HEATQUIZ: GAME-BASED LEARNING IN HEAT AND MASS TRANSFER

Rohlfs, W.*, Welten, S., Rietz, M., Sabelberg, E., Ehrenpreis, C., Cammiade, L., Figueiredo, P. and Kneer, R.
Author for correspondence
Institute of Heat and Mass Transfer,
RWTH Aachen Univeristy,
52056 Aachen,
Germany,
E-mail: rohlfs@wsa.rwth-aachen.de

ABSTRACT

Heat**Q**uiz is a mobile application (APP) for smart phones that is designed to support students in learning the fundamentals of heat and mass transfer. With the intention of game-based learning, the students can gain practice and a gut instinct in conductive, convective and radiative heat transfer and mass transfer. The trade-off between playability and educational content is the main challenge in designing teaching applications, especially playable on smart phones with limited display size. A main objective in the app design is that each game should be playable within minutes, for instance while waiting for the bus and that no paper should be needed in the solution process. Last but not least, the graphical appearance is of high importance following the slogan "You eat with your eyes (first)!" The current version of **H**eat**Q**uiz contains five game modes covering conductive and radiative heat transfer as well as mass transfer. I would like to encourage the readers of this article to test the app themselves. It is free to play and available in Google Play-Store.

INTRODUCTION

The bachelor course "Heat and Mass Transfer" at RWTH Aachen University is with more than 1500 students each year one of the larges classes of this subject worldwide. Despite everydays office hours during the entire semester and additional self-learning tutorial groups, personal care of each student remains almost impractical. Thus, revolutionary teaching methods are desired that do not rely on a one-to-one student-teacher relationship but that support the students in self-learning. A mobile application (APP) is thus a promising tool for the students to gain practice and a gut instinct in conductive, convective and radiative heat transfer and in mass transfer.

Although mobile applications on smart phones or tablets cannot replace traditional teaching methods, they do allow for new ways of teaching, learning and practicing. An APP can be used for instance while sitting in the bus or waiting for a friend. However, this requires that a single question can be solved reasonable fast and without paper and pencil. The limited space and the required self-explanatory task description call for thoughtful and well-structured game implementation that is well-adopted to the educational content.

Reviewing the existing mobile application in the field of heat transfer shows that there are a few applications available. However, these applications are either lexica of the fundamental heat transfer knowledge, formularies, simple multiple-choice quizzes, or heat transfer related calculators. To the best of our knowledge, there was no program available for practicing heat and mass transfer related questions that are relevant in the bachelor course level. Nevertheless, good teaching applications exist in other engineering disciplines. A striking example is "Schnittkraftmeister" designed and developed at the University of Graz, which allows students to practice internal forces in beams.

The current version of **H**eat**Q**uiz contains five game modes with in total more than 250 questions. Fundamental educational content in conduction, radiation, and mass transfer is covered. The remainder of this paper is structured as follows. First, we present the underlying game engines and their working principles. Thereafter, we present the game modes that are available in the current version of the program. Finally, the acceptence of **H**eat**Q**uiz in the German lecture "Heat and Mass Transfer" at RWTH Aachen University is discussed. An outlook concudes this paper.

It should be emphasized that **H**eat**Q**uiz is non-commercial and free to use for students and teachers worldwide.

GAME ENGINES

The current version of **H**eat**Q**uiz contains two different game engines, responsible for the graphical appearance and the gameplay. Each game engine can be used to design special types of questions, such as drawing temperature profiles, entering view factors or expressions for the surface brightness. Nevertheless, the game engines are designed to be highly flexible, allowing to be applied for other teaching material as well.

