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Learning Thermal Expansion with Unity: An Interactive Simulation

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Abstract

The use of Unity and Virtual Reality in education facilitates active exploration, safe experimentation, and personalized learning, enhancing knowledge retention. Their integration transforms traditional teaching by providing innovative and immersive experiences that allow users to understand the concepts of science easily. In this context, an interactive simulation was developed using the Unity 3D graphics engine and the C# programming language to study the phenomenon of thermal expansion, addressing the complexity of solid materials' behavior under temperature changes. The model's accuracy was evaluated through numerical validation, comparing the simulated results with theoretical values. The simulation showed a close correlation with expected values, with an error margin of less than 1%, confirming its high fidelity in representing thermal expansion. It is concluded that the use of Unity and VR significantly contributes to understanding key concepts in thermal physics, offering an effective and visually engaging alternative for educational laboratories.

Keywords: Simulation, Unity, Study of Thermal Expansion, Learning, Pedagogic.

Introduction

Simulations are interactive environments that facilitate the visual and practical learning of scientific concepts. They connect real phenomena with their theoretical foundations, allowing access to models used by expert physicists. A previous research by Hamed and Aljanazrah (2020) report that they contribute to teaching effectiveness, foster motivation, and improve the understanding of physics through virtual experimentation.

The use of simulations in physics education has been the subject of various studies highlighting their effectiveness in enhancing the comprehension of complex concepts. Research has emphasized the potential of online simulators to provide interactive and visual learning experiences (Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006) which proves beneficial for learning physics. Likewise, the impact of simulation software in the teaching of geometric optics (Penjor, Utha, & Seden, 2022) has been analyzed, showing improvements in students' academic performance. These studies suggest that virtual simulations are effective tools for strengthening the teaching-learning process in physics, facilitating comprehension and student performance.

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Simulations provide students with powerful tools to understand physical phenomena. It has even been found that students who previously used simulations achieved better results in conceptual questions and real constructions compared to those who only used physical equipment (Perkins, Adams, Dubson, Finkelstein, Reid, Wieman, & LeMaster, 2006).

Simulations are more effective when students' exploration is partially guided, either by the instructor during class or through assignments, laboratories, or discussion activities that follow an inquiry-based approach. This document presents a simulation and offers suggestions on how to use them effectively in different learning environments.

In this work, Unity is integrated with 3D models to create an immersive environment for experiential learning, aimed at developing an understanding of complex concepts such as the study of thermal expansion in response to temperature variations. The use of the educational environment created with the simulation seeks to promote active exploration and risk-free experimentation in education, optimizing knowledge retention. Additionally, it allows for content personalization according to students' needs, fostering a dynamic and inclusive learning experience. Ultimately, with this combination of 3D models and Unity, the goal is to contribute to the transformation of traditional teaching by providing innovative and engaging experiences.

Thermal expansion is a highly significant physical phenomenon for the industry. If this phenomenon is not adequately considered, disasters such as train derailments due to rail deformation due to temperature raising, building collapses caused by internal stresses in their materials, pipeline ruptures in water or gas distribution systems, and structural failures in bridges could occur. These situations highlight the importance of understanding and anticipating the impacts of thermal expansion in different contexts. (Zhang, Liu, Stichel, & Yang, n.d.)

For this reason, it is of utmost importance that this phenomenon is taught in the academic field not only from a theoretical perspective but also through practical experiences. However, one of the greatest challenges is that real experiments are not always accessible to students due to infrastructure limitations, budget constraints, or lack of access to them, as the research made by Castro Gómez (2024) suggests. This makes it necessary to seek alternatives that compensate for these shortcomings and allow students to understand, in a practical and visual manner, the physical behavior of materials subjected to temperature changes before interacting with a real experiment. Additionally, it can serve as a complementary tool to the traditional guide and the theoretical explanation prior to the laboratory.

Currently, many experimental practices are conducted without a clear definition of objectives, which significantly reduces their learning potential (Feisel & Rosa, 2005), this lack of guidance prevents students from developing a deep understanding of experimental concepts. Therefore, it is essential to implement prior preparation that clarifies the purposes of each experiment, allowing the laboratory experience to be transformed into a more meaningful learning opportunity.

