# From the classroom to the game: applying available pedagogical guidelines in game-based learning

Pedro Santos Bartolomé
Process Engineering for Sustainable Systems (Process)
KU Leuven
Leuven, Belgium
pedro.santosb@kuleuven.be

Tom Van Gerven
Process Engineering for Sustainable Systems (Process)
KU Leuven
Leuven, Belgium
tom.vangerven@kuleuven.be

***Abstract*—Abundant literature of game-based learning for engineering education exists, due to growing technical advances, familiarity, and previous studies showing improvements on engagement. Similarly, studies on pedagogical guidelines for traditional lectures are abundant and have been shown to improve student learning. However, literature is very limited on educational games for engineering designed using pedagogical principles. To address this issue we collect, from available guidelines validated for classroom settings, 17 guidelines that can be directly applied into pedagogical game design: these guidelines are studied, and a demonstration of their application is shown during the design of a pedagogical game for Vapor-Liquid equilibrium.**

**Keywords—Game-based learning, Serious games, Active learning.**

## I. Introduction

The idea of integrating game-based learning into engineering classes is not new: *educational games* (games that focus on pedagogic objectives rather than entertainment, also known as *serious games*) have been used and registered as part of the literature. We can see examples that range from interactive simulations where one studies the behavior of a distillation tower [1], to racing games to learn automatic control [2], machining web applications for mechanical engineering [3], phone games for organic chemistry [4], 3D chemical plants [5], labs [6], [7], up to VR and AR applications [7]–[10] to show only a few examples.

The origin of this motivation is clear: in some cases games can perform better than traditional instruction [11], [12]. This is not an exclusive property of games: much has been written complaining about traditional instruction for engineering [13], mainly, that it's boring and demotivating, with many students choosing to drop out [3]. Engineering is an inherently active discipline, and yet, to learn it, most hours are spent sitting in lectures given by speakers of ranging ability, teaching content of which even in the best case, little can be retained after some hours have passed.

Research shows that an alternative approach is more successful [14]–[19]: *active learning* is the name given to a range of teaching approaches that seek to make classes more effective by increasing the relevance for the student. Problem-based learning, flipped classrooms and project-based learning, are approaches shown to be effective by making the student become more active, and take responsibility of their own learning.

It is then no surprise that game-based learning, an activity where the player is inherently active, has been seen as an approach to solve the same issue (sometimes even used conjointly with active learning, as in [20]). However, due to its special technical demands, game-based learning is normally studied apart from the other active learning approaches, which has led to a loss of information. Unlike other examples of active learning, which benefit from useful guidelines (see [21]) that can be used to help implement them successfully, educational games are still in a state of infancy within finding their own pedagogic guidelines [9], [22], and examples in literature such as [1]–[9] show that they are generally designed ad-hoc, with almost no help from previous pedagogic research.

This is the fundamental issue that the authors have looked to address in this work, where pedagogic guidelines used in active learning that can be incorporated directly into educational game design have been compiled. The authors will demonstrate the application of these guidelines for design by integrating them in an educational game for helping students learn about vapor-liquid equilibrium.

The rest of the work is divided into three sections: the first reflects on the previous literature on educational game design, and compiles and describes the pedagogic guidelines taken from the general field of active learning. Section III shows the design of an educational game for introductory vapor-liquid equilibrium implementing the guidelines. The final section provides the conclusion and final comment of the work.

## II. Pedagogical guidelines

Despite the ample literature regarding educational games, it is hard to find pedagogical guidelines for the designer: on the one hand there exists a literature of descriptive models such as [23], designed for analyzing the pedagogical content in existing games. As these models are intended for analyzing finished games, designers would find it challenging to make use of them during the design process. Prescriptive models, intended to help design games, also exist. However, they are not very specific, due to the nature of game design.

Just like no military plan can survive first contact with the enemy, no prototype design can survive first contact with the players. In both cases, one of the engaged parties might plan what they want to happen (although even the designer might find themselves doing something else once they start testing their own game), but they cannot predict with certainty how the other party will react to their actions. The approach to tackle this issue in game design is prototype iteration: a prototype is developed, and then iterated on and tested with students until the result is satisfactory [24].

