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# Object-oriented Graphics Architectures for Global Illumination

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**Abstract**

The paper presents several examples of object-oriented graphics architectures derived from OO Testbed for Global Illumination. A new architecture based on explorer–with–map paradigm is described and projected on serial HW architecture of Cohen&Demetrecsu.

## 1 Introduction

Special graphics architectures developed mostly in eighties and in the first half of nineties are distinctively functionaly oriented. New methods of global illumination emphasize the broadening gap between HW and SW evolution. To compute realistic image we use the entire computing power of universal processor. Time consuming algorithms solve light equation numerically for every picture element (pixel or subpixel) and resulting image is then composed with the minimum assistance of graphics accelerator. Special HW is utilized only to write new pixel values to image memory and to return individual pixel values for subsequent processing. A good example is OpenGL architecture - recall how much of its power is in fact used for raytraced scenes.

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When examining different OO implementations of graphics systems and libraries we find that objects and abstract classes are used mainly for modelling part. Such system usually provides abstract solids, materials and lights, from which the specialized classes are derived and instantiated to objects forming the scene. Objects generate drawing primitives using some kind of *RenderSelf* method. Rendered points are stored directly to frame&depth buffer, multipixel primitives pass through the standard 3D graphics pipeline.

Pipeline solves smooth interpolated rendering of simple drawing primitives, whose geometry and color can be processed efficiently with fast interpolators. The idea originates in seventies and the resulting architecture is thus partitioned to serialy connected function blocks. Data stores attached to processes (functional blocks) save optional parameters for relevant functional transformation. This arrangement obviously cannot solve global illumination as the every single step in pipeline uses only local relations between primitives and lights. Simplified result of analysis reveals typical arrangement of functional block depicted as data flow diagram ([Your89]) in Figure 1a. Naive conversion from DFD to OO yields *pseudo object* with triad of methods *SetState, GetState, Transform* and weakly [1] encapsulated attributes - Figure 1b.

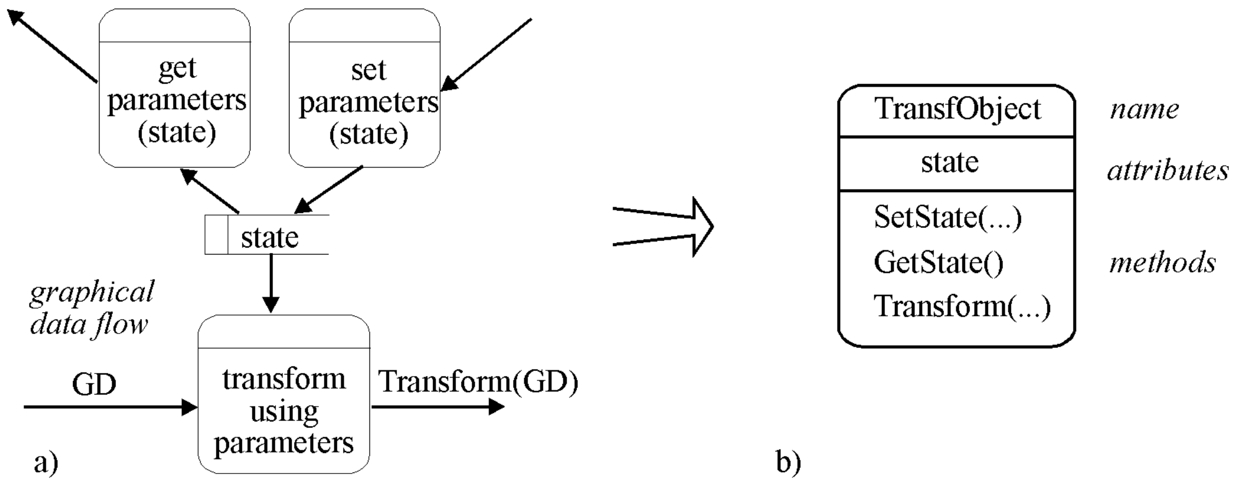

Figure 1: a) Processes and data store b) "Pseudo object" in pipelined processing

Transforming traditional program structures to objects this way is straightforward, but it violates rules and recomendations that make OO technology

[1] *SetState, GetState* methods serve for direct access to the parameters.

powerfull. Such conversion preserves original function oriented structure and it brings nothing new.

The importance of OO architectures has been recognized long time ago. The growing number of OO aplications and the vision of reused SW objects to be sold on demand from catalog calls for the unified architecture concept applied at all system levels. This work wants to emphasize the above mentioned discrepancies and to reveal uniform view of OO HW and SW architectures.

## 2 Previous work

Graphical entities may be often found in OO literature as examples of multi-layered class hierarchies. These hierarchies tend to organize graphical objects to the classes that share either the same type of model (implicit surfaces, parametric surfaces, B-rep primitives) or the same type of access methods (constructors, manipulators) or both ([Egbe92],[Slus96]). Several authors designed object-based renders suitable for implementation of broad classes of geometry and lighting methods. As an example see [Fell95, Fell96], that describes *Minimum Rendering Tool*–MRT. Architecture uses *part-of* hierarchy *Scene-Object-Surface* where *Surface* is a base class for all illumination models. Object *Image* is an agent using *Camera* that controls the main loop over all pixels. It communicates with *IllumScene* containing several *Light*s. Other approaches exploit some kind of physically based rendering architecture. Slusallek and Seidel [Slus95] use abstract class *GeoObject* specialized to *Surface* and *Volume* classes, *LightSourceShader*, *Shader*, *VolumeLighting* and *Lighting*. The resulting Vision architecture replaces explicit knowledge neccesary for global illumination with local propagation methods that use only direct communication between the entities. Classes *View*, *Camera* and *Film* take care of image description that is strictly separated from scene description.

