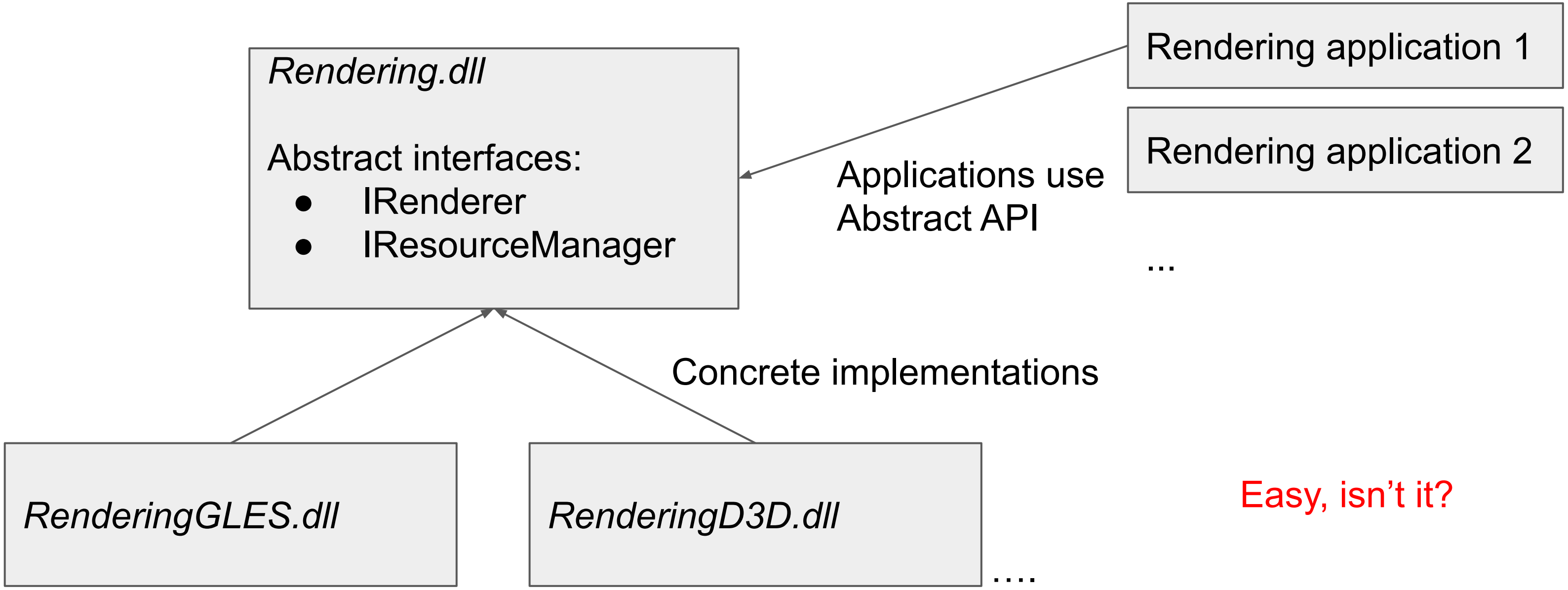
VU Design & Implementation of a Rendering Engine

Scene Representation

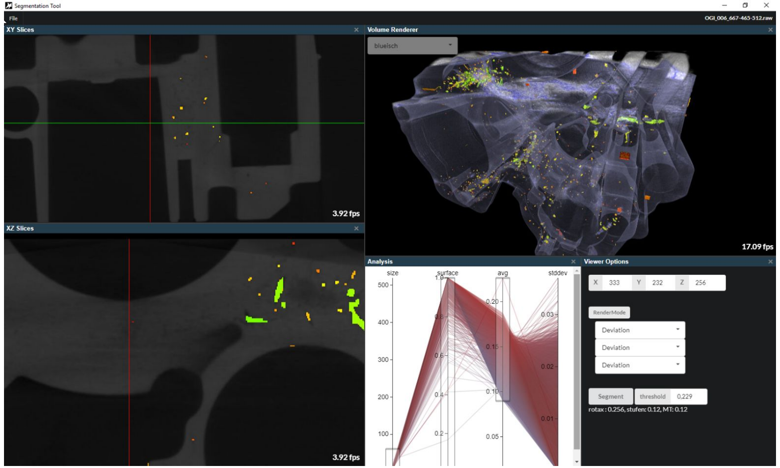
Our overall motivation...

- Use common rendering lib for many rendering applications

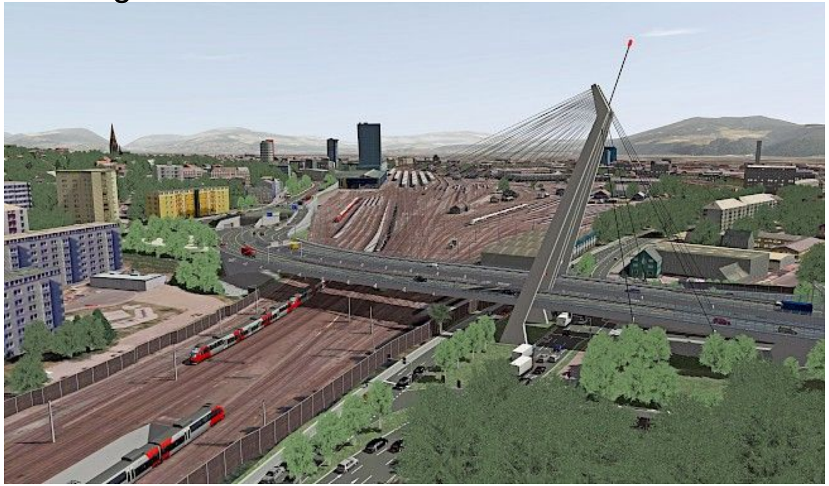


Many application areas...

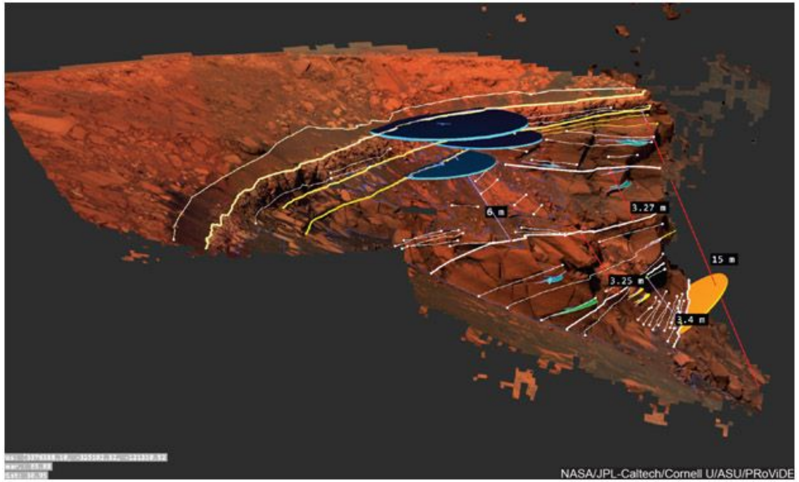
Flooding simulation



Industrial CT Scan Visualization



Infrastructure Visualization/Planning: GearViewer



Geological annotations on surfaces

Versatile scene representation needed

- Each application has its own domain “language”
- Common task: describe static or dynamic 2D/3D scenes
- We look for a description language which works for a *wide range* of applications.
- How could we model different scenes?
    - Domain specific notation with built-in entities such as
        - Bridges, bones, buildings, dip-and-strike tools for geospatial applications etc.
        - This notation we will later call the **semantic scene graph**
    - Notation for 3D objects, interaction etc.
        - Talk about geometries, transformations
        - This notation we will later call the **rendering scene graph**
        - no domain logic

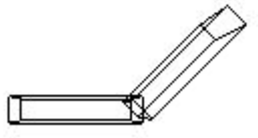
Design space is huge

- How to represent the scene?
- How to expose an API to the application programmer?
- How to make the library extensible?
- How to do resource management (e.g. GPU buffers)?
- How to do GPU optimizations?

- Aardvark had several solutions
- Many approaches failed.
- This lecture summarizes some facets of the above questions.

