ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022
Paper ID #37625

Work-in-Progress: Developing an IoT-based Engaged Student Learning Environment and Tools for Engineering and Computer Science Programs

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Abstract

The COVID-19 pandemic forced education institutions everywhere to rapidly pivot to an online format in which students must often work remotely. The rapid transition has been especially challenging for STEM related courses in which students require access to physical devices to complete their work. We describe the initial steps of an NSF funded project focused on creating learning environments and materials designed to support engaged remote student learning. The approach utilizes IoT learning kits that are lent to students to provide hands-on learning experiences and promote remote engaged learning at students' own chosen environment.

The IoT involves infrastructure in which a wide variety of physical devices interact with one another and share information. When designing, working with or combining these devices, engineering students must consider, among other things, sensors and signals, sensor and system integration, input and output interfaces, system functions, control, network management, system architecture and storage, power consumption and management issues, as well as testing and measurement for validation of proper functionality. Computer science students, on the other hand focus more on cloud infrastructure services for the support and management of IoT devices as well as the security and communications aspects of these systems; computer science students are also involved in, among other things, system architecture and storage, device control, real-time operation, system integration, user interface, and app development to facilitate the proper use of the IoT devices.

This paper describes the initial efforts underway at two Hispanic Serving Institutions in South Texas to develop IoT-based hands-on engaged student learning environments and tools targeting students studying remotely in computer science, electrical engineering and mechanical engineering programs. Three aspects of remote learning are being investigated: 1) Hands-on active problem- and project-based learning (PBL) through the use of IoT kits, 2) Off-campus engaged student learning through hands-on projects using IoT kits, and 3) Scaffolding and Transfer Learning from mathematical concepts to explain the underlying physics theory of the sensors.

Keywords: Internet of Things (IoT), Problem-based-learning, Project-based-learning, PBL, Hands-on learning, engaged student learning, transfer learning

Introduction

Internet of things (IoT) can be described as a network of devices, software, sensors, actuators and connectivity that allows all these things to interact and exchange data. International Telecommunications Union (ITU) defines IoT as "A global infrastructure … enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [1]. Similarly, "through the exploitation of identification, data capture, processing and communication capabilities, the IoT makes full use of things to offer services to all kinds of applications" [1]. In IoT, a "thing" is defined as "an object of the physical world (physical things) or the information world (virtual things), which is capable of being identified and integrated into communication networks" [1]. IoT has shown significant proliferation in industry and our daily lives. As such IoT presents itself as new technology and tools, offering teaching and learning environments for engineering and computer science students with hands-on engaged learning. The multidisciplinary nature of IoT systems also lends itself to remote learning where students, individually or in teams, may focus on different aspects of engineering and computer science concepts, such as sensors, actuators, microcontrollers, embedded systems, wired and wireless communication, visualization, and interfacing, to name a few.

Remote learning became significantly more important during the COVID-19 pandemic forcing institutions of higher education to conduct teaching and learning via online media. Gayle and Mangra describe the necessity for reliable Internet, hardware and software that enable online teaching and learning including a reliable computer and simulation software, such as PSpice for circuit analysis [2]. The authors also recognize the significance of cloud-based models and services for remote simulation-based experimentation. The challenge, of course, is conducting remote experiments beyond software simulations that require physical hardware and related devices to complete. Hsieh worked on lab materials that incorporate a remotely-accessible 3D printer to conduct remote labs related to additive manufacturing [3]. The students were able to model and view their design remotely through a software interface with their computing device. Han *et al.* share their experiences in transitioning to fully online teaching in integrated design, circuits and instrumentation, and capstone design courses [4]. The authors moved toward simulations and software design solutions for the design courses, while combining simulation software, and required limited electronic devices and parts to be purchase by students for the circuits and instrumentation courses. These examples rely heavily on software-based solutions, and with some exceptions as explained above, offer limited hands-on experiences with physical devices and instruments.