The work presented in this paper was inspired primarily by SW architecture described in [Chen95]. We will shortly review the features of architecture in the next section.

## 3 Testbed for Global Illumination

Any rendering system contains three fundamental parts: *geometry*, *display architecture* and *shading methods*. This the starting point of the "Testbed for global illumination" described in [Chen95]. For the short review of this architecture, following examples and derived architectures we employ notation of FUSION method [Cole94] - object models (OM) and object interaction graphs (OIG).

Display architecture exploits camera based projection methods and hidden surface ellimination in image space. Shading methods are closely related to surface properties and can have both local and global scope. A basic object of testbed is *Scene*. It encapsulates 3D and 2D world objects organized in *part-of* hierarchy: *Frame*, *Camera*, collection of *RenderableObject*s and collection of *Light*s. Each *RenderableObject* contains instances of two objects: *Geometry* and *Shader*. *Geometry* describes the shape of geometrical entities the system is able to render. *Shader* takes over the most of functionality that resided originaly in render. It is bidirectional in the sence that shader not only can evaluate intensity at a surface point but also can deposit energy. The communication between *Shader* and *Geometry* is accomplished through dynamic object *Neighborhood*, an abstraction of the differential geometry at a point on the surface of geometrical entity.

The *Scene* also defines display architecture, i.e. local or global illumination algorithms, viewing and lightning. The authors applied unified approach to renderables and lights - any *Light* contains instance of *RenderableObject* and so it has *Geometry* that defines the shape of light and can be rendered with *Shader*. The class *Light* has virtual method *GiveIntensity*, that returns the intensity of light at given point in space. The *part-of* arrangement of classes is show in Figure 2.

*Scene* is specialised according different illumination methods. Virtual method *Render* explores all renderables and projects visible surface points to the plane of frame. For every visible *RenderableObject* it calls its "part-of" object *Shader* and using either *Collect* or *Deposit* it takes or hands over light energy. This is the core of experimental architecture that enables to implement various rendering methods.

Some examples are described in following sections. To show the behaviour of rendering architectures we use object interaction graphs. OIG illustrates the cooperation among individual objects and collections of objects. Hier-

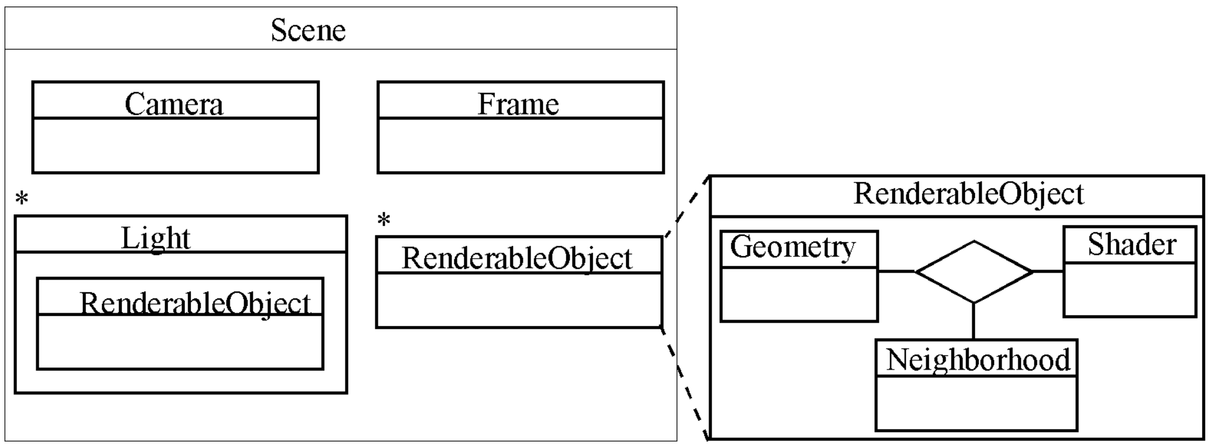

Figure 2: Object model - *part–of* class hierarchy

archical message numbering demonstrates sequential and possible parrallel message passing.

## 3.1 Example I - Scene with local lighting

OIG in Figure 3 shows simple solution of specialised object *RTScene* that is designed to render a scene with local illumination of visible objects. Visibility and lighting are calculated for primary rays. Method *Render* first initiates the states of relevant objects (frame, camera). (1) *WhatCamera* is used to set the viewing transformation and ideal picture quality with respect to optics parameters of "real" camera. *RTScene* implements standard ray-casting algorithm. It adresses the collection of renderable objects with messages (2)*Intersect*. When the intersections exist *RTScene* receives the "names" of new *Neighborhood* objects representing intersection points and it selects the appropriate surface point i.e. the closest one. (3)*Collect* message activates internal *Shader* of selected object. The *Shader* calculates local lighting model for the neighborhood with precalculated attributes - message (3.1)*Inspect*. It may use "standard" shadow rays (3.2, 3.3) that find all visible lights and their contribution to neighborhood intensity. Finally the overall intensity is stored to frame buffer with (4)*Modify* message.