In response to this need, an interactive 3D simulation was developed to represent the phenomenon of thermal expansion on solids. This tool not only makes it easier to learn in an experimental environment where physical laboratories are unavailable but also enhances teaching by providing an immersive and accessible educational experience. (Kolil & Achuthan, 2024; Verawati & Purwoko, 2024)

Contributions to the Literature

This study presents a pedagogical tool intended for use in educational environments to reinforce students' knowledge of the physics topic "Thermal Expansion," a thermodynamic phenomenon present in a wide variety of engineering applications. The simulation was created using the Unity graphics engine, which enables the recreation of the real experimental experience with models that were created using the 3d modeling tool Blender.

The simulation presented in this article has the capability to complement a laboratory guide, providing students with an easier way to understand the concepts of thermal expansion, ultimately making them better prepared to face the real experiment.

This application significantly reduces the need for purchasing expensive equipment, building dedicated laboratory spaces, or hiring technical personnel for maintenance and repair. It also minimizes personal risks associated with handling electrical devices and high-temperature materials.

It is also a valuable tool for professors, as they can design activities based on the simulation and have students submit a report that demonstrates their level of understanding.

Theoretical Framework

Thermal Expansion

The expansion phenomenon that occurs when heating a material can be explained by observing its constituents. When a material is heated, there is an increase in the kinetic energy of its constituents. This excitation affects the stability of the interaction forces between them, allowing the material to expand in all directions (Sears & Salinger, 1975) (if the material is isotropic, it will do so uniformly everywhere), as shown in Fig.1:

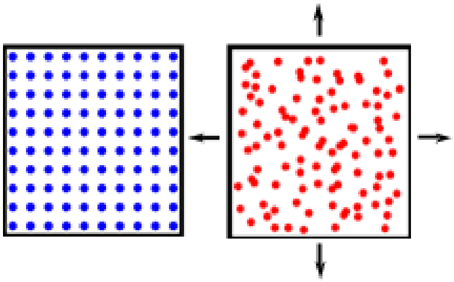

Figure 1. Graphical Representation of the Expansion Occurring Within An Isotropic Material.

(Source: Authors' Own Work)

Now, this would be a somewhat complex case to address in an experimental practice due to the difficulties in measuring the change in length in all directions of the material. Although measuring the change in volume is simpler, it is even more practical to limit the problem to a single dimension.

Imagine a solid bar of length $\mathbf{L_0}$, with a thickness **r** such that $\mathbf{L_0 >> r}$, and one of its ends anchored to a wall. If the temperature of the bar is uniformly increased (meaning that each point of the bar experiences the same temperature increase $\mathbf{\Delta T}$), there will consequently be a length increase $\mathbf{\Delta L}$. (See Fig.2)

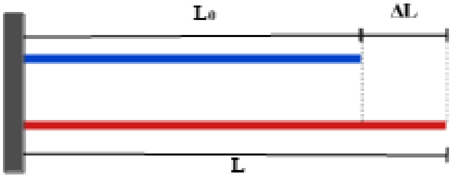

Figure 2. Graphical Representation of a Bar Heating and Expanding at One of Its Ends. (Source: Authors' Own Work)

It becomes evident that the length of the bar is a function that depends on temperature. In fact, according to the equation of state established by thermodynamic laws, it depends on both temperature and the tension force applied to it (Young & Freedman, 2020), in the following form:

$$dL = dT + \left(\frac{\partial L}{\partial F}\right)_T dF$$

However, the tension will be considered constant at all times (dF=0), which leaves us with an equation that, when expressed without infinitesimal changes, is:

$$\Delta L = \left(\frac{\partial L}{\partial T}\right)_F \Delta T \qquad (1)$$

Thus leading to:

$$L = L_0(1 + \alpha\Delta T) \qquad (2)$$

Where $\alpha = \frac{1}{L_0}\left(\frac{\partial L}{\partial T}\right)$

This parameter is called the **coefficient of thermal expansion** and describes how much the length of the bar changes in relation to its original length. It has units of K^{-1}

Virtual Experiment Setup

The simulation is based on the real experiment commercialized by companies like Phywe (n.d) or Leybold (n.d). This experiment consists of two key elements:

- **Dilatometer**: This is the device where the metal bars are inserted for the experiment. Water flows through this apparatus at a certain temperature via hoses, and it features a measuring clock that records the changes in length. The clock mechanism operates through the pressure exerted by the expansion of the metal bars.