Scene description in OpenGL

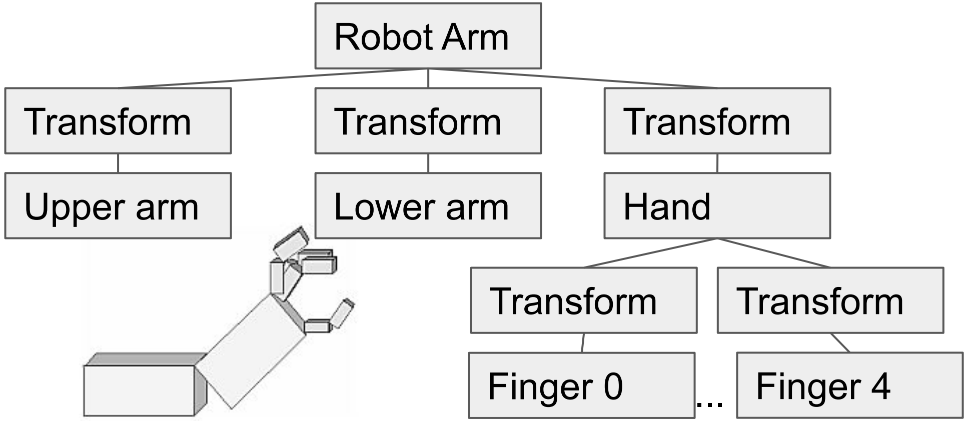
- Example: old school OpenGL
- OpenGL had abstraction mechanisms built in:
  - Matrix stack
- Next level of abstraction:
  - Move OpenGL code into utility functions.
  - Additional utility functions can be used to modify graphics state.



```
void display(void)
{
   glClear (GL_COLOR_BUFFER_BIT)
   glPushMatrix();
   glTranslatef (-1.0, 0.0, 0.0);
   glRotatef ((GLfloat) shoulder, 0.0, 0.0,
1.0);
   glTranslatef (1.0, 0.0, 0.0);
   glPushMatrix();
   glScalef (2.0, 0.4, 1.0);
   glutWireCube (1.0);
   glPopMatrix();

   glTranslatef (1.0, 0.0, 0.0);
   glRotatef ((GLfloat) elbow, 0.0, 0.0, 1.0);
   glTranslatef (1.0, 0.0, 0.0);
   glPushMatrix();
   glScalef (2.0, 0.4, 1.0);
   glutWireCube (1.0);
   glPopMatrix();

   glPopMatrix();
   glutSwapBuffers();
}
```

OpenGL Red Book 1.1, robot.c

Scene decomposition

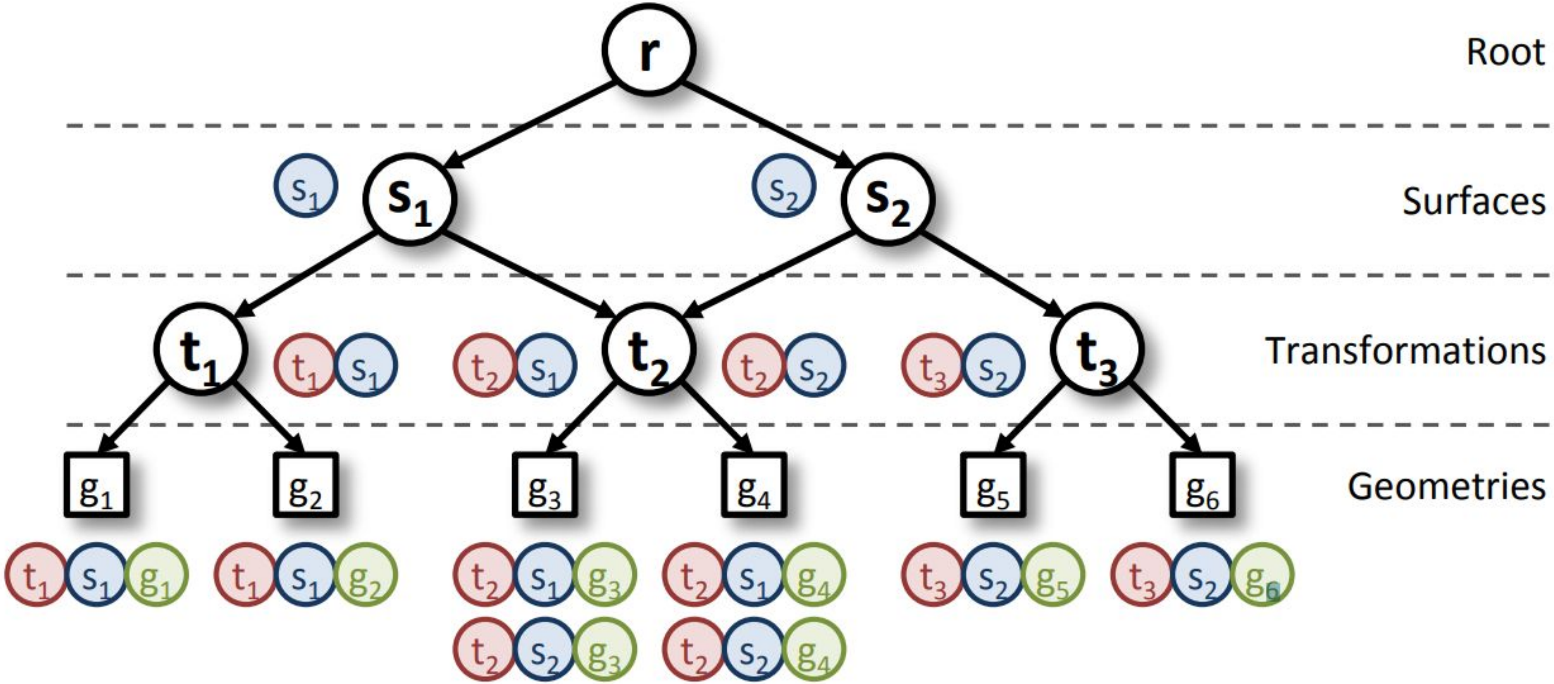



```
void RenderRobotArm()
{
      RenderArm(lowerArmTransform);
      RenderArm(upperArmTransform);
      RenderHand(handTransform);
}

void RenderArm() {..}

void RenderHand()
{
      RenderFinger(trafo);
      ...
}
```

Towards an explicit data representation of scenes

- Represent each geometric entity as node
- Special purpose nodes for changing appearance
  - Transformation nodes
  - Shader nodes
  - Material nodes
  - Specify light etc…
- Nodes can be **composed together** in order to make more powerful nodes
- Scene description can be modified by rendering application
  - e.g. nodes can be stored in variables, modified, used at various points etc.

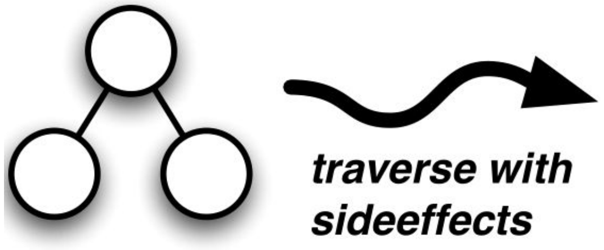
Attributes for scene graphs



[Wörister 2012] attributes in a scene graph.

The traditional rendering scene graph

- When using explicit data representation for entities and state-changing nodes, we arrive at a simple scene graph.
- The scene can be rendered by traversing the scene graph.

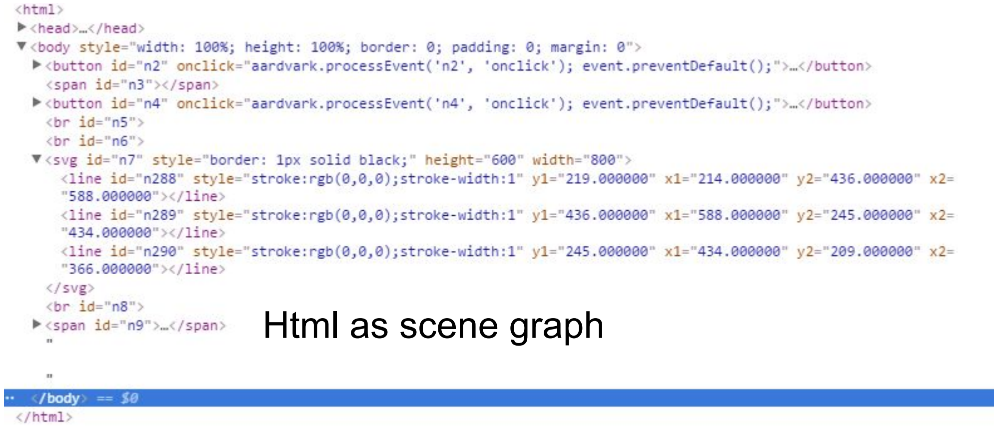



```
Graphics.setViewTrafo (…)
Graphics.setShader    (…)
Graphics.render       (…)
Graphics.setViewTrafo (…)
...
```

Traverse with side effects means: walk over structure and issue appropriate commands to the underlying graphics hardware.

Scene graphs ‘most general’ description

- Maya for example uses node based scene description: Hypergraph.
- Most other engines as well
  - Most scene exchange formats are some sort of scene graph
    - VRML, SVG, COLLADA, X3d,...
- A simple object list is a (rather boring) scene graph as well
- Techniques mentioned here carry over to other areas
  - Most UI frameworks use some sort of scene graph (e.g. WPF)
  - Modelling tools often use graph structure for defining materials etc.

