The Remote FPGA Lab and its Usage in Teaching Digital Design

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Abstract:

Historically students in 271 used physical lab kits that included an Intel DE1-SoC, a breadboard, and TTL chips. The usage of the remote lab at UW started in 2021 to teach EE 371 course and continued since then. In fall 2022, the remote lab was used in teaching 271. This report highlights the rationale behind using the remote lab in teaching digital design courses with a focus on EE 271. It is noteworthy to state that this report is a result of my 10+ years experience teaching digital logic (EE 271 or equivalent) using lab kits and my experience of using the remote lab for almost 4 years. This report highlights the following:

- Student feedback and surveys on using the remote lab (overwhelmingly positive).
- Pedagogical impact (with award-winning paper comparing the remote lab to the hands-on lab).
- Cost analysis (with a significant cost saving from using the remote lab).
- Advanced features that support students learning and understanding of design concepts.
- Remote Lab usage.

Students Feedback (EE 271, fall 2022):

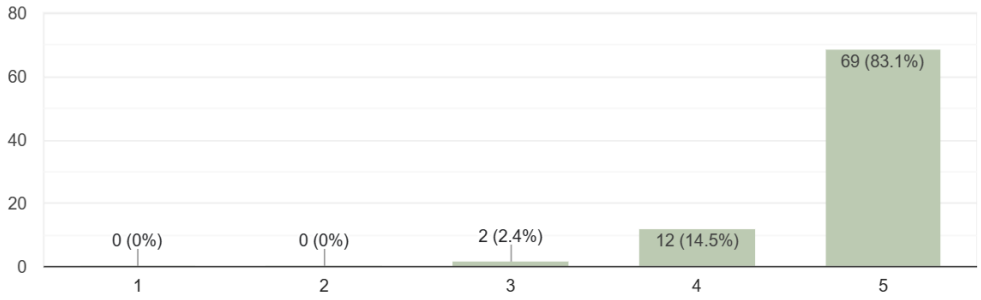
A comprehensive survey was distributed to EE 271 class in the fall of 2022, to gauge the students' perspective on equitable access to engineering education, digital inequalities, diversity, equity, and inclusion; in light of their experience using the remote lab. An IRB was sought and approved from the UW Human subject division. The result of this anonymous survey is published in the upcoming ASEE paper in June 2023[1]. Part of the survey, there was a section to collect students' feedback on their overall experience with the remote lab. The results, shown below, were overwhelmingly positive, with 83 out of 85 total enrolled students responding to the survey.

(The appendix includes responses from the IRB approved survey.)

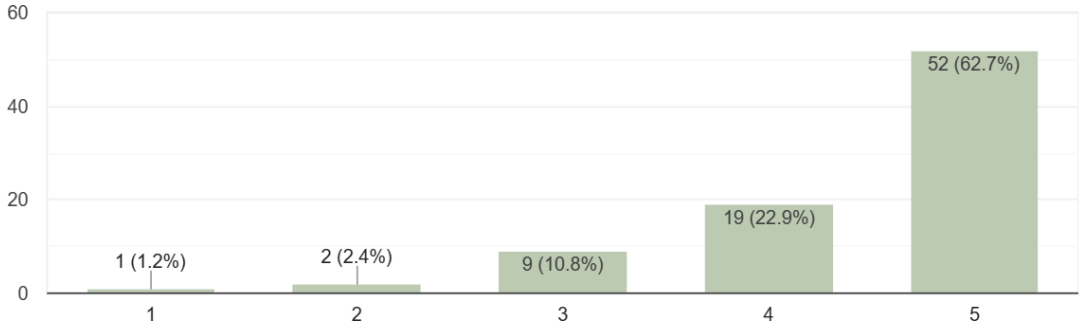
[1] M. Inonan, A. Paul, D. May, and R. Hussein, "RHLab: Digital Inequalities and Equitable Access in Remote Laboratories, **to appear in** *American Society for Engineering Education ASEE conference*, 2023.

A. Paul, M. Inonan, D. May, R. Hussein, "Exploring Diversity, Equity, and Inclusion in Remote Laboratories", **to appear in** *American Society for Engineering Education ASEE conference*, 2023.

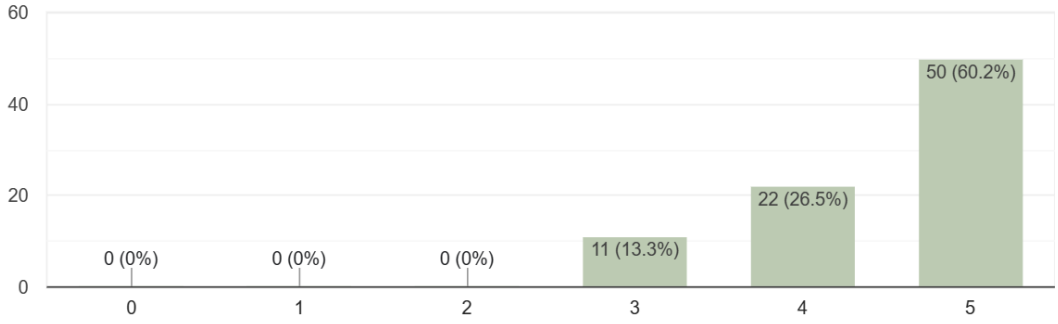
On a scale of 1 (low) to 5(high), I was able to complete my lab assignments using the remote FPGA lab