- **Thermostat and water container:** The thermostat regulates the temperature of the water through metal pipes connected by hoses, which then transport the water to the dilatometer. This system ensures that the water flows at the adjusted temperature, allowing precise control of the experimental process.

The main reason for using hot water instead of direct heat is that water allows for much more precise and uniform temperature control.

Unity

There are numerous cross-platform engines that allow for the development of interactive simulations, most of which are created in programs like Geogebra, MatLab, among others (Dias, Santos Castro, & Coelho, 2023). However, Unity was chosen due to its versatility, power, and widespread popularity. Unity (Unity Technologies, n.d) is a graphics engine that supports the creation of 2D, 3D, and augmented reality environments. Additionally, for the creation of 3D models of the simulation elements, the 3D modeling program Blender (Blender Foundation, n.d) was used.

One of the main advantages of Unity is the use of the C# programming language, an object-oriented language known for its power and flexibility. This object-oriented approach is particularly beneficial in the context of Unity, as it allows for the modular and reusable structuring of code, which facilitates the creation and management of the interactive and dynamic elements of the simulation.

The decision to use Unity is not only based on its technical capabilities but also on its potential to expand the reach of the simulation. As a cross-platform tool, it allows the simulation to be implemented on various devices, such as computers, tablets, or even virtual reality devices, thus ensuring more inclusive and flexible access for students and educators.

Methodology

This simulation is designed to operate through multiple codes that manage both the visualization and behavior of objects within the virtual environment. These codes play a crucial role in the user experience, as they determine which elements are displayed on the screen and how they interact with each other.

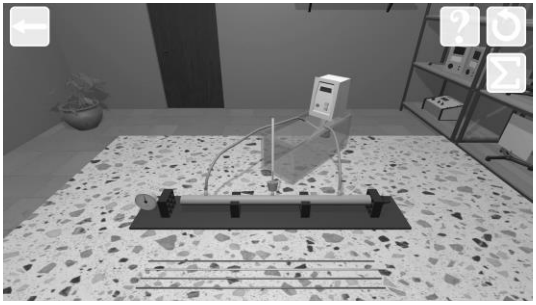

Figure 3. Main Interface of the Simulation.

The main implemented features include:

Texts

- The simulation has a help menu with a guide text to assist the user in navigating the simulation. It also includes a section that shows that when a key on the user's keyboard is pressed, an action occurs (move the camera, increase/decrease the temperature, etc.).

Dilatación Térmica

La dilatación térmica es un fenómeno que se manifiesta en cualquier material. Al calentarse, las moléculas del material adquieren energía cinética, lo que provoca una mayor agitación que lleva a un incremento en la distancia entre ellas. Esto es lo que ocurre a nivel microscópico, mientras que a nivel macroscópico se observa un aumento en el volumen del material.

Esta simulación permite llevar a cabo la práctica experimental de dilatación térmica lineal en diversas barras de metal, las cuales presentan comportamientos diferentes al someterse a un aumento de temperatura.

El principal objetivo de la simulación es determinar el valor del coeficiente de dilatación lineal de cada barra de metal. Para ello, es fundamental conocer las ecuaciones que describen el comportamiento de la expansión, las cuales se encuentran disponibles pulsando el botón con el símbolo Sigma.

Figure 4. First Page of the Guide Text That Directs the User on the Proper Use of the Simulation.

- When using the thermostat view, a text representing the temperature in degrees Celsius (°C) can be seen. This text changes as the temperature selected by the user changes (either with the thermostat buttons or with the slider at the top). (See Fig. 5)

Figure 5. Text From the Thermostat in the Simulation Representing the Current Temperature in Degrees Celsius.

