

Project Elements: A computational entity-component-system in a scene-graph pythonic framework, for a neural, geometric computer graphics curriculum

G. Papagiannakis^{1,2,5}  M. Kamarianakis^{1,2,5}  A. Protopsaltis^{3,5}  D. Angelis^{1,2,5}  P. Zikas^{4,5} 

¹ Foundation of Technology Hellas - ICS, Heraklion, Greece

² University of Crete, Dept. of Computer Science, Heraklion, Greece

³ University of Western Macedonia, Dept. of Electrical and Computer Engineering, Kozani, Greece

⁴ University of Geneva, Dept. of Computer Science, Geneva, Switzerland

⁵ ORamaVR SA, Geneva, Switzerland and Heraklion, Greece

Abstract

We present the Elements project, a lightweight, open-source, computational science and computer graphics (CG) framework, tailored for educational needs, that offers, for the first time, the advantages of an Entity-Component-System (ECS) along with the rapid prototyping convenience of a Scenegraph-based pythonic framework. This novelty allows advances in the teaching of CG: from heterogeneous directed acyclic graphs and depth-first traversals, to animation, skinning, geometric algebra and shader-based components rendered via unique systems all the way to their representation as graph neural networks for 3D scientific visualization. Taking advantage of the unique ECS in a Scenegraph underlying system, this project aims to bridge CG curricula and modern game engines (MGEs), that are based on the same approach but often present these notions in a black-box approach. It is designed to actively utilize software design patterns, under an extensible open-source approach. Although Elements provides a modern (i.e., shader-based as opposed to fixed-function OpenGL), simple to program approach with Jupyter notebooks and unit-tests, its CG pipeline is not black-box, exposing for teaching for the first time unique challenging scientific, visual and neural computing concepts.

CCS Concepts

• **Social and professional topics** → *Computer science education; Software engineering education;*

1. Introduction

Computer Graphics is a challenging teaching subject [SWLR17, MS23], as it borrows knowledge from multiple computational scientific areas [BWF*17] such as mathematics, biology, physics, computer science and specifically software design, data structures and GPU programming through shader-based APIs. Along with the multiple pedagogical approaches, there exist a variety of tools and frameworks [TRK17, AGCCFGVP18, Mil14, SWLR19, BSP17, PB21, WHS*19, WLD*22, TRK17] that facilitate CG development; however, only a small subset is oriented towards teaching a hands-on, programming and assignment-based approach of a part of or the complete modern graphics pipeline, from shader-based visualisation all the way towards neural computing. An approach that seems to yield positive feedback from the students is the use of notebooks [PB21], usually based on WebGL, that help visualize concepts such as lighting, shadows and textures in an interactive way [WHS*19]. Such tools offer limited functionality as they focus on specific CG aspects, detached from the CG pipeline [WLD*22] such as the GLSL shaders [TRK17]. In such approaches, students

may focus and learn in depth how a particular task is performed or how specific parameters affect the final rendered scene, but they usually have trouble comprehending how these operations are interconnected into a single pipeline. Another strategy to teach the entire operation of the OpenGL pipeline is via the employment of frameworks [AGCCFGVP18, Mil14, BSP17]. These packages usually contain examples and helper functions that perform batch-calling of simpler OpenGL functions, based on their functionality, e.g., shader initialization or VAO/VBO creation, thus facilitating students understanding without exposing them to low-level code, until they are ready to handle or tamper with it. Such frameworks are usually written in C++/C# and are suitable both for teaching as well as small or intermediate projects. A main drawback of them is that several CG pipeline operations are treated as black-boxes, thus not providing the practical knowledge of all stages of the rendering pipeline to students, like the calculation of the global transformation matrix of a 3D mesh in a scenegraph. Furthermore, these frameworks are not extensible in a simple, straightforward and open-source way towards state-of-the-art python-based neural

© 2023 The Authors.

Proceedings published by Eurographics - The European Association for Computer Graphics. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

computing for geometric deep learning frameworks such as graph neural networks.

1.1. A rising tide: ECS and Scenegraphs

The management of interactive scenes in MGEs and graphics systems is based on a hierarchical data structure, the *scenegraph*, a heterogeneous, directed acyclic graph, that is traversed to render a frame [RH94]. The scenegraph contains all the data required to replicate the scene, including among others, geometry, materials, camera specifications and light information. All graph nodes inherit properties from their ancestors and the object mesh data of a specific node are stored on child leaf nodes. The nodes are usually referred to as *gameobjects*, *actors* or plain *objects* in MGEs, whereas the related data stored within them are usually denoted as *Components*. Scenegraph edges denote connectivity and hierarchy; different traversals ensure initialisation, update, culling and rendering of all scenegraph nodes.

