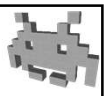
Course Plan



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

★ appearance

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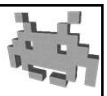
Signals typically stored in textures (in videogames) 3/4



Small scale geometric detail (see Bumb-maps)

- Each texel = a distance from a surface value
  - The texture sheet is a "displacement map" (sometimes "height map")
- Each texel = a normal of the (wrinkled) surface
  - The texture sheet is a "normal map"
  - If not specified otherwise, a Tangent space (sometimes, Object space)

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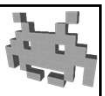
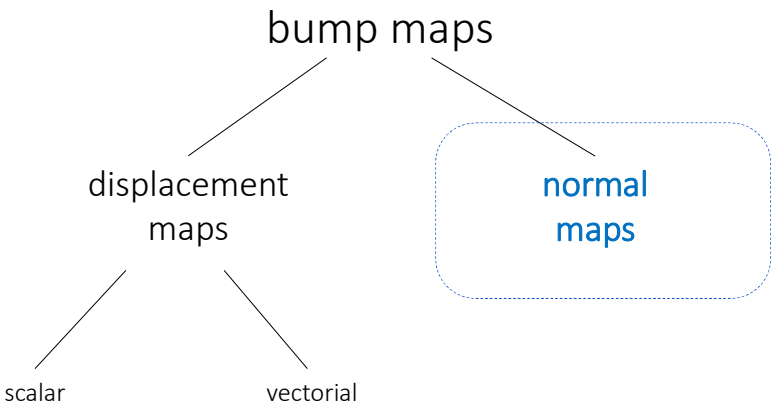
Tassonomy of Bump maps





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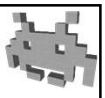
Normal Map: notes



- Affects the lighting only
  - not the parallax
  - not the silhouette of the object
  - The lighting reflects the hi-freq detail of the object
    - dynamically (with variable lights!)
  - Resulting illusion: still convincent
    - If we are not trying to model a macro-structure
- In rendering: use the normal from the texture
  - (for lighting)
  - Instead of the interpolated per vertex normal
- Normals can be expressed simply in cartesian coord
  - But not always (∃ better ways to express unit vectors!)

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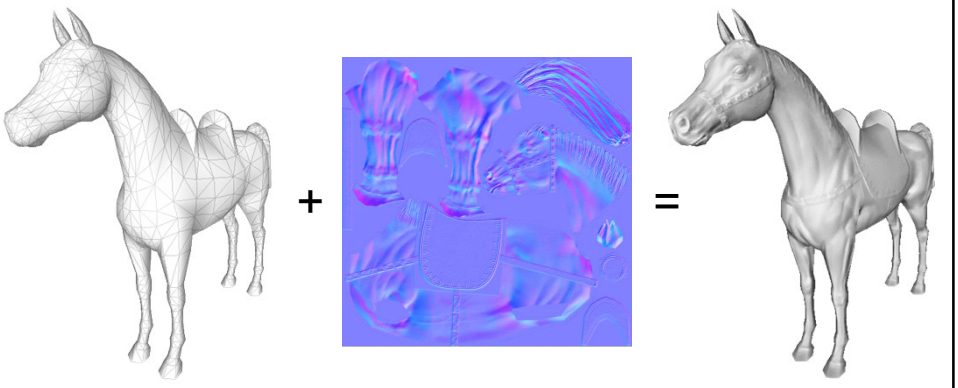
Normal-maps

see demo!



Low-poly mesh
(uv-mapped!)

Normal-map
(encodes
a normal per texel)

richness of *cheap*
geometric detail
(apparently)

assets courtesy of "Mount&Blade" (Talesworlds)

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Normal maps only affect lighting

Do they provide a convincing illusion of 3D shape details?

