An on-line Project Based Learning assignment: programming an event-driven simulator to analyze queuing-based systems

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ABSTRACT
We describe a Project Based Learning (PBL) assignment, targeted for MSc students (Computer Science/Electrical Engineering degrees). They are asked to design and develop, from scratch, an event-driven simulator and afterwards use it to analyze the performance of queuing-based systems. Previous experiences were well received by the students, as we prove by reporting the results from the surveys we conducted to the students that did the assignment in the last two course editions. We also present how the proposed activity can be adapted as an on-line task, based on the experience that we have gathered during the confinement period due to the COVID-19 pandemic. We introduce a number of tools, and we discuss their effectiveness and how they could be improved, based on the opinions given by the students themselves.

CCS CONCEPTS
• Applied computing → Collaborative learning; Distance learning; • Networks → Network performance modeling; Network simulations; Network performance analysis.

KEYWORDS
project based learning, network modeling, system-level simulation, on-line lecturing

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1 INTRODUCTION
Event-driven simulation is one of the most widespread tools in various engineering areas, to tackle the analysis of systems’ performance and behavior. In particular, its use within the networking realm is rather relevant, to tackle the analysis of networks, communication architectures, and protocols. The most typical use-case is exploiting tools (simulators) that are based on such technique, but in some cases, the users do not fully understand their operation insights, and they carry out a development on a higher level, by using the interfaces provided by such frameworks.

Although there exist various event-driven simulators, such as ns-3 1, OMNET++2, we argue that a more detailed knowledge of an event-driven engine, would actually ease students the use of more advanced and complete simulation frameworks. We also believe that the use of such broad tools to carry out the analysis of the systems that are considered in the proposed PBL would actually be a bit overkill. In fact, after completing this assignment, the students have another one, where they use ns-3 to analyze the behavior of transport protocols (TCP). Since they have built their own event-driven simulator, they are in a better position to exploit ns-3, despite its learning curve.

Hence, we describe in this paper a Project Based Learning (PBL) activity where the students, collaborative working in 3/4 people groups, are asked to develop a simple event-driven simulator from scratch. The use of PBL has been proven effective in many realms [7] and its usage in engineering has been assessed in the past. For instance the authors of [6] analyze the advisors’ and students’ perspective when carrying out a computer science PBL assignment, and they analyze its effectiveness. More concretely, the experience gathered over 5 years of PBL for object-oriented development is reported in [3]. Similarly, the authors in [5] discuss the goodness of PBL for discussing the development of distributed services.

In our case, students are asked to use such simulator to analyze the performance of various systems, which can be also analytically modeled (queuing theory, teletraffic), so they can actually assess the validity of the developed tool. In particular, we ask the students to develop the simulator in C, but this can be easily adapted to the syllabus of the corresponding degree.

The PBL activity also includes the writing of a report, where students need to describe their design and development. They also need to discuss the results that were obtained and how they yield the correctness of the development.

This activity is currently scheduled during the 1st year of a MSc program in Telecommunications Engineering (which combines courses from Electrical Engineering and Computer Science degrees). The course name is “Network design and operation”. Despite the complexity of the assignment, we will show that the students who

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1https://www.nsnam.org/
2https://omnetpp.org/
have taken such course in the latest years have a rather positive opinion about it.

On the other hand, the COVID-19 pandemic has had a tremendous impact on our teaching activities, which needed to be adapted to an on-line methodology. We also discuss herewith how the PBL activity could be adapted to consider such circumstance, based on the experience we have recently had during the confinement period in Spain.

The paper is structured as follows: Section 2 depicts the learning objectives of the PBL activity and Section 3 discusses how collaborative and on-line tools can be used to adapt the activity, so it does not require to be in-person. In this section we also show students’ feedback from another course where such on-line tools and methodologies were used during the confinement. Section 4 introduces the design of the whole assignment, discussing two particular examples that have been used during the last year. Section 5 presents the opinions from students that have undertaken the activity during the last two years. Finally, Section 6 concludes the paper, highlighting the most important takeaways, and introducing some ideas to further broaden the proposed activity.

