Change the Traditional Way of Teaching Electric Drives Laboratory with Design of Experiment

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***Abstract*—This paper presents the authors' experience in flipping the traditional way of teaching Electric Drives Laboratory course using a component on design of experiment (DOE). Traditionally, the lab manual looks more like a cook-book. The inclusion of the DOE satisfies the "design" aspect of the ABET Student Outcome on "ability to design and conduct experiment, as well as to analyze and interpret data". The challenge comes when limited information is "fed" to students and they are forced to "search" for available ingredients and to creatively "cook" a meal, and write down the recipe. A detailed lab flipping process with well-planned structural guidance will be reported, experience will be shared, and future plan will be proposed.**

Keywords—design of experiment, electric drives lab

I. Introduction

In the traditional Electrical Engineering curriculum, courses are taught progressively from the most fundamental subjects to more advanced ones. The laboratory courses usually are scheduled in the same semester as the subject courses to assist the teaching of concepts and to enhance students' mastery of the subject matter. Table I lists the laboratory courses in the ECE curriculum at Gannon University as an example.

TABLE I. List of lab courses in ECE curriculum

Lab course #	course name	semester
ECE106	Eng. Tools applications lab	Freshmen first
ECE141	Digital logic design lab	Freshmen second
ECE229	Circuits I lab	Freshmen second
ECE241	Circuits II lab	Sophomore first
ECE247	Microprocessors lab	Sophomore first
ECE322	Electronics I lab	Sophomore second
ECE334	Electronics II lab	Junior first
ENG327	Automatic control lab	Junior second
ECE465	Power electronics (has lab portion)	Junior second
ECE328	Electric drives lab	Senior first
ECE357	Senior design lab I	Senior first
ECE358	Senior design lab II	Senior second

Traditionally the laboratory manual looks more like a cook-book, whereby students follow the steps or procedures to set up the experiment, conduct measurements, gather data, and validate the concepts or theory taught in the course. Student learning is enhanced and the students gain first-hand evidence verifying what they have learned from the hands-on experience. However, this approach is lacking the components of critical thinking, synthesizing and creativity, which are key factors of student success in their senior capstone design course and in their future careers. Over the years, the benefits of DOE implementation in engineering and other science curricula have been reported [1-4]. In addition, the "design" aspect of the particular ABET Student Outcome on "ability to design and conduct experiment, as well as to analyze and interpret data" can be specifically measured by DOE.

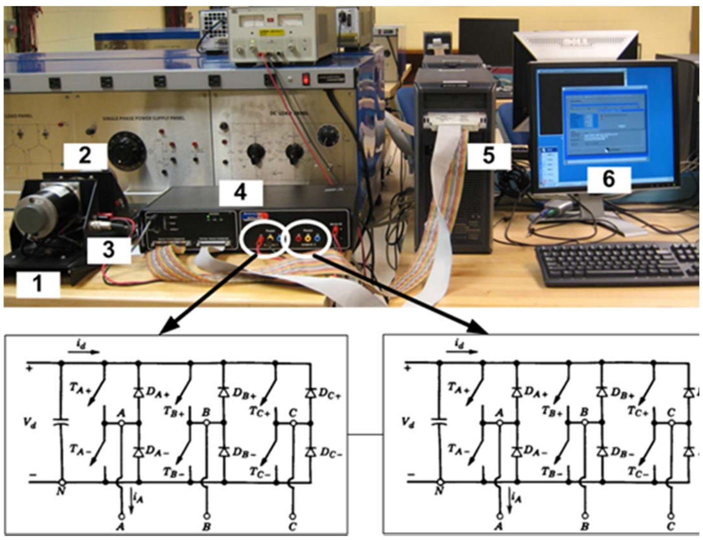
At Gannon University, we have been including the *design of experiment* component in some of the laboratory courses. Circuits I lab was revised in spring 2015 for the inclusion of DOE and positive experience has been reported in [5]. As an advanced level course, Electric Drives Lab (scheduled in the senior first semester) was also recruited for the design experiment course list. The authors have been introducing the design of experiment as the fifth lab activity in the course for two semesters. The intention was to introduce a more advanced level of DOE concept and activities to this advanced laboratory. There are some positive outcomes as well as lessons learned during the delivery of this laboratory course.