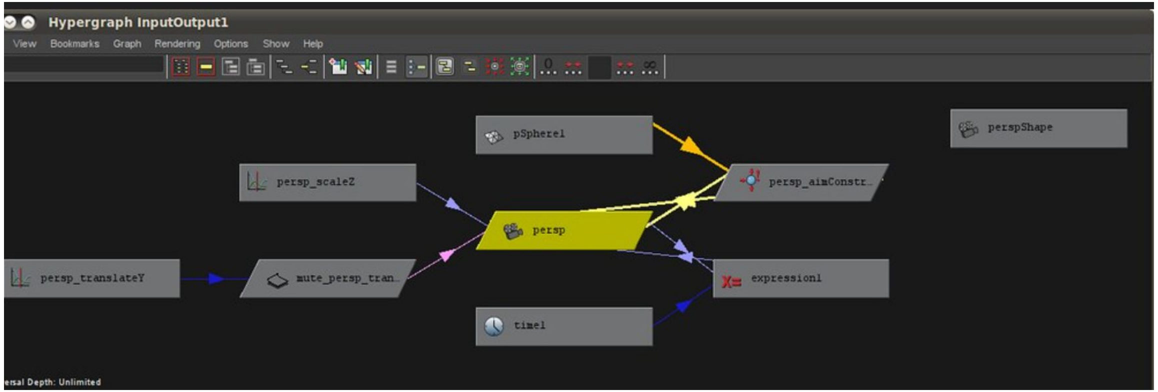


```
<html>
▶<head>…</head>
▼<body style="width: 100%; height: 100%; border: 0; padding: 0; margin: 0">
  ▶<button id="n2" onclick="aardvark.processEvent('n2', 'onclick'); event.preventDefault();">…</button>
   <span id="n3"></span>
  ▶<button id="n4" onclick="aardvark.processEvent('n4', 'onclick'); event.preventDefault();">…</button>
   <br id="n5">
   <br id="n6">
  ▼<svg id="n7" style="border: 1px solid black;" height="600" width="800">
     <line id="n288" style="stroke:rgb(0,0,0);stroke-width:1" y1="219.000000" x1="214.000000" y2="436.000000" x2=
     "588.000000"></line>
     <line id="n289" style="stroke:rgb(0,0,0);stroke-width:1" y1="436.000000" x1="588.000000" y2="245.000000" x2=
     "434.000000"></line>
     <line id="n290" style="stroke:rgb(0,0,0);stroke-width:1" y1="245.000000" x1="434.000000" y2="209.000000" x2=
     "366.000000"></line>
   </svg>
   <br id="n8">
  ▶<span id="n9">…</span>
   "
   "
   </body> == $0
</html>
```

Html as scene graph

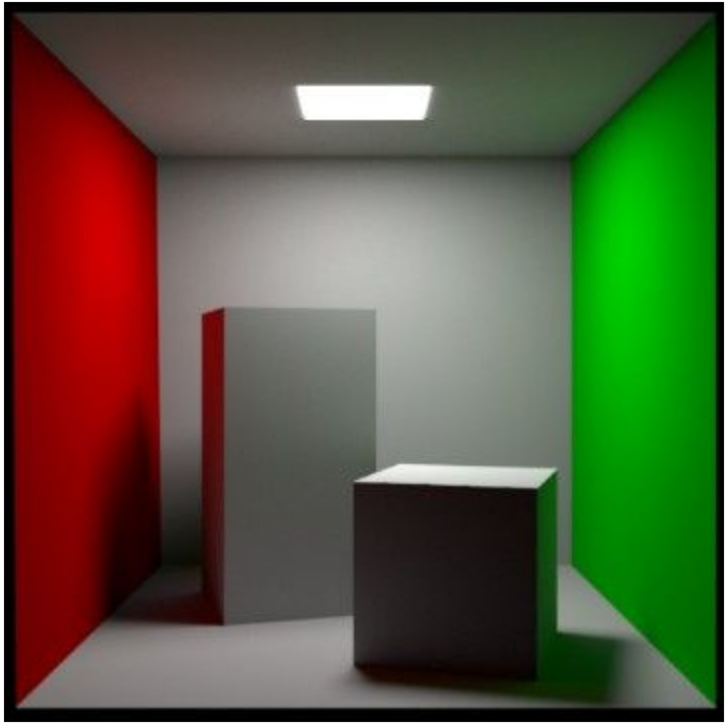
Example: Maya Hypergraph

- Helps to structure scene
- Transformation hierarchy



Example: Renderman scene description language

- Hierarchical scene description
- Various attributes and node types
    - ConcatTransform
    - Transform
    - But also light properties
- ASCII description



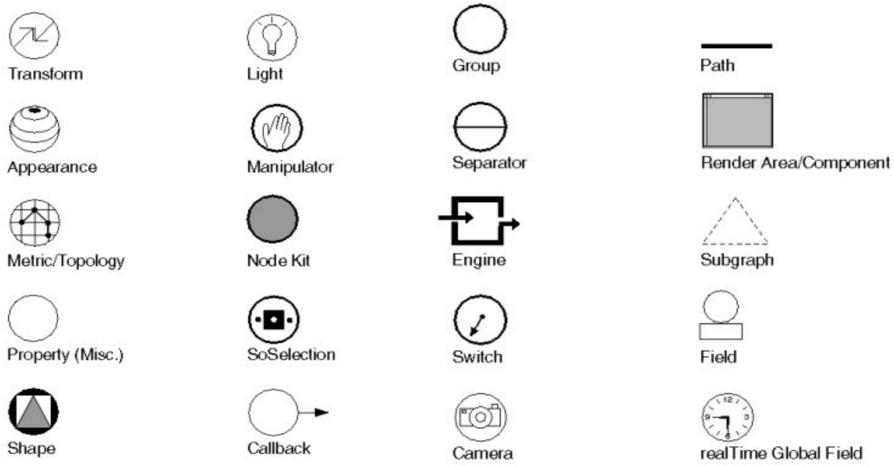
Jan Douglas Bert Walter,
https://www.janwalter.org/jekyll/rendering/renderman/2015/04/13/cornell-box-renderman.html

```
Option "statistics" "endofframe" [1]
Exposure 1.0 1.0
#Display "cornell_box.exr" "openexr" "rgba"
Display "cornell_box.exr" "it" "rgba"
#Integrator "PxrPathTracer" "handle" "int numLightSamples" [4]
"int numBxdfSamples" [4]
Hider "raytrace"
  "constant string integrationmode" ["path"]
  "constant int incremental" [1]
  "int minsamples" [32]
  "int maxsamples" [1032]
Integrator "PxrVCM" "PxrVCM"
  "int maxPathLength" [10]
  "int mergePaths" [1]
  "int connectPaths" [1]
PixelVariance .007
Format 500 500 1.0
ShadingRate 1.0
Projection "perspective" "fov" [ 39.14625166082039 ] # lens 45.0,
aspect 1.0
Rotate 180 0 1 0 # right handed
Scale -1 1 1 # right handed
```

```
WorldBegin
  Other boxes and light omitted…..
  # cornell_box
  Attribute "identifier" "name" "cornell_box"
  AttributeBegin
    ConcatTransform [
      -1.0 -1.5099580252808664e-07 0.0 0.0….
    ]
    # cbox_green [2]
    Opacity [1.0 1.0 1.0]
    Color [0.0 0.5 0.0]
    Bxdf "PxrLMDiffuse" "cbox_green2" "color frontColor" [0.0 0.5 0.0]
    PointsPolygons
      [ 4 ]
      [ 0 1 2 3 ]
      "P" [
        0.0 0.0 0.0
        0.0 548.7999877929688 0.0
        0.0 548.7999877929688 559.2000122070312
        0.0 0.0 559.2000122070312
      ]
  AttributeEnd
WorldEnd
```

(Open)Inventor

- Idea: functionality first
- Support for animations
- Transformation hierarchy
- Nodes can be defined and reused
- Event nodes for interactions