(on a scale of 1 (low) to 5 (high), I gained solid skills in design verification using ModelSim



On a scale of 0 (very poor) to 5 (excellent): My experience of using the remote lab platform this quarter is



Additionally, the response to the end of quarter course evaluations is as follows:

Overall Summative Rating represents the combined responses of students to the four global summative items and is presented to provide an overall index of the class's quality:

Combined Median	Adjusted Combined Median
4.8	4.8

(0=lowest; 5=highest)

Challenge and Engagement Index (CEI) combines student responses to several *IASystem* items relating to how academically challenging students found the course to be and how engaged they were:

CEI: 5.4

(1=lowest; 7=highest)

SUMMATIVE ITEMS

	N	Excellent (5)	Very Good (4)	Good (3)	Fair (2)	Poor (1)	Very Poor (0)	Median	Adjusted Median
The course as a whole was:	30	70%	27%	3%				4.8	4.7
The course content was:	30	77%	20%	3%				4.8	4.8
The instructor's contribution to the course was:	30	83%	17%					4.9	4.9
The instructor's effectiveness in teaching the subject matter was:	30	77%	23%					4.8	4.8

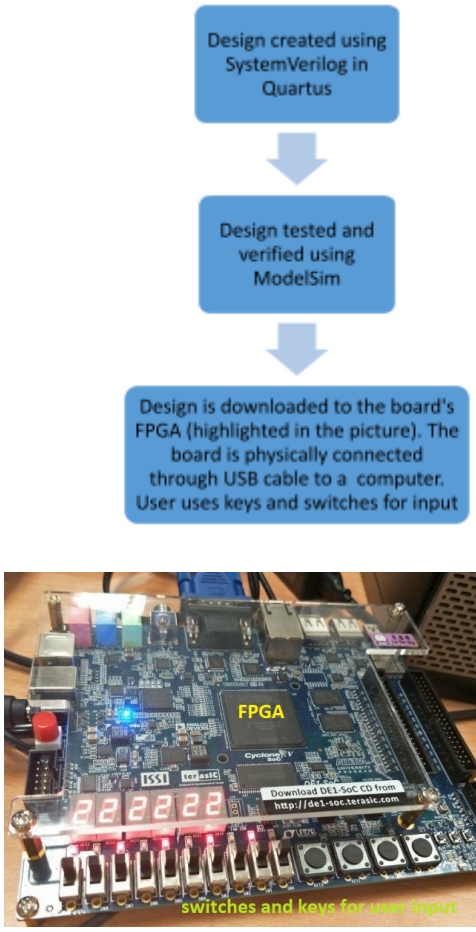
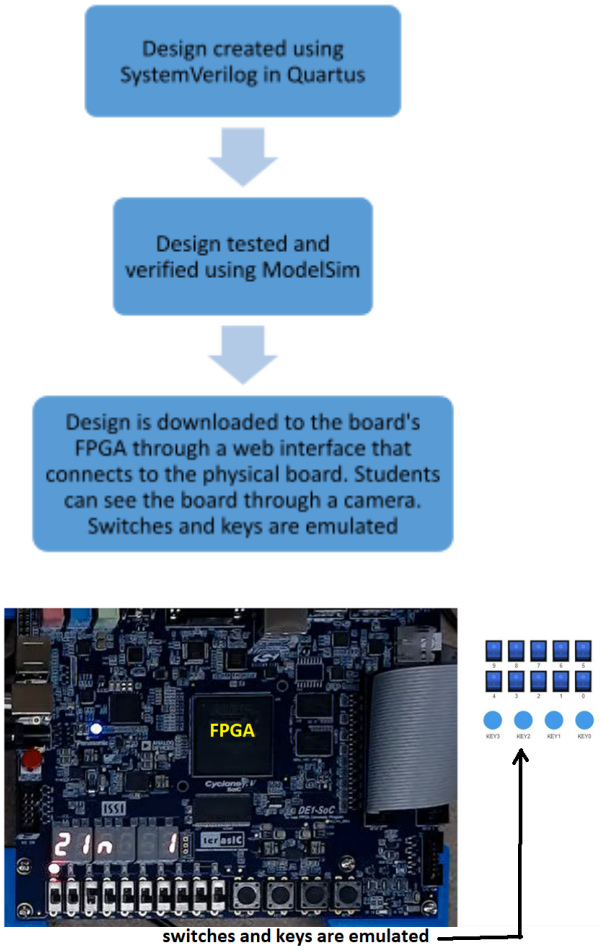
STANDARD FORMATIVE ITEMS