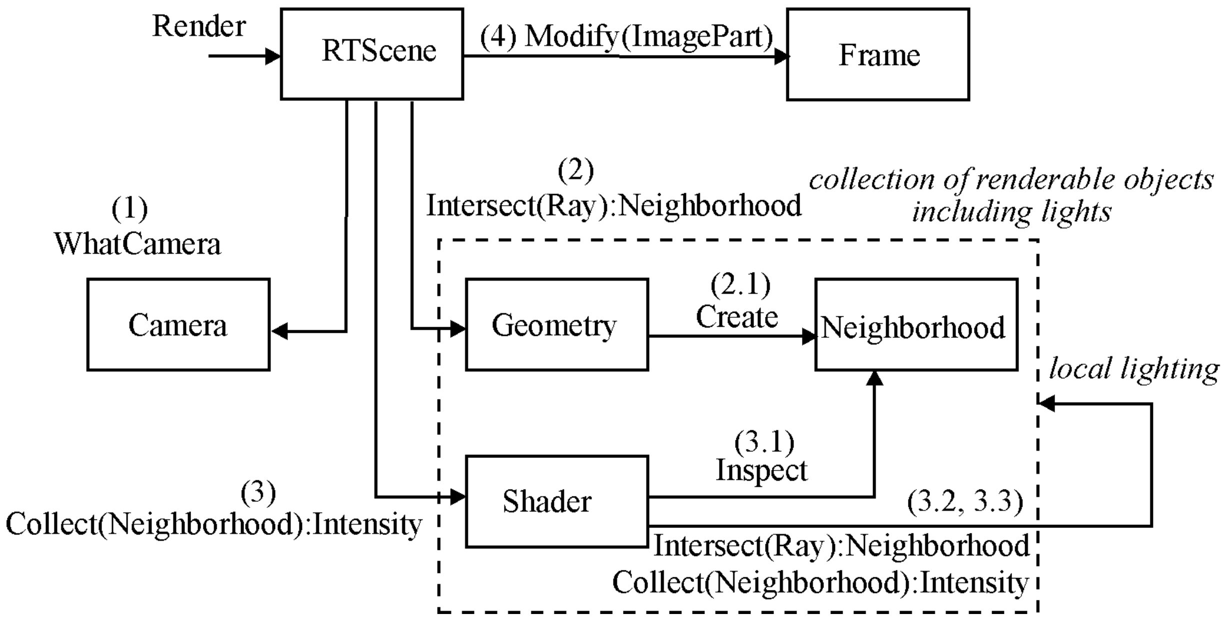

Figure 3: OIG for local illumination - ray casting method

## 3.2 Example II - Ray tracing with secondary rays

*RTScene* can be easily adapted for recursive ray tracing method. OIG in Figure 4 shows the principle:

Object *Shader* activated with message (3)*Collect* casts secondary rays with respect to BRDF and *Neigborhood* of *RenderableObject*. The collection of secondary rays forms the (unorganized) queue and recursion is thus replaced with iteration. *RTScene* takes over secondary rays with (3.3)*InspectRay* and ray tracing continues with the subsequent messages (3)*Collect*. Every step of ray traycing adds some light energy to original pixel or subpixel with (4)*Modify(ImagePart)*.

Secondary rays have no special intelligency, they only store the state of running computation. This version enables to control computation in several ways: to limit the number and depth of secondary rays, to test the rays importance and to use various adaptive antialiasing methods. The lights included in collection of renderables are processed in the same way as other objects and they pass their light energy also with *Collect* message.

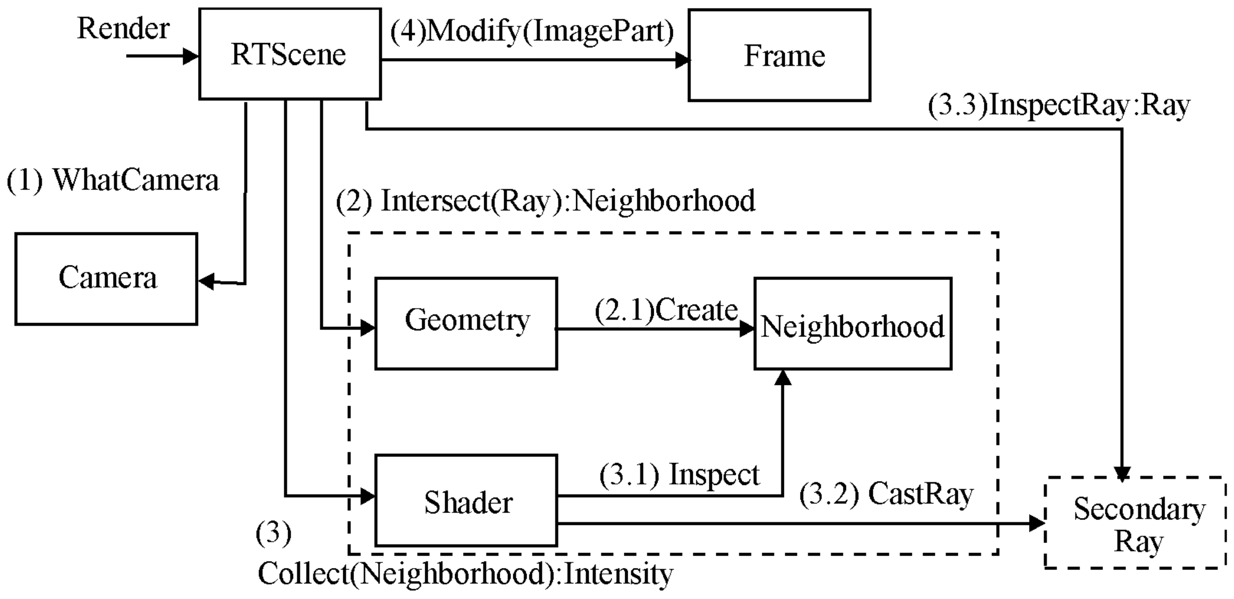

Figure 4: OIG - ray tracing with secondary rays

## 3.3 Example III - Ray tracing with *Ray* objects

Different solution uses dynamically created *Ray* objects. As shown in Figure 5 *RTScene* responds to message *Render* by casting primary rays. Every object in *Ray* collection addresses renderable objects with (3)*Intersect* message and it is responsible to select the appropriate intersection and neighborhood. *Shader*s of renderable objects also cast the new *Ray*s. Criteria terminating computation are distributed both in rays and shaders and can be applied locally. Ray is responsible to collect light intensity and to (5)*Modify* pixels in frame. Compared with example II in previous section here *Ray* objects have more sophisticated logic. They can be also specialised and use some ray-coherent approaches, e.g. beam tracing.