2 PBL GOALS

As was previously introduced, the proposed PBL activity entails the development of an event-driven simulator, starting from scratch. Its correct operation is first assessed by using a classical queuing model, a $M/M/1$. The students are asked to consider different arrival and/or service rates, and to use the simulator to obtain the performance indicators of the system (transfer time, waiting time, occupancy, etc). Since all of them have worked with such model in previous BSc courses [1], they are asked to use the corresponding performance expressions to validate the development.

Afterwards, each group is assigned a different system, which could also be analytically modeled and analyzed. Based on previous experiences, an appropriate choice for that system would be exploiting the problem statements that were proposed in previous queuing theory courses [2], since students have the numerical solution, and they can thus check again the validity of the results yielded by the simulator.

In this section we discuss the PBL goals. Its design is rather broad, and it thus covers a wide range of aspects, which can be easily adapted to the particular syllabus. We first introduce the learning objectives, which are more related to the course and program where the activity is proposed (i.e. they could be adapted to other areas). Afterwards we identify the horizontal competencies that are covered by the proposed PBL.

2.1 Learning objectives

The proposed PBL has the following four learning goals:

- Programming skills.
- System modeling.
- System level simulation and performance analysis.
- Scientific report writing in English using \LaTeX.

The first aspect that is fostered in the activity is programming skills. As was mentioned earlier, we initially propose the use of the C programming language to develop the simulator. The reason for this choice is to give continuity to the programming language the students are more used to. In our case (University of Cantabria), there are various courses in the Telecommunication Engineering BSc and MSc programs that use C for the corresponding lab assignments. In any case, the use of another particular programming language does not have any impact on the PBL design. It goes without saying that programming expertise is of utter relevance for many engineering areas, in particular to the networking realm, and the successful completion of this activity would allow the students to strengthen such skills.

C has one distinctive feature, which can be seen both as an advantage and as a drawback. The core of the event-driven simulator boils down to a queue of structures that needs to be always sorted (according to the time the events are scheduled to occur). This is done by a single-linked list, using dynamic memory allocation and pointers. The students face some difficulties, since they might not be used to such low-level programming tasks. On the other hand, we argue that this actually helps to better understand the insights of how the even-driven core operates. In any case, if other programming languages are promoted, for instance C++ or Python, the assignment could be easily adapted to exploit some of the structures or container libraries they offer.

Modeling appears as one of the most relevant skills in engineering syllabus, in particular in computer networking. In order to make the proposed activity more attractive and interesting to the students, the particular systems that they are asked to evaluate by means of the event-driven simulator are problems that were proposed in previous queuing theory courses [2]. In this sense, students could assess whether the results obtained with the simulator are correct, and enrich the corresponding report with the discussion of the particular model. As was mentioned earlier, they start by considering the classical M/M/1 system, but they are afterwards asked to consider more specific and complex systems. The match between theoretical and simulator results also allows students to reinforce their modeling skills and the role of Markov chains.

Once the simulator is finalized, the students need to derive performance indicators to characterize the behavior of the corresponding system. This requires the capacity to understand the realization of independent experiments, the generation of random variables, the notion of seed, and how to carry out Monte-Carlo analysis. They also need to discuss the statistical tightness of the results.

First of all they would need to generate random variables. In most of the cases we will use Poisson processes and memoryless service times, so they would need to build exponential distributions, based on the inverse transform method, which uses a uniform random variable between 0 and 1. They also need to understand the need to change the corresponding seed to obtain different random sequences. Based on that, the are asked to perform various independent experiments and to study not only the average performance, but the corresponding variance too, by means of the confidence intervals. In this sense, the students are enlighten about Monte-Carlo analysis, and how simulators should be used when there exists some randomness (uncertainty) in the corresponding results.

In order to produce the corresponding performance figures, they need to create output files, appropriately parse them, and use an
additional application (for instance, \textit{gnuplot}\textsuperscript{3}, \textit{Matlab}\textsuperscript{4}, \textit{R}\textsuperscript{2}) to create the corresponding graphics.