	N	Excellent (5)	Very Good (4)	Good (3)	Fair (2)	Poor (1)	Very Poor (0)	Median	Relative Rank
Course organization was:	30	70%	23%	3%	3%			4.8	5
Sequential presentation of concepts was:	30	80%	17%	3%				4.9	1
Explanations by instructor were:	30	73%	27%					4.8	6
Instructor's ability to present alternative explanations when needed was:	30	73%	23%	3%				4.8	10
Instructor's use of examples and illustrations was:	30	83%	13%	3%				4.9	3
Quality of questions or problems raised by the instructor was:	30	73%	23%	3%				4.8	8
Contribution of assignments to understanding course content was:	30	63%	33%		3%			4.7	11
Instructor's enthusiasm was:	30	90%	7%	3%				4.9	12
Instructor's ability to deal with student difficulties was:	30	73%	23%	3%				4.8	13
Answers to student questions were:	30	70%	27%	3%				4.8	14
Availability of extra help when needed was:	30	70%	23%	3%		3%		4.8	16
Use of class time was:	30	70%	27%	3%				4.8	7
Instructor's interest in whether students learned was:	30	83%	17%					4.9	9
Amount you learned in the course was:	30	80%	20%					4.9	2
Relevance and usefulness of course content were:	30	83%	17%					4.9	4
Evaluative and grading techniques (tests, papers, projects, etc.) were:	30	60%	33%	3%		3%		4.7	17
Reasonableness of assigned work was:	30	57%	40%	3%				4.6	18
Clarity of student responsibilities and requirements was:	30	67%	27%	3%	3%			4.8	15

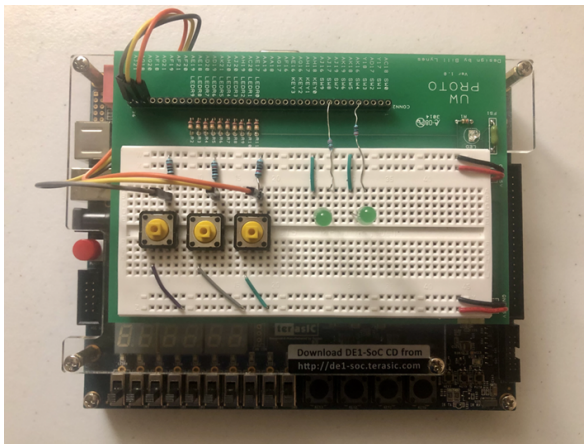
Differences between traditional and remote labs and is remote lab a virtual lab

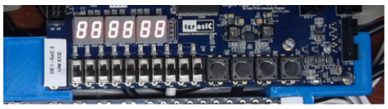
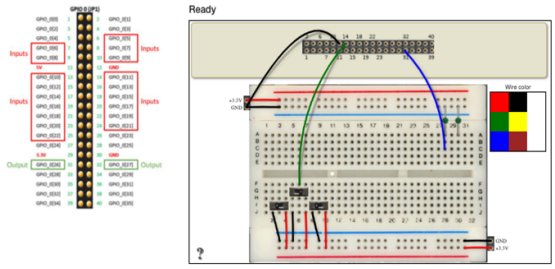
The remote lab is not a virtual lab. Students use real hardware (the same board they would receive in a lab kit) but access it remotely to download their design to. The use of a remote lab closely resembles real life scenario in an industry setting such as in ASIC design. The following table shows the main differences between physical lab kit and the remote lab

Traditional lab (using lab kits)	Remote lab

Design Flow	**Design Flow**
	
No time limit for students to use the board. This often results in students skipping the second step of the design flow and instead using the board as their way of testing their design.	Students get 2-3 minutes to see their design running on the board. They may get multiple sessions of 2-3 minutes each if needed. However, if the design flow is properly followed, 2-3 minutes is enough to see a correctly compiled, simulated code in action on the board. The time limit emphasized the purpose of using the remote lab, which is that students should spend time on their design and verifying it offline, with the usage of the FPGA being the last step. *It is worth noting that some students find the time limit frustrating and this is why they prefer physical boards and not simulating. However, that way they do not get the skills that industry is demanding, where they highly encouraged to simulate before testing.*
Course meets the learning outcomes. However, based on some informal discussions with some	Course meets the learning outcomes with a strong preparation of students in design and verification.