## 3.4 Example IV - Radiosity

The *Shader* method (3)*Deposit* supports the computation of global illumination model with radiosity. It allows the object to store incoming energy to *Neighborhood* and in accordance with the optical properties to emit the part of this energy. Various combinations are possible but the architecture offers cheap and easy solution especially for progressive radiosity. OIG for the *Scene* with radiosity is in Figure 6.

Configuration factors are computed using projection to frame&depth buffer.

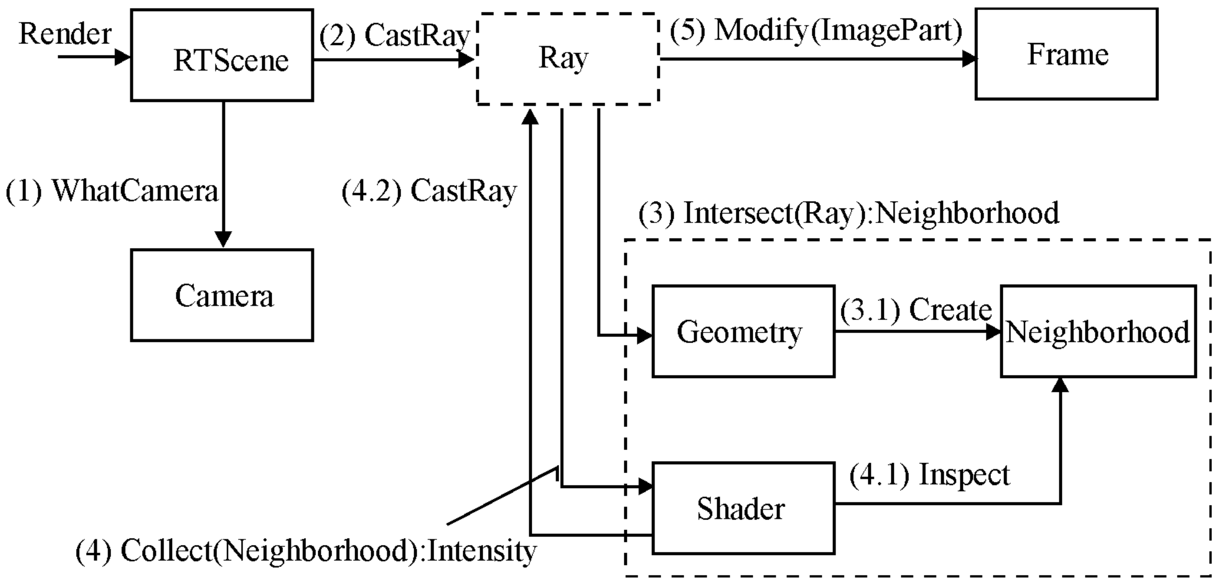

Figure 5: Ray tracing with *Ray* objects

Intermediate results are stored into a renderable object e.g. in the form of a *radiosity map*. Progressive radiosity is computed as following:

```
Repeat
   Find RenderableObject with the greatest deposited energy.
   For all other objects:
      Place camera to surface, that will receive the energy.
      Project all objects with camera to ReceivingObject,
      store projection in Frame.
      // Frame&depth buffer is used for HSE//
      Visible part of emitter determines config.factor.
      Store the portion of energy with Deposit
      in receiving object.
until (valid terminating condition).
```

Deposited energy may be used in further processing, e.g. when ray traycing.

## 3.5 Objects in 3D scene with sorting

Useful abstraction for 3D sorting used in graphical applications is explorer-map analogy. More or less intelligent object *Explorer* is to fulfill commands