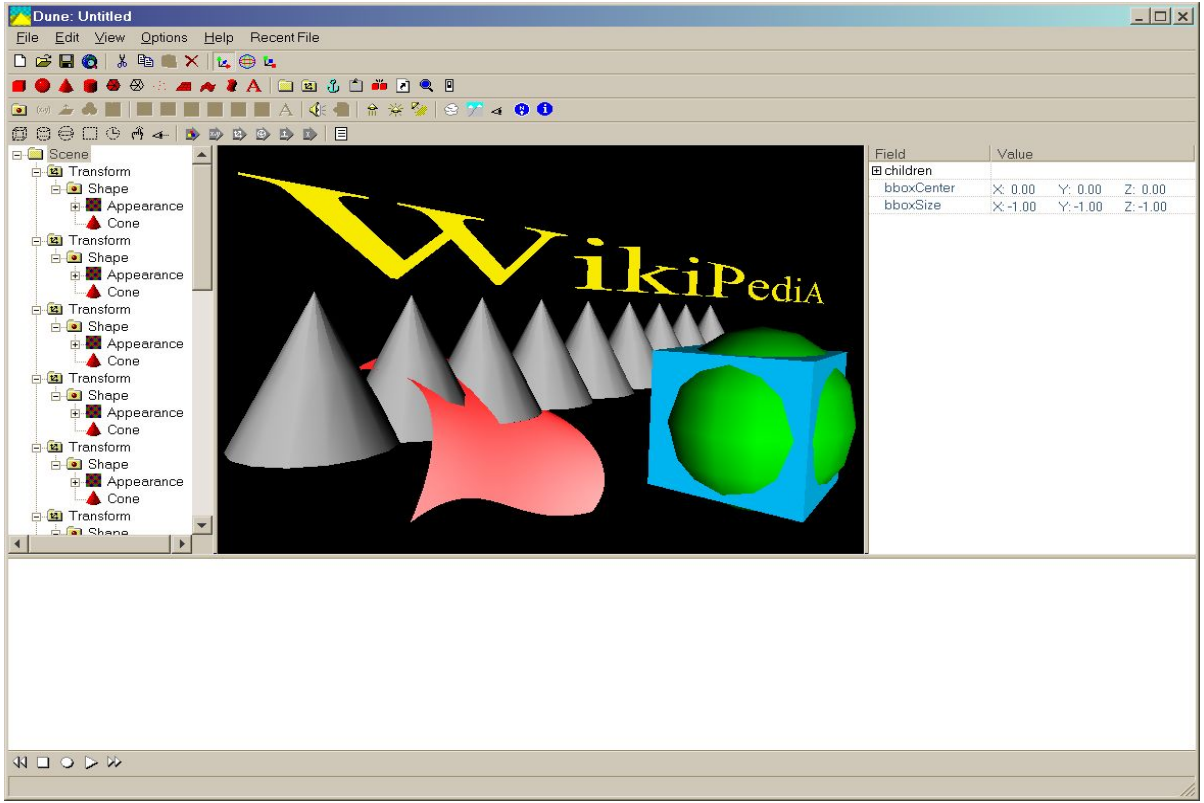



```
DEF Blade Separator { # Blade geometry and properties
   Transform { # Blade interior
      translation 0.45 2.9 0.2
      rotation 0 1 0 0.3
   }
   Separator {
      Transform {
         scaleFactor 0.6 2.5 0.02
      }
      Material {
         diffuseColor 0.5 0.3 0.1
         transparency 0.3
      }
      Cube {
      }
   }
   Separator {  # Blade frame
      # .... (Details omitted)
   }
}
```

[The Inventor Mentor]

Virtual Reality Modeling Language (VRML)

- Similar to inventor.
- Default geometry nodes
- Complex geometry nodes use IndexedFaceSet etc.
- Trafo stack
- Materials, animations via interpolators
- portable
- Dune editor ->



https://de.wikipedia.org/wiki/Virtual_Reality_Modeling_Language#/media/Datei:Screendump-dune-3d.png

Example: hierarchical transformations in unity

Transform.parent

SWITCH TO MANUAL

public Transform **parent**;

Description

The parent of the transform.

Changing the parent will modify the parent-relative position, scale and rotation but keep the world space position, rotation and scale the same.

See Also: SetParent.

How to define scene graphs

- Many tools use GUIs for defining scene graphs
- There are **external domain-specific languages** for defining scene graphs
  - VRML
  - X3d
  - Renderman scene description
- Alternatively, there are **internal domain-specific languages**
  - Scene graph API or library, exposed by rendering lib
  - Can be written and transformed by general purpose programming language
    - Most flexible specification technique. When serializing the internal structure we (might) arrive at an external domain-specific language.

Goals of a scene graph implementation

- The core features:
  - Scene graph can be used to **efficiently render** the described scene
  - We need some mechanisms to **update scene data**

- A reusable modular system
  - We often want to write a scene graph library
  - We want an **extensible/flexible system** (can not anticipate every possible use case)

Scene graph implementation techniques

- Simple traversal based implementation should be easy, right?
- More difficult than expected
- In fact most scene graph implementations have implementation problems
- Let’s look at various implementation techniques

Any implementation ideas?

Towards a scene graph implementation

- Object-Oriented Implementation obvious.

```
public interface Sg
{
    void Render();
}
```

An Interface for scene graphs.

```
public class Group : Sg
{
    ...
    public void Render()
    {
        foreach(var c in children){c.Render();}
    }
}

public class Renderable : Sg
{
    public void Render()
    {
        GL.Draw();
    }
}
```

Implementation of node types.

Extending the object oriented approach

- Transformations can be implemented directly.

```
public class Transform : Sg
{
    Sg child; Trafo t;
    public Transform(Trafo t, Sg child) {
        // ..
    }
    public void Render()
    {
        GL.PushMatrix();
        GL.MultMatrix(t);
        child.Render();
        GL.PopMatrix();
    }
}
```

Where to bind pipeline/shader inputs

- In plain OpenGL/D3D/Vulkan/GLES we know where to bind pipeline/shader inputs.
- However, this behaviour is not appropriate for a general scene graph.
  - We don’t know the shaders in advance
  - Geometry can be reused for multiple sub scene graphs
- We cannot provide input assignment for shaders.
- Thus, we need to resolve this situation when the information is present
  - Immediately before the draw call we know the shader and all its values
- One solution to this is to use **semantic** identifiers.

How to define geometries

- In rendering applications there are often sophisticated mesh data-structures for specifying geometries.
- In this part of the rendering engine it is beneficial to work with flat (indexed)geometries.
- For binding geometries to arbitrary shaders, we typically want to use semantic -> Array mappings.

```
class IndexedGeometry
{
    public IndexedGeometryMode Mode { get; set; }
    public Array IndexArray { get; set; }
    public Dictionary<string, Array> IndexedAttributes { get; set; }
    public Dictionary<string,object> SingleAttributes { get; set; }

}
```

The need for a traversal state

- Nodes have direct translation to graphics states? Two problems:
  - Nodes which have no direct graphics API representation
  - Nodes only the combination of which have graphics API representations -> need mechanism for communication (e.g. uniform buffers and binding locations)
- Thus: we need a place to store intermediate values.
- Solution: Equip the traversal function with a traversal state.

```
public class TraversalState
{
    public Shader Shader;...
}

public interface Sg
{
    void Render(TraversalState state);
}
```

states.

Demo

In the lecture we show the implementation of a simple scene graph system.

Dynamic data

- Dynamism
  - Either modify fields directly
    - Problem: we always need to track references directly into scene graph
  - Or explicitly model changeability
    - For structural changes we still need references

```
public class Transform2 : Sg
{
    Changeable<Sg> child; Changeable<Trafo> t;
    public Transform2(Changeable<Trafo> t, Changeable<Sg> child)
    {
        // ..
    }
    public void Render()
    {
        GL.PushMatrix();
        GL.MultMatrix(t.Value);
        child.Value.Render();
        GL.PopMatrix();
    }
}
```

```
public class Changeable<T> {
    public T Value { get; set; }
}
```

Common operations for scene graphs

- So far, we can render the scene graph.
- What if we would like to do other stuff like
  - Computing levels of detail
  - Writing the scene graph to disk
  - Computing the bounding box for a scene graph
- How about we add another interface member:

```
public interface Sg3
{
    void Render(TraversalState state);
    Box3d ComputeBoundingBox(TraversalState state);
}
```

On extensibility

How to add a new node type:

- Simply add a new subclass of the interface *Sg*

How to add a new Operation:

- Simply (?) add a member to the interface

Problem:

- We want to provide a reusable library
- Sg is defined in the core library
- Each user would need to edit this base interface in order to add new features !!!!

Suggestions?

The visitor pattern

```
public interface SgVisitor
{
    void Visit(Renderable2 r);
    void Visit(Group g);
    void Visit(Transform2 t);
}

public interface ISg
{
    void Accept(SgVisitor visitor);
}
```

User code can add visitors, by subclassing the SgVisitor class:

```
public class
ComputeBoundingBoxVisitor :
SgVisitor { }
```

```
public class Renderable2 : ISg
{
    public void Accept(SgVisitor visitor)
    {
        visitor.Visit(this);
    }
}
```

```
public class RenderVisitor : SgVisitor
{
    public void Visit(Transform2 t) { }
    public void Visit(Group g) { }
    public void Visit(Renderable2 r) { }
}
```

You win some, you lose one:
How to add node types now?