<table>
<tr><td>students, they mentioned that they usually found the verification step with Modelsim “frustrating” so they would rely on the board to test their design.</td><td></td></tr>
<tr><td>Breadboarding

Students use a physical breadboard on top of the FPGA board for the first introductory lab. (picture is for demonstration but it doesn’t show TTL chips that are included in the lab kit)</td><td> 
 

Students use a virtual breadboard interfaced with the remote FPGA board, for the first introductory lab.
(picture is for demonstration but it doesn’t show TTL chips, which are supported in the remote lab)</td></tr>
<tr><td colspan="2">The introductory lab that uses a breadboard represents about 10% (or less) of the labs and is meant for the following:
● introduce students to logic gates and TTL chips
● Let students know that TTL are not programmable and therefore they are not a feasible solution for a complex digital design.
● We will not use TTL chips in building digital circuits and will use FPGAs that would make hundreds of logic gates. The programmability of FPGA is the way to go with digital design prototyping, which is typically a prerequisite for ASIC design.
It is important to note that wiring up circuits on a breadboard is not the focus of EE 271, the focus is to use the programmable capability of FPGAs to build complex digital circuits (which is a step towards ASIC design). Students get more experience with breadboards from circuits courses which students pointed out in some of their feedback (appendix).</td></tr>
<tr><td>Additional hardware (such as VGA, mouse, game controllers) would be needed for a final freestyle project</td><td>Other peripherals (such as VGA, mouse, game controllers) are supported on the remote lab. No additional hardware is needed for purchase.</td></tr>
<tr><td>Kits must be returned once the quarter finishes.</td><td>Students can still access the remote lab after the quarter is over.</td></tr>
</table>

Evidence of the effectiveness of using remote labs:

- The learning outcomes associated with using a remote lab environment for students were studied. The study compared two modes of learning by evaluating one lab assignment that was given to students in a remote offering and in a previous traditional offering. Students using the

remote lab environment scored higher overall and significantly higher within the *analyze* levels of Bloom's taxonomy. These results align with the findings of other studies that underscore the effectiveness and efficiency of remote laboratory environments.

  - Reference: Hussein, Rania, and Wilson, Denise, "Remote versus In-hand hardware laboratory in digital circuits courses", American Society for Engineering Education ASEE conference, Electrical and Computer Engineering Division, July 26-29, 2021. **Best paper award**.

- A study on the industry perspective on the expected preparedness of students specifically on using verification tools. The study surveyed industry professionals from companies such as Intel, Microsoft, and Cadence.
  - References: Li, Shuowei, and Hussein, Rania, "Effectiveness of using remote laboratories in promoting simulation and verification tools", 20*th annual International conference on Remote Engineering and Virtual Instrumentation REV 2023.*
- A study on evaluating part of the BEADLE project (a project funded by Intel) to introduce a gradual transition from digital foundational concepts such as truth tables, boolean expressions and k-maps to SystemVerilog and FPGA. The project used the remote lab and was rolled out in EE 271, fall 2022. Findings suggest that BEADLE positively impacted students' understanding of electrical engineering concepts, as shown by pre- and post-assignment surveys and reflection questions. This supports the potential of remote laboratory-based education as a viable option.
  - Reference: R. Hussein, R. Maloney, P. Orduna, J. Ander Beroz, L. Rodriguez-Gil, "RHL-BEADLE: Bringing Equitable Access to Digital Logic Design in Engineering Education", **to appear in** the *American Society for Engineering Education ASEE conference*, June 2023.

There are many other studies by other researchers that show the effectiveness of remote laboratories. The reader can refer to the references section of the aforementioned papers for more papers.

Cost Analysis:

Lab kits:

The following table on the cost of EE 271 lab kits was provided by Chris Overly.

Cost / Kit	$465
Qtrs/Kit	6
Cost / Use	$78
Crs. Fee	$50
Loss/Use	$28
Students/Yr	270
Loss / Year	$7,425

This means that each FPGA will be amortized in 6 quarters, and therefore the cost of the kit ($465) per student per quarter will be $77.50 ($465 / 6). Given that the number of students per year is 270, the **total cost per year, before course fees, is $20,925** ($77.50 x 270). However, as the 270 students pay a $50 fee (270 x 50 = $13,500), the loss per year is $7,425 ($20,925 - $13,500).

Additionally, **there is an overhead due to the labor cost** of preparing the lab kits every quarter, distributing them, and collecting them back to be turned around for the following quarter. This overhead was used to be done by Bill Lynes but after his retirement, this is now done by the EE store TA that the department hires annually.

Remote Lab:

The remote FPGA lab has 36 DE1-SoC boards at UW, which students can remotely access to download their code to. The lab at UW is part of a distributed remote FPGA lab shared between 5 universities in 4 countries that are connected through a global network of remote laboratories called LabsLand. This means that students get access to the boards at UW and if all boards are occupied, they get to use boards at the other universities in the network, including the University of Michigan. The availability of similar labs in different locations worldwide accommodated load sharing at different time zones.

The students at UW access the remote **for free**. The cost of running the remote is exclusively the server room, electricity, and occasional setup/restart or upgrades to the system. **No overhead cost** (and if any unforeseen comes up it will be very minimal). **Zero loss**. The cost saving is significant compared to the $20,925 from using a physical kit. Since the remote lab has been established, we did not have any broken hardware that needed to be turned around. Additionally, the remote lab did not use any of the course fees that students pay.

The company that provides the cloud services, integration and global scheduling, LabsLand, **waives any maintenance fee** because other universities and institutions access the remote laboratory paying a subscription fee.

