Transistor teaching back to Transfer-Resistor

A summary table of definitions and students' perceptions

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***Abstract*— The Bipolar Junction Transistor (BJT) study is a regular subject on analog electronic subjects taught in the initial phase of electronic engineering courses. This electronic component, often considered elementary, is far from being simple to explain because it covers several concepts, such as three Regions of Operation, two Working Regimes, and two Region of Operation Boundaries. It is not surprising then that students often find it difficult to understand the functioning of this component. The present article describes partially the work developed by a team with a number of students in order to understand the difficulties of teaching/learning the BJT. We present the students' perceptions from the analysis of several traditional and modern means to support the learning of the BJT. Interestingly, the learning BJT model considered simpler for beginner students corresponds to the model that originally gave it the name i.e. Trans-Resistor (Transistor).**

Keywords*— *Bipolar Junction Transistor, leaning support means, students perceptions

I. Introduction

Higher-level education is seen as a key factor and as an essential role for people who wants to have future success in modern societies. Its importance is well recognized regardless of the significant costs carried for every country. In fact, the number of people who pursue this level of education has impressively risen in the last half century. This increase in students brings new challenges for both, each country's economy and teaching systems [1]. Traditional methodologies mainly centered on the professor have been revealed to be ineffective when delivered to the masses [2]. This unsustainable situation has led not only to an adjustment of teaching strategies but and also to divert more attention into students and teaching/learning methods [3,4]. The Bologna reform brought a reorganization inside universities in order to optimize education resources [5,6], which in turn led to a tendency for shortening their degrees' time and to center them in a given knowledge specific area [7,8]. These kinds of degrees became very narrow, with a high level of specialization and a thin scope. This is a new strategy that brought advantages and disadvantages, particularly in the case of engineering education [9]. On one hand, this strategy allows the development of technological and educational processes closer to each other [10]. As the scope becomes narrower, the easier it is to achieve a higher skill level, and in particular if it is supported by technological means.

On the other hand, the mentioned strategy brings the disadvantage of decreasing competences in terms of abstraction for dealing with more realistic and complex models. This is an issue that assumes special importance in Electric and Electronic Engineer courses. Traditionally, in the first years students work mostly with simpler and ideal models of electrical elements and then, in last years, they use more realistic and detailed models.

This is important in Electronic Engineer Degrees where electronic subjects are typically divided in two different arenas commonly called Digital Electronic and Analog Electronic. At a degree level, we can observe a fragmentation, i.e. students taking options that will later define their own jobs. Inside the Electronic Engineering degree we can see students clearly oriented to hardware design, while others prefer software design. Even inside hardware design, a new fragmentation takes place: a very important part of students prefers digital design, whereas just a few others select the analog and mixed-signal design. As a consequence, we have an unbalanced situation resulting on lots of specialists in the digital arena, contrasting with few in the analog arena. In fact, there exist a few analog programmable / configurable components, called PSoC and FPAA [11], but the market acceptance has been slow and they are not usually part of the Analog Electronic curricula. The students' inclination for digital circuits instead of analog and mixed-circuits is clear. The reason that explains this behavior, however, is more complex than the simple division of the type of signals involved. The fact is that the design flow of each arena presents significant differences as a consequence of each arena's maturation state. In the digital area, the design is mostly based on s*oftware*, whereas in the analog arena the design is based on *hardware* and also on components *behavior* knowledge. One of those components is precisely the Bipolar Junction Transistor (BJT). For teachers this is no more than one elemental component. For students, it is nowhere as simple, for this component poses important constraints on its understanding.

The BJT study is a regular subject on analog electronic subjects taught in the initial phase of electronic engineering courses. This basic current amplifier electronic component, often considered elementary, is far from being simple to explain because it covers several concepts, such as three *Regions of Operation*, two *Working Regimes*, and two *Regions of Operation Boundaries,* besides other features. Students often find this non-linear component difficult to understand. A significant part of the traditional means of teaching / learning support available today has been developed for the previous generation of engineering students, therefore it is scientifically correct but may not be adequate for the new generation engineering students. They are naturally digital natives, with less initial ability to deal with models involving a high level of abstraction, and more likely to seek and accept information in the form of electronic support such as text, slides and movies.