- Normal maps won't affect:
  - Parallax, or object silhouette
- Still, illusion is very convincing
  - for small scale details, and adequate mesh/texture resolution
  - The lighting (think "*chiaroscuro*")
    tricks the eye notwithstanding the geometric shape
- It's not the first time we observe this in this course
  - We have seen other cases where the normal used for lighting is chosen independently from the actual 3D shape of the mesh
  - Normals (as vertex attributes, or texels value) don't have to be the real surface normal: small discrepancies are ok
  - For example…

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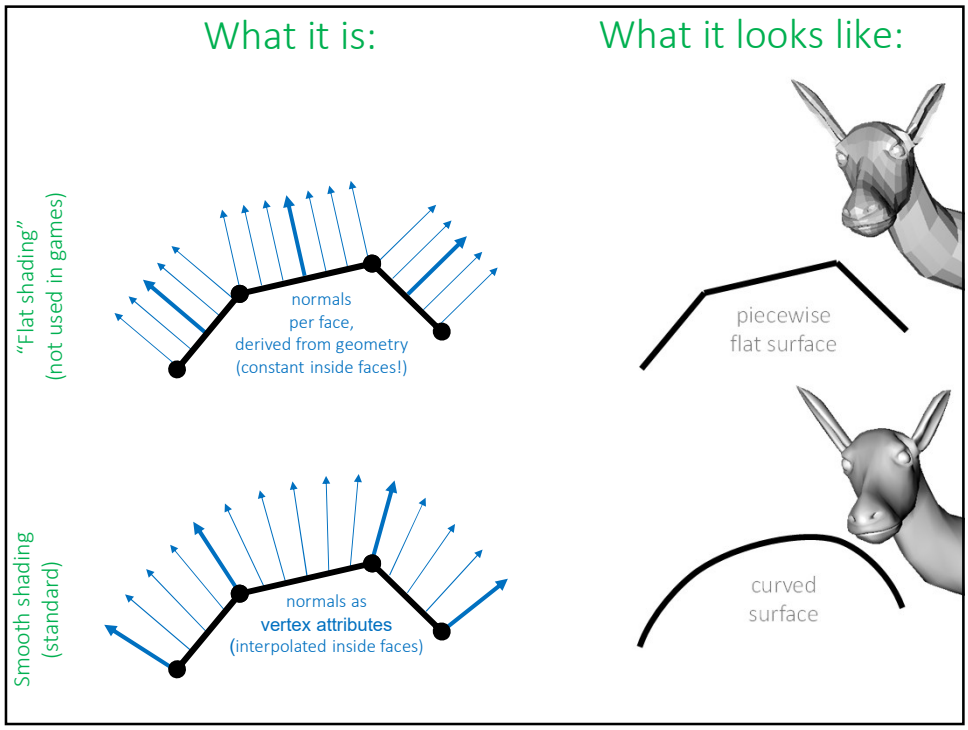
What it is:
What it looks like:
"Flat shading"
(not used in games)
normals
per face,
derived from geometry
(constant inside faces!)
piecewise
flat surface
Smooth shading
(standard)
normals as
vertex attributes
(interpolated inside faces)
curved
surface

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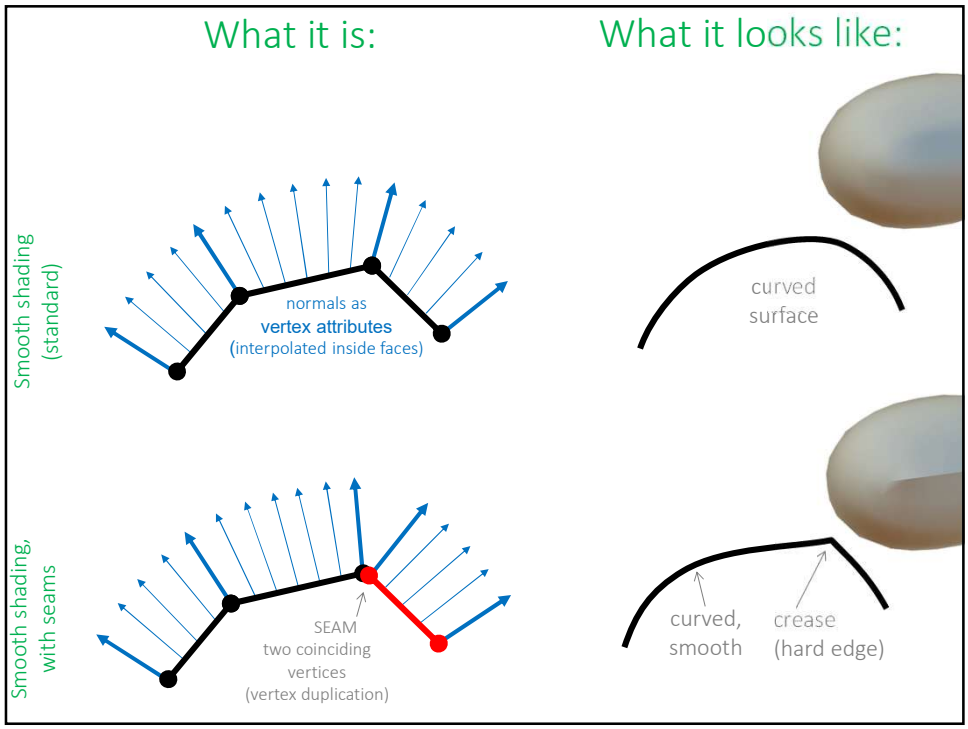
What it is:
What it looks like:
Smooth shading
(standard)
normals as
vertex attributes
(interpolated inside faces)
curved
surface
Smooth shading,
with seams
SEAM
two coinciding
vertices
(vertex duplication)
curved,
smooth
crease
(hard edge)