IoT based learning has been previously described by Agrawal *et al.* who developed an IoT laboratory for a future course before the COVID-19 pandemic [5]. This work represents learning tools for IoT concepts that were intended for a traditional (non-remote) course. Although at the time of its publication the laboratory was not yet implemented, its content shows hands-on exercises for the laboratory. Jones describes the design of a hardware kit and laboratory exercises to offer students hands-on experiences with embedded systems as well as IoT [6]. Remote learning was not targeted in this application. In their 2021 survey paper on IoT in education, Ronoh *et al.* recommend that IoT courses should have practical skills as one of the learning outcomes, which can be successfully achieved via problem-based learning (PBL) [7].

The authors' findings support that IoT is conducive to cooperative learning, and can be incorporated in flipped classrooms and labs. There were not many examples of IoT in remote learning environments in the paper. Ramya *et al.* describe an IoT platform-based remote laboratory for teaching sensors and its applications. Using embedded systems, the team's goal was to allow students to monitor sensor data through a remote mobile application [8]. The authors describe two experimental stations to which the students had access. These examples allow students to monitor remote measurements in pre-determined and set-up experiments.

In the work presented here, we focus on three types of courses that allow students to work individually or in teams but independently through IoT kits. With the challenges of remote learning in project-based learning, IoT became a natural choice to tackle hands-on learning needs of students in remote learning environments. In this project IoT was targeted as a remote learning technology and tool that allows hands-on engaged student experiences with physical devices such as IoT kits and sensors, software modeling and simulation capabilities, and communication through the cloud to achieve individualized or team-based PBL remotely. With this in mind, through an NSF grant (see Acknowledgment), the project team secured funds to purchase IoT kits that are lent to the students for the duration of their course or project. This IoT-based project not only enables remote engaged student learning in times affected by the COVID-19 pandemic, but also allows distributed learning [9]. With IoT-based projects, the dependence on physical laboratories is significantly reduced, though not necessarily entirely eliminated, adding flexibility to students' learning environments.

The goal of this project is to enable 1) Hands-on active problem- and project-based learning through the use of IoT kits, 2) Off-campus engaged student learning through hands-on projects using IoT kits, and 3) Scaffolding and Transfer Learning from mathematical concepts to explain the underlying physics theory of the sensors. This paper summarizes the initial efforts for student recruitment, student projects for PBL, and course material development for IoT and transfer learning.

Developing the IoT-based Engaged Student Learning Environment and Tools

Figure 1 summarizes the process for developing IoT-based engaged student learning environments for the targeted STEM programs.

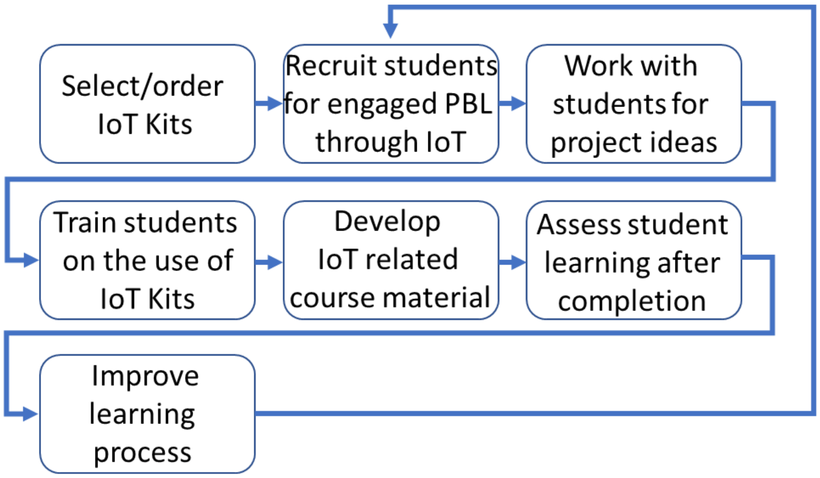

Figure 1. Representation of process for developing IoT-based engaged student learning environment and tools

This iterative process starts with the selection and ordering of the IoT kits for enabling remote and engaged student learning through hands-on experiences for engineering and computer science students at two Hispanic-Serving Institutions (HSIs). In project-based courses, the project team works with individuals and teams of students to identify an IoT-based project area that would accomplish the pedagogical objectives while being of interest to students. The students are then trained on the use of IoT kits. The instructors work on developing IoT related course material appropriate for the targeted courses to assist students with the IoT concepts, devices, applications and implementation. Finally, student learning is assessed through surveys and student performance. Student learning is improved from lessons learned by fine tuning the process as well as teaching material, delivery, and other methods based on feedback and other objective methods.

