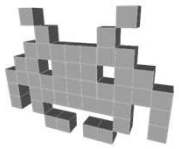
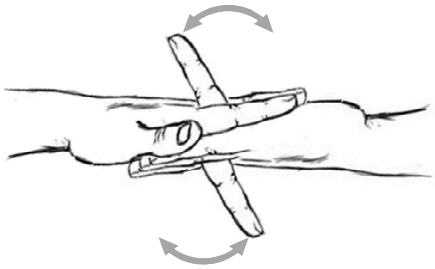
3D VideoGames
Unimi

Animations in games



Marco Tarini



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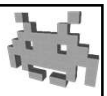
Course Plan



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 **Materials**
lec. 8: Game **Textures**
lec. 9: Game **3D Animations**
lec. 10: **3D Audio** for 3D Games
lec. 11: **Networking** for 3D Games
lec. 12: **Interactive Agents** for 3D Games
lec. 13: **Rendering Techniques** for 3D Games

★ ★
computer animation

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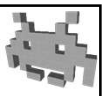
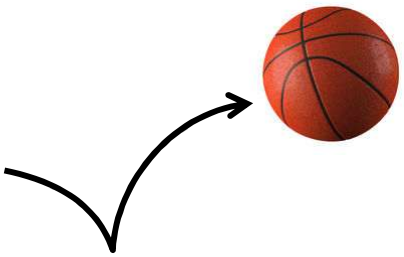
Computer animation in games



1. of rigid objects



(6 DoF per object)

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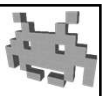
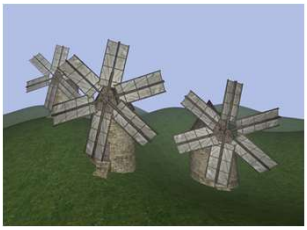
Computer animation in games



1. of rigid objects
   - or rigid sub-parts of complex objects



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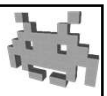
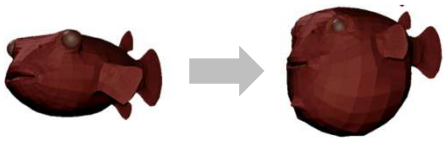
Computer animation in games



2. Free-Form deformations
   - of soft bodies



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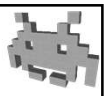
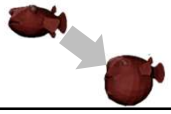
Types of animation and DoF (per keyframe)

DoF = Degrees of Freedom



Rigid 	6 DoF per object (or, e.g., 9, with anisotropic scaling)
Articulated 	~50-100 DoF per object (e.g. 1-3 DoF per joint x 25 joints)
Free form 	300-10.000 DoF per object (e.g. 3 per-vertex)

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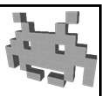
Computer animation in games



3. of articulated models
   - mixed case: bodies that are partially rigid, but with parts that bend
   - internal skeleton assumed
   - most virtual characters!

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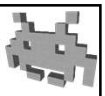
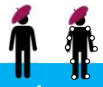
Animations in games





Authored

- Assets!
- Control: easy.
  full control by artists
  (e.g. for dramatic effect)
- Realism: hard
  it's up to the artist skill
- Flexibility: little
  Doesn't adapt to env.
- (consumes RAM)

Procedural

- Physic engine
- Control: hard
- Realism: easy
  built-in physical laws
- Flexibility: great
  Adapts to env. / context
- (consumes GPU)

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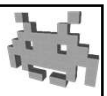
A digression on terminology (in video-game parlance)



Depending on the context, the *opposite* of "procedural", can be…

- baked :
  'pre-cooked', 'computed-then-stored', 'frozen' into an asset,
  (when something is procedurally generated);
  as opposed to : the game engine produces it on-the-fly/on-demand
- asset :
  stored as an asset (irrespective of origin),
  i.e., read by the game engine from the disk (or streamed from web);
  as opposed to : the game engine produces it on the fly/on-demand
- scripted :
  computed by a (*simple!*) script
  the procedure to create something can well be a script!
  as opposed to : produced by a full-fledged, complex simulation
- authored / manually designed / manually edited :
  made by a digital artist (*as opposed to:* by a program)
- (fully) simulated :
  output of a (*complex!*) simulation (*as opposed to:* by a simple one)
  e.g. "this anim. is just procedural, is not a real physical simulation"

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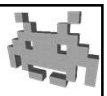
Types of authored animations



- of objects made of rigid subparts
  - including joints: robots, cars…
  - → use "(forward) kinematics" animations
    (scripted changes of the modelling transforms
    in a scene graph)

  ← as we know

- of deformable articulated objects
  - with some internal skeleton
  - e.g.: most virtual characters:
    humans / animals / monsters
  - → use "skinning" / "rigging"

  ← see in 2 lectures

- of generic deformable objects ("soft bodies")
  - e.g., human faces making expressions, an umbrella opening,
    a pufferfish puffing
  - → use "blend shapes"

  ← next lecture!

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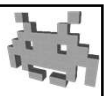
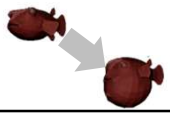
Animations in games



	Non-Procedural (ASSETS)	Procedural (PHYSIC ENGINE / ETC)	
Rigid 	Kinematic Animations	Rigid body dynamics	
Articulated 	Skeletal Animations	Ragdolling	Inverse kinematics
Free form 	Blend-Shapes	~~(general) soft-body simulation~~ *usually too expensive*	Cloth/ garments Ropes

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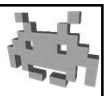
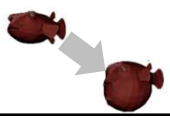
Keyframes and in-betweens



	Non Procedural (ASSETS)	Procedural (PHYSIC ENGINE / ETC)
Rigid 	stored Keyframes + generated in-betweens	
Articulated 	stored Keyframes + generated in-betweens	
Free form 	stored Keyframes + generated in-betweens	

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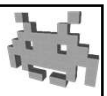
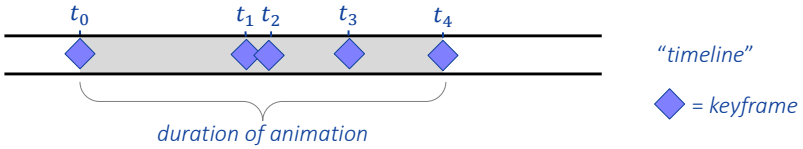
Keyframes and in-betweens: concept
(applies to *all kinds* of scripted animations)



- The animation asset stores only a subset of the frames ("key"-frames)
  - each with its own associated *time*



- Other frames ("in-betweens") are interpolated keyframes
  - 👍 saves storage RAM (only keyframes are stored)
  - 👍 saves artist work (only keyframes are constructed)
  - 👍 animation can very smooth (avoids temporal aliasing) e.g., even when played at extreme slow-motion
  - this implies the ability to *interpolate* key-frames!

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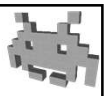
Keyframes and in-betweens: concept
(they apply to *all kinds* of scripted animations)



the "temporal resolution" of the animation

- keyframes distribution can be *adaptive*
  - keyframes denser or sparser as needed
- in-betweening happens automatically on demand, in real time
  - e.g., at each refresh of video
- *times* associated to keyframe are chosen arbitrarily
  - not necessarily as an integer number, of video frames
  - all frames shown on screen will be in-betweens
- the better the interpolation schema → the better in-betweens → the fewer keyframes are needed
- editing the animation: ← asset
  - editing individual keyframes
  - editing keyframe *times* (e.g., to vary speed)
  - 1. pick a new time t_i (not a keyframe)
    2. bake the in-between at t as a new keyframe
    3. edit it!

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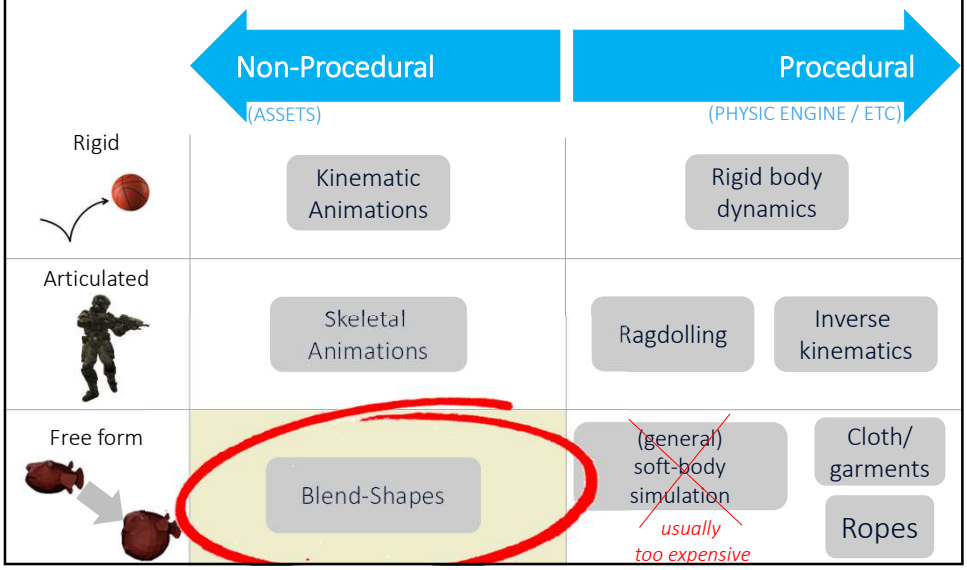
Animations in games
(of 3D Solid Objects)



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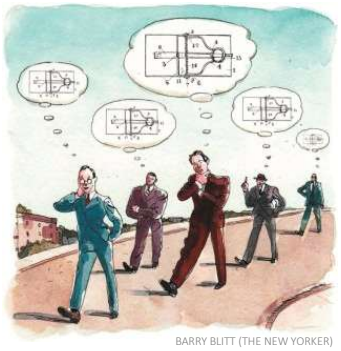
Asset for free-form animations: Blend-shapes

- Also known as:
  - Morph-targets
  - Face-morphs
  - Shape-keys
  - Per-vertex animations
  - Vertex-animations
  - …



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Blend shapes: concept

Walk cycle
(Monkey Island
LucasArt 1991)

- Animation in 2D (old school) games:
  a sequence of sprites
- Animation in 3D games:
  just a sequence of meshes?