DRAW PROFILES

The first game engine that has been developed for **H**eat**Q**uiz is designated to teach students how to derive and draw temperature profiles. The main view illustrates the task (see Fig. 3) with all required information being visualized. The user can click on any white box that waits to be filled with the correct temperature curve. Clicking on any white box inside a material (1) opens a cascaded selection screen (decision tree), see Fig. 1. In the first step, the user has to decide if the curve is increasing, decreasing, or constant. In the second step, a more precise description of the curve is requested (linear, decreasing or increasing slope, etc.). A small image of the chosen profile is finally inserted in the main figure. Clicking on any white box at material boundaries where the contact boundary condition needs to be specified opens a selection screen with three slide controls (see later Fig. 4, bottom). The three sliders can be moved upwards and downwards to specify the different slopes as well as a possible jump condition at the interface, required for concentration profiles. By clicking on the blue check mark, the user confirms his input and a small image of the specified boundary condition is also inserted in the main figure. Entered information can be revised by clicking again on the small image. If all empty boxes are filled with a profile, the user can check his solution by clicking on the appearing green check mark button. Wrong solutions are highlighted and the user can switch between his incorrect solution and the correct solution by clicking on the question mark symbol.

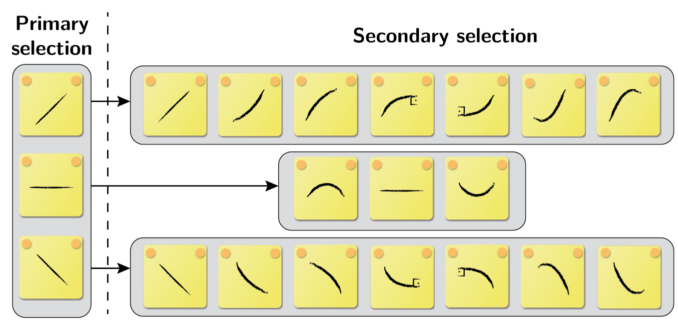

Figure 1. Selection menu: Choosing the correct slope and curvature in a decicion tree.

This game engine is the outcome of a long discussion with many tries and errors. Initially, we started each question with a little introduction of a few lines of text. However, playing the game ourselves showed that reading the text is highly annoying. Thus, we decided to illustrate all the required information just graphically. A further idea was to draw the profiles by hand and to evaluate the hand-drawn profile. However, this turned out to be too complex from the programming and interpreting point of view. The slider for defining the boundary conditions at the material interfaces is a solution to the high number of different concentration profiles with a jump conditions at the interface.

ENTER EQUATIONS

The second game engine has initially been designed to teach students how to derive expressions for the surface brightness but has now also been used for other educational content. The main view consists of three different panels. A graphic of the task (left), a keyboard (right), and an input line similar to a common calculator (see later Fig. 6, top). For a graphic, any suitable image in .png or .jpg format can be used. The keyboard is the most special part, as it can be defined individually for each task. All characters are in LaTeXformat, allowing for more sophisticated characters such as $\dot{Q}$, an integral, or a root expression. If required, question-specific indices can be added. Entering the solution is straight forward and can be revised by pressing the clear button. Pressing the check button leads to the solution screen where the user solution (top) and the correct solution (bottom) are compared to each other. Depending on the level of correctness, the user receives points for his solution, see Fig. 2. Thereby, the program can identify identical solutions accounting for the commutative law for addition and multiplication. Furthermore, expressions in brackets can be properly expanded. To treat other types of identical solutions, alternative solutions can be defined in the solution tag. This is for instance required for a black body, where the student can either write $\dot{Q} = A\varepsilon\sigma T^4$ or $\dot{Q} = A\sigma T^4$ because $\varepsilon = 1$.

For creating new tasks with this game engine, three different information are required: 1) A suitable image that contains all required information to solve the task. 2) The definition of the keyboard characters and the list of indices, and 3) the solution tag.