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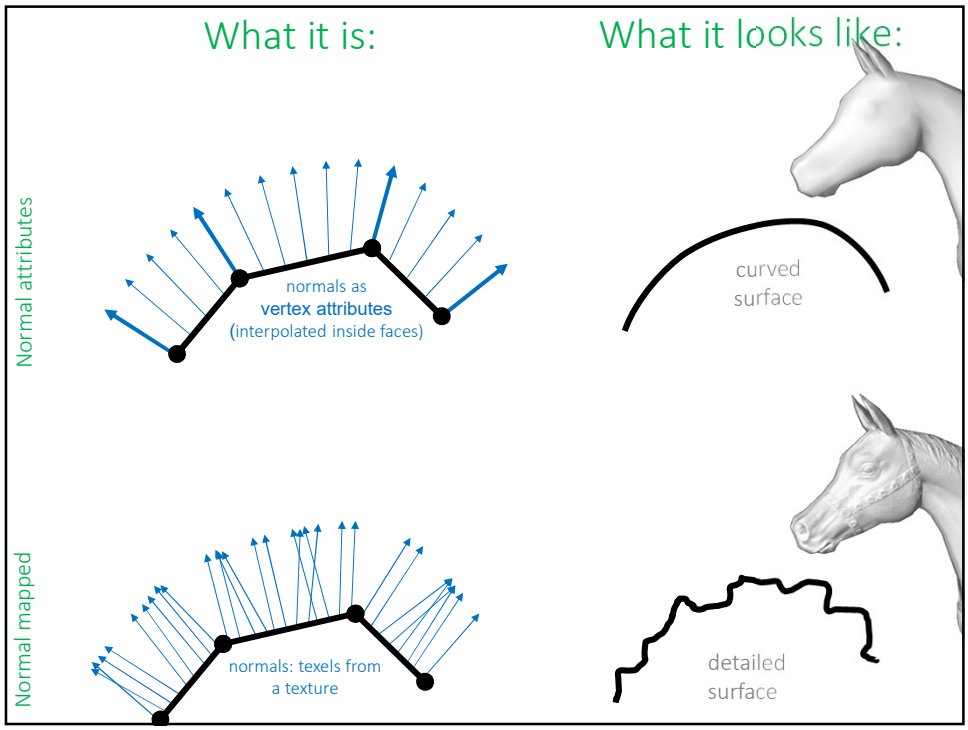
What it is:
What it looks like:
Normal attributes
normals as
vertex attributes
(interpolated inside faces)
curved
surface
Normal mapped
normals: texels from
a texture
detailed
surface

