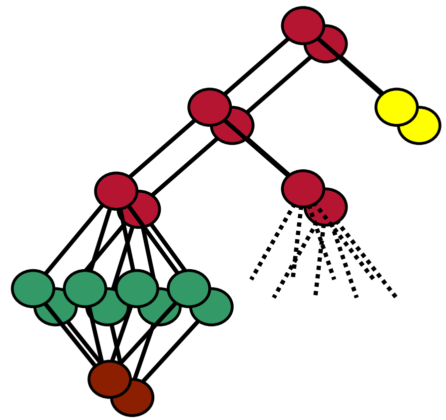
Virtual Reality & Physically-Based Simulation
Scenegraphs & Game Engines



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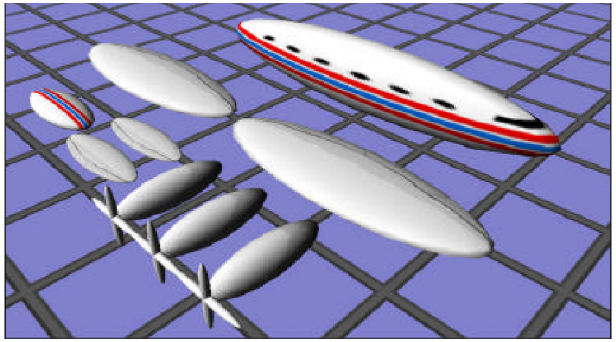
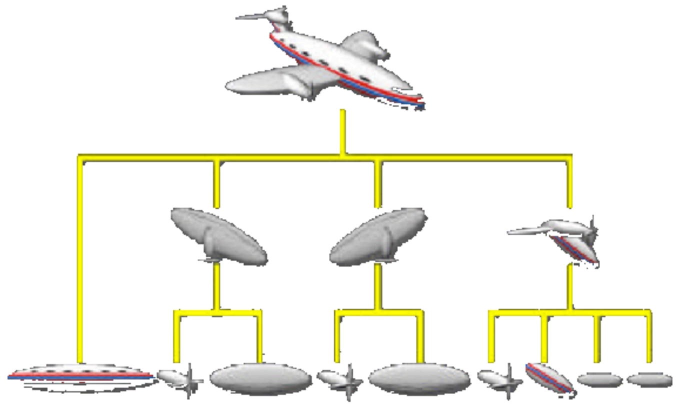
Overall System Architecture

	Game Logic & AI	
Sound Renderer (sound propagation)	Scene Graph (3D geometry manager & database)	Physically-based simulation
Sound Library	OpenGL	Force-Feedback Library

Motivation

- Immediate mode vs. retained mode:
  - Immediate mode = OpenGL / Direc3D = Application sends polygons / state change commands to the GPU → flexibler
  - Retained mode = scenegraph = applications builds pre-defined data structures that store polygons and state changes → easier and (probably) more efficient rendering
- Flat vs. Hierarchical scene descriptions:

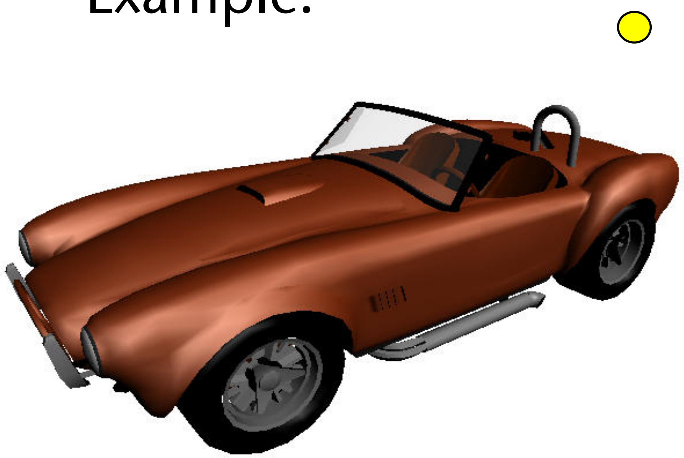


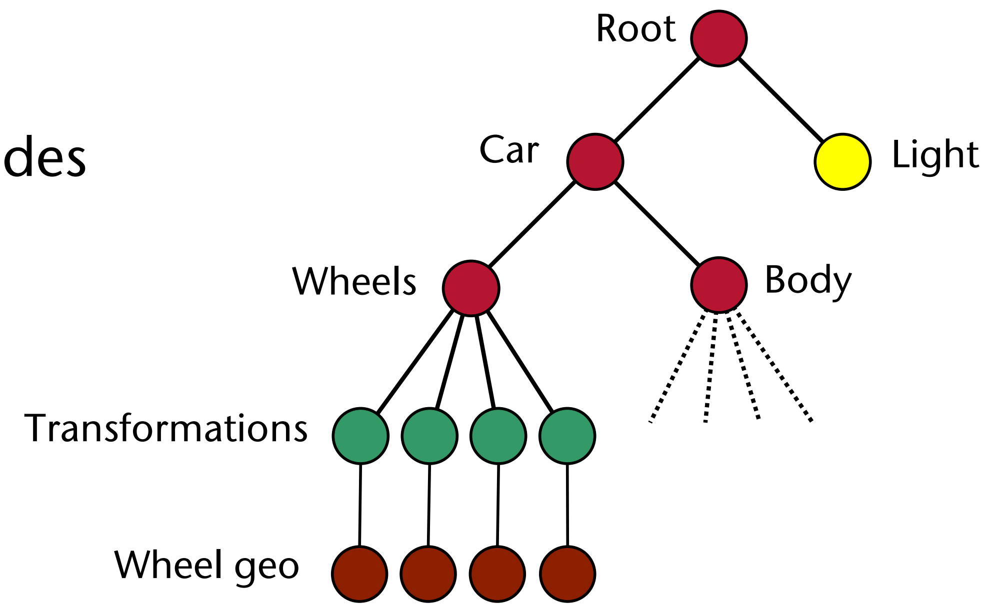


- *Code re-use* and *knowledge re-use*!
- Descriptive vs. imperative (cv. Prolog vs. C)
  - Thinking objects ... not rendering processes

Structure of a Scene Graph

- Directed, acyclic graph (DAG)
  - Often even a proper tree
- Consists of heterogeneous nodes
- Example:





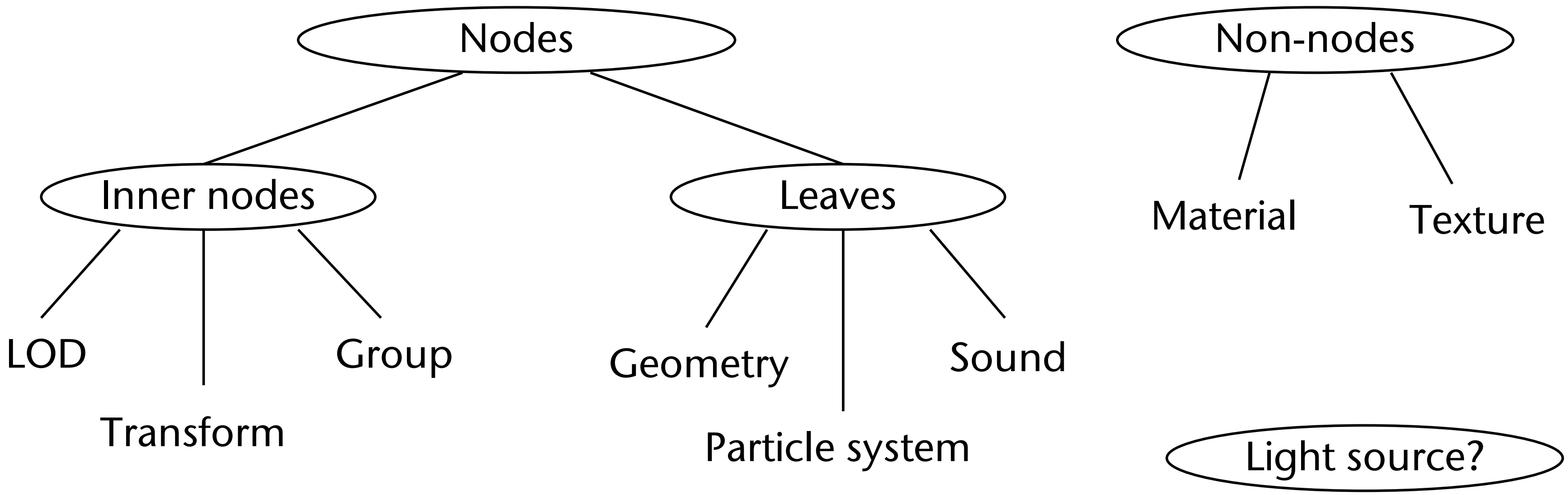
- Most frequent operation on scene graph: rendering
  - Amounts to depth-first traversal
  - Operation per node depends on kind of node

Semantics

- Semantics of a node:
  - Root = "universe"
  - Leaves = "content" (geometry, sound, ...)
  - Inner nodes = forming groups, store state (changes), and other non-geom. functionality, e.g., transforms
- Grouping: criteria for grouping is left to the application, e.g., by
  - Geometric proximity → scenegraph induces a nice BVH
  - Material → good, because state changes cost performance!
  - Meaning of nodes, e.g., all electrical objs in the car under one node → good for quickly switching off/on all electrical parts in the car
- Semantics of edges = inheritance of states
  - Transformation
  - Material
  - Light sources (?)

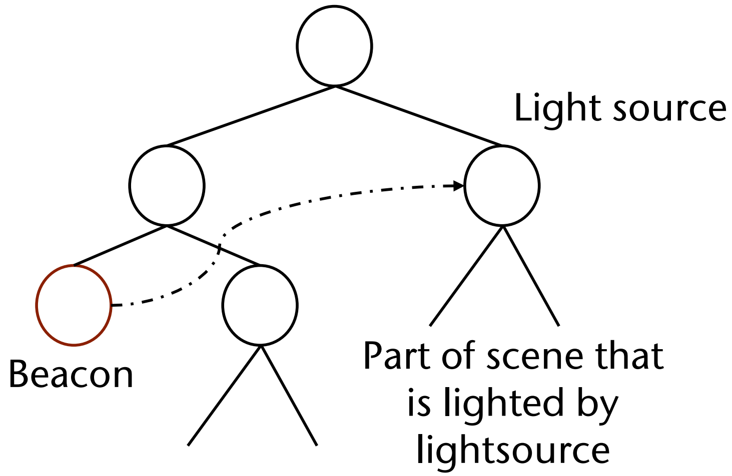
Kinds of Nodes

- There are 2 hierarchies: scenegraph hierarchy + class hierarchy
- The flexibility and the expressiveness of a scenegraph depends heavily on the kinds and number of node classes!
- Some classes (or, rather, their instances) will not be part of the scenegraph, but still be in the overall scene

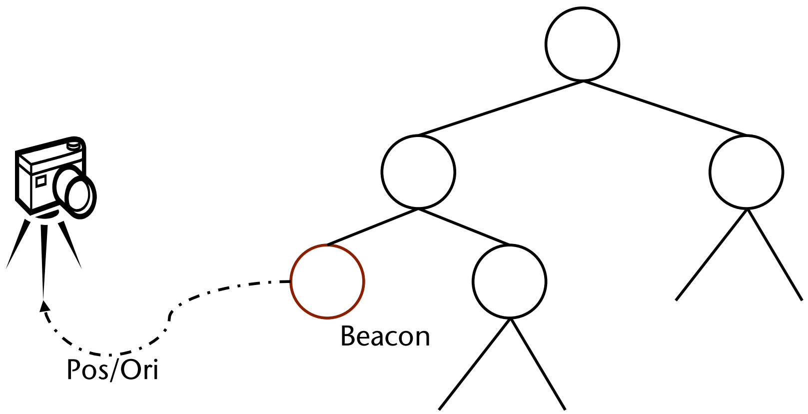


Issues

- Light sources:
  - Usually part of the scenegraph
  - Problem with naïve semantics: what if light source should move/turn, but not the scene it shines on?
  - Solution: beacons
    - Lightsource node lights its sub-scene underneath
    - Position/orientation is taken from the beacon



- Camera: to be, or not to be a node in the scenegraph?
  - Both ways have dis-/advantages
  - If not a node: use beacon principle