II. Electric Drives Lab Structure and Selection of the Lab Activity for DOE

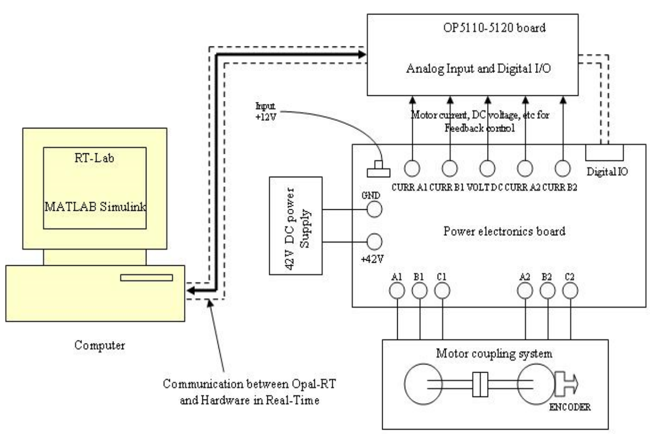
This section briefly introduces the content structure of the electric drives laboratory course. Based on our experience, the experiment to be flipped cannot be randomly chosen; rather we need to make sure that students have gained sufficient exposure and experience with laboratory equipment, essential setup for similar experiments, and knowledge content of subject before asking them to perform a design experiment. The conclusion of this section will lead to the rational selection of a specific experiment which students were asked to design.

The electric drive laboratory is equipped with six state-of-the-art Opal-RT-based Hardware-in-the Loop (HiTL) workbench stations. Each station consists of two PCs, one DC power supply, one FPGA card, one power electronics converter box, several machine dyno-sets, oscilloscopes, and various types of meters and wires. Figure 1 shows the picture of one station with the following itemized components:

- Item1-permanent magnet DC motor to be controlled;
- Item2-DC generator acting as the load to the DC motor;
- Item3-digital optical (or electromagnetic) encoder to measure the motor speed;
- Item4-power electronics converter box and PWM driver board. There are two three-leg converters. Based on the PWM switching signals, these two converters can work as DC/DC converter, DC/AC single phase inverter, as well as DC/AC three phase inverter. This enables the possibility of operating a DC and an AC machines at the same time.
- Item5-FPGA card and I/O ports housed in a Linux PC. The FPGA card will host the rapid-prototyped controllers.
- Item6-PC with Matlab/Simulink installed for model building, modification and monitoring.



(a)



(b)

Fig. 1. a) Opal-RT workbench setup and (b) Opal-RT based electric-drives laboratory system

As seen in Table I, the electric drives laboratory course is scheduled in the first semester of the senior year. To successfully carry out the lab sessions, students need to have knowledge in power electronics, automatic control, circuits, electric machines, FPGA, sensors and feedbacks, test and instrument, etc., which they all acquire from previous years of study. The electric drives laboratory course is designed to combine all the above mentioned subject's knowledge into an integrated system.

TABLE II. LIST OF LAB ACTIVITIES IN ELECTRIC DRIVES LAB

Item	Topics
1	Lab Safety, Introduction to OpalRT System and demonstration
2	Simulation and real-time implementation of a switch-mode dc/dc converter
3	No-load dc motor open loop speed control/test
4	Characterization of dc motor
5	Dc motor speed control
6	Four-quadrant operation of dc motor
7	Characterization of induction motor
8	V/f control of induction motor

Table II lists the eight laboratory activities for one semester. The activities are designed progressively from easy to complicated. Each laboratory activity is built upon the knowledge and experience gained from previous laboratory activities. Students begin the laboratory activities by familiarizing themselves with the station as their first laboratory exercise.

