

# Active learning in control education: a pocket-size PI(D) setup

Jasper Juchem\* Amelie Chevalier\* Kevin Dekemele\*  
Mia Loccufier\*

\* Ghent University, Department of Electrical Engineering, Metals,  
Mechanical construction and Systems, Technologiepark 125, B-9052,  
Ghent, Belgium (e-mail: jasper.juchem@ugent.be)

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**Abstract:** Active learning techniques have the possibility to enhance student performance. In control engineering these techniques unravel concepts such as feedback control, proportional-integral-derivative control, system dynamics, etc. This paper presents the development of pocket-size PID setups and how they are implemented in an undergraduate course of control engineering. The setup makes use of an electrical circuit which has the capability of mimicking a wide range of processes, thus appealing to the multidisciplinary character of the student group. Custom-made analog PID printed circuit boards are developed, making each part of the controller transparent. Open-source software is used to build a graphical user interface to communicate with data-acquisition cards used in industry. It is shown in this paper that investing in mobile setups which are numerous, allows for active learning in control education. This leads to better understanding of abstract concepts and increased student performance.

*Keywords:* Active learning, Lab setups, Mass-producible, Analog PID

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## 1. INTRODUCTION

Nowadays, control is ubiquitous in a technological society. Examples can be found in chemical engineering (Escobar and Trierweiler (2013); Chen et al. (2012)), in electrical engineering (Ren et al. (2016); Dounis et al. (2013)), in electronics (Ferreira et al. (2003)), in applied physics (Khutoryan et al. (2014)), and in computer science engineering (Meng et al. (2016)). Hence, there is a need for a basic course on control education which addresses a broad range of engineering students. Literature works on control education often provide multidisciplinary examples to relate to a large variety in backgrounds (Åström and Hägglund (1995); Åström and Murray (2009)). At Ghent University, the basic control course is taught to bachelor-level students of electrical, electromechanical, biomedical, chemical and physics engineering. This combination of different backgrounds of the students presents an interesting environment to develop multidisciplinary classes which appeal to all students.

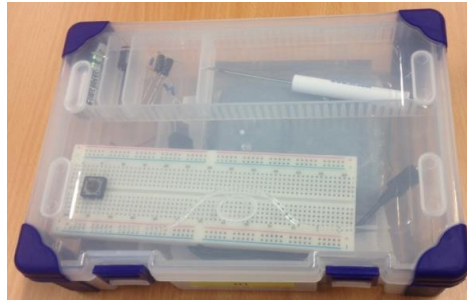
Theoretical concepts such as feedback control and PID controllers are introduced in this course. ‘Hot topic’ techniques such as active learning, have shown an increase in student performance and understanding of abstract theoretical concepts (Freeman et al. (2014)). However, due to increasing class sizes (U.S. Department of Education (2018)), applying active learning techniques is not obvious.

Nowadays, the most common techniques for practical sessions are remote labs, virtual labs, group work, individual practical sessions and demonstrator sessions. Virtual laboratories have the advantage that no real setup is required (Balamuralithara and Woods (2019); Guerrero-Mosquera et al. (2018)). A simulator allows students to

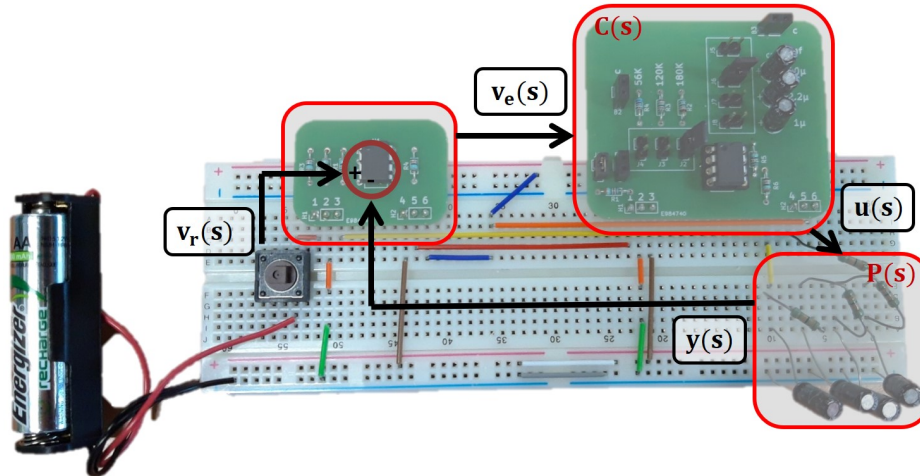
perform measurements on simulated systems. A common practice for virtual laboratories discussed in literature is the use of internet to distribute the simulator software among the students. Remote labs also use the Internet to provide practical lab sessions to large number of students (Chevalier et al. (2017)). With remote labs, only one setup is needed and students log on remotely. The downside of both virtual and remote labs is that they are highly dependent on the quality of the Internet connection. Literature also presents the benefit of hands-on experience when the students perform individual measurements on a real setup (Balamuralithara and Woods (2013); Judge (2017)). The main downside is the large number of setups needed to provide this learning experience. This is associated with a high cost Judge (2017). Therefore, the conclusion can be made that the choice which practical is given, is often based on a trade-off between individual practical experience and number of available setups.