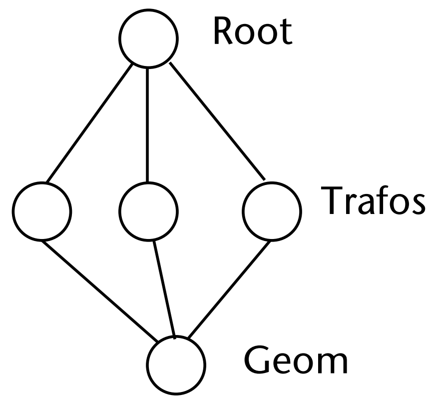


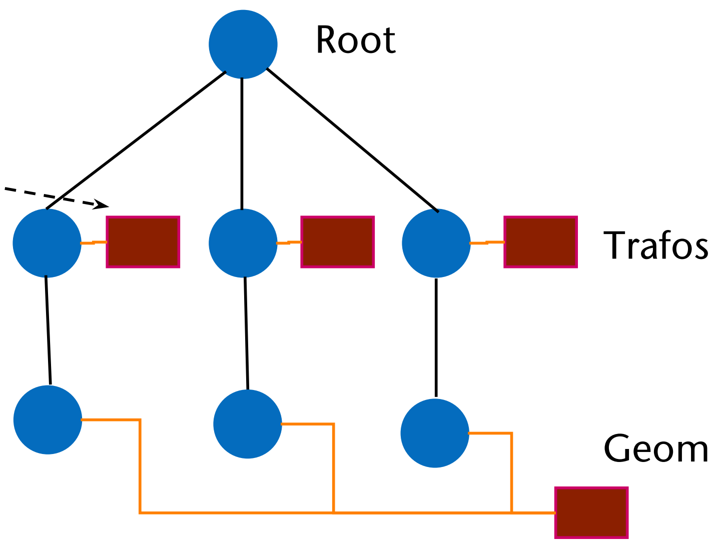
Material

- Material =
  - Color, texture, lighting parameters (see Phong)
  - Property of a node
- Semantics of materials stored with inner nodes: top-down inheritance
  - Path from leaf to root should have at least one material
  - Consequence:
    - Each leaf gets rendered with a unique, unambiguously defined material
    - It's easy to determine it
- Bad idea (Inventor): inheritance of material from left to right!

Sharing of Geometry / Instancing

- Problem: large scenes with lots of identical geometry
- Idea: use a DAG (instead of tree)
  - Problem: pointers/names of nodes are no longer *unique/unambiguous*!
- Solution: separate structure from content
  - The tree proper now only consists of *one kind* of node
  - Nodes acquire specific properties/content by attachments / properties
  - Advantages
    - Everything can be shared now
    - Many scenegraphs can be defined over the same content
    - All nodes can acquire lots of different properties/content





Thread-Safe Scenegraphs for Multi-Threading

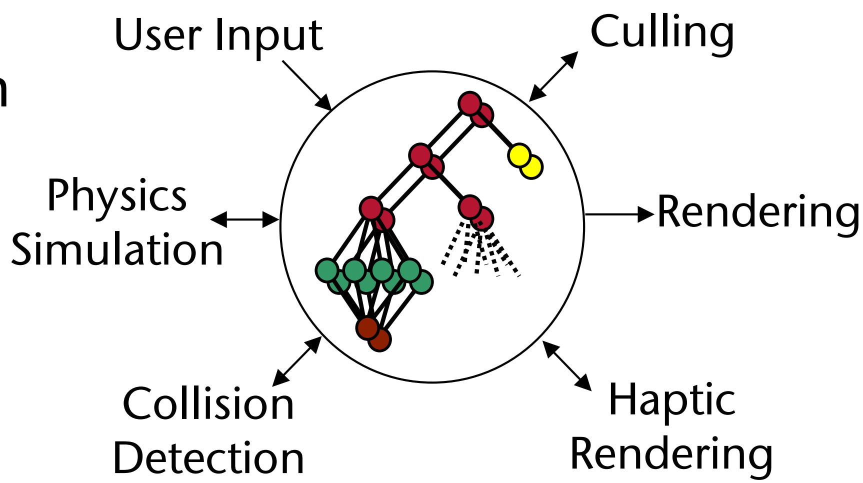
- Idea: several copies of the scenegraph
- Problem: memory usage & sync!
- Solution:
  - *Copy-on-Write* of the attachments
    → "Aspects"
  - Each thread "sees" their own aspect
  - Problem: easy access via pointers

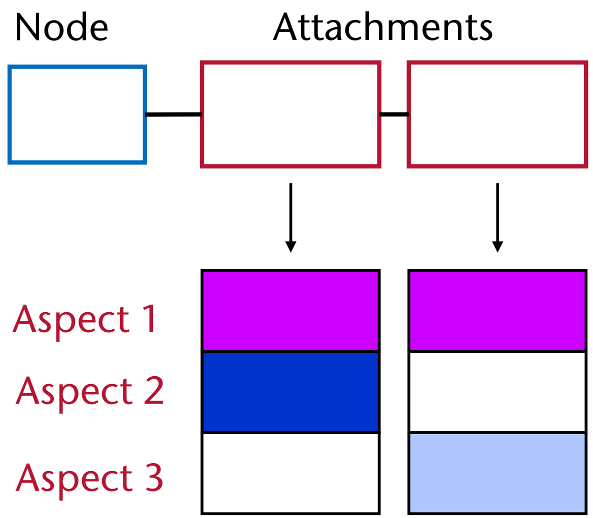
    ```
    geom->vertex[0]
    ```

    does not work any more
  - Solution (leveraging C++):
    - "Smart Pointers"

    ➢ Needs one "pointer class" per node. Ex.:

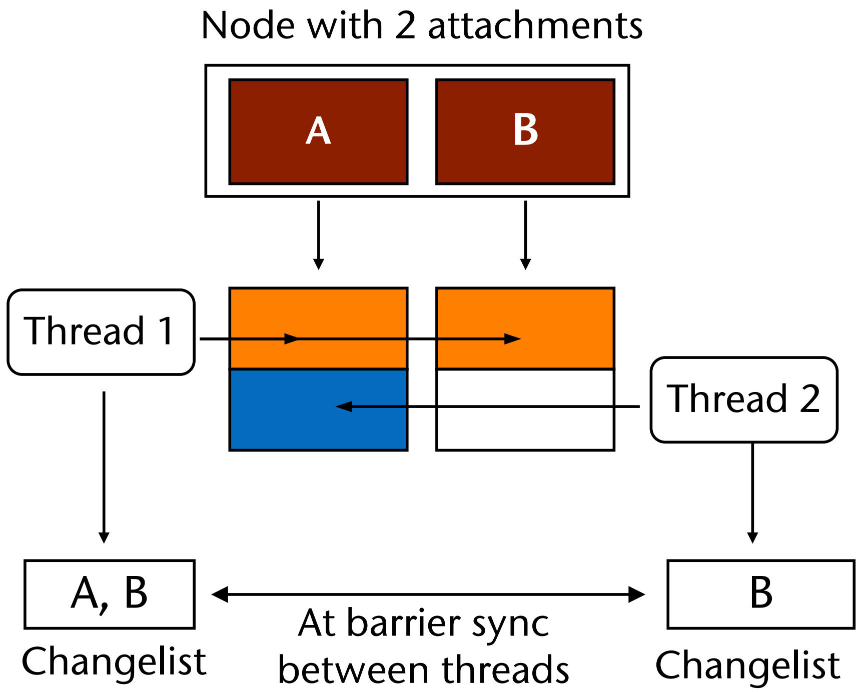
    ```
    geomptr = Geometry::create(…);
    geomptr->vertex[0] ...
    ```





Distributed Scenegraphs

- Synchronisation by changelists
  - Make scene graph consistent at one specific point during each cycle of each thread
    → barrier synchronization



- Distributed rendering:
  - Goal: rendering on a cluster
  - Problem: changes in the scenegraph need to be propagated
  - Solution: simply communicate the changelists
    - Items in the changelist = IDs of nodes/attachments to be changed + new data

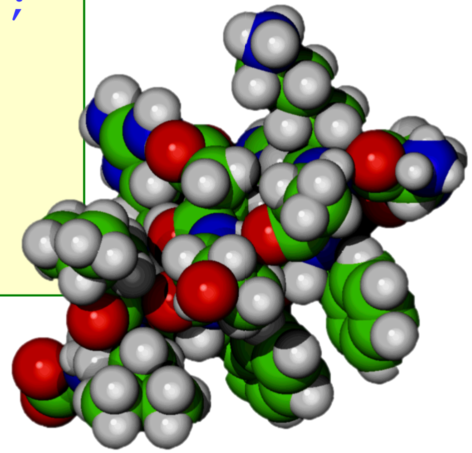
Issue: Memory-Layout for Fast Rendering

- Frequent problem: the elegant way to structure data (from the perspective of software engineering) is inefficient for fast rendering
- Terminology: "Array of Structs (AoS)" vs. "Struct of Arrays (SoA)"
- For illustration: example of visualization of molecules
  - Following good SE practice, we should design classes like this

```
class Atom
{
public:
    Atom( uint atom_number, Vec3 position, ... );
private:
    Vec3   position_;
    uint   atom_number_;
    Atom * bonds_[max_num_bonds];
    ...
};
```

- And the class for a molecule:

```
class Molecule
{
public:
    Molecule( const std::vector<Atom> & atoms );
private:
    std::vector<Atom> atoms_;
    ...
};
```



- Memory layout of a molecule is now an AoS:

pos	num	bonds	pos	num	bonds	pos	num	bonds	

- Problem with that: memory transfer becomes slow
- Alternative: Struct of Arrays

```
class Molecule
{
private:
    std::vector<Vec3>  position;
    std::vector<uint>  atom_number;
   ...
};
```

pos[0] pos[1] pos[2] . . .	atom_number[0] . . .	

Criteria for the Usage of Scenegraphs

- When is a hierarchical organization of the VE effective:
  - Complex scenes: many hierarchies of transformations, lots of different matierals, large environment with lots of geometry of which usually only a part can be seen (culling)
  - Mostly static geometry (opportunities for rendering optimization, e.g., LoD's)
  - Specific features of the scenegraph, e.g., particles, clustering, …
- When not to use a hierarchical organization / scenegraph:
  - Simple scenes (e.g., one object at the center, e.g., molecular vis)
  - Visualization of scientific data (e.g., CT/MRI, or FEM)
  - Highly dynamic geometry (e.g., all objects are deformable)

Fields & Routes Concept by Way of X3D/VRML

- What is X3D/VRML:
  - Specification of nodes, each of which has a specific functionality
  - Scene-graph definition & file format, plus ...
  - Multimedia-Support
  - Hyperlinks
  - Behavior and animation
  - "VRML" = "Virtual Reality Modeling Language"
- X3D = successor & superset of VRML
  - Based on XML
- VRML = different encoding, but same specification
  - Encoding = "way to write nodes (and routes) in a file"

Hello World

- In X3D (strictly speaking: "XML encoding"):

Like the <html> tag in HTML

Root node

Definition of nodes

```
<?xml version="1.0" encoding="UTF-8"?>
<X3D profile='Immersive'>
<Scene>
  <Shape>
    <Text string="Hello" "world!" />
  </Shape>
</Scene>
</X3D>
```

- In VRML:

No explicit root node in VRML

```
#X3D V3.1 utf8
Shape {
  geometry Text {
    string [ "Hello" "world!" ]
  }
}
```

Tip: Use an ASCII editor wich identifies *matching brackets* as a text unit

Nodes and Fields (aka. Entities and Components)

- Nodes are used for describing …
  - … the scenengraph (the usual suspects):
    - Geometry, Transform, Group, Lights, LODs, …
  - … the behavior graph, which implements all response to user input (later)
- Node := set of fields
  - "Single-valued fields" and "multiple-valued fields"
  - Each field of a node has a unique identifier
  - These are predefined by the X3D/VRML specification
- Field types:
  - field = actual data in the external file
  - eventIn, eventOut = used only for connecting nodes, data that won't be saved in a file
  - exposedField = combination of these (xxx, set_xxx, xxx_changed)

Types of Fields

- All field types exist as "single valued" (**SF**...) and as "multiple valued" kind (**MF**...)
- Example of an SF field:

```
<Material diffuseColor="0.1 0.5 1" />
```

X3D

```
material Material {
  diffuseColor  0.1 0.5 1
}
```

VRML

- MF fields are practically the same as arrays
  - Special notation for signifying an MF field and to separate elements

