pyGANDALF - An open-source Geometric, ANimation, Directed, Algorithmic, Learning Framework for Computer Graphics

John Petropoulos
ORamaVR
Greece
University of Crete
Greece
john.petropoulos@oramavr.com

Manos Kamarianakis
ORamaVR
Greece
University of Crete
Greece
Institute of Computer Science, Foundation for Research and Technology - Hellas
Greece
manos.kamarianakis@oramavr.com

Antonis Protopsaltis
ORamaVR
Greece
University of Western Macedonia
Greece
antonis.protopsaltis@oramavr.com

George Papagiannakis
ORamaVR
Greece
University of Crete
Greece
Institute of Computer Science, Foundation for Research and Technology - Hellas
Greece
george.papagiannakis@oramavr.com

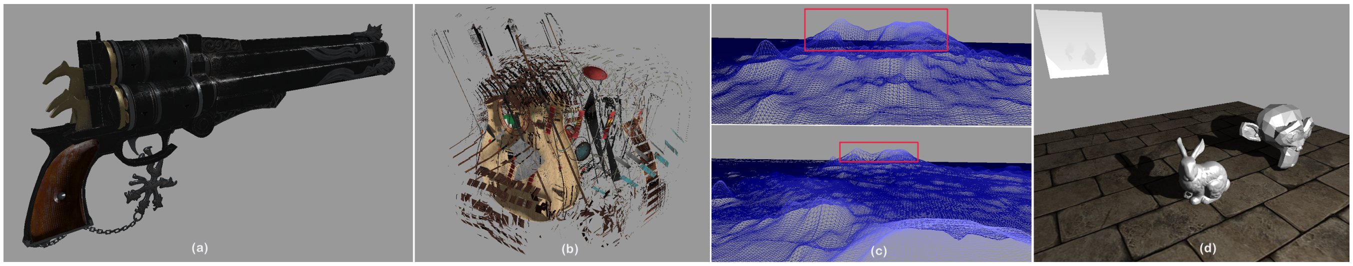

Figure 1: Using the proposed pyGANDALF framework to educate and implement CG concepts: (a) Rendering of a pistol 3D model[1] using the Physically Based Rendering technique. (b) Geometry shader manipulates vertices[2] in-between the vertex and fragment stages, creating a triangle-explode visual effect. (c) Tessellation shaders create a dynamic level of detail of a terrain rendered with heightmap. (d) Shadow mapping technique with dynamic and soft shadows.

Abstract

In computer graphics (CG) education, the challenge of finding modern, versatile tools is significant, particularly when integrating both legacy and advanced technologies. Traditional frameworks, often reliant on solid, yet outdated APIs like OpenGL, limit the exploration of cutting-edge graphics techniques. To address this, we introduce *pyGANDALF*, a unique, lightweight, open-source CG framework built on three pillars: *Entity-Component-System* (ECS) architecture, *Python* programming, and *WebGPU integration*. This combination sets pyGANDALF apart by providing a streamlined ECS design with an editor layer, compatibility with WebGPU for state-of-the-art features like compute and ray tracing pipelines, and a programmer-friendly Python environment. The framework supports modern features, such as Physically Based Rendering (PBR) capabilities and integration with Universal Scene Description (USD) formats, making it suitable for both educational demonstrations and

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Authors' Contact Information: John Petropoulos, ORamaVR, Greece and University of Crete, Greece, john.petropoulos@oramavr.com; Manos Kamarianakis, ORamaVR, Greece and University of Crete, Greece and Institute of Computer Science, Foundation for Research and Technology - Hellas, Greece, manos.kamarianakis@oramavr.com; Antonis Protopsaltis, ORamaVR, Greece and University of Western Macedonia, Greece, antonis.protopsaltis@oramavr.com; George Papagiannakis, ORamaVR, Greece and University of Crete, Greece and Institute of Computer Science, Foundation for Research and Technology - Hellas, Greece, george.papagiannakis@oramavr.com.

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real-world applications. Evaluations by expert users confirmed that pyGANDALF effectively balances ease of use with advanced functionality, preparing students for contemporary CG development challenges.

CCS Concepts

• **Computing methodologies** → *Graphics systems and interfaces*; • **Social and professional topics** → **Computer science education**; *Software engineering education.*

Keywords

Real-time rendering, GPU, Graphics API, WebGPU, OpenGL, Programming framework, Teaching

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1 Introduction

Learning computer graphics poses several challenges for students, particularly in mathematics, transformations and projections, and logical problem solving [Suselo et al. 2017]. A solid grasp of linear algebra, calculus, and geometry is crucial for understanding core concepts like transformations, lighting calculations, and 3D to 2D projections [Mashxura and Siddiqov 2023]. Many students struggle with these mathematical foundations, leading to confusion with matrix multiplication, coordinate systems, and perspective projections. Graphics programming also demands complex problem-solving skills, including debugging shaders, optimizing rendering pipelines, and understanding hardware constraints [Balreira et al. 2017b].

Various tools and frameworks simplify the learning process and bridge the gap between theory and practice [Papagiannakis et al. 2023, 2014; Toisoul et al. 2017; Unterguggenberger et al. 2023]. Balreira et al. [Balreira et al. 2017a] found that OpenGL was the most widely used graphics API in university education in 2017, due to its portability, low barrier to entry, and extensive documentation and tutorials. OpenGL's cross-platform design made it a reliable foundation for teaching computer graphics principles, fostering a broad understanding of rendering techniques and graphics pipeline operations.