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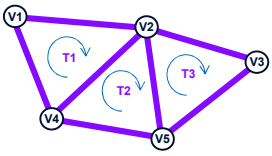
Mesh (data structure)



connectivity (indexed)

Tri:	Wedge 1:	Wedge 2:	Wedge 3:
T1	V4	V1	V2
T2	V4	V2	V5
T3	V5	V2	V3

geometry:

Vert:	Pos
V1	(x, y, z)
V2	(x, y, z)
V3	(x, y, z)
V4	(x, y, z)
V5	(x, y, z)

attributes:

UV	Col
(u, v)	(r, g, b)
(u, v)	(r, g, b)
(u, v)	(r, g, b)
(u, v)	(r, g, b)
(u, v)	(r, g, b)

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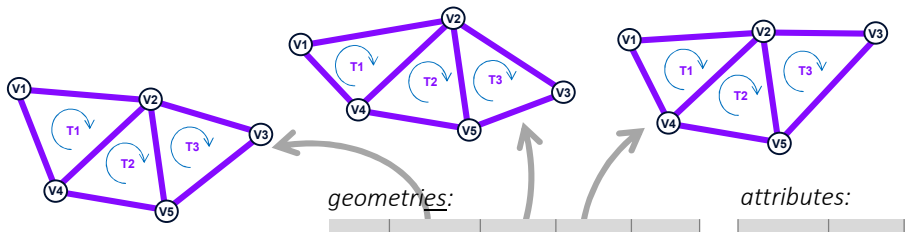
Blend shapes (data structure)



geometries:

Vert:	Base Shape	Shape 1	Shape 2	...
V1	(x,y,z)	(x,y,z)	(x,y,z)	...
V2	(x,y,z)	(x,y,z)	(x,y,z)	...
V3	(x,y,z)	(x,y,z)	(x,y,z)	...
V4	(x,y,z)	(x,y,z)	(x,y,z)	...
V5	(x,y,z)	(x,y,z)	(x,y,z)	...

attributes:

UV	Col
(u,v)	(r,g,b)
(u,v)	(r,g,b)
(u,v)	(r,g,b)
(u,v)	(r,g,b)
(u,v)	(r,g,b)

*connectivity (**indexed**)*

Tri:	Wedge 1:	Wedge 2:	Wedge 3:
T1	V4	V1	V2
T2	V4	V2	V5
T3	V5	V2	V3

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Blend-shapes

- A mesh with multiple associated **geometries**
- I.e. a sequence of meshes ('**shape**s') with
  - shared connectivity
  - different geometries
  - shared attributes
    - except normals / tangents dirs
    - shared UV-map, per vertex colors…
  - (and shared textures as well)

aka '**morph**'
aka '**morph-target**'
aka (key)-'**frame**'
aka '**shape-key**'

- Two possible equivalent encodings:
  - **Absolute** mode:
    - each *shape* stored as per-vertex positions (points)
  - **Relative** mode:
    - *base shape* (or *rest shape)*: stored as per-vertex positions (points)
    - any other *shape*: stored as differences with the *base shape* (vectors)

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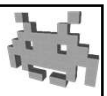
Blend-shapes
(as a data structure, in e.g. C++)



- Indexed mesh :

```
class Vertex {
  vec3 pos;
  rgb color;
  vec3 normal;
};

class Face{
   int vertexIndex[3];
};

class Mesh{
  vector<Vertex> vert; /* geom + attr */
  vector<Face> tris;   /* connectivity */
};
```

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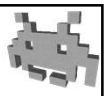
Blend-shapes
(as a data structure, in e.g. C++)



- Blend-shape (absolute):

```
class Vertex {
  vec3 pos [ N_SHAPES ] ;
  rgb color;
  vec3 normal [ N_SHAPES ] ;
};

class Face{
   int vertexIndex[3];
};

class Mesh{
  vector<Vertex> vert; /* geom + attr */
  vector<Face> tris;   /* connectivity */
};
```

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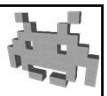
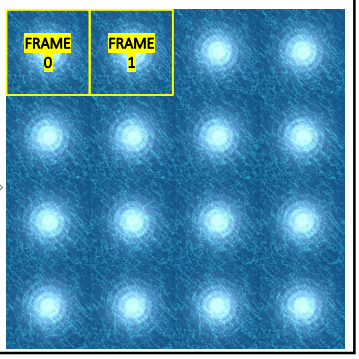
All shapes of a blend-shape will always share… (so, a blend-shape *cannot* change)…



- The mesh connectivity
  - Eg. no change mesh res, remeshing
- Therefore, the surface topology
  - E.g. no breaking apart, no fusions, no hole appearing
- The mesh attributes
  - Such as color, UV-map…
  - Exceptions: normals
    (and positions, if we consider them attributes)
- The textures
  - *Side note:*
    "texture animations"
    are a thing:
    a sequence of texture sheets
    or texture sub-images constituting
    the frames of a (looped?)
    2D animation run on top of surfaces



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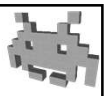
Blend-shapes: a few common interchange formats



- Formats supporting blend-shapes include:
  - .GLTF (Khronos)
    "`morphTarget`", relative encoding
  - .DAE (Collada)
  - .FBX (Autodesk)
- Older / simpler alternatives:
  - .MD5 ("quake", valve)
  - or, just store a sequence of meshes (es .OBJ)
    - making sure connectivity is coherent!
      (vertex, face ordering must be the same – can be tricky)

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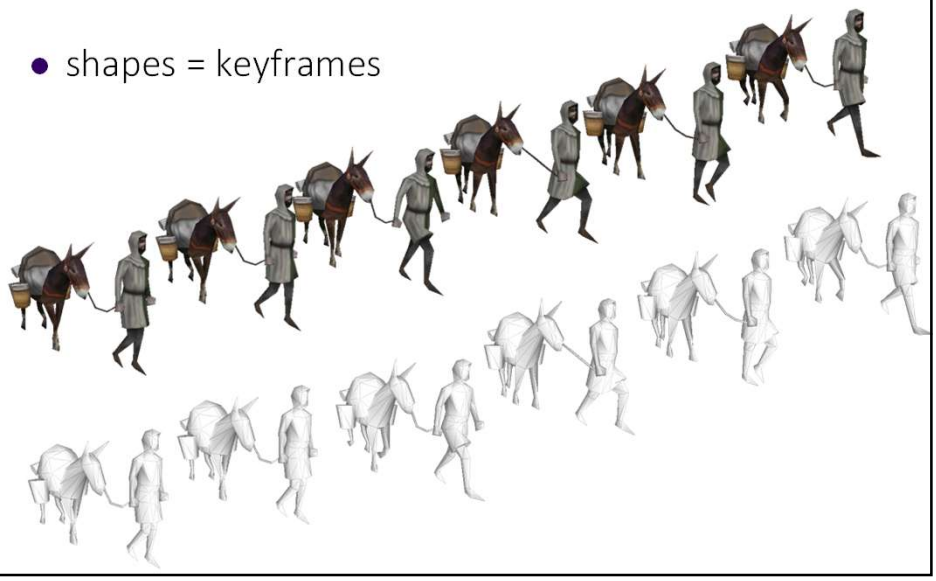
Uses of Blend-Shapes: temporal sequences

- shapes = keyframes



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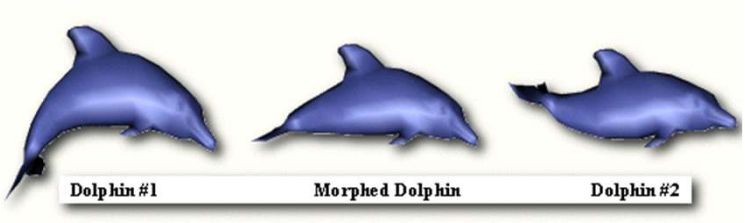
Uses of Blend-Shapes: temporal sequences

- Temporal sequences
  - shapes = keyframes



  - Looped animations: last keyframe = first keyframe

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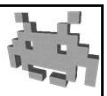
Blending keyframes of a temporal sequence



- shapes = keyframes of the animation
  - shape_A  with time t_A
  - shape_B  with time t_B
  - shape_C  with time t_C
  - shape_D  with time t_D
- given current time t with $t_B \leq t \leq t_C$
- *then…*
  - which shapes to blend? shape_B , shape_C
  - weights? $w_B = \frac{t - t_C}{t_B - t_C}$ $w_C = (1 - w_B) = \frac{t - t_B}{t_C - t_B}$

