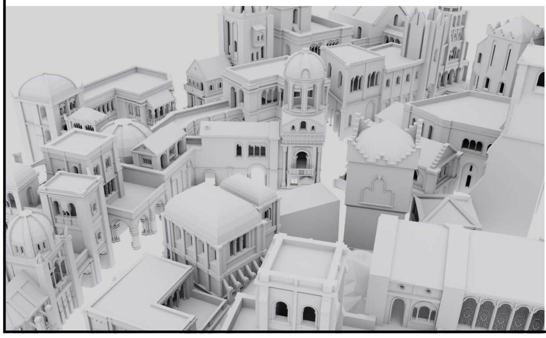
3D video games 2023/2024

the Scene Graph

Marco Tarini



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Course Plan

lec. 1: Introduction ●
lec. 2: Mathematics for 3D Games ●●●●●●
lec. 3: Scene Graph ●
lec. 4: Game 3D Physics ●●●◖ + ◗●
lec. 5: Game Particle Systems ◖
lec. 6: Game 3D Models ◗●
lec. 7: Game Textures ●●
lec. 9: Game Materials ◖
lec. 8: Game 3D Animations ◗●●
lec. 10: Networking for 3D Games ●
lec. 11: 3D Audio for 3D Games ●
lec. 12: Rendering Techniques for 3D Games ●
lec. 13: Artificial Intelligence for 3D Games ●

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Recap:
3D Spatial Transforms

- Math functions
  - input: point / vector / versor
  - output: point / vector / versor

  Thus, can be applied to any 3D thing (apply them to all positions directions etc ...)

- Three components: ... modelling the State / Act of:
  - Scaling — Size / Rescale up (if > 1), down (if <1)
  - Rotation — Orientation / Rotate
  - Translation — Position / Displace

can be "uniform" ("isotropic")
or not ("anisotropic", different factors in X,Y,Z)

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Recap: transformation associated to an object in the scene

- Any object associated to a spatial location in the game is given its transformation, which goes
- From:
  - local space *a.k.a.*
  - object space *a.k.a.*
  - pre-transform space
  - *a.k.a.* «*castle*» space / «*hero*» space / «*camera*» space / «*chainsaw*» space / «*bazooka*» space / etc
- To:
  - global space *a.k.a.*
  - world space *a.k.a.*
  - post-transform space

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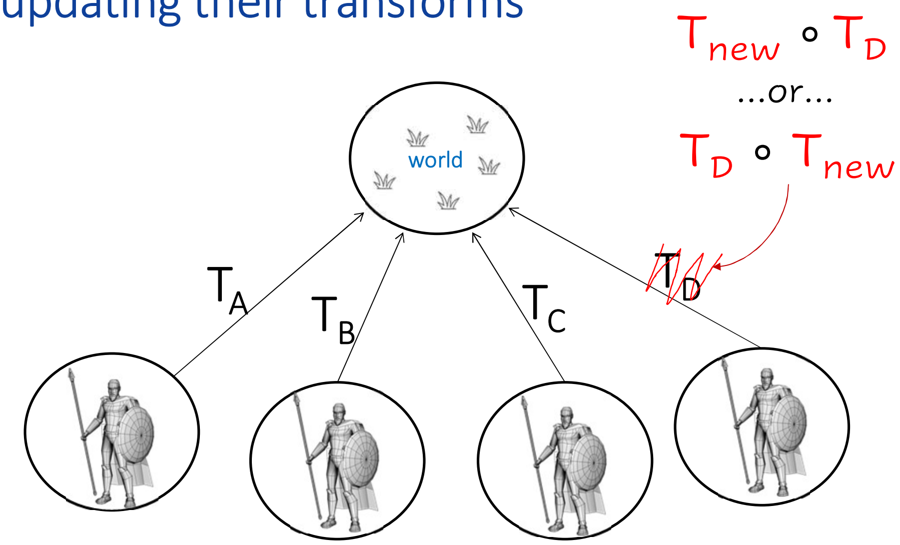
Moving objects around = updating their transforms



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Moving objects: two ways of updating per-object Transforms

- Let T_{new} be a new transformation to be applied to object D (w.r.t. its current placement)
  - Say: **rotation** = ide **scaling** = 1 **translation** = (-2,0,0)
  - T_{new} = "*move two units to the left*" (assuming X = right)
- How to update transformation T_D ? Two ways:
  - $T_D \leftarrow T_D \circ T_{new}$ = object D moves 2 units on its left
  - $T_D \leftarrow T_{new} \circ T_D$ = object D moves 2 units on world's left (meaning, i.e., "*West-ward*")

We call this "applying the new transformation in local space" or "in global space respectively"
E.g., in unity: see parameter "relativeTo" of method Transform.Translate