However, recent advancements have prompted many educators to reconsider their approach to teaching computer graphics. The emergence of modern APIs such as Metal, Direct3D12, Vulkan, and WebGPU has shifted the focus towards newer technologies. Among these, Vulkan and WebGPU are the only APIs with the potential to replace OpenGL in graphics programming curricula due to their cross-platform capabilities, which are essential for effective teaching.

2 Architectural pillars of the proposed CG framework

We decided to propose a new framework built on three pillars: *WebGPU integration*, the *ECS principle*, and *Python* as the programming language. Let us delve deeper into the rationale behind our choices.

Why WebGPU. As previously mentioned, the primary choice for a cross-platform graphics API boils down to Vulkan and WebGPU. Vulkan, being a more mature and well-established API, is supported by the Khronos Group, which includes all major GPU manufacturers, operating system vendors, and various individual, academic, and industry members. However, Vulkan is notoriously verbose and requires extensive manual management of low-level concepts such as synchronization and resource handling [Unterguggenberger et al. 2023]. This complexity makes it cumbersome for novices, as a simple triangle rendering program requires nearly 1000 lines of code.

Choosing Vulkan would necessitate creating an abstraction layer to assist students and ease their learning process, which would likely resemble the WebGPU API. The WebGPU API (specifically its native desktop variant, not the browser version) serves as a layer on top of low-level APIs like Direct3D12 or Vulkan on Windows, Vulkan on Linux, and Metal on MacOS. It reduces the verbosity and complexity of these low-level APIs just enough to make them easier and faster to code with, while still maintaining low-level abstractions that provide fine-grained control over the hardware.

Numerous state-of-the-art examples [Kenwright 2022] [Kenwright 2023] using the WebGPU API showcase its capabilities in a learning-focused environment. These examples highlight how WebGPU enables complex, visually stunning graphics in the browser, offering an accessible platform for students and educators to explore modern graphics programming.

Therefore, WebGPU emerged as the clear choice for our purposes. While its relative youth and instability may result in delays in supporting the latest features and occasional API changes or deprecations, its backing by major organizations like the W3C and Khronos Group ensures a reliable development trajectory. Moreover, its balance between ease of use and providing sufficient control makes it an ideal option for teaching modern graphics programming.

Why Python. Another crucial decision in designing a framework for educational purposes is selecting the programming language. Experiences with using Vulkan and the C++ programming language, as described by [Unterguggenberger et al. 2023] [Unterguggenberger et al. 2022], indicate that students found the intricacies of C++ more challenging than using the Vulkan API itself, even through an abstraction layer. This observation, along with the recent advancements in Deep Learning, closely related to computer graphics developments and predominantly Python-centric, made Python an easy choice for our framework's language, allowing it to natively support deep learning extensions.

Additionally, Python is a very programmer-friendly and beginner-friendly language, enabling students to concentrate on graphics programming without struggling with the compiler and the complexities of a lower-level language like C++. This exclusive focus

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[1] Source for pistol model: https://artisaverb.info/PBT.html
[2] Source for Original Guitar Model: https://sketchfab.com/3d-models/survival-guitar-backpack-799f8c4511f84fab8c3f12887f7e6b36

on graphics programming maximizes the learning impact of students in Graphics principles. Experiences with using python as the framework language, as described [Papagiannakis et al. 2023], indicate that pythonic frameworks have a lot of potential and positive impact on the students' performance and they can easily adapt if they are not so acquainted with python.

Why ECS. The last and perhaps most fascinating choice in creating our framework was the decision to use an Entity-Component-System (ECS) architecture. The ECS pattern, widely used in 3D applications and game development, decouples data from behavior, simplifying development. It is based on data-oriented design and composition, where entities are assigned independent components, contrasting with the inheritance model of object-oriented design. ECS offers advantages such as enhanced performance in graphics scenes with numerous objects, improved maintenance and parallelization and understanding of the application's components.

Our implementation does not prioritize achieving maximal performance, such as rendering the maximum number of entities or optimizing for cache efficiency—considering that Python is an interpreted language. Instead, it focuses on promoting good coding practices. We aim to introduce students to a programming paradigm they might not have encountered before, helping them grasp graphics principles and develop skills that will enable them to write efficient and parallelizable software in the future.

3 Related Work

Over the years, numerous tools, frameworks, and libraries have been developed to facilitate CG development [Toisoul et al. 2017], [Andujar et al. 2018], [Miller 2014], [Suselo et al. 2019], [Bürgisser et al. 2017], [Pattanaik and Benamira 2021], [Wünsche et al. 2019], [Wuensche et al. 2022]. While a small subset of these is suitable for use in modern CG curricula for educational purposes, their applicability varies. In this context, WebGL notebooks [Pattanaik and Benamira 2021] have proven helpful for visualizing and understanding concepts such as lighting, shadows, textures, and GLSL shaders [Toisoul et al. 2017; Wuensche et al. 2022; Wünsche et al. 2019] by focusing on individual parts of the CG pipeline.

Teaching the complete OpenGL pipeline can be achieved using more comprehensive frameworks, such as those described in [Andujar et al. 2018; Bürgisser et al. 2017; Miller 2014], which abstract several OpenGL routines. These frameworks assist students in understanding the functionality of these routines without exposing them to low-level code.