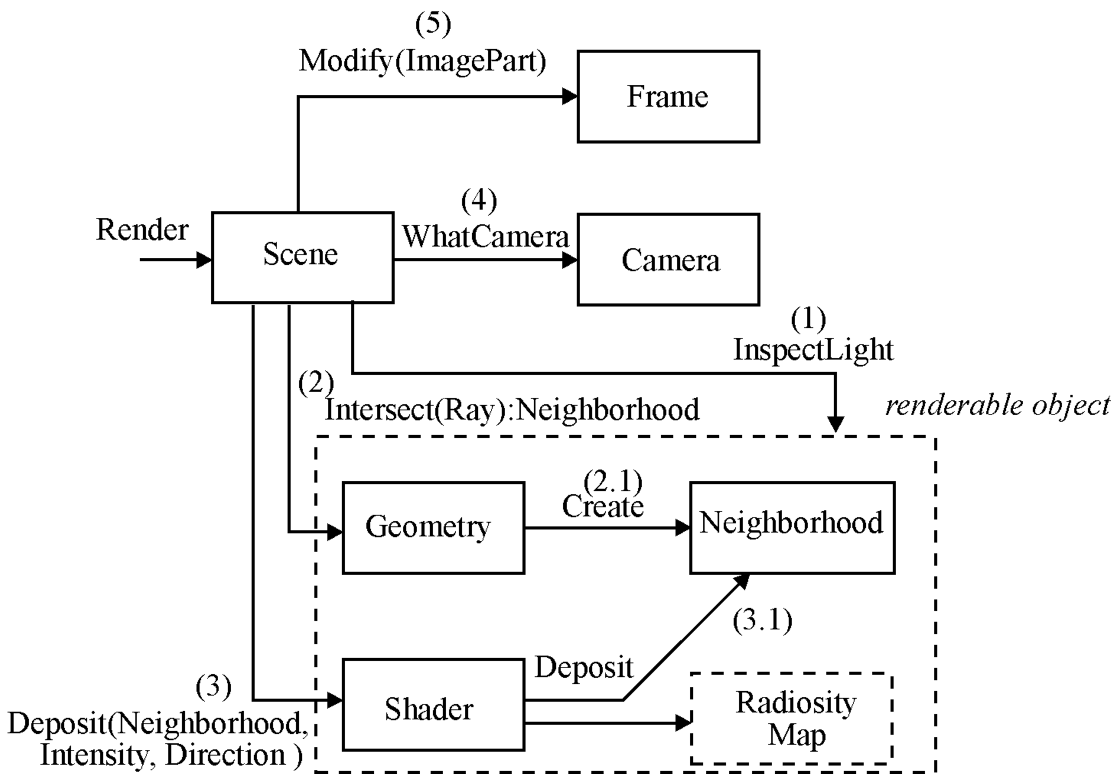

Figure 6: Progressive radiosity - basic arrangement

(virtual methods) *GoOn* and *GoBack*. The method *GoOn* serves for walking around the 3D scene in such a way that activating site (some controller or agent) would get progressively all neccessary information (e.g. the names of visible objects). In a trivial case (no map or when a new map of yet unexplored area is completely blank) *Explorer* sends messages to all registered objects one by one without any sorting. The method *GoBack* returns *Explorer* to some predefined or remembered starting point.

Sophisticated sorting methods based on computational geometry results provide the sorting structures, which significantly reduce the number of tested and reported objects. These methods are based either on global space subdivision done in preprocessing phase, or on dynamicaly maintained local sorting structures. Object *Explorer* is designed at high abstraction level and it serves as prototype - base class, that can be further specialized, i.e. trained for more sophisticated behaviour. Scenario for sorted scene with explorer is shown in Figure 7.

The dashed line in Figure 7 shows the traditional border that separates HW and SW part of rendering system.

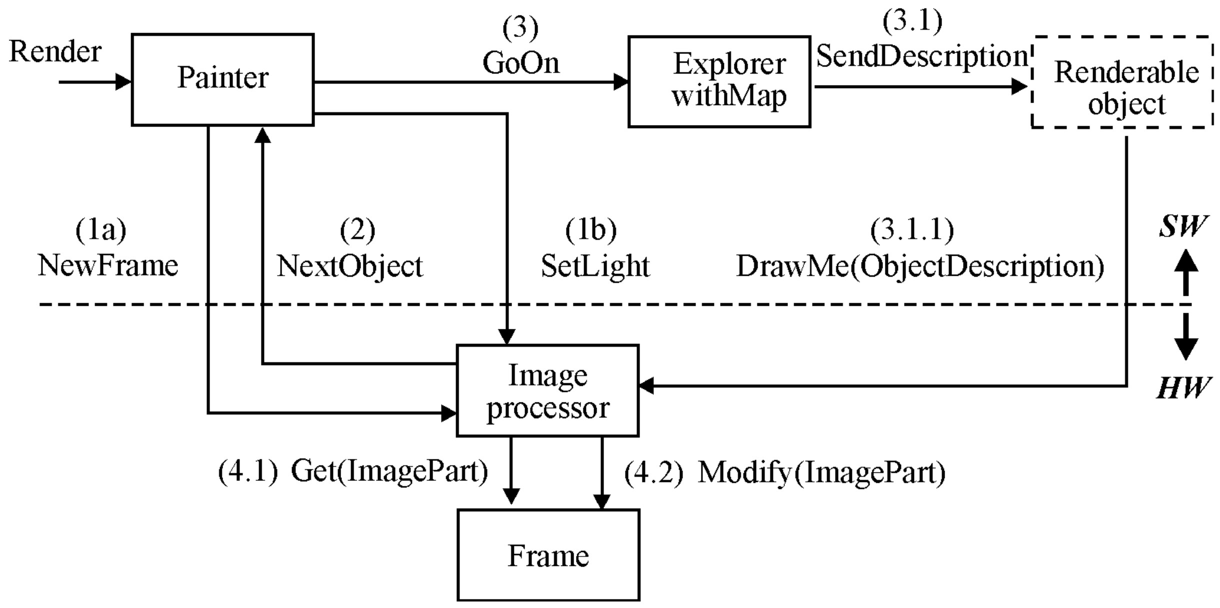

Figure 7: OIG - Architecture of scene with sorting

## 4 Architecture Cohen&Demetrescu

The foregoing examples indicate the interesting possibilites of OO SW architectures. It is clear that such architectures offer many possibilities for experiments with rendering methods and that they can be used as a tool to explore new and optimal OO architectures. In the next section we will try to setup the analogous model for (parallel) HW architecture. As essencial architecture we selected the generalised Cohen&Demetrescu architecture.

Architecture Cohen&Demetrescu belongs to the class of parallel architectures of *procesor/object* type. The description and features may be found in [Deme80]. Figure 8 shows this architecture in general form that allows MIMD parallelism. Every processor gets object data and computes its contribution to scene image. Data stream passing through serialy connected processors is used to compose final image. The original design described one-pass generation of complete image, but we allow the more flexible feedback loop closed via frame buffer.

