noted that introducing network simulators such as the Cisco Packet Tracer [23] led to increased motivation for both students and instructors. Concerning an understanding of network mechanics, Goldstein et al. [12] proposed an active learning framework utilizing the Cisco Packet Tracer, confirming through pre- and post-tests that students’ understanding significantly improved. Regarding problem-solving skills, Zhang et al. [24] reported that using a Cisco Packet Tracer enabled students to acquire practical network skills. Network simulators are sometimes introduced to reduce the cost of procuring network devices [9]. Although concerns have been raised that the use of virtualization technology may lower the quality of education by preventing students from interacting with real networks, Chamberlin et al. [25] found no differences in educational effectiveness between groups using physical labs and virtual networking software, Cisco Packet Tracer. On the other hand, Abdullah et al. [8] reported that students found value and interest in learning through a combination of multiple approaches, physical networks and virtual networks. Frezzo et al. [26] explain the anticipated educational effects of features implemented with the Cisco Packet Tracer, such as automatic scoring, from a theoretical perspective. Smith et al. [27] extended the capabilities of the Cisco Packet Tracer to enable remote collaborative learning.

Other researches not only aim to utilize existing simulators, as mentioned above, but also seek to improve their functionality and develop new educational simulators. Saha et al. [28] have developed a web application “ns2web,” addressing the difficulties of installing and running simulations with Network Simulator version 2 [29]. Pullen [10] conducted practical exercises using an open-source network simulator called “Java Network Workbench 2 (JNW2).” Rahman et al. [7] proposed the complementary use of the wide-area network modeling tool Delite, the network simulator ns-3 [30], and the network topology generation tool Brite [31]. Ruiz-Martínez et al. [32] developed a virtual environment called “VNUML-UM,” which allows users to practically learn advanced computer network concepts such as mobility, load balancing, and high availability. Wannous et al. [33] built a web-based system called “NVLab,” enabling users to create network designs and manage virtual machines. Jevremovic et al. [34] implemented “IPA-PBL,” an e-learning tool designed for learning the theory and procedures of IP address configuration, in a problem-based learning (PBL) classroom setting. Given the abundance

of network simulations, Ghazali et al. [35] compared five simulators from the perspective of their ease of introduction into education. Chou et al. [36] compared the Cisco Packet Tracer and GNS-3 (Graphical Network Simulator-3) [37] based on their ability to represent networks virtually.

However, when these prior studies are considered for adoption in high school settings, several challenges emerge. First, each study tends to concentrate on a narrow aspect of networking. Cisco Packet Tracer, for example, emphasizes topology, packet transmission, or routing. Covering a broader range of topics would require combining several tools, which is impractical given the limited class time in high schools. Second, most simulators are designed for general professional use, so they present detailed and highly precise information. High school students must invest considerable effort just to interpret the large volume of data displayed. Third, expert-oriented simulators rarely specify an explicit learning sequence. Students and teachers are left uncertain about how to structure learning with the tool. Preparing supplementary worksheets places a significant burden on teachers and can become an obstacle to introducing simulators in high school courses.

In contrast, ProtoSim, the educational simulator proposed in this study, incorporates several design choices that lower these barriers. First, ProtoSim aims to give students a comprehensive understanding of networking mechanisms across all layers of TCP/IP. The simulator visualizes every layer and illustrates how data change as they traverse the layers, helping learners grasp overall relationships. Second, ProtoSim selects what to visualize based on instructional relevance rather than strict technical completeness. For instance, it displays the structure of each TCP/IP layer and the data within those layers, while omitting complex elements such as ACK packets when they are not essential for the high school curriculum. Third, ProtoSim integrates the simulator with an electronic textbook. The textbook offers curriculum-aligned content in a systematic order, so learners can progress independently by simply following the material. It also includes missions that provide immediate correctness feedback, enabling students to confirm their understanding and move confidently through the exercises.

III. PROTO-SIM: INTERACTIVE LEARNING ENVIRONMENT

This section describes the proposed interactive learning environment, ProtoSim, which allows students to experientially learn the mechanisms of the TCP/IP protocol suite.

A. Learning Objective

The learning objective of ProtoSim was defined as “to be able to concretely imagine how data flows based on the network mechanisms centered around communication protocols.” As mentioned in section I, this learning objective is based on the curriculum of the compulsory subject “Informatics I” in Japanese high schools. Understanding the overall mechanisms of networks enables high school students to engage in comprehensive problem-solving and use networks more efficiently.