When it comes to teaching the modern WebGPU graphics API, a few viable options exist. One such option is the use of Three.js [Danchilla 2012] and Babylon.js, renowned open-source JavaScript libraries for creating and displaying animated 3D graphics in web browsers. Originally developed to simplify WebGL complexities and not specifically for educational purposes, they are now expanding to support WebGPU. However, WebGPU integration in these libraries is still in progress and has not yet been officially released. Moreover, WebGPU support in browsers often requires enabling developer flags or may not be universally available. Despite their programmer-friendly nature and direct browser execution, these limitations currently hinder their suitability for educational use.

Another learning-focused framework, *Vulkan All the Way* [Unterguggenberger et al. 2023] modernizes computer graphics education by integrating the Vulkan API into the curriculum at TU Wien, Institute of Visual Computing & Human-Centered Technology, Vienna, Austria. Instead of completely replacing the existing OpenGL-based course, they allowed students to choose between the two APIs for their assignments. To address the unavoidable complexity associated with Vulkan, especially for undergraduate students, they developed an abstraction layer on top of Vulkan to simplify development and setup. The results, gathered through surveys, indicated that students responded positively to the Vulkan-based option. They found it helpful and interesting, with relatively few issues regarding its difficulty and complexity compared to OpenGL. Notably, students reported more difficulties with the C++ programming language than with the Vulkan API itself. This insight underscores our decision to use Python as the primary programming language for the proposed CG framework, as it alleviates such challenges and makes the learning process more accessible and manageable.

Another noteworthy initiative in advancing CG education is described by *Project Elements* [Papagiannakis et al. 2023]. In this project, authors transitioned from a C++ based framework [Papagiannakis et al. 2014] to a Python-based one, incorporating a unique Entity-Component-System (ECS) within a scenegraph architecture. The new framework was deployed at the University of Crete, Department of Computer Science, Heraklion, Greece, and at the University of Western Macedonia, Department of Electrical and Computer Engineering, Kozani, Greece. Although they continued using OpenGL as the main graphics API, the transition to the new Python-based framework was reported to be smooth. This conclusion was supported by surveys and grade results indicating that students adapted easily to Python. While the new assignments were not directly comparable to those from the previous C++ framework, the students' performance suggested effective adaptation to a Pythonic framework, reinforcing our decision to use Python. Elements is also experimenting on a WebGPU implementation in a feature branch.

4 The pyGANDALF Framework

In this section, we introduce pyGANDALF, a framework designed to advance the computer graphics educational process. We will examine the framework's structure and features, illustrating how it enables educators and students to enhance their teaching and learning capabilities. pyGANDALF aims to modernize computer graphics curricula and address the challenges associated with teaching this complex subject.

4.1 Architecture and design

As previously discussed, pyGANDALF is implemented in Python and supports both the OpenGL and WebGPU graphics APIs, utilizing an Entity-Component-System (ECS) architecture. It also includes an editor layer that provides a user-friendly interface for editing and creating scenes efficiently.

4.2 Entity-Component-System Setup

We have designed a custom ECS implementation tailored to our framework's needs. This implementation focuses on creating a simple and easy-to-understand API while adhering to the principles of a pure ECS architecture. Given that the framework is intended for educational purposes rather than production, we prioritize clarity and ease of use over maximizing performance and cache efficiency, especially since we are using Python. However, as demonstrated in the performance evaluation, the results are quite respectable.

In our pure ECS architecture:

- Entities are represented by Universally Unique Identifiers.
- Components consist only of data, encapsulating no behavior.
- Systems manage functionality and behavior.

All the elements described above are contained in a Scene (Listing 1); the framework is designed to support multiple scenes at runtime and allows for easy and fast switching between them.

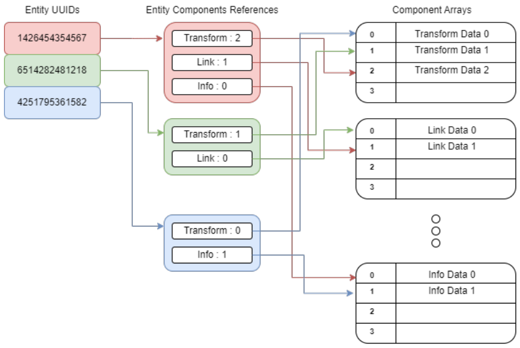


Figure 2: Entity Component System setup in pyGANDALF.

Before discussing the management of systems, we refer to Fig. 2 to shed light to the data handling mechanisms within our ECS implementation. Our approach involves maintaining an array of all entities alongside dedicated arrays for each component type, ensuring that components of the same type are grouped together. To map components to their corresponding entities, we employ an intermediate structure that stores entity-component references. This structure functions as a dictionary, where the component type serves as the key and the index within the component array is the value. This organization allows us to efficiently retrieve the desired component for a given entity, provided it exists.

```python
# Create a scene
scene = Scene()

# Enroll entities to scene
root = scene.enroll_entity()
entity = scene.enroll_entity()

# Register components to root
scene.add_component(root, TransformComponent())
scene.add_component(root, InfoComponent('root'))
scene.add_component(root, LinkComponent(None))

# Register components to entity
scene.add_component(entity, TransformComponent())
scene.add_component(entity, InfoComponent('entity'))
scene.add_component(entity, LinkComponent(root))
```

Listing 1: Scene creation entity registration and addition of components

Next, we examine the handling of systems, as illustrated in Listing 2. When a system is instantiated, the components it will operate on are defined. For an entity to be processed by the system, it must possess all specified components. This filtering of entities and components occurs during system initialization, and the resulting entities and components are cached within the system for efficient access. The framework also supports runtime addition and removal of components, ensuring that the cached entities and components within each system are dynamically updated.

```python
class GravityComponent(Component):
    def __init__(self):
        self.force = 5.0

class TransformComponent(Component):
    def __init__(self, translation, rotation, scale):
        self.translation = translation
        self.rotation = rotation
        self.scale = scale

GravitySystem([GravityComponent, TransformComponent])
```