Views

The simulation is set in a 3D environment, which allows the user to immerse themselves in an environment familiar to reality (with a virtual reality setup). To facilitate the observation of each element, four different views have been implemented:

1. **View 1 (Main):** This is the default view, where all elements are displayed in a single frame.
2. **View 2 (Measurement Clock):** Designed to take measurements of the length expansion of the bars, this view focuses the entire frame on the measurement clock of the dilatometer.
3. **View 3 (Thermostat):** The frame is centered on the thermostat and its target temperature value. Through this view, the thermostat can be turned on or off, as well as the temperature adjusted.
4. **View 4 (WhiteBoard):** This external view focuses on a whiteboard that displays the formulas necessary for carrying out the experiment.

Each view can be accessed using the numbers 1, 2, 3, and 4 on the keyboard. Views 2 and 3 can be selected by clicking on the corresponding elements, while views 1 and 4 are activated with buttons in the user interface.

Metallic Bars

Each bar that can be used in the simulation has an initial length of L0 = 70 cm and a distinct thermal expansion coefficient, which can be seen in the Table 1:

Each bar is an object that has an attached code allowing it to be moved by clicking on it and placing it in the Dilatometer. At the same time, if there is a bar in the dilatometer different from the one selected, it will return to its initial position. The code can be seen in Fig.6.

```
using System;
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

public class BarsController : MonoBehaviour
{
     public Transform coords, originCoords;
     public float transitionSpeed = 10f, coef;
     public Vector3 targetPosition;
     public Calculus temperature, temperature0, barOn, setCoefficent;
     public BarsController[] returningBars;
     public GameObject guidePanel;

    void Start()
    {
       targetPosition = this.transform.position;
    }

    public void MoveBar()
    {
       targetPosition = coords.position;
       temperature.barTemperature = temperature0.temperature0;
       barOn.barOn = true;
    }

    public void ReturnBar()
    {
       targetPosition = originCoords.position;
    }

    private void OnMouseDown()
    {
       MoveBar();
       setCoefficent.SetCoefValue(coef);
       returningBars[0].ReturnBar();
       returningBars[1].ReturnBar();
       returningBars[2].ReturnBar();
    }

    private void Update()
    {
       this.transform.position = Vector3.Lerp(this.transform.position, targetPosition, Time.deltaTime * transitionSpeed);
       if(guidePanel.activeSelf)
       {
          this.GetComponent<BoxCollider>().enabled = false;
       }
       else
       {
          this.GetComponent<BoxCollider>().enabled = true;
       }
    }

}

```

Figure 6. Bars Control Code’s Excerpt.

Measuring Gauge

The dilatometer has a measurement clock attached to its left side, with a range of 0 - 2mm and a minimum scale of approximately 0.01mm. This clock has a needle with the following section of code assigned:

```
// Equation
        totalLength = length0 * (1 + coefficient * (barTemperature - temperature0));
        deltaLength = totalLength - length0;

        needle.transform.eulerAngles = new Vector3(needle.transform.eulerAngles.x, n
eedle.transform.eulerAngles.y, (360f/2e-3f) * deltaLength);
```

Figure 7. Code Excerpt Showing the Functioning of the Measurement Clock's Needle.

This code calculates the length (L) as a function of temperature using equation (2), then computes ΔL, and this value is used for the needle's rotation. By applying a transformation that takes advantage of the linear relationship between the change in rotation along the needle's z-axis and ΔL, a length change value can be translated into rotation.

$$Rotation = \frac{360°}{2mm} \cdot \Delta L$$

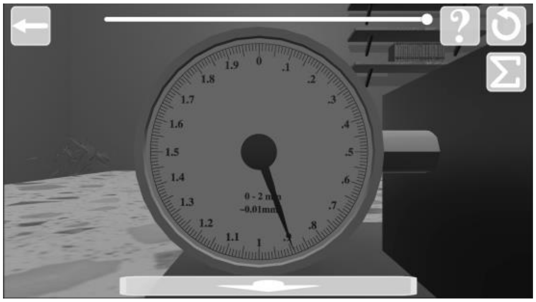

Figure 8. Measuring Clock in Operation. Can It Take a Measurement?