- Primitive data types: the usual suspects

Field type	X3D example	VRML example
`SFBool`	**`true / false`**	**`TRUE / FALSE`**
`SFInt32`	**`12`**	**`-17`**
`SFFloat`	**`1.2`**	**`-1.7`**
`SFDouble`	**`3.1415926535`**	
`SFString`	**`"hello"`**	**`"world"`**

Reminder: for each SF-field there exists an MF-field

- Higher data types:

Field type	example
`SFColor`	`0 0.5 1.0`
`SFColorRGBA`	`0 0.5 1.0 0.75`
`SFVec3f`	`1.2 3.4 5.6`
`SFMatrix3f`	`1 0 0  0 1 0  0 0 1`
`SFString`	**`"hello"`**

- Special field types:

Field type	X3D example	VRML example
`SFNode`	`<Shape> ... </Shape>`	`Shape { ... }`
`MFNode`	`<Shape>`… , `<Group>`… oder `<Transform>`…	`Transform {` `children [... ] }`
`SFRotation`	`0 1 0 3.1415`	
`SFTime`	`0`	

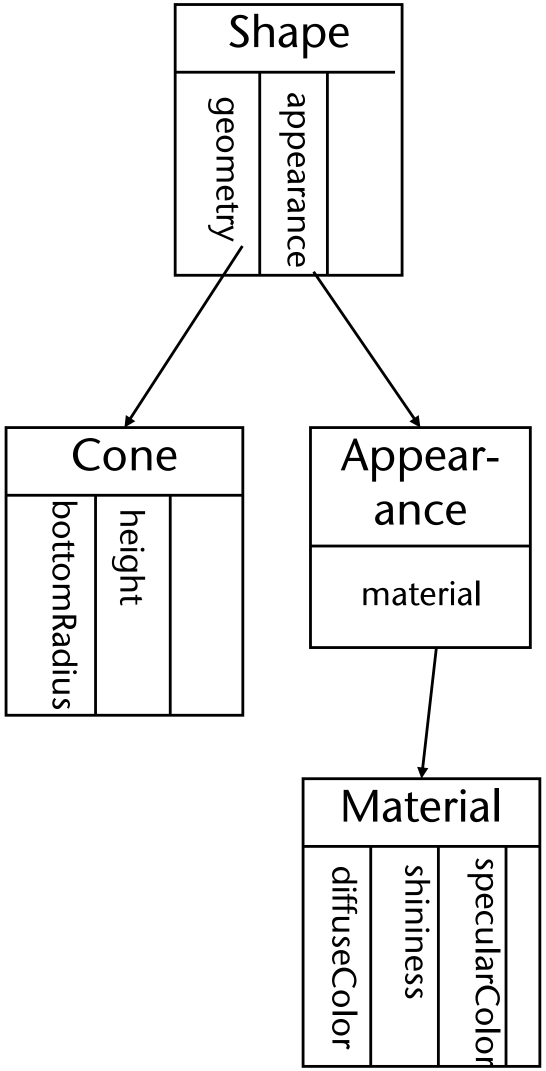
- General remarks on the design of X3D/VRML:
  - The design is orthogonal in that there exists a **`MF`**-type for every **`SF`**-type
  - The design is not orthogonal in that some types are generic (e.g. **`SFBool`**, **`SFVec3f`**) while others have very specific semantics (e.g. **`SFColor`**, **`SFTime`**, etc.)
    - It is not clear whether this is good or bad ...

Types of Nodes to Describe the Scenegraph

- All scenegraphs have a set of different kinds of nodes to define the tree:
  1. Nodes for grouping / hierarchy building
  2. Nodes for storing actual geometry
  3. Nodes for storing appearance, i.e., material def's, textures, etc.
- In X3D/VRML, for instance:
  1. **`Shape, Group, Transform, Switch, Billboard, LOD, ...`**
  2. **`TriangleSet, IndexedTriangleSet, IndexedFaceSet, IndexedTriangleStripSet, Box, Sphere, Cylinder, NurbsPatchSurface, ElevationGrid, ... ...`**
  3. **`Appearance, Material, ImageTexture,`**

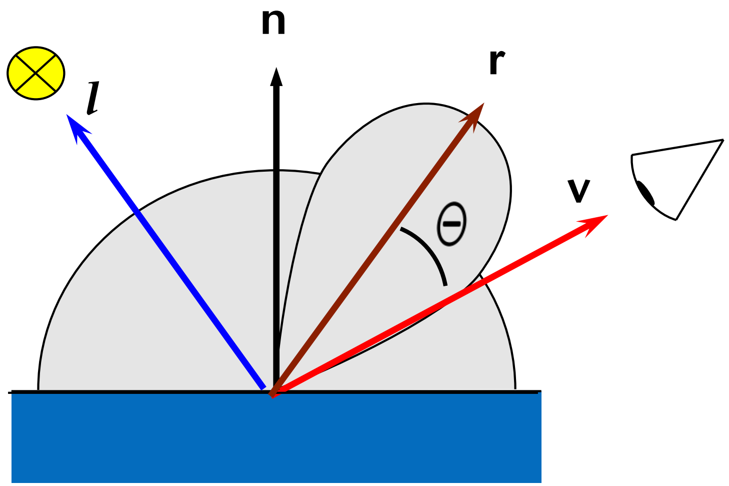
A Simple Example

```
#X3D V3.1 utf8
Shape {
  geometry Cone {
    bottomRadius 1
    height       2
  }
  appearance Appearance {
    material Material {
      ambientIntensity 0.256
      diffuseColor     0.029 0.026 0.027
      shininess        0.061
      specularColor    0.964 0.642 0.980
    }
  }
}
```



Specifying the Material

- Usually, the Phong model is assumed:



$$I_{\text{out}} = I_{\text{amb}} + I_{\text{diff}} + I_{\text{spec}}$$

$$I_{\text{diff}} = k_d I_{\text{in}} \cos\phi$$

$$I_{\text{spec}} = k_s I_{\text{in}} (\cos\theta)^p$$

$$I_{\text{out}} = k_d \cdot I_a + \sum_{j=1}^{n} (k_d \cos\phi_j + k_s \cos^p\theta_j) \cdot I_j$$

$$= k_d I_a + \sum_{j=1}^{n} (\, k_d(\mathbf{n}\boldsymbol{l}) + k_s(\mathbf{r}\mathbf{v})^p \,) \cdot I_j$$

k_d = diffuse reflection coefficient

k_s = specular reflection coefficient

p = *shininess*

- In VRML/X3D:

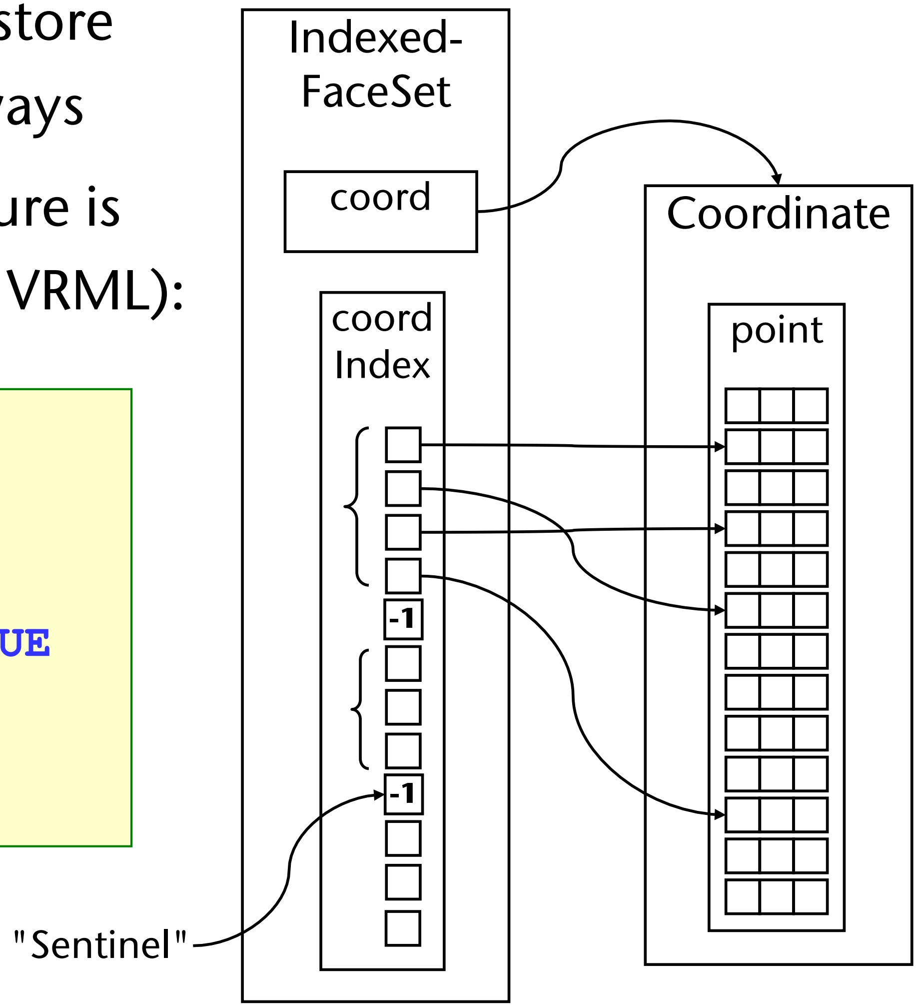
```
Material {
  SFFloat ambientIntensity 0.2
  SFColor diffuseColor     0.8 0.8 0.8
  SFColor specularColor    0 0 0
  SFFloat shininess        0.2
  SFColor emissiveColor    0 0 0
  SFFloat transparency     0
}
```

Common Data Structures to Specify Geometry

- Most scene graphs and game engines have internal data structures to store geometry in memory-efficient ways
- One very prominent data structure is the **`IndexedFaceSet`** (here in VRML):

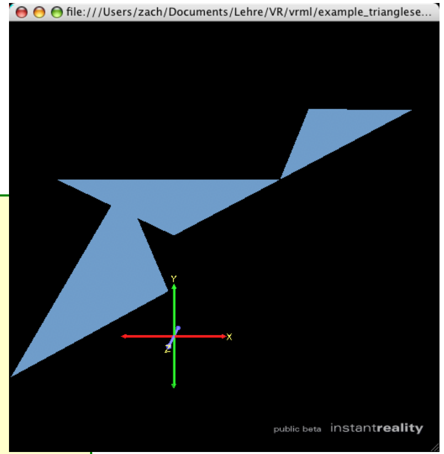
```
IndexedFaceSet {
  SFNode   coord         NULL
  MFInt32  coordIndex    []
  SFBool   ccw           TRUE
  SFBool   normalPerVertex TRUE
  SFBool   solid         TRUE
  SFFloat  creaseAngle   0.0
}
```

```
Coordinate {
  MFVec3f point []
}
```



- Example:

```
Shape {
  geometry IndexedFaceSet {
    coord Coordinate {
      point [ -2 0 3, -0 1 1, -1 3 0,
               0 2 0,  2 3 1, -2 3 1,
               3 5 -2, 4 4 2 ]
    }
    coordIndex [ 0 1 2 -1  3 4 5 -1  6 4 7 -1 ]
    solid FALSE
    ccw TRUE
  }
  appearance Appearance { … }
}
```