The teaching support structure of the transistor has remained reasonably constant over the years since this component is always the same. However, there have been efforts and proposals from various authors, especially to increase the diversity of teaching methods. In [12], the author proposes the reutilization of teaching methodologies of digital circuits that can be applied in the teaching of analog programmable circuits. In [13], the author introduces a methodology based on sub-division to explain the macroblock of the Operational Amplifier. Instead of going from the elementary circuits (e.g., Resistor, Transistor), an intermediate phase of sub-blocks is proposed. In [14], the author describes the teaching of circuits with BJT through the motivation of the students for their practical use.

The present article describes partially the development of means to support engineering teaching (slides, films) with a methodology that always involves the teacher and the student. In the first stage, a definition and synthesis of the various operating zones and operating regimes was made. Interestingly, the learning model considered simpler by the student coincides with the model that originally gave it the name, Transfer-Resistor (Transistor), i.e., a resistor controlled by a current [15].

II. Methodology and Developed Learning Support Means

The aim of this work is to perceive whether electronic students are prepared to deal with different models imposed by real components, identify their difficulties and link them to actual gaps in their education. The method of research here is *ex post facto* research [16]; the researcher takes the effect and examines the data retrospectively in order to establish causes, relationships and explanations. The collected data consisted in some class discussions' transcriptions and courses and degrees curricula analysis. The results relate to Electric Power Systems Engineering at ISEP (Polytechnic of Porto School of Engineering) students at the end of their first year, second semester (2016). A teacher/researcher perception triggered this research. In order to test his perception, he placed the hypothesis of his students in the end of his course "Electronics" not being able to explain nor comprehend the actual behavior of an electronic component in terms of Model.

In electrical engineering teaching all the components are represented in the form of Models that have an associated specific behavior. The model of a nonlinear component is often described through the association of several linear components. However, the teacher has been noting the difficulty of students intellectually transposing the model to its component. An example is the junction diode. Its operation is traditionally explained by the *V-I characteristic curve* of the diode [I_D = f (V_D)] that relates the voltage V_D on its terminals with the across current I_D.

For the diode on the ON state, one of the most common used model includes a voltage of 0.7 V in series with a conduction resistance. This situation often creates conflicts since voltage sources are, for students of the 1st year, systematically associated to devices that *promote* electrical current. However, if it is said that the *V-I characteristic curve* of the diode reflects its *resistive behavior*, these doubts promptly disappear. After that, a diode at ON state is them seen as a *resistive limiter*, i.e., device which limits its own voltage to a value of 0.7 V instead a device which promotes the electric current; nor could it be otherwise, since the *V-I characteristic curve* of the diode expresses a resistive behavior. After that, it becomes simpler to speak of about several *V-I characteristic curves* such as those of a Zener diode or that of a Voltage Dependent Resistor (VDR), TRANSIL, etc., devices especially important to include in electrical installation against over-voltages resulting from lightning discharges.

For the diode on the OFF state, the typical model consists on an open switch, again a resistor, and a very high one at that.

During electronic class the students preferred a similar approach to explain how BJT works. In fact, the teacher had already identified that students reveal difficulties on understanding how the TBJ works using the traditional BJT model approach. Once students seemed to prefer an approach based on the *V-I characteristic curve*, then the teacher challenged a group of 3 volunteer students to develop a work that reflected their vision. This challenge was accepted and the work was divided in several parts:

a) The BJT working mode: regions of operati, the boundaries between operating zones; working regimes;

b) BJT model: definition of a basic model for BJT;

c) BJT Percetion analisys: of the clarity of those previous concepts in various means used by the student to study BJT; Ethernet sites, slides, videos, books;

*d) BJT Supporting mean*s *development:* develop a set of slides; movies

*e) BJT Supporting mean*s *evaluation:* teaching / learning satisfaction questionnaires.

In this paper we are focusing on points a), b) and also, but briefly, the point c).

III. Bipolar Junction Transistor working mode

Technically this component has three pins and appears in a large variety of enclosures. Fig. 1 shows a transistor example and the correspondent symbol.

