# AN EPISTEMOLOGICAL BREAKTHROUGH[1]

## TEACHING (AND LEARNING) PHASE DIAGRAMS AT THE FRESHMAN'S YEARS

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### Abstract

It can be argued that knowledge of "phase diagrams" is a precondition to all materials science, since this tool is fundamental to understand and justify many of the process-microstructure-property relationships observed in the technology. Consequently, teaching phase diagrams assumes a prominent role in most undergraduate engineering courses. The present work identifies the set of beliefs associated with the knowledge of phase diagrams and discusses their impact on learning. The structure of three disciplines of the Materials Engineering undergraduate course at the Escola Politécnica da Universidade de São Paulo, held up to the 5th semester, is analyzed, regarding their methodological aspects. Understanding the relational interdisciplinary connections help to identify how the main beliefs associated with phase diagrams are chronologically introduced to the students and to suggest a relevance order to this process resulting in a less traumatic experience (with a consequent gain in learning ability).

**Keywords**: Engineering education; Materials science; Phase diagrams; Pedagogy.

## UMA RUPTURA EPISTEMOLÓGICA

## ENSINANDO (E APRENDENDO) DIAGRAMAS DE FASES NO CICLO BÁSICO

### Resumo

Pode-se argumentar que o conhecimento de “diagramas de fases” é fundamental para toda a ciência dos materiais, já que esta ferramenta é fundamental para justificar muitas das relações entre microestrutura, processo e propriedades na tecnologia. O ensino de diagramas de fases, assim, assume um papel preponderante na maioria dos cursos de graduação em engenharia. O presente trabalho identifica o conjunto de *Crenças* (*Beliefs*) associados ao conhecimento de diagramas de fases e discute seu impacto na aprendizagem. As estruturas de três disciplinas do núcleo introdutório (até o 5° semestre) do curso de Engenharia de Materiais da Escola Politécnica da USP são analisadas com respeito a seus aspectos metodológicos. A compreensão das relações interdisciplinares permite identificar como os principais saberes associados a diagramas de fases são introduzidos para os estudantes e sugere uma ordem de relevância para este processo, resultando em uma experiência menos traumática.

**Palavras-chave**: Educação em engenharia; Ciência dos materiais; Diagramas de fases; Pedagogia.

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## 1 INTRODUCTION

Phase diagrams constitute fundamental tools for the description of many microstructure-process-property relationships in technology. The binary Fe-C phase diagram, for example, is used in many of classical textbooks in Physical Metallurgy to describe different aspects of the processing of steels and cast irons. Haasen,(1) for example, discusses the relationships between crystal structures of the ferrite and austenite phases an their relation with the austenite stabilizing effect of carbon additions to steels. Reed-Hill,(2) on the other hand, dedicates an entire chapter of his classical book to the iron-carbon system, including a detailed description of steel heat treatment. Finally, Porter and Easterling(3) use the Fe-C phase diagram to discuss a more sophisticated case study in welding of low carbon steels.

The examples quoted above show that knowledge of phase diagrams is assumed to be completely dominated by a student in the later stages of a metallurgical or materials engineering course (when these examples are normally discussed). The apprehension of this knowledge in the earlier stages of the course, however, is not trivial. This is dramatically demonstrated by the extreme difficulty with which, for example, an average Physicist deals with trivial aspects of working with phase diagrams (e.g. reading a solubility limit or even identifying the domains of stability of phases or mixtures of phases) when he or she first gets in touch with it.

The aim of the present work is to employ the tools of epistemology in an attempt to identify how this knowledge is apprehended by an average student of the Metallurgical and Materials Engineering courses at the Escola Politécnica da Universidade de São Paulo. It is suggested that this learning process, at least in the present days, is traumatic, almost violent, and leads to the misleading consensus among the students that learning phase diagrams is “difficult”. As a consequence, a recommendation is made for the temporal distribution of the main concepts (in the epistemological language, the *beliefs*) along the introductory courses in order to soften this traumatic aspect, improving the learning ability of the students.