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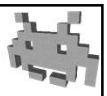
Blending keyframes of a temporal sequence with transition functions



- shapes = keyframes of the animation
  - shape_A  with time t_A
  - shape_B  with time t_B
  - shape_C  with time t_C
  - shape_D  with time t_D
- given current time t with $t_B \leq t \leq t_C$
- *then…* *transition function*
  - which shapes to blend? shape_B , shape_C
  - weights? $w_B = f\left(\frac{t - t_C}{t_B - t_C}\right)$ $w_C = (1 - w_B)$

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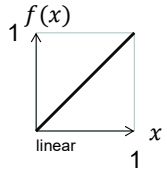
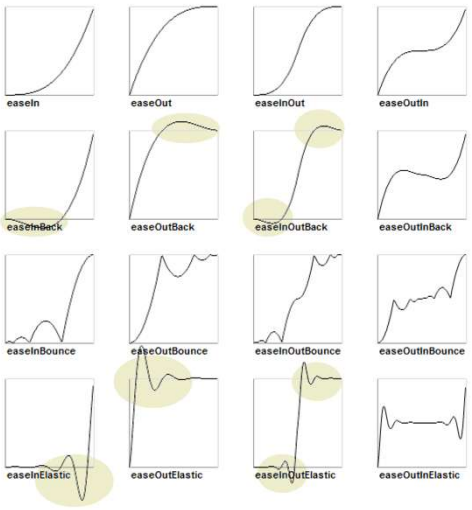
Transition functions
(applies to all animation types with keyframes)

- Not necessarily the Linear one



$f(x) = x$



NB: = extrapolation !
i.e. exaggeration

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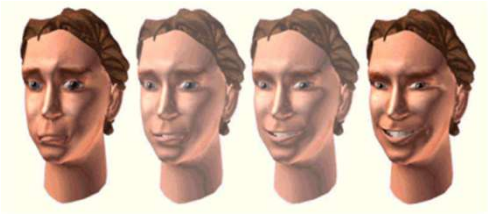
Uses of Blend-Shapes: facial expressions / animations



shape A shape B

here: shapes = facial expressions
(typical use; that's why they are also called "face morphs"

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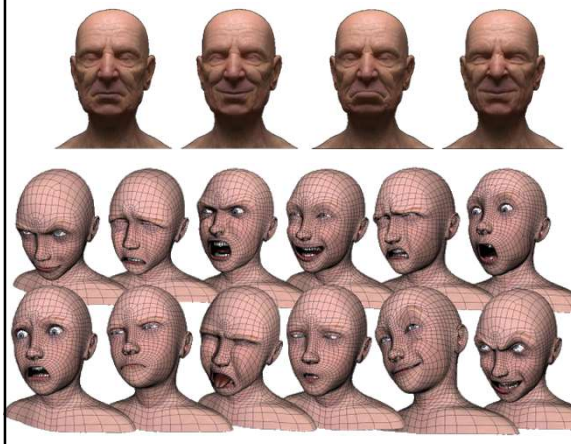
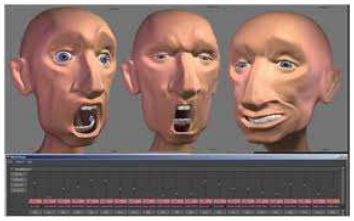
Uses of Blend shapes: facial expressions / animations





Here, used together with skeletal animations (see next topic)
(for mandible, neck, eyeballs)

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About the two ways to encode a blend-shape

- The **absolute mode** is natural when shapes are designed to be used as *alternatives*.
  Example:
  - keyframes of an animation sequence.
    $shape_1$ = keyframe of time 5
    $shape_2$ = keyframe of time 9
    at time 6, we use …. w_1 w_2 $0.75\ shape_1 + 0.25\ shape_2$
- The **relative mode** is natural when shapes are designed to be *superimposed* with various degrees of strength.
  Example:
  - $shape_1$ = left-eye closed
  - $shape_2$ = smile
  - base + $shape_1$ + $shape_2$ = wink

  Another example
  - $shape_1$ = fat
  - $shape_2$ = long chin w_2
  - base + 0.4 $shape_1$ + 0.9 $shape_2$
    = a bit fat & long-ish chin
- But the two ways are equivalently expressive.
  - They can achieve the same set of shapes
  - In **absolute mode**, Σw_i=1
  - In **relative mode**, there is no such condition, but it's equivalent to use the absolute mode, with $w_{base} = 1 - \Sigma w_i$
  - when Σw_i>1 , this means that we are implicitly using an extrapolation

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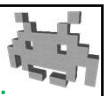
Blending shapes of a blend-shape



	using Absolute Encoding	using Relative Encoding
what we store	S_b , S_0 , S_1 , S_2 … (base shape (positions); shapes (positions))	S_b , R_0 , R_1 , R_2 … (shapes (vectors))
equivalent to	$S_b + R_0$, $S_b + R_1$	$S_0 - S_b$, $S_1 - S_b$
how to blend between… … two shapes i and j	NATURAL $w_i S_i + w_j S_j$	$S_b + w_i R_i + w_j R_j$
… three shapes i,j and k	$w_i S_i + w_j S_j + w_k S_k$	$S_b + w_i R_i + w_j R_j + w_k R_k$
… n shapes $A = \{i, j, k \dots\}$	$\sum_{i \in A} w_i S_i$	$S_b + \sum_{i \in A} w_i R_i$

using normalized weights w in 0 to 1 with $\Sigma w = 1$

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Blending shapes of a blend-shape

	using Absolute Encoding	using Relative Encoding
what is stored	S_b , S_0 , S_1 , S_2 … (base shape (positions); shapes (positions))	S_b , R_0 , R_1 , R_2 … (shapes (vectors))
equivalent to	$S_b + R_0$, $S_b + R_1$	$S_0 - S_b$, $S_1 - S_b$
how to modify rest shape… … toward shape i	$(1 - w)S_b + w S_i$	NATURAL $S_b + w R_i$
… toward two shapes i and j	$(1 - w_i - w_j)S_b + w_i S_i + w_j S_j$	$S_b + w_i R_i + w_j R_j$
… toward n shapes $A = \{i, j, k \dots\}$	$\left(1 - \sum_{i \in A} w_i\right) S_b + \sum_{i \in A} w_i S_i$	$S_b + \sum_{i \in A} w_i R_i$

using any set of weights w in 0 to 1 with ~~$\Sigma w = 1$~~

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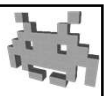
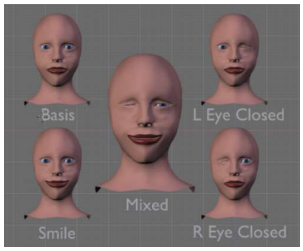
Example



- Shape 0 = base shape
- Shape 1 = smile
- Shape 2 = left eye closed
- Shape 3 = right eye cloed



«wink» = 75% smile, right eye fully closed

How to blend the shapes to get a wink (which weight to use), if the blend-shape is encoded in…

A: Relative mode?

B: Absolute mode?

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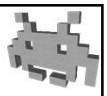
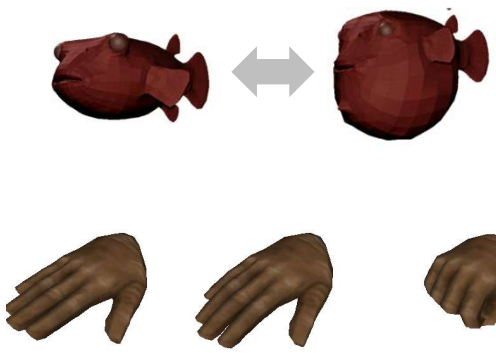
Uses of Blend-Shapes: generic deformations



- Baked poses



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Uses of Blend-Shapes: variants of one given object

- mixable!

masculine outfit

feminine outfit

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Uses of Blend-Shapes: variants of one given object

- mixable!

human

orc

goblin

dwarf

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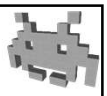
Uses of Blend shapes



- A blend shape modelling a face space ("face-morphs")

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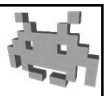
Uses of Blend shapes



- Provide a range of variations for a given class of model (e.g. a characters)
- Many games (expecially RPGs) will use this as a part of a mechanism to allow players to customize their character appearance (custom avatars)
  - At the end of the process, the result of the blending can be baked into a standard mesh!
- See http://www.makehumancommunity.org/ for a good open-source suite (to create humanoid meshes) based on this concept

MAKE HUMAN™

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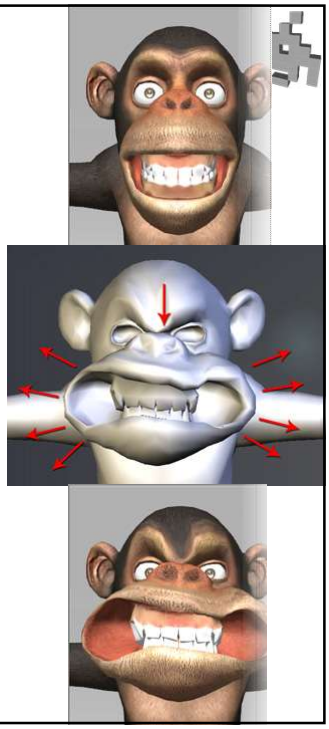
Blend shapes: authoring

1. Editing base shape
   - including:
     uv-mapping, texturing, etc.
2. Re-edit it
   for each shape-key!
   …while preserving:
   connectivity,
   textures, etc:
   - with low poly editing
   - or with subdivision surfaces…
   - or with parametric surfaces…
   - or with scupting.