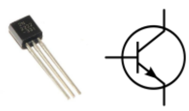

Fig. 1. Bipolar Transistor example and the correspondig schematic diagram.

One important part of this work was to study the topic and define a set of simple definitions related to the bipolar transistor, in order to later synthetize its mode of operation. The BJT can operate in three different *Regions of Operation* which are designated as:

- Cutoff
- Active
- Saturation

Is important to define the BJT *Regions of Operation Boundaries*. Finally, the BJT can operate in two *Working Regimes* that are designated as:

- Linear
- Switching

According to students opinion, (later demonstrated in the satisfaction questionnaires), "*definitions should be short and clear"*. One major task was to establish definitions according previous requirements. The first approach was to define literally the *Regions of Operation* and *Working* R*egime*. It was difficult, because each author tended to establish their own definition, and sometimes there were conflicts among them.

A. Bipolar Junction Transistor models

The bipolar transistor is a complex component, not easy to explain in a simple model. They are many models to explain bipolar transistors; some are simpler but disjointed from reality and others more realistic but much more complex. Fig. 2 presents a model currently used to explain the transistor behavior.

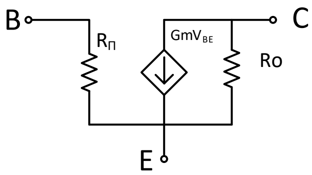

Fig. 2. BJT simplified pi model.

This model was considered considerably complex for beginners. The equivalent model presented in the Fig. 3 is only used when the BJT operates in the Active Region. For the remaining Regions of Operation, others models should be used. One main task was to establish a very simple model for Base–Emitter and Collector–Emitter pair pins. For Base–Emitter, the considered best approach was the diode corresponding to a well-known PN junction. Later in the developed slides, students emphasized that the P-N diode, Base-Collector in a BJT and Gate – Cathode in a Thyristor all present the same behavior. For the Collector–Emitter equivalent, the model considered easiest to understand was a variable resistance dependent on the base current. The simple model for a NPN transistor is shown in Fig. 3.

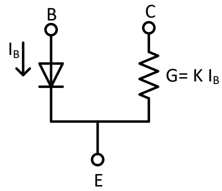

Fig. 3. A simple model for a NPN transistor.

The Collector–Emitter behavior can be represented as a resistance modulated by the Base–Emitter current. In fact, historically, the name of Transistor has it origin on Transfer – Resistor and according to the students involved in this study, this component working description is sufficiently *simple* and *comprehensive* to be used as the initial model for the study of transistors. For Collector–Emitter equivalent model, students consider three possibilities according the Region of Operation. *Cutoff*, *Active* and *Saturation* were considered, respectively, an open switch, a variable resistor and a closed switch. Note that this Resistor is a controlled one, which imposes a collector current that is given:

$$I_C = \beta \ I_B \qquad (1)$$

In simpler words, this resistor acts as a *current limiter* controlled by a *control current* I_B. Later on, this controlled resistor will be replaced by a controlled current source in order to have a more realistic and complex transistor model.

In short, the students defined a set of definitions (i) for all three regions of operation, (ii) for the two boundaries of operation, (iii) for the two working regimes, and (iv) a Collector-Emitter equivalent for each region. The results of these definitions are summarized in Table 1.

TABLE I. SUMMARY OF REGIONS SETTINGS OPERATION AND OPERATING REGIME OF TRANSISTOR

		BJT parameters						BJT-Regions of Operation Boundaries	BJT Collector – Emitter Equivalent	BJT Working Regime	
		V_{BE}	I_B	I_C	I_C/I_B	V_{CE}	V_{CB}			*Linear*	*Switching*
BJT Regions of Operation	Cutoff	<Vγ	= 0	= 0	–	V_{CC}	> 0	$I_B \neq 0$			•
	Active	≃Vγ	> 0	> 0	β	<V_{CC} > Vγ	> 0			•	
	Saturation	≃Vγ	> 0	> 0	< β	< Vγ	< 0	$V_{CB} = 0$			•