Prototype iteration implies that very specific prescriptive models for educational game design will not be very useful, as interaction with the students will show that certain aspects of the educational game are not working as intended, others are working better than intended and should be focused on, and yet others are providing information that the student should have access to, or show that further information is required that the designers didn't originally think of. All of these insights found during testing of a prototype will lead to changes, which will have to be tested again to observe the effects, leading to further changes to the prototype. This is especially true for educational games that have to be played outside of the class environment or in large classes, those where the teacher does not have the ability to intervene in the moment to stop incorrect behavior or misconceptions the students might be developing.

The literature shows that useful prescriptive design models such as [24], [25] encourage this aspect of prototype iteration. These models focus on two design principles: maintaining constructive alignment (see guideline 1 below) and focusing on prototype iteration with students, principles that the authors encourage completely as well, but that will leave many designers with too many open directions and too little indication. Instead of looking for prescriptive models that give a step by step path to the final design, guidelines must be general, for the designer to apply them at a case by case basis depending on their specific educational game idea and their existing design.

Some pedagogic guidelines specifically for the design of educational games are researched in the literature (see the meta-analysis by [12]), but this is normally focused on aspects that pertain specifically to games, and still mostly a subject of research rather than widely applied. This stands in contrast with active learning guidelines for classrooms, which are well researched and widely applied by many teachers.

In this section we will now go over the concept of active learning, and those existing guidelines that can be translated into game design. If we have found literature pertaining to the use of a specific guideline in educational games, we will include it as well.

### A. *Active Learning*

Active learning means placing the student in an active position during the learning activity, as opposed to the passive position in which students are placed in traditional education. The main attraction of active learning is that it has been repeatedly shown to work quite well within traditional education, and particularly for engineering topics [14]–[19].

Active learning can be taken in many approaches, such as inverted classrooms, problem-based learning or project-based learning, and many guidelines have been developed to integrate it within traditional curricula [21]. We see game-based learning as a branch of active learning, as it is clear that a student playing a game is in a more active role than one listening to a lecture. With this in mind, we have extracted from those active learning guidelines compiled by [21], 17 that we found especially valid for educational game design (see Table I).

While, to some extent, any active learning guideline is applicable for game-based learning, many of them are dependent on external circumstances such as the presence of a teacher or on the use of the classroom environment as it is normally understood. Here, however, we have considered only those that can be directly incorporated into the play of the game itself, without needed of anything external: these 17 are guidelines that can be considered during the design of a educational game, and that will become a part of the play experience of the students independently of in what environment they will end up engaging with the game.

### B. *17 guidelines for educational games*

*Write and use observable Learning Objectives:* Explicit learning objectives that are realistic and observable, as opposed to abstract objectives such as “understand” or “know”, allow to focus more clearly on the intended outcomes, to judge if they are being achieved, and to plan all the elements of the game to address them. This last approach is known as *constructive alignment*, and has been shown to be effective in game-based learning [26], [27], to the point where it has become a basis of the prescriptive design models (see [24], [25]). [28] provides a popular taxonomy that can be used for the design of learning objectives, and [29] proposes a framework for which type of game to design depending on the level of learning objective.

*Inform students of the Learning Objectives*: Learning objectives help students focus on the relevant parts of the experience, as well as allowing them to organize better their own study efforts.

*Introduce deliberate practice*: Practice should be focused towards those aspects the student performs worse at, rather than practicing all aspects equally [30]. Weak aspects are those where most improvement can be made.

*Avoid content overload*: Too much information can hamper learning, if the student has to spread too thin [31]. Include only material that is necessary to know, and avoid blocks of text or other ways of presentation where the student faces large amounts of information. Instead, [26] suggests adding interesting but unnecessary material in internal encyclopedias similar to those used in games like *Civilization*. In the same line, consider making simulations simpler than the real world: [32]–[34] remark that in game-based learning, higher accuracy does not cause more learning.

*Present real-world problems before theory*: Firstly, this motivates students, by giving them a reason to pay more attention to the theoretical content once it is presented. Additionally, by facing problems before they are fully equipped with the theory, they can explore and study them more fully, facing a *desirable difficulty* that helps deepen learning.

*Induce (spaced) repetition*: Introduce the same concept multiple times, and have the students deal with it repeatedly. Instead of many repetitions in a short amount of time, aim for spacing in-between, which improves long-term learning.