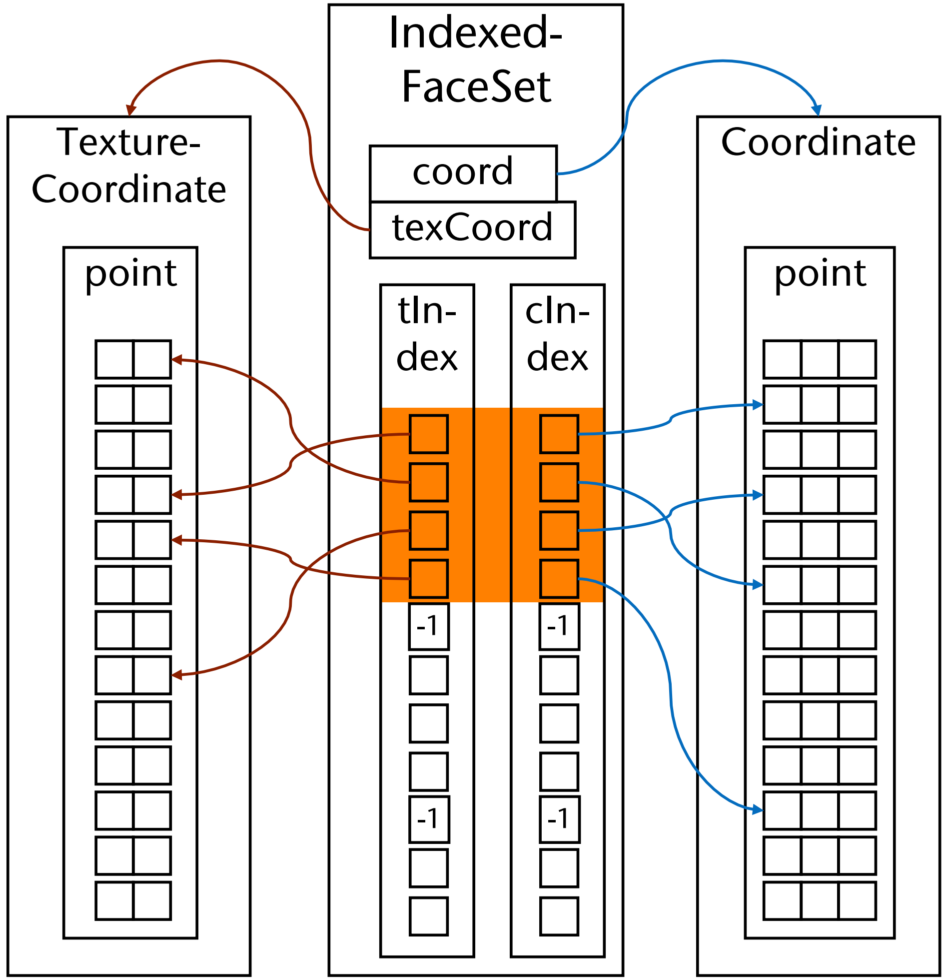
example_indexedtriangleset.wrl

- Geometry stored this way is called a mesh
  - Although this example rather looks like a "polygon soup"

Specification of Further Attributes per Vertex

- In meshes, you can always specify additional vertex attributes , eg., normals or texture coordinates per vertex
- Texture coords are stored as follows:

```
IndexedFaceSet {
   SFNode   coord
   MFInt32  coordIndex
   SFNode   texCoord
   MFInt32  texCoordIndex
   SFBool   ccw
   SFBool   normalPerVertex
   SFBool   solid
}
```



The OBJ File Format

- Only geometry and textures
  - Usually only used for polygonal geometry
  - Can store NURBS, too
- Only in ASCII
  - Very easy to read and parse as a human
  - Extremely easy to write a loader (takes just an afternoon)
- No hierarchy

Example

```
# A cube
mtllib cube.mtl
v 1.000000 -1.000000 -1.000000
v 1.000000 -1.000000 1.000000
v -1.000000 -1.000000 1.000000
v -1.000000 -1.000000 -1.000000
v 1.000000 1.000000 -1.000000
v 0.999999 1.000000 1.000001
v -1.000000 1.000000 1.000000
v -1.000000 1.000000 -1.000000
vt 0.748573 0.750412
vt 0.749279 0.501284
vt 0.999110 0.501077
vt 0.999455 0.750380
vt 0.250471 0.500702
vt 0.249682 0.749677
vt 0.001085 0.750380
vt 0.001517 0.499994
vt 0.499422 0.500239
vt 0.500149 0.750166
vt 0.748355 0.998230
vt 0.500193 0.998728
vt 0.498993 0.250415
vt 0.748953 0.250920
```

```
vn 0.000000 0.000000 -1.000000
vn -1.000000 -0.000000 -0.000000
vn -0.000000 -0.000000 1.000000
vn -0.000001 0.000000 1.000000
vn 1.000000 -0.000000 0.000000
vn 1.000000 0.000000 0.000001
vn 0.000000 1.000000 -0.000000
vn -0.000000 -1.000000 0.000000
usemtl Material_ray.png
f 5/1/1 1/2/1 4/3/1
f 5/1/1 4/3/1 8/4/1
f 3/5/2 7/6/2 8/7/2
f 3/5/2 8/7/2 4/8/2
f 2/9/3 6/10/3 3/5/3
f 6/10/4 7/6/4 3/5/4
f 1/2/5 5/1/5 2/9/5
f 5/1/6 6/10/6 2/9/6
f 5/1/7 8/11/7 6/10/7
f 8/11/7 7/12/7 6/10/7
f 1/2/8 2/9/8 3/13/8
f 1/2/8 3/13/8 4/14/8
```

Indices defining one vertex of a face (v-ID/vt-ID/vn-ID)

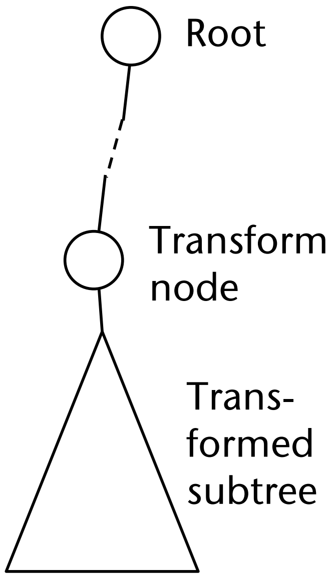
Keyword tells what the information the line contains
(v = vertex, vt = texture coords, vn = vertex normal, f = face)

The FBX File Format

- Geometry and textures
- Scene graphs (geometry hierarchies)
- Animations
- ASCII (pretty well human readable) and binary

Transformations

- Transformations are stored by special kinds of nodes
  - All children underneath will get transformed by it
- There are three ways how to store transforms in a scenegraph
  - A single transform node can store just one transform, e.g., rotation
  - A single transform node can store one xform per kind (only the common ones), in a pre-defined order
  - A single transform node can store a 4x4 matrix
    - It is up to the application programmer to convert standard xforms (e.g., rotation + translation) to 4x4 matrix



- The transformation node:

```
Transform {
  MFNode      children              []
  SFVec3f     center                0 0 0
  SFRotation  scaleOrientation      0 0 1 0
  SFVec3f     scale                 1 1 1
  SFRotation  rotation              0 0 1 0
  SFVec3f     translation           0 0 0
}
```

C	translation
R_1	rotation
S	scaling
R_2	rotation
T	translation

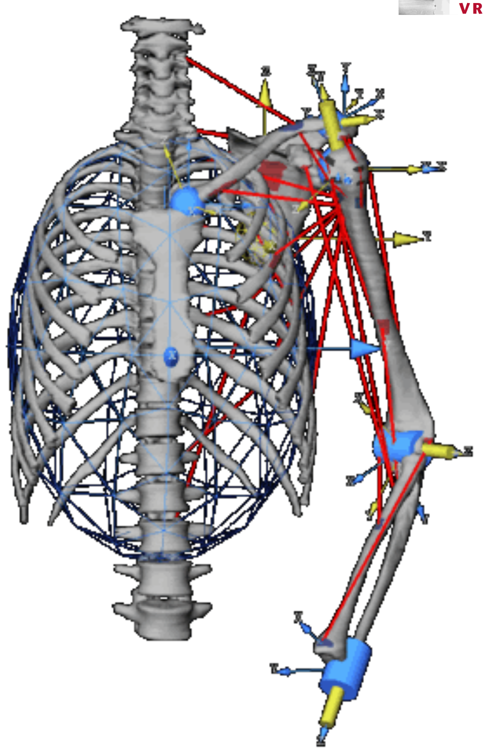
- Meaning:

$$M = T \cdot C \cdot R_2 \cdot R_1 \cdot S \cdot R_1^{-1} \cdot C^{-1}$$

with

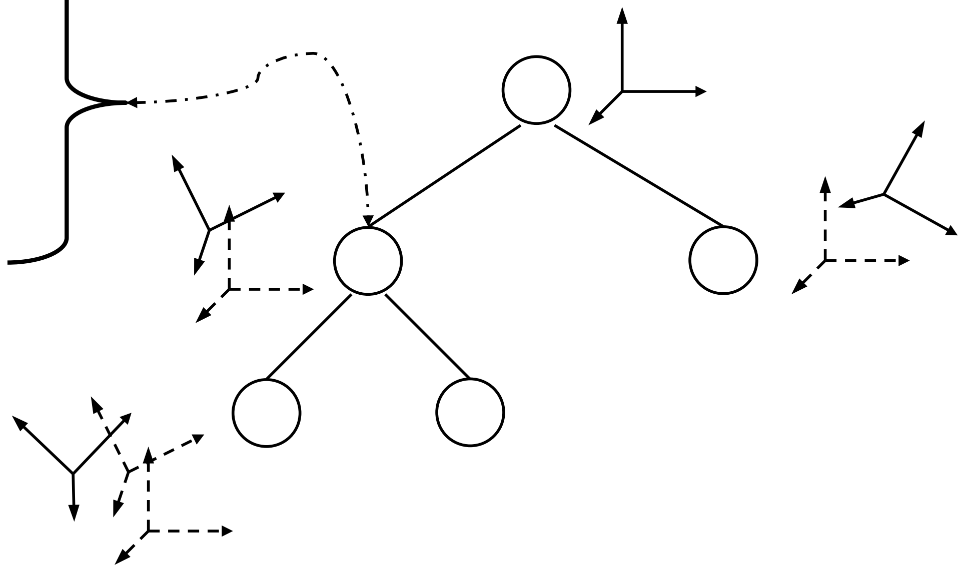
$$\mathbf{p}_{\text{world}} = M \cdot \mathbf{p}_{\text{model}}$$

Hierarchical Transformations

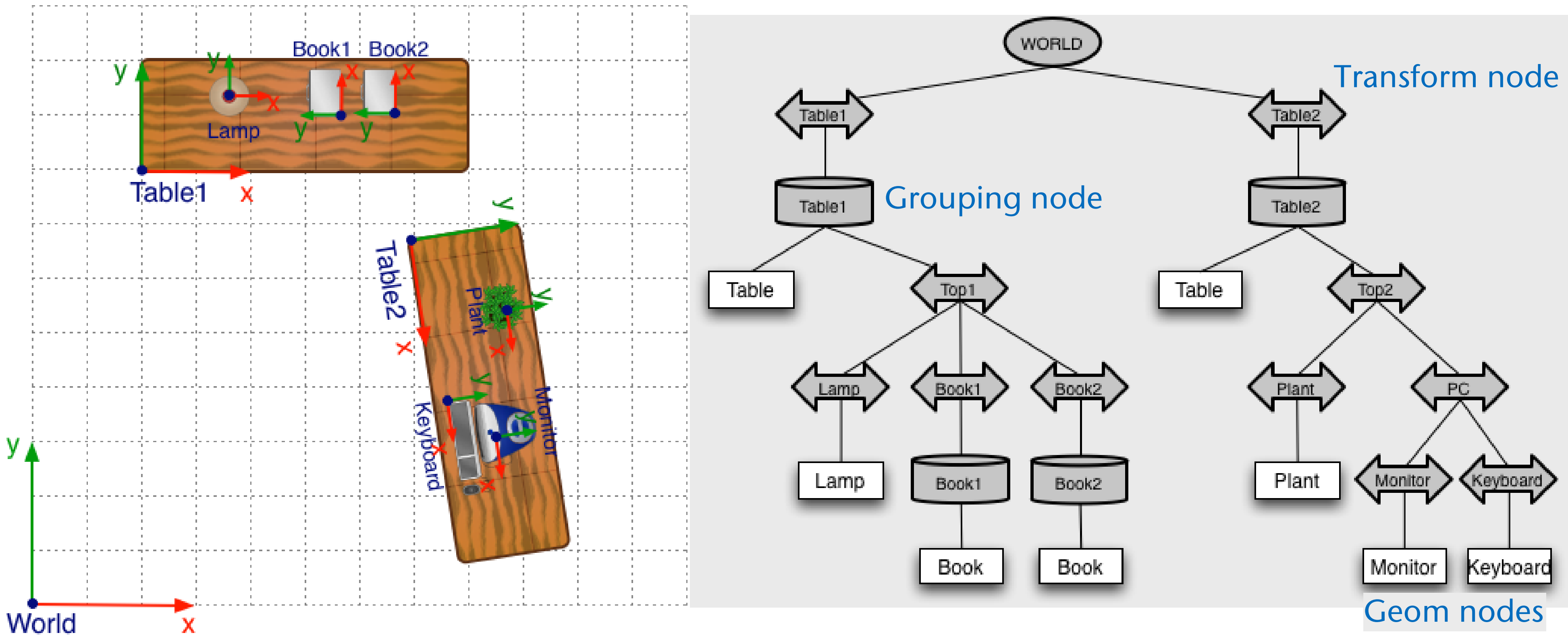


- One of the core concepts of scenegraphs
- Transformation node ≡
  new local coordinate system (frame)
  - Always specified as a transformation **relative** to its parent coord frame
- In OpenGL 2:

```
pushMatrix();
multMatrix( M );
      traverse sub-tree
popMatrix();
```