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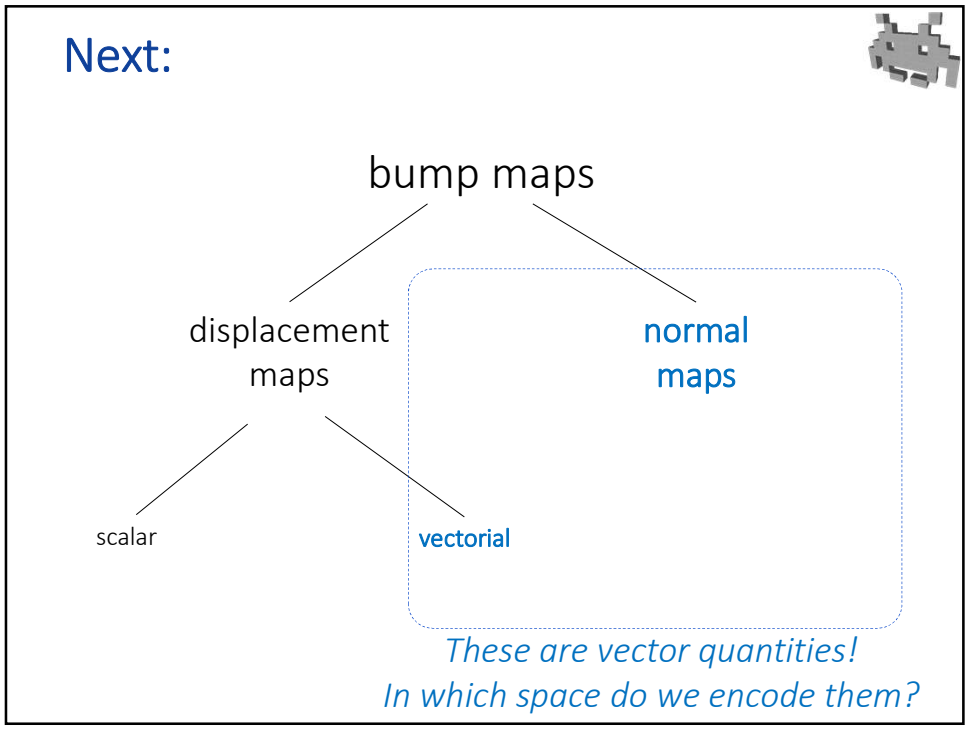
Next:
bump maps
displacement
maps
normal
maps
scalar
vectorial
These are vector quantities!
In which space do we encode them?

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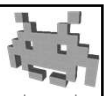
Normal Maps: in which space are the normals encoded?



i.e, texture normals and mesh vertices are expressed in the same space

- If object space: Object-Space Normal-Maps
  - ☺ the per-vertex normal becomes unnecessary!
    - The normal from texture substitutes it
  - ☺ Trivial to apply (during rendering)
    - just use the normal fetched from the texture for lighting
  - ☹ normal-map is bound to a specific object
    - cannot be reused for different objects
  - ☹ Each region of the normal map is bounded to one specific area region of the object!
    - Injective UV-maps only!
    - e.g. no tiling, no exploitation of symmetries

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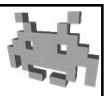
Normal Maps: in which space are the normals encoded?



- Tangent space: Tangent Space Normal-Maps (the standard kind, in games)
  - ☹ extra attributes are now needed per vertex:
    - The tangent space:
      - Normal direction
      - Tangent direction
      - Bitangent direction

basically, a TS normal map specifies how to modify the per-vertex normal instead of replacing it

  - ☺ normal-map can be shared by different objects
  - ☺ non injective UV-maps can be used
    - e.g., the normal-map can be tiled
    - e.g., symmetries can be exploited
  - ☺ normal-map is independent from the mesh
    - e.g. can be constructed without knowing the mesh

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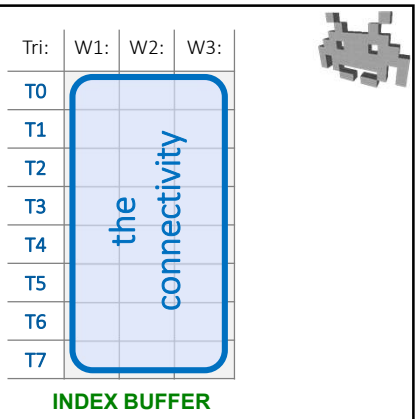
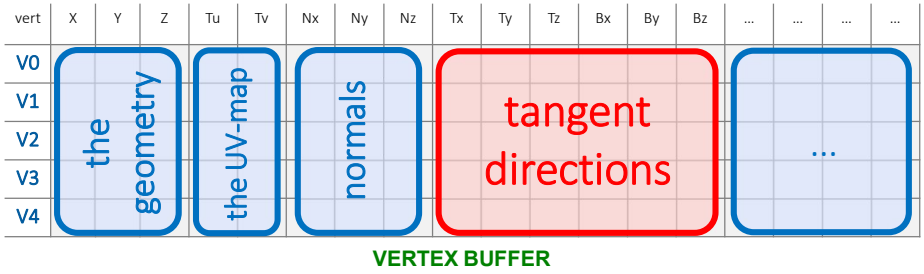
Tangent directions are mesh-attributes