Compositing architecture can work in many different ways. The examples of possible HW/SW architectures are listed below:

- Processors are specialized for certain object classes. Serially passing data, pixels with color and depth are modified by individual processors.

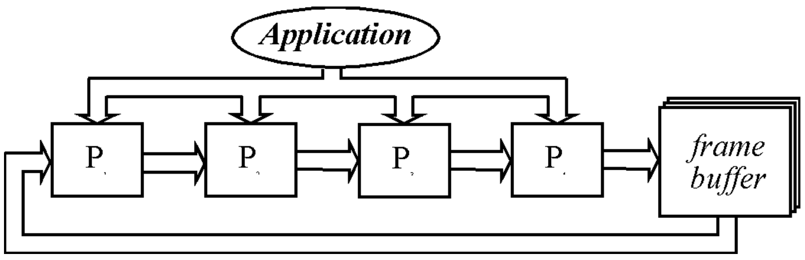

Figure 8: Generalized architecture Cohen&Demetrescu

One-pass antialising can be also applied.

- The first processor expands incoming pixel data to the group of subpixels. This subpixel collection is processed step by step in chained processors that may be optimized for different types of primitives. Last processor computes convolution filtering and antialiased pixel data are stored in frame buffer.

- Processors use intermediate frame buffers to store some part of image. Special composition blocks synchronously assemble final image and store it to frame buffer. Composition blocks solve visibility (using pixel depth) and transparency (e.g. $\alpha$-blending). Architecture distributes input primitives to slected processors according their specialisation and workload (Figure 9).

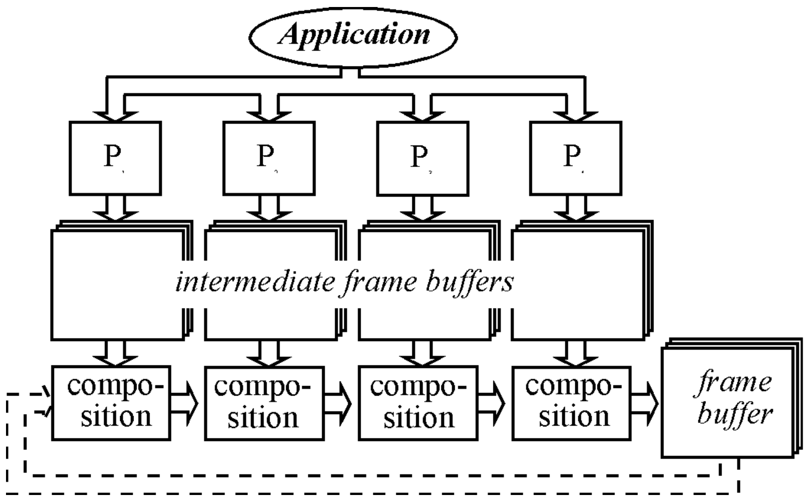

Figure 9: Composition architecture

- Drawing primitives are defined as halfspaces $F(x, y, z) \leq 0$ [Fuch85, Fuch89]. Special pixel processors evaluate in constant time multipixel regions covered by primitives. Result is again composed serialy [Moln92].

Object interaction in generalized Cohen&Demetrescu architecture is depicted in Figure 10. It is similar to architecture in Figure 7, object *ExplorerwithMap* is not shown here.