As was mentioned before, the students need to write a scientific report to describe the design and implementation of the event-driven simulator, to depict the corresponding analytical system models, and to discuss the results. In order to broaden the scope of the PBL activity, and provided it has several advantages on terms of collaborative work, we decided to enforce the students to use \LaTeX{} to write such report. The use of on-line frameworks, such as \textit{Overleaf}\textsuperscript{6} strongly eases the collaboration between them in this particular task. Even if they are not used to this type of writing tool, providing them with a complete template is usually enough. The experience tells that, despite some initial difficulties, the students see the benefits of using \LaTeX{} to write the corresponding report.

### 2.2 Horizontal competencies

We have discussed the learning goals that the proposed assignment aims to fulfill. We discuss below the generic competences that are also needed to successfully face the PBL activity. These are skills that take an essential role in the training process of any engineering-related program and, in particular, in the networking realm.

First of all, since the assignment is proposed to be carried out by 3/4 students, it becomes very important they attitude towards collaborative work, which will surely be of utter relevance in their future professional career.

Even if the activity entails some seminars where the instructors would be able to provide support, answer questions, and discuss with the students, most of the proposed tasks entail individual or group work, where the students would need to be able to self-learn some of the required skills or concepts.

Engineers spend much time writing reports. This competence is not adequately covered in many traditional courses, where mostly exams are used to assess the skills and knowledge acquired by the student. Sometimes, they face their first report when preparing the BSc/MSc thesis. We understand that it is important to train this competence, and to introduce how to correctly structure a report, how to add bibliography, etc.

In programs where English is not the main language (as the one where this activity is proposed), it is also interesting to ask the students to write the corresponding report in English, to foster linguistic abilities, which will be also very relevant for the professional career for the graduates.

### 3 ON-LINE ADAPTATION

This PBL assignment was originally conceived as a regular in-person activity, with a number of seminars that were scheduled to help the students, especially during the initial phases. After the COVID-19 outbreak in Spain, the Government called an alarm-state, and people were confined. Teaching activities were required to continue on an on-line fashion. There is much uncertainty on how next years are going to be, until the health crisis ends. In this section we discuss how the proposed activity could be carried out on-line. For that, we will use the experience that we have acquired in other courses and similar activities, during this last term, and the lessons that were learned. In any case, the following proposals could be adapted to the particular circumstances, and the responsible instructors should be flexible enough to perform small adjustments if the conditions change, for instance, if a hybrid on-line/in-class approach is possible.

The first session that was scheduled consisted on a seminar to give students an outlook on how an event-driven simulator could be implemented using a single-linked list in C. This seminar should cover at least the following concepts: structure of an event, how to introduce events in the list, and how to appropriately handle them. This seminar can also be used to assign the corresponding systems to the different groups. If this cannot be done during a regular in-person lecture, there are three possible strategies that could be taken: (1) prepare a self-contained report about the topics that were covered during the seminar; (2) conduct the seminar using a conference tool, with some supporting material; (3) produce a video with detailed explanations. The three approaches could be together used and, in fact, this is recommended.

During the confinement we have adapted lab assignments of a BSc syllabus, by applying the aforementioned adaptations at some extent. First of all, we heavily extended the corresponding assignment text, including supporting material on the aspects the students were asked to develop. In previous years, the corresponding information was discussed in-class by the instructor. We also had on-line sessions, where the students could ask the instructor any question they had, and we finally provided some videos, with some additional explanations, which the students could check off-line whenever they wanted.

In order to gather information about the students’ perception, we asked them to complete a survey that was answered by 32 students (around half of the overall course students). First, Figure 1 shows the students’ opinion about the usefulness of including more information on the assignment text, with supporting material about the topics and concepts they were asked to work on. As can be seen, making the assignment text self-contained is positively received by most of the students, although some of them did not find it particularly helpful. Surprisingly, one student did not use it, which leads us to think that other people of the group did most of the assignment work.