For the basic control course at Ghent University, the choice was made to keep the advantage of hands-on experience during individual practical sessions even with increasing class sizes. The developed setups for individual practical sessions should be numerous, portable and cheap. Furthermore, it is important that the setup evolves with the progression of the course.

This paper presents a pocket-size PID setup which appeals to a variety of students and shows how it is implemented in an undergraduate course. The setup is a low-cost and modular active learning tool and is used to understand an impressive variety of dynamical systems and their control. It is battery-fed and the students can work with their own computer, so no additional hardware is necessary. Custom-made analog PID printed circuit boards are developed



a) The box containing all needed components.



b) The breadboard with the closed-loop PI-controller. The control loop is indicated with the important signals.

Fig. 1. The pocket-size PID setup.

which allow to explain the task of each PID component in a transparent way. As the entire setup is analog, each signal in the process can be measured (e.g. control effort, error signal, output, etc.). Measurement is done via a data-acquisition card and a newly developed graphical user interface (GUI) made in open-source software.

The paper is structured as follows. In the second section, the setup is described. The context, open-loop dynamics and closed loop dynamics are addressed. The developed GUI in the open-source software Python is also presented. The third section gives the educational context in which this setup is implemented in the undergraduate course. A conclusion is provided in the last section.

## 2. MATERIALS AND METHOD

### 2.1 Context

The setup should appeal to multiple disciplines at once. In the world of control two types of dynamical responses can be found: an S-shaped curve response (process control) and an oscillatory response (robotics and mechatronics). Both types can be imitated by electrical circuits if the correct components are selected. Therefore, the choice is made to develop an electrical circuit which can evolve with the progression of the course. The entire setup is battery powered, making it movable and workable on any location. Data-acquisition is done via DAQ cards and a personal

computer. Open-source software is preferred, as it allows easy access and good documentation for the students.

The entire setup is contained in a small plastic box with dimensions  $23 \times 15.5 \times 6$  cm (see Fig. 1) and it contains:

- Breadboard
- Pushbutton switch (NO)
- 9 V batteries (2x)
- Differentiator (PCB)
- Analog PI(D) controller (PCB)
- 1.2 V battery
- NI USB-6000
- Various resistors, capacitors, and coils

In total 90 setups are developed to provided active learning opportunities to large groups of students. A large amount of setups allows the teacher to organize individual practical sessions in parallel. This has the advantage that each student receives individual hands-on experience without the need for an excess of contact hours. Each setup has a total cost of €134 per setup. The major part of this price is due to the acquisition card. This deliberate choice introduces a professional DAQ-card to the students. Mass production of these setups has been an intensive collaboration between the technical and academic personnel. The necessary Printed Circuit Boards (PCB) where soldered in-house using assembly line techniques.

## 2.2 System Dynamics: open-loop

Understanding system dynamics is the first objective of the setup. The breadboard is used to easily develop and update the process to obtain different dynamical characteristics. The various resistors, capacitors, and coils can be placed in numerous configurations to obtain certain process characteristics.

The breadboard contains a normally-open push-button switch. This switch allows to connect the 1.2 V battery with the process in an instance. This enables the students to explore a step response of the process they have built on their breadboard.