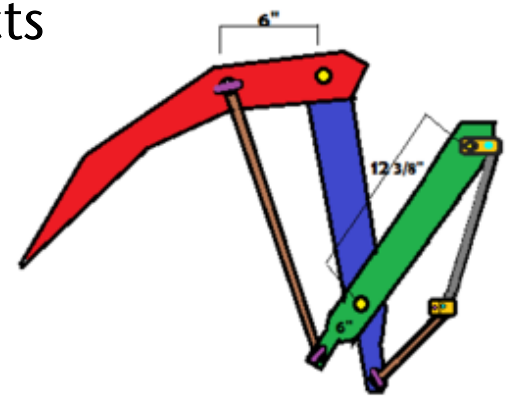


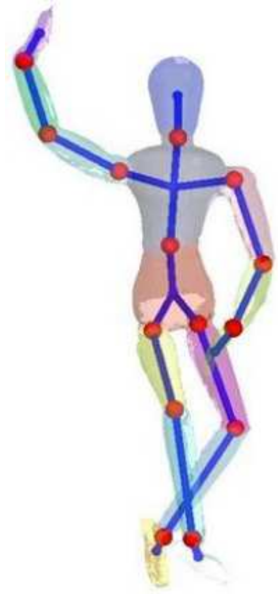
Another Example



- Advantage:
  - Transform in node Table1 makes table + objs on top of it move
  - Change of transformation in Top1 makes all the objs on the table top move, but not the table

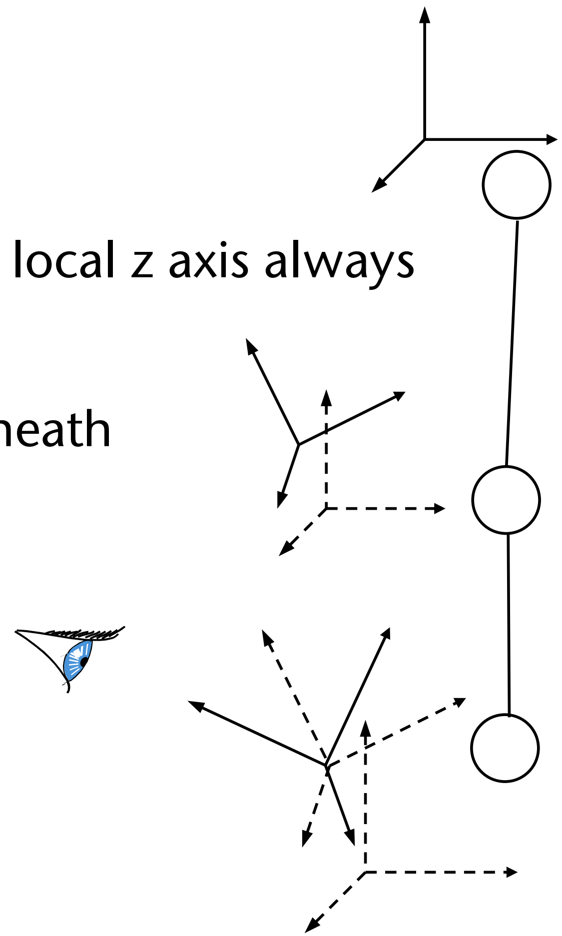
- Very convenient for articulated objects
  - E.g., robots, skeletons, ..
- Remark: 2D drawing programs (Photoshop et al.) create a similar hierarchy when you group objects





Specialized Transform Nodes

- Billboard:
  - Automatically computes a rotation, such that it's local z axis always points towards the viewpoint
  - Applies this transformation to the subtree underneath
  - Usage: fake complex geometry by textured rendered on a single polygon (or a few)
  - Geometry has to be far away



The Behavior Graph

- Animations and simulation eventually cause changes in the scene graph; e.g.:
  - Changes of transformations, i.e. the position of objects, e.g. of a robot arm
  - Modification of the materials, e.g. color or texture of an object
  - Deformation of an object, i.e. changes in the vertex coords
- All these changes are equivalent to the change of a field of a node at runtime

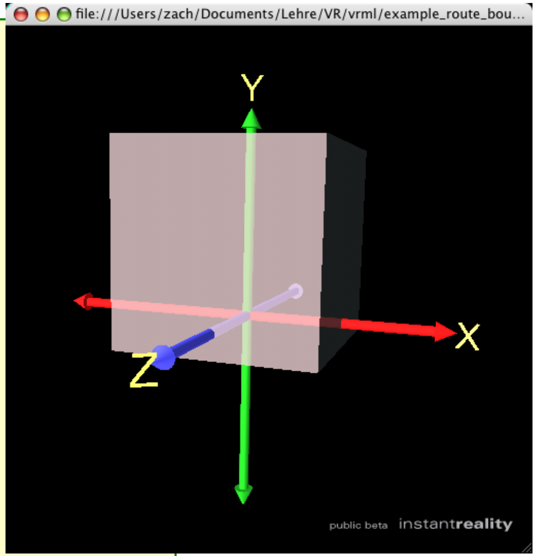
Events and Routes

- The mechanism for changing the X3D/VRML scene graph:
  - Fields are connected to each other by so-called routes
  - A *change* of a field produces a so-called event
  - When an event occurs, the *content* of the field from the route-start is *copied* to the field of the route-end ("the event is propagated")
- Other terminology: *data flow paradigm / data flow graph*
  - Used in most game engines today, and in scientific visualization tools for a long time
- Syntax of routes:

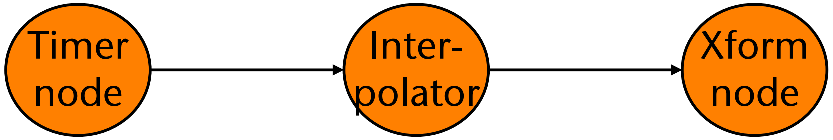
```
ROUTE Node1Name.outputFieldName TO Node2Name.inputFieldName
```

A simple example

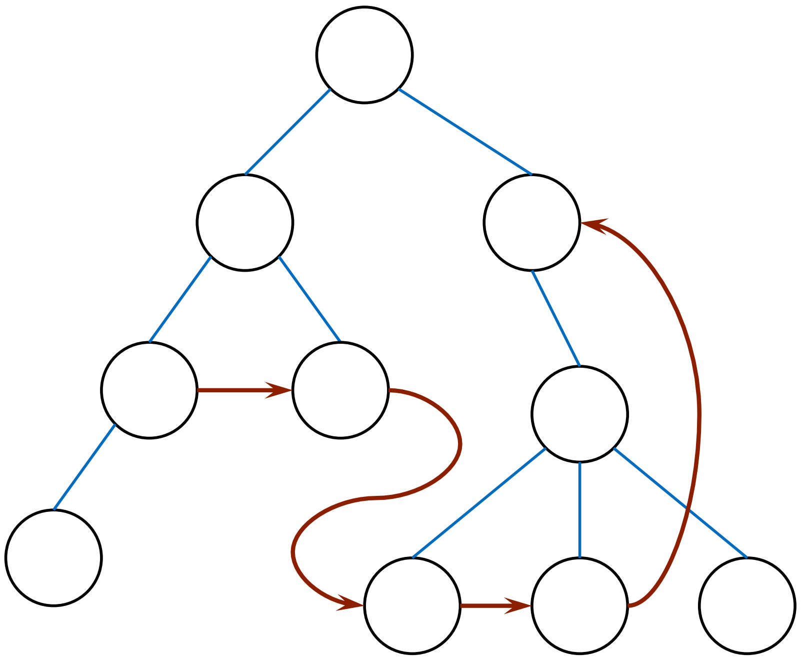
```
DEF timer TimeSensor {
  loop TRUE
  cycleInterval 5
}

DEF pi PositionInterpolator {
  key      [ 0        0.5     1       ]
  keyValue [ 0 -1 0, 0 1 0, 0 -1 0 ]
}

DEF trf Transform {
  translation 0 0 0
  children [
    Shape { geometry Box { } }
  ]
}

ROUTE timer.fraction_changed TO pi.set_fraction
ROUTE pi.value_changed TO trf.set_translation
```



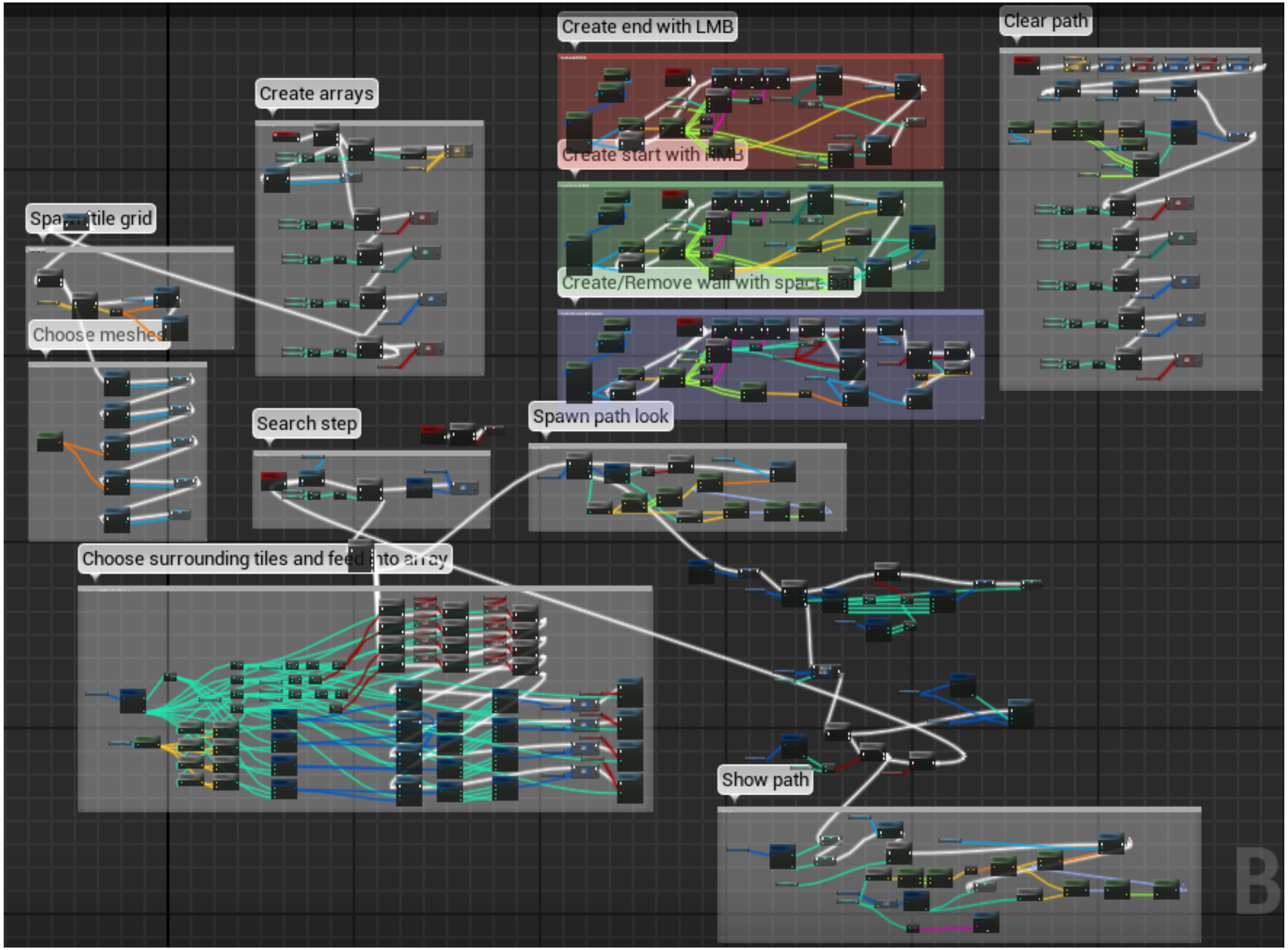
example_route_bounce.wrl



- Routes connect nodes ⟶ behavior graph:
  - Is given by the set of all routes
  - A.k.a. route graph, or event graph (blueprint in Unreal engine)
  - Is a second graph, superimposed on the scenengraph