Student Recruitment

Three categories of courses are targeted for remote engaged student learning through IoT at the two HSIs. The first category of courses includes senior capstone design project courses, which are a sequence of two courses which incorporate PBL in collaborative team projects in the two institutions independently. The second category of courses involve Directed Independent Study courses, or their equivalent at different institutions, which entail a study contract between a professor and a student with predetermined course learning outcomes that are equivalent in rigor to an engineering or computer science course, depending on the student's major. These courses are typically used by students to substitute for a technical course such as an elective. These courses can be conducted through problem- or project-based learning pedagogies, or other methods. The third category of courses includes courses such as Sensors and Systems that targets electrical and mechanical engineering students and serves as a technical elective at Texas A&M University-Corpus Christi (TAMUCC), and Embedded Mechatronic Systems aimed at electrical engineering, mechanical engineering and computer science students at Texas A&M University-Kingsville (TAMUK).

IoT Kits

The IoT kits targeted in this project were purchased from Keysight Technologies (model U3813A) with built-in sensors, BeagleBone device, XBee Zigbee kit, connecting cables and other peripherals that are all expandable as needed [10]. On board sensors include analog and digital sensors such as temperature, pressure, current and IMU sensors. Additional sensors can be acquired and used in the IoT system. The IoT kits are available to students in the above-mentioned courses to be taken to their private spaces to work in their own time and location through a borrowing contract. Additional funds are also made available to students who are pursuing specific projects that require unique sensors, measuring devices and other electronic supplies to augment the kits.

Hands-on Active Problem- and Project-based Learning through the Use of IoT Kits

Targeted students in this project include underrepresented students in STEM who are taking one of the courses offered by the project team who are engineering and computer science faculty at the two HSIs. Students are recruited from the three categories of courses described previously. With the exception of Sensors and Systems course at TAMUCC, which has not yet been delivered since the inception of the project, all students involved in the IoT projects (seniors in capstone design projects or their equivalent; juniors/seniors in directed independent study courses or their equivalent, at the two HSIs) are engaged in hands-on problem- and project-based learning that enables location-independent engaged student learning.

So far two senior capstone project teams have adopted IoT-based projects at the HSI, TAMUCC. These teams are interdisciplinary, and are composed of electrical engineering, mechanical engineering and mechanical engineering technology students. Similarly, two interdisciplinary teams have taken on senior design projects, with one team composed of in electrical engineering, computer science, mechanical engineering students, and the other team composed of electrical engineering students at the HSI, TAMUK. Over 50% of the students at both institutions are among historically underserved student populations [11], [12].

The following summarizes the four senior capstone design projects, and their IoT-related deliverables.

Project 1 (Texas A&M University-Corpus Christi, Department of Engineering):
IoT-based Sensing and Vibration Delivery through a Knee Sleeve.
This project team is comprised of six multidisciplinary (three electrical engineering, two mechanical engineering, one mechanical engineering technology) students. The project deliverables include a sensor-fitted knee sleeve that captures signals from muscles and delivers therapeutic vibrations through a motor as an actuator at appropriate vibration frequency. The device must be connected through an IoT interface for sensor signal monitoring and processing. The output to the motor must be determined through sensor fusion that is displayed real time that will select the optimal frequency for the motor for appropriate level of vibrations. Figure 2 shows the team's conceptualization of the project that involves IoT.