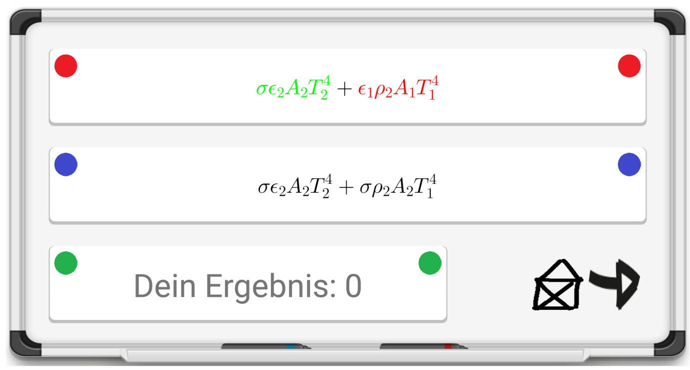

Figure 2. Solution screen: Showing the solution entered by the user (top) and the correct solution (bottom). In this example of a surface brightness question, the first term is correct (green) and the second term misses a σ. Because body 1 is a black body, it is irrelevant whether the term ε_1 is added or not.

GAME MODI

Utilizing the two different game engines, the current version of **HeatQuiz** supports four game modes which include: Temperature and concentration profile, surface brightness and view factors. This section explains the basics of all four game modes.

TEMPERATURE PROFILES

HeatQuiz was initially invented for the students to practice the fundamentals of conductive heat transport. The main task is to develop temperature profiles within solid bodies, where the entire problem is governed by the heat equation, also known as

Fourier's law:

$$\dot{Q}(x) = -\lambda \cdot A \cdot \frac{\partial T}{\partial x} \tag{1}$$

In the simplest case, heat flux $\dot{Q}$, area A, and thermal conductivity λ are constant throughout the body. In this case, the temperature gradient $\partial T/\partial x$ is constant, leading to a straight temperature profile, see Fig. 3 (top, right compartment). In principle, every term in this equation can be altered and dependent on the spatial coordinate. If area and heat flux remain constant, the temperature gradient must change inverse to the change in thermal conductivity. For instance, a variation of the thermal conductivity λ can arise in multi-body systems with sharp changes across the different materials leading to a kink in the temperature profile (see Fig. 3, top, material interface). In a similar way, the area A can vary, leading also to a changing temperature gradient for a constant heat flux. A variable area is typical for the radial heat transfer in pipes or spheres, as shown in Fig. 3, center. In those cases, the temperature gradient decreases with increasing radial direction due to the increasing surface area.

Heat sources and heat sinks affect the heat flux $\dot{Q}$, which can either increase or decrease. Recalling Fourier's law, a rising heat flux increases the temperature gradient and vice versa. Figure 3 (center) shows a pipe that combines a changing surface area, a heat sink, and an adiabatic inner part. Owing to the adiabatic inner part of the pipe, the temperature is constant. This is specified by the boundary condition on the pipe axis, the temperature profile in the white area, and additionally in the boundary condition at the material interface.

In all cases described above, upper and lower side walls are adiabatic, such that heat transfer arises only in horizontal direction. A very common type of problems in heat transfer is fins, also known from CPU coolers in computers. In a classical fin problem, heat is conducted through the material in one direction and heat is released to the ambience by convection in the other direction. In **H**eat**Q**uiz, boundaries with convective heat transfer are marked with a blue curve, a given temperature, and a given heat transfer coefficient α . Figure 3 (bottom) presents a more complex task with different boundary conditions along the work piece. The temperature profile needs to be specified in all six boxes. A heat flux is prescribed on the left side while the right side is adiabatic. In the two outer regions, a convective boundary condition applies while the center region is heated by a constant heat flux. Note that this case is not well-defined by the graphical illustrations as different profiles can arise depending on the intensity of the heat fluxes ($\dot{Q}_1$ and $\dot{Q}_2$) and the length scales. To remove the ambiguity, little red arrows indicate the direction of the heat flux across the two domain borders. Basically, the physical explanations given above are sufficient to solve all heat transfer problems in **H**eat**Q**uiz. The combination of the different effects however yields to more complex problems. Currently, **H**eat**Q**uiz contains 60 different questions subdivided into the three categories "basic", "heat sources", and "fins".