Listing 2: System instatiation

In Listing 3, a basic gravity system is demonstrated, which operates on both a gravity component and a transform component. During each frame, a rudimentary gravity force is applied to the transform component of each entity.

```python
class GravitySystem(System):
    def on_create_entity(self, entity, components):
        pass

    def on_undate_entity(self, ts, entity, components):
        gravity, transform = components
        transform.y -= gravity.force * ts
```

Listing 3: Gravity System example

4.3 Handling Dual APIs

To support both OpenGL and WebGPU, we created two distinct systems, each responsible for rendering entities in their respective API. By leveraging Python's dynamic typing, both systems utilize the same Mesh and Material components, preventing unnecessary duplication and simplifying the overall design.

By maintaining a unified set of components and utilizing Python's flexibility, we ensure that the same entity data can be processed by either rendering system. This dual-API support allows students to become familiar with and gain insights into both OpenGL and WebGPU without the need for redundant code or data structures.

To manage dual APIs, we implemented two distinct rendering systems: the OpenGL Rendering System and the WebGPU Rendering System. The OpenGL Rendering System processes entities with Mesh, Material, and Transform components, utilizing OpenGL-specific calls to render the scene. Similarly, the WebGPU Rendering System processes entities with Mesh and Material components, but employs WebGPU-specific calls to render the scene.

This approach ensures that students can explore the unique aspects and capabilities of both OpenGL and WebGPU, fostering a deeper understanding of modern graphics programming. Additionally, it highlights the adaptability and reusability of the ECS architecture across different graphics API contexts.

In the WebGPU rendering system, rather than issuing a separate draw call for each renderable entity—an inefficient approach—the framework groups renderable entities based on their material instance and vertex data. This strategy enables the framework to dispatch instanced draw commands in WebGPU, rendering multiple entities with the same material and mesh in a single draw call. In contrast, the OpenGL rendering system handles these entities with individual draw calls per material instance to simplify the implementation, avoiding the complexities of instanced drawing, which requires custom draw commands. In the future, a new and separate rendering system could be implemented in OpenGL to utilize instanced drawing, further improving rendering performance.

4.4 Handling Resources

Supporting multiple graphics APIs requires efficient resource management, including textures, shaders, and materials. To facilitate this, we implemented helper singleton classes specific to each API. These classes manage resource creation, usage, and reuse, ensuring efficient performance and a streamlined development experience.

Each type of resource is managed by an API-specific singleton class. The *Textures class* ensures textures are loaded, stored, and accessed efficiently. The *Shaders class* maintain a repository of compiled shaders to avoid redundant compilations. Special attention was given to material management to optimize performance. Lastly, the *Materials class* is reused whenever possible, reducing the overhead of creating new instances.

In Listings 4 and 5, we provide examples illustrating the creation of a material that utilizes a shader and a texture. These examples demonstrate the straightforward API provided by our framework for resource management, ensuring ease of use and efficiency.

```
# Build texture
OpenGLTextureLib().build('pistol_albedo', TextureData(TEXTURES_PATH / '
       fa_flintlockPistol_albedo.jpg'))

# Build shader
OpenGLShaderLib().build('default_mesh', SHADERS_PATH/'lit_blinn_phong.vert',
       SHADERS_PATH / 'lit_blinn_phong.frag')

# Build Material
OpenGLMaterialLib().build('M_Pistol', MaterialData('default_mesh', ['
       pistol_albedo'], glossiness=2.0))
```

Listing 4: Resource management in OpenGL

```
# Build texture
WebGPUTextureLib().build('pistol_albedo', TextureData(path=TEXTURES_PATH / '
       fa_flintlockPistol_albedo.jpg'))

# Build shader
WebGPUShaderLib().build('default_mesh', SHADERS_PATH / 'webgpu' / '
       lit_blinn_phong.wgsl')

# Build Material
WebGPUMaterialLib().build('M_Pistol', MaterialData('default_mesh', ['
       pistol_albedo']))
```

Listing 5: Resource management in WebGPU

4.5 Editor

The framework includes an editor layer that offers a user-friendly UI for editing and creating scenes quickly and efficiently. This editor layer supports full serialization, allowing scenes to be saved and loaded in the Universal Scene Description (USD) format. The editor layer can be enabled or disabled via a simple flag, enhancing its versatility.

The editor implementation is seamlessly integrated into the ECS architecture. Each panel in the editor is represented as an entity, with dedicated components that facilitate the construction of various UI layouts. This design leverages the *Dear ImGui Bundle* [Bundle 2023] package, which is widely recognized for its efficiency in creating immediate mode and real-time user interfaces.

By integrating the editor into the ECS, we achieve several benefits:

- Consistency: The editor's functionality is encapsulated within systems, maintaining a consistent approach throughout the framework.
- Extensibility: The editor can be easily extended using the same API, allowing for future enhancements without significant restructuring.

One minor setback is that the editor layer is currently available only when using the OpenGL API. This limitation arises because the WebGPU API is relatively new, and there is no implementation for it in the Dear ImGui Bundle package yet. This limitation means that while students can benefit from a rich, interactive editor interface with OpenGL, they will have to forego this convenience when working with WebGPU until further support is developed.