Entity-Component-System is an architectural pattern, mainly used in 3D applications and game development [Nys14,PQKN17], that decouples data from behavior, simplifying the development. It heavily relies on data-oriented-design and composition, where created entities are assigned independent components, in contrast with object-oriented- design, where such components would be inherited from base classes. This architecture enables a) improved performance in applications with many objects (e.g physics based simulations) and b) improved maintenance and understanding of the application's objects.

The ECS model has gained a lot of attention in various game frameworks (EnTT, <https://github.com/skypjack/entt>), [RH19] and a variation of it is in the core of most MGEs. For example, Unity is currently restructuring its core-engine, towards adopting the DOTS (acronym for Data Oriented Technology Stack) system (<https://unity.com/dots>) that features an ECS architecture, to tackle violations caused by previous data-oriented programming principles and achieve better fps performance in complex scenes. In our work, we provide a unique core ECS in a scenegraph architecture, in order to teach several key CG concepts in a data-oriented approach that facilitates connectivity with neural computing and geometric deep learning.

1.2. Current approaches in modern CG teaching

To enable a CG hands-on programming approach, students are usually given a framework and initial pipeline skeleton examples, upon which they may build up their first CG applications. Such approaches utilize a MGE, or a C/C++ framework.

MGEs, such as Unity and Unreal engine, are high-level tools that provide excellent visualizations of content using all CG principles, but most low-level details of the CG pipeline are kept hidden in a black-box. For instance, any Unity programmer may easily create CG content, such as a shadowed cube with no knowledge in lighting or shadow algorithms, or animate a simple model without having to deal with the frame (linear or spherical) interpolation process and the calculation of the world transformation matrix, or rotate an object without knowing the details of Euler angles or quaternions.

In that frame, as the learning objectives of all CG courses include the low-level experimentation of students with all basic CG principles, CG professors have suspended the use of game engines in undergraduate CG courses. On the other hand, game engines are widely used in graduate CG courses, where students have already mastered CG principles well.

In many CG curricula, professors have opted for the use of C/C++ CG frameworks or packages, prioritizing the learning of basic principles of the CG pipeline (rendering, lighting, shading). Although frameworks are often hierarchically structured and code exploration is, in some cases, possible at some levels, the complexity of such frameworks is great, hindering swift prototyping and connection with rapidly growing scientific domains. Furthermore, a fully educational-tailored experience at all levels is still not feasible, and state-of-the-art concepts, such as ECS on a scenegraph and design patterns are not utilized yet.

1.3. Our pythonic, ECS in a Scenegraph, approach: ECSS

In this paper, we introduce the *Elements* project, that aims to provide the power of the Entity-Component-System (ECS) in a Scenegraph (ECSS) *pythonic* (i.e., using latest python 3 language features and software design patterns) framework, suitable to be used in the context of a CG curriculum with extensions to scientific, neural computing and geometric deep learning.

As a central idea, we have implemented a software-design-pattern based scenegraph, combined with an Entity Component System (ECS) [Bil02] principle, which dictates a data-oriented rather than an object-oriented programming approach. By opting to ECS, we were able to serve the main approach that MGEs abide to and grants them the ability to effectively manage even extremely complicated scenes.

In our ECSS, the functionality of our scenegraph is provided via the Composite pattern, our Entities are just Grouping nodes with an ID, our Components contain only data that can be easily extended using the decorator pattern, and all functionality (rendering, update etc.) is only performed in our Systems that are traverse the scenegraph of Entities and Components via the visitor pattern. Finally, events and messages in our ECSS can easily be handled using the observer pattern.

Although scenegraphs, shader-based GPU programming and ECS are well known principles in the CG community, the existence of a framework that incorporates all of them and exposes them as easily accessed notebooks for scientific and neural computing has not appeared in the bibliography so far, to the best of our knowledge. Included in Elements (see Fig. 1), the pyECSS (acronym for **python ECS on Scenegraphs**), is a unit-test python package, that, for the first time, incorporates both of these principles, in a comprehensive way, suitable for teaching to CG students.

The pyGLV (acronym for computer **G**raphics for deep **L**earning and scientific **V**isualization in **python**) package of Elements exploits the pyECSS benefits and provides the necessary graphics algorithms to allow the creation and visualization of 3D scenes via the OpenGL and GLSL APIs and languages. The use of simple functions allows the creation of Entities (scene root and objects)

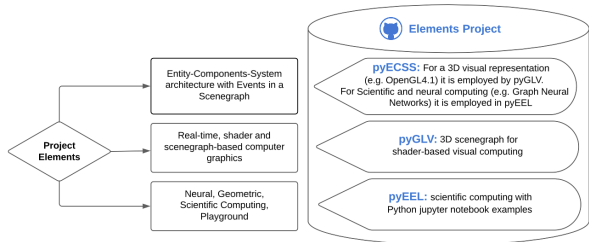


Figure 1: The Elements Project: *pyECSS*, *pyGLV* & *pyEEL*.

and their Components (geometry, camera, lights, transformation) of objects in the 3D scene, CG programmers can quickly dive into the concept of a scenegraph, an approach that will help them easily adapt to the pipeline of MGEs. The built-in Systems (TransformationSystem, CameraSystem) and the shader functions prove to be essential for beginners, as they help them grasp the CG principles without initially worrying about low-level implementation details.