The expression problem (1)

- The OOP approach:
  - Easy to add **nodes** (subclasses)
  - Hard to add new **operations** (all other nodes need to be changed)
- The Visitor approach:
  - Easy to add new **operations** (visitor implementations and subclasses)
  - Hard to add new **nodes**
- Apparently both approaches have their drawbacks

The expression problem (2)

- Formulated by Wadler in 1998 (see further reading)
  - Informally: Extensibility in both, data variants and operations while maintaining static type-safety, i.e. the compiler tells us if a node misses important implementation.
- The expression problem is a common ‘benchmark’ for programming language expressiveness
- Definition:
  - Define a datatype by cases (node types) and functions operating on them
    - Cases can be added at any time
    - Functions operating on those cases can be added at at any time
  - After adding additional cases or operations, no module needs to be adapted or recompiled.
- Many non-solutions and also solutions
- Often of limited use for us :(

The expression problem in practice

- Two approaches
  - Cut back on functionality
  - Cut back on static type-safety
- Most scene graph implementations use visitors anyways.
  - e.g. OpenSceneGraph
- There are other solutions
  - Object Algebras [Oliveira and Cook 2012]
  - Look nice at first glance but hard to work with in practice.
  - Excellent paper on that topic:
    - The expression problem revisited, Torgersen 2004: http://www.daimi.au.dk/~madst/ecoop04/index.html

A critical view on rendering scene graphs

- Each application has its own domain “language”
  - Example: geologists use special tools in geospatial visualization (dip and strike)
- From an application developer's view, higher level of abstraction desired
  - Talk about domain entities (e.g. building, measurement tool, Flamingo, ...) instead of rendering specific entities such as renderable, trafo or shaders.
- Robert F. Toblers *Semantic Scene Graph* Implementation
  - Solves extensibility problem
  - … and provides clean separation of rendering state from conceptual state.

Different levels of abstraction

Scene Graph needs to deal with:

- Inheriting rendering state
- Transformations
- Shaders
- Operations (e.g. extract geometry)

But also:

- Logic operations such as Pick, Rotate, Generate Procedural geometry etc.
- Two different views

Toblers work shows how to align those levels of abstractions

Research Paper 1:

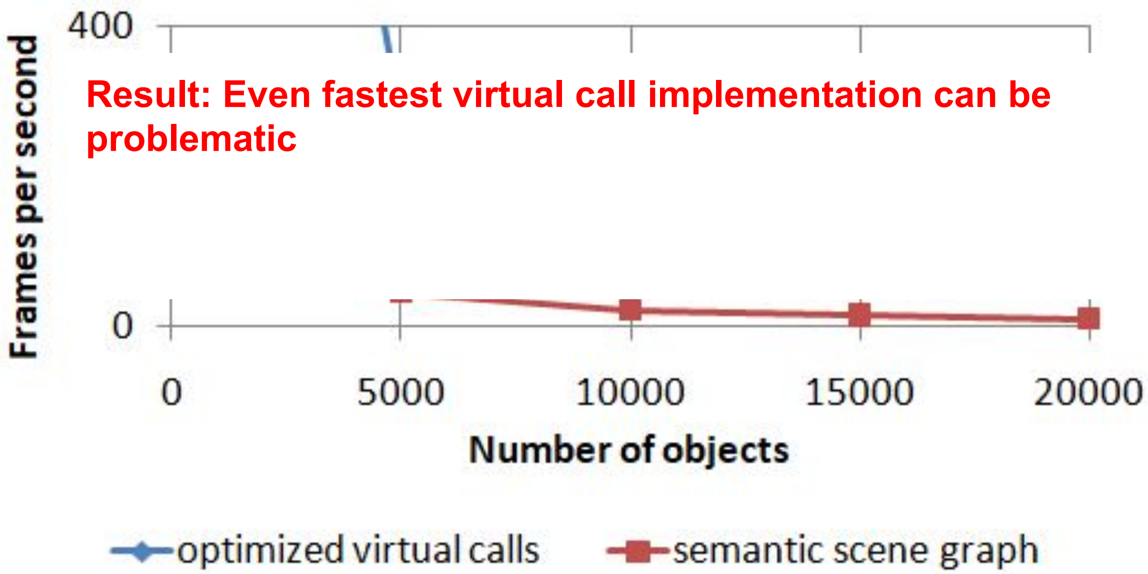
Separating semantics from rendering: a scene graph based architecture for graphics applications

Analysis of the semantic scene graph approach

- Provides extensibility
  - New nodes can be implemented easily (subclass of instance)
  - New traversal can be implemented easily (subclass of traversal)
  - strictly speaking not typesafe since rule binding could fail at runtime
- Support for high-level scene description
  - via semantic scene graph

- The abstract implementation has its cost: We quickly run into **performance** problems!

What is the cost of scene graph traversal?



Result: Even fastest virtual call implementation can be problematic

[i7-4790, lightweight example, might be much worse in real-world scenarios]

On the performance of scene graphs….

- The more flexible the scene graph implementation is, the more overhead we have.
- Observation: Performance is proportional to the number of nodes visited.
- Thus, the structure/factorization of the scene graph has impact on performance.
    - This is not desirable.

- There is quite some research in the field of scene graph optimization….

Optimizations for scene graph systems

Common optimizations

- Reduce scene graph size
- Optimize scene graph for faster rendering

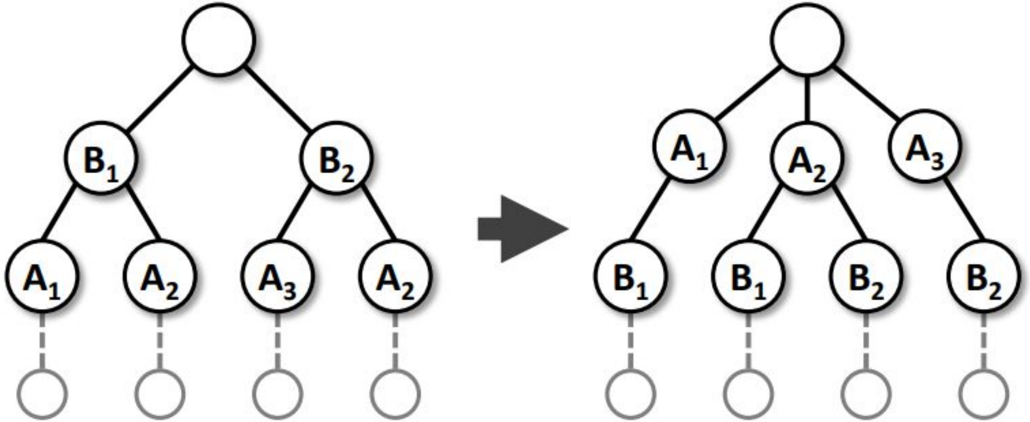
Two types

- Persistent transformations
    - Apply persistent transformation to the scene graph (commonly before runtime)
- Alternate runtime representation
    - Maintain and additional, optimized runtime representation

Example: Scene Graph Transformation

Pull up costly state changes [patent, Strauss 1999]

- Pull up and merge nodes which apply the same state.
- Find semantically equal scene graph with less nodes resulting in fewer state changes.

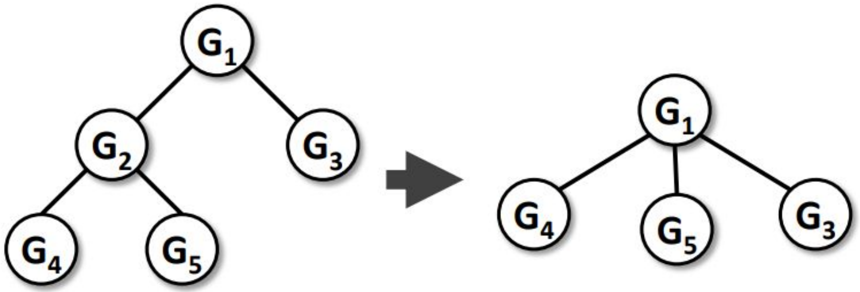


[Wörister 2012]

Assumption: A is more costly than B
Before: Set A 4 times, Set B 2 times
After optimization: Set A 3 times, change B 2 times

More optimizations….