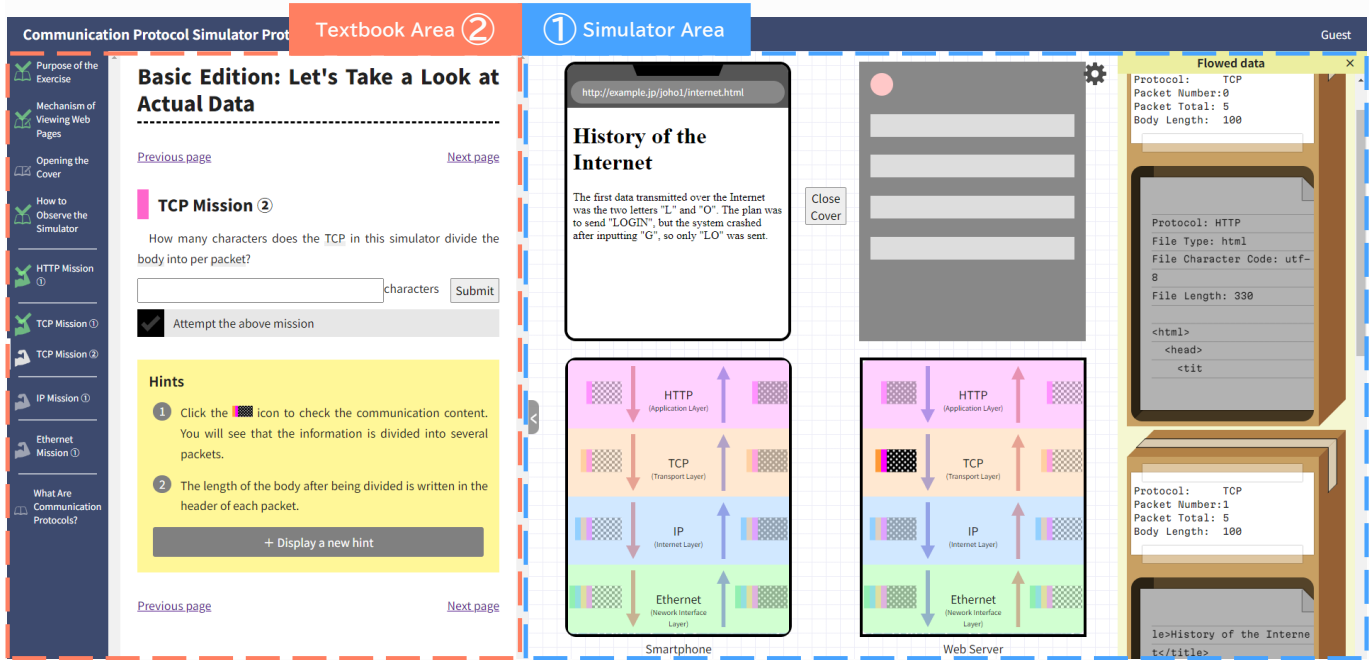


Fig. 1. The main screen of proposed interactive application, ProtoSim, consists of a simulator area and textbook area.

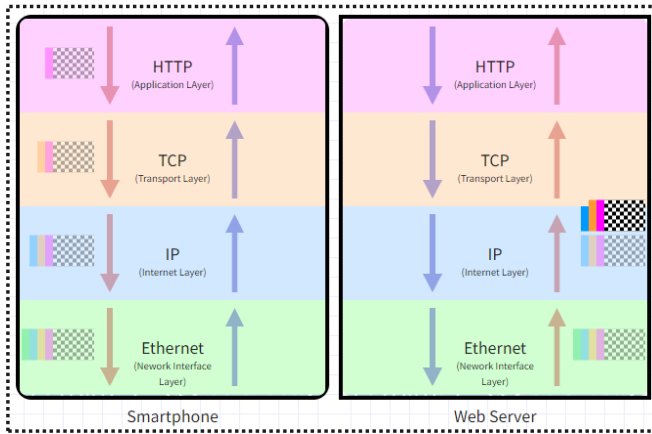


Fig. 2. In the simulator area, an animation depicts data icons flowing and leaving trails as a virtual smartphone processes a URL input.

However, there are two barriers to achieving this learning objective.

First, students must understand the connections between different learning topics related to networks. In the “Informatics I” textbooks, learning topics such as packet communication, routing using IP addresses, and error correction are presented in a fragmented manner, with unclear relationships among them. It is essential to grasp the overall structure of networks, understanding that these mechanisms are processed sequentially according to the multi-layer structure of the TCP/IP protocol suite.

Second, students, even those not specializing in computer science, must be able to learn actively. Traditional teaching methods, such as textbooks and lectures, tend to make students passive learners, making it challenging to maintain their motivation. To address this, autonomous learning support

features that allow learners to engage in hands-on activities are necessary.

B. Design Principles

Considering the learning objective and challenges involved in achieving them, the design principles of ProtoSim were defined as follows:

- DP1. Communication is carried out in a virtual network based on the user’s actions, and the contents of the data flowing through the TCP/IP layer structure are concretely visualized.
- DP2. The simulator is integrated with the textbook, offering features such as automatically evaluated missions and autonomous learning support features to help achieve the missions.