We also saw that videos could be used to explain some particular details, problems, etc. The dynamics of the on-line lectures are rather different from traditional in-class sessions, especially if the number of students is large: it is difficult to establish an appropriate feedback between the instructor and students, there might be some

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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Opinion about the usefulness of adding supporting material in the assignment text, so that it becomes self-contained}
\end{figure}

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\footnotesize
\textsuperscript{3}http://www.gnuplot.info/
\textsuperscript{4}https://www.mathworks.com/products/matlab
\textsuperscript{5}https://www.r-project.org
\textsuperscript{6}https://www.overleaf.com
Finally, the use of the Learning Management System (LMS) would ease the process of PBL delivery and grading. Moodle\(^8\), Blackboard\(^9\) or any other choice (depending on the particular organization) could be used for this.

## 4 ASSIGNMENT DESIGN AND EXAMPLES

Once we have detailed the learning objectives of the proposed PBL activity, as well as how it could be adapted to an on-line methodology, we provide herewith the design of the assignment, and a couple of the systems whose performance the students were asked to analyze by means of the developed simulator.

### 4.1 Initial validation: M/M/1

The M/M/1 system is one of the most well-known queuing models [4]. As such, it serves as a useful means to assess the validity of the event-driven simulator. An M/M/1 consists on a single resource system, with an infinite buffer, where clients wait until the resource can process them. It considers that clients arrive according to a Poisson process of rate \( \lambda \) s\(^{-1}\) (i.e. the time between consecutive arrivals corresponds to an exponential random variable with mean \( \frac{1}{\lambda} \) s), and that the service time can be modeled with an exponential random variable, with mean \( \frac{1}{\mu} \) s. Provided the system works under stability condition, i.e. \( \lambda < \mu \), we can establish its occupancy, as \( \rho = \frac{\lambda}{\mu} \), which matches the percentage of time the resource is busy.

Based on the aforementioned parameters, the behavior of the system can be fully characterized: probability of having \( i \) clients in the system, average time in the system, average waiting time, etc.

The students are asked to use the event-driven simulator to mimic the behavior of the M/M/1 system. Two different events are considered: arrival and departure. When an arrival event is handled, the next arrival event is scheduled, using a realization of an exponential random variable. In addition, the simulator would need to check whether the resource is busy or not. When it is idle, the client can start its processing, so a new event, corresponding to the departure of such client, is scheduled. On the other hand, if the resource is busy, the packet needs to be added to the buffer.

When handling a departure event, the simulator needs to check whether there is any packet waiting to be processed at the buffer. If this is the case, a packet is dequeued and a new departure event is scheduled, using a realization of an exponential random variable.

The students need to establish how to log information during each experiment, which would afterwards allow assessing the correctness of the simulator. They could later modify the value of the arrival or service rates, and study the system performance evolution with them, comparing the results with the analytical ones.

All students have some basic knowledge on queuing theory, since they took a 2nd year BSc course covering those topics, and the M/M/1 system was fully addressed therein [1].

### 4.2 Complex system

Once the validation with the M/M/1 is finished, the students are asked to exploit the event-driven simulator engine to analyze the performance of another system, which is different for each group. As

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\(^{7}\)For instance, github, https://github.com

\(^{8}\)https://www.moodle.org

\(^{9}\)https://www.blackboard.com/
As this example was proposed as a problem in the aforementioned 2nd year BSc course that was mentioned earlier (Problems 20 and 25 from [2], respectively).

In the first example, we consider a computing system, with two processors and without any buffer, so applications cannot wait when there are not enough resources to be processed. There are two types of requests: (a), (b), which are equally probable. The overall arrival rate (Poisson process) is \( \lambda \) s\(^{-1}\). Applications of type (a) require one single processor to be served, while the two processors are required for type (b) requests. The processing time for the first group of applications is \( \mu^{-1} \) s, while applications (b) need twice that time (\( 2\mu^{-1} \) s). Since the system does not have any buffer, any application arriving at the system that cannot be processed is lost.

Figure 3 shows the Markov chain for this system. In addition, the students might check the Youtube video\(^\text{10}\) for a detailed discussion on how the corresponding model is built.