- In Lab 2, students are asked to first simulate a switch-mode dc/dc converter within Simulink environment, and then implement it with the real hardware dc/dc converter setup while only leaving the switching signal generation portion as "software." Using the oscilloscope, students can view the real output voltage waveform from the converter. These waveforms are compared with the waveforms obtained from the simulation using the virtual scope in Simulink to gain insides.
- Lab 3 is the open-loop DC motor speed control under no-load condition. Students are asked to use the dc/dc converter built in Lab 2 to supply different voltage levels to the armature winding of the DC motor so as to control its speed. Students need to understand the functionality of the digital encoder and how to convert its output signal to speed value in the proper unit. The communication block provided by Opal-RT performs this specific task.
- Lab 4 is to conduct a series of experiments to gather sufficient data for the characterization of the permanent DC motor. Upon completion, the machine equivalent parameters, such as armature resistance R_a, armature inductance L_a, induced back electromagnetic-force voltage constant K_e, electromagnetic torque constant K_t, friction coefficient B, Column friction torque T_B, and equivalent inertia J are determined. With these parameters, students can construct an accurate model for the DC motor.
- Lab 5 is the closed-loop speed control of the DC motor which is based on all the results from the previous three laboratories. Students need to design two PI controllers; one for inner current loop and one for the outer speed loop control. They are required to figure out how to implement

these controllers in both the virtual simulation environment and the HiTL setup.

- Lab 6 is the automatic four-quadrant operation of the DC motor, which is an extension of Lab 5.
- Labs 7 and 8 are related to AC induction motors

From above description of the laboratory activities, one can see that labs 2 and 4 are not, while labs 5 and 6 could be good candidates for design of experiments. Taking into account of the complicity of HiTL system as well as the closed-loop feedback controller design, we concluded that Lab 5 is the perfect candidate for the design of experiment. Labs 1 through 4 provide students sufficient exposure to laboratory equipment, hands-on experience and system information needed to perform a DOE on Lab 5.

III. Design OF experiment for the closed-loop speed control of DC motor

The original Lab 5 manual used over the past few years is a 12-page detailed cook-book type manual. We flipped the traditional way of teaching this particular laboratory by not giving students the Lab 5 manual and providing them with a one-page brief instruction of what was expected to happen as the result of this laboratory activity. In other words, students were required to design their own experiment to realize the closed-loop speed control of the permanent DC motor.

In the beginning, students were a bit confused. They did not instantly know where to start. On the one hand, they have gained sufficient knowledge of the workbench station and hands-on experience from the previous four laboratory activities. On the other hand, they are confronted with the challenge to carry out an experiment with so limited information. They are so used to being "fed" the information. The challenge comes as they are forced to "search" for available ingredients and to creatively "cook" a meal, and to write down the recipe. The following subsections will detail our approach on how to lead (guide) students along with every step of the way to successfully complete designing and conducting the experiment. Students have what it takes to do this job, they just need to be guided patiently.

A. *Critical thinking and synthesis*

This is a good opportunity to lead students to critical thinking and synthesizing their prior acquired knowledge with the interaction between subsystems. A series dialog took place for the preparation of designing Lab 5 activity.

- Students were guided to summarize and reflect on the process and results of the previous four laboratory activities. During the discussion, they started to realize that they have been working with all the essential subsystems of the expected system for several weeks.
- Students were reminded to closely examine each subsystem to identify the ranges (or limitations) of essential parameters.
  - Current and voltage limits of the DC power supply
  - Current, voltage, frequency, speed limits of the DC motor
  - Current and switching frequency limits of the power electronics converter box
- Students were reminded to pay attention to the HiTL design and implementation procedure of the Opal-RT operational system. This procedure has to be followed strictly to build/edit the model, compile the model, load executable codes to the FPGA card, execute the experiment, monitor the parameters, and to react/troubleshoot in a faulty situation. Otherwise, if any of the steps is missing or executed in the wrong sequence, the communication between the target and host systems will be disconnected and the execution will freeze. It will take a considerably long time to reboot/recover the system.
- Students were guided to synthesize the interaction among different subsystems and to identify the functionality of each subsystem in the expected system that host Lab 5 activities.

With the above guided discussion, students finally gained a clear picture of what was supposed to be performed. Rather than diving directly into hardware implementation, they chose to do the virtual simulation first.