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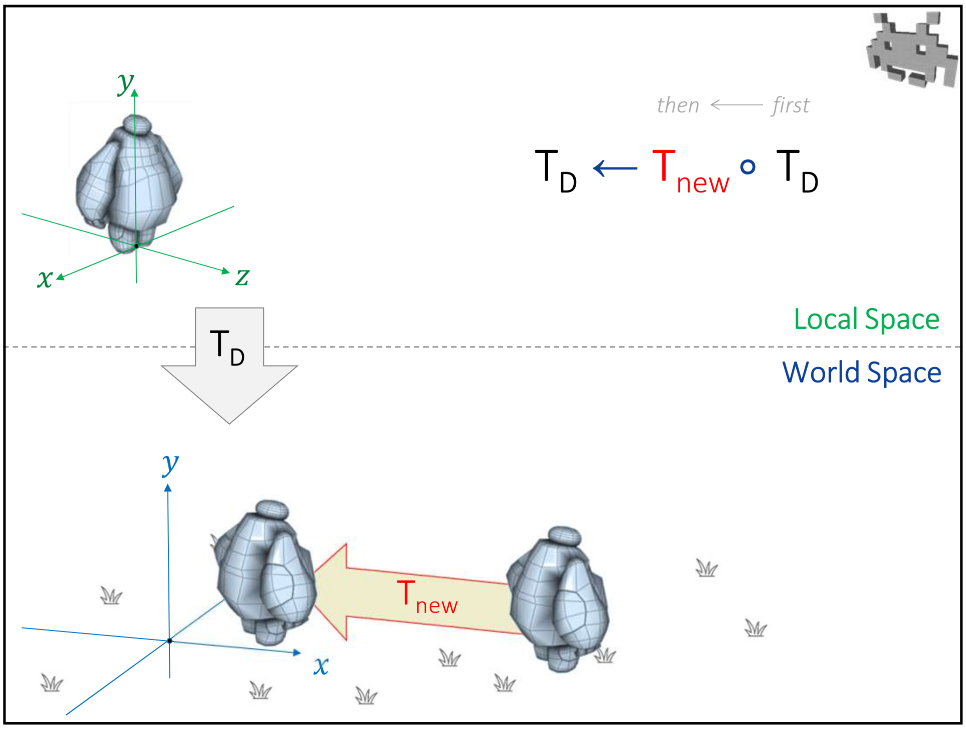
then ⟵ first
$T_D \leftarrow T_{new} \circ T_D$
Local Space
World Space
T_D
T_{new}
y
x
z

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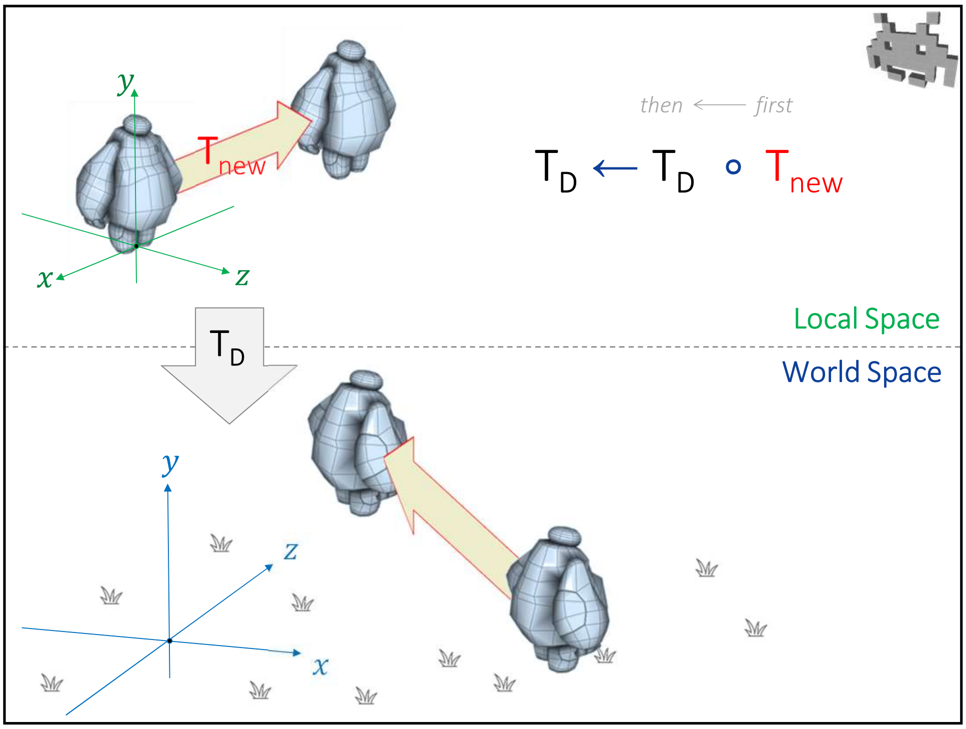
then ⟵ first
$T_D \leftarrow T_D \circ T_{new}$
Local Space
World Space
T_D
T_{new}
y
x
z

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Moving objects: two ways of updating per-object Transforms

- Let T_{new} be a new transformation to be applied to change object D (w.r.t. its current placement)
  - Say: **rotation** = ide **scaling** = 2 **translation** = (0,0,0)
  - T_{new} = *"scale it up by* ×2" (note: volume gets ×8 bigger)
- How to update transformation T_D ? Two ways:
  - $T_D \leftarrow T_D \circ T_{new}$ = object D enlarges from its center
  - $T_D \leftarrow T_{new} \circ T_D$ = object D enlarges from world's center (i.e. moves away from it)

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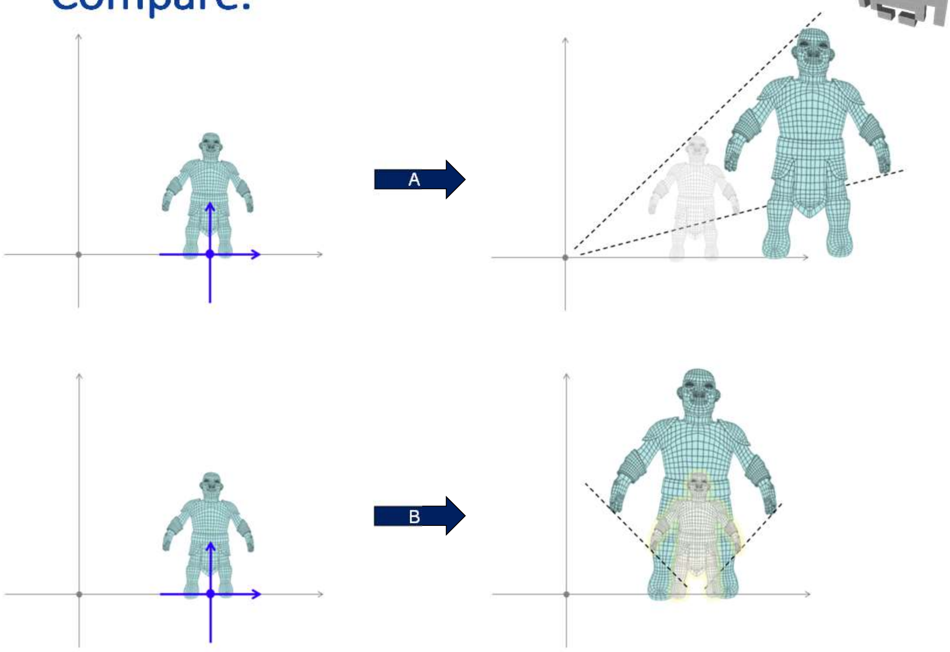
Compare:



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Moving object: two ways of updating per-object Transforms

- Let T_{new} be a new transformation to be applied to change object D (w.r.t. its current placement)
  - Say: rotation = *j* scaling = 1 translation = (0,0,0)
  - T_{new} = *"flip by* 180° *around Up axis"* (assuming Y = up)

- How to update transformation T_D ? Two ways:
  - $T_D \leftarrow T_D \circ T_{new}$ = object D rotates around its up axis (e.g., goes supine-to-prone if was laying down)
  - $T_D \leftarrow T_{new} \circ T_D$ = object D rotates in world's up axis

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Objects in the scene

- Nodes in the scene host any object that is has a position, including...
  - Static Meshes
  - Animated meshes
  - The camera observing the scene
  - 3D GUI elements
  - Spawn points
  - Colliders (hit boxes)
  - Microphones
  - Sound emitters
  - Particle systems (the emitter)
  - Etc
- Each such object has its own associated transform
  - And, therefore, its own local ("object") space
  - The transform goes from local space to world space

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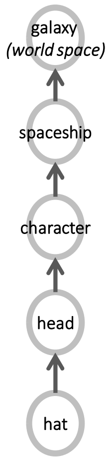
Hierarchical scenes

- So far, we assumed that the transform of each object goes from local to global in one step
- In reality, scenes can be defined hierarchically
- That is, objects have sub-objects in them
  - a «city» is made of «houses» made of «walls» made of «bricks»
  - a «hat» sits on an «head» which is part of a «character» who sits in a «spaceship» moving across the «galaxy»
  - a car is a «hull» plus four «wheels»



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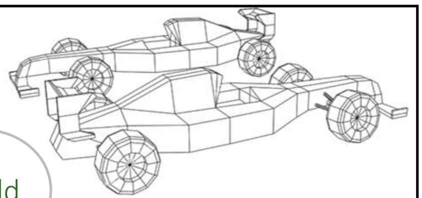
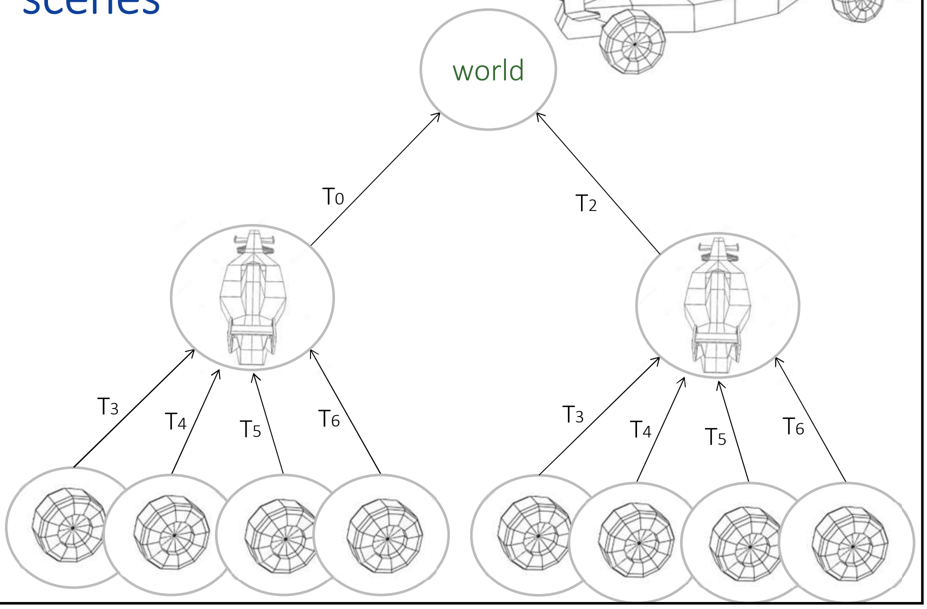
Hierarchical scenes





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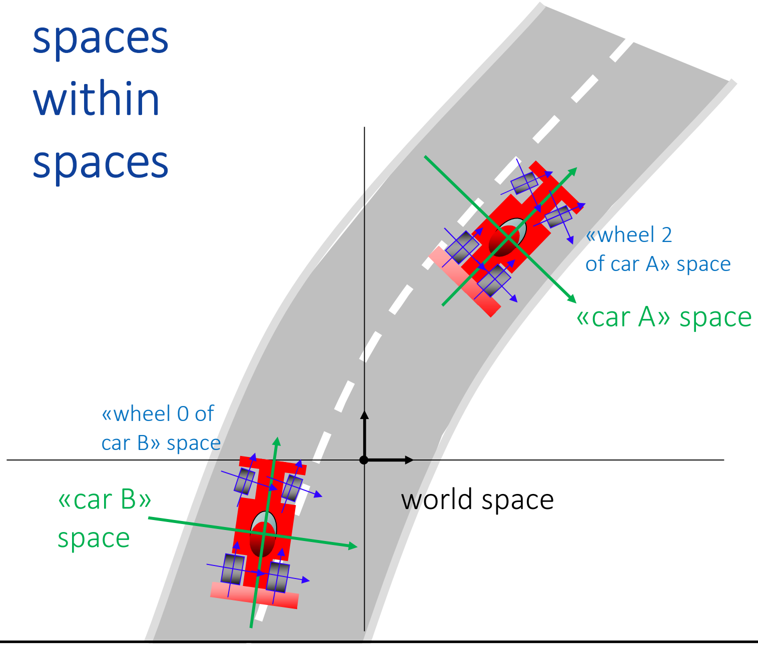
Hierarchical scene: spaces within spaces