To elaborate further about DP2, Skinner [38], who proposed Programmed Instruction, emphasized the importance of immediate feedback in reinforcing learners’ correct responses and understanding. Moreover, receiving prompt feedback can motivate and encourage students to persistently engage in self-regulated learning. In other words, a learning environment in which immediate feedback is obtainable, even when utilized for self-paced learning, is expected to be highly effective.

C. Overview of ProtoSim

Based on the above design principles, an interactive learning environment “ProtoSim” was developed as a web application to allow students to experientially learn the mechanisms of TCP/IP protocol suite¹. As indicated by the dashed lines in figure 1, the main screen of ProtoSim consists of a simulator

¹Latest version of ProtoSim is available at <https://protosim.csle-lab.org/>.



Fig. 3. In the simulator area, the contents of the data are visualized by transforming them into tangible objects, such as papers for HTTP, boxes for TCP and IP, and voltages for Ethernet.

area that visually simulates the data flow along the layers of TCP/IP, and a textbook area that promotes autonomous learning along with missions.

D. Simulator Area

In the simulator area, students can observe the flow of data within a virtual network following the TCP/IP protocol suite as they navigate webpages on a smartphone. The scenario of browsing webpages on a smartphone was chosen, as it is expected to enhance motivation by incorporating situations familiar to high school students. In addition, the users initially only see the surfaces of the smartphone and web server, with the underlying mechanisms and specific data content becoming visible through their interaction. This incremental increase in information allows students to gradually learn new content.

When students enter a URL on the virtual smartphone within the simulator, they can view animations of icons representing the data flows, as shown in figure 2. Furthermore, these flowing icons leave traces, and by clicking on one of them, users can concretely examine the data content, which are visualized according to the properties of each layer, as illustrated in figure 3. HTTP data is represented as a simple piece of paper, illustrating how it is divided into multiple pieces at lower layers. For TCP and IP, cardboard boxes are used to represent encapsulation, with headers displayed on the top like an address label. In Ethernet, data is ultimately represented as a sequence of 0s and 1s, which is depicted using voltage levels to illustrate the concept. These operations to see visualization of data flows align with DP1.

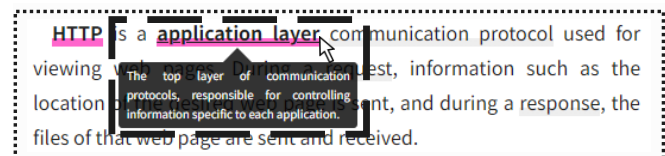


Fig. 4. Hovering the mouse cursor over specialized terms in the textbook area reveals their explanations.

E. Textbook Area

The textbook area displays the learning content synchronized with the simulator area. The learning content is organized into several pages to clarify the key learning focus and the simulator functions used on each page, thereby reducing cognitive load. These contents comprehensively cover all layers of the TCP/IP protocol suite, starting from the application layer and ending at the network interface layer as table I.

The specialized terms on each page are underlined, and an explanation is provided when hovering the mouse cursor over them, as shown in figure 4. Many pages feature short-answer questions, called “missions.” By entering the answers into the response field and pressing the submit button, the system automatically determines the correctness of the answers, as shown in figure 5. Beneath the missions, there is a hint section where hints are progressively revealed each time the display button is pressed, as illustrated in Figure 6. These functionalities were designed in accordance with DP2 to support students’ autonomous learning.

TABLE I
STRUCTURE OF PAGES AND MISSIONS IN THE TEXTBOOK AREA.

Page	Overview of Missions (or Content)
Purpose of the Exercise	(Learning objectives of the lesson are presented)
Mechanism of Web Page Browsing	(Instructions on how to use the simulator are presented)
Opening the Lid	(Instructions on how to use the simulator are presented)
Understanding the Simulator	(Instructions on how to use the simulator are presented)
HTTP Mission ①	Answer the path where the file of the specified URL's web page is stored
TCP Mission ①	Answer how many packets the response to the specified URL is divided into
TCP Mission ②	Answer how many characters the simulator splits into packets
IP Mission ①	Answer the IP address of the smartphone in the simulator
Ethernet Mission ①	Answer whether a high-voltage cable state corresponds to 0 or 1
What are Communication Protocols	(Summarizes the lesson's content)