The value designated by Vγ refers to the conduction voltage of a PN junction and its value is:

$$V\gamma \approx 0{,}7\ V \qquad (2)$$

This table was especially well received by the students involved in this study because it is very compact and especially simple. It should be noted that the definitions mathematically depend on equalities (= sign) or inequalities (signs > or <). Also, one of the great advantages recognized is the clear identification of the boundary between the *Active* region and *Saturation* region. In the available literature this border is often defined in an unclear way and based in examples such as: ”a BJT is in saturation region when, for example, V_{CE} == 0.2V”. In this table it is clear that the boundary between *Active* and *Saturation* occurs for $V_{CB} = 0$

B. Students' perceptions

There are many means available for supporting learning about the bipolar transistor. The information can be presented in the traditional book support or in electronic support accessible through the internet. In this part, we must take into account two important aspects: Concepts' consistency and the correspondent student's perceptions. Note that those concepts associated to the transistor operation are not widely accepted. One of them is the boundary between the *Active* / *Saturation* region. For students, it is more important to have one than none. However, some learning means give examples instead definitions.

Students' perceptions is probably the most complicated issue to overcome. In fact, teachers have high level of knowledge about the bipolar transistor subject and as such, all learning means are satisfactorily clear. For students who only have low level of knowledge, the situation is completely different, everything becomes very complicated to understand. Thus, for a teacher, it is very hard to perceive student´s difficulties and perceptions. One way to overcome this in our work is to use students as kind of perception sensor. This is why we decided, from a very early stage of this study, to put students in the work team in order to reduce the risk of developing means that are not really useful for learning.

C. Avaiable learning support means perceptions

A team of students from the third year of Electronic Engineering degree developed this part of the work based on a scenario: the main idea was to suppose that they were on their first year degree and they need to study for an exam on an Electronic subject. What kind of means of studying would be used? All actions should be as realistic as possible. When questioned about learning means that would be considered, they chose internet sites, slides and videos. Despite not being chosen by the team, the teacher suggested also including some books for later comparison purposes. Then, it was suggested to select some examples of each kind, making only one remark: the selection should reflect a real situation as much as possible. No further suggestion was made and all selected examples were their responsibility only.

We had previously selected a set of transistor working concepts and the next step was to assess them using a psychometric scale commonly involved in research that employs questionnaires. This scale uses limits from 1 to 5, corresponding to a lesser degree of satisfaction to a higher degree of satisfaction, respectively. It is important to emphasize that the present means analysis **does not** correspond to any kind evaluation of the means utilized, but only to a set of **student's perceptions**. All analyzed means can be absolutely correct, both scientifically and pedagogically, and yet obtain a low assessment level in this work. Moreover, the analyzed means are probably adequate for a given level of electronic knowledge but on this work the target is to identify and/or develop learning means to support leaning on bipolar transistor for students on the very early stage of Electronic Degree. As said, the analyzed means were as listed:

- internet sites
- internet slides
- internet videos
- books

For all examples and for reasons of privacy, the order of assessed means does not match the order in the correspondent order in the associated table. All sites were assessed on May, 2016. For Internet Sites, the students selected the sites listed below:

- http://www.radioamadores.net/transistores.htm
- http://www.portaleletricista.com.br/transistor-funcionamento-e-aplicacoes/
- http://www.ebah.pt/content/ABAAAAV-oAB/transistor-bipolar-juncao
- https://en.wikipedia.org/wiki/Bipolar_junction_transistor
- http://www.allaboutcircuits.com/textbook/semiconductors/chpt-4/bipolar-junction-transistors-bjt/
- http://www.electronics-tutorials.ws/transistor/tran_1.html
- http://www.electronica-pt.com/componentes-eletronicos/transistor-tipos

Table II presents all considered transistor working concepts perceptions for selected above sites.