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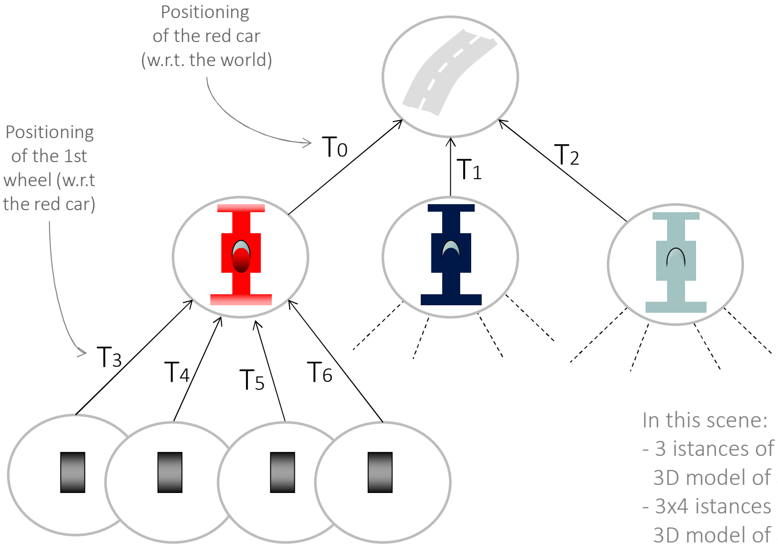
Scene graph



In this scene:
- 3 istances of the same 3D model of a vehicle
- 3x4 istances of a same 3D model of a wheel

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Scene graph

A tree (i.e. a hierarchical structure)

- Each nodes has its own space (a reference frame)
  - The Local Space of that node
- To each node we associate:
  - Instances to… stuff:
    anything at all that has a place in the virtual scene:
  - 3D models, lights, cameras, virtual microphones
    spawn points, explosions, etc
- Root node: world space
  - Global Space = local space of the root
- To each arch: we associate the "local" transform
  - the transform going from the local space of the child node
    to the local space of the parent node

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Local VS Global Transformations

- Local transform (a.k.a. «relative» transform)
  - from: the local space of a node
    to: the local space of its parent
  - Stored per object!
- Global transform (a.k.a. «absolute» transform)
  - from the local space of a node
    to the world space
    (which the "local" space of the root)
  - Procedurally obtained/defined by:
    cumulating all local transforms from node to root
- benefit: changing the transform associated to a node affects its entire subtree

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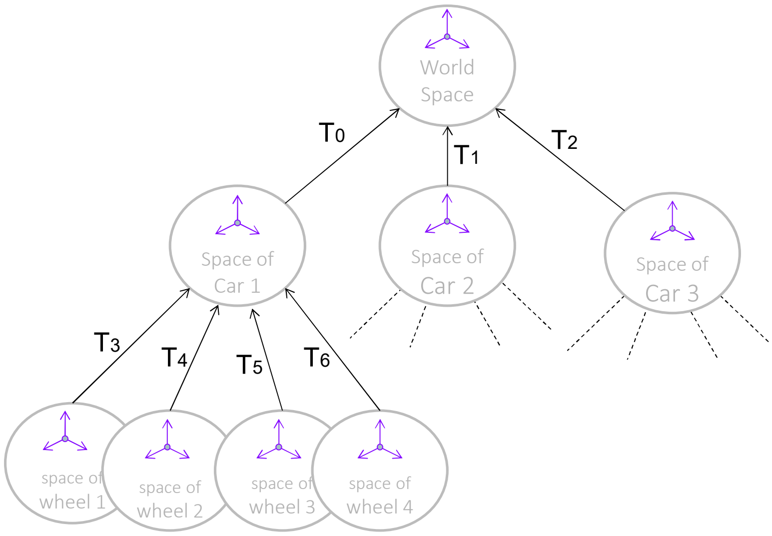
Scene graph



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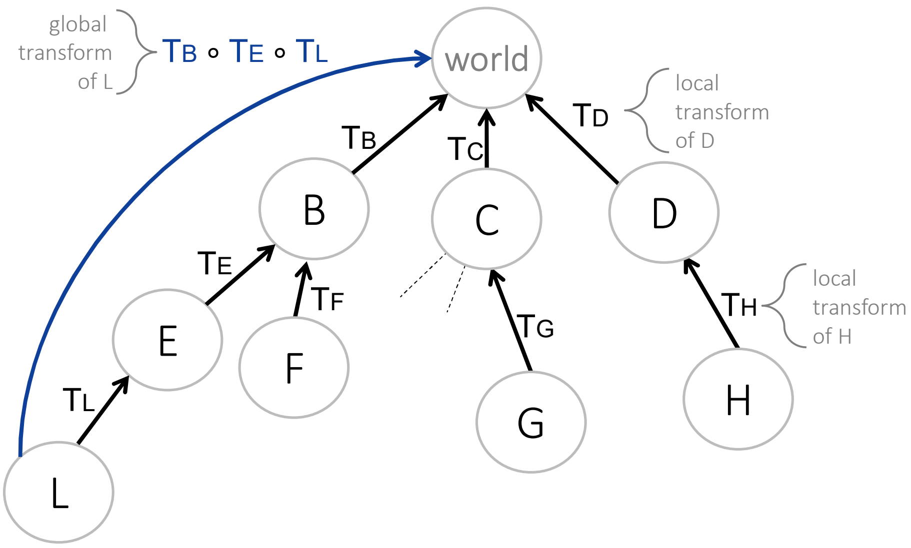
Local VS Global Transforms



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Changing a node positioning… *in local space* (refer the schema in prev slide)

- Say T is the transform consisting of moving an object 2 units on the X
  - T = { Scale = 1, Rotation = ide, Translation = (0,0,2) }

transform expressing an action on L

- Task:
  - we want node **L** to undergo transform T in local space.
  - Meaning: we want **L** to be moved 2 units (its *own* units) in the direction of its right (assuming Unity axis conventions)
  - How do we do it?

$$T_L \leftarrow T_L \circ T$$

(make sure you understand why!)