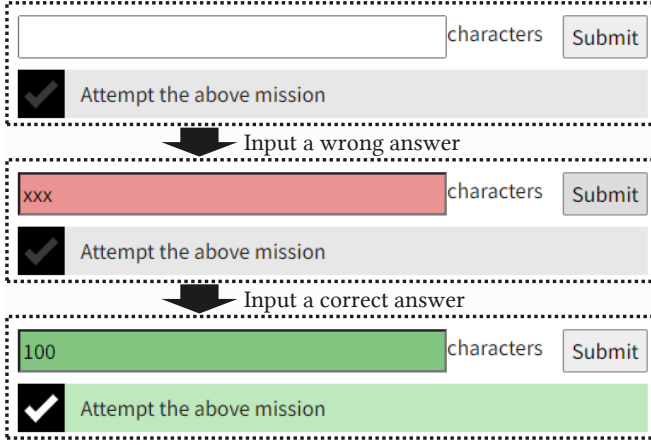


Fig. 5. When the student submits an answer to the mission, automatic feedback on correctness is provided.

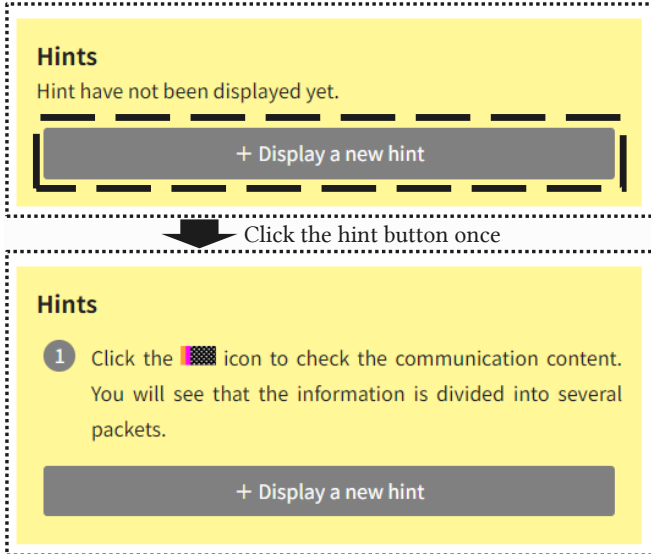


Fig. 6. Clicking the button to display hints reveals new hints one by one.

F. Log Collection

ProtoSim collects log data for a variety of user interactions. The recorded interaction types include pressing the hint dis-

play button, mouse enter and leave events on technical terms, and completing missions. Each interaction produces a single log entry that stores not only the interaction type but also supplementary fields specific to that type. For example, a log entry for mouse enter on a technical term records which user triggered a mouse enter event on which term and at what timestamp. By matching the corresponding enter and leave entries, the system reconstructs mouse hover events and calculates the duration of each technical term hovered.

IV. EVALUATION

To evaluate the effectiveness of ProtoSim, an educational practice was conducted. This section provides a detailed explanation of the process.

A. Design of the Educational Practice

Educational practice was conducted in seven high school classes in Japan. Of the students who participated in all learning activities, 211 consented to cooperate in the study. This study received ethical approval from an IRB committee (code number 2022-27).

Dividing learners into separate groups was difficult to justify to the cooperating school on ethical grounds, so every student in every class followed the same learning sequence. Instead, the lesson design followed a flipped-learning model that combined pre-class on-demand videos with in-class ProtoSim activities. To evaluate learning outcomes, we used a repeated-measures design with a pre-test (before the first face-to-face lesson) and a post-test (after the second lesson). In addition, questionnaires were administered after video viewing and after each face-to-face lesson to capture students' perceptions at each phase.

B. Flow of the Educational Practice

The video viewing was assigned as homework during a long vacation, as the students watched them at their own timing over approximately two weeks. They watched six short videos (created using the PtM system [39]), each approximately five minutes long. Each video covered the following topics: the devices that make up a network, the layered structure of communication protocols, the application layer, the transport

TABLE II
RESULTS OF POST-VIDEO VIEWING AND POST-LESSON QUESTIONNAIRES (4-POINT LIKERT SCALE, N = 211).

Question †	Post-Video		Post-Lesson 1		Post-Lesson 2	
	AVG.	SD	AVG.	SD	AVG.	SD
I enjoyed the <u>video/lesson</u>	2.55	0.88	3.30	0.61	3.25	0.61
The difficulty of the <u>video/lesson</u> was appropriate	2.73	0.74	3.26	0.64	3.25	0.58
The amount of the <u>video/lesson</u> was appropriate	3.05	0.74	3.39	0.58	3.37	0.56
I understood the learning content of the <u>video/lesson</u>	2.83	0.65	3.17	0.62	3.14	0.61
The explanations in the <u>video/left half of ProtoSim screen</u> were clear	3.06	0.67	3.45	0.60	3.37	0.61
Overall, I am satisfied with the <u>video/lesson</u>	2.91	0.74	3.29	0.67	3.30	0.58

† The left side of the underline indicates post-video questions, while the right side indicates post-lesson questions.

layer, the internet layer, and the network interface layer. After watching each video, participants completed the questionnaire related to the video as a form of reflection.