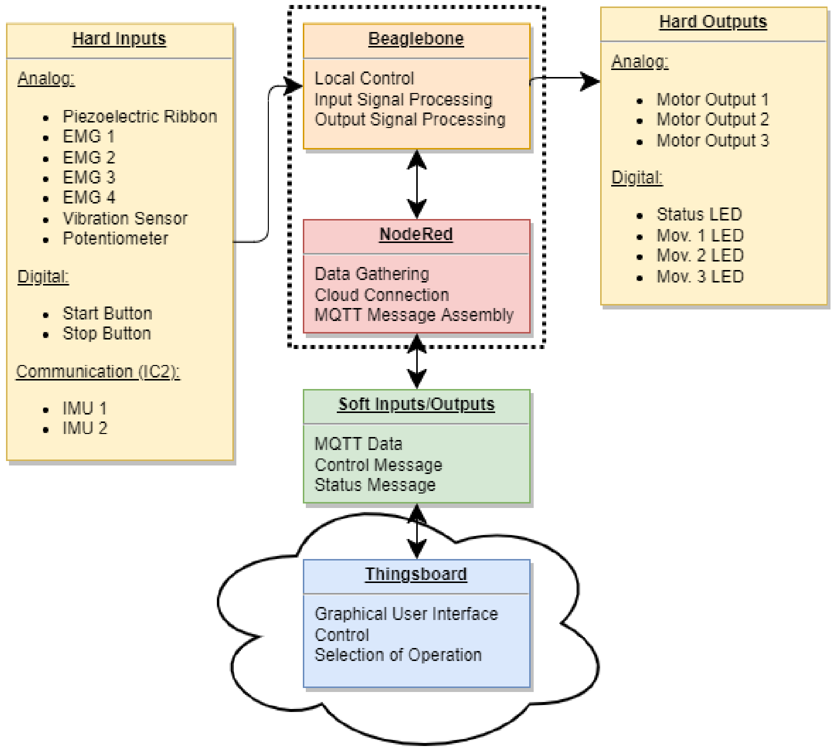

Figure 2. Representation of IoT interfaces in Project 2 (courtesy of Aaron Mooney) [13]

Project 2 (Texas A&M University-Corpus Christi, Department of Engineering):
Autonomous Debris Detection and Removal Aquatic Robot, Phase II (ADDRAR II).
This project has six multidisciplinary (two electrical engineering, four mechanical engineering) student members. The project deliverables include an aquatic robot capable of collecting debris in the water, and returning it to home position. The final prototype must involve a vision-based solution for detection of floating debris on the surface of the water. IoT must be used for real-time visualization of sensor data and storage in the cloud for future data analysis.

Project 3 (Texas A&M University-Kingsville, Department of Electrical Engineering and Computer Science):
Smart Irrigation System.
This project is led by three electrical engineering senior students. Their goal is to poll various sensors and log into a Website to store sensor data to assist the farmer in determining irrigation needs.

Project 4 (Texas A&M University-Kingsville, Department of Electrical Engineering and Computer Science:
Machine Learning Robotic Arm.
This interdisciplinary project team is comprised of nine students, two studying computer science, two studying electrical engineering, and five studying mechanical engineering. The project focuses on the design and development of a manufacturing arm with machine learning capabilities. IoT technologies are being investigated as a mechanism to enable the storage of

data captured by sensors in the cloud to support the continuous improvement in the ability to recognize colors and shapes.

In the second category courses, at TAMUCC, one student is engaged in a Directed Independent Study course titled IoT: Devices and Communication. The general student learning outcomes of this course include exploring IoT concepts, technologies, devices, communication protocols, cybersecurity; implementation of IoT data flow through selected communication protocol and data access across platforms and devices; developing an IoT solution using the IoT kit, and finally deploying the IoT solution and performing data analytics.

At TAMUK, in Embedded Mechatronics Systems course, which is one of the third category of courses, the course professor introduced concepts on applications of IoT, investigating cybersecurity issues with the IoT systems, and how security issues would impact some of the design. Students were challenged to determine if they needed to implement their own firewall, other security measures, such as biometrics, or voice control over the Internet, to allow system security. Students were asked to consider whether they need to put in physical system constraints such as automatic shutdown, if hacked.

In the Embedded Mechatronics Systems course, PBL was implemented by assigning a high-level system design for an end-of-course IoT-based project. For each student's chosen IoT-based embedded system for the project, each student was tasked with developing a block diagram for the main functions/subsystems with input and outputs; system constraints; the control and/or processing concept and strategy for the system; the embedded system IoT-based project's control, processing or system objectives; and any system associated cybersecurity concerns. The student deliverables for this project include a report and presentation summarizing this information.