### 1.1 Structure of the Courses

The 13 engineering courses at the Escola Politécnica da Universidade de São Paulo are organized into disciplines distributed over ten semesters (five years). Irrespective of the particular engineering speciality the student chooses (or will choose, in some cases) each year all 750 new students attend a common set of disciplines during semesters 1 and 2. The first contact of the student with materials science (and hence, with phase diagrams) takes place at semester 2, in the discipline PMT 2100 – Introduction to Materials Science for Engineering (four lectures of 50 minutes each week, during about 15 weeks). The classes are not segregated, in the sense that the students who opted for all engineering specialities are intermixed (as part of a policy to foster interdisciplinarity in engineering). The contents referring directly to phase diagrams in this discipline are discussed in two weeks (i.e. four lectures), but the second week is dedicated to the study of the Fe-C phase diagrams and, hence, contents related with phase transition kinetics and basic steel physical metallurgy are also included.

At the end of the first year of course, 120 student, who previously opted in the university entrance application for the so called “chemistry great area” are allowed to choose between one of the following options: Chemical Engineering (60 positions), Petroleum Engineering (10 position), Mining Engineering (10 positions) and the

Materials Common Nucleus (40 position). The students who opted for the Materials Common Nucleus will later (at the end of the 6th semester) further decide between the Metallurgical Engineering (20 positions) and the Materials Engineering (20 positions) courses. Irrespective of the particular choice, these 120 will have a second contact with Materials Science (and with Phase diagrams) in the 3rd semester, at the discipline PMT2200 – Materials Science (four lectures of 50 minutes each week, during about 15 weeks). Contents directly related to phase diagrams are given in two lectures (i.e. 1 hour 40 minutes).

Finally the students who opted for the Materials Common Nucleus attend a third discipline in the 5th semester fully dedicated to phase diagrams: PMT2307 – Phase Diagrams (four lectures of 50 minutes each week, during about 15 weeks). As can be seen, the course structure is considerably complex, both the dedicated time and the attendance are different for the three disciplines. First, the early contact of the student with phase diagrams is limited in time, second the attendance in not homogeneous: the *students* of PMT2307 are a subset of the students of PMT2200, which are a subset of the students of PMT2100.

## 1.2 Epistemology

The word “Epistemology” is derived from the greek language, through composition of “έπιστήμη” (knowledge, science) and “λόγος” (theory) and, hence, can be understood as the **theory of knowledge**.(4) It is a sub-area of Philosophy and deals with the nature and scope of knowledge, what is knowledge, how is knowledge acquired and so on. Classical (platonic) epistemology distinguishes two forms of knowledge: *knowing that* and *knowing how*. As it will be discussed in the present work, much of the stress involved in learning phase diagrams results from a confusion about the two forms of knowledge. The reader must keep in mind that this view of knowledge in epistemology has been criticized by contemporary philosophers,(5) but it will nevertheless be used in this work since the distinction between the two forms of knowledge is clear in the case of phase diagrams.

Standard epistemology defines a precondition to knowledge called “*belief*”. This concept can be drawn back from the works of Plato(6) and can be defined as some prediction that will be proved to be useful or successful in the future. The *belief* is contrasted with the concept of “*truth*” which is a prerequisite for something to be believed in. It is not correct to assign knowledge to a fact that is believed in, but which is proved to be false by some means (for example, nobody *knows* today that the earth is flat, because the spherical shape of earth has been accurately proved).

The link between belief and truth is constructed by the concept of “*justification*”, which, according to Plato is a belief which has “been given an accounted of”.(6) That is, a true belief can only be considered so, if someone´s is given a good reason to do so. Using these three concepts, standard epistemology defines knowledge as a “*justified true belief*”. Again, modern philosophy criticizes this view of knowledge using counterexamples,(7) but it will be used in the present work because knowledge of phase diagrams hardly fall on these complex logical puzzles. It must be stated that the concept of *justification* is subjective. Everybody **knows** the first law of thermodynamics because we have heard affirmations that all careful experiments performed until today shows that it holds, but almost nobody in the world has performed one of such experiments, or even has competence to interpret these results. This example shows that sometimes the *common sense* is used as a form of justification.