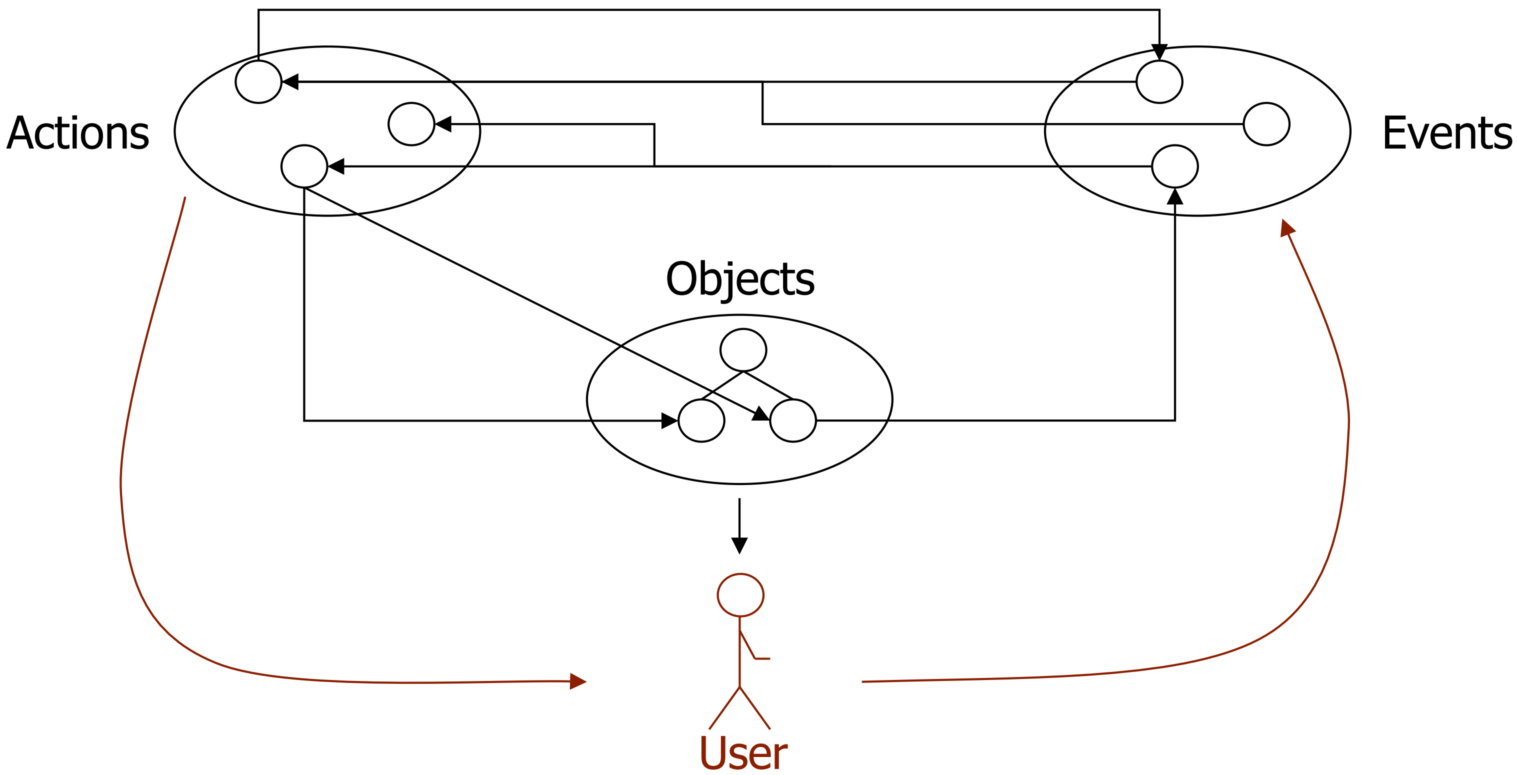


Example from Unreal



A* path finding behavior graph

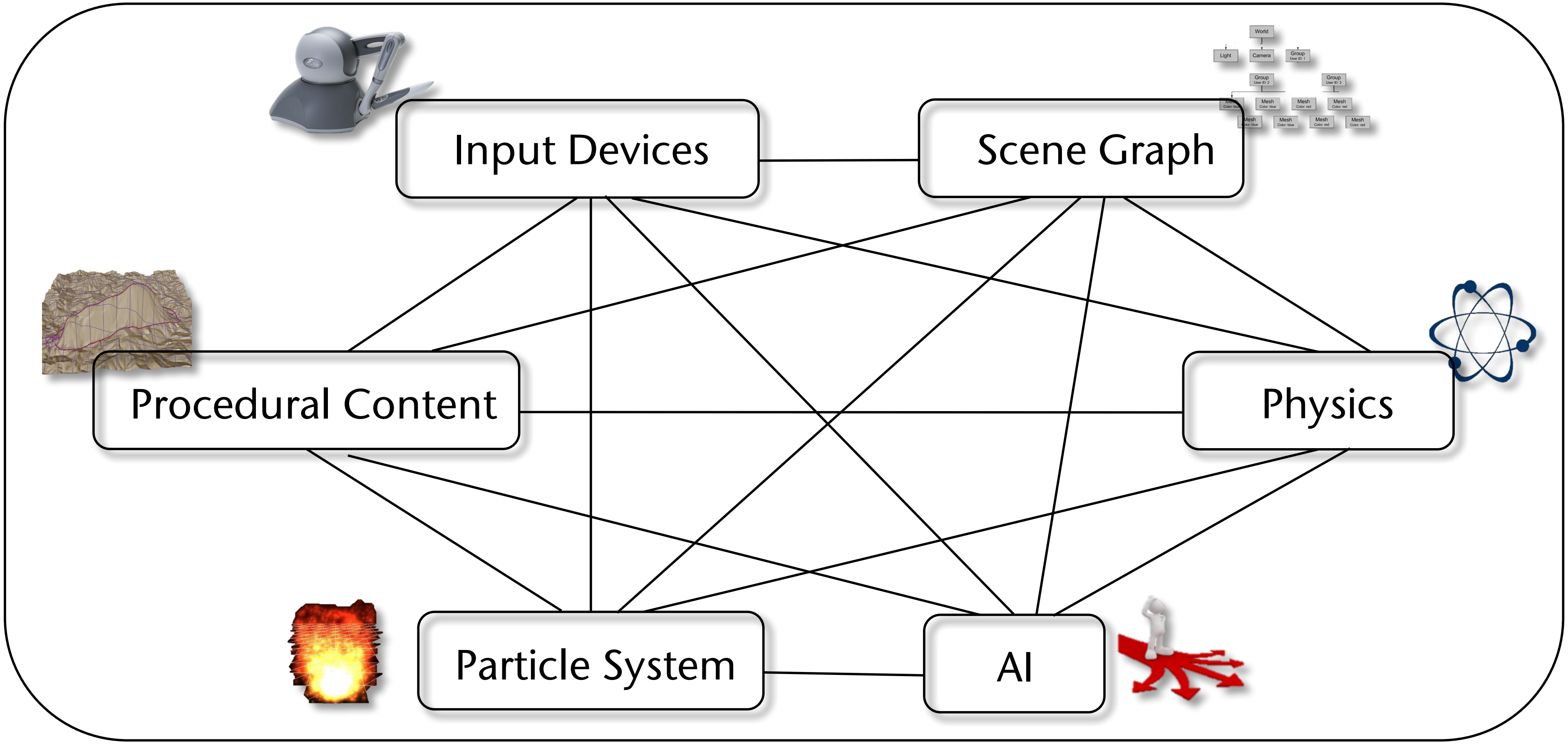
Digression: The AEO-concept



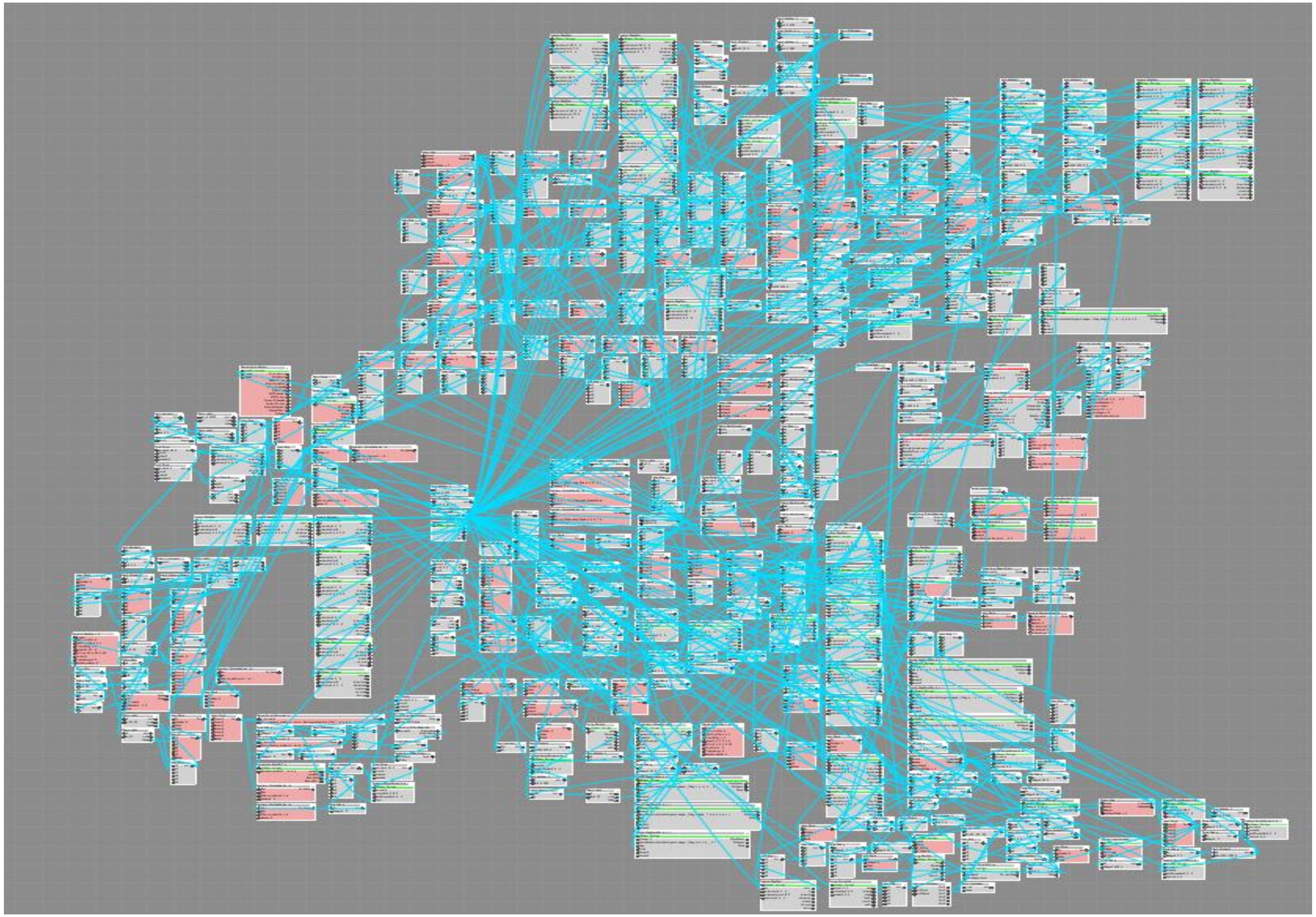
- In X3D/VRML:
  - Actions & objects are all nodes in the same scene graph
  - Events are volatile and have no "tangible" representation

New Concepts for Data Flow in VR/Game Engines

- Modern systems usually consist of many different components
- Classic approach: fields-and-routes-based data flow
- Problem: many-to-many connectivity