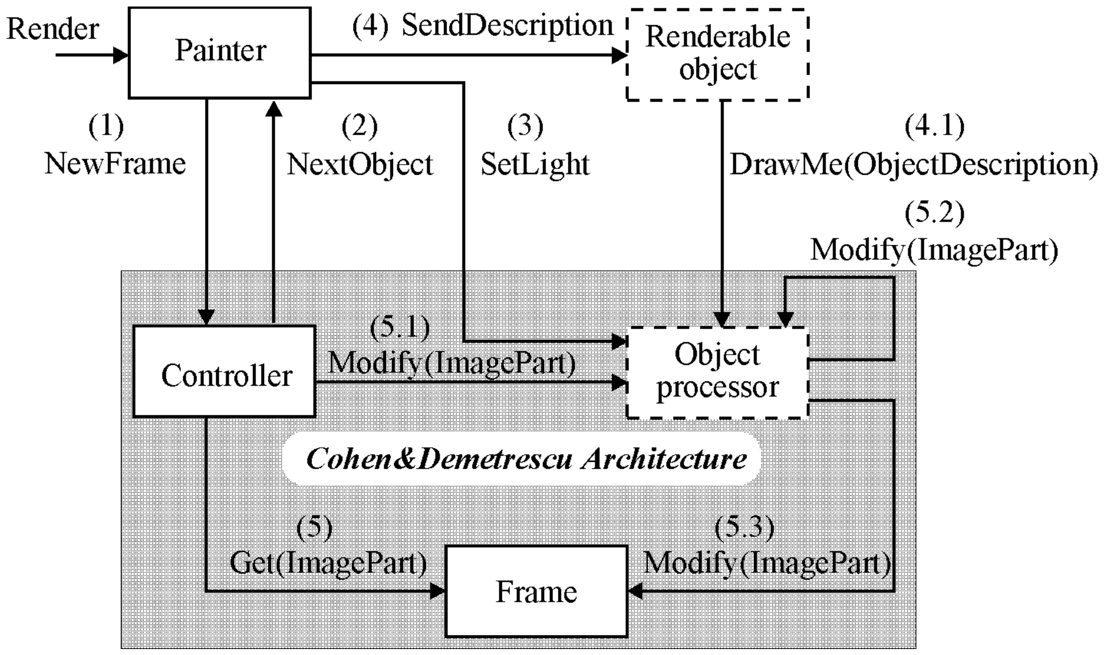

Figure 10: OIG - Rendering in generalized Cohen&Demetrescu architecture

## 5 SW and HW OO architecture overlay

We attempt to find convenient architecture, that would combine both the principles of object oriented system design for realistic rendering and the principles of parallel solution of graphic tasks in specialized architectures. To demonstrate unifying approach with an example we chose architecture with dynamic objects of class *Ray*, that uses the similar work breakdown structure as the architecture *RTScene* (Figure 5). When we combine explorer/map architecture with raytracing architecture, we get the structure with behaviour scetched in Figure 11. Object *Scene* is replaced by object *Painter*, *RenderableObjects* contain *Geometry* and *Shader* as before. *Shader* remains the part of renderable object, but it is accesable for *UniversalShader* with the method (6)*GetShader*. Shading is derived from environment of point in 3D space and renderable objects may undergo more shading methods.

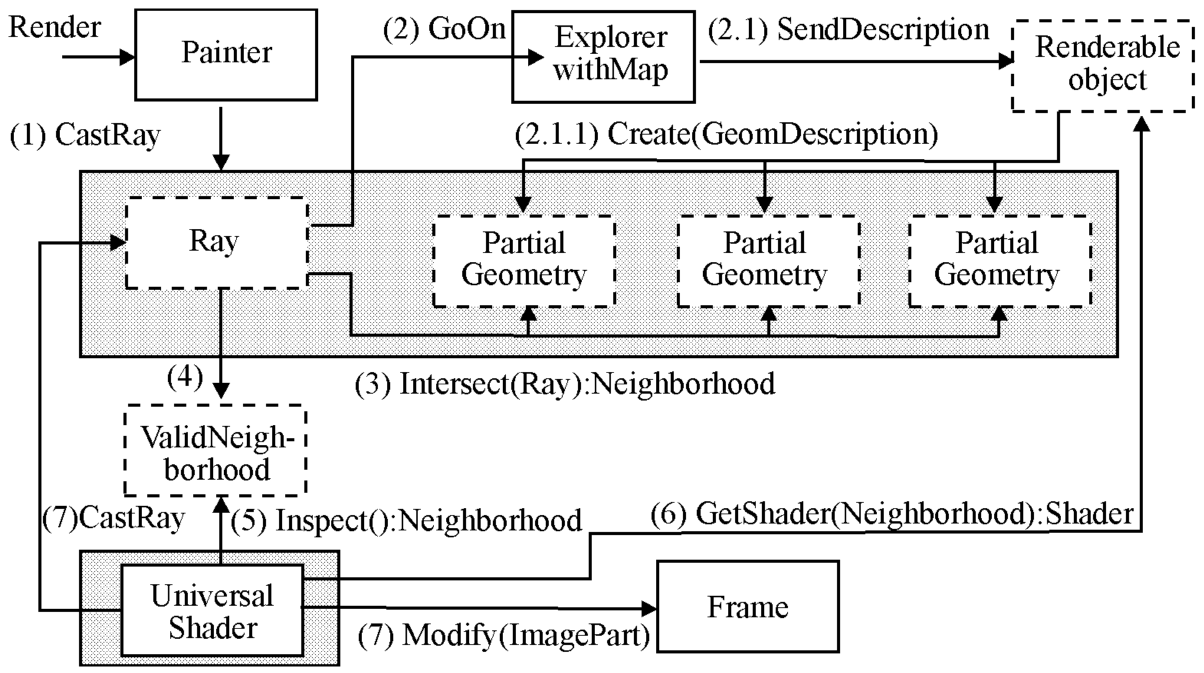

Figure 11: OO architecture - scene with realistic rendering

Architecture offers at least two apparent places suitable for parallel solution with a special HW architecture. Objects of type *Ray* and *Geometry* form the (unorganized) queue of planned geometric tasks that are to find intersection of some ray with the nearest surface ((3)*Intersect*). Here it is possible to employ generalized Cohen&Demetrescu architecture composed of *ray processors* and *geometry processors.*

Object *ExplorerwithMap* that is responsible for space sorting and searching (maintaining and using map) activates relevant, but not neccessary visible renderable objects. Activated objects choose (are placed into) suitable geometry processor and provide part of their geometry in *GeomDescription* data. Temporary *PartialGeometry* objects are mapped to geometry processors that solve ray-geometry intersections. During serial processing the geometry processors compute and select the nearest intersection with differencial neigborhoods. The result is stored as *ValidNeighborhood.* This new object stores also the description of original ray. *ValidNeighborhood* objects form the second processing stream for specialized shading architecture. *Universal-Shader* takes over *ValidNeighborhood* with (5)*Inspect* message, then asks for object shader ((6)*GetShader*) and activates one or more shader processors. Architecture may contain either several identical shaders or a combination of special shaders e.g. for procedural or mapped textures. Shaders store calculated pixel or region information to frame buffer, but they also generate new secondary rays with (7)*CastRay*. Assuming that ray besides geometry information contains also the data used for light energy integration this architecture supports various global illumination techniques. Reorganized architecture that unifies OO description of all partial rendering methods is in Figure 12.