Students/Trainees from those institutions:

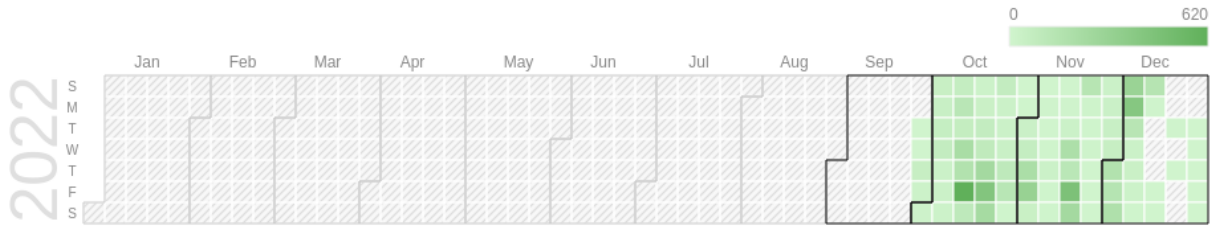
- See the logo of the University of Washington and are aware that they are using equipment located at UW.
- If all the boards at UW are busy, there is a global queue, and students of UW go first in the queue than anyone from anywhere else. Students of UW therefore are not affected by the usage by third parties.

Remote laboratory usage:

In autumn 2022, 187 students enrolled in EE 271 and EE 371 concurrently used the remote FPGA lab, resulting in 16,572 accesses to FPGAs. The lab experienced a median time of 5 seconds per session waiting for an FPGA board to become available, with an average of 5.70 and a standard deviation of 5 seconds.

Additionally, given that there is no student fee, students can have access even after the class is over. This has the potential to promote students' participation beyond a formal classroom setting.

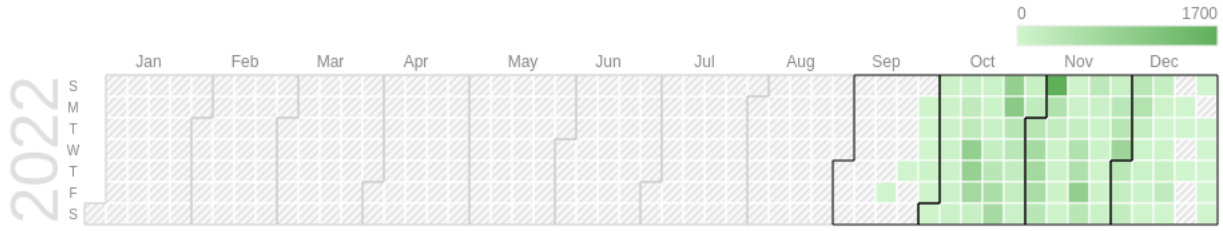
The cloud service allows us to also analyze when students used the laboratory. This is EE 271 in autumn 2022:



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00	29	39	22	14	46	95	14
01:00	14	17	3	10	55	60	16
02:00	13	6	2	4	22	21	12
03:00				1		9	16
04:00		5				1	13
05:00							13
06:00			1		2		
07:00			1	2	2	2	
08:00	4	6	3	9	12	8	
09:00	5	15	13	38	26	5	6
10:00	9	21	26	38	70	1	19
11:00	40	11	35	87	52	24	35
12:00	63	34	49	66	51	35	25
13:00	80	37	60	100	104	51	28
14:00	38	36	77	115	175	45	24
15:00	30	24	61	104	185	50	56
16:00	36	32	68	82	178	30	72
17:00	23	33	51	87	204	42	60
18:00	67	22	45	90	199	68	53
19:00	62	36	56	54	190	58	65
20:00	54	31	73	45	184	64	52
21:00	46	42	42	69	166	75	73
22:00	72	44	64	85	149	83	114
23:00	50	17	36	59	111	47	70

In the figure above, each number represents the number of laboratory sessions by students in each particular time, summing all the times during the time range 9/1/22 - 12/31/22. For example, the 29 on the top left corner means that in total students connected 29 times, summing all the times that students used the lab at midnight on Monday throughout the four month period.

Or for example, we can select all students (EE 271 and EE 371) between 9/1/22 - 12/31/22:



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00	85	134	97	131	91	117	83
01:00	49	50	47	76	113	83	55
02:00	50	30	43	40	86	58	38
03:00	14	2	28	20	43	21	40
04:00	35	7	22	12	23	19	18
05:00	10	12	12	6	24	2	19
06:00	1	13	2	17	12	4	12
07:00	17	36	16	16	11	9	9
08:00	29	39	27	31	22	28	7
09:00	46	39	62	66	47	23	34
10:00	53	74	86	86	88	25	82
11:00	133	54	159	176	99	75	180
12:00	126	92	157	169	104	77	170
13:00	146	89	222	223	167	112	175
14:00	153	138	282	255	246	106	158
15:00	170	112	326	215	277	113	259
16:00	222	142	316	214	297	85	311
17:00	197	174	245	280	354	99	334
18:00	227	160	220	267	293	149	371
19:00	252	126	201	175	317	125	279
20:00	260	131	241	247	306	140	325
21:00	296	180	257	246	273	164	364
22:00	321	237	354	233	229	227	345
23:00	290	162	223	201	163	148	259

It is possible to filter by student, day, range of days, or groups.