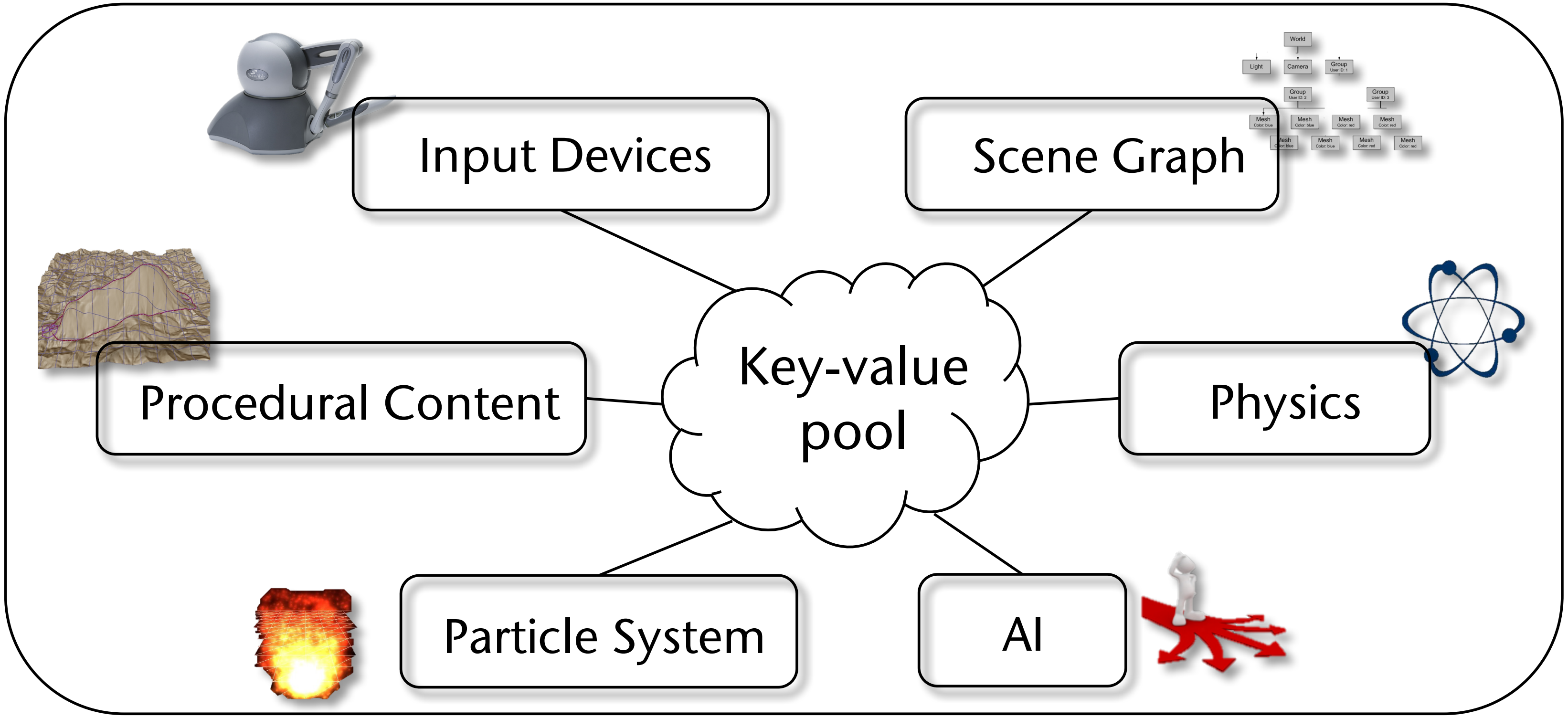
- Quickly becomes inviable



Dynamic Player Movement (CryEninge 3)

Our Novel Approach: the Key-Value Pool

- Assign a unique key to each route (link, connection)
- Producer stores value with key in KV pool ⟶ KV pair
  - Corresponds to generating an event in the data flow paradigm
- Consumer reads value from KV pair every time in its loop
- Set of all KV pairs ⟶ KV pool

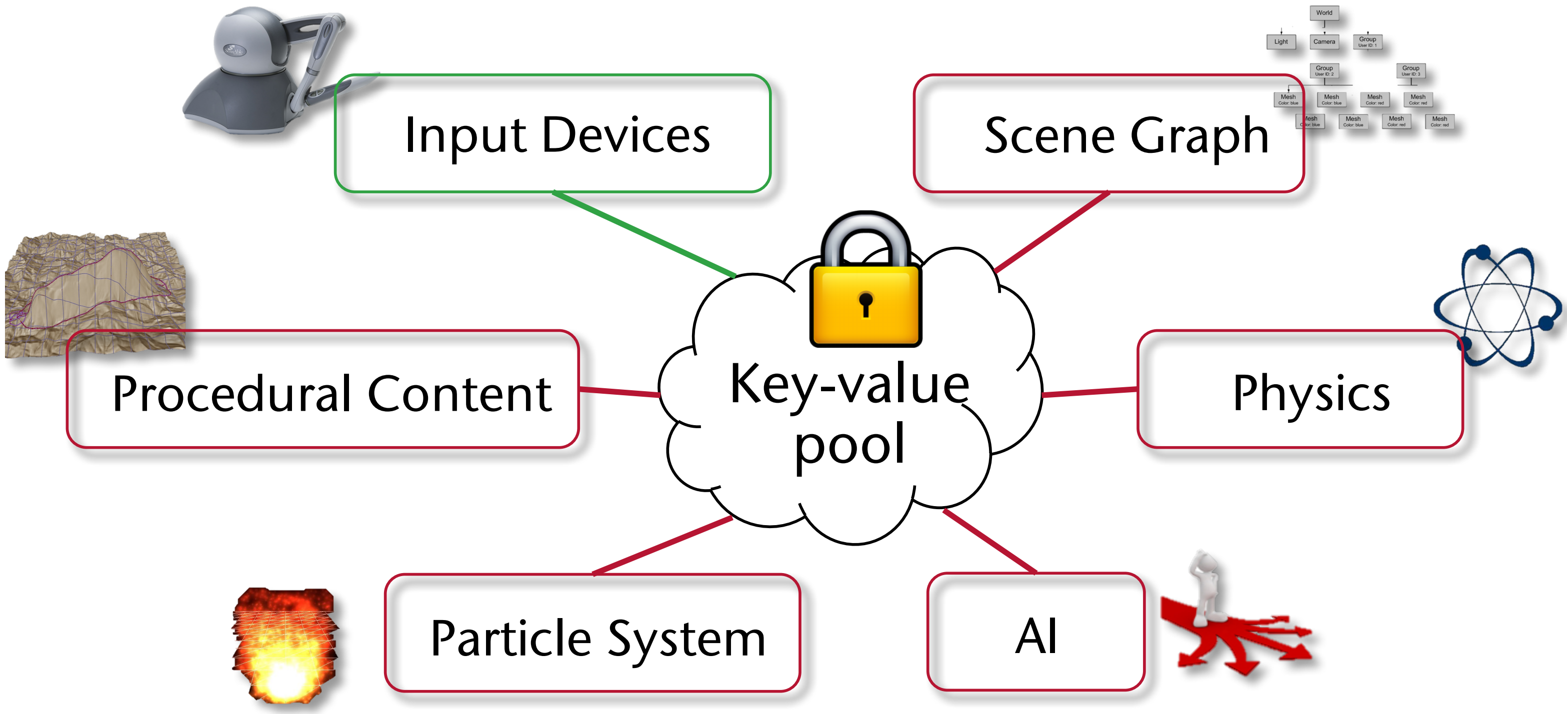


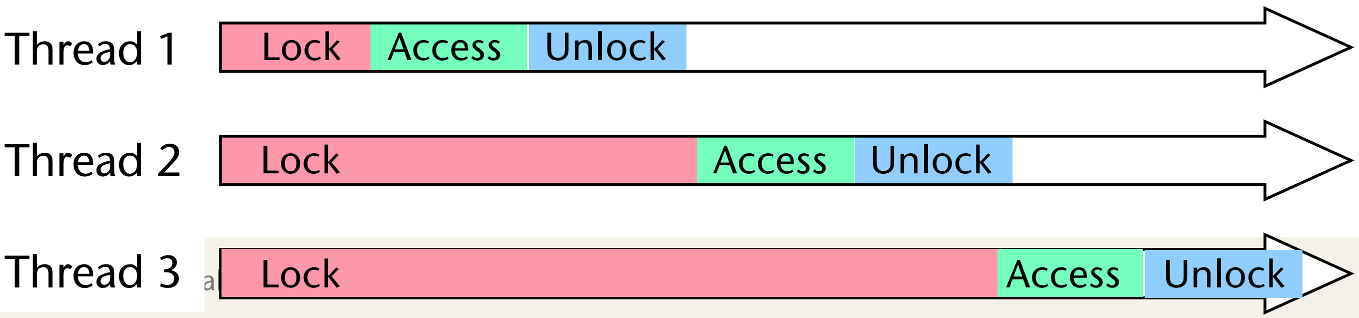
Advantages of the Approach

- KV pool holds complete state of the virtual environment
- Can save/load state, or unwind to earlier state
- One-to-many connections are trivial

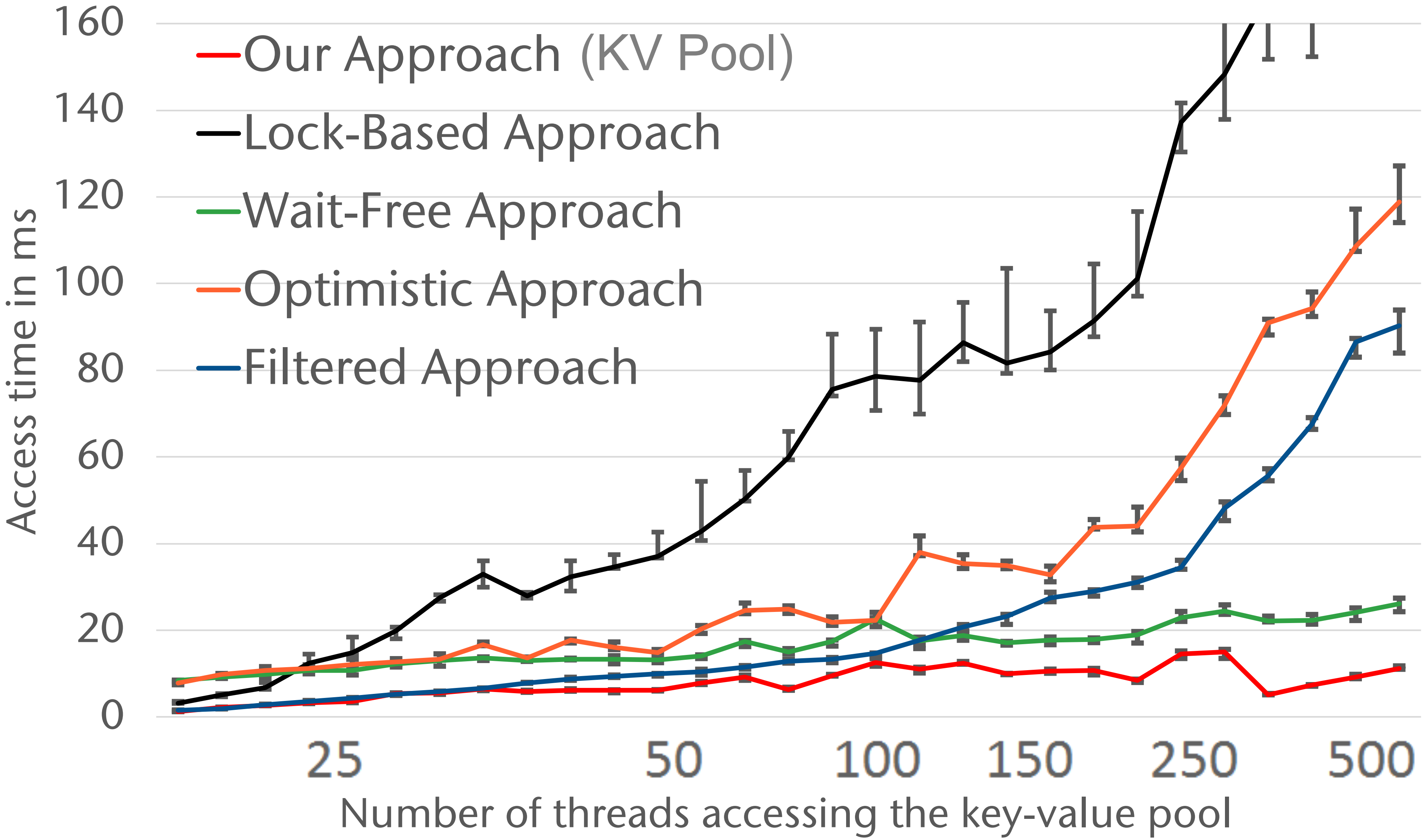
Classic Blocking Data Structures

- One lock per KV pair, or one lock for the whole KV pool ⟶ both have disadvantages ⟶ in any case: lots of waiting