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Changing a node positioning… *in global space* (refer the schema in the prev slide)

- Say T is the transform consisting of moving an object 2 units on the X
  - T = { Scale = 1, Rotation = ide, Translation = (0,0,2) }

transform expressing an action on L

- Task:
  - We want node **L** to undergo transform T in global space.
  - Meaning: we want **L** to be moved 2 units (*world* units) in the East direction (if that's how global ref. frame works)
  - Note: we can only change its local transformation (because we only want to affect node L)

$$T_L \leftarrow T_L'$$

  - How to the new value T_L' ?

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Changing a node positioning… *in global space* - solution

- *Global transform* of L before the change:

$$\mathrm{T_B} \circ \mathrm{T_E} \circ \mathrm{T_L}$$

- The *Global transform* of L which we want (after the change):

$$\mathrm{T} \circ \mathrm{T_B} \circ \mathrm{T_E} \circ \mathrm{T_L}$$

- The *Global transform* of L which we have (after the change):

$$\mathrm{T_B} \circ \mathrm{T_E} \circ \mathrm{T'_L}$$

- Matching them

$$\mathrm{T} \circ \mathrm{T_B} \circ \mathrm{T_E} \circ \mathrm{T_L} = \mathrm{T_B} \circ \mathrm{T_E} \circ \mathrm{T'_L}$$

- Doing the math…

$$\mathrm{T'_L} = \underbrace{\mathrm{T_E^{-1}} \circ \mathrm{T_B^{-1}} \circ \mathrm{T} \circ \mathrm{T_B} \circ \mathrm{T_E}} \circ \mathrm{T_L}$$

therefore, this is the transformation
applied to the local transform of node L
to make T happen in global space to node L

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Changing a node positioning… *in global space* - solution

$$\mathrm{T'_L} = \underbrace{\mathrm{T_E^{-1}} \circ \mathrm{T_B^{-1}}} \circ \mathrm{T} \circ \underbrace{\mathrm{T_B} \circ \mathrm{T_E}} \circ \mathrm{T_L}$$

Inverse of the
global transform
of E
(the parent of L)

the
global transform
of E
(the parent of L)

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Assigning a new positioning… *in global space* (refer the prev schema in slide 26)

- Say T is a transform describing a new global positioning we want for object L in world space
  - T = { scale: (global) sizing of L,
    rotation: (global) orientation of L,
    translation: (global) position of L } — transform expressing the state of L
- How to replace its local transformation T_L ,
  so that its global transformation becomes T?

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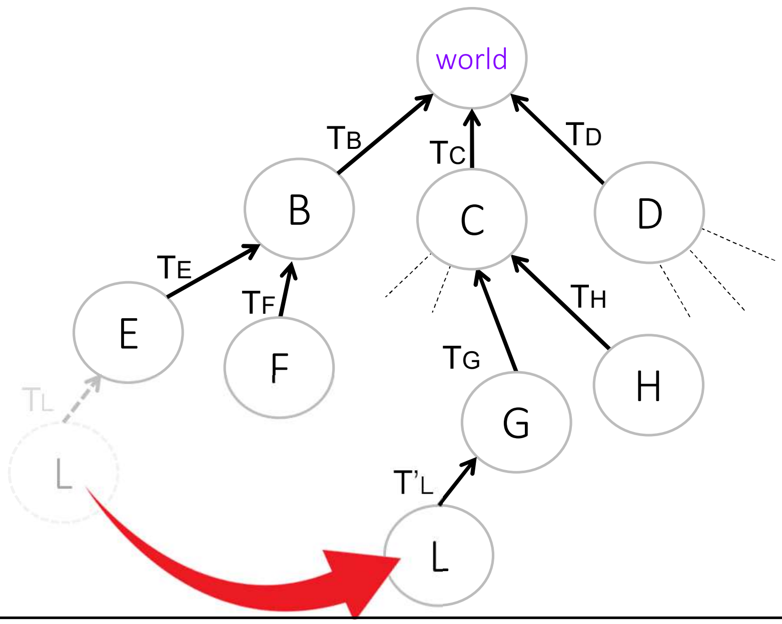
Changing the hierarchy



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Changing the hierarchy... *without* changing the position

- Event:
  - In the above example, node L is detached from its parent (E), and becomes a child of the node G
  - (this means that, from now on, its positioning won't be affected by movement of E or of B : L it is no longer a part of the same compound object, it detached)
  - In that moment, we don't want (the content of the) node L to change its world positioning (pos, orientation...).
  - That is, Global transformation of L must stay constant
- Question:
  - How to achieve this result by reassign its associated local transform T_L (which is the only thing we store for L)?