*Introduce variation*: Variety increases retention of knowledge, by allowing the student to face the same concept in different instances. Learning is enhanced by interacting with the same concept in different situations, environments, and tasks.

*Actively engage students*: Games foster learning by placing students at the center of the learning process [35]. This active element can be hampered by taking away agency from the student, and by placing passive elements such as cutscenes.

*Provide support (scaffolding)*: While active learning encourages students to take more control of their own learning, there is still a need for support and guidance during learning, which can be provided by placing questions, giving fast feedback, or providing strategies for tackling the problem. This is often known as *scaffolding*, and for the particular case of game-based learning it has been shown to improve the performance of students when compared with other approaches such as open exploration [36], [37].

*Introduce retrieval practice*: Retrieval practice is the exercise of remembering a topic from memory, without looking up any notes. It has been shown to be more effective than other ways of studying such as highlighting important information, or making concept maps.

*Foster the student's self-efficacy*: Higher self-efficacy (perception of their own competence) leads to increased results, both in learning results and in effort, as well as in the job market. Provide the student with early successes to improve their self-efficacy, and use supportive feedback.

*Avoid time pressure*: Feeling time pressure can decrease motivation and performance in students, lowering the self-image of slower students, and giving less time for other elements that encourage learning, such as reflection, retrieval or repetition. This guideline is in particular need of research, because for the case of games, time pressure can also lead to increased engagement and a sense of "flow" (even when it causes the players to fail more) [38], effects whose impact on learning remains unclear.

*Induce commitment to misconceptions*: To correct a misconception, a student should first commit to it, then be faced with a demonstration of it being wrong, and finally be shown the correct belief. This cycle leaves a more lasting impression, and so it can be used when addressing incorrect beliefs held by the students.

*Benefit from peer instruction*: By grouping students, those with higher knowledge get the learning benefits of tutoring those with lower level, while the students with lower level benefit from the extra tutoring. Research of games shows collaboration among students when playing a game can cause positive effects some times, but not always [12], [39] (this research addresses only in-person collaboration and not online or time-delayed, regarding which the authors could not find results in the literature).

*Use interleaving*: Instead of blocking learning objectives separately, as most educational programs do (e.g., dedicate the first block exclusively to vapor-liquid equilibrium, the second to liquid-liquid equilibrium, the third to solid separations, etc.), interleaving is the practice of mixing these blocks (place problems for the three blocks together, and have the students solve them simultaneously). It has been shown to provide significant improvements in learning, both on the short and long term [40], [41].

*Place gaps in learning materials*: Incomplete materials, such as those missing formulas, diagrams or words, have been repeatedly shown to improve learning for students over the complete versions [42].

*Encourage students to reflect*: Reflection is a key part in the integration of knowledge, which lays mostly within the control of the student. Often the students already choose to reflect during the play of an educational game without any special encouragement, but reflection can also be encouraged by providing questions, checklists, asking the student to explain something, inducing discussion with other students, or asking for a debriefing as a final task. [43] found that some successful options to encourage self-reflection in educational games can be prompts, collaboration, and worked examples. Regarding prompts, [44] found focused self-explanation prompts were more effective than recall or abstract self-explanation.

*Keep testing the prototype*: As the astute reader will guess, this guideline is game-specific and not actually extracted from any active learning guides, which is why it has been marked as the 0$^{th}$ guideline. It is, however, so fundamental to educational game design, that it seemed reasonable to stress it none the less. Testing a game as early and as often as possible (even if it is just with placeholder art or only with a few mechanics) is fundamental to avoid surprises deep into the process.

Since these guidelines have been tested specifically for lectures, it appears unlikely that all of them will be useful for every educational game. As examples, guideline 2 (*Inform students of the Learning Objectives*) is inappropriate for an educational game where the student should not be aware of the intended learning outcomes (*stealth instruction*), and guideline 7 (*Introduce variation*) might be inappropriate for a game targeting a very specific learning goal, such as a standardized safety procedure for a specific chemical plant. It is to be expected that the closer the game is intended to be to an academic environment, the more these guidelines will apply. However, since learning is a universal experience based on fixed psychological patterns [45], the authors expect the guidelines to be positive to some extent for a large variety of educational games.