Temperature

Internally, the temperature is represented as a numerical value constrained between 0°C and 100°C (due to the freezing and boiling points of water). This value is determined by user input, either through the slider, the thermostat buttons, or the keyboard. The user-defined value is then used to calculate the target length of the bar based on thermal expansion. However, the measurement clock indicator does not instantly reach this length. Instead, the needle moves gradually, simulating the realistic behavior of a measuring instrument in a physical environment. This approach adds a level of realism that enhances user immersion.

A thermometer is also included to visually display the increase in temperature of the bars, which also rises gradually.

Results and Experimental Findings

When simulations are combined with tasks following a guided inquiry approach, students interact with the simulation to discover, explain, or reason about key concepts in physics. They are often asked to explore cause-and-effect relationships, both qualitatively and quantitatively, or to make connections to their everyday experiences.

When collecting data on the change in length concerning a temperature change (which varies from 0°C to 100°C in steps of 10°C), the obtained data corresponds to Table 1.

Steel		**Aluminum**		**Brass**		**Copper**	
Temp.	**L**	**Temp.**	**L**	**Temp.**	**L**	**Temp.**	**L**
0	-0.19	0	-0.38	0	-0.31	0	-0.3
10	-0.11	10	-0.23	10	-0.19	10	-0.18
20	-0.04	20	-0.08	20	-0.06	20	-0.06
25	0.00	25	0.00	25	0.00	25	0.00
30	0.04	30	0.08	30	0.06	30	0.06
40	0.12	40	0.23	40	0.19	40	0.18
50	0.19	50	0.38	50	0.31	50	0.3
60	0.27	60	0.54	60	0.44	60	0.42
70	0.35	70	0.69	70	0.57	70	0.53
80	0.42	80	0.85	80	0.69	80	0.65
90	0.5	90	1.00	90	0.82	90	0.77
100	0.58	100	1.16	100	0.95	100	0.89

Table 1. Data Collected from the Change in Length with Different Materials.

All of these data can be represented in a graph showing the linear behavior of the involved variables (see Fig.9).

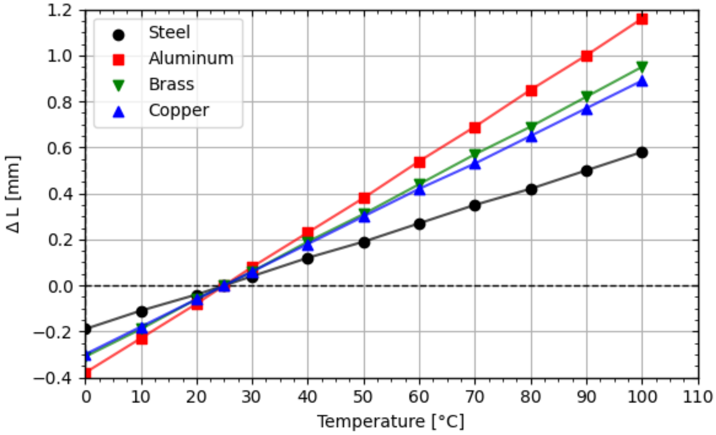

Figure 9. Representative Graph of the Change in Length With Respect to Temperature In Different Materials.

Additionally, the slope of the resulting line will be essential for calculating the thermal expansion coefficient. The following section presents the analysis and calculates the percentage error using the equations:

$$\alpha = \frac{A}{L_0} \qquad (3)$$

Where A represents the slope of the line

$$\varepsilon_{\%} = \frac{|\alpha_{teo} - \alpha_{exp}|}{\alpha_{teo}} \qquad (4)$$

Using (3) and (4) we obtain that the error with respect to the reported literature values are described in Table 2.

Material	**ε (Error)[%]**
Steel	3.6×10^{-1}
Aluminum	4.5×10^{-3}
Brass	5.6×10^{-3}
Copper	2.4×10^{-1}

Table 2. Percentage Error of Data.