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Changing the hierarchy... *without* changing the position

- The local tranform $\mathrm{T_L}$ stored for L is substituted by some new local transformation $\mathrm{T'_L}$:
  $$\mathrm{T_L} \leftarrow \mathrm{T'_L}$$
  the problem is then to find this $\mathrm{T'_L}$
- *Global transform* of node L *before* the change:
  $$\mathrm{T_B} \circ \mathrm{T_E} \circ \mathrm{T_L}$$
- *Global transform* of node L *after* the change:
  $$\mathrm{T_C} \circ \mathrm{T_G} \circ \mathrm{T'_L}$$
- They must be the same, so (doing the math!)...
  $$\mathrm{T'_L} = \mathrm{T_G^{-1}} \circ \mathrm{T_C^{-1}} \circ \mathrm{T_B} \circ \mathrm{T_E} \circ \mathrm{T_L}$$

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Changing the hierarchy… *without* changing the position

- The math:

$$T_B \circ T_E \circ T_L = T_C \circ T_G \circ T'_L$$

composite both sides with T_C^{-1} on the left…

$$T_C^{-1} \circ T_B \circ T_E \circ T_L = \cancel{T_C^{-1}} \circ \cancel{T_C} \circ T_G \circ T'_L$$

composite both sides with T_G^{-1} on the left…

$$T_G^{-1} \circ T_C^{-1} \circ T_B \circ T_E \circ T_L = \cancel{T_G^{-1}} \circ \cancel{T_G} \circ T'_L$$

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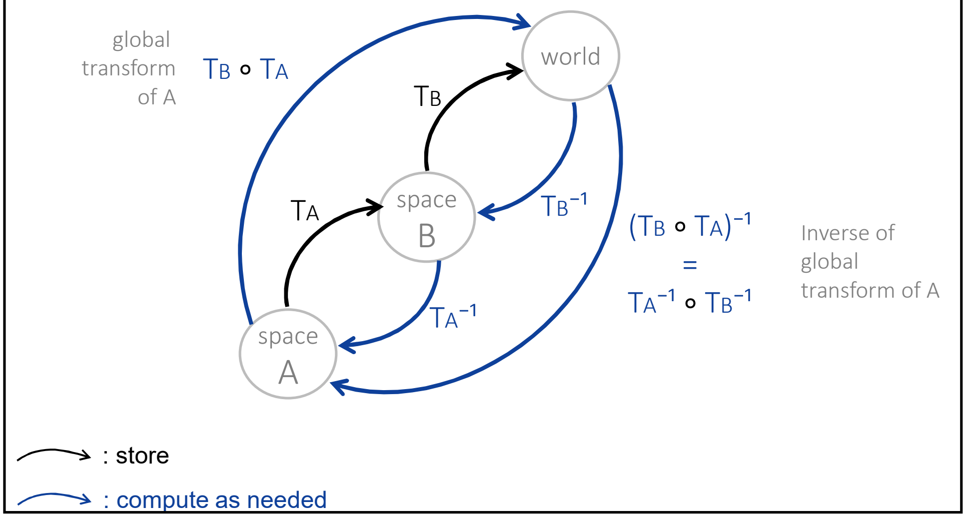
Reminder: inverse of a composite transform (or, in general, function)



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Reminder: inverse of a composite transform (or, in general, function)

$$(T_B \circ T_A)^{-1} = T_A^{-1} \circ T_B^{-1}$$

- The inverse of “first Ta then Tb” is “the inverse of Tb” followed by “the inverse of Ta”
- As it’s natural! If you…
  - “take a step *forward*, *then,* turn by 90° *clockwise*”

  …then, to go back to the starting pos, you need to…
  - “turn by 90° *counter-clockwise*, *then*, take a step *backward*”

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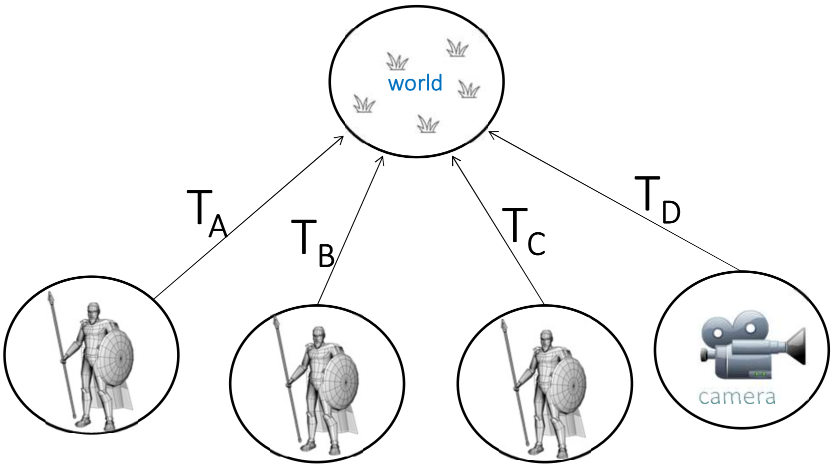
The camera in the scene graph



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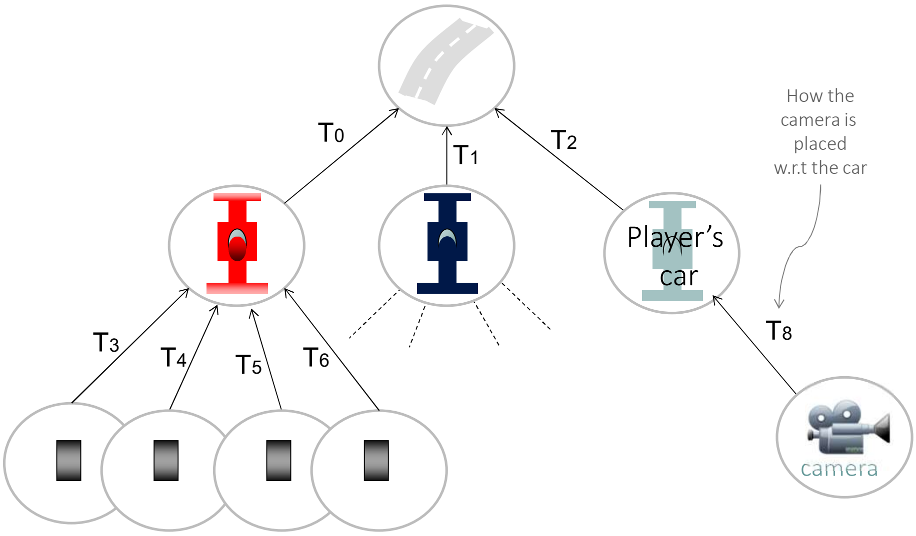
The camera is in the scene graph