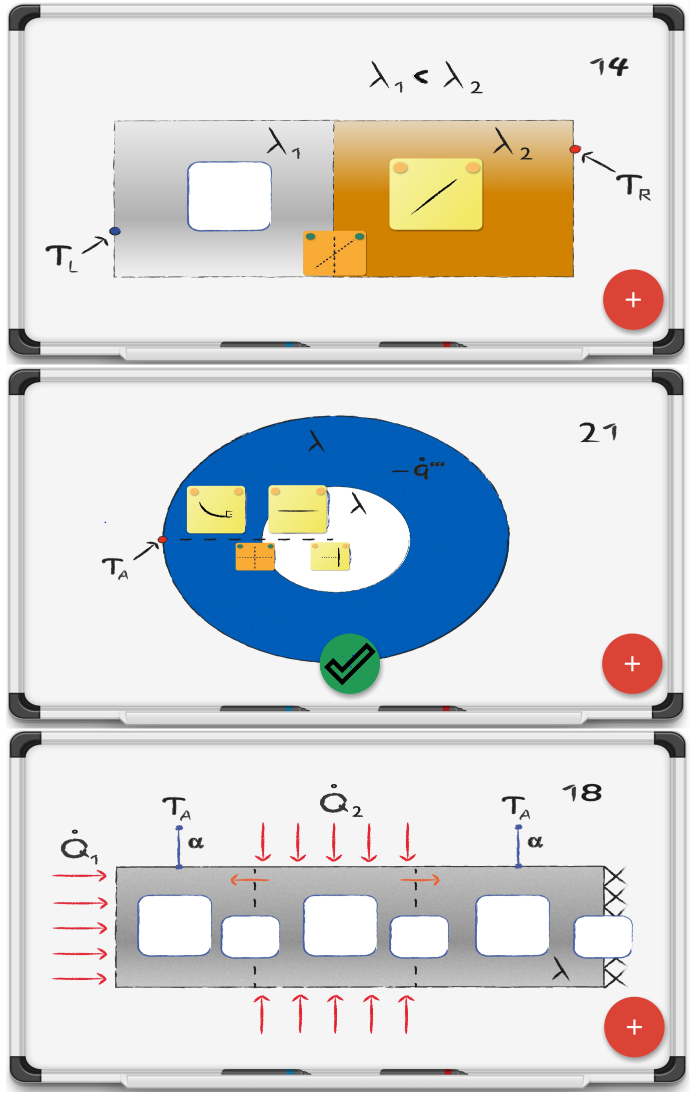

Figure 3. Multi-body heat transfer problem which requires the specification of the temperature profile in each body and a specification of the temperature kink at the interface.

CONCENTRATION PROFILES

The game mode "concentration profiles" grounds on the same game engine as the game mode "temperature profiles". The entire problem is governed by the mass diffusion equation:

$$J(x) = -D \cdot A \cdot \frac{\partial C}{\partial x} \tag{2}$$

Differently from heat transfer, where continuity of temperature is given, a concentration jump appears across medium interfaces. The difference in mass concentration can empirically be described by a constant, which also specifies the direction of the concentration jump. For liquid-gas interfaces, this constant is named by William Henry (1774-1836),

$$H_{CC} = \frac{C_1}{C_2}, \tag{3}$$

where C_1 and C_2 are the respective interface concentrations in both phases. Similarly, the thermodynamic jump at liquid-liquid, gas-solid or liquid-solid interfaces is defined using an adsorption equilibrium constant $K_{CC} = C_1/C_2$, also named Nernst constant. Depending on the respective case, H_{CC} or K_{CC} is given. The student has to specify the direction of the concentration jump by moving the center slider upwards or downwards as shown in the bottom plot of figure 4. Currently, **H**eat**Q**uiz contains 16 questions. An examplary question is presented in Figure 4.