B. *Virtual simulation of a cohesive system*

The top-level view of the cascaded closed-loop speed control of the PM DC motor implemented in Simulink model is shown as in Fig. 2. With what they have learned from Automatic Control, two PI controllers are designed; one for the current/torque loop and the other is for the speed loop for control of DC motor speed. The following discussions took place among students at this stage:

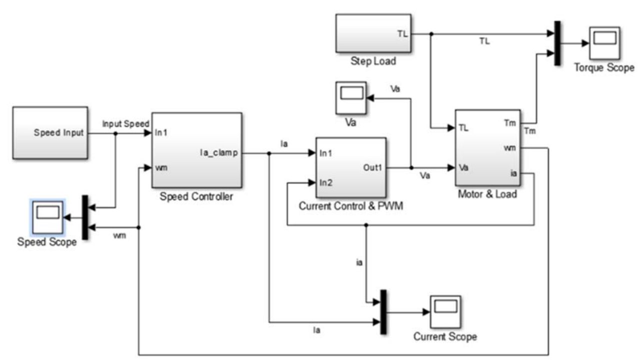


Fig. 2. Top level view of closed-loop DC motor speed control virtual simulation model

- Why is the cascaded control needed? Can we only implement the speed controller and eliminate the current/torque controller? Why or why not?
- Why is accurately modeling the electrical machine important?
- Can we trust all the results that simulation provided to us? To what extent they can be trusted?

After several rounds of trial and error, students achieved a reasonable speed response and current response as shown in Fig. 3. The speed reference (shown in pink) changes from 0 to

200 rad/s at 2s and then to 400rad/s at 4s. The real motor speed (in black) reaches the required speed within a reasonable time and has zero steady-state error. The current has similar response while staying within the current limitation—6A which is 120% of the rated current.

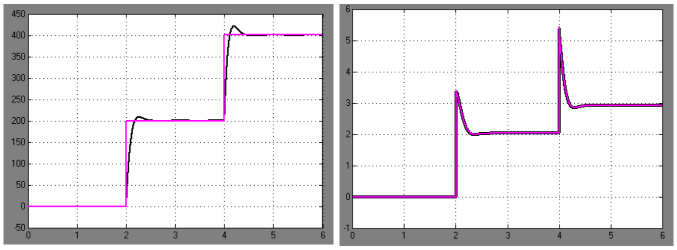


Fig. 3. Speed and current responds from the virtual simulation

C. *Design the experiment with a cohesive system consisting of available hardware and software pieces*

Now the discussion goes in a different direction—it looks good in simulation, but will it really work in a real hardware setup? This is the moment when students have to decide which part of the simulation will be replaced by real hardware and which part will stay as software. Fig. 4 shows the top level Simulink model with Opal-RT library blocks prepared for HiTL real-time simulation. It is certain that the Console block will stay with the host PC. The Console consists of a human machine interface (HMI) including a slide bar as the input for the reference speed, sensor signals (speed, current, and voltage) display on virtual scopes as shown in Fig. 5 for monitoring and control. The device interface communication between the host PC and the hardware FPGA card have been taken care of through Opal-RT customized OpComm blocks.

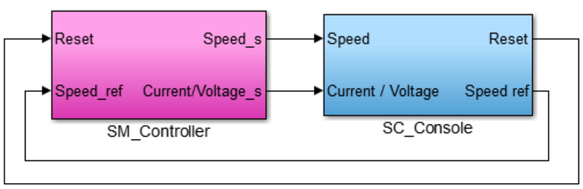


Fig. 4. Top level Simulink model with Opal-RT blocks prepared for HiTL

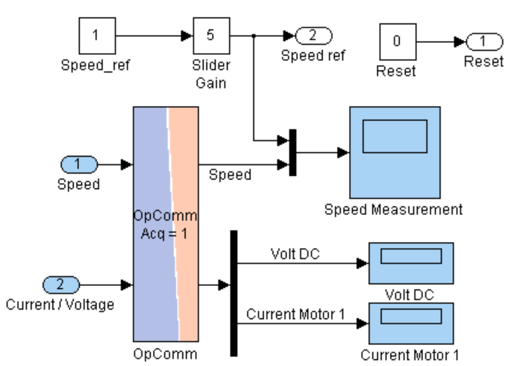
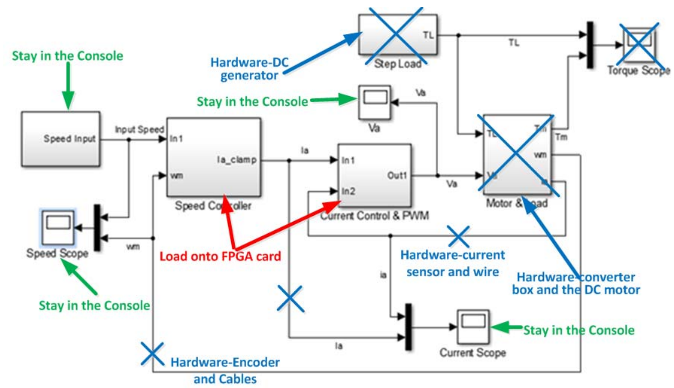