![Markov chain for example (1)](image1)

Figure 3: Markov chain for example (1)

The students could analyze the time spent in the system for the two types of applications, as well as their corresponding loss probability. As this example was proposed as a problem in the aforementioned 2nd year BSc course, the students could easily assess the validity of the simulator operation (Problem 20 from [2]). Then, they could modify some of the input parameters, for instance arrival rate or processing times, and study how the performance varies. They could also change the corresponding distributions (for instance, using constant processing times), to see how this affects the performance that was analytically obtained.

The second example considers a computing system with one processor, and a waiting buffer with capacity to keep just one application. Furthermore, it enforces an energy-aware operation. In this sense, to minimize the number of on/off transitions, the operation of the system establishes that when an application is received and the processor is idle, it is not immediately started, and the request is kept at the buffer. When the next request arrives, the processor is started, and it is not powered down again until the system gets empty. If a request arrives when there are two applications in the system (one in the processor and one in the buffer, waiting), it is lost. We consider an arrival rate of \( \lambda \) s\(^{-1}\), and a processing time of \( \mu^{-1} \) s. The corresponding Markov chain is shown in Figure 4, and the students could also check a video with the corresponding explanation in Youtube\(^\text{11}\).

![Markov chain for example (2)](image2)

Figure 4: Markov chain for example (2)

The students, besides having access to the video with the corresponding model, could also check the correctness of the simulator behavior by means of the numerical results they have in the corresponding problem from the 2nd year BSc course on teletraffic fundamentals (Problem 25 from [2]). They could obtain the loss probability, the waiting time, the time the processor is active, etc, and how these parameters vary with the system load (i.e. increasing the arrival rate). They could also modify the energy-aware operation, and discuss the impact of such performance indicators.

5 PREVIOUS EXPERIENCES

The proposed PBL activity has been already carried out in previous years, using a traditional in-class methodology. Although the students state that it is a rather time-consuming and complex project, they reckon it is quite interesting and in general they are overall quite satisfied with it.

We gathered the opinion of around 40 students from the last two years, and we asked them about some particular aspects of this assignment. Below, we report the most interesting outcomes of such survey, which could help us to fine tune the formulation of the assignment. First of all, we wanted to assess the students’ overall satisfaction with the PBL activity, as well as whether they believe that the learning goals had been appropriately covered.

In order to contextualize their opinions, it is also worth depicting how the assignment was graded. First, the students were asked to

\(^{10}\)Available in Spanish in https://youtu.be/Nav-S4HyzMU, at time 0:11

\(^{11}\)Available in Spanish in https://youtu.be/Nav-S4HyzMU, at time 3:54
present to their instructor, on a dedicated session, the correct behavior of their simulator. Then, they needed to write a report, discussing the obtained results and comparing them with the analytical performance of the corresponding models. The course instructors used such reports to establish the grade for the assignment.

Figure 5 shows how the students answered to the following two questions, ranging from 1 (very little) to 5 (very much).

Q1. Did you overall like the PBL activity?
Q2. How do you think the learning goals were fulfilled?

As can be seen, most of the students were quite satisfied with the activity, having an average value of 3.95 for the answers to Q1, despite its complexity. On the other hand, the average result for Q2 was even higher (4.33), and there was not any student stating that the learning goals were not fulfilled (there was not anyone giving a mark of 1 or 2 to Q2).

We also wanted to assess whether the students were happy with some of the horizontal competencies that were covered in the proposed assignment. In particular, we wanted to understand whether the collaborative work was well received by the students, and whether they understood the need to write the scientific report who was required as the last task of the PBL activity. For that we asked the following two questions, also using the same answer ranks as before:

Q3. Do you agree that the writing of the report was relevant within the scope of the activity?
Q4. How do you reckon the effort was fairly distributed among the group members?

Figure 6 shows how the answers of the students to such questions were distributed. Although they were able to build their groups as they wanted, the results yield that there existed a non-negligible number of students who were not completely happy about how the workload was distributed among the group members. There is one person who had the most negative opinion and 9 of them stating that they were not satisfied with the workload sharing, reaching a mean value of 3.7. On the other hand, even if it was a time-consuming task, the students showed a good perception about the writing of the scientific report. Only one person had a negative opinion (mark 1 or 2) and another one did not answer this question, yielding an average value of 4.13.