Lastly, the Elements' *pyEEL* (acronym for **E**xplore - **E**xperiment - **L**earn using **p**ython) repository holds various jupyter notebooks, suitable for both beginners and experienced programmers. Our aim is to evolve this repository to a knowledge-hub, a place where tutorial-like notes will help the reader comprehend and exploit the *pyECSS* and/or the *pyGLV* package to their full extent. As many research frameworks in diverse scientific and neural domains are python based, we envision to further contribute in such scientific areas, as Elements is best suited for data visualization, immersive analytics and geometric deep learning with graph neural networks (GNNs).

1.4. Benefits of using the Elements project in CG curricula

Below is a list of the benefits from using Elements in a CG class, both as an instructor as well as a student.

1. **ECS in a Scenegraph (ECSS).** Teaching the benefits of ECS when applied in a scenegraph will allow the students to understand the main CG concepts using a rendering pipeline that is very similar to the ones utilized by MGEs, which can support rendering million of objects in real-time. This will assist students on organizing and designing a scene or on incorporating new features. As individual Systems can work autonomously and in parallel with other Systems, a faster rendering can be obtained. This ECSS approach can also be followed in other domains besides CG, or for other CG tasks besides scene rendering, like physics computations. To this end, ECSS functionality is encapsulated in the standalone *pyECSS* python package.
2. **A python-based, visual computing framework based exclusively on software design-patterns.** Python is a language that is both ideal for novice and proficient CG programmers as well as becoming a defacto standard in neural computing. Its versatility comes from the rapidly growing variety of developed scientific libraries and frameworks, by its large active community of developers and scientific computing domain experts, that exploit python's rapid prototyping ability. Much of the functional-

ity of the Elements' packages is simplified via unit-tested methods and classes, requiring minimal initial setup and actions by a novice CG programmer to obtain a completely rendered frame. Despite its simplicity, such functionality is provided through a white-box CG pipeline, where all its intermediate steps may be accessed and tampered. The use of software design patterns allows to easily extend the features supported by Elements. In that respect, the implementation of a new component and the respective system that traverses it, is now a simple task due to the use of ECS; the resulting extensibility potential makes the project future-proof.

3. **Versatile CG teaching approaches:** The Elements' framework allows both typical bottom-up approaches, explaining the basic function and tools one by one and then assembling them together, as well as also top-to-bottom approaches, thus starting from the creation of a scene-graph and its visualization and sequentially explain the under-the-hood CG pipeline algorithms and operations.
4. **Tailored for Education:** Elements is a lightweight system, tailored for training needs and available for free as open-source. As opposed to the use of commercial MGEs, which are proprietary products of huge magnitude, completeness and complexity, the proposed project offers a more targeted educational tool, suitable for novice and intermediate CG programmers. Its design enables students to dive deep into the rendering pipeline in a simple and distraction-less way, that is suitable for an undergraduate CG course.

2. The key components of the Elements project

2.1. The *pyECSS* package

The *pyECSS* python package, based on pure software design patterns, features a plain but powerful CG architecture with Entities, Components and Systems in a Scenegraph. A class diagram of the *pyECSS* package and their in-between dependencies is shown in Fig. 2. The *pyECSS* package, after a simple installation via PyPi, allows the programmer to easily create a scenegraph using Entities and Components as nodes. A simple example is shown in Listing 1, where several entities are created and interconnected via parent-child relationships and component nodes are added to each entity.

```

1 # Adding and Connecting Entities
2 scene = Scene()
3 sw = scene.world
4 root = sw.createEntity(Entity(name="Root"))
5 entity1 = sw.createEntity(Entity(name="Entity1"))
6 sw.addEntityChild(rootEntity, entity1)
7 entity2 = sw.createEntity(Entity(name="Entity2"))
8 sw.addEntityChild(entity1, entity2)
9 entity3 = sw.createEntity(Entity(name="Entity3"))
10 sw.addEntityChild(rootEntity, entity3)
11 ...
12 # Adding Components to Entities
13 transl = sw.addComponent(entity1, BasicTransform())
14 shader2 = sw.addComponent(entity1, Shader())
15 vArray2 = sw.addComponent(entity1, VertexArray())
16 mesh2 = sw.addComponent(entity1, RenderMesh())
17 orthoCam = sw.addComponent(entity2, mycamera)

```

Listing 1: Scenegraph creation code snippet where we add and connect entities and components.