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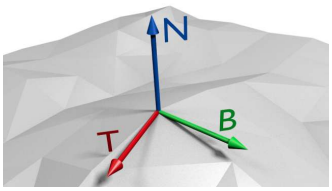
Tangent space (aka TBN space)

- A vector space defined ∀ point of the surface:
  - Z axis: Normal
    - orthogonal to surface
  - X and Y axis: tangent vectors
    - parallel to the surface
    - X = Tangent
    - Y = "Bi-Tangent"
      (sometimes, but inappropriately: *Bi-Normal)



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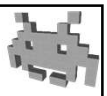
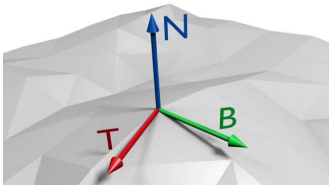
Tangent space (aka TBN space)



- How to store them?
  - As 3 versors stored as (per-vertex) **attributes**
    - So, they are interpolated inside faces (like any other attribute)



  - Optimizations are possible!
    - Not necessarily stored as 3 vectors (9 scalars)
    - E.g.: instead of storing B, we store N and T, then B = N × T
  - Note: they have discontinuities
    → seams (vertex duplications) are necessary
    - In first approximation, the same ones required by the UV-map (but non only! why?)

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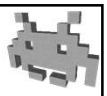
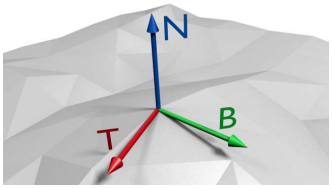
Tangent space (aka TBN space)



- How to compute them?
  - Normal
    - as usual (see lecture on mesh)
  - Tangent & Bi-Tangent
    - determined by the UV-map!
    - T = gradient of U coordinate
    - B = gradient of V coordinate



- details:
  - All three are defined (and constant) inside faces, then averaged at vertices (see per-vertex normal computation)
  - T,B,N can be *only approximatively* orthogonal to each other
  - T,B,N reference frame can be left-handed or right-handed (even different "handedness" in different parts of the same mesh)

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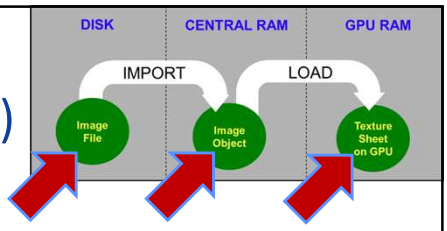
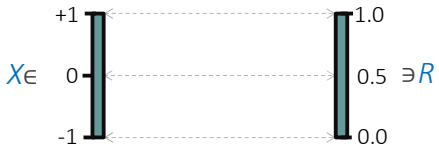
Normal-map: storage (as an rgb image)



- Idea: store it as an RGB texture
  - $R \leftrightarrow X$
  - $G \leftrightarrow Y$
  - $B \leftrightarrow Z$

(because normals are unit vectors)

- but $X,Y,Z \in [-1,+1]$ while $R,G,B \in [0,+1]$
  thus, a linear mapping is needed:



$$R = \tfrac{1}{2}(X + 1)$$
$$X = 2R - 1$$

- Advantage: we can use compressed interchange file format intended for RGB images (e.g. png, jpg) for textures
- Note: other, more efficient representations of versors exists

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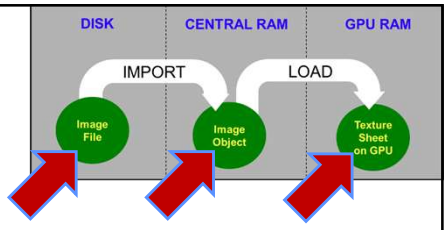
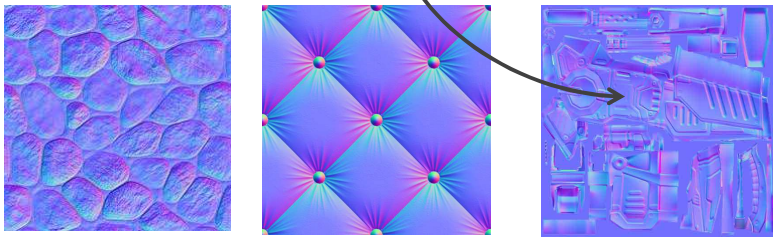
Normal-maps: storage (as a texture)