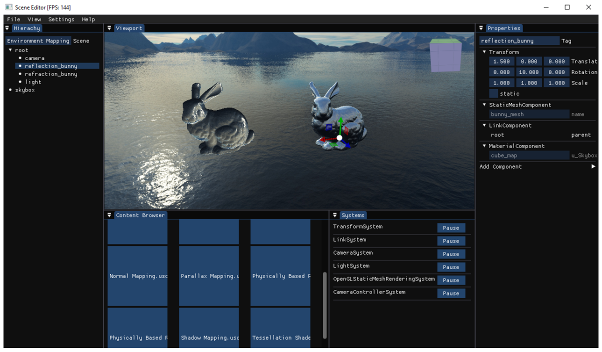
5 Educational examples - Using pyGANDALF in CG curriculum

To aid in learning and exploration, pyGandalf includes a plethora of examples that demonstrate a wide range of graphics techniques, from fundamental to more advanced concepts. These examples serve as valuable resources for educators, researchers, and developers, facilitating the transition from educational settings to real-world applications.

The examples provided with the framework are categorized based on their level of complexity and difficulty. This structured approach ensures that students gradually build their knowledge and skills, starting from basic concepts and progressing to advanced techniques. Below, we distinguish four main categories based on CG concepts and implementation difficulty, and we suggest the weeks during a typical CG course when these examples should be explored:

- **Introductory (Week 1-2):** These examples use Jupyter notebooks in Python to guide users step-by-step in creating their first computer graphics applications using the framework. Detailed explanations accompany each step, aiming to familiarize students with the framework API and prepare them to develop their projects independently.
- **Beginner (Week 3-7):** These examples range from opening an empty window with a clear color to rendering a first triangle. Students will learn about textures, cameras, and how to set up a scenegraph hierarchy.
- **Intermediate (Weeks 8-13):** In these examples, students will progress to rendering more complex meshes and learning about the Blinn-Phong shading model (Fig. 4). They will explore cube and environment mapping (Fig. 3), create custom systems and components, and manage multiple scenes.
- **Advanced (Week 10-13):** At this stage, students will delve into advanced shader techniques and rendering pipelines. They will explore tessellation (Fig. 1c) and geometry shaders (Fig. 1b), as well as more recent innovations like compute shaders. Additionally, students will explore Physically Based Rendering (PBR) (Fig. 1a) to understand advanced shading

techniques. Furthermore, students will be exposed to fundamental techniques such as normal mapping, parallax mapping and how it contrasts with normal mapping, and finally shadow mapping (Fig. 1d) to get familiar with notion of multiple rendering passes to achieve complex effects.



reflection_bunny Tag
Transform
1.500 0.000 0.000 Translat
0.000 10.000 0.000 Rotation
1.000 1.000 1.000 Scale
static
StaticMeshComponent
bunny_mesh name
LinkComponent
root parent
MaterialComponent
cube_map u_Skybox

Figure 3: The pyGANDALF scene manipulation editor. The example shown depicts a bunny made of ice (left) and silver (right) being lit by the Environment mapping.

All examples are implemented using both OpenGL and WebGPU APIs. This dual implementation provides valuable insights into the differences between modern low-level APIs and more high-level legacy ones. By comparing the two, students will gain a deeper understanding of the trade-offs between different API designs, deal with performance considerations, learn about certain features in modern APIs that lead to improved performance, and understand the detailed control offered by low-level APIs and how it contrasts with the abstractions in legacy APIs.

6 Evaluation

In this section, we present the evaluation methods used, along with their results, accompanied by a brief discussion and analysis. The evaluation is divided into two main components: the performance assessment of the framework and an expert-based evaluation of its educational impact.

Figure 4: Applying a filter to an original image[3] (left) with Compute Shaders. The result is shown on the right.

Table 1: A performance comparison for time required to render scenes of diverse complexity, using WebGPU, OpenGL without editor and OpenGL with editor in pyGANDALF. (Higher is better, highlighted in bold).

Scene	WebGPU	OpenGL	OpenGL + Editor
Scene 1	850 fps	**1200 fps**	910 fps
Scene 2	**815 fps**	450 fps	350 fps
Scene 3	**545 fps**	105 fps	85 fps
Scene 4	**541 fps**	103 fps	82 fps
Scene 5	**355 fps**	72 fps	61 fps

6.1 Performance Evaluation

We assessed the performance of the pyGANDALF framework on a Windows 10 PC with the following specifications: an Intel Core i9 9900K Processor (8 cores/16 threads, 12 MB Cache, 4.9 GHz max boost), an NVIDIA GeForce RTX 2080 GPU with 8 GB GDDR6 Video RAM, and 16 GB of DDR4 RAM at 3600 MHz.

Our benchmarking scenarios were designed to simulate common graphics application use cases, including simple rendering tasks, complex scenes with multiple objects, and dynamic interactions. The framework's performance was evaluated across the following scenarios:

- Scene 1: A simple scene with a single model and a skybox.
- Scene 2: A more complex scene with 10 models and a skybox.
- Scene 3: A significantly more complex scene containing 50 models and a skybox.
- Scene 4: A duplicate of Scene 3, where all 50 models are dynamically rotated every frame.
- Scene 5: A highly complex scene with 100 models and a skybox, with all 100 models rotating every frame.

We evaluated the performance of both graphics API implementations (OpenGL and WebGPU) in terms of frames rate and memory usage, which are common metrics for such frameworks. Regarding OpenGL, we distinguished two scenarios, depending on whether the editor layer was enabled or not.