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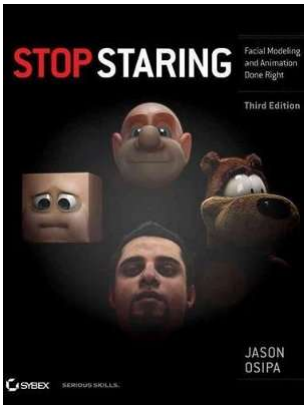
Blend shapes: authoring

- Handbook for blend-shape based face animation:
  - “Stop Staring” (3d edition) Jason Osipa
  - Covers: style, expression…
  - Non technical (high level)
  - Not about specific tools e.g. Blender, Maya



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Blend shapes: pros and cons

- During authoring (by artists):
  - 👍 flexible, expressive, huge number of DOF… (too many?)
  - 👎 work intensive to construct
  - 👎 expensive to store
- During use (by game engine)
  - 👍 easy to use (just define global weights)
  - 👎 RAM cost
  - 👎 little degree of freedoms (too few?)

but not as bad as old 2D sprites

because they didn't have
(1) sharing of connectivity, textures, attributes …
(2) key-frames / in-betweens!

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Blend shapes: challenges

- Capturing:
  - from a stream of meshes
  - e.g. : from a RGBD camera (like Microsoft Kinect) to a blend-shape: open problem!
- Compression
  - e.g.: reduce number of keyframes (can you think of an algorithm?)
- Streaming
  - server sends animation to client while it runs
- LOD-ding
  - like for meshes (but more difficult: same connectivity must be good for all shapes)

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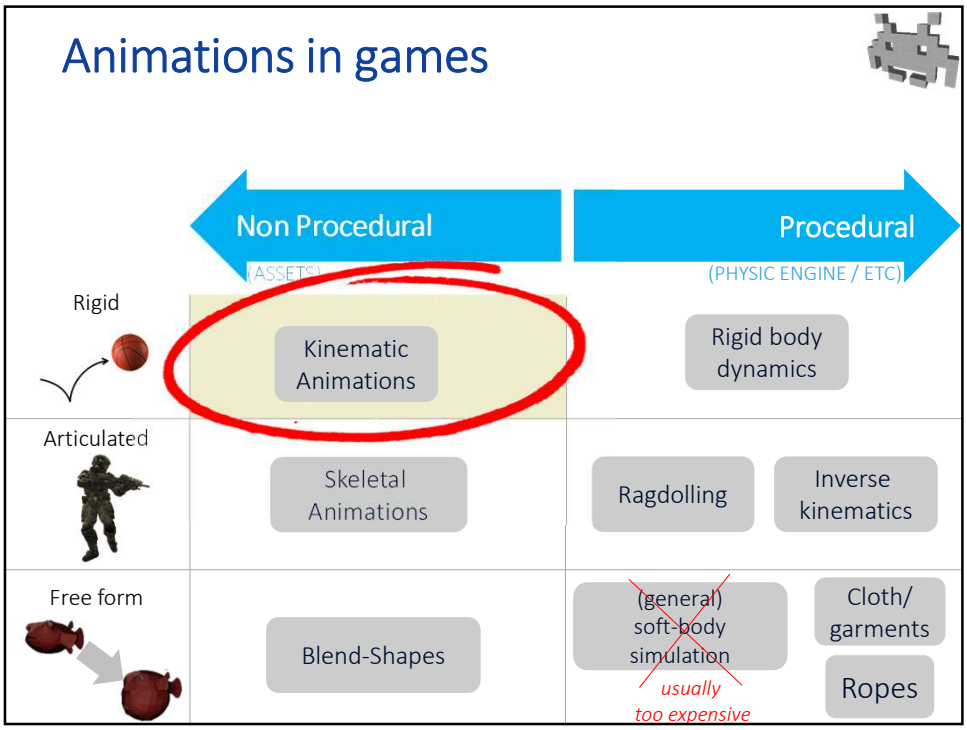
Animations in games



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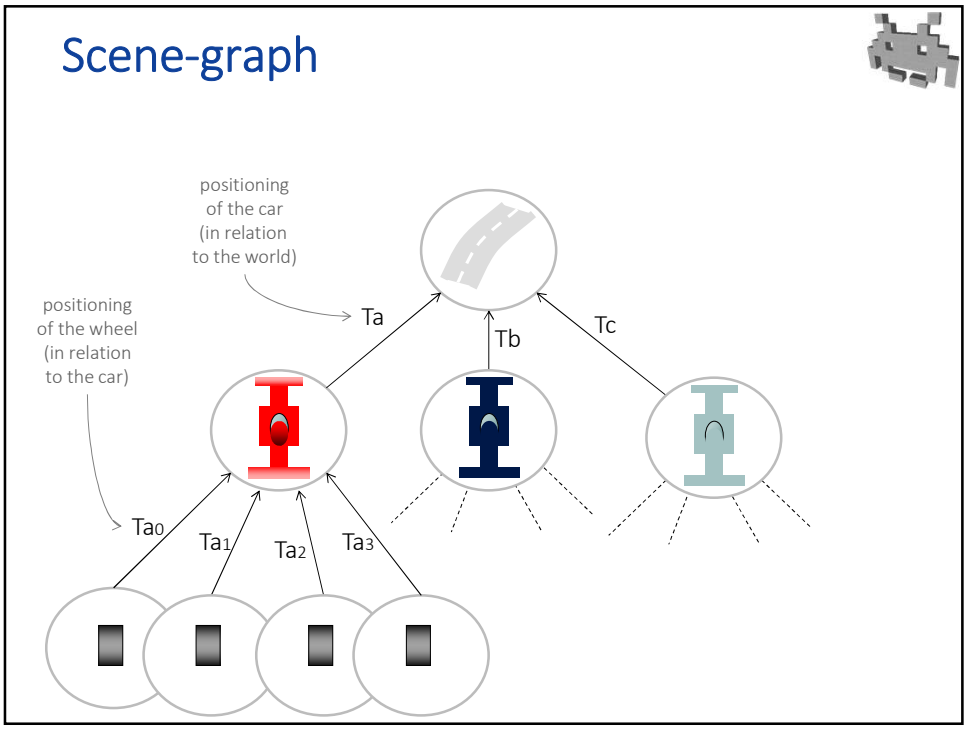
Scene-graph



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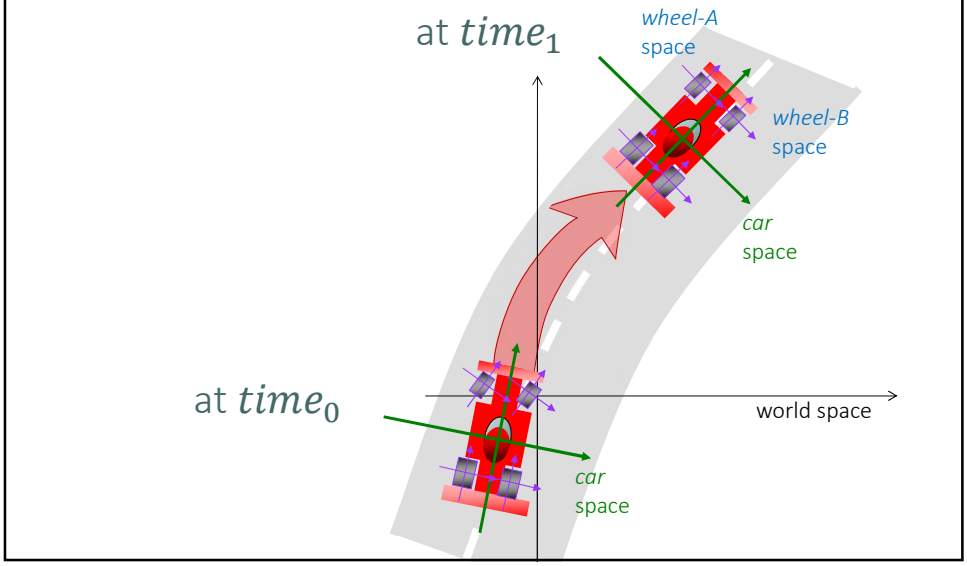
An animated scene-graph…
(a type of "kinematic" animation)