E.g.: to make the camera follow the car…



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The camera in the scene

- The camera node is particularly important for the rendering (of course)
- The inverse of its associated global transform goes from Camera space (or View Space)…
  - (where the camera is in the origin, looks toward Z (or minus Z in some systems) etc.)
  - (its a space where the rendering is convenient to do)

  …to World Space
- In Computer Graphics, the *inverse* of global transform of the camera is called the View Transforms

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Transforms for the Graphics engine (link to Computer Graphics course)

- In a rendering engine, there are a few standard transformations useful to render an object
- They are named:
  - "Model" matrix: from object space to world space
    - Captures how the scene is modelled (by a scener)
    - It's what we call "global" transformation
    - "matrix" only because trasnforms are usually encoded as 4x4 matrices by Rendering engines & graphics APIs
  - "View" matrix: from world space to view space
    - Captures how the scene is viewed (by the camera)
  - "Model-View" matrix: from object space to view space
- Computing them from the scene graph is easy!

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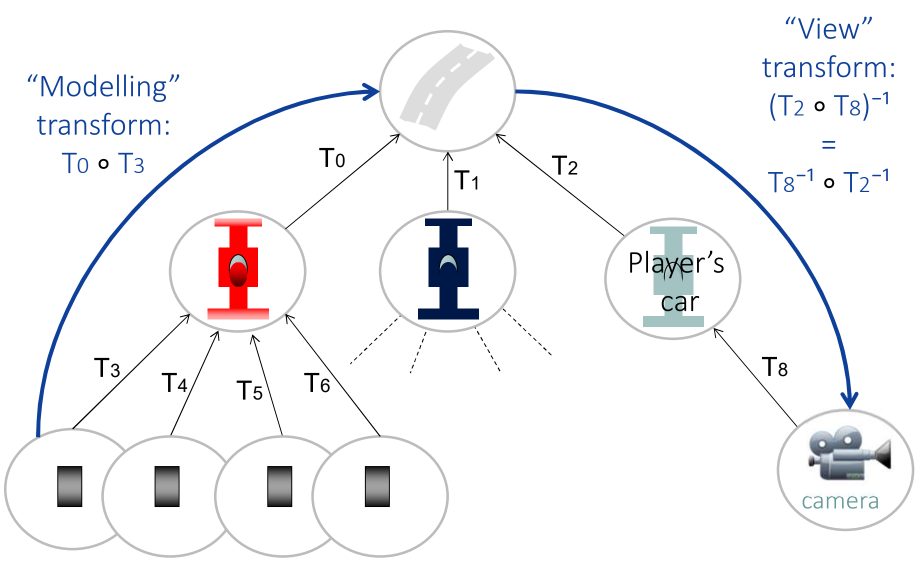
Transforms for the Graphics engine



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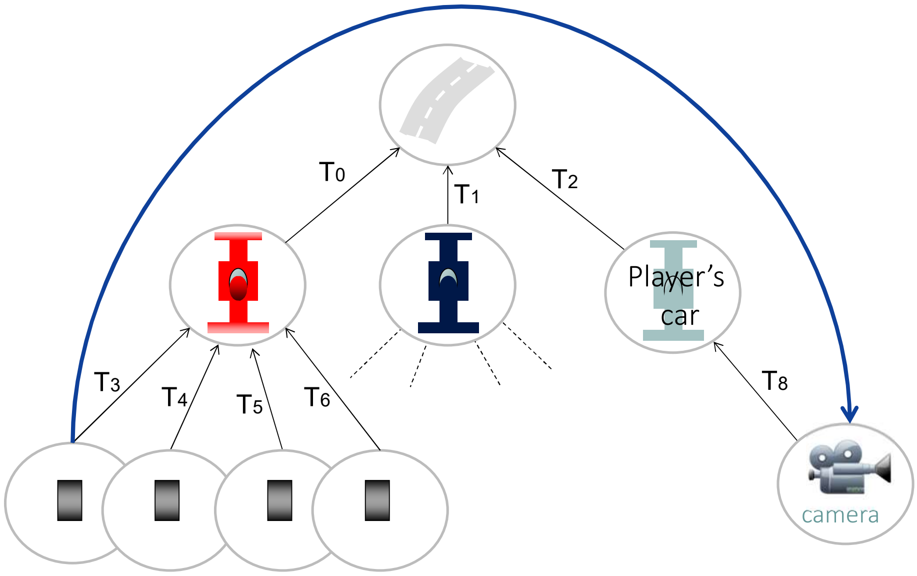
Transforms for the Graphics engine

"Model-View" transform: $T_8^{-1} \circ T_2^{-1} \circ T_0 \circ T_3$



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The camera in the scene graph

- Camera:
  - Like any other object in the scene, the camera sits in a node the scene-graph
  - for the scene to be rendered, there must be a camera somewhere in the graph!
  - View Space = Local Space of the camera
  - (Screen Space is a similar, and sometimes equivalent, concept)
- the View Space is convenient to perform the rendering
  - Because, in view space, coordinates describe where things are w.r.t. the camera!
  - For example: $z > 0 \Rightarrow$ object in front of the camera,
    $z<0 \Rightarrow$ object behind the camera (don't render)
- Camera animations = move camera
  - by doing anything that changes its global transformation
  - e.g., a script changing its local transform… or the one of its parent!