6.1.1 Frames per second. The results of this comparison are depicted in Table 1.When comparing OpenGL implementations with and without the editor, we observed a 20-25% reduction in performance with the editor attached. This decrease is anticipated due to the additional resources required for rendering the editor's UI and managing its systems. Despite this performance drop, the editor consistently maintains frame rates above 60 fps, even in the most demanding scenes, ensuring smooth operation.

In contrast, the WebGPU implementation demonstrates a significant performance advantage over OpenGL. This improvement is largely due to the lower-level nature of the WebGPU API, which enables more effective optimizations. The most notable factor contributing to this performance boost is the use of instanced drawing techniques in WebGPU, which significantly enhances rendering efficiency.

6.1.2 CPU & GPU Memory Usage. We compared CPU and GPU memory consumption across three scenarios: (a) OpenGL, (b) WebGPU, and (c) OpenGL with the editor, for all five test scenes. The

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[3] Source: https://www.pexels.com/photo/close-up-photo-of-butterfly-4121222/

analysis reveals that the presence of the editor does not significantly impact memory usage in OpenGL implementations. When comparing WebGPU to OpenGL, WebGPU required approximately 200 MB more GPU memory, considering memory usage ranged from approximately 400 MB to 600 MB for scenes 3 through 5. In terms of CPU memory, OpenGL consistently used around 200 MB across all scenes, regardless of scene complexity. In contrast, WebGPU's CPU memory usage increased with scene complexity, ranging from 385 MB to 535 MB. This additional CPU memory usage is due to WebGPU's instanced drawing technique, which necessitates extra CPU-side buffers for storing model matrices before transferring them to the GPU.

6.2 Educational evaluation

6.2.1 Experimental Setup. Following a cognitive walkthrough evaluation protocol [Blackmon et al. 2002], CG experts assessed the effectiveness of the pyGANDALF framework. Seven computer graphics experts, who are also former students of the Computer Graphics (CS358) and Interactive Computer Graphics (CS553) courses from the Department of Computer Science at the University of Crete, Greece, participated in the evaluation. The evaluators were divided into two groups: (1) the first group used the pyGANDALF framework to implement a scenario in both OpenGL and WebGPU, and (2) the second group used Python along with the OpenGL and WebGPU APIs without any additional framework. The evaluators were tasked with implementing a typical scenario that would be assigned in a classroom setting, aiming to assess the framework's capacity to enhance student success and learning outcomes [Mahatody et al. 2010]. The evaluation was guided by a structured set of questions, which the evaluators addressed after completing each implementation step. Specifically, the evaluation of the pyGANDALF framework included the following questions [Bligård and Osvalder 2007; Hart and Staveland 1988], and each question was rated on a scale from 1 to 5, where 1 indicated a very negative response and 5 indicated a very positive response.

1. How clearly do the tools communicate the availability of functionalities?
2. How intuitively do the tools guide you in achieving the desired effects?
3. How effectively do the tools help you understand the correspondence between API features and the desired functionalities?
4. How well do the tools facilitate the association of API features with their expected outcomes?
5. How sufficient is the feedback provided when a functionality is performed?
6. How mentally demanding was the task?
7. How successful were you in accomplishing the assigned tasks?
8. How much effort was required to achieve your level of performance?
9. How discouraged, irritated, stressed, or annoyed did you feel during the process?

The task assigned to the evaluators was described as follows: "Create a house consisting of a cube as the base and a pyramid as the roof. The house should rotate around its y-axis in each frame. The cube should be textured with a brick pattern, while the pyramid should be colored orange. Additionally, a perspective camera should be set up to view the house properly." To provide a more structured evaluation and a clearer assessment of the framework's effectiveness, this task was divided into five distinct sub-tasks (milestones):

- Task 1: Attributes - Definition of vertex data and layout
- Task 2: Textures - Load and use textures
- Task 3: Shaders - Load, compile and use shaders
- Task 4: Camera - Set up camera and projection
- Task 5: Uniforms - Add interactivity to the scenario

Before each evaluation session, the facilitator briefed the evaluators on the goals and objectives of the pyGANDALF framework. Additionally, both groups were provided with a set of fundamental examples that demonstrated core concepts and functionalities. These examples were designed to guide the evaluators and help them become familiar with the task.

6.2.2 Results. Figure 5 (Top) presents the results for Group 1, where all tasks received average scores above 4 for questions related to intuitiveness and clarity. In contrast, scores for questions concerning required effort and experienced frustration were below 2. In Figure 5 (Bottom), we see that Group 2's scores for intuitiveness and clarity were consistently below 3.5, while their scores for required effort and experienced frustration were above 2.5.

These results indicate that the evaluators found the pyGANDALF framework to be more intuitive and clearer compared to the implementation without a framework. Furthermore, evaluators using pyGANDALF experienced significantly fewer negative emotions and required less effort to complete the task.

Figure 6 illustrates that Task 5, "Uniforms - Add interactivity to the scenario," exhibits the highest deviation in responses within Group 1. This variation suggests potential areas for improvement in task clarity, even though it received strong overall ratings. The increased variability may be attributed to the requirement for evaluators to create and implement their own system and component to achieve the desired results. Evaluators who were less familiar with the ECS philosophy might have encountered more challenges, leading to disparate levels of difficulty.

In contrast, the remaining tasks demonstrate a low standard deviation (<1) in responses, indicating a high level of agreement among evaluators regarding their ratings.