- Examples of tangent space normal-map

Prevailing normal : X=~0 , Y=~0 , Z=~1
⇒
Prevailing color: R =~0.5 , G=~0.5, B=~1
(~light blue)



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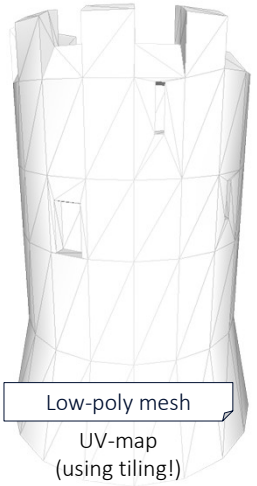
E.g.: Tiled (tangent space) Normal Maps

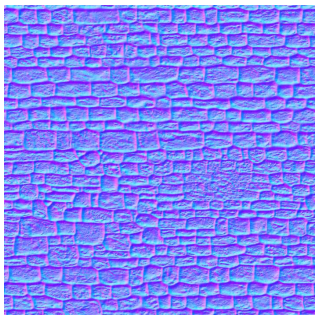
not even possible, with object-space NM!



Low-poly mesh

UV-map
(using tiling!)
Tangent dirs.

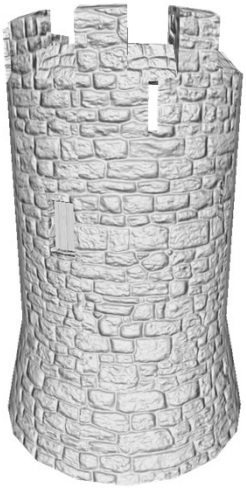
+



Normal-map

Tileable!

=



assets courtesy of "Mount&Blade" (Talesworlds)

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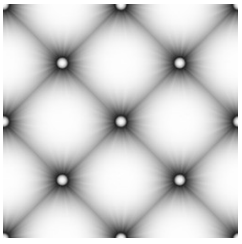
Bump-maps assets at a glance
(can you tell which is which?)

Tangent Space
Normal map

the default kind

Object Space
Normal map



Displacement
Map (scalar)

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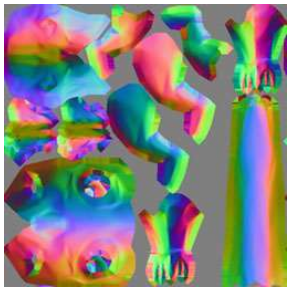
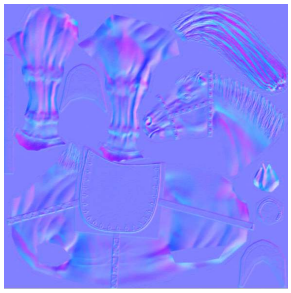
Spot the difference



Object Space Normal map

1:1 UV-map
right leg ≠ left leg



(Tangent Space) Normal map

UV-map NOT injective
Exploited symmetries!
Left side of head = right side of head

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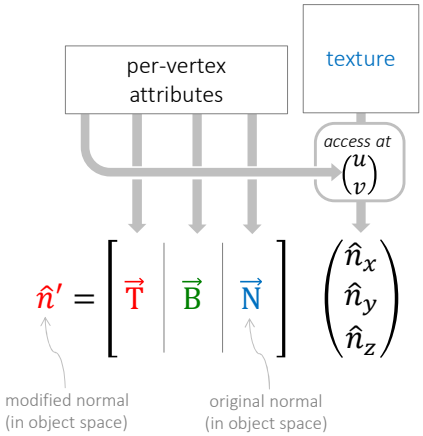
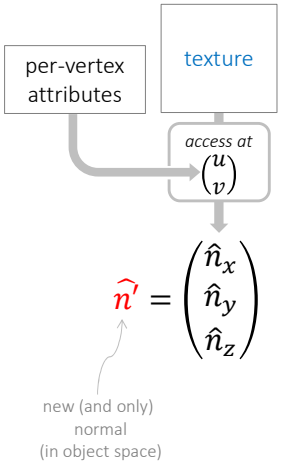
Normal Maps types: implementation

Tangent Space Normal-maps



$$= \hat{n}_x \vec{T} + \hat{n}_y \vec{B} + \hat{n}_z \vec{N}$$

Object Space Normal-maps



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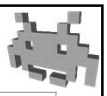
Normal map comparison (a summary)