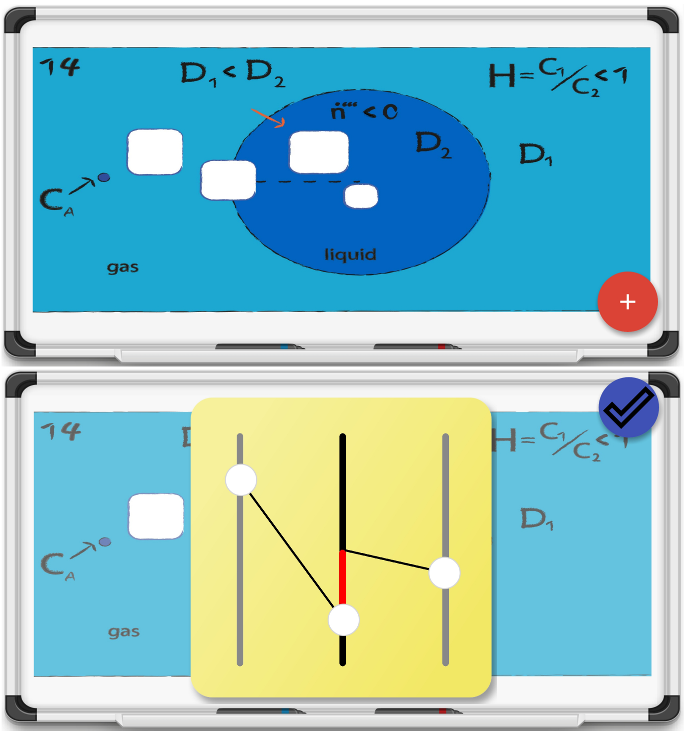

Figure 4. Exemplary question in the mass transfer game mode with interfacial concentration jump (top). The slider to define the concentration jump and gradients at the interface in the bottom figure.

VIEW FACTORS

View factors describe the proportion of diffuse radiation which leaves a surface and strikes on anotherone. View factors depend on the specific geometry of the problem. For simple cases, these factors can be calculated analytically. **H**eat**Q**uiz allows practicing this calculation for a number of different two- and three-dimensional configurations. Figure 5 shows a simple case of a hemisphere (body 2) and a circular plane (body 1). Obviously, radiation emitted from the body 1 will entirely strike on body 2. Thus, the view factor of body 1 to body 2, denoted as $\phi_{1,2}$ is equal to one. More difficult is to calculate the

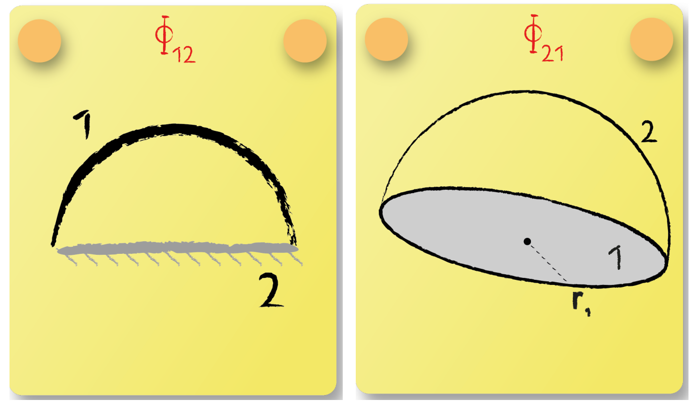

Figure 5. Exemplary cases for determining view factors of two- and three-dimensional objects.

portion of radiation leaving body 2 and striking on body 1. The reason for the increased complexity is that a part of the radiation will also strike on body 2 itself. As such body 2 is called a self-viewing object. Two important relations will help us to resolve the problem. First, the superposition rule (or summation rule) which states that the entire radiation leaving body two will either strike on body 2 itself or will strike on body 1. There are no other objects involved. Thus: $\phi_{2,1} + \phi_{2,2} = 1$ The second relation is called the reciprocity theorem that relates the view factor $\phi_{1,2}$ to the view factor $\phi_{2,1}$ by the ratio of their respective areas $\phi_{1,2}A_1 = \phi_{2,1}A_2$ Using the reciprcity theorem and the areas $A_1 = \pi r^2$ and $A_2 = 2\pi r^2$ (three dimensional problem) we can calculate $\phi_{2,1} = \phi_{1,2} \cdot \frac{A_1}{A_2} = \frac{1}{2}$ Finally, the summation rule provides $\phi_{2,2} = 1 - \phi_{2,1} = \frac{1}{2}$. In **H**eat**Q**uiz, the student has to calculate the view factors and enter the correct value by using the adaptive keyboard (see Fig. 6). The current version of **H**eat**Q**uiz contains 46 questions subdivided into the categories “simple”, “medium”, “hard”, and “3D”. Examplary questions are presented in Figure 6.