Depending on the choice of the electrical components (resistors, capacitors, and inductors), different dynamic responses can be obtained. The typical overdamped, underdamped and critically damped responses of the second order system can be seen in Fig. 2a. Higher order systems, such as the fourth order system in Fig. 2b, can provide different dynamic responses depending on the investigated output. The effect of zeros in the transfer function can be addressed in this way.

Materials for self-study are being provided to the students so that they are able to build the electrical circuits

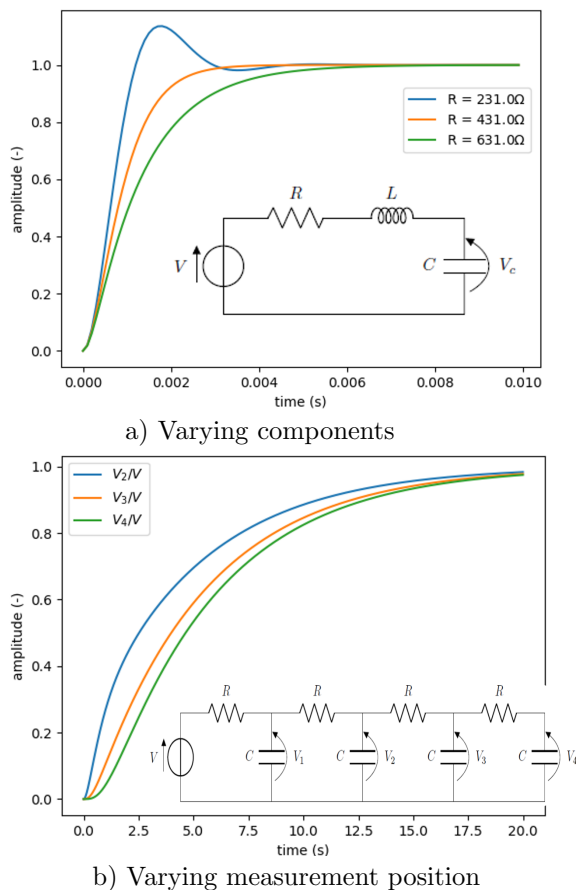


Fig. 2. Different types of system responses that can be explored with the setup. In a) an RLC circuit is built and the voltage over the capacitor is given for different resistor values ( $L = 102 \text{ mH}$ ,  $C = 2.2 \text{ }\mu\text{F}$ ). In b) the position of the DAQ is altered without changing the circuit.

on the breadboard independently. This allows for the time of the contact hours to be fully dedicated to the control engineering concepts such as system dynamics and feedback control.

Based on the open-loop dynamics of the process, a fitting sampling time is selected. This sampling time can be adjusted in the developed graphical user interface (see section 2.4).

## 2.3 PI control: closed-loop

In Fig. 1b the loop is closed to take advantage of the concept of negative feedback. To achieve negative feedback the process output signal needs to be subtracted from a reference signal. The reference signal is again implemented by instantly enabling a 1.2 V battery using the push-button switch. A differential amplifier circuit is used to achieve the error  $v_e$  between the reference  $v_r$  and the process output  $y$  voltage. The circuit consists of an opamp circuit, as presented in Fig. 3. This circuit is soldered on a custom-made Printed Circuit Board (PCB). The input and output pins of the circuit are broken-out using header pins, which are arranged as to fit into the breadboard.

It is assumed that the working point of the opamp stays in the linear range. Hence, it is safe to assume that  $v_+ = v_-$ . Moreover, the input impedance is high, such that no current flows into the (non-)inverting port. If  $R_1 = R_2 = R_3 = R_4$ , then  $v_e = v_r - y$ . The bandwidth of the opamp is chosen large enough to avoid interference of the opamp dynamics with the process.