As previously stated, the view of knowledge as a “justified true belief” is employed in the present work because it is useful. In particularly it mirrors the way a typical student learns something: a (true) concept is presented to the student and justified by the teacher, until it turns out to be believed. The first task of this work, therefore, corresponds to identify the set of beliefs relative to phase diagrams which has to be transmitted to the students.

## 2 BELIEFS RELATIVE TO PHASE DIAGRAMS

Let us focus our attention to the following definition:
“Phase diagram is a map, characteristic of a given *thermodynamic system*, which shows the domains of stability of *homogeneous and heterogeneous equilibria* as a function of two or more *state variables*”.
The highlighted terms are concepts which a first year student, supposedly, already dominates[1]. Nevertheless, the teacher is forced, even in such a trivial affirmative, to reintroduce these ideas, which seem unfamiliar to the student. The reason is that, up to that point, the student was faced with these concepts in a quite abstract form (for example, the most quoted example of a thermodynamic system is the “universe”, which is totally useless, in the same way examples of heterogeneous equilibria are mixtures of oil and water or sand and water which do not present obvious dependencies with state variables). These concepts, in the context of phase diagrams, assume, on the contrary, a quite concrete form, e.g. the “system” is formed by a set of elements, the homogeneous or heterogeneous equilibria can be intuitively understood or even be observed in a microscope (e.g. a solid/liquid mixture inside a solidifying casting mold or a pearlitic microstructure in a steel) depending strongly on the state variables, and so on. This simple example shows the kind of difficulty that a teacher faces when dealing with freshmen students in the introductory courses. A simple statement about this fact is able to break resistances by the side of the student, allowing him or her to understand that Phase Diagrams are concrete (in the sense that they are not abstract) properties of thermodynamic systems.
The underlined sentence is, in the present author's opinion the first and most fundamental Belief associated with the phase diagrams. The justification can be achieved by different strategies. The teacher can, for example, start with cooling curves of a initially liquid alloy as a function of composition, building the *solidus* and *liquidus* lines in an isomorphous system. Avner, for example, uses this strategy in his textbook.(8) The teacher can also access intuitive knowledge of the student about phase transitions. For example, one of the teachers responsible for the PMT2100 discipline uses the idea of precipitation in a $NH_3Cl/H_2O$ solution as a function of temperature to discuss the idea of solubility limit.(9) Anyway, to stress the concrete aspect of phase diagrams it would be recommended that the teacher works with real existing systems and data (for example, the Cu-Ni phase diagram instead of a generic isomorphous or the true solubility curve of $NH_3Cl$ in $H_2O$ as a function of temperature).
Next, the student learns that Phase diagrams are useful tools in materials science and technology. The justification of this belief requires exposing the student to a large number of examples coming from technology. These examples should be worked out to learn the kind of phase diagram information which allows to understand the relations between microstructure, process and properties. This is a typical “knowing

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[1] *In the Brazilian educational system these concepts are introduced during the Secondary Course, the Brazilian equivalent to the American “High School” and to the German “Gymnasium”.*

that" situation[2] and requires learning a set of skills: how to read the equilibrium composition of a phase in a two-phase mixture, how to apply the lever rule, in other words, how "to read" a phase diagram.

Here the teacher approaches are variable, almost chaotic. The teacher of the discipline PMT21000 faces the formidable task of teaching the lever rule to first year engineering students. Most of them will not recognize the use of this knowledge in the future, since they will, in the majority, move to a course different from the ones of the chemistry great area. So, from the student perspective, they have to learn this "only" in order to get the "grades" in the discipline. The teacher struggles with the dilemma between being pragmatic, transmitting how to use the lever rule, or teaching where do the lever rule comes from.