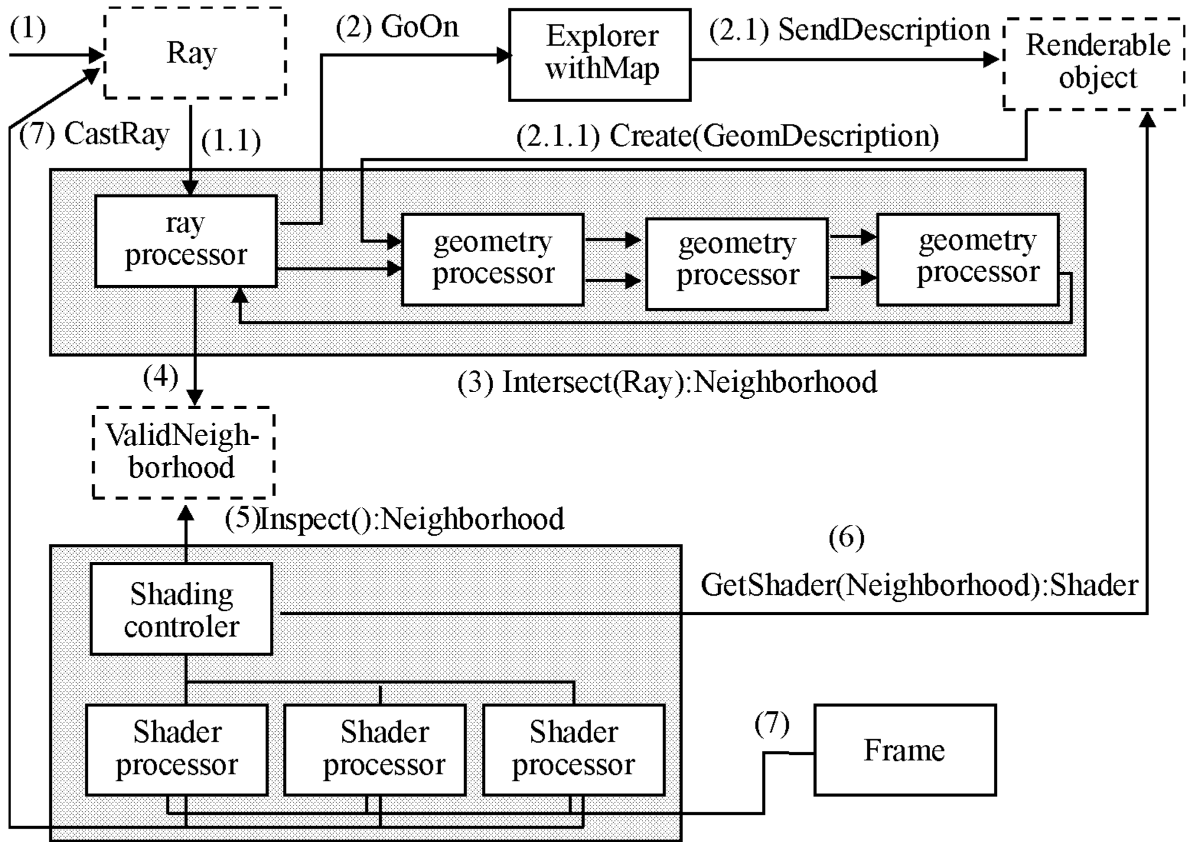

Figure 12: OO architecture projected on parallel architecture

Model in Figure 12 shows one particular solution - OO design of RT architecture. As we want in the future to follow the same philosofy for more complex architectures we generalize the previous architecture to the form shown in Figure 13.

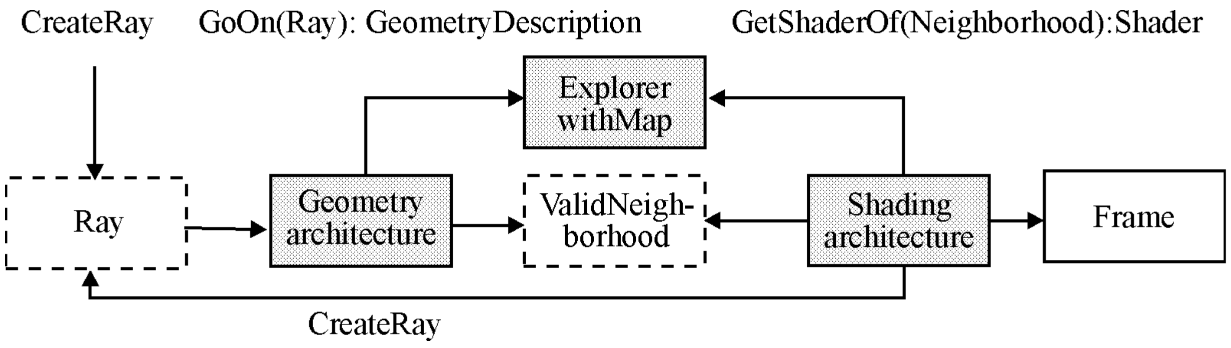

Figure 13: Conceptual architecture for realistic rendering

The properties of the derived architecture are briefly listed below:

1. Architecture consist of 3 main parts: *ExplorerWithMap*, *GeometryArchitecture*, *ShadingArchitecture.* All parts are independent subsystems with defined responsibilities, interface and behaviour. Objects can be exchanged or modified easily because they are loosely coupled.

2. The behaviour of each object and of complete architecture can be described with short specification.

3. All active objects can exploit parallel solution realized with general or a special architecture.

4. Dynamic objects *ValidNeighborhood* facilitate asynchronous communication amid geometry tasks (intersections etc.) and integration tasks (computation and composition of light contributions at surface and/or image points).

5. Objects can be used in different assemblage not only for derivates of classical rendering methods but also for the systems with haptic feedback.

## 6 Conclusion and Further Work

We have presented an experimental OO architecture for the scenes with global illumination. Design defines the fundamental classes that form the base for detailed decomposition and can be easily augmented. Our goal is to develop uniform architecture both for visualisation and haptics, i.e use differential environments for force feedback computation.

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