Pedagogical Approach

The thermal expansion simulation developed in this study establishes itself as a powerful educational tool, offering an interactive experience highly similar to real experimentation. Its design allows students to explore the phenomenon dynamically, repeating the practice as many times as needed to reinforce their understanding without material or time constraints. Additionally, its execution is efficient, with a low computational cost that ensures a smooth, real-time simulation.

Beyond its pedagogical value, this tool stands out for its flexibility and ease of use. It not only provides an engaging and intuitive learning environment but also allows instructors to easily adapt it by incorporating their own questions or adjustments based on course needs. Integrated into Unity, its customization is accessible even to those with no programming experience.

In this context, the simulation serves as a bridge between theory and real experimentation, functioning as a structured guide for practical work. The results obtained from a test group reinforce its positive impact: students who first used the simulation achieved better assimilation of concepts and reduced the time required to complete the real experiment by 30% compared to those who only performed the laboratory practice. This demonstrates that integrating digital tools not only enriches physics education but also optimizes practical learning.

An added advantage is that its use can help reduce the dependency on physical infrastructure and technical resources often required in experimental settings. By relying on virtual models, institutions may avoid the challenges associated with equipment procurement, maintenance, and potential safety concerns, especially when handling high-temperature materials or electrical components.

Discussion

While it is useful for students to understand real-world, non-idealized situations, the simulation uses a structure that allows them to first explore and build conceptual understanding with idealized setups, before transitioning from the ideal to the complexities encountered in reality.

The simulation has proven to be quite consistent compared to the actual experimental practice. The error obtained is a direct consequence of the resolution of the virtual measuring clock, which differs from the real one, as these clocks do not have infinite resolution. There is a possibility of selecting a number that does not match 100% with the exact measurement (which is embedded in the simulation code, ensuring precise behavior).

Regarding the values obtained for the thermal expansion coefficient (α), the differences from the reported theoretical values are minimal, with percentage errors below 1% in all cases. This level of agreement suggests that the linear model used to represent the relationship between length change and temperature is appropriate for describing the behavior of the materials analyzed in the temperature range studied (0°C to 100°C).

From an educational perspective, the simulation enables students to apply theoretical concepts of thermal physics, thereby deepening their understanding. Furthermore, by offering a safe and accessible alternative to traditional experimentation, it fosters broader participation and reduces barriers to learning in contexts where access to specialized equipment or laboratory conditions might be limited.

Conclusions

This simulation has proven to be an effective tool for modeling thermal expansion in common materials such as aluminum, steel, brass, and copper. The results obtained show a high degree of agreement with theoretical values, with expected deviations due to the virtual measuring instrument, which was designed to resemble a real one, including measurement resolution. This demonstrates the simulation's ability to accurately replicate experimental conditions and facilitate the interpretation of physical phenomena.

Furthermore, its role in teaching is highlighted, serving as a powerful tool to complement the real experiment and/or develop the theory behind it (Reyes, Isleta, Regala, & Bialba, 2024); not only optimizing the understanding of theoretical concepts but also allowing the exploration of scenarios that would be difficult or costly to reproduce in reality.

In general, the combination of simulations and real physical experiments presents an invaluable tool in the academic field, enabling students to explore and understand phenomena such as thermal expansion in a practical and interactive way. In the specific case of this experiment, improving the accuracy of simulations and extending the analysis to materials with different coefficients of thermal expansion allows students to consolidate their understanding of the fundamental laws of thermodynamics and their application in real-world contexts.

Data Availability: The main output of this work is the interactive simulation. This simulation is freely accessible to the public and can be found at the following link: https://simulabsphysics.com/special-projects/thermal-expansion?title=Dilatación+térmica&autors=Dewin+A.+Soto+C.. All relevant educational content, visualization tools, and parameter controls discussed in this article are integrated within the simulation itself. No additional datasets were generated or analyzed during the course of this study. However, the source code or design methodology can be made available from the author upon reasonable request for academic or non-commercial purposes.

Competing Interests: The authors declare no competing financial or personal interests that could have influenced the design, development, or description of the simulation presented in this article.

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