TABLE II. TRANSISTOR WORKING CONCEPTS PERCEPTIONS FOR SELECTED FOR *INTERNET SITES*

Transistor Operation	Transistor Working Concepts	Site #						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Transistor Regions	***Regions identification***	5	1	2	1	1	4	5
	Regions sequence	1	1	1	1	1	1	1
	Region characteristics	1	1	2	1	1	2	2
	Region boundaries	1	1	1	1	1	1	1
	Collector – Emitter equivalent	2	1	2	1	1	1	3
Transistor Regimes	***Regimes identification***	1	1	1	1	1	1	2
	Regions for Switching regime	1	1	1	1	1	1	1

For *Internet Slide Sites* the selected sites are listed below:

- http://slideplayer.com.br/slide/1486956/
- http://slideplayer.com.br/slide/282772/
- http://slideplayer.com.br/slide/1468596/
- http://pt.slideshare.net/firozamin/3bipolar-junction-transistor-bjt
- http://aries.ucsd.edu/NAJMABADI/CLASS/ECE65/12-W/Slides/ECE65_W12-BJT.pdf

Table III presents all considered transistor working concepts perceptions for selected above sites.

TABLE III. TRANSISTOR WORKING CONCEPTS PERCEPTIONS FOR SELECTED FOR *INTERNET SLIDE SITES*.

Transistor Operation	**Transistor Working Concepts**	**Slide site #**				
		1	**2**	**3**	**4**	**5**
Transistor Regions	***Operation regions identification***	2	5	3	5	4
	Regions sequence	2	4	1	1	3
	Region characteristics	1	3	4	2	3
	Region boundaries	1	1	1	2	3
	Collector – Emitter equivalent	1	1	5	2	1
Transistor Regimes	***Regimes identification***	1	1	2	2	1
	Regions operation for Switching regime	1	1	1	2	1

For *Internet Videos* the selected sites are listed below:

- https://www.youtube.com/watch?v=koYahjuYZe8
- https://www.youtube.com/watch?v=qqKgcJJN5r0
- https://www.youtube.com/watch?v=iwoebVm7ZVg
- https://www.youtube.com/watch?v=BAdCpVBhEvI&list=PLz5lDMUFoTXY2i302mV8rh0KkU17i10uN
- https://www.youtube.com/watch?v=usRAuTFK0wU&list=PLz5lDMUFoTXY2i302mV8rh0KkU17i10uN&index=2
- https://www.youtube.com/watch?v=SAZ8tttGW8c
- https://www.youtube.com/watch?v=uuPWfFHshZQ

Table IV presents all considered *transistor working concepts* perceptions for selected above sites.

TABLE IV. TRANSISTOR WORKING CONCEPTS PERCEPTIONS FOR SELECTED FOR *INTERNET VIDEOS*.

Transistor Operation	**Transistor Working Concepts**	**Video site #**			
		1	**2**	**3**	**4**
Transistor Regions	***Operation regions identification***	5	1	2	1
	Regions sequence	1	1	1	1
	Region characteristics	1	1	2	1
	Region boundaries	1	1	1	1
	Collector – Emitter equivalent	2	1	2	1
Transistor Regimes	***Regimes identification***	1	1	1	1
	Regions operation for Switching regime	1	1	1	1

For *Books* the selected examples are listed below:

- Sedra, A., Microelectronics Circuits, Oxford Press, 5.ª ed., 2004
- Richard C. Jaeger, Microeletronic Circuit Design, 4ºed
- Neamen, D., Microelectronics, Circuit Analysis and Design, McGraw Hill, 3.ª ed.ª, 2007.

Table V presents all considered *transistor working concepts* perceptions for selected books.

TABLE V. TRANSISTOR WORKING CONCEPTS PERCEPTIONS FOR SELECTED FOR *BOOKS*.

Transistor Operation	**Transistor Working Concepts**	**Book #**		
		1	**2**	**3**
Transistor Regions	***Operation regions identification***	3	4	3
	Regions sequence	3	3	3
	Region characteristics	3	4	3
	Region boundaries	3	3	3
	Collector – Emitter equivalent	3	3	3
Transistor Regimes	***Regimes identification***	3	3	3
	Regions operation for Switching regime	3	3	3

D. Supporting means development

In this phase of the work, the student's team proposed to develop some new supporting means, trying to reflect on it the identified missed information from their perceptions. The proposed new supporting means was a set of slides to which a sound track would be later added in order to produce a movie. The advantages were clarity, color and movement that captivated the student's attention. A beta version was already developed but working only in Portuguese language and available on [17]. Fig. 4 presents an image from that set of slides.