SURFACE BRIGHTNESS

Surface brightness is the total radiative flux that leaves a body surface comprising the bodies emitted, transmitted, and reflected radiation. Depending on the bodies optical properties ε, τ, and ρ, which are the emission, transmission, and reflection coefficient respectively, an equation for the surface brightness can be deduced. **H**eat**Q**uiz contains questions with wavelength-independent (grey bodies) and wavelength-dependent optical properties. For questions with wavelength-independent properties, small symbols indicate whether the body has transmissivity or reflective characteristics or if it is a black-body. In Fig. 7 (top), the symbol indicates a grey body that is both, reflective and transmissivity. As such, the equation for the surface brightness must account for the own emission of the body, $A_1\varepsilon_1\sigma T_1^4$, the reflected portion, $A_1\rho_1\sigma T_A^4$, and the transmitted portion, $A_1\tau_1\sigma T_A^4$. The sum of the three expressions is the desired solution. Due to the relation $\varepsilon + \rho + \tau = 1$, the reflected and transmitted part could be rewritten as $A_1(1-\varepsilon_1)\sigma T_A^4$. Note, both alternative so-

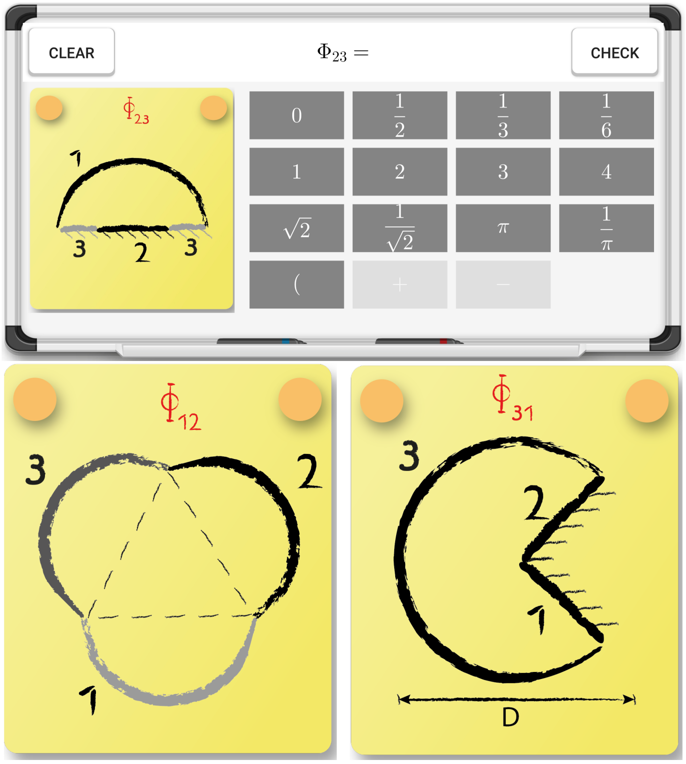

Figure 6. Game mode "View factors": Top row: Input window with input lines and customized keyboard. Bottom row: Exemplary two-dimensional questions.

lutions are marked as being correct in **HeatQuiz**. To guide the students and give them a structure in constructing the desired solution, **HeatQuiz** allows for a separate input of the three terms. After adding one expression the student can click on the enter button such that the expression is transferred to the top input box. However, it is also possible to add the entire solution to the problem at once. The current version of **HeatQuiz** contains 35 questions subdivided into the categories "simple", "medium", "hard". Questions of the type "hard" contain wavelength dependent optical properties.