Additionally, an analysis of specific tasks reveals that "Shaders - Load, compile, and use shaders" and "Textures - Create and use textures" achieved near-perfect scores. This finding reinforces our commitment to providing a clear and intuitive approach to resource management within the framework, while ensuring that the educational experience remains comprehensive and accessible to students.

A remarkable result regards the time that groups required to finish their implementation. Group 1, using the pyGANDALF framework, required an average of 55 minutes to finish their implementation, which is 20 minutes less than the group not using it.

7 Conclusion and Future Work

This paper presents pyGANDALF, an innovative open-source educational framework for computer graphics, available at https:

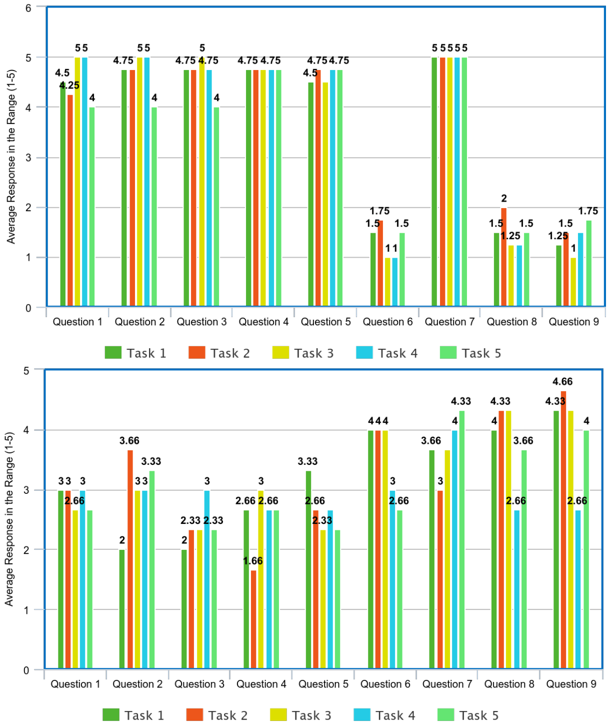

Figure 5: Average responses for each task from Group 1 (Top) and 2 (Bottom), rated on a scale from 1 to 5, with 1 indicating very negative response and 5 indicating a very positive response

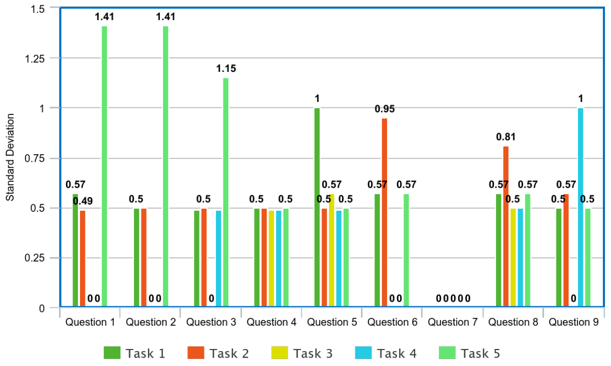

Figure 6: Standard Deviation of Responses for Each Task in Group 1.

//github.com/papagiannakis/pyGandalf. pyGANDALF is built upon three key pillars: the Entity-Component-System (ECS) architecture, support for both modern (WebGPU) and legacy (OpenGL) graphics APIs, and a user-friendly Python interface. This combination is unique to pyGANDALF and provides a distinctive approach to teaching and learning computer graphics.

The framework's educational value is underscored by its design, which integrates cutting-edge concepts with foundational graphics techniques. The dual support for WebGPU and OpenGL offers students exposure to both modern and legacy APIs, facilitating a deeper understanding of GPU hardware and the evolution of graphics programming. This comprehensive exposure prepares students to innovate and contribute to advancements in the field by embracing both new and traditional approaches.

An expert-based evaluation further supports the framework's effectiveness, demonstrating that pyGANDALF provides a more efficient and less frustrating experience compared to traditional methods. The diversity of educational examples included in the framework—spanning from fundamental to advanced graphics techniques—enables students to explore various computer graphics concepts, replicate them in their projects, and gain practical experience.

In conclusion, pyGANDALF not only simplifies the teaching and learning of computer graphics but also equips students with the knowledge and tools to advance the field. Future work will focus on expanding the framework's capabilities, integrating additional graphics techniques, and enhancing its educational resources to support an even broader range of learning objectives. Further large-scale evaluations are planned, including studies with control groups in graduate and undergraduate computer graphics courses, aimed at revealing pyGANDALF's educational impact and providing deeper insights for its potential improvements.

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References

Carlos Andujar, Antonio Chica, Marta Fairén, and Alvar Vinacua. 2018. GL-Socket: A CG Plugin-based Framework for Teaching and Assessment. In *EG 2018 - Education Papers*, Frits Post and Jirí Žára (Eds.). The Eurographics Association.

D. G. Balreira, M. Walter, and D. W. Fellner. 2017a. What we are teaching in introduction to computer graphics. In *Proceedings of the European Association for Computer Graphics: Education Papers* (Lyon, France) *(EG '17)*. Eurographics Association, Goslar, DEU, 1–7. https://doi.org/10.2312/eged.20171019

Dennis Giovani Balreira, Marcelo Walter, Dieter W Fellner, et al. 2017b. What we are teaching in Introduction to Computer Graphics.. In *Eurographics (Education Papers)*. 1–7.

Marilyn Hughes Blackmon, Peter G Polson, Muneo Kitajima, and Clayton Lewis. 2002. Cognitive walkthrough for the web. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 463–470.