The face-to-face lessons consisted of two 50-minute sessions, during which time the students engaged in learning activities using ProtoSim. In the first session, the students learned how to use ProtoSim and completed the HTTP mission. The second session covered the remaining TCP, IP, and Ethernet missions. The teacher managed the lesson progression following the TCP/IP layers, reading out and explaining each layer's missions, allowing the students to work on the missions on their own, and concluding with a review of the answers for each layer.

Moodle was used in both the preparatory phase and on the day of the class. On-demand videos were delivered via Moodle, and questionnaires and tests were likewise administered through the platform.

C. Evaluation Objective

The objective of the educational practice is to evaluate whether the learning objectives were achieved and whether each design principle was effective. The achievement of learning objectives is assessed by identifying what students were able to understand through pre- and post-tests. For DP1, which focuses on the concrete visualization of data flow, the connection between ProtoSim's features and students' understanding is clarified based on students' subjective evaluations of each feature gathered through questionnaires, as well as an analysis of which questions showed improved accuracy in the pre- and post-tests. For DP2, which emphasizes supporting autonomous learning, the ways in which students utilized ProtoSim are examined through subjective evaluations of the lesson and ProtoSim's features gathered via questionnaires, as well as an analysis of operational log data.

This study partially compares the outcomes after on-demand video viewing with those after lessons utilizing ProtoSim. Due to educational considerations in a Japanese high school, it was not possible to conduct a perfectly controlled experiment. In this comparison, differences in learning styles must also be taken into account. However, by combining these results with other metrics such as evaluation items for each function and objective operation log data, the effectiveness of ProtoSim is assessed comprehensively.

D. Detailed Metrics

After watching the last on-demand video, students answered a questionnaire regarding the entire set of videos. Additionally, for each of the two face-to-face lessons, students answered a post-lesson questionnaire during the latter part of the session. These questionnaires asked about basic aspects such as enjoyment, difficulty, understanding and satisfaction, which they scored on a 4-point Likert scale with options of "Strongly Disagree (1)," "Disagree (2)," "Agree (3)," and "Strongly Agree (4)." They also provided their feedback on the video/lesson through open-ended responses, which were consolidated into representative examples based on their content. In the questionnaire conducted in the second face-to-face lesson, they subjectively evaluated each of the six features of ProtoSim, such as the animated visualization and automatically evaluated missions, implemented based on the design principles, following the same 4-point Likert scale.

The students completed a pre-test at the beginning of the first face-to-face lesson and a post-test at the end of the second lesson. The two tests contained the same set of 12 multiple-choice questions designed to measure participants' understanding of the overall communication mechanisms and more detailed specifications of each communication protocol. The questions were created by the first author with reference to several textbooks for the Japanese high school subject "Informatics I." The other three authors, including a high school teacher who usually teaches "Informatics I," reviewed their appropriateness and confirmed that the set comprehensively assesses network topics at the high school level. In other words, the 12 questions included items that were not specifically addressed in ProtoSim, and were intended to examine broader learning effects. To identify differences between the two tests, the McNemar test was used, considering a significance level of 0.05.

The operational log data were analyzed to elucidate the utilization of ProtoSim in the lessons. Data on who hovered over which technical terms and for how many seconds to view their explanations were aggregated to clarify how this function was used. Additionally, the distribution of the number of hints displayed per student was examined to identify differences in the usage of hint features among students.

E. Results

Table II indicates the results for the basic items of the post-video and post-lesson questionnaires. In every aspect, includ-

TABLE III
RESULTS OF POST-SECOND LESSON QUESTIONNAIRES REGARDING DESIGN PRINCIPLES (DP) (4-POINT LIKERT SCALE, N = 211).

DP	Question	AVG.	SD
DP1	The animation of the icon moving when entering a URL was easy to understand	3.74	0.46
DP1	The display such as the cardboard boxes and waveforms on the far right side of the screen was easy to understand	3.55	0.57
DP2	The table of contents on the left side of the screen helped me to study independently	3.35	0.65
DP2	The feature that displays explanation when hovering the mouse cursor over terms helped me to study independently	3.51	0.59
DP2	The automatic correctness evaluation feature in missions helped me to study independently	3.50	0.60
DP2	The hint feature in missions helped me to study independently	3.45	0.72

TABLE IV
RESULTS OF THE OPEN-ENDED FEEDBACK FROM POST-LESSON QUESTIONNAIRES (EXCERPT OF REPRESENTATIVE EXAMPLES). ORIGINAL JAPANESE SENTENCES WERE CAREFULLY TRANSLATED INTO ENGLISH.