Scaffolding and Transfer Learning from Mathematical Concepts to Explain the Underlying Physics Theory of Sensors

According to Perkins [14], "Transfer of learning occurs when learning in one context or with one set of materials impacts on performance in another context or with other related materials". This applies to the use of mathematics skills in engineering classes, and the lack of this transfer, or students not seeing the connections between their mathematics courses and engineering concepts, has proven to be a barrier to some students. The disconnect between math and engineering concepts has also been observed through some of the data used for ABET reporting. Hwang and Ham [15], as well as Meirinka *et al.* [16] find that in many instances there are limited interactions between mathematics and engineering departments, and these limited communal activities can hinder students' achievement. Students' self-efficacy in mathematics has a strong relationship with students' mathematics achievement, and teacher interaction results in students' higher academic achievement [17].

These three concepts prompted the inclusion of a mathematician in the project. The goal is to increase students' self-efficacy in mathematics and the transfer of learning from math to engineering. This goal will be achieved by including short mathematics pre-assignments with the Sensors and Systems class, taught by an engineering faculty, that tie the mathematics utilized in this engineering course to the content the students learned in their mathematics classes. Sensors and Systems comprise the third targeted and stand-alone course category. Often students do not see the relevance of the abstract math content to the hands-on work in labs. Engineering textbooks try to minimize this gap by giving the required formulas into which the appropriate numbers have to be plugged in, sometimes with no further or insufficient discussion of the context. Collaboration between the mathematics and engineering faculty have been under way [18], and are expected to build connections for students and help math instructors redesign the presentation of calculus concepts for engineering students with an eye on later applications.

The key idea is to frame the assignments in a positive way consistent with the idea of helping self-efficacy instead of putting a barrier in front of each lab. In the Sensors and Systems course, the math is related to the behavior and operation of sensors which are part of IoT systems as one of the "things" that make up Internet of Things. In addition, sensor calibration for IoT and other applications require appropriate math. To make learning exercises and tools available for remote learning, we plan to use the free online platform www.webwork.maa.org through the Mathematical Association of America.

The assignments will be designed by the mathematician. A first step was for the mathematician to read the course textbook [19] and sort out which formulas lend themselves to transfer assignments.

In the second chapter of the Sensors and Systems course textbook [19], the transfer function for a sensor is discussed. This function is learned from ground truth data that are then fitted with a function. Fitting measurements $(x_1, y_1), \dots (x_n, y_n)$ with a linear function $y = mx + b$ amounts to solving the overdetermined system shown below

$$\begin{bmatrix} 1 & x_1 \\ \vdots & \vdots \\ 1 & x_n \end{bmatrix} \begin{bmatrix} b \\ m \end{bmatrix} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix},$$

which can be written in matrix notation as $\boldsymbol{Av} = \boldsymbol{y}$. The vector $\boldsymbol{v}$, where $\boldsymbol{v} = [b, m]$, that minimizes $||\boldsymbol{Av} - \boldsymbol{y}||^2$, satisfies the normal equations $\boldsymbol{A}^T\boldsymbol{Av} = \boldsymbol{A}^T\boldsymbol{y}$. This concept is covered in the Linear Algebra mathematics course, but often quickly forgotten. The generalization of using Vandermonde matrices for fitting polynomials and a discussion of their condition number is well suited in this case to enable transfer learning. In addition, it is possible to tie these concepts to fitting with Legendre polynomials, which is discussed in the Numerical Mathematics class. It should be noted that the textbook has an appendix A that derives the formulas for linear and quadratic fits as minimization problems to be solved with calculus methods, instead of explaining them in terms of projections, but the notation used, though common in engineering, is quite different from what students had seen in Linear Algebra further limiting intuitive transfer learning.

In the Sensors and Systems course, "linearized" transfer functions are covered; it would be helpful to have an assignment that clarifies the difference between the linearization of a function by a tangent line approximation encountered in calculus 1 and a least squares "linearization".

This is a good opportunity to reinforce a central concept from calculus 1 while contrasting it with least squares fits.

The concept of the (double) integral as a limit of Riemann sums change shows up for example in one of the textbook problems which asks the student to "show that the unit of inductance, the henry (H), which is the ratio of magnetic flux and current, in base SI units is $kg \cdot m^2/A^2 s^2$." It is recognized that the students may find it challenging to relate this question to what they have learned before – transfer learning has not occurred or occurred at a less than desirable level. Therefore, a hint is provided "Magnetic flux is the integral of magnetic flux density over area and the magnetic flux density ($kg/A \cdot s^2$) [which] was defined in [previous problem]".