Object Space Normal map:	Tangent Space Normal map:
Replaces the normals of the object	Modifies the normals of the object
No normal attribute required on the mesh anymore	Requires two extra attributes on the mesh: T an B versors (in addition to the normal)
Constructing the texture requires to know the mesh it will be applied to	Textures can be constructed independently from the mesh (just like a color map!)
E.g., a normal map cannot be constructed from a displacement map (w/o the mesh)	E.g., a normal map can be constructed from a displacement map
It's impossible to share a normal map between models (barring exceptions)	Normal maps can be shared between different models
"unwrapping" UV-maps required (barring exceptions)	Can be applied to non-injective UV-maps
E.g., no tiled textures. E.g., no symmetry exploitation	E.g., tiled textures ok, E.g., symmetry exploitation ok
E.g., east-wall and south-wall of a castle: different normal maps required	E.g., east wall and south wall of a castle: same normal map.
Looks colorful (if encoded as RGB)	Looks azure-ish (if encoded as RGB)

THE STANDARD TYPE, IN GAMES

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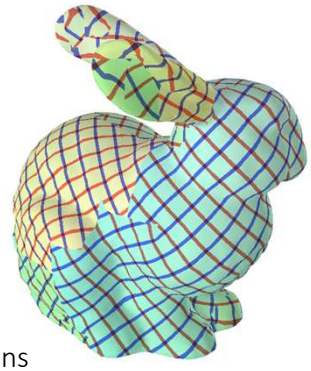
How to construct T and B vectors from the UV-map (a mesh preproc.)



- Concept (a mental experiment)
  - STEP 1: color a texture with a grid
    - horizontal blue lines = U direction
    - vertical red lines = V direction
  - STEP 2: apply it to the Mesh!
  - STEP 3: look at it:
    - the T vectors are the Blue lines directions
    - the B vectors are the Red lines directions
- T and B directions are defined in a triangular face
  - then, they are averaged at vertices
  - (just like the normal directions!)

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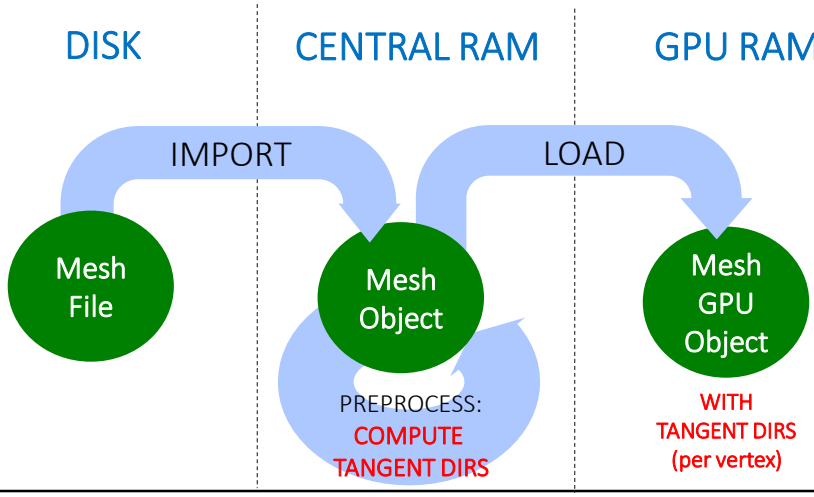
Extracting Tangent/Bitangent directions from the UV-map



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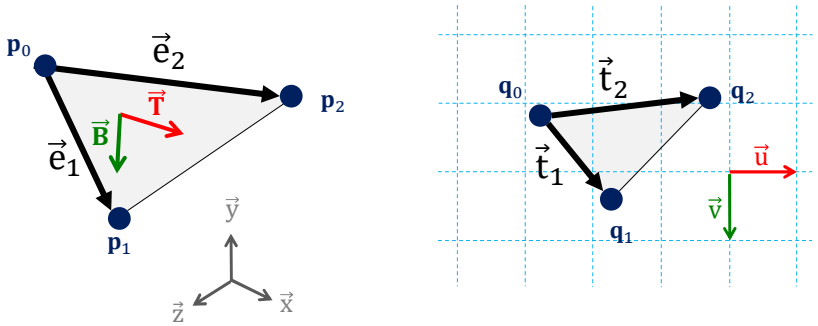
Extracting T and B vectors from the UV-map (in a triangle)

- Object Space (3D)
- Texture Space (2D)



Idea:

$\vec{u}$ is some linear combination of $\vec{t}_1$ and $\vec{t}_2$ $\Rightarrow$ $\vec{T}$ is the same linear combination of $\vec{e}_1$ and $\vec{e}_2$

$\vec{v}$ is some linear combination of $\vec{t}_1$ and $\vec{t}_2$ $\Rightarrow$ $\vec{B}$ is the same linear combination of $\vec{e}_1$ and $\vec{e}_2$

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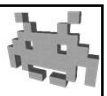
Extracting T and B vectors from the UV-map (in a triangle)



- Input: 3D vertices $\mathbf{p}_{0,1,2}$ and 2D vertices $\mathbf{q}_{0,1,2}$
- Find 3D *edge vectors* $\vec{e}_{1,2}$
  and 2D *edge vectors* $\vec{t}_{1,2}$
- Find scalars a, b and c, d such that…

$$a\,\vec{t}_1 + b\,\vec{t}_2 = \vec{u} = \begin{bmatrix}1\\0\end{bmatrix} \qquad c\,\vec{t}_1 + d\,\vec{t}_2 = \vec{v} = \begin{bmatrix}0\\1\end{bmatrix}$$

- Then

$$\vec{T} = a\,\vec{e}_1 + b\,\vec{e}_2 \qquad \vec{B} = c\,\vec{e}_1 + d\,\vec{e}_2$$

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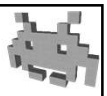
Extracting T and B vectors from the UV-map (in a triangle)



- Input: 3D vertices $\mathbf{p}_{0,1,2}$ and 2D vertices $\mathbf{q}_{0,1,2}$
- Find $\vec{e}_1 = \mathbf{p}_1 - \mathbf{p}_0$ $\qquad \vec{t}_1 = \mathbf{q}_1 - \mathbf{q}_0$
  $\vec{e}_2 = \mathbf{p}_2 - \mathbf{p}_0$ $\qquad \vec{t}_2 = \mathbf{q}_2 - \mathbf{q}_0$
- Find scalars a, b and c, d such that…

in matrix form: solve with a 2x2 matrix inversion

$$\left[\vec{t}_1 \,\middle|\, \vec{t}_2\right]\begin{bmatrix}a & c\\ b & d\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} \Rightarrow \begin{bmatrix}a & c\\ b & d\end{bmatrix} = \left[\vec{t}_1 \,\middle|\, \vec{t}_2\right]^{-1}$$

- Then

$$\vec{T} = a\,\vec{e}_1 + b\,\vec{e}_2 \qquad \vec{B} = c\,\vec{e}_1 + d\,\vec{e}_2$$

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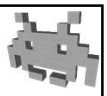
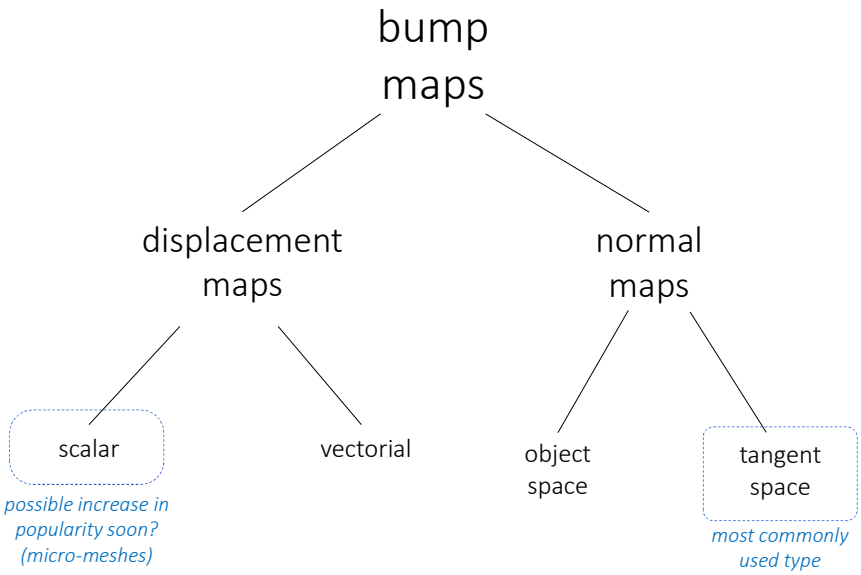
Types of Bump maps: summary





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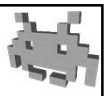