Topic	Description
Mission	“It was easy to follow because it was in a simple mission format.” “Having missions made it clear whether I understood the content.” “I was happy because I was able to clear the missions.”
Hint	“The missions were difficult, but I was happy because I could solve them after looking at the hints.” “When solving problems, the hints provided made it easier to understand.” “The explanations on the left side were easy to understand, and I could solve the missions without hints.”
Term	“It was easy to understand because I could learn the meaning of words with underscores.” “It was convenient that hovering over important words displayed their meanings.” “I appreciated being able to immediately confirm the meaning of words.”

TABLE V
CORRECT ANSWER RATES FOR PRE- AND POST-TESTS (N = 211).

#	Question Overview	Pre-test	Post-test	χ^2	p
1	Match the names of devices to the four blanks in a diagram representing a home network	17.1%	19.9%	0.947	0.255
2	Match LAN, WAN and Internet to the three blanks in a diagram representing a large network	39.8%	38.9%	0.067	1.494
3	Match the names of the four layers to the blanks in a diagram representing TCP/IP	9.0%	55.9%	91.598	0.000*
4	Choose one advantage of a layered structure of communication protocols from four options	46.0%	47.9%	0.333	0.585
5	Match client, server, request, and response to the blanks in a diagram representing the WWW	38.9%	57.3%	20.836	0.000*
6	Match scheme name, domain name, and path to the blanks in a diagram representing URL	33.2%	53.1%	19.600	0.000*
7	Match circuit switching and packet switching to the respective diagrams	71.1%	73.5%	0.373	0.542
8	Choose one advantage of packet switching over circuit switching from four options	53.6%	56.9%	1.089	0.222
9	Choose the theoretical number of usable IPv4 addresses from eight options	25.6%	28.0%	0.490	0.446
10	Choose one reason for using domain names instead of IP addresses from four options	37.4%	49.3%	13.889	0.000*
11	Choose the parity bit to be added to the data “11100011” based on even parity	47.4%	53.1%	2.118	0.095
12	Choose the number of data containing errors from eight pieces of data with parity bits	28.9%	24.2%	1.724	0.128

* $p < 0.05$

ing enjoyment, difficulty, understanding, and explanation, the evaluations after the face-to-face lessons yielded better results than those after on-demand video viewing.

Table IV presents the feedback provided in the post-lesson questionnaires. Some responses noted that the mission exercise format was easy to engage with, allowed students to confirm their understanding, and brought a sense of accomplishment when completed. While some students mentioned that the hint feature was helpful, others reported successfully completing missions without using the hints. Regarding the feature that displays explanations when hovering the mouse cursor over technical terms, students found it convenient and easy to use. Additionally, some appreciated the visual clarity provided by the color highlighting, which emphasized the importance of the terms.

Table III shows the results of the subjective evaluation of the six features of ProtoSim based on the design principles asked in the post-second lesson questionnaire. All evaluation items received high scores. Looking more closely, while the

animation of flowing data was particularly well-received, the display of the table of contents and the hint function received slightly lower evaluations, with some variations observed among individual students.

Table V presents the correct answer rates for the pre- and post-tests, where χ^2 and p denote the McNemar test statistic and the corresponding two-tailed p -value, respectively. Asterisks have been added to the p -values for four questions for which significant differences were observed. Notably, a significant increase in the correct answer rate was observed in question 3, which asked students to name each layer of the TCP/IP protocol suite, and in question 6, which required them to identify the basic structure of communication involving client, server, request, and response.

Table VI summarizes the number of times and the duration that the mouse cursor hovered over each technical term. It reveals notable variability in the frequency and duration of hovers for each term. In particular, there was active engagement in checking the meanings of fundamental terms related

TABLE VI
TOTAL COUNT AND SECONDS TO HOVER THE MOUSE CURSOR ON TERMS
(N=211).

Term	Total Count	Total Seconds
Web Server	348	936.70
Request	256	688.59
Communication Protocol	243	730.58
Response	222	522.59
Packet	183	504.43
URL	105	301.76
Address Bar	97	216.63
IP Address	82	240.85
HTTP	76	188.29
TCP	72	220.06
Body	71	160.44
Ethernet	69	189.83
Header	67	190.21
Application Layer	56	154.65
Web Browser	55	130.45
Information Communication Network	55	141.22
Transport Layer	46	154.34
Network Interface Layer	38	144.19
Internet Layer	27	78.80
IP	15	35.12

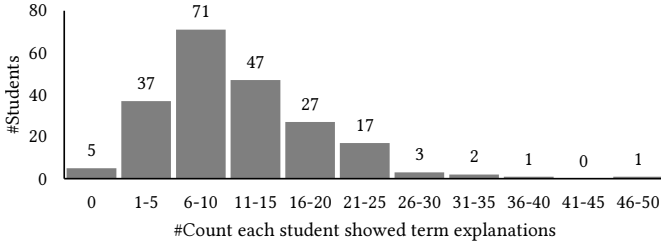


Fig. 7. Distribution of the count that each student showed explanations by hovering the mouse cursor on terms (N=211).