In the Sensors and Systems course, the topics on electric and magnetic sensors and actuators, have plenty of vector calculus content. For example, in the discussion of the Hall effect, it is mentioned that the potential difference is the integral of the electric field intensity, E, along the path of length, L. Even if E is assumed to be constant to simplify the discussion, this is a good reminder for students of concept of line integrals covered in Calculus 3. The same topics also lend themselves well to a refresher of vector fields, surface integrals and cross products. For example, the flux of a magnetic field is obtained as the integral of the flux density over a surface. An example of a cross product would be the Lorentz force. It is the combination of electric and magnetic force on a point charge due to electromagnetic fields. A particle of charge, q, moving with a velocity, $\boldsymbol{v}$, in an electric field, $\boldsymbol{E}$, and a magnetic field, $\boldsymbol{B}$, experiences a force of $\boldsymbol{F} = q\,\boldsymbol{E} + q\,\boldsymbol{v} \times \boldsymbol{B}$. Some exercises on Green's Theorem in its curl or divergence forms might be able to help student learning at this point, and are planned implementations in the next delivery of the Sensors and Systems course.

The above-mentioned scaffolding and transfer learning efforts will ensure the engineering students can connect the math that they have learned to sensors, and, in-turn, IoT applications, by helping them better understand the mathematical background in the behavior and operation of sensors as "things". It is expected that pre- and post-surveys will reveal students' improved understanding of targeted math concepts. In addition, data collected for ABET reporting will be analyzed to observe outcomes of math transfer learning.

Challenges and Lessons Learned

Due to manufacturing and supply chain issues onset by the COVID-19 pandemic, the delivery of the IoT kits were delayed. The project team diverted to other accessible devices to introduce the students to IoT, including Arduino and Raspberry Pi interfaces. Upon receiving the advanced IoT kits, anecdotal evidence from students have revealed the steep learning curve for these IoT kits, based on the detailed instructions and the strict protocols that must be followed for the safety, functionality, as well as connectivity of the devices. The project team is currently working on additional learning material to alleviate the challenges associated with familiarization and proper use of the IoT kits. In Sensors and Systems course, the students will be guided to engage in hands-on IoT based engaged learning through laboratories that are similar to those described in [20] and developed by the manufacturer of the IoT kits as a starting point.

Even though this project came about due to the hands-on engaged student learning needs during the COVID-19 pandemic, some changes in student attitudes have been observed even after face-to-face learning has resumed; more students than before prefer to have the option to work from home and do labs and projects remotely. Some of the students' off-campus commitments have not fully been removed as parents (single or otherwise), employees (part- or full-time), or care takers (of the elderly, sick, or children). IoT-based learning provides a scalable and distributed learning opportunity to meet the learning outcomes of the engineering and computer science disciplines.

Summary and Conclusion

This paper discusses the work in progress towards the development of IoT-based engaged student learning environments and tools for engineering and computer science programs. The initial work involved the purchase of IoT kits and recruiting students for projects that will allow PBL through remote and engaged student learning using IoT kits. The students can borrow the IoT kits for the duration of their project. Four senior capstone design teams across the two HSIs have taken on IoT-based projects. One student is being supported as a directed independent study student where materials are developed to meet the student learning outcomes of the course that entail learning IoT concepts and implementing an IoT solution using the IoT kit. Finally, transfer learning topics have been identified for Sensors and Systems course to enable students to connect and build on, as scaffolds, various math concepts they learned in their various mathematics courses. Continued work involves implementation of the transfer learning topics in Sensors and Systems, and assessment of IoT-based engaged student learning.

For educators interested in adopting IoT-based remote learning, it is recommended that a scalable seed project, as a scaffold, that could later be developed into a full-scale project is considered. Such a project would be useful in bringing students up to speed with the particular hardware and software tools to achieve the targeted student learning outcomes.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. 2044255. This project was determined to be exempt from IRB review by Texas A&M University-Corpus Christi Institutional Review Board (IRB Number: TAMU-CC-IRB-2021-0227).

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