Lars-Ola Bligård and Anna-Lisa Osvalder. 2007. An analytical approach for predicting and identifying use error and usability problem. In *HCI and Usability for Medicine and Health Care: Third Symposium of the Workgroup Human-Computer Interaction and Usability Engineering of the Austrian Computer Society, USAB 2007 Graz, Austria, November, 22, 2007. Proceedings 3*. Springer, 427–440.

Dear ImGui Bundle. 2023. *Dear ImGui Bundle: an extensive set of ready-to-use widgets and libraries, based on ImGui.* https://pthom.github.io/imgui_bundle/index.html

Benjamin Bürgisser, David Steiner, and Renato Pajarola. 2017. bRenderer: A Flexible Basis for a Modern Computer Graphics Curriculum. In *EG 2017 - Education Papers*, Jean-Jacques Bourdin and Amit Shesh (Eds.). The Eurographics Association.

Brian Danchilla. 2012. *Three.js Framework.* Apress, Berkeley, CA, 173–203. https://doi.org/10.1007/978-1-4302-3997-0_7

Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Human Mental Workload*, Peter A. Hancock and Najmedin Meshkati (Eds.). Advances in Psychology, Vol. 52. North-Holland, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

Benjamin Kenwright. 2022. Introduction to computer graphics and ray-tracing using the webgpu api. In *15th ACM SIGGRAPH Conference and Exhibition on Computer Graphics and Interactive Techniques in Asia 2022.*

Benjamin Kenwright. 2023. Web Programming Using the WebGPU API. In *ACM SIGGRAPH 2023 Courses* (Los Angeles) *(SIGGRAPH '23)*. Association for Computing Machinery, New York, NY, USA, Article 21, 184 pages.

Thomas Mahatody, Mouldi Sagar, and Christophe Kolski. 2010. State of the art on the cognitive walkthrough method, its variants and evolutions. *Intl. Journal of Human–Computer Interaction* 26, 8 (2010), 741–785.

Miryahyoyeva Mashxura and Ilhomjon Meliqo'ziyevich Siddiqov. 2023. Effects of the Flipped Classroom in Teaching Computer Graphics. *Eurasian Research Bulletin* 16 (2023), 119–123.

James R Miller. 2014. Using a software framework to enhance online teaching of shader-based opengl. In *Proceedings of the 45th ACM technical symposium on Computer science education*. 603–608.

George Papagiannakis, Manos Kamarianakis, Antonis Protopsaltis, Dimitris Angelis, and Paul Zikas. 2023. Project Elements: A Computational Entity-component-system in a Scene-graph Pythonic Framework, for a Neural, Geometric Computer Graphics Curriculum. In *Eurographics 2023 - Education Papers*, Alejandra Magana and Jiri Zara (Eds.). The Eurographics Association. https://doi.org/10.2312/eged.20231015

G. Papagiannakis, P. Papanikolaou, E. Greassidou, and P. Trahanias. 2014. glGA: an OpenGL Geometric Application Framework for a Modern, Shader-based Computer Graphics Curriculum. In *Eurographics 2014 - Education Papers*. The Eurographics Association.

Sumanta N. Pattanaik and Alexis Benamira. 2021. Teaching Computer Graphics During Pandemic using Observable Notebook. In *Eurographics 2021 - Education Papers*, Beatriz Sousa Santos and Gitta Domik (Eds.). The Eurographics Association.

Thomas Suselo, Burkhard C Wünsche, and Andrew Luxton-Reilly. 2017. The journey to improve teaching computer graphics: A systematic review. In *Proceedings of the 25th International Conference on Computers in Education (ICCE 2017). APSCE, Christchurch, New Zealand*. 361–366.

Thomas Suselo, Burkhard C. Wünsche, and Andrew Luxton-Reilly. 2019. Technologies and Tools to Support Teaching and Learning Computer Graphics: A Literature Review. In *Proceedings of the Twenty-First Australasian Computing Education Conference* (Sydney, NSW, Australia) *(ACE '19)*. Association for Computing Machinery.

Antoine Toisoul, Daniel Rueckert, and Bernhard Kainz. 2017. Accessible GLSL shader programming. In *Proceedings of the European Association for Computer Graphics: Education papers*. 35–42.

J. Unterguggenberger, B. Kerbl, and M. Wimmer. 2022. The Road to Vulkan: Teaching Modern Low-Level APIs in Introductory Graphics Courses. In *Eurographics 2022 - Education Papers* (Reims). The Eurographics Association, 31–39.

J. Unterguggenberger, B. Kerbl, and M. Wimmer. 2023. Vulkan all the way: Transitioning to a modern low-level graphics API in academia. *Computers & Graphics* 111 (2023), 155–165.

Burkhard Claus Wuensche, Kai-Cheung Leung, Davis Dimalen, et al. 2022. Using an Assessment Tool to Create Sandboxes for Computer Graphics Teaching in an Online Environment. In *Proceedings of the 10th Computer Science Education Research Conference* (Virtual Event, Netherlands) *(CSERC '21)*. Association for Computing Machinery, New York, NY, USA, 21–30.

Burkhard C. Wünsche, Edward Huang, Lindsay Shaw, Thomas Suselo, Kai-Cheung Leung, Davis Dimalen, Wannes van der Mark, Andrew Luxton-Reilly, and Richard Lobb. 2019. CodeRunnerGL - An Interactive Web-Based Tool for Computer Graphics Teaching and Assessment. In *2019 International Conference on Electronics, Information, and Communication (ICEIC)*. 1–7.