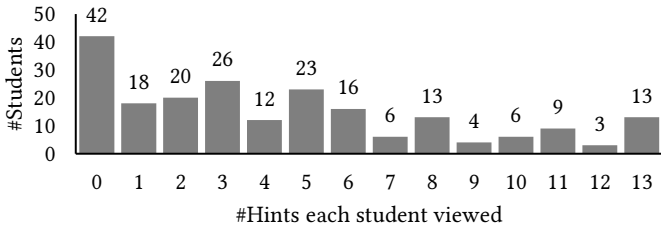


Fig. 8. Distribution of the number of hints viewed by students.

to the overall structure of communication, such as “request” and “response.” In contrast, more specific terms, such as the names of individual layers, were less frequently explored for their meanings. Additionally, figure 7 presents the distribution of the number of times each user hovered their mouse cursor over technical terms, based on the aggregated data. This shows that while the feature was used by most students, the frequency of its use varied significantly among individual learners. These counts only include valid mouse hovers lasting between 1 and 10 seconds.

Figure 8 shows the distribution of the hints displayed per student. While 42 students engaged in the exercises without viewing any hints, 13 students viewed all 13 hints, and the number of students varied for the other frequencies.

V. DISCUSSION

A. Achievement of Learning Objective

The learning objective of ProtoSim was “to be able to concretely imagine how data flows based on the network mechanisms centered around communication protocols.”

From the questions that showed a significant increase in correct answer rates between the pre- and post-tests, it became clear that students deepened their understanding of the overall structure of the TCP/IP protocol suite and the communication framework in client-server systems. While some other questions focusing on specific layers or mechanisms also showed improvements in correct answer rates, the number of questions with statistically significant differences was limited. The learning objective explicitly emphasized understanding the overall structure of computer networks, and the results aligned with that intent. To examine potential transfer, the test also sampled per-layer particulars, yet discernible gains surfaced only in a narrow set of topics, notably URL structure and the advantages of domain names.

Additionally, according to the students’ subjective evaluations, it was found that they were able to understand the learning content better in the lesson using ProtoSim compared to watching on-demand videos, which is also presumed to have contributed to their confidence and interest. This result should be considered meaningful for high school students, who may not necessarily aim to major in computer science or become networking professionals. It is expected that their interest in computer networks will encourage them to apply what they have learned in everyday life and to pursue deeper study at the university level.

B. Effectiveness of DPI

DPI was that “communication is carried out in a virtual network based on the user’s actions, and the contents of the data flowing through the TCP/IP layer structure are concretely visualized.”

In the students’ subjective evaluations of ProtoSim’s features, both the function that allows them to view an animation of data icons flowing when entering a URL into a virtual smartphone and the function that simulates and visualizes data contents using concrete objects like boxes or voltage were rated highly. Among these, the former received particularly outstanding scores compared to other subjective evaluation items. The animated content that depicts data traversing all layers of the TCP/IP suite aligns with what was assessed by the post-test items that showed a statistically significant increase in correct response rates. Therefore, it is reasonable to infer that ProtoSim’s animation feature, developed based on DPI, contributed to helping students concretely imagine the flow of communication.

Animation is expected to deepen understanding of phenomena involving motion and change. In networking, data is transferred from a server to a smartphone and moves through the layers of the TCP/IP protocol suite within a device. The content also changes, such as headers being appended as the data traverses layers. Given these characteristics of the learning content, the finding that animation was effective is

theoretically well grounded. Visualizing data transformations across TCP/IP layers has not been addressed in prior research and constitutes one of the advantages of the newly developed ProtoSim.

C. Effectiveness of DP2

DP2 was that “the simulator is integrated with the textbook, offering features such as automatically evaluated missions and autonomous learning support features to help achieve the missions.”

In the students’ subjective evaluations of ProtoSim’s features, all four functions, including the table of contents, technical term explanations, automatic correctness checking for missions, and mission hints, received high ratings. However, a closer analysis revealed some variation in the scores.

The table of contents feature, which helps students understand the flow of learning and their current position, received slightly lower ratings compared to the other features. However, the evaluation of the amount of the lesson was relatively high, suggesting that students did not feel the learning content was excessive. This is likely because the textbook content was divided into pages corresponding to each layer in the table of contents, and the lesson itself proceeded layer by layer, thereby reducing cognitive load.