Among the people using the UW FPGAs through LabsLand is Intel Corporation for customer training. Intel also encourages the usage of LabsLand FPGAs in the main website of the Intel FPGA Academic Program:

https://www.intel.com/content/www/us/en/developer/topic-technology/fpga-academic/overview.html

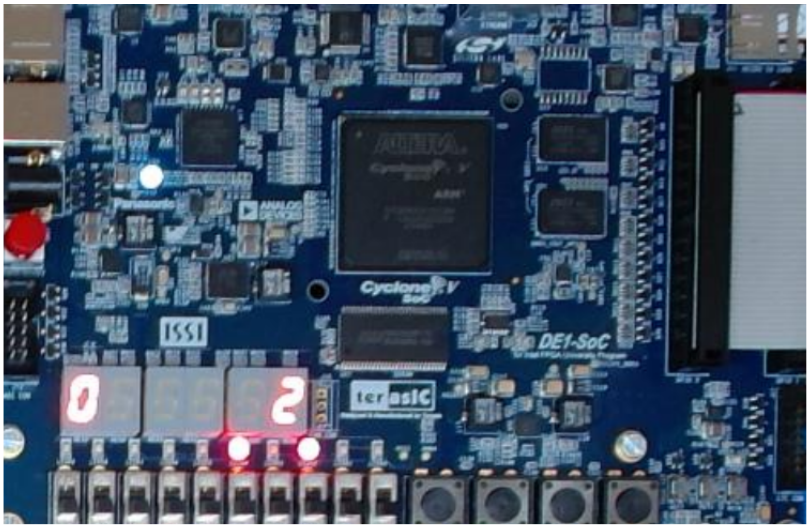
Additional features of the remote laboratory:

Additionally, the physical kit is limited to a set of switches, buttons, LEDs, and 7-segment displays. It has additional features (VGA, audio, GPIO) that can only be used by students if spending an additional cost.

However, in the remote laboratory, given that the equipment is digitized, students can access a wider range of sensors (in addition to the switches, buttons, LEDs, 7-segment displays, VGA, and audio), and even mix the experience with simulations to visualize better the learning goals.

For example, in the case of the DE1-SoC, the RHLab, in collaboration with LabsLand, has developed in February 2023 a 3D simulation of a parking lot that is connected to the DE1-SoC GPIOs. In the 3D simulation there are 3 parking spots, each one equipped with a presence sensor and an actuator (an LED), and the parking lot entrance and exit has also two gates that have their own actuators (controlling the gates) and sensors (presence sensor before each gate), and an LED to show that there is no spot available in the parking lot.

These sensors and actuators are connected to the GPIOs of the FPGA. Therefore students in SystemVerilog can interact with a real-world application, and visualize it with external agents (moving cars), in a very intuitive way, while still controlling and seeing in real-time the real FPGA that controls the simulation:



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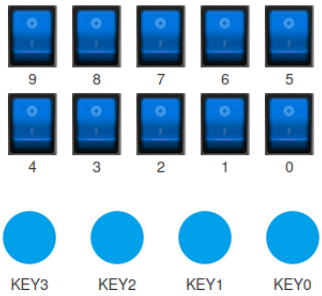
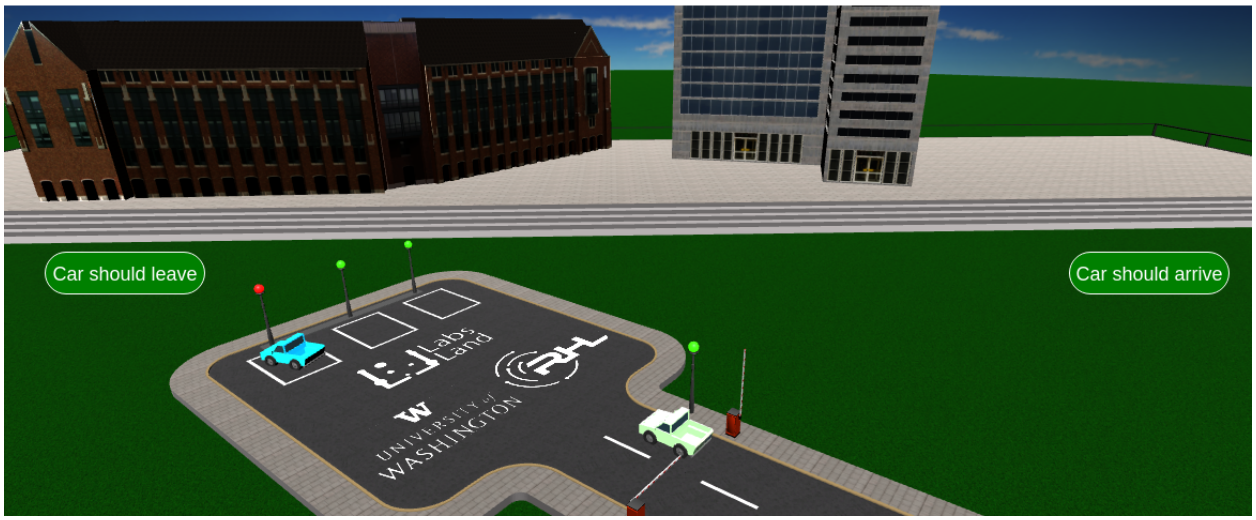
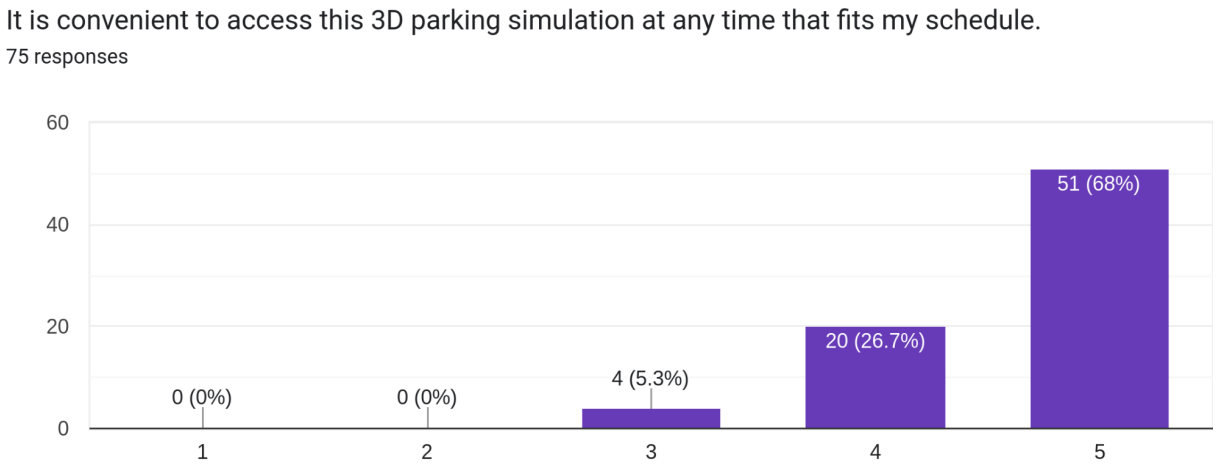
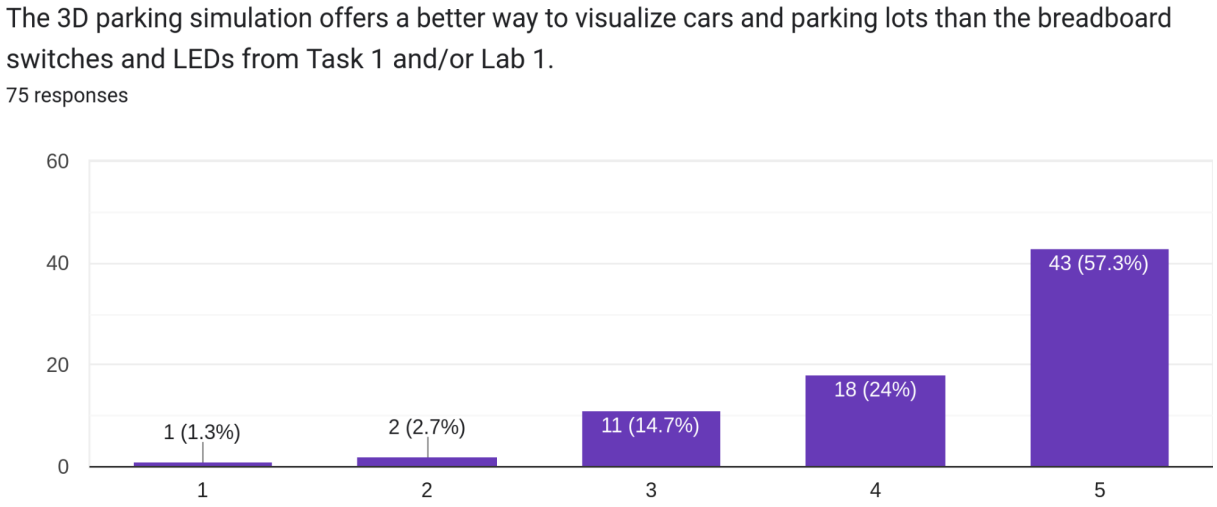




The library to create simulations is open-source, so it can be used by UW, LabsLand, and other universities to create other similar simulations, and it would be possible to create specific simulations for making EE 271 labs more interesting for students.