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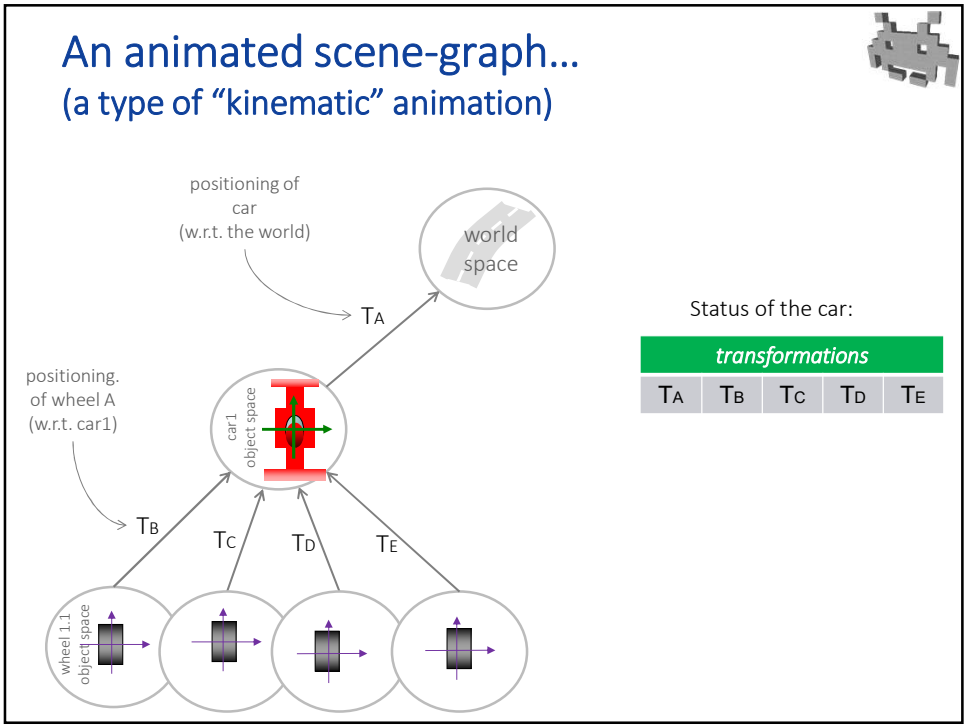
An animated scene-graph…
(a type of "kinematic" animation)



Status of the car:

transformations				
T_A	T_B	T_C	T_D	T_E

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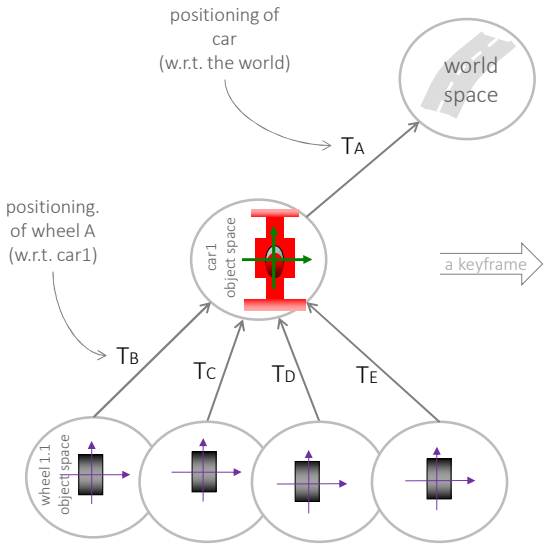
An animated scene-graph…
(a type of "kinematic" animation)



a keyframe

Animation of the car:

time	*transformations*				
t_0	$T_{0,A}$	$T_{0,B}$	$T_{0,C}$	$T_{0,D}$	$T_{0,E}$
t_1	$T_{1,A}$	$T_{1,B}$	$T_{1,C}$	$T_{1,D}$	$T_{1,E}$
t_2	$T_{2,A}$	$T_{2,B}$	$T_{2,C}$	$T_{2,D}$	$T_{2,E}$
t_3	$T_{3,A}$	$T_{3,B}$	$T_{3,C}$	$T_{3,D}$	$T_{3,E}$

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An animated Scene-graphs…
(a type of "kinematic" animations)

- Given a scene-graph, a simple way to define an animation for it:
- keyframe = the definition of local transformations T_i (one for each moving part)
  - Storing a keyframe: storing all local transformation (or: produce them as a function of time with a simple script)
  - Note: often it's enough to only redefine the rotation parts. Translation and scaling can be shared by all key-frames.
  - Interpolated frames (in-betweens): interpolate each local transformation between two keyframes
  - Applying a frame: derive the global transformation, as usual and apply them to nodes (this is known as: "forward kinematics")

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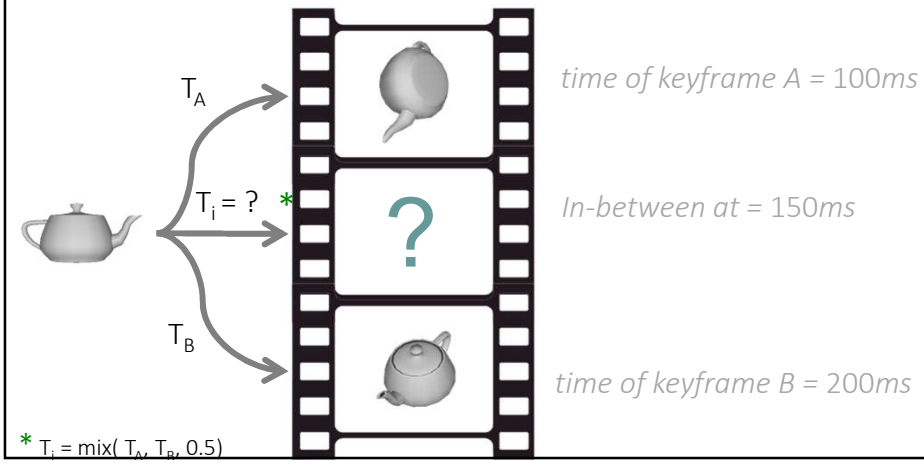
Interpolating keyframes
of a kinematic animations: we interpolated the (local) transforms!



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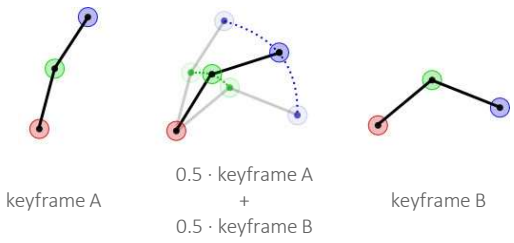
Interpolating keyframes
of a kinematic animations

Keyframes (stored)
and
in-betweens (interpolation)

Note: first we interpolate local transformations, then we cumulate them into the global transformations. This makes keyframe interpolation very expressive: that is, able to interpolate between very different keyframes with good results.



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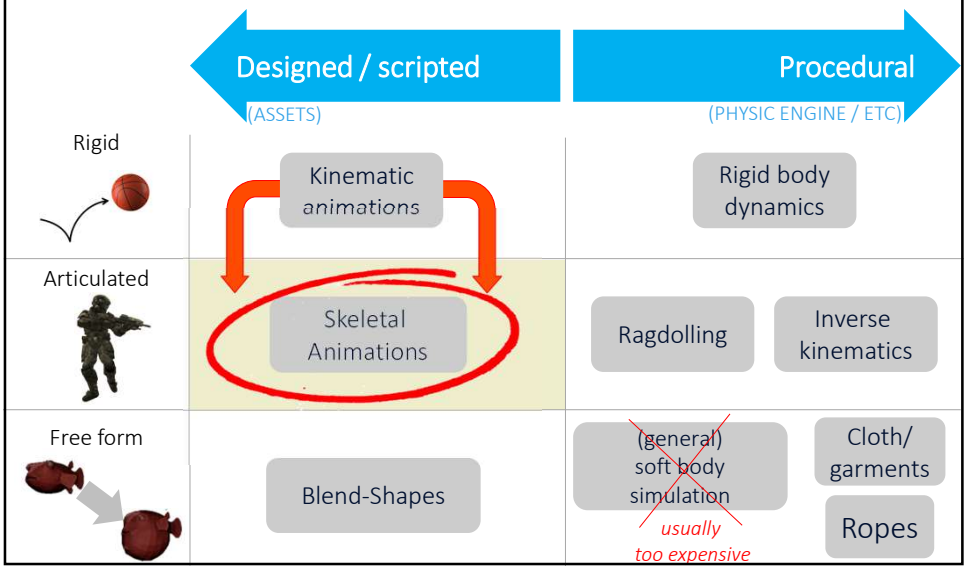
Animations in games
(of 3D Solid Objects)



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From kinematic animation to skeletal animations
From a bunch of robot pieces…

- So far, our kinematic animations have one mesh in each node
  - e.g., car, wheel 1, wheel 2, wheel 3, wheel 4
- That works well, for simple structures
  - with a few moving parts
  - like a car, a windmill …
- Imagine doing a humanoid "robot" that way
  - you need around 25-60 nodes (called "bones")
  - individual meshes for: arms, upper arm (brachium) forearms, three meshes for each finger…
  - it's possible, but…
    - inefficient to render (lots of "draw calls")
    - uneasy to manage (lots of pieces / files?)
    - a nightmare to design / author ("sculpt me a nice-looking calf")
    - and… looks right only for robots (each part is rigid!)