The teacher, for example, may decide to demystify the lever rule using the following exercise:

Consider a binary system A - B of total mass $m$ , with average concentration $w$ of component B, in thermodynamic equilibrium at temperature T. This equilibrium consists of two phases $\phi$ and $\theta$ of unknown masses $m^{\phi}$ and $m^{\theta}$. From the phase diagram we know that these two phases possess at that temperature, respectively, concentrations $w^{\phi}$ and $w^{\theta}$ of component B. What are the equilibrium values of $m^{\phi}$ and $m^{\theta}$ in function of $m$, $w^{\phi}$ and $w^{\theta}$?

Solution:

From the definition of concentration and using mass balance we know that the total content of B in phase $\phi$ is given by:

$$m_B^{\phi} = m^{\phi} w^{\phi} \qquad (1)$$

similarly, we have for phase $\theta$:

$$m_B^{\theta} = m^{\theta} w^{\theta} \qquad (2)$$

but we also have:

$$m_B = mw \qquad (3)$$

and

$$m_B = m_B^{\phi} + m_B^{\theta} \qquad (4)$$

Substituting Equs. (1), (2) and (3) into (4) we have:

$$w = \frac{m^{\phi} w^{\phi} + m^{\theta} w^{\theta}}{m} \qquad (5)$$

Here it is useful to introduce the (new) concept of mass fraction of a phase, $\eta$:

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[2] *Like the one proposed by M. Polanyi: learning how to drive a bicycle is quite different of learning the physics behind bicycle driving and the former requires a lot of falls.*(10).

$$\square^{\square} = \frac{m^{\square}}{m} \quad \text{and} \quad \square^{\square} = \frac{m^{\square}}{m} \qquad (6)$$

Using (6) we can rewrite Equs. (4) and (5) as:

$$\square^{\square}\,\square\,\square^{\square} = 1 \qquad (7)$$

and

$$w = \square^{\square} w^{\square}\,\square\,\square^{\square} w^{\square} \qquad (8)$$

which can be solved, for example, for $\eta^{\theta}$, leading to:

$$\square^{\square} = \frac{w - w^{\square}}{w^{\square} - w^{\square}} \qquad (9)$$

which is the lever rule.

The answer to the exercise requires determining the masses of $\phi$ and $\theta$, which are given by:

$$m^{\square} = \square^{\square} m \quad \text{and} \quad m^{\square} = \square 1 - \square^{\square}\square m \qquad (10)$$

This exercise is valuable since it is simple and works with quantities which are familiar to the student, like mass and concentrations. It can be solved together with the student in about five minutes and results in the positive effect that the lever rule is naturally introduced, as well as the definition of a subsidiary variable, the mass fraction of a phase. It is important not to skip the last step and to insist that the student gives the answer in terms of the masses of the two phases.

The solitary use of this exercise, however, is problematic. Analysis of Equ. (9) shows that the B concentration in **phase** $\phi$ enters in evidence for the expression of the mass fraction of **phase** $\theta$. The teaching experience of this author shows that this simple apparent logical inversion is sufficient to induce errors and a generalized blockade in the learning of the rule. Here it becomes evident that learning how to build the lever rule is different from learning how to apply it. Pointing at this inversion with this exercise allows the student to become aware of these errors, avoiding them.

The exercise above was solved in a generalized fashion, but in view of the first Belief it would be useful either to develop it using a real phase diagram, or, at least, applying the results afterwards to an existing phase diagram.

Of course, developing the skills described above take a lot of effort by the student (and requires a lot of dedication by the teacher), but they cannot be considered equivalent to the second belief. The application to a technological problem is required to achieve this objective. Here, for example, the introduction of the Fe-C phase diagram is recommended, not only by giving the teacher a direct connection with an important technological process (heat treatment of steels), but also by allowing the study of a complex phase diagram, with many new ideas and concepts (for example, metastable phase diagrams, eutectoid reaction and microstructures, the peritectic reaction, and so on).

Considering the structure of the courses at the Escola Politécnica, it is clear that the skills and technological links to phase diagrams have to be worked out over and over again in the different disciplines. This repetition is healthy, provided a clear progression in the content is achieved at each step. For example, the concept of tie-line is first introduced in PMT2100 using binary phase diagrams, but is reintroduced in PMT2200, this time referring to ternary phase diagrams and the usage of the Gibbs triangle.