Next, the error signal  $v_e$  is used by the feedback controller to calculate the control effort, i.e. the output of the controller. For the sake of a basic control course, a conventional PI controller is chosen. The controller is implemented using two op amps, as shown in Fig. 4. The ratio of the controller's output, the control effort  $u(s)$ , and the controller's input, the error signal  $v_e(s)$ , is given by:

$$\frac{u(s)}{v_e(s)} = K_p \left( 1 + \frac{1}{T_i s} \right) \quad (1)$$

Notice that the components  $R_6$  and  $C_1$  are variable. This allows the student to tune the parameters of the PI controller in equation (1). Assuming that the working point of the opamps is in the linear region, the input impedance is high and bandwidth of the opamps is sufficiently large, the relation between the PI parameters and the electrical components in Fig. 4 is given:

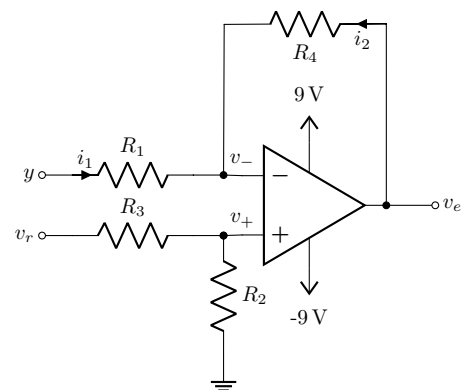


Fig. 3. Differential Amplifier.

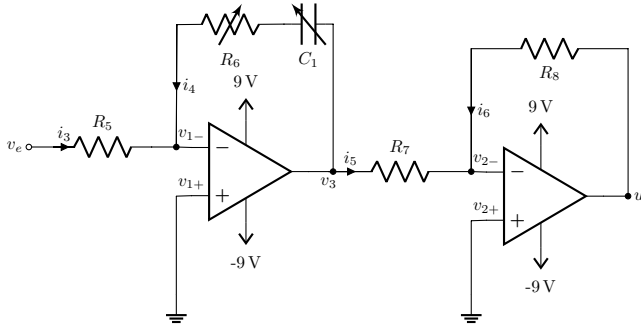


Fig. 4. PI controller.

$$K_p = \frac{R_6 R_8}{R_5 R_7} \quad (2)$$

$$T_i = R_6 C_1 \quad (3)$$

Notice, that changing  $K_p$  is independent of  $C_1$ . Hence,  $K_p$  and  $T_i$  can be chosen without any constraints from a set of provided resistor and capacitor values. The values for the electrical components in the differential amplifier and the PI controller are given in Table 1. Notice that the variable resistor  $R_6$  and capacitance  $C_1$  consists of discrete values, which are selected with the help of a jumper. For the case  $C_1 = \infty$ , the PI-controller reduces to a P-controller.

Table 1. The values of the electrical components given in Fig. 3 and 4.

| Differential Amplifier | PI-controller                       |
|------------------------|-------------------------------------|
| $R_1$ 390k $\Omega$    | $R_5$ 39k $\Omega$                  |
| $R_2$ 390k $\Omega$    | $R_6$ 56, 120, 180k $\Omega$        |
| $R_3$ 390k $\Omega$    | $R_7$ 390k $\Omega$                 |
| $R_4$ 390k $\Omega$    | $R_8$ 390k $\Omega$                 |
|                        | $C_1$ 1, 2, 2.2, 10, $\infty \mu F$ |

All opamps are fed with two 9V batteries. Notice that the entire circuit, both the process and the controller, is working with continuous signals and are fully analog. No discretisation is involved, which makes this a good test case for starting control students. Moreover, the student is able to measure all signals in the control loop. This transparency is again an added value for the learning process. An extra feature is that no (noisy) sensors are necessary, as all signals have the unit of voltage and can be measured directly with a data-acquisition unit. This results in signals with low noise levels.

The full setup is given in Fig. 1b. Depending on the task a breadboard without or with the additional wiring is given for open-loop or closed-loop measurements respectively. The wiring is always the same and does not need adaptations during the lab session. The setup represents each part of control loop visually, which is often a too abstract concept for beginners.

Remark that the PCB is designed in such a way that the PI-board can easily be expanded to include a D-action as well. A parallel capacitance across resistor  $R_5$  allows the students to explore P(I)D control.

#### 2.4 Data-acquisition in Python

Data-acquisition can be done with any hardware that is able to sample a voltage signal. In this case, the National Instruments USB-6000 is chosen. The device has 8 Analog

In (AI) ports with a maximal sampling frequency of 10kHz. This is one of the most basic data-acquisition units of the National Instruments USB line, but these specifications suffice for the project. This makes the NI USB-6000 the most cost effective choice to keep the total cost of each setup at a minimum. The device can be connected to a personal computer with USB 2.0 and uses serial communication with 12MB/s.