TABLE I. 17 PEDAGOGICAL GUIDELINES FOR EDUCATIONAL GAME DESIGN

| | ***Pedagogical guidelines*** | ***Relevant studies*** |
|---|---|---|
| 1 | Write and use observable Learning Objectives | |
| 2 | Inform students of the Learning Objectives | [46] |
| 3 | Induce deliberate practice | [30] |
| 4 | Avoid content overload | [31] |
| 5 | Present real-world problems before theory | [47] |
| 6 | Induce (spaced) repetition | [48] |
| 7 | Introduce variation | [49] |
| 8 | Actively engage students | [19] |
| 9 | Provide support (scaffolding) | [50] |
| 10 | Introduce retrieval practice | [51] |
| 11 | Foster the student's self-efficacy | [52] |
| 12 | Avoid time pressure | [53] |
| 13 | Induce commitment to misconceptions | [54] |
| 14 | Benefit from peer instruction | [55] |
| 15 | Use interleaving | [41] |
| 16 | Place gaps in learning materials | [42] |
| 17 | Encourage students to reflect | [56] |
| 0 | Keep testing the prototype | [24] |

## III. CASE STUDY

Our target has been to begin the design process for a educational game that can be used to supplement traditional instruction for the first year of chemical engineering in the topic of vapor-liquid equilibrium (VLE). Previous experience has shown that this topic is challenging to the students, as it is always one of the sources of mistakes during the examinations (a previous study by [57] shows that students often retain misconceptions regarding this topic). It is also one of the fundamental topics in chemical engineering, as it is the basis of a branch of separation operations.

Since our intention is to integrate the use of the game into traditional education, the length of a play session should be as short as possible, to fit within an exercise session or even a lecture. An additional limitation is the amount of resources that can be destined into the design, since it is not intended to be a major project, in contrast to some educational games available in literature.

Firstly, the authors analyze the basic content of VLE to choose some general learning objectives: the students will have to be able to understand the concept of vapor pressure, understand how it influences the VLE behavior of single components and mixtures, and be able to apply Raoult's law to predict this behavior in binary mixtures. To address these objectives, we decide on a setup where the student is a researcher investigating these same topics, and will be hired to answer evaluating questions regarding VLE.

A 2D game environment is decided on: this is done to reduce workload, and because it did not appear that the topic would benefit from 3D. The art was obtained from the open repository of [58], as a placeholder until final art can be produced. The design requires at least three elements: the player, the research equipment (with controls for pressure and heat), and a prompt which asks questions regarding the topic. This basic setup (implemented in Unity) can be seen in Fig. 1.


Fig. 1. View of the starting game prototype. Elements from right to left and top to bottom: Funds display, research equipment (pressure control, heat control, visualization), evaluating questions prompt, player character.

After this initial step, we give a look through each guideline, and how they can be implemented to improve the design (if relevant):

*Write and use observable Learning Objectives:* Although we have chosen learning objectives that are already specific, they are not directly observable in the game. Instead, we will specify some more clear objectives:

1. (Understand) *Identify* the vapor pressure of a single component for various temperatures;
2. (Apply) *Predict* the state changes of a VLE single component system of known vapor pressure under changes of pressure and temperature;
3. (Apply) *Predict* the state changes of an ideal VLE multiple component system of known vapor pressures and total concentrations under changes of pressure and temperature;
4. (Apply) *Calculate* the equilibrium concentration of a component in each phase of an ideal VLE binary system, for known vapor pressures, using Raoult's Law.

These four Learning Objectives are measurable inside a educational game, and we will integrate them into the design by using them to categorize the questions that will be placed to the student in the game, which will be divided into four levels of growing difficulty.

*Inform students of the Learning Objectives*: We will integrate this guideline by providing the learning goals along with the introductory information to the game (the manual).

*Induce deliberate practice*: Since we have categorized the questions into four learning objectives, we can induce deliberate practice by keeping track of the performance of the student in each learning objective, and assign questions from the objective with lowest performance.