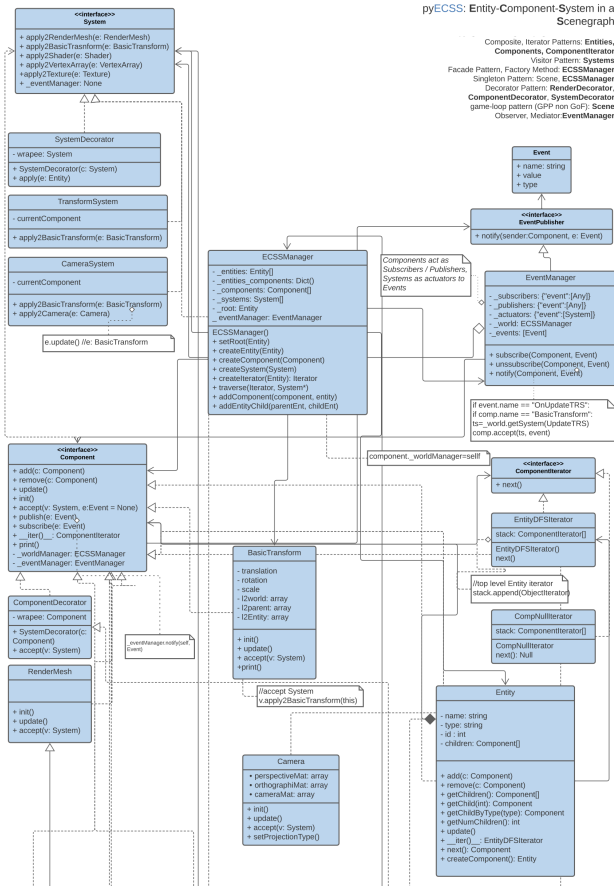


Figure 2: pyECSS class diagram

Within the developed ECSS framework entities act as unique identifiers, components contain the associated data and systems are classes that operate on both of them, performing various tasks, such as updating the position of an entity based on the root or passing a visible object to the vertex shader.

The advantage of using an ECSS is that it allows developers to build flexible, modular systems that can easily be extended and modified. It also makes it easier to reason about the interactions between different objects in the scene, since each object is represented by its own set of components. Such ECSS architectures are particularly useful in CG and gaming applications, where scenes with large number of objects, each with complex behaviours, that need to be updated and rendered in real-time, is a common issue.

2.2. The pyGLV package

The pyGLV python package, based on pure software design patterns, utilizes the previous ECSS architecture, via the pyECSS package. Its main aim is to showcase the applicability of basic, cross-platform, OpenGL-based, real-time computer graphics, in the fields of scientific visualization and geometric deep learning. A class diagram of the pyGLV package and their in-between dependencies is shown in Fig. 4.

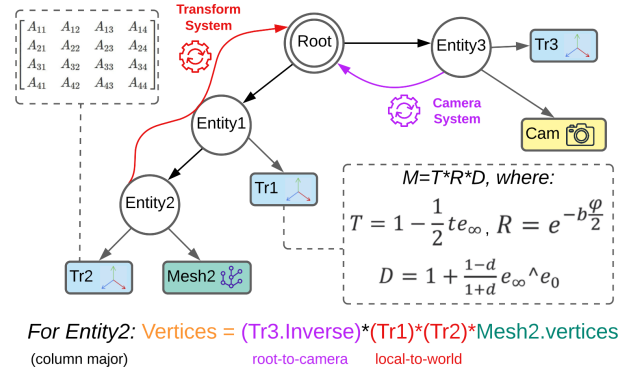


Figure 3: A simple scenegraph based on ECS. Circular nodes correspond to Entities while rectangular correspond to Components. The directed edges imply a parent-to-child relationship. Transform system evaluates the local-to-world matrix for all entities the root-to-camera is determined via the Camera System. Transformation data for Entity1 is provided in matrix form, whereas CGA multivectors are employed for Entity2; e_{∞}, e_0 are basis multivectors, t, b are the translation vector and the rotation axis expressed as multivectors, ϕ is the rotation angle, d is the dilation factor and e, \wedge denote the exponential and wedge product functions.

The pyGLV contains the implementation of many built-in components, that are used to setup CG scenegraphs, using the pyECSS package.