It is favorable to use open-source software, because it is free and, thus, it can be downloaded and installed locally on any computer. The choice for the Python 3.x programming language resorts in the facts that i) it is well-documented, ii) a python library *nidaqmx* for National Instruments for data-acquisition exists, and iii) Python 3.x is used in the undergraduate basic programming course. This allows the student to maintain a knowledge continuation and avoids the need to learn a new programming language. Moreover, the signal processing/analysis is done in Python as well using the *Python Control Systems* library.

For the data-acquisition, a GUI is created that can be used to change the sampling time, to start and stop the acquisition, and to save the data array to a .csv file. The code for the GUI is available in a GitHub repository and can be easily downloaded. All programming is done in Anaconda, which is a free and open-source distribution of Python that simplifies package management and deployment.

The full installation procedure is the following:

- Step 1:* Install Anaconda software: the free software is available on their website.
- Step 2:* Install NI DAQmx drivers: on the National Instruments website, all drivers are freely available. The driver allows a serial connection between the data-acquisition card and the computer.
- Step 3:* Download GUI code: the GUI code is available in a GitHub repository and can be cloned to a local working directory. By running the code the GUI opens and can be used immediately.
- Step 4:* Install Python libraries: a text file with all libraries and their corresponding version is provided. A new Python environment is created. By uploading the requirements.txt-file, the libraries are automatically installed.

### 3. EDUCATIONAL CONTEXT

The basic control course at Ghent University is called ‘Modeling and Control of Dynamical Systems’. The total number of students in this undergraduate course is 180. The course content consists of:

- Introduction
- Modeling
- Linear Time-invariant Systems
- Open- and closed-loop dynamics
- Proportional-Integrating-Differential control
- Control Design: Root Locus
- Modeling and Control in Frequency domain

The course theory is given in 12 contact sessions which are interchanged with 12 exercise sessions. Before the education innovation project of the course, the 12 exer-

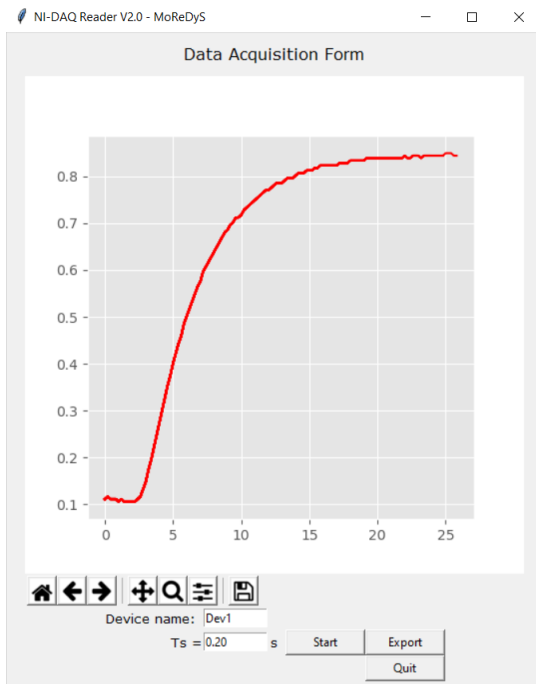


Fig. 5. Data-acquisition user interface created in Python 3.x. An open-loop step response of the fourth order system.

cise sessions were classical exercises on paper. With the development of the setups, 3 practical sessions are introduced which replace the previously classical exercises. The following practical sessions are introduced:

- Class 1: Experimental modeling
- Class 2: Closed-loop control
- Class 3: Computer aided design

The lab assignments given to the undergraduate students are presented in the following subsection.

### 3.1 Lab assignment for undergraduate students

The students were split into two groups of 90 students. For each student a setup is available due to the large amount of setups developed in this research.

#### Class 1

In the first practical session, the students are asked to perform open-loop measurements. They are asked to build an RC circuit, a circuit with 4RC combinations in parallel and an RLC circuit. During this session, the students become familiar with first order, second order and higher order responses as presented in Fig. 2. The open-loop response of the fourth-order system can be seen in Fig. 5.