The hint feature, which provides guidance for completing missions, showed a larger standard deviation in its evaluation scores. Analysis of the learning log data revealed considerable variation in how frequently students used the hint function, with some students not using it at all. This finding is consistent with the theoretical background that the hint feature is intended to bridge gaps between students. For high-performing students who were able to complete the missions without relying on the hints, it is natural that the feature seemed unnecessary. On the other hand, there were students who relied on the hint function to progress through the exercises. Thus, the variation in evaluations among students can be positively interpreted as a sign that the function effectively supported autonomous learning.

The automatic correctness feedback of missions received relatively high ratings among the autonomous learning support features. In the free-response section, students expressed joy at successfully completing missions and mentioned that the missions helped them confirm their understanding. These responses are believed to contribute to the high subjective ratings in the four-point Likert scale items measuring enjoyment and understanding. Additionally, some students noted that the mission-based format made learning easier, suggesting that the mission feature provided a solid foundation for the learning process. Taken together, these findings are consistent with the Skinner-based rationale introduced when defining DP2, namely that immediate feedback can reinforce correct responses and sustain self-regulated learning [38]. Compared with prior work, ProtoSim explicitly defined a concrete learning sequence and mission tasks, making stepwise automatic correctness judgment feasible and thereby enabling the immediate feedback that supported students’ autonomous learning.

According to table III, more useful than the hint feature during the missions was the functionality that displayed ex-

planations when students hovered their mouse cursor over technical terms. Analysis of the log data in table VI and figure 7 confirmed notable variation in the number of hovers per term and per student. This indicates that students were actively seeking information based on their individual levels of understanding and the demands of the missions, demonstrating autonomous learning. This feature, like the hint feature, appears to have sufficiently achieved its theoretical objective of bridging gaps among students.

From the above, it can be concluded that the mission feature, developed based on DP2, served as the core of the learning activities. Furthermore, through the use of the technical term explanation and hint features, students actively engaged in autonomous learning to deepen their understanding.

VI. LIMITATION

In this study, a fully controlled experiment could not be conducted due to educational considerations in Japanese schools. Instead, two evaluation methods were adopted. First, a pseudo-comparison was conducted by sequentially implementing lessons that involved watching on-demand videos and using the proposed material. Second, the differences between this study and previous educational systems – specifically, the visualization methods and support for autonomous learning – were evaluated. The results based on these evaluation methods demonstrated the usefulness of this study, but the inability to conclusively state that it is significantly superior to previous studies is a limitation of this research. To strengthen these evaluations, future work will include conducting a fully controlled experiment.

There is also room to improve the testing protocol. In this study, a knowledge-focused post-test was administered immediately after the lesson using ProtoSim. To evaluate whether more transferable and practical skills were acquired, it would have been possible to include a delayed assessment or to assign more authentic troubleshooting tasks using real devices with intentionally incorrect network settings. Because this research was conducted in real classroom practice at Japanese high schools, time constraints precluded such evaluations, although they should be pursued in future work.

VII. CONCLUSION

Nowadays, it becomes very important even for high school students, who do not necessarily major in CS, to be able to concretely imagine how data flows based on the overall network mechanisms in preparation for potential issues on the network. To achieve this goal, this paper proposed ProtoSim, an interactive learning environment designed for high school students to learn the TCP/IP protocol suite. One of ProtoSim’s features is the ability to input a URL into the virtual smartphone within the simulator, allowing users to view icons representing data, developed based on DP1. Another feature of ProtoSim is the mission system with automatic correctness judgment, developed based on DP2. To evaluate these functions and assess the achievement of the learning

objective, an educational practice utilizing ProtoSim was conducted in a Japanese high school. As a result, significant improvement in accuracy rates was observed in the pre- and post-tests for questions related to the overall structure of network mechanisms, such as the layered structure of communication protocols and client-server communication. The achievement was supported by subjective evaluations from students and the analysis of operational logs, which revealed that ProtoSim's features contributed to students' understanding comprehensive mechanics of network and fostering an autonomous learning attitude. It is believed that lessons incorporating ProtoSim enabled students to imagine how data flows within a network, which is expected to enable students to make appropriate decisions when network issues arise.

The authors aim to make ProtoSim accessible to a broader learners. This paper focused specifically on computer science education in high schools. At the same time, the need to learn networking broadly under tight time constraints may also arise in other settings, such as university general education. There is potential applicability in vocational training as well, although it should be noted that ProtoSim does not cover all specialized topics. The intended usage is therefore to first grasp the overall picture with ProtoSim and then proceed to study more specialized content in depth. In such cases, whether learners can integrate the overview gained with ProtoSim and the subsequent details in their mental models requires further evaluation. Feature refinements on ProtoSim features may also be necessary to make connection. By continuing iterative improvement and evaluation, the authors hope it will evolve into a system that supports the learning of a wider range of people.

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