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Changing a node positioning… *in view-space* (refer the schema in the prev page)

- Say T is (again) the transform consisting of moving an object 2 units on the X
- Assume the camera is in node H
- Event:
  - We want node L to undergo transform T in view space.
  - Meaning: we want L to be moved 2 units (camera space units) on the right of the screen
  - This is useful e.g. from a GUI point of view. Move an object as dragged by a mouse
  - Note: we still can only change its local transforamtion:

$$\mathrm{T_L} \leftarrow \mathrm{T'_L}$$

  - Task: find $\mathrm{T'_L}$

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Changing a node positioning… *in view-space* : solution

- *View-space positioning* of L before the event:

$$\underbrace{\mathrm{T_H^{-1}} \circ \mathrm{T_C^{-1}} \circ \mathrm{T_B} \circ \mathrm{T_E}}_{\mathrm{V_L}} \circ \mathrm{T_L} = \mathrm{V_L} \circ \mathrm{T_L}$$

$\mathrm{V_L}$ Model-View transform of L

- *After the event,* we want it to be:

$$\mathrm{T} \circ \mathrm{V_L} \circ \mathrm{T_L}$$

- *After the event,* it will be:

$$\mathrm{V_L} \circ \mathrm{T'_L}$$

- Matching them:

$$\mathrm{T'_L} = \mathrm{V_L^{-1}} \circ \mathrm{T} \circ \mathrm{V_L} \circ \mathrm{T_L}$$

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Summary

- Thanks to the ability to efficiently compute compositions and inverses of transformations…
- …we can store only the local transform of every node (from its local space to its parent space), and dynamically get
  - the global transform (from its local space to world space),
  - the model-view transform (from its local space to camera space)
  - or actually any transform from a local-space of any node A to the space of any other node B in the graph

  (these transforms represent positioning of B w.r.t A)

  transforms considered as **states**
- …we can apply
  - any new transform T
  - to move to any node X in the graph
  - in the space of *any other node* Y (e.g., in world space, in local space, in view space, or actually in the space of another node)

  acting only on the local transformation of X
  - Which can still the only thing we store at the nodes

  transforms considered as **actions**

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Spaces (where to compute stuff)

- Anything that requires the computation from 3D stuff (versor,vectors,points)…
  - E.g. see "geometry problems" in past lecture ("does the guard see the fly?" etc)
  - E.g.: lighting computation!
- …must use versors/vectors/points expressed *in the same space*!
  - Any node of the graph can be chosen for this… (among other choices)
  - All elements must be brought to the space of this node
  - Some choices can be more convenient than others
- Examples:
  - Physics simulation, collision detection: world space
  - Lighting computation: Object space? World space? View space?

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Exercises (refer the the schema in slide 31)

- Report the *global transform* of node L
- I place a camera in node H:
  report the View Transform for this scene
- Say T is a transformation that translates by (0,2,0)
- How do you apply T to L …
  1. in L Space (the local space of L)?
  2. in World space?
  3. in View Space?

  (that is, which of the stored transformations changes, and how)
- Find the origin of space E in space H, and viceversa
- A microfone is in (the origin of) node E, and a speaker is in (the origin of) node H. Find the distance from the mic to the speaker

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Authoring a 3D scene in a game

- E.g. as a part of the Level Design
- Two different parts, by different artists:
  - 3D modellers make «scene props»
    - the 3D models to be assembled
    - (including their texutres etc)
  - sceners compose the scene
    - they assemble the props into a Scene Graph

= asset

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Scene Graph as a data structure: Mechanisms for shared subtrees

- The scene-graph will often contain multiple copies of shared subtrees
  - Existing implementation implement shared subtrees in different ways
  - In Unity: see "Prefabs"
  - In Unreal: see "BluePrints"

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Rendering composite scenes: multi-instancing

- Each node contains a reference (e.g. pointer, or index) to one 3D object (e.g. a 3D mesh, etc) model
  - E.g. all wheels of all cars are the same "wheel" model
- Different *instances* of the same object can appear in multiple locations of the scene
  - E.g. all wheels of all cars are the same "wheel" model
  - Advantage:
    only one 3D model in RAM,
    but many identical 3D models on the screen
  - Each model is associated to a different transform, plus other data, e.g. different "materials"

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Nodes of a scene-graph in unity GameObjects & Transforms

A node = a GameObject with

- a transform field, containing
  - its local transform
  - links to Parent, Children (and siblings) – which are "transforms"
- any number of associated "components", which represent anything residing in that node, like
  - Meshes (to display at this nodes)
  - Cameras: active one(s) produces the rendering(s)
  - "RigidBodies": objects controlled by the physics (see physics)
  - "Colliders": geomtry proxies used for collisions (see physics)
  - "Particle systems" : (i.e. the "emitters" of particles)
  - Sound producers / receivers
  - Scripts …

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Nodes of a scene-graph in unity GameObjects & Transforms

- The Transformation actually stores the local transf:
  - **`localPosition`**, **`localRotation`**, **`localScale`**
  - goes from a node to its parent
- the Global transformation can be accessed via the *properties*: ← it feels like assigning / reading a field, it actually means invoking setters/getters (C# trick)
  - **`position`**, **`rotation`**, **`scale`** ("global" is left implicit)
  - what does getting / setting them really do? (exercise)
  - this it doesn't always work for "scale": ~~`scale`~~ lossyScale (read only)
    Why? (A: it's because anisotropic scaling)

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Digression on unity properties and components

- In C#, a *property* has a syntax making it look like a field (you can read or assign it) but it's actually *getter* and *setter* methods
  - `obj.xx = 3` …*means*… `obj.set_xx( 3 )`
  - `foo = obj.xx` …*means*… `foo = obj.get_xx()`
- In Unity, a *component* is a generic something attached to a GameObject
  -
    ```
    GameObject g;
    g.getComponent< type >()
    ```
    returns component of required type (if it exists)

nodes in the scenegraph

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Nodes of a scene-graph in UNREAL ENGINE USceneComponent

A node within a graph with:

- link to parent / children:
  - getParentComponents
  - getChildComponent(index)
- stuff associated to a node: UPrimitiveComponent (subclass)
  - models, physical bodies, etc
- Local Transform: (fields)
  - RelativeLocation , RelativeRotation, RelativeScale
- Global Transform: (methods)
  - GetComponentTransform() /* return transformation */

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