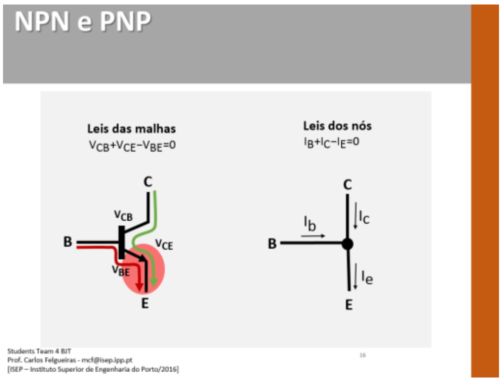

Fig. 4. Image of one slides from the set developed by the students team.

The adopted methodology, options and strategy will be explained in further presented work, following the validation of results using a pre-post questionnaires procedure.

IV. Discussion, Learning Developed Means and Preliminary Results

This section analyses results from student's perceptions. Analyzing all previous tables we can globally conclude that the perceptions of the selected means to support learning on bipolar transistor are poor. This result was as surprising as unexpected. The substantiation was also made by the student as follows.

In regard to *Internet Sites*, students said that the subject is exposed is either very superficial or too deep. Too little or too much information is equally unsatisfactory for beginners. The number of operation regions was poorly passed, and the respective order was never referred. In the set of slides developed by students, they emphasize this issue. Authors frequently refer "the BJT changes from the Cutoff to Saturation". This kind of phrase is widely used but, if not conveniently explained at least once, it creates in the student the notion that a BJT can pass directly from Cutoff Region to Saturation Region (and *vice-versa*) without going through the Active Region, which is incorrect. What really happens is that the passage through the Active Region is so quick and transient that it is not considered a stable state. Regarding Regions Boundaries and BJT *Working Regimes*, it was never mentioned.

In relation to *Internet Slide Sites*, students can perceive an improvement in clarity on the Operation Regions and the associated working order. However, the explanation about *Regions Boundaries* and *Working Regimes* still poor.

In relation to *Internet Videos*, students said that they were had the best performance of all analyzed means. Only the *Working Regime* and the shifting from *Cutoff Region* to the *Saturation Region* during the *Switching Regime* was poorly explained.

In relation to *Books*, student said that is the least attractive of all means because they present very plain text and too many definitions, being the least picked piece of information. For this reason, the rating was only medium.

The most interesting phase in this work was the verification that, along with this study, some information in some sites has changed. Students were pleased to verify that the information was clearly improved. Their comments stated "*... In the end, we are right in our analysis, since they have changed the information on the site in order to improve clarity for the students, according to our perspective…*" This moment was very rewarding for both students and teachers.

According to the students involved, it is necessary to develop a set of teaching resources oriented to the modeling of real components using ideal components and the graphic visualization of the behavior through the *V-I characteristic curve*. This aspect is very important to translate the graphical behavior of components or circuits. The role of the source acting as a current promoter and sources that function as current limiters should be clear. At the graphical level, no distinction is made, but the sources that promote the electric current do not dissipate thermal energy whereas sources that act as limiters convert electrical energy into heat, since they are inherently resistive. The behavior of the BJT using a controlled current source explains the electric behavior; the explanation that this is a limiter explains the thermal behavior. It is thus easier to explain the limitations in dissipated power of the components, e.g. VDR

V. Conclusion

The BJT is frequently considered an elemental component from Analog Electronics. Far from simple, it is a complex component that needed to be understood very deeply at behavior level. Our perceptions study tends to reveal that available learning support means apparently are more useful for teachers than students in the early phase of the engineering courses. A team of students accepted the challenge to analyze a set of resources used to support teaching / learning in BPT. Interestingly they support the idea that BJT models should be dynamic. BJT models should be simpler for beginners and growing in complexity along the course. They also developed a set of slides and videos aiming, in their opinion, to be clearer for beginner students in electronics.

Our next work will include slides and movie description and further validation.

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