- Removing redundancies



[Wörister 2012] Removing ‘useless’ group nodes

- Creating meta nodes, which apply multiple states at once
- Example: Texture atlas creation for removing texture switches

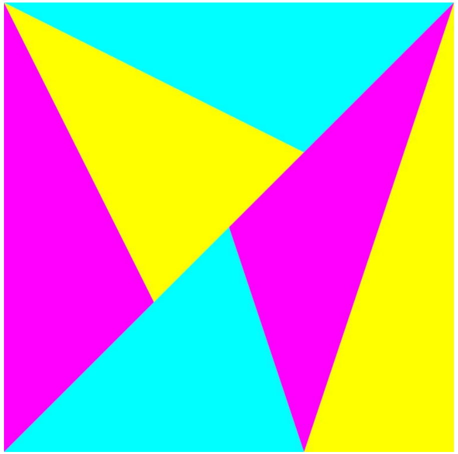
Example: OpenSceneGraph's optimizations

REMOVE_REDUNDANT_NODES	*Collapse Hierarchy* and *Flatten Hierarchy* (p. 9)
MERGE_GEOMETRY	*Collapse Geometry* (p. 10)
TRISTRIP_GEOMETRY	*Converting geometry to triangle strips* (p. 7)
SHARE_DUPLICATE_STATE	*Share Attributes* (p. 9)
FLATTEN_STATIC_TRANSFORMS_ DUPLICATING_SHARED_SUBGRAPHS	*Push transformations into vertices* (p. 6)
FLATTEN_STATIC_TRANSFORMS	Same as above but without subgraph duplication
SPATIALIZE_GROUPS	*Spatial Partition* (p. 10) using a quadtree or octree
TEXTURE_ATLAS_BUILDER	*Generate Macro Texture* (p. 10)

[Wörister 2012]

Geometric optimizations

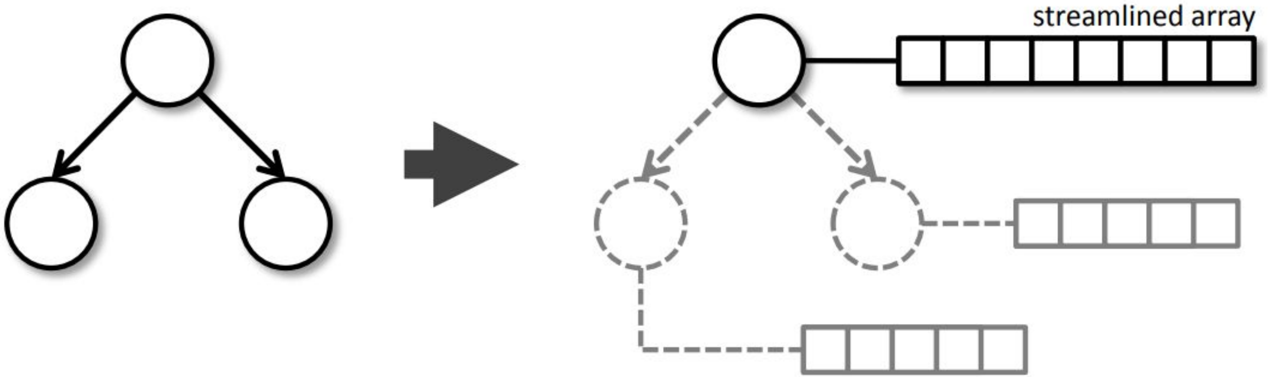
- Triangle rendering vs triangle strips
- Vertex shader cache locality: Fast Triangle reordering for vertex locality and reduced overdraw [Sander et al. 2007]
- Carefully do your profiling work: papers on that topic might build on wrong assumption for your target hardware
- More on those topics later...



A critical view on persistent scene graph optimizations

- Scene graph optimizations defeat the purpose of scene graphs:
  - A clean, and understandable description of the scene
- Alternative optimization data-structures more attractive.
- Hard to implement - will see details in paper later

.



[Wörister 2012] Streamlined array, used at shortcut at runtime

Practical problems with optimization steps

- Most optimizations require a scene graph rewrite, or the scene graph needs to be analyzed for optimization informations.
- Observation: if we use traversal state to capture all state, the traversal state at leaf nodes contains all data we need
- Therefore, we only need to query the leaf nodes for further use in optimization steps

Practical problems with optimization steps

- Idea: Capture traversal states which are present at leaf nodes
- Problem: the traversal state object mutates while traversing !!!
- -> just capturing the traversal state variable useless
- We need to perform a deep copy of the traversal state -> expensive

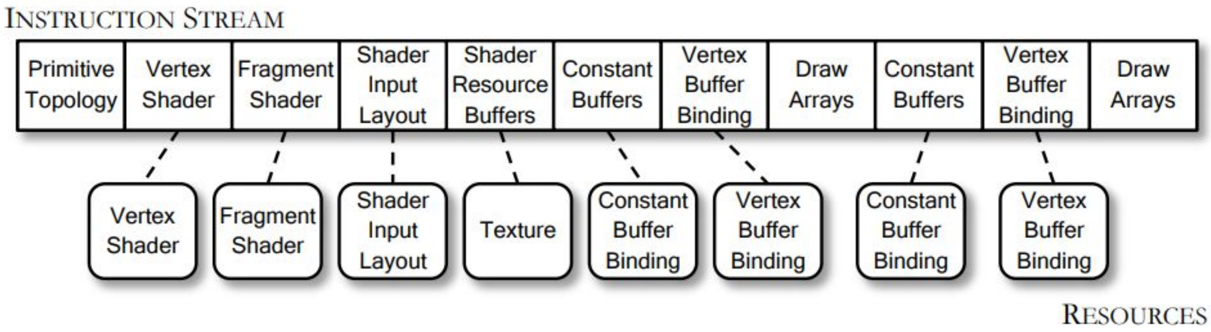
General problem: optimization conflicts with dynamism….

Research Paper 2:

Lazy Incremental Computation for Efficient Scene Graph Rendering.

Instruction types in render caches

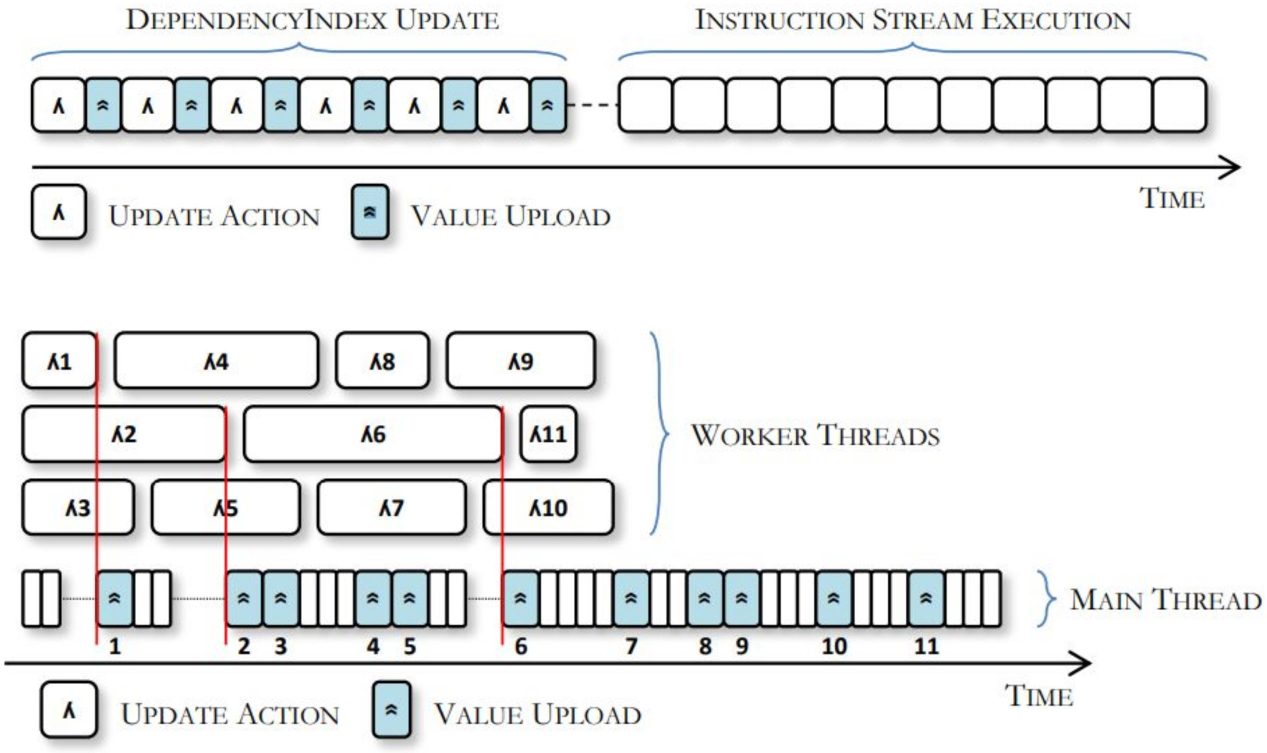
ROUTINE	PARAMETERS
SetPrimitiveTopology	a *primitive topology*
SetVertexShader	a *vertex shader*
SetShaderInputLayout	a *shader input layout*
SetFragmentShader	a *fragment shader*
SetGeometryShader	a *geometry shader*
SetVertexBufferBinding	a *vertex buffer binding*
SetIndexedVertexBufferBinding	an *indexed vertex buffer binding*
SetConstantBuffers	a set of *(slot-index, constant buffer)* pairs
SetShaderResourceBuffers	a set of *(slot-index, constant buffer)* pairs
DrawIndexed	*start index* and *element count*
DrawArrays	*start vertex* and *element count*