- **BasicTransform.** A component that stores the objects' coordinate system with respect to its parent entity, in the form of a product of a translation, rotation and scaling matrix.
- **Camera.** A component storing the camera setup information in the form of a view matrix; it can be generated via the `ortho` or `perspective` functions, contained in the `pyECSS.utilities` package.
- **RenderMesh.** A component that stores the basic geometry of an entity, such as the vertex positions and face indices of an object. It may also contain the colour of the object or the colour of each vertex, as well as the normals of each face triangle.
- **VertexArray.** A component used to store the vertex array object (VAO) and vertex buffer object (VBO) for entities that will be passed to the vertex shader.
- **Shader.** A component that stores the data required for an OpenGL-GLSL Shader; it contains basic vertex and fragment shaders ready to be used.

The code segment in Listing 1, depicts the attachment of `BasicTransform`, `RenderMesh`, a `VertexArray` and `Camera` components on various entities of the scene. Depending on the situation, new components may be created to store different types of data, while existing components may be decorated to allow the storage of additional data of the same or equivalent representation formats, such as store transformation data in alternative algebraic forms such as dual-quaternions.

Furthermore, the pyGLV package contains the implementation of a set of systems, responsible to digest the scenegraph and apply various tasks of the CG pipeline, such as the evaluation of the

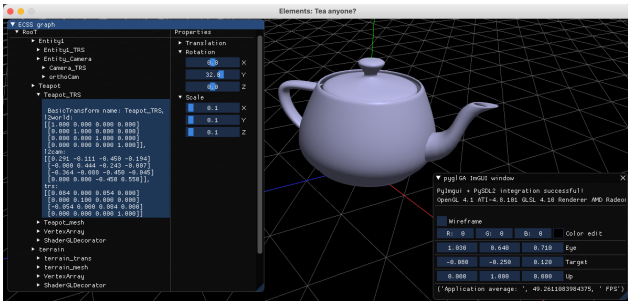


Figure 5: A simple scene with Newell’s teapot being lit by the Blinn-Phong algorithm. The camera (view, target and up) can be changed in real-time via the GUI, generated by the *imgui* package. An introductory step towards understanding camera, primitives and scene inspection and manipulation.

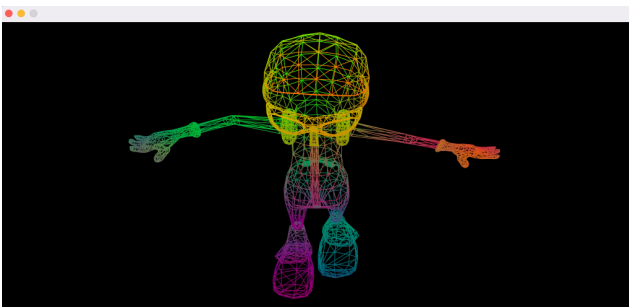


Figure 6: A rigged model imported and animated using the animation equation. A dedicated component and system is responsible for storing and digesting the animation model and data.

4.2. Geometric Algebra Support for Elements

This assignment dealt with the creation of a component and a system that enables the utilization of Geometric Algebra. Current CG teaching frameworks [PPGT14] employ typical representation forms to describe the translational, scaling and rotational information of each object. This involves vectors or matrices for the translation/scale matrices, and euler angles or quaternions for rotation. Regardless of the form chosen, all data must be transmuted to the equivalent matrix, that will be sent to the GPU shader. Using the developed component and system, introduced in this work, it is possible to use Geometric Algebra (GA) *multivectors* to represent such transformations (translations, rotations and dilations), which are an evolution step of current representation forms [KCL*22]. As such, the use of GA-based forms (motors, rotors and dilators) as decorated Transform components, and their digestion from the decorated Transform system, can be accomplished with no modifications in the existing pipeline or code that renders the scene. In fact, the programmer may use diverse algebraic formats (matrices, vectors, quaternions, dual-quaternions, multivectors) to define the Transform or Mesh components of an object, with minimal programming effort, since systems digesting such components work independently and in parallel (see Fig. 3).

We use geometric algebra in order to teach our students a uni-

fying model for transformations, instead of using 3 algebras: euclidean algebra, quaternion algebra, dual-quaternions in affine geometry. Especially referring to Projective and Conformal GA, multivectors can be used to express both translations, rotations as well as dilations (uniform scalings, exclusive to CGA) and are suitable for CG rendering and animation [Pap13].

4.3. Graph Neural Network for Elements

In the context of a graduate CG course, students were assigned to investigate a connection between Elements and trending machine/deep learning techniques. Google’s SceneGraphFusion [CWWT*21], which extracts semantic scene graphs from a 3D environment generated from RGB-D images, highlight the importance of graph representations of 3D scenes in the process of labeling and extracting hierarchical data from the graph. As Elements is based on a scenegraph representation, the identification of equivalent graphs, that store similar information, and their subsequent feeding to a suitable GNN, would lead the way to performing a simple predictive task.