*Avoid content overload*: We will avoid introducing more elements, or any knowledge that is not part of the learning objectives, e.g. we avoid explaining a molecular view of VLE. We also keep the questions as short as possible, and the machinery as simple as possible, e.g. the heat control will only show temperature values, and not any heat values, to avoid adding an additional variable for the student to pay attention to. Finally, we will present the levels of questions sequentially, so the student will have the chance to master the first learning objective before advancing into the second, third, etc. New levels are reached by buying more equipment with the money obtained from correct answers.

*Present real-world problems before theory*: Students will be presented with real world questions regarding VLE, the answers for which they must find with the research equipment. To make questions more practical, air-water is chosen as the binary system (simplifying "air" as a pure component), since this is the most common VLE system students encounter. The theoretical content is intended to be presented afterwards, in a traditional lecture, and is not included in the design.

*Induce (spaced) repetition*: Each learning goal will be assigned many questions, so the students can practice multiple times and learn from mistakes. Questions are not placed in a battery to be asked one after another in quick succession, but instead some spacing is given between questions. However, as the game intended length is relatively short, the major benefits of spacing (waiting hours or days) cannot be achieved.

*Introduce variation*: The questions address four different learning objectives, and will each be given a different context, ranging from everyday situations such as cooking or weather conditions into extraordinary ones like geographic or space expeditions. However, this is not a lot of variation, and this remains a weak point of the design. Higher variation could be achieved by including different characters and laboratory situations (e.g. switching between a public and private research facility, or between research and process implementation), or by using other elements beyond water and air, but all the proposals the authors have handled either go against some of the other guidelines, or are too resource-demanding for the intended project. The guideline remains one to pay special attention to during the continuing design process.

*Actively engage students*: The student will be placed in control through all the game, and can choose what action to take at any point, with no cutscenes or mandatory actions.

They can choose when and how to address a question, and how to structure their research with the equipment.

*Provide support (scaffolding)*: To provide support for the students, scaffolding questions are introduced: these questions, unlike the evaluating ones, cannot be failed, and instead only ask the player to reach a certain state with the equipment (for example, place water at 105 °C and 1 atm). These provide a safe guide for the player to get familiar with the controls and the behavior of the system, in what is often termed *guided exploration*. Additionally, when evaluating questions are answered, the feedback will provide useful advice.

*Introduce retrieval practice*: When the students chooses to answer a question, they will be placed into a fixed state, where they cannot do anything else before they answer (particularly important, they cannot look for the answers with the research equipment).

*Foster the student's self-efficacy*: After each level increase (and at the start), the game will wait until some scaffolding questions have been answered before starting to present evaluating questions (since the scaffolding questions cannot be failed, this will provide early successes which help foster self-efficacy). Further, we will avoid critical remarks for failed questions, and the main character will be addressed as a respected and competent researcher.

*Avoid time pressure*: We avoid any influence of the speed of the student, except to provide some spacing between questions. Students have as much time as needed to answer any of the questions, and to decide when they wish to engage with them.

*Induce commitment to misconceptions*: We target students that have not yet seen the material, and so misconceptions were not explicitly considered in the design. However, the evaluating question system forces commitment of the student to a certain answer before receiving feedback, and so can be used to tackle misconceptions that arise during further testing.

*Benefit from peer instruction*: In order to simplify design and avoid technical challenges of implementing a multiplayer system, the design game does not include any peer instruction. This point can be tackled outside of the game design by placing players in groups.

*Use interleaving*: Instead of removing previous learning objectives, as the student advances through the learning objectives they will continue to receive questions of the previous ones. This stands in contrast with many educational games where each level tackles a specific concept.

*Place gaps in learning materials*: Since the game does not include any theory, this guideline was not found relevant. If the decision is made to include theory in the game as well, it will be included as incomplete notes from a previous researcher.

*Encourage students to reflect*: Feedback from questions answered will make remarks about characteristics of the behavior of the system that the student should focus on. Further, after the game is finished, the student will be given a prompt to reflect on the learning goals, how they have advanced in their understanding through the game, and what they are still lacking on.

*Keep testing the prototype:* As we keep testing the prototype, we found valuable insights that led to changes in the design. Firstly, it was found that the topic is too complex to address in such a limited time, and so it was decided to neglect the effect of liquid concentrations by assuming air is not absorbed into water, and focus instead exclusively on evaporation. It was also found that it was easy to fail many questions initially, and so restarting the game with newly acquired knowledge has become a part of the player loop. Scaffolding questions had to be given their own question prompt, because a single prompt asking two kinds of questions was confusing. A quest marker indicating the current scaffolding question was also asked for by testers, to reduce overload.