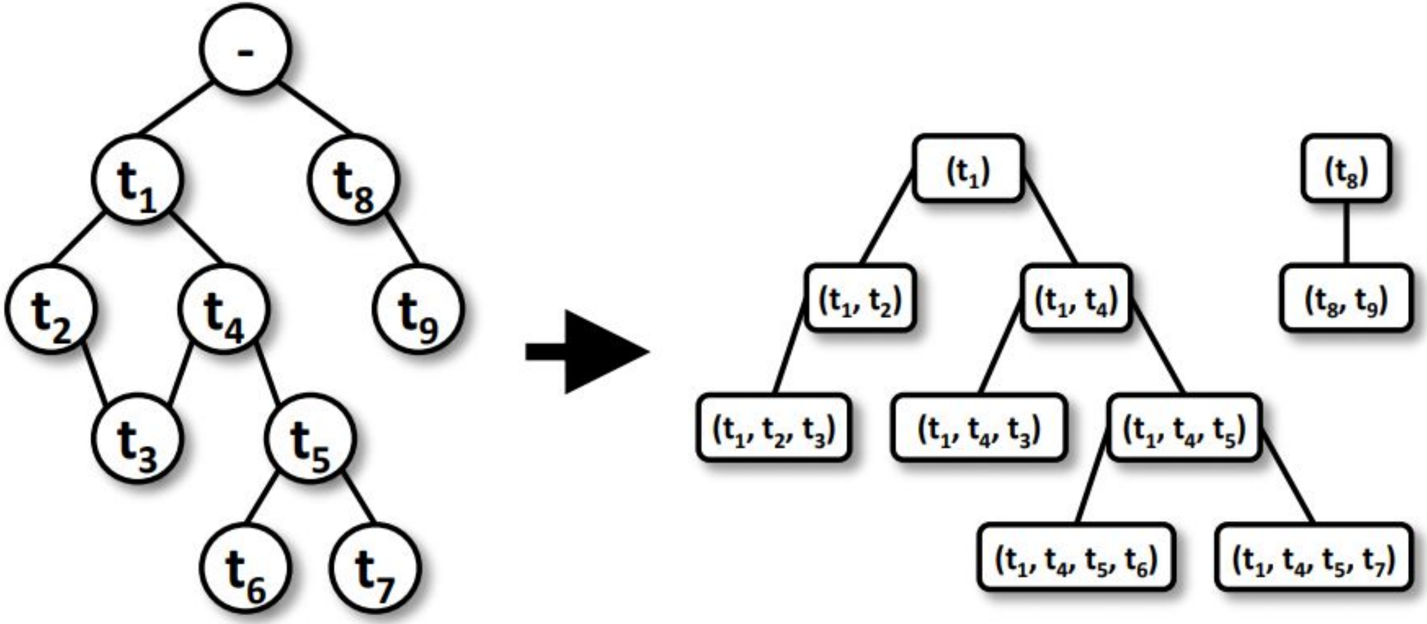
Implementation details for render caches

```
interface RenderJobBuilder
{
   void SetPrimitiveTopology(PrimitiveTopology pt);
   void SetInputLayout(IShaderInputLayout inputLayout);
   void SetSurface(Surface surface);

   void SetConstantBuffer(int slot, IConstantBuffer buffer, ShaderType shaderType);
   void ClearConstantBuffer(int slot, ShaderType shaderType);
   void SetShaderResourceBuffer(int slot, IShaderResourceBuffer buffer,
      ShaderType shaderType);
   void ClearShaderResourceBuffer(int slot, ShaderType shaderType);

   void SetIndexBuffer(Buffer indexBuffer);
   void BeginVertexBufferBinding();
   void BindVertexBuffer(String semantic, Buffer buffer);
   void EndVertexBufferBinding();

   void DrawIndexed(int startIndex, int elementCount);
   void DrawIndexed(int elementCount);
   void DrawArrays(int startIndex, int elementCount);
   void DrawArrays(int elementCount);
}
```

Interleaved, multithreaded resources updates



Memoization for efficient trafo updates



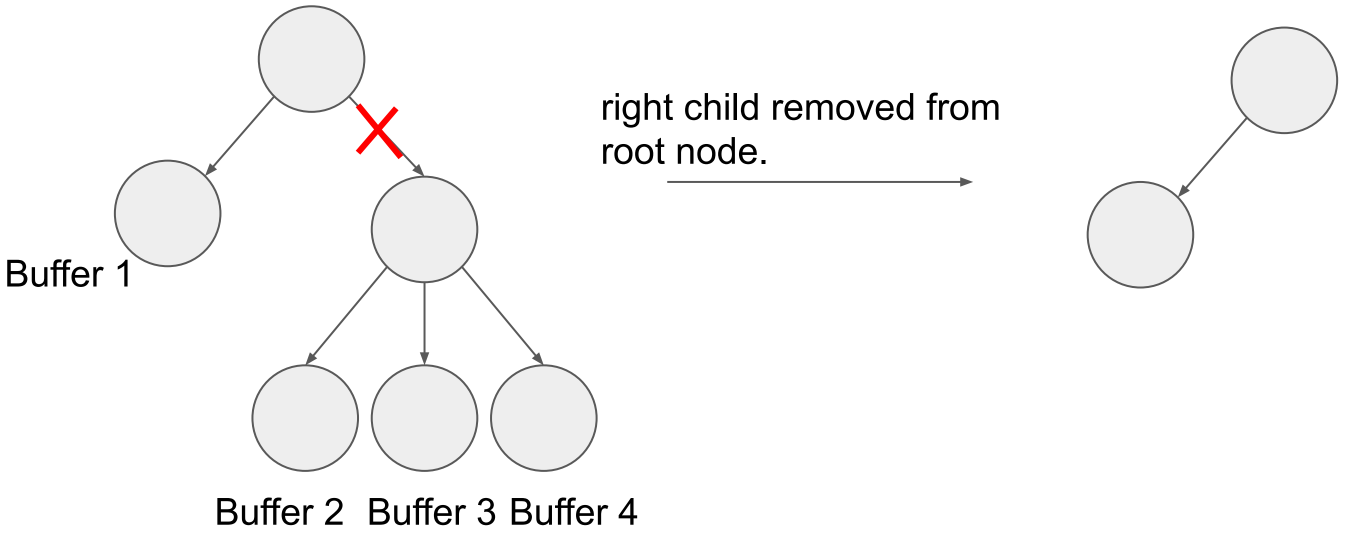
Resource management - approach 1

- GPU resources live in scene graph nodes directly
- Whenever we construct a rendering scene graph node (or visit it the first time), we construct the resource

Resource management

- Two options:
  - **The precise way:** If node is about to be removed, immediately start traversal which collects the graph's resources and destroy them
    - is this even possible? What if the inner state of the graph has been changed and we can't reconstruct the original traversal?
  - **The lazy way:** Each time a resource is used, add it to least recently used queue. Old elements can be removed.
- Both options are problematic
  - Consider high-frequency switching between two variants: Here we want to be lazy
  - Consider high memory pressure: Often we don't want to wait for resources to eventually go away.