Manipulating the Elements scenegraph, students were able to explore various equivalent graph representations, that could be used as input to graph-based machine/deep learning models. A major task in this process was to acquire a clear understanding of node, edge and graph features and how these could be derived from the original entities and components of the scenegraph. As an example, mesh components stored in the scenegraph, holding vertex positions and the face indices, can be transmuted to subgraphs, where nodes correspond to vertices, and node features to edges extracted through the face indices (neighbouring vertices correspond to neighbouring nodes). An alternative approach would store an entity’s location with respect to its parent-entity as an edge feature, holding the corresponding translation, rotation and scale vertex, and replace the mesh data by a label (such as “cube” or “pyramid”), that could either be given or predicted by another GNN.

Depending on the different graph representation form, various tasks were performed using standard GNN techniques. For example, in the first representation described above, a GNN could successfully identify if a specific shape, for example “a cube”, existed in the scene, whereas, the second representation form allowed the prediction of spatial relationships such as “is there a pyramid on top of a cube?”. Since 3D models can also be seen as point clouds, after a certain reformatting pre-processing step, we fed them to a classifier, based on the PointNet++ [QYSG17] architecture, for point cloud classification. The model was trained for 50 epochs on a dataset of 40 different types of Geometric objects (2D and 3D) and achieved over 90 percent of accuracy on the test set. After completion of the training process (see Fig. 7), the model could easily be integrated in any Elements project, to classify the different GameObjects in the scene.

As an ongoing graduate project, a generative artificial intelligence approach is being investigated. By using suitable representations and employing more complicated ML/DL techniques (involving transformers, graph convolutional networks, etc.) we aim to provide a model that can generate a complicated scenegraph based on user text or voice input, e.g., “a ring of cubes”, “a solar system with two centers”, “the interior of a house” or “a virtual

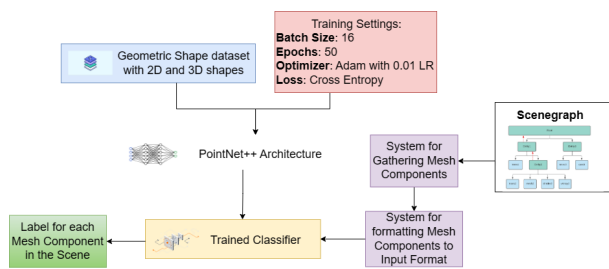


Figure 7: GNN training process - Object labelling using ECSS.

operating room”. The auto-creation of such scenes is not straightforward, and should be decomposed in a set of simpler tasks, such as the generation of 3D objects and their spatial arrangement.

5. Using Elements in existing CG curricula

The Elements project has been employed as a teaching material for a graduate (CS-553 Interactive Computer Graphics) and an undergraduate (CS-358 Computer Graphics) CG course at the University of Crete (UoC), Greece as well as for the undergraduate (ECE-E34 Computer Graphics) CG course at the University of Western Macedonia (UoWM), Greece. The number of students actively participated in these assignments, using the Elements project, were 28, 24 and 24 respectively.

There were two assignments within the undergraduate course taught in UoC that regarded the use of the Elements project. The first one, given on week 5, regarded simple tasks such as using the built-in functions for transformations (translate, rotate and dilate), for camera-related functions (`lookat` and `perspective`), as well as generation of models (polygons and sphere) in a constructive way. The second one was given on week 8 and involved evaluation of normals via model processing, scene manipulation via a GUI system and implementation of the Blinn-Phong model. Although there were 4 less participants in the second assignment (28 in the first and 24 in the second), the grades indicate that students quickly gain expertise on the Elements project, just a few weeks after, and managed to perform better, even in more demanding subjects (see Fig. 8, comparing orange and blue bars).

In UoWM, the traditional approach of teaching OpenGL in C/C++, without the use of a specific framework, was augmented with Elements. Students, having already acquired knowledge on basic OpenGL programming, attended three 2-hour laboratory lectures in order to get acquainted with Elements and were given a single, optional, related assignment, aiming to evaluate and compare students’ understanding on basic and advanced CG pipeline stages. The assignment involved the built a 3D scenegraph, along with the generation of custom polygonal 3D models, a GUI system that allows transformations and animations applied on a single or group of 3D objects, and the Phong illumination model through GPU scripting. Even after such a short introduction, the 24 students that participated managed to easily adapt. Course evaluations highlighted the direct relation of Elements with the taught theory, compared to the traditional OpenGL teaching approach; their grades, shown as gray bars in Fig. 8, are quite above average.