STATISTICS

How often do students play **HeatQuiz**? Do students use the game just before the exam or do they start practicing already weeks ahead? The statistics shown in Fig. 8 give an answer to these questions. Obviously, there is a significant increase in games played per day just before the exam and the oral examination. This was especially evident in the summer exam (August 2018). Note that the lecture Heat and Mass transfer is only in the winter semester at RWTH Aachen University. In the last winter semester, **HeatQuiz** was used more frequently during the lecture time. Mostly because we promoted the APP multiple times during the semester. Up to now, **HeatQuiz** was used more than 50.000 times.

A further relevant question tackles the acceptance of **HeatQuiz** by the students. Are the 50.000 solved questions

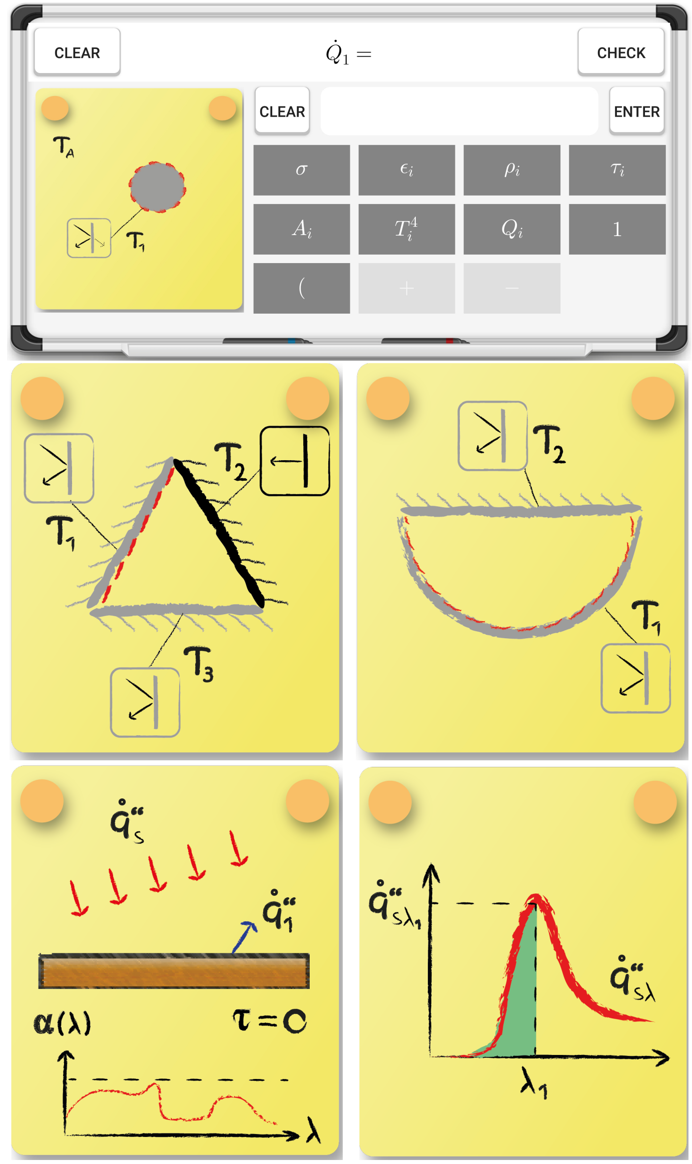

Figure 7. Game mode "Surface Brightness": Top row: Input window with two input lines and customized keyboard. Mid row: Exemplary questions with with wavelength-independent optical properties. Bottom row: Exemplary questions with wavelength-dependent optical properties.

equally distributed through the students or are there only a few students using the APP with a very high frequency. The logarithmic plot in Figure 9 gives an answer to this question. Obviously, there are a few users that played the APP a few hundred times. However, this could have also been one of the game developers. More relevant are the approximately 100 students that solved more than 130 questions. In addition, more than 500 students solved at least 15 questions. Although, the total number of questions played so far seems to be high, we think that the use of the APP is still low compared to our expectations. This semester, 1200 students participated in the exam and we had approximately