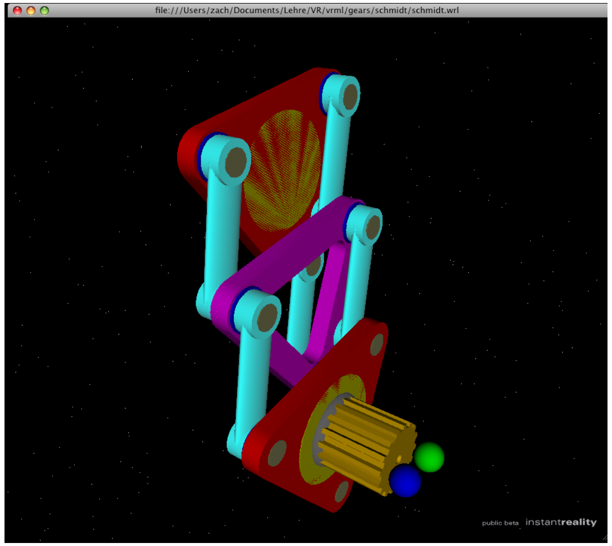
Performance: Read (50%) & Write (50%) Operations

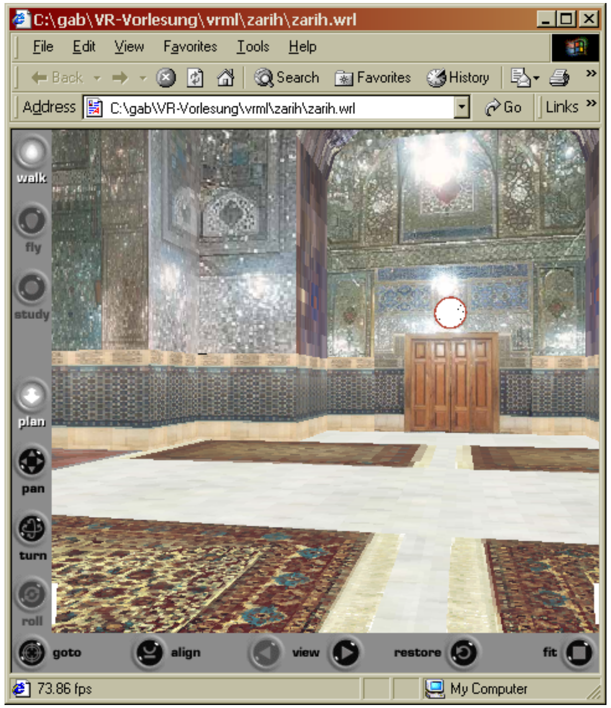


Demos

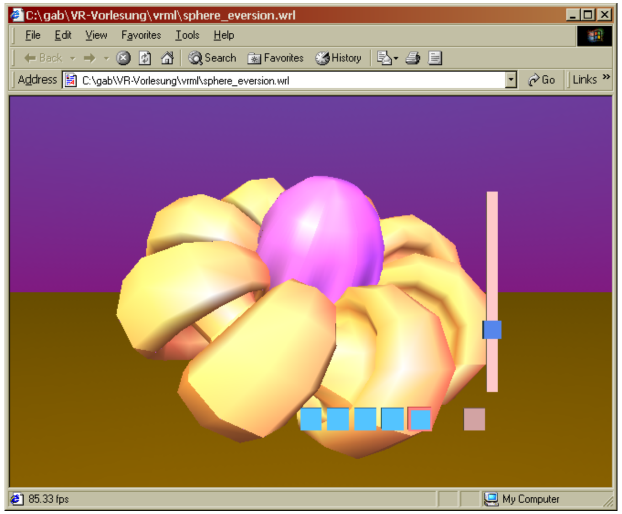
Would somebody be interested in implementing them on Unreal or Javascript? (for Mac)   Credits, credits ☺

Illustration of complicated kinematics (hier: *Schmidt Offset Coupling*)



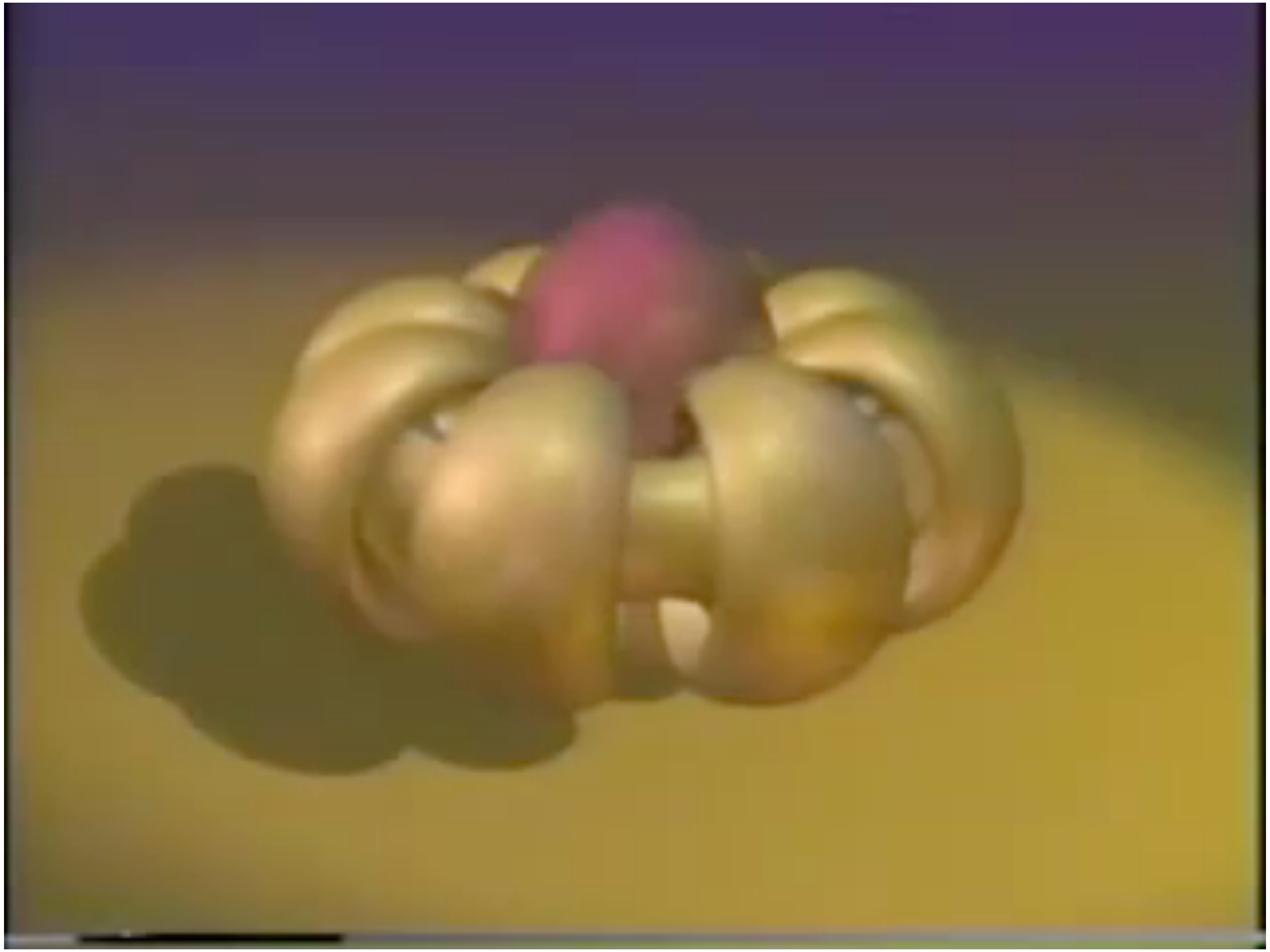


Cultural heritage
(Quelle: www.aqrazavi.org)

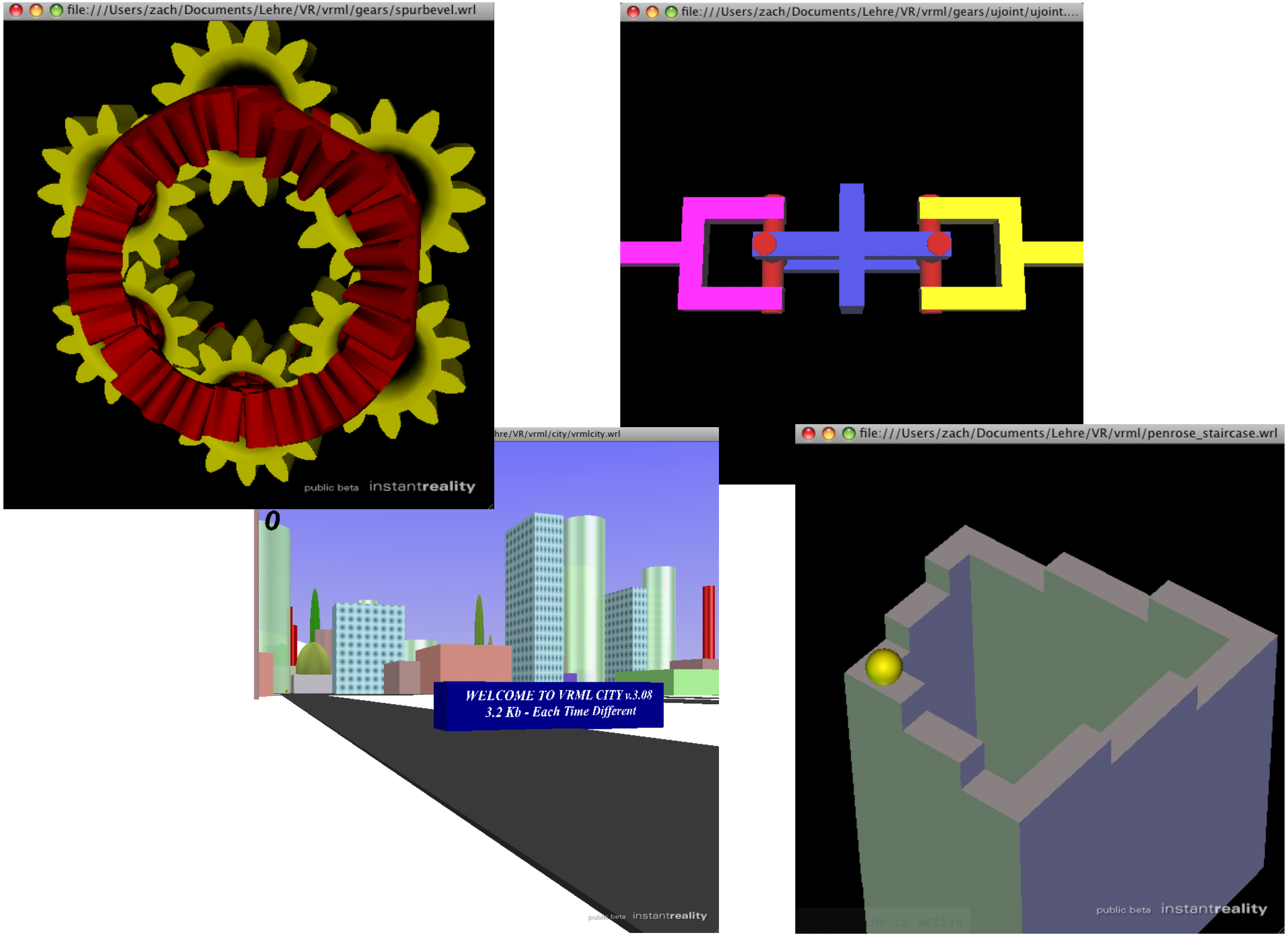


Education
Bsp.: *sphere eversion*

Sphere Eversion (Video)



http://www.youtube.com/watch?v=BVVfs4zKrgk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public beta instantreality
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hre/VR/vrml/city/vrmlcity.wrl
WELCOME TO VRML CITY v.3.08
3.2 Kb - Each Time Different
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