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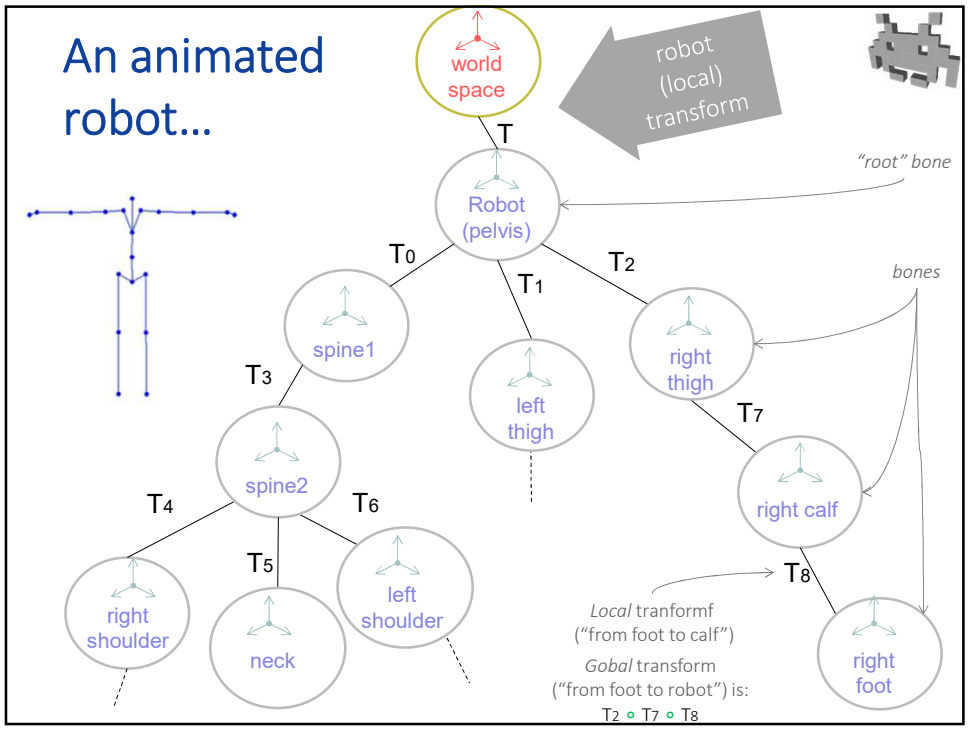

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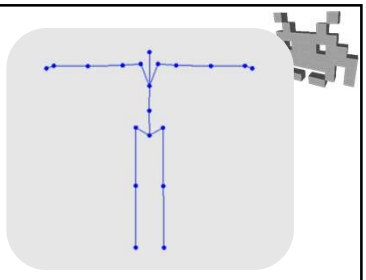
Skeleton : data structure 1/2



- A tree of bones
- bone:
  - a node of the hierarchical skeleton
  - a reference frame (space) used to express pieces of the animated model
  - eg, for a humanoid: *forearm, calf, pelvis, …*
  - (animation bones != biological bones)
- Space of the *root* bone =(def)= object space (of the entire character)
- How many bones in a skeleton of a standard humanoid?
  at least: 22-24 (typically)
  reasonable: ~40-50 bones.
  high: a few 100s (includes "bones" for hair, for outfits…)

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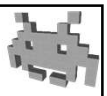
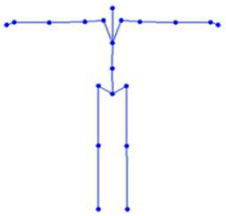
Skeleton : data structure 2/2



1. Hierarchy (tree) of bones
   - a root bone on top



2. A special pose «rest pose»
   - 3D models are to be modelled in this pose
   - also: «T-pose», «T-stance»,
     - same reason why T-shirts are called T-shirts ;)
   - also: «A-pose», when arms are bent down

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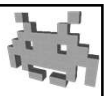
Pose: data structure



One transformation for each bone *i*

- Local transform: (of bone *i*)
  - from: space of one *i*
  - to: space of bone father of *I*

often, only the rotation component

("fixed length bones": translations defined once and for all by the skeleton)

- A pose is a keyframe in a skeletal animation
  - a skeletal animation is a sequence of poses

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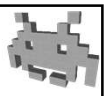
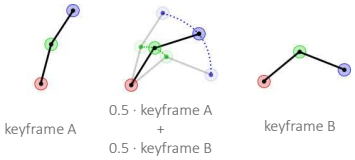
Keyframes and in-betweens in a skeletal animation



- Poses in a skeletal animations can be easily mixed
  - by blending local per-bone transforms <= this is the key!
- This interpolation works very well:
  very different key-frames can be blended with good results



  - much superior interpolation power than, for example, blend-shapes!
  - keyframes can be very far apart
  - e.g.: decent walk-cycles with just 4 key-frames! (2 per step, mirrored)
  - e.g.: decent attack animations with just 2 key-frames! (charge, discharge)
  - (better results can always be obtained inserting new key-frames, as usual)

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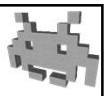
… to a single articulated model… (skinning)



- Instead of one mesh in each bone…
  - 1 mesh for the right foot, 1 mesh for head, 1 for neck…
  - with the left foot mesh is expressed in left foot space, etc, like normale
- …let's use a single mesh mesh, but "*skinned*"
  - 1 mesh per the entire "robot" (the character)
  - the mesh is all expressed in the character space:
    the reference frame of the **root** bone
  - a new per vertex attribute : *index of bone*
  - that vertex will follow that bone
  - example: a vertex on the left feet: will be marked as "left feet"
  - it will be transformed as if it was a part of the mesh of the left feet
  - How to do so?

the "skinning" of the mesh

- A skinned mesh can be animated / posed!
  - With the animation / pose specified in the skeleton

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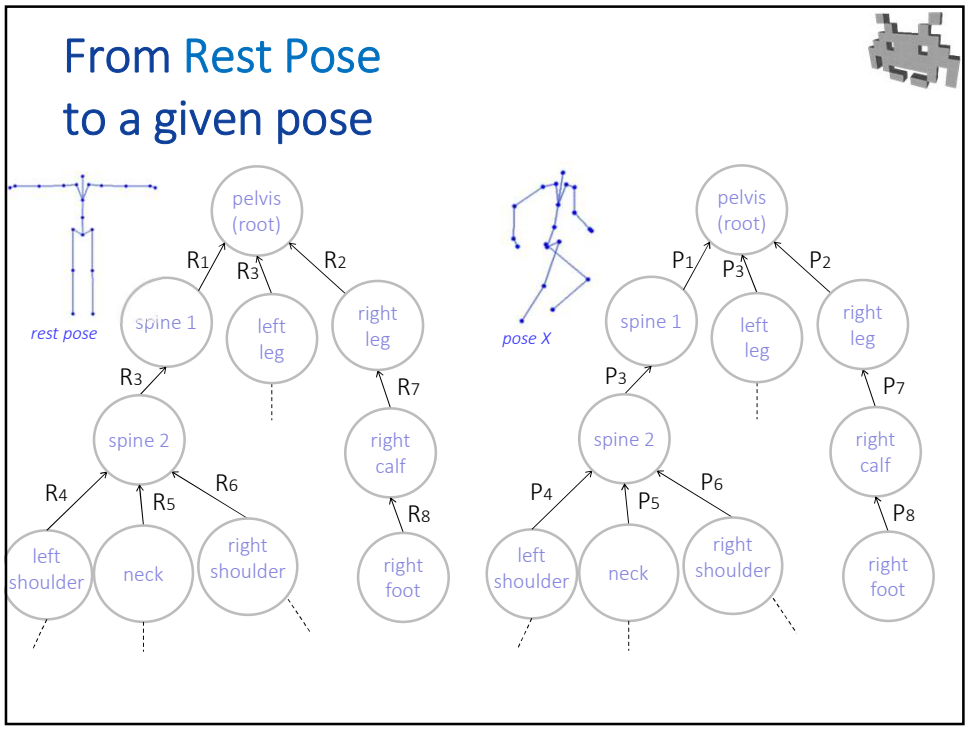
From Rest Pose
to a given pose
rest pose
pose X
pelvis (root)
spine 1
spine 2
left leg
right leg
right calf
right foot
left shoulder
neck
right shoulder
R1
R2
R3
R4
R5
R6
R7
R8
P1
P2
P3
P4
P5
P6
P7
P8

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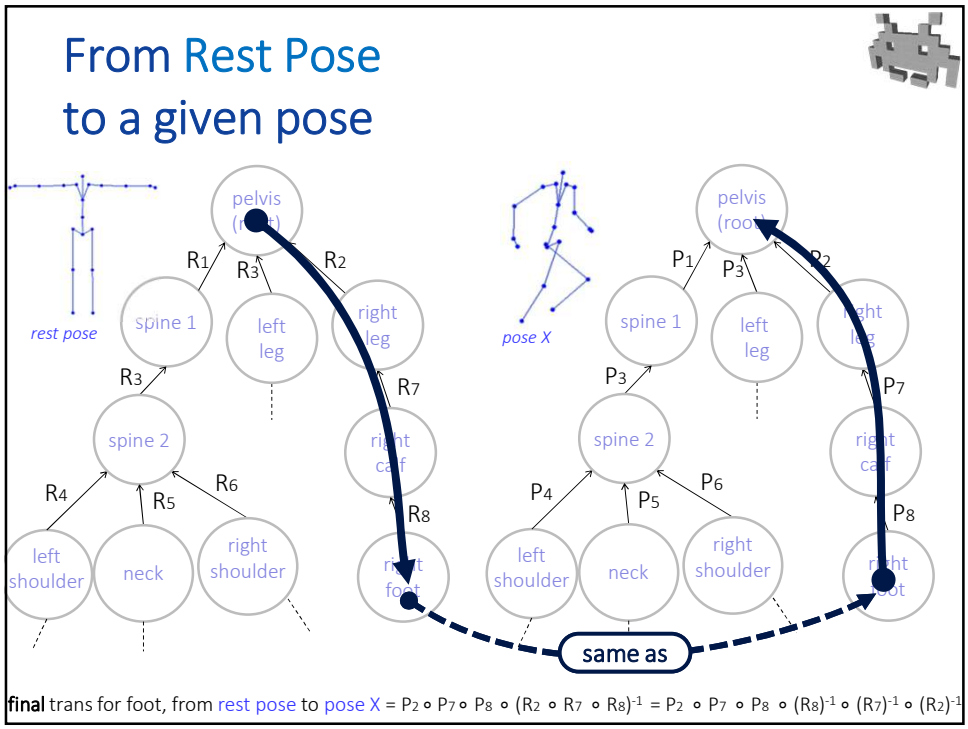
From Rest Pose
to a given pose
rest pose
pose X
same as
final trans for foot, from rest pose to pose X = P2 ∘ P7 ∘ P8 ∘ (R2 ∘ R7 ∘ R8)-1 = P2 ∘ P7 ∘ P8 ∘ (R8)-1 ∘ (R7)-1 ∘ (R2)-1