Fig. 2 shows a view of the current game prototype, after these changes have been implemented, while Fig. 3 shows the structure of the game loop the players engage in. Further iterations will still be performed, placing particular attention on the topic of how to include further variation, the guideline that was not yet addressed to the full satisfaction of the authors.

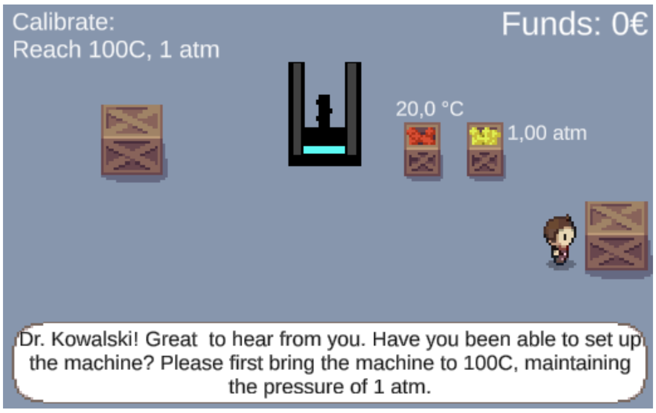


Fig. 2. View of the current game prototype. Scaffolding questions prompt has been added, as well as a display on the top left. The first scaffolding question is shown at the bottom.

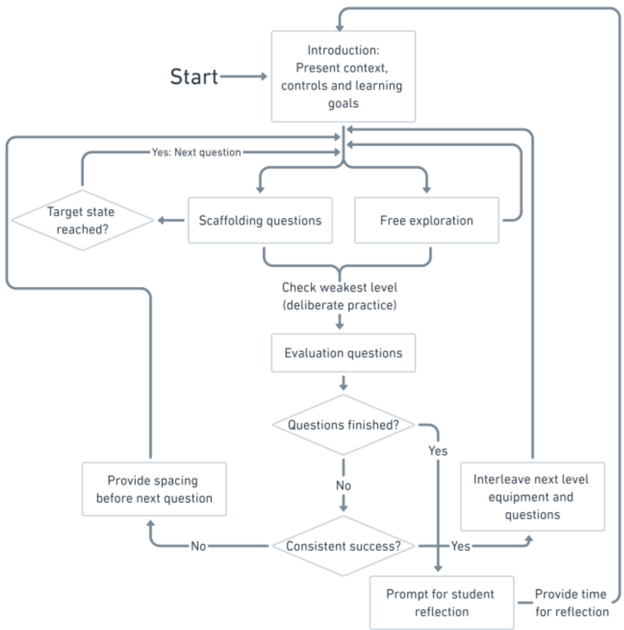


Fig. 3. Current prototype game loop.

A playable version of the game prototype is currently hosted in [59]. See also the webpage of the CHARMING EU project (charming-etn.eu).

## IV. Conclusion

17 pedagogical guidelines selected from active learning strategies, which have been shown in active learning literature to perform well for improving learning (particularly within traditional engineering courses), can be easily translated from the traditional classroom environment to the process of educational game design with minimal effort. Further, we have demonstrated how they can be addressed during the design loop of a educational game, to provide valuable insight that helps guide design towards more effective learning.

Although the guidelines have been mainly studied in the context of traditional education, and the authors have not conducted specific studies to show if these guidelines continue to increase learning after changing media, those that have been studied in existing game-based learning literature have been validated as effective. This shows a favorable pattern, which encourages the use of these already effective guidelines into the comparatively new medium of educational games, until contradicting results are found.

The authors believe that the compiled guidelines will prove useful and help improve the learning outcomes of future educational games for engineering, particularly for games that are to be integrated into traditional education, the environment for which the guidelines proved effective originally. We hope that future research will look more positively to the idea of designing educational games with some pedagogic guidelines in mind instead of the current standard of ad-hoc design: not only would this lead to more efficient serious learning, but it would also create valuable literature of how each educator addresses these challenges for their own field.

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