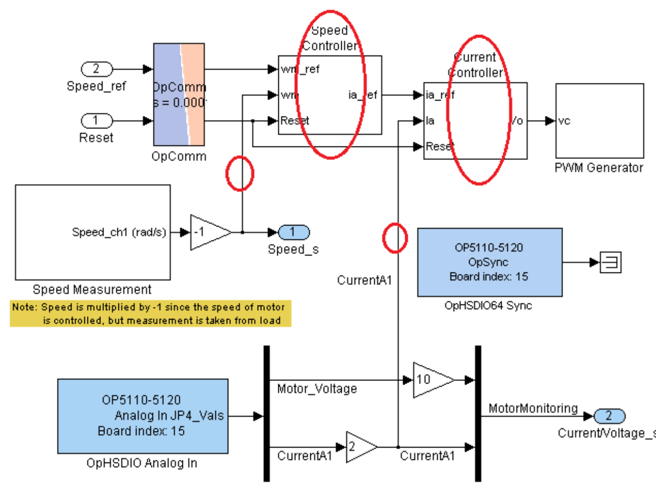
Fig. 5. The Console with speed reference input and speed, current, votlage displays

Fig. 6 (a) displays the duplicated virtual simulation model (as shown in Fig. 2) with notes and symbols indicating the "fate" of each block while building the cohesive system with replacement by the available hardware and software pieces.

- Green color: those items will stay within Console
- Blue cross and color: those items will be replaced by real hardware. They are the PM DC motor under test, the PWM converters, the DC generator acting as the load to the motor, the encoder and cable, and the current voltage sensors with wires.
- Red color: only those two PI controller blocks will stay as software, which after being compiled, will be loaded to the FPGA card.



(a)



(b)

Fig. 6. (a) Virtual simulation model and the equivalent (b) the Opal-RT based Master block

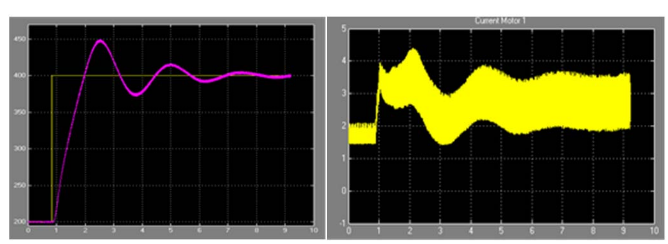


Fig. 7. Speed and current testing waveform with HiTL system

Students realized that the hardware setup is very similar to Lab 3. The only difference is the inclusion of the two PI controllers and the feedback signals required on the software side. They used the Master block from Lab 3 and modified it to the one shown in Fig. 6 (b). The red ovals indicate the additions. The model was compiled and loaded to the FPGA card. Fig. 7 shows the sample result of the real-time speed control of the DC motor. All the recorded values of subsystems are within the defined limits. The DC motor speed is automatically controlled meeting the define response speed and accuracy. Until now, designing and conducting the experiment and gathering data are successful.

D. Laboratory manual versus laboratory report

As part of the design of experiment requirement, upon successfully conducting Lab 5, students are asked to write a laboratory procedure as a manual instead of as a laboratory report to meet the documentation requirement. The laboratory manual needs to have the following content:

- Lab objectives
- Introduction and background theory
- Virtual off-line simulation
- HiTL implementation
- Test results, analysis and interpretation
- Conclusions and discussions

The following are the expected goals for students in producing the laboratory manual:

- Students reflect on the entire process of designing and conducting the experiment. Writing a laboratory manual requires students to view the laboratory activities from a different perspective; to thread their critical thinking and discussion in a very logic way; and to present the information with professional format. This practice is similar to writing a test plan in industry where design, manufacturing, and testing facilities are clearly defined and most of the cases are at different locations. To validate a designed product, design engineers usually create product test plans. Those test plans will be carried out by other technicians or even at off-site remote testing facilities. The quality and format of the test plan (laboratory manual) is a big factor in influencing the results of the test data gathered and analyzed.