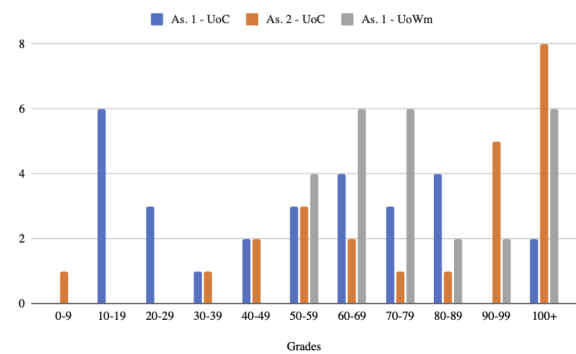


Figure 8: The student grades of the two UoC and one UoWM Elements-based assignments. The horizontal axis shows the grade ranges and the vertical the number of students within each range.

6. Performance

Using Elements, the rendering of moderately complex scenes is possible in real-time; in our tests, we managed to load up to 150 objects, each one of approximately 2900 vertices, without dropping below 60fps (tested with a MacBook Pro, 2.6 GHz 6-Core Intel Core i7, 16 GB 2667 MHz DDR4, Intel UHD Graphics 630 1536 MB). All parts of the implementation are intentionally written in python, to promote student understanding and allow the fast creation of proof-of-concept examples. Our primary goal when designing Elements was the maximization of the educational impact rather than the rendering performance.

7. Conclusions and Future Work

In this work, we have presented Elements, a novel open-source pythonic entity-component-systems in a scenegraph framework, suitable for scientific, visual as well as neural computing. The python packages comprising Elements: `pyECSS`, `pyGLV` and `pyEEL` include the basic implementation of such an approach along with useful examples that may be used to quickly introduce even inexperienced CG programmers to main CG-programming principles and approaches. Despite its simplicity, it remains white-box, allowing users to dive in the graphics pipeline and tamper with any CG pipeline step. Empowered by python’s rapid prototyping and developing ability, users may implement new or decorated components and/or systems to extend the functionalities offered by Elements. The impact of Elements’ features (current and future) on various scientific domains/packages are demonstrated in jupyter notebooks, in the `pyEEL` repository, towards creating a learning hub for both novice and intermediate developers.

Taking advantage of the ECSS underlying system, this project aims to bridge CG curricula and MGEs, that are based on the same approach. This will prepare students, that develop their CG knowledge, to take the next step to game engines. The bridging will also enable rapid prototyping in Elements and a subsequent easy port to game engines, to further evaluate its performance or other metrics, not accessible in a python environment.

Work in progress involves the integration of the Elements project

with open source packages, such as OpenXR, that will allow the 3D scene to be output in virtual or augmented reality head-mounted displays, which will in turn allow enhanced data visualization and, ultimately, immersive analytics. Furthermore, the connection with modern Unity-based frameworks such as [ZPL*23] are also actively explored. As major neural deep learning frameworks are python-based, we aim to provide more powerful and versatile ways of scientific visualization (input/output, to/from). Furthermore, we will strengthen the connection of Elements with GNN-based geometric deep learning techniques towards performing more complex tasks, such as generating a new ECSS.

A subjective grade-based comparison with previous years is not feasible, as different frameworks, assignments and syllabus were used back then. However, we will keep on monitoring the benefits that Elements can bring to CG curricula that adopt its use and conduct further evaluations on student reactions as well as randomized control trials, towards highlighting the added pedagogical values of using the proposed project instead of classical C/C++ or other frameworks.

Acknowledgements

We would like to thank Ioanna Patsoura and Mike Kentros for their contribution, related to the assignments presented in this paper.

Code Availability

Elements is available via open-source at <https://papagiannakis.github.io/Elements/>.