We also wanted to assess the perceived effort of the students to finalize the assignment, and we wanted to correlate it with the expertise that was required in two particular aspects: modeling and programming skills. In particular, we asked the students whether they believe that their previous knowledge on these particular topics was enough to appropriately tackle the task, from 1 (not at all) to 5 (they were enough).

Figure 7 shows the distribution of answers when correlating the effort with the previous modeling skills knowledge. In each square we represent in a varying sized circle the times that the corresponding marks were given to each aspect. As can be observed, most students found that the assignment required quite a great effort, having the bigger circles at the lower rows, the average value was 3.8 for this particular question. On the other hand, the students think that their previous knowledge on system modeling was enough to face the PBL activity, but without a clear correlation with the perceived effort. In any case, 20% of the students mentioned that they were enough, having an average value for this question of 3.5. In this sense, we need to take into account that in the third year of the BSc program, the students select an itinerary. Approximately 40% of them decided to take computer networks intensification, where they took a more
We have presented a PBL activity that we have been using in a 1st year MSc course in Telecommunications Engineering (Computer Science/Electrical Engineering). It first entails the design and implementation of a proprietary event-driven system-level simulator in C programming language. Then, the students (in groups of 3/4 people) exploit such framework to analyze the performance of a system that can be also theoretically analyzed. The task also requires writing a scientific report. We have discussed the learning goals and competencies that this assignment addresses, and we have presented a couple of examples of the systems that were included in the PBL activity.

Based on the surveys that were conducted during the last two years, we have seen that the proposed activity, despite being perceived as a rather complex and time-consuming assignment, received positive opinions from the students, who highlighted the fact that the learning objectives were fulfilled.

On the other hand, based on the experience we gathered during the confinement period that was called by the Spanish Government due to the COVID-19 situation, we have also discussed how the proposed PBL activity could be carried out on an on-line fashion. We have mentioned the strategies that were used (also in lab assignments) during such period, and how they were perceived by the students. The takeaway message is that the students reckon the usefulness of the videos as a means to present the corresponding system models, as well as having self-contained assignments, with appendices to cover the required theoretical concepts. Their opinion about on-line lab sessions, albeit being positive, was not as good, and we should thus find strategies to make them more attractive.

Hence, the key fundamental lessons that we learned from the proposed PBL activity and its evolution towards on-line methodology are:

- The effort required to complete the assignment is well received by the students, provided they found it interesting and it is well rewarded (in terms of qualification).
- It is important to use models that they have studied in previous courses, or they can understand, to assess the validity of their simulator.
- The students reckon the interest in exploiting a wide range of aspects, from different courses: statistics, programming, modeling, etc. Hence, the activity should be planned on a MSc course (or last BSc course).
- The availability of the instructors for small Q&A sessions, workshops, or just replying emails is also rather relevant.
- Providing the students with material they can check off-line, for instance videos to discuss the models they would need to analyze, was very well received.

Considering such on-line experience, and the previous opinions on the proposed PBL activity, we can identify some aspects that will be addressed in future course editions:

- To improve the students’ perception about the on-line lab sessions. One possible strategy (depending on the tool possibilities) would be having smaller-conferences (matching the corresponding groups), and the instructor shifting between them.
- To clarify what is expected from the scientific report. Not only by depicting the required elements of information, but also establishing a rubric, which could guide the students to produce more professional reports.
- To engage off-line participation from the students. One strategy would be having forums in the corresponding LMS, where students would ask questions, and not only the instructors, but also other students could give answers to them. We could even envisage some sort of gaming, given some additional points to participatory students.

![Figure 8: Correlation of previous programming skill expertise and the required effort to complete the PBL activity](image-url)
• To improve the collaborative work, by asking the students to report their participation within the group, and/or to carry out self assessments in that particular aspect.
• Another aspect that would be worth considering is promoting poster or elevator pitch sessions, where the different projects would be introduced to all students.

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