IV. CONCLUSIONS, LESSONS LEARNED AND FUTURE PLAN

A. Conclusions

Designing an experiment is an important skill which most of the ECE curriculum fails to emphasize. Our teaching experience with electric drive lab course demonstrates that with the proper level of guidance, students can quickly pick up and practice this skill. As shown in Fig. 8, the two green blocks have been added to the experimental flow.

B. Lessons learned

After delivering the electric drives laboratory course with the inclusion of design of experiment for two semesters, we have learned several valuable lessons which we would like to share with our peers.

1. The level of information provided to students before they design the experiment is a key factor influencing student learning outcomes. If the provided information is too sparse, students are left dry and confused and won't perform well. On the other hand, if the information provided is too detailed, students will still stay in the "being fed" stage and won't feel the urgency to search for information. Unfortunately, our data from the fall 2014 semester fell into the first case, while fall 2015 resulted in the latter case.

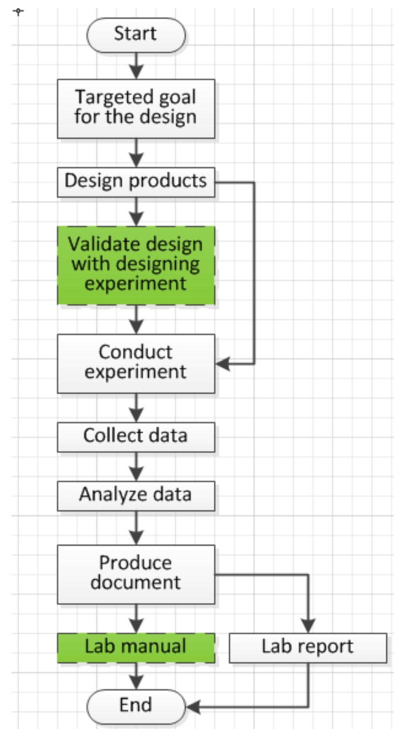


Fig. 8. Experimental flow chart

2. An "oral" lab manual is a barrier for implementing the DOE successfully. To let students truly experience designing experiments, neither the cook-book type written manual nor the "oral" lab manual should be provided. One important lesson we have learned is that the instructor cannot be too deeply engaged in the students' discussion during the stage of designing the experiment. Otherwise, if the instructor gives the right answer and provides detailed guidelines too quickly, it is the same as providing students with the "oral" lab manual. The key point is to listen to the student's discussion, view their document, and provide feedback, but not give away the answer too easily.

3. Designing the experiment needs to be well planned and the expectations need to be clearly defined.

This reverse process of learning requires students to be more proactive in identifying (1) the factors to be tested, (2) the levels of those factors, and (3) the structure and layout of experimental runs and operating conditions. Students are therefore made more aware of how to deal with measurement errors, unexplained variations, and how to properly use the equipment in the laboratory. These three points are precisely the essence of the DOE. By doing so, the process will instill critical thinking into the student learning process while performing DOE activities.

- In this paper's case, the factors are the motor speed, motor current, motor terminal voltage, and system responding time.
- Clearly define the limits of the selected factors based on what is expected to happen. For this case, these are the limitation of the motor current, the allowed range of power electronics converter current, the maximum motor speed, maximum motor terminal voltage, maximum frequency of the lowest harmonics, and the maximum overshoot allowed.
- Design the experiment as a cohesive system consisting of both hardware and software.
- Conduct the experiment
- Create study questions that help to analyze data collected for validation purposes
- Produce a laboratory manual that allows others to follow and repeat the experiment.

C. *Future plans*

While we are drafting this manuscript, we just came to realize that there is not enough evidence from the student's side to access and evaluate the outcomes of our two semesters' teaching practice of designing experiment due to the reasons listed in "Lessons learned." In both semesters, students successfully conducted Lab 5 activities, gathered and analyzed validated data, and produced the document. After the second round of review, we concluded that the documentation students produced is the mix of a Lab manual and a Lab report. We plan to fix this in fall 2016.

- We will improve the access and evaluation process by introducing an evaluation matrix and rubrics before and after the design of experiment activities.
- We will revise the scope and depth of the information provided to students prior to performing the design of experiment.
- We will also avoid giving away the "oral" cook-book type of Lab manual.

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