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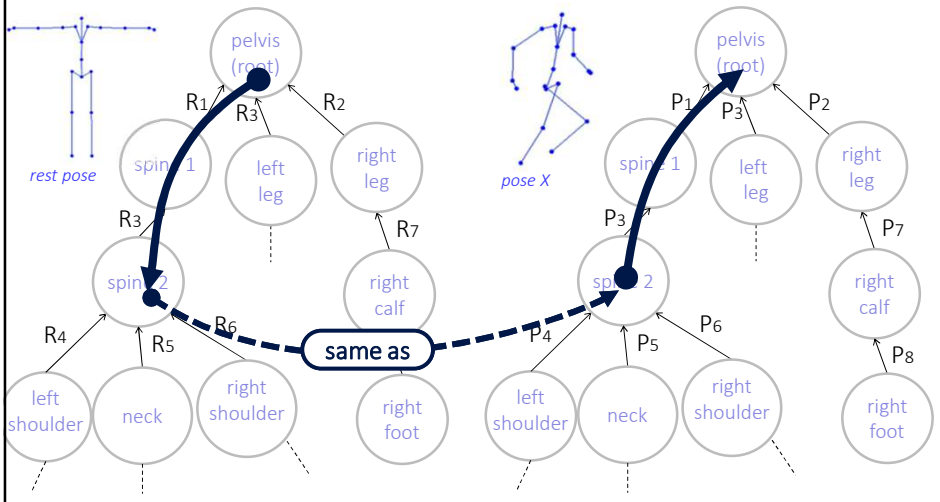
From Rest Pose to a given pose



final trans for the spine, from rest pose to pose X = $P_1 \circ P_3 \circ (R_1 \circ R_3)^{-1} = P_1 \circ P_3 \circ (R_3)^{-1} \circ (R_1)^{-1}$

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Bone transforms in a pose. E.g. for «right foot» bone:

- Local Transform: P_8
  - from *«right foot»* to *«right lower-leg»*
- Global Transform: $P_2\ P_7\ P_8$
  - from *«right foot» space* to *«character» space*
  - uses the Hierarchy of the Skeleton
    - once computed, skeleton hierarchy no longer needed
- Final Transform: $P_2\ P_7\ P_8\ R_8^{-1}\ R_7^{-1}\ R_2^{-1}$
  - from *«character» space* in rest pose to *«character»* space in dest. pose
  - uses the Rest Pose of the Skeleton ($R_1 \dots R_N$)
    - once this is computed, Rest Pose is no longer needed

the local frame of the character, which is the frame of the root bone

the mesh (vertex positions & normals) is defined in this space!

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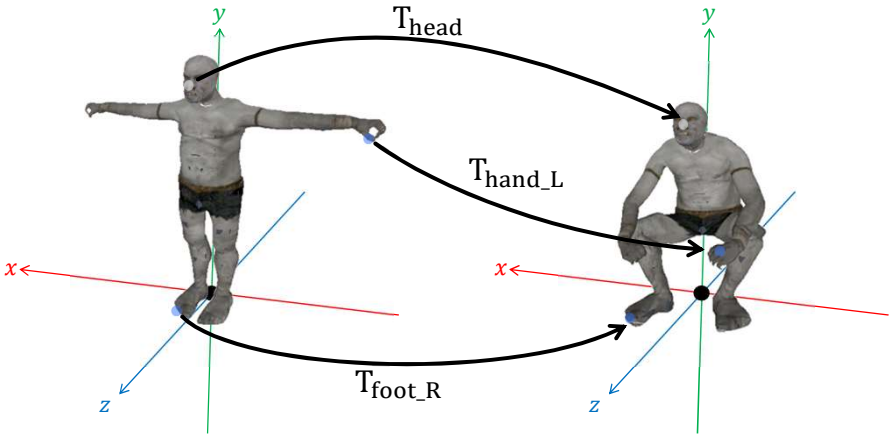
The Final Transforms
defined per bone, for a given pose



Object Space
(mesh vertices are defined here, in Rest pose)

Still **Object Space**
but in the given pose

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Blend skinning: when a vertex can be attached to multiple bones

- We have seen that a mesh vertex follows the bone it is linked to
- Let's further refine this: each vertex is linked not to a single bone, but to a combination of several bones
  - Up to N_max, a constant (e.g. 4)
  - It will follow an interpolation of the (final) transformations associated to the bones.
- In a skinned mesh with blend skinning, each vertex has, as attributes, N_max bone indices, and 4 weights
- This type of skinning is the default type of skinning used in modern game

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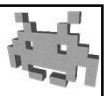
Skinned Mesh: data structure



- A Mesh with a skinning
  - A per vertex attribute
  - Stored per vertex:
    - [bone index , weight] x N_{max}
    - example:

bone links

Vertex 134 →

Bone Index	Weight
9 *(Spine B)*	0.4
13 *(Chest)*	0.1
15 *(Shoulder Right)*	0.4
16 *(Forearm Right)*	0.1

$\sum = 1$

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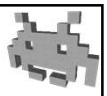
N_max = How many bone links for each vertex (at max)



- It's a call of the Game engine!
- typical used values:
  - 1 (non-blended skinning) (bonus: no need to store weights)
  - 2 (cheap, e.g., for mobile games)
  - 4 (top quality – standard)
  - more: not typically used in games (currently)
- Can one lower N_{max} ?
  - yes, in preprocessing
  - e.g., task for a game tool
  - e.g.: Unity does this during skinned mesh import (if asked to)

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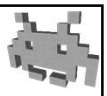
(but why put a hard-wired bound on the number of bone links?)



- Reduces performance cost
  - N_{max} tranforms need be interpolated in GPU
    - in vertex shader
  - GPU = no good at control:
    - always uses exactly N_{max} trasf
    - unused bones: weight = 0
- Reduces VRAM footprint
  - reduces storage
  - fixed length arrays: good for GPU
    - N_{max} (index,weight) pairs
    - even where fewer are locally needed (e.g., if 1 bone, weight is automatically 1)

example:

Bone Index	Weight
9 *(Head)*	1.0
--	0.0
--	0.0
--	0.0

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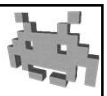
Summary 1/2: we defined skeletal animations starting from kinematic animations



Idea 1 (kinematic anim.): it's a robot made of connected rigid parts…

- use sub-tree of the scene graph, called "skeleton"; its nodes are called "bones" (biological metaphors)
- e.g. a bone for the "head", "neck", "right forearm"… (maybe 20-100 bones)
- a pose = a (local!) transform for each bone = a configuration of the entire skel.
- animation keyframes = poses!
- animation asset = a sequence of keyframes (each with its time value)
- good in-betweening of keyframes! We interpolate these local transforms. Can interpole very different poses – few keyframes suffice for complex anim.
- But: a separate mesh in each "bone"? a mesh for the "head", the "neck", the "right-forearm" … (each mesh is, as always, defined in its own space, and resides in its bone).
- problem: many draw-calls (rendering not efficient!)
- problem: each moving part is rigid (good for a robot, not a biological character)
- problem: hard to author / handle so many individual parts? (without seeing the whole)

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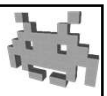
Summary 2/2: we defined skeletal animations starting from kinematic animations



Idea 2 (skinning): let's use a unified "skinned" mesh instead…

- which is defined in a single space (character local space, in "rest pose")
- "rest pose" = a special pose: the mesh is modelled around it
- in each vertex, store an index of 1 bone : we "link" that vertex to that bone
- that vertex will be transformed by the final transformation associated to that bone in that pose (at rendering time!), into it's pos in the current pose
- the mesh is now a "skin" (biological metaphor again): a surface that follows the underlying skeleton

Idea 3 (blend skinning) : let's make the skin more deformable…

- we link each vertex to N *different* bones, each with its own different weight (summing up to 1)
- vertex will be transformed using a blend of final transformations
- two variants for doing so: LBS and DQS (both used in games)
- The skinning of the mesh (per vertex data: its bone links) controls how the that mesh deforms