References

- [AGCCFGVP18] ANDÚJAR GRAN C. A., CHICA CALAF A., FAIRÉN GONZÁLEZ M., VINACUA PLA Á.: Gl-socket: A cg plugin-based framework for teaching and assessment. In *EG 2018: education papers* (2018), European Association for Computer Graphics (Eurographics), pp. 25–32. 1
- [Bil02] BILAS S.: A data-driven game object system. In *Game Developers Conference Proceedings* (2002). 2
- [BSP17] BÜRGISSER B., STEINER D., PAJAROLA R.: bRenderer: A Flexible Basis for a Modern Computer Graphics Curriculum. In *EG 2017 - Education Papers* (2017), Bourdin J.-J., Shesh A., (Eds.), The Eurographics Association. 1
- [BWF*17] BALREIRA D. G., WALTER M., FELLNER D. W., ET AL.: What we are teaching in introduction to computer graphics. In *Eurographics (Education Papers)* (2017), pp. 1–7. 1
- [cWWT*21] CHENG WU S., WALD J., TATENO K., NAVAB N., TOMBARI F.: Scenegrphfusion: Incremental 3d scene graph prediction from rgb-d sequences. *2021 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)* (2021), 7511–7521. 6
- [KCL*22] KAMARIANAKIS M., CHRYSOVERGIS I., LYDATAKIS N., KENTROS M., PAPAGIANNAKIS G.: Less is more: Efficient networked vr transformation handling using geometric algebra. *Advances in Applied Clifford Algebras* 33, 1 (2022), 6. <https://link.springer.com/content/pdf/10.1007/s00006-022-01253-9.pdf>. 6
- [Mil14] MILLER J. R.: Using a software framework to enhance online teaching of shader-based opengl. In *Proceedings of the 45th ACM technical symposium on Computer science education* (2014), pp. 603–608. 1
- [MS23] MASHXURA M., SIDDIQOV I. M.: Effects of the Flipped Classroom in Teaching Computer Graphics. *Eurasian Research Bulletin* 16 (2023), 119–123. 1
- [Nys14] NYSTROM R.: *Game Programming Patterns*. Genever Benning, 2014. 2
- [Pap13] PAPAGIANNAKIS G.: Geometric algebra rotors for skinned character animation blending. In *SIGGRAPH Asia 2013 Technical Briefs*. 2013, pp. 1–6. 6
- [PB21] PATTANAİK S. N., BENAMIRA A.: Teaching Computer Graphics During Pandemic using Observable Notebook. In *Eurographics 2021 - Education Papers* (2021), Sousa Santos B., Domik G., (Eds.), The Eurographics Association. 1
- [PPGT14] PAPAGIANNAKIS G., PAPANIKOLAOU P., GREASSIDOU E., TRAHANIAS P. E.: glga: an opengl geometric application framework for a modern, shader-based computer graphics curriculum. In *Eurographics (Education Papers)* (2014), pp. 9–16. 6
- [PQKN17] POIRIER-QUINOT D., KATZ B. F., NOISTERNIG M.: EV-ERTims: Open source framework for real-time auralization in architectural acoustics and virtual reality. In *20th International Conference on Digital Audio Effects (DAFx-17)* (Edinburgh, United Kingdom, 2017). 2
- [QYSG17] QI C. R., YI L., SU H., GUIBAS L. J.: Pointnet++: Deep hierarchical feature learning on point sets in a metric space. *Advances in neural information processing systems* 30 (2017). 6
- [RH94] ROHLF J., HELMAN J.: Iris performer: A high performance multiprocessing toolkit for real-time 3d graphics. In *Proceedings of the 21st annual conference on Computer graphics and interactive techniques* (1994), pp. 381–394. 2
- [RH19] RAFFAILLAC T., HUOT S.: Polyphony: Programming interfaces and interactions with the entity-component-system model. *Proc. ACM Hum.-Comput. Interact.* 3, EICS (jun 2019). 2
- [SWLR17] SUSELO T., WÜNSCHE B. C., LUXTON-REILLY A.: 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 (2017), pp. 361–366. 1
- [SWLR19] SUSELO T., WÜNSCHE B. C., LUXTON-REILLY A.: Technologies and tools to support teaching and learning computer graphics: A literature review. In *Proceedings of the Twenty-First Australasian Computing Education Conference* (New York, NY, USA, 2019), ACE '19, Association for Computing Machinery, p. 96–105. 1
- [TRK17] TOISOUL A., RUECKERT D., KAINZ B.: Accessible glsl shader programming. In *Proceedings of the European Association for Computer Graphics: Education papers*. 2017, pp. 35–42. 1
- [WHS*19] WÜNSCHE B. C., HUANG E., SHAW L., SUSELO T., LEUNG K.-C., DIMALEN D., VAN DER MARK W., LUXTON-REILLY A., LOBB R.: Coderunnergl - an interactive web-based tool for computer graphics teaching and assessment. In *2019 International Conference on Electronics, Information, and Communication (ICEIC)* (2019), pp. 1–7. 1
- [WLD*22] WÜNSCHE B. C., LEUNG K.-C., DIMALEN D., VAN DER MARK W., SUSELO T., ALEX M., SHAW A., LUXTON-REILLY A., LOBB R.: 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* (New York, NY, USA, 2022), CSERC '21, Association for Computing Machinery, p. 21–30. 1
- [ZPL*23] ZIKAS P., PROTOSALTIS A., LYDATAKIS N., KENTROS M., GERONIKOLAKIS S., KATEROS S., KAMARIANAKIS M., EVANGELOU G., FILIPPIDIS A., GRIGORIOU E., ANGELIS D., TAMIOLAKIS M., DODIS M., KOKIADIS G., PETROPOULOS J., PATERAKI M., PAPAGIANNAKIS G.: Mages 4.0: Accelerating the world's transition to vr training and democratizing the authoring of the medical metaverse. *IEEE Computer Graphics and Applications*, 01 (feb 2023), 1–16. 8