#### Class 2

In the second practical session, the students are asked to use tuning rules, such as Ziegler-Nichols, to design P and PI controllers for different systems. The students are asked to build a fourth order system with 4RC combinations in parallel. The higher order process is approximated by

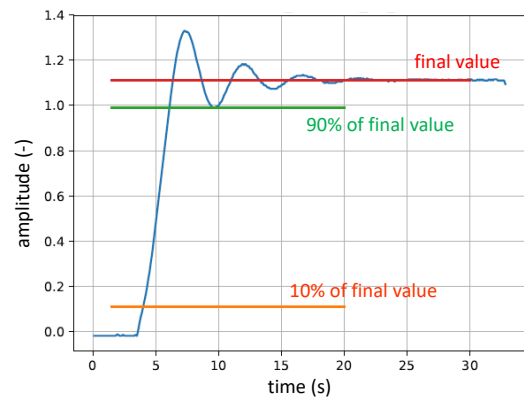


Fig. 6. Step response of the fourth order system with P-control.

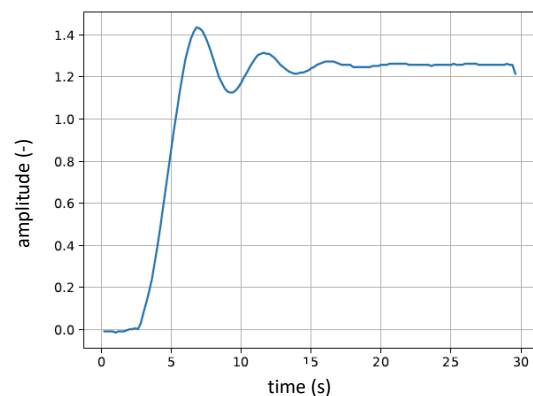


Fig. 7. Step response of the fourth order system with PI-control.

a first-order-plus-dead-time model. Using the obtained model parameters, the student can apply the Ziegler-Nichols tuning rule to get a P controller. The measured response of the P controller on the fourth order system is shown in Fig. 6.

Based on the obtained graph the students are asked to read the final value, the rise time, the overshoot and steady state error. This allows them to get acquainted with the terminology in control. Afterwards, the students are asked to apply the Ziegler-Nichols tuning rules again to make a PI controller for the system and perform measurements. The resulting step response (see Fig 7) allows them to grasp the concept of integrating action, i.e. the steady state error disappears.

#### Class 3

In the third practical session, the students are asked to perform computer aided design (CAD) in both time and frequency domain. Using Python code, the root-locus techniques are used to design a P(I)(D) controller. The second part of the task deals with the use of Bode and Nyquist plots in Python to design the controllers and assess concepts such as robustness and stability.

Specifically, first-order-plus-dead-time processes are approximated using Padé approximations in order to make use of root-locus. Based on the obtained root-locus plot of the open-loop system, the closed-loop characteristics can

be changed based on specifications such as damping, overshoot, settling time, etc. The stability criteria of Bode and Nyquist can be used to assess the stability of the designed closed-loop process. Concepts such as robustness, phase margin and gain margin are addressed in this section.

#### 4. CONCLUSION

The number of students attending a course grows and their educational background shows an increasing diversity. Active learning is becoming an important pillar in education as it is shown that it improves the students understanding. The lecturer faces a tremendous challenge to achieve this in combination with the aforementioned problem, the need emerges to create a large amount of small setups that can be used in any classroom without additional infrastructure. It is of paramount importance that each student can work individually at their own pace. Related to a basic control course, a portable setup was developed to carry out open-loop measurements and closed-loop control using an analog PI controller. As the entire experiment consists of analog voltage signals, the closed-loop becomes fully transparent. One can observe every signal in the loop.

A succession of three lectures gives the students insight in basic control concepts. First, a step response of processes with a variety of dynamical responses is examined: both over-, critically, and underdamped processes are explored. Next, relevant tuning strategies are explored. And finally, the computer-aided controller design is practiced. Also, some frequency domain tools are explored.

The modularity allows the setup to grow with the theory course and to provide some hands-on insight in the theory and exercises. The setup is fully battery-powered. Hence, there are no restrictions on which classroom should be available. Its cheap production cost allows to make large batches, i.e. 90 setups. Combined with open-source software, Python 3.x, the setup is easily accessible to all students. Moreover, Python includes a very powerful control and automation inspired library *Python Control Systems*, which allows immediate analysis of the acquired signals.

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