This feature was used in EE 371 in one of the assignments with overwhelming good feedback by students:





Some comments from students on the usage of the 3D parking simulator:

"Very easy to understand which put the focus on the actual coding rather than understanding how to show each edge case with switches, buttons, and LEDs"

“One factor that is important for me in FPGA design is understanding what the expected output should be after the design has been implemented. The parking lot 3D simulator gave us a way to more clearly visualize the lab specification which I found to be very helpful.”

“I think the simulation is very nice for understanding the spec of the lab and what the final product should be like, I usually struggle to write the project because I don't understand the specs and don't know what is to be expected”

Conclusion:

This report presented strong evidence that the remote laboratory is an effective tool over lab kits in promoting students' learning. The evidence is based on research studies and students feedback. It is also a cost-effective solution to offer the digital design courses to larger cohorts of students without the significant cost and overhead that is typically associated with lab kits.

Motions:

Motion 1: Due to its effectiveness in promoting students' learning and due to being a cost efficient solution, update the EE 271 MCD to use remote lab instead of physical lab kits.

or

Motion 2: Update the MCD of EE 271 from “using lab kits” to “using remote labs, lab kits, or other tools or platforms that promote modern teaching and prove success in meeting the course’s expected learning outcome”.

Appendix

Sample responses from an anonymous IRB approved survey distributed to EE 271 students in fall 2022. More responses were provided in the survey, but the comments shown represent common themes. All results from this study will appear in future publications.

Features that students liked about the remote lab:

- *I love the remote lab because I do not have to be in a physical lab to do my work. Instead, I can study where I'm comfortable and still get the same work done. For the most part, I thought everything was really easy to use. There are a lot of FPGA boards available so I never had to wait longer than a minute to use it.*
- *I like how I could edit the code after uploading the file to the lab so I could make quick fixes if I forgot to do something on Quartus. I also enjoy the UI when interacting with the board - it was very intuitive and seemingly realistic. Overall, it was a great website/service and I didn't have any notable challenges using it.*
- *I liked the seamlessness of the remote lab, that allowed for easy access to the inputs and to see clearly how the LEDs/HEXes on the board changed.*
- *I liked the concept of the remote lab itself. I find the many other EE classes focus on the wiring of the hardware so much so that it is what we spend most of our time doing. For example, the*

remote lab allows us to spend more time with designing and system verilog to know what we are actually doing.

- *I really liked the accessibility of the lab. I do my homework late at night and I really liked being able to work with my lab partner whenever we were able to meet up and debug more efficiently and not waste as much time with the hardware malfunctioning.*
- *I like how I can access it online! It makes it very accessible. It's also very easy to use.*
- *I enjoyed the fact that I was able to run my lab at my own convenience instead of waiting my turn or having to go to a special place.*
- *The remote lab was very easy to use and far more convenient than showing up to an in-person lab. I also appreciate the fact that the remote lab was available 24/7.*
- *I thought it was great that I didn't have to worry about carrying around a large piece of hardware/lab kit in order to perform the labs from anywhere. I could just sit in the library or hub after any class with my laptop and be fully equipped to work on my projects. The only complain I have is that uploading and then synthesizing the code sometimes took a while to do, but overall it wasn't really an issue for me.*
- *It allowed for freedom in working time and gave equal opportunity to most users*
- *I liked how accessible and hassle free the remote lab felt*
- *I liked that I didn't have to schedule time into my day to physically visit the lab. I usually work on homework at night and I don't feel comfortable walking around late at night, so this made it so I could work on my project and simulate it right away.*
- *I think it is a much more efficient approach than working with a physical circuit, and allows us to spend more time on the new material. It is also easily accessible and can be accessed anywhere which is extremely convenient.*
- *You do not need to carrier a lab kit and it works with mac os*
- *The accessibility of the lab was good for testing out code with a simple click. The other features the remote lab has, such as the boole designer or digital trainer are also a great way of learning and verifying answers. This makes it easy to progress on your own.*
- *I liked that the remote lab could be accessed 24/7 and that most times I didn't have to wait to run my design. If I did have to wait, it was at most 10 seconds.*
- *I feel that the website was very accessible and easy to use. I especially liked the in-site code editor and the ability to edit, upload, and download code easily. Furthermore, the GUI for interacting with the board once the code was uploaded was also super easy to use.*
- *I really like how fast the time to reserve the FPGA board was. One feature I used often and liked was the Boole designer to check my Boolean expressions.*
- *I was skeptical at the beginning of the quarter, but it has really grown on me and I am very happy we used this platform.*
- *Overall, the remote lab has been a very positive experience. There are very few downsides, which are all minimal, while it provided several highly impactful benefits with schedule and cost. Had the remote lab not been available, I am sure I would have been caused much more stress for the course.*
- *I just want to note that I haven't tried accessing the remote lab from my phone or tablet, but when using the "tablet" mode of my laptop to access the remote lab, my experience was still good.*

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