Resource management - approach 1

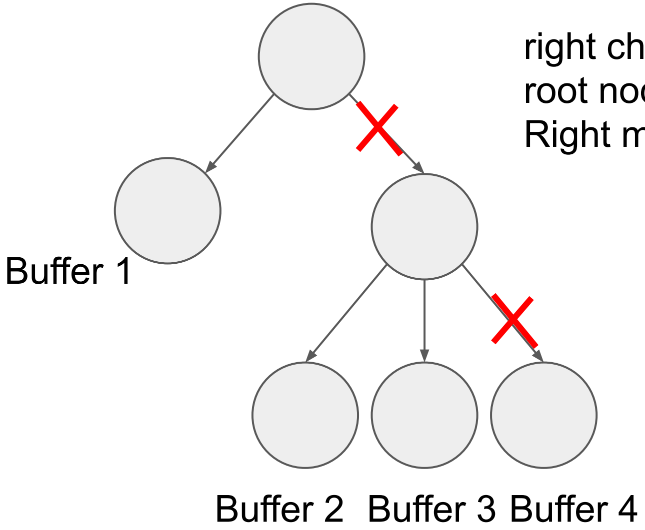


Resources: {$\text{Buffer}_1..\text{Buffer}_4$}

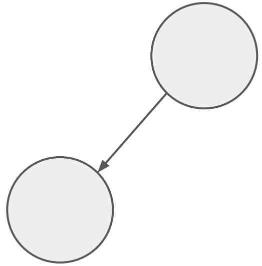
Resources: {Buffer_1}

To be destroyed: {$\text{Buffer}_2..\text{Buffer}_4$}

Concurrent (or batch) modification



right child removed from
root node.
Right most node removed as well



Buffer$_4$ is not found during *DisposeTraversal*

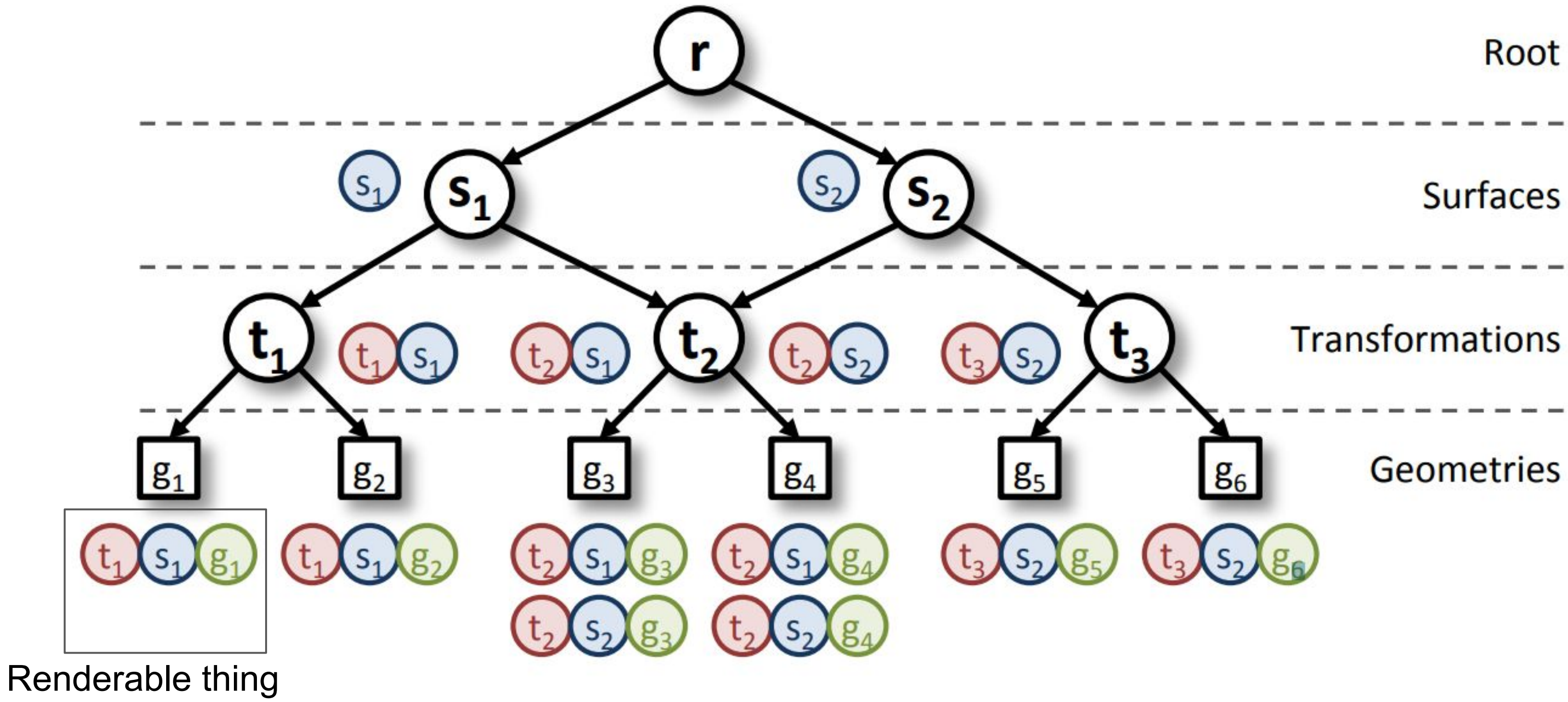
Resources: {Buffer$_1$..Buffer$_4$}

Resources: {Buffer$_1$}
To be destroyed: {Buffer$_2$..Buffer$_4$}

Concurrent (or batch) modification

- Need to be processed in nesting order:
  - First dispose inner nodes
- This requirement makes the thing really complex!

Collecting renderable things



A different view

- Use notion of **renderables**
- Graphics code assembles renderables
- Renderable objects interpreted by render loop
- Render object contains all graphics state

```
list { RenderObject_1,
       RenderObject_2,
       … }
```

```
for ro in renderObjects:
  Graphics.setViewTrafo ro.Trafo
  Graphics.setShader ro.Shader
  Graphics.render ro.Geometry
```

Resource management - approach 2

- Decouple resource management from scene graph structure
- Instead of traversing the scene graph to collect resources, cache resources per renderable object
- No silver bullet, but easier in practice

From scene graphs to render objects

- There is not a single canonical scene graph structure
- Different views to structure a scene
  - Spatially
  - Semantically
  - High-performance view
- Optimizations should be carried out in separate data structures
  - Example: Scene graph and culling structure is often not the same -> Culling should be performed in a specialized geometry grid/hierarchy

- Scene graphs are fine as user API

Render objects for specific applications

- Application dictates what to include in render object
  - ‘game object’
- We focus on simpler objects which don’t capture full state, making some problems easier
- Render objects could have:
  - Transformation
  - Material
  - Mesh
- Render objects allow for optimization:
  - Game objects can be executed fast (tight loop)
  - Can be compared efficiently (good for state sorting)

Render objects in a general framework

- Very flexible representation required.
- Render objects consist of:
    - Rasterizer state
    - BlendState
    - Viewport
    - Shader
    - Uniform values
    - Vertexbuffers*
    - Indexbuffer
    - Instancebuffer*
    - Draw call description
    - ….
- What is the cost?
- Similar to Vulkan pipeline

Takeaways

- Scene graphs are a common way to represent scenes
- If we want extensibility, the implementation becomes more difficult
    - Remember the *expression problem*
- The *semantic scene graph* approach provides:
    - A separation of semantic scene description and concrete graphics scene graphs
    - Rule objects can be used to capture dynamism. This way we don’t need to modify all visual states from outside of the scene graph.

Takeaways (2)

- The more flexible the implementation, the more overhead we have
  - Overheads can be significant (and performance much weaker than GPU throughput)
- Common problems of scene graph implementations (to think of)
  - Extensibility
  - Efficiency
  - Optimizations are particularly hard if traversal state can be modified arbitrarily
  - In presence of arbitrary modifications, resource management often becomes a burden

Takeaways (3)

- There are several optimization techniques for scene graphs
  - Most approaches try to reduce overheads by reducing the graph’s size
- When looking at the problem it is easy to choose the wrong path
  - It is better not to squeeze in various different ‘views’ into scene graphs!
- Better approach: compute render objects and perform optimizations on those...
- A fundamental problem arises
  - We need to constantly translate scene graphs to render objects
  - Is there a better way?
  - Could we just compute the set of render objects once, and update them accordingly to the changes?

What’s next?

- How to update render objects efficiently
- How to squeeze out performance of our graphics hardware
- How to implement high performance renderers….

Further reading

- OpenSg, A multi-thread safe foundation for scene graphs and its extension to clusters, Voß et al. 2002, https://dl.acm.org/citation.cfm?id=569679
- The original expression problem email, Wadler 1998, http://homepages.inf.ed.ac.uk/wadler/papers/expression/expression.txt
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- Extensibility for the Masses: Practical Extensibility with Object Algebras, Oliveira and Cook 2012, https://www.cs.utexas.edu/~wcook/Drafts/2012/ecoop2012.pdf
- Separating Semantics from Rendering: A Scene Graph based Architecture for Graphics Applications, Tobler F. Tobler 2011, https://www.cg.tuwien.ac.at/courses/RendEng/2015/RendEng-2015-11-16-paper1.pdf
- Lazy Incremental Computation for Efficient Scene Graph Rendering, Wörister et al. 2013, https://www.cg.tuwien.ac.at/courses/RendEng/2015/RendEng-2015-11-16-paper2.pdf

Further Reading (2)

- The Inventor Mentor, https://webdocs.cs.ualberta.ca/~graphics/books/mentor.pdf
- Paul S. Strauss. System and method for optimizing a scene graph for optimizing rendering performance, 1999, US Patent 5896139
- Sander et al. 2017, http://gfx.cs.princeton.edu/pubs/Sander_2007_%3ETR/tipsy.pdf
- Wöristers thesis 2012, A Caching System for a Dependency-Aware Scene Graph https://www.cg.tuwien.ac.at/research/publications/2012/Woerister_2012_ACS/Woerister_2012_ACS-Thesis.pdf
- Scene graphs, past present and future, blog post: http://www.realityprime.com/blog/2007/06/scenegraphs-past-present-and-future/#today