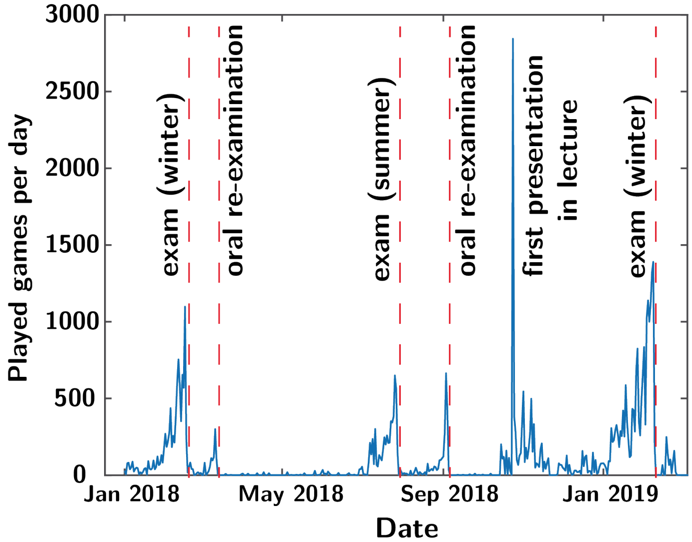

Figure 8. Utilization of **H**eat**Q**uiz in the last two years.

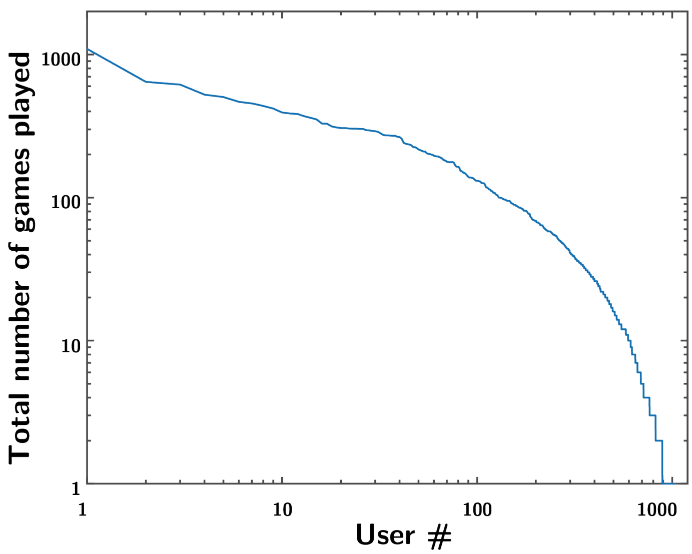

Figure 9. User behavior in **H**eat**Q**uiz.

200 different questions online prior to the exam. If every student would solved each question only once, a total number of 200.000 events should have been registered in this semester.

One remaining question thus is ”Why do not all students use **H**eat**Q**uiz?” and, coming from that question ”Is it necessary to improve **H**eat**Q**uiz such that students have an increased interest in using the APP?”.

Note: For statistical reason, **H**eat**Q**uiz receives some information from the user. This information includes an anonymous user ID, randomly created by the APP. The user ID is especially required for the High Score. In addition, the results of each game that has been played are stored including the problem ID, the points received, and a time stamp. We strictly avoid the transfer of personal data.

OUTLOOK

The next major step in the development process of **H**eat**Q**uiz is the design of a new game mode named “Energy balances”. Defining energy balances is the major task in heat and mass transfer which leads to the governing system of equations of the proposed problem. Teaching the students when and how to use global or local energy balances and how to derive the differential equation, for instance for a fin-type problem, is educational content in almost every heat transfer claas. In addition, we plan to develop a quiz of dimensionless numbers, asking the physical meaning of common dimensionless numbers such as Reynolds, Nusselt, or Prandtl number. The same game engine will also be applicalbe for practising the units of dimensional numbers.

ACKNOWLEDGMENT

I would like to thank all students and colleagues who supported me with useful criticism and input as well as the German “Stifterverband” and RWTH Aachen University for financial support that allowed me to initialize and conduct this teaching project.