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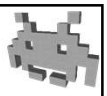
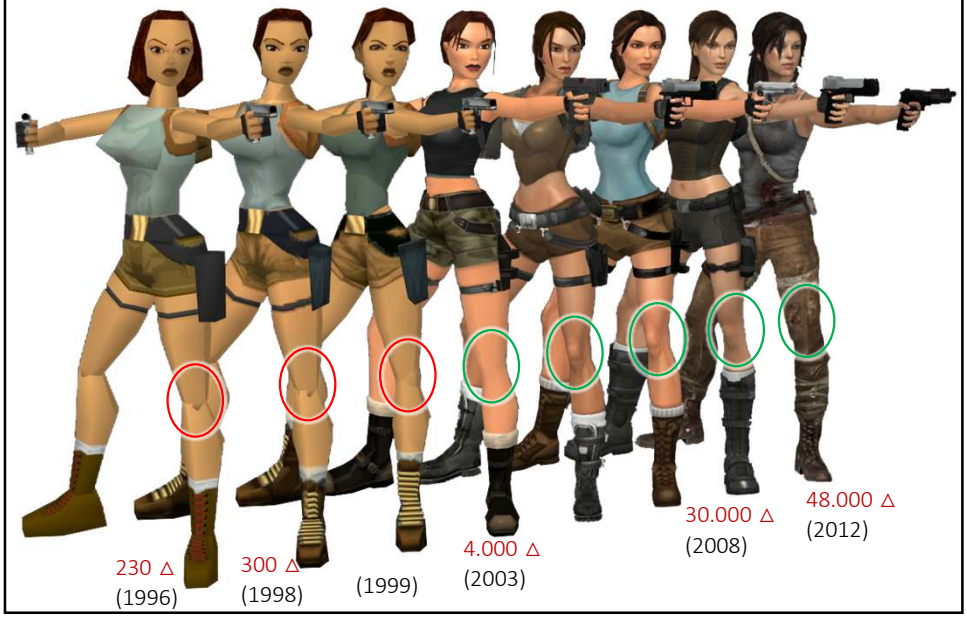
(this story actually happened)





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(this story actually happened)

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(summary) Skeletal animations: 3 types of assets (3 data structures)

- Skeleton
  - Tree of bones
  - Space of root bone = space of character
  - ∀ bone => reference frame (in rest pose)
    - reference frame of the root bone ≡ object space
- Skinned 3D mesh
  - Mesh with links: vertices => bones
  - ∀ vertex: attributes: [bone index , weights] × N_{max}
- Skeletal animations
  - Sequence of keyframe poses
  - ∀ pose, ∀ bone = a **local** transform (to the parent bone)

examples of interchange formats (for all three):

- .SMD (Valve), .FBX (Autodesk), .BVH (“behaviors” Biovision)

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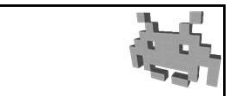
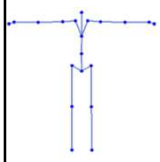
Skeleton : data structure



- A three of bones (e.g. parent index of each bone)
- A rest pose



bone index	parent	transform
0 (pelvis) [root]	-	R[0]
1 (spine)	0	R[1]
2 (chest)	1	R[2]
3 (shoulder sx)	2	R[3]
4 (shoulder dx)	2	R[4]
	...	...
10 (calf)	9	R[10]
...	...	...

Rest pose:
Per-bone (local) transforms
They includes:

- a Rotation: always!
- a Translation: basically, how to reach the next joint (e.g. elbow) from the prev (e.g. shoulder)
- a Scaling: no need

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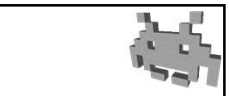
Skeletal Animation : data structure



- A sequence of poses (1 pose = 1 keyframe)
  - RAM cost of a pose:
    (num keyframes) × (num bones) × (transform size)
  - RAM cost of the entire animation (e.g. "walk"):
    (num keyframes) × (num bones) × (transform size)
  - Each pose assigned to time dt
    - delta from start of animation t_0
  - Can be looped (e.g. a walk cycle)
    - interpolation 1st keyframe with last keyframe
- To manipulate the poses,
  (e.g. interpolate them, store them, and more – see later)
  we express them as local transofrms
- To quickly apply them to the skinned mesh vertices,
  we precompute (and store) poses as final transforms

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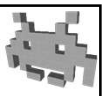
Pose (for a given skeleton) : data structure



- pose = array of **local** transforms (**keyframes**, ready to be **interpolated**)
  - defined for one given skeleton
  - RAM cost: n_bones x bytes_for_a_tranform

bone index	transform
0 (pelvis) [root]	L[0]
1 (spine)	L[1]
2 (chest)	L[2]
3 (shoulder sx)	L[3]
4 (shoulder dx)	L[4]
	…
10 (calf)	L[10]
…	…

Local Transform

Each includes:

- a Rotation: always!
- a Translation: maybe
  If not, use the one defined in the **rest pose** of the skeleton.
  ==> typically, a pose does not redefine bone *lengths*.
- a Scaling: usually not
  a pose joint cannot enlarge a part of the character

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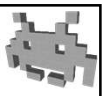
Pose (for a given skeleton) : data structure in GPU



- pose = array of **final** transforms (ready to be **applied to vertices**)
  - defined for one given skeleton
  - RAM cost: n_bones × bytes_for_a_tranform

bone index	transform
0 (pelvis) [root]	F[0]
1 (spine)	F[1]
2 (chest)	F[2]
3 (shoulder sx)	F[3]
4 (shoulder dx)	F[4]
	…
10 (calf)	F[10]
…	…

final transforms

computed in preprocessing as:

$L[0] \circ L[1] \circ (R[1])^{-1} \circ (R[0])^{-1}$

local transforms of *this* pose (after keyframe interpolation

local transforms of *rest* pose

Note:
the skeleton is used to compute this. Once this is done, the skeleton is no longer necessary to apply this pose to a skinned mesh

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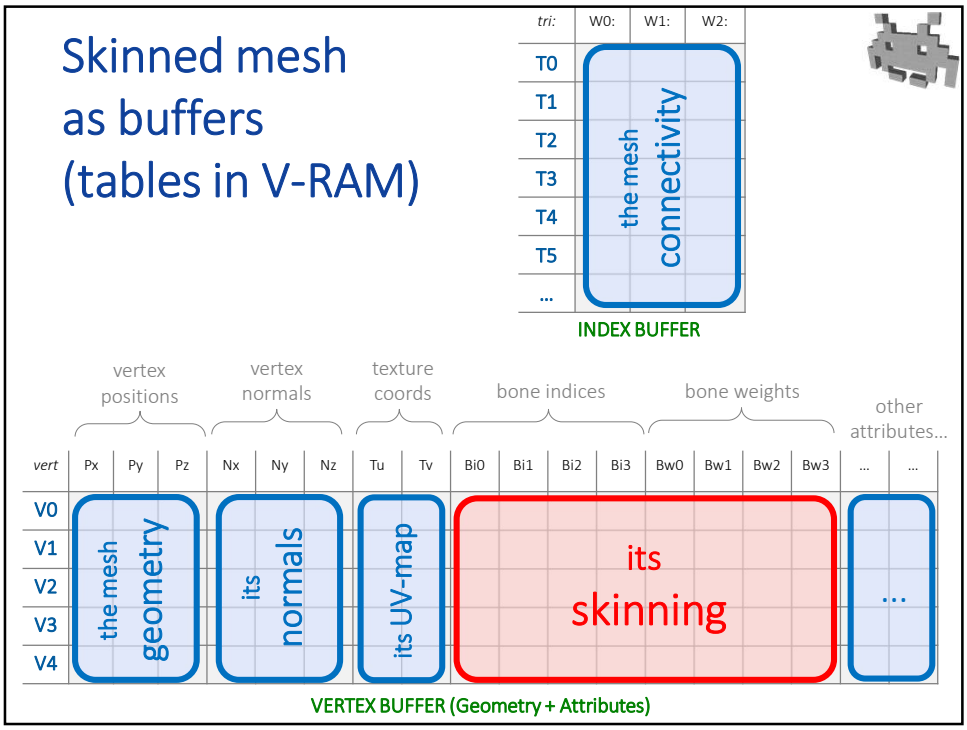
Skinned mesh as buffers (tables in V-RAM)



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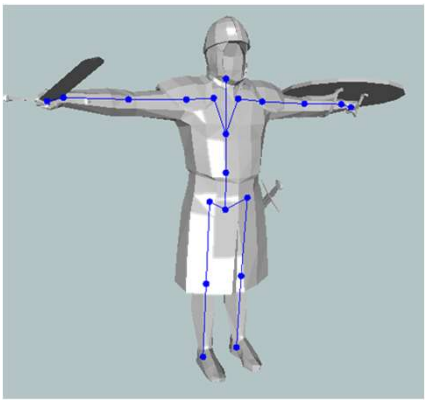
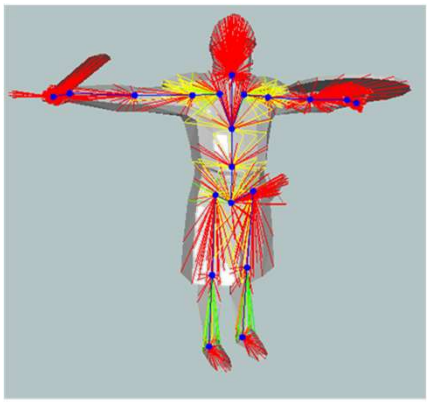
Skeletons and Skinned Meshes



Skeleton
the hierarchical structures of bones
the rest pose transformations (per bone)



Skinned mesh
a mesh with link-to-bones stored as a (per-vertex) attributes

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