Finally a third Belief associated with Phase Diagrams is here suggested: Phase diagrams and (gibbsian) thermodynamics are closely related. More than one student (as well as several professionals, including teachers) report the utility of demonstrating the relation of phase diagrams with Gibbs free energy curves to learning. This relation transcends the simple objective of showing how the different phase diagram types are built from more fundamental properties. It grants the student also a way to fix, in a graphic manner, thermodynamic concepts like the determination of the stable equilibria in open systems by minimization of the free energy, chemical potential definition and its relation with the partial molar Gibbs energy.

The simple introduction of the free energy curves and of phase diagrams as their consequences must be made with care. Fundamental concepts in thermodynamics are needed in this case. The teaching experience of the present author, as professor of PMT2200 shows how difficult this connection can appear to a thirds semester student. The “phase diagram lecture” of PMT2200 starts with a detailed derivation of the condition for thermodynamic equilibrium in open systems, which ends up in the definition of the Gibbs free energy, and after that, the building of a prototype phase diagram using the common tangent construction. This part takes about 50% of the lecture (i.e. 50 minutes).

The students of PMT2200, which have only basic ideas about thermodynamics, mostly derived from the secondary school, show a remarkable resistance to understand the common tangent construction. A simple idea, so praised by most of the advanced students, is completely alien to the third semester student!

## 3 CLOSING REMARKS AND RECOMMENDATIONS

The preceding discussion identified three beliefs associated with learning phase diagrams, these are summarized in Table I. Of course, this classification is subject to different interpretations and should not be considered as absolute. Still, the present author is convinced that this division is useful and its adoption in introductory materials science course should help the student to learn the subject “phase diagrams” in a less violent fashion.

The three beliefs are thought as hierarchic and should be introduced to the student, at least initially, in the order given in the table. As a matter of fact, many typical “errors” in this process are known to perturb phase diagrams learning, for example, failure in showing the usefulness of phase diagrams result in students who are learning phase diagrams only as “another” subject, disconnect from “real world”. Teaching only the tools (the lever rule, for instance), lead the student to learn phase diagrams as an automaton, contributing, again, to the feeling that “phase diagrams are useless”. Finally, introducing Gibbs free energy curves to unprepared students result in perplexity and, of course, reduces the positive impact that the demonstration of the connection between free energy curves and phase diagrams will have in the future (one has already “spoiled the secret”). The result is a rebellious student which learns phase diagrams by the power of the grades and not by perceiving them as a useful tool to technology.

**Table 1** – Summary of the beliefs associated with learning phase diagrams and major tools available to the teacher to accomplish this task

| Belief | Tools | Recommendations |
|---|---|---|
| Phase diagram as thermodynamic property of a system | Phase diagrams of real systems, phase diagram as a map | Use real phase diagrams and or build a phase diagram from easy and intuitive “experiments” |
| Phase diagram as a tool in materials science and technology | Reading solubility limits, lever rule, phase rule. Applying it to “real” materials technology | Do not neglect the link with technology, it is a powerful motivation to engineering students |
| Phase diagram as a byproduct of gibbsian thermodynamics | Building phase diagrams out of Gibbs free energy curves | The needed thermodynamics should be taught in parallel (or at least simultaneously) |

Regarding the disciplines in the Escola Politécnica, the adherence to these ideas is not perfect, particularly in discipline PMT2100, but all steps are present in the four lectures dedicated to phase diagrams. The two lectures in PMT2200 are mostly dedicated to the third belief, but beliefs one and two are reworked, by introducing ternary systems (and the Gibbs triangle) and a particular example of using phase diagrams in microelectronics, which links to other contents discussed in the discipline.

The “epistemological breakthrough” of the title refers to the violent process of learning phase diagrams in the first two years of an engineering course and to all engineering students. More conservative courses introduce phase diagrams in a latter time and to a selected audience, composed of future materials engineers. The purpose of this work is to point out that this violent process can be softened by properly motivating the student, showing how useful phase diagrams are both for technology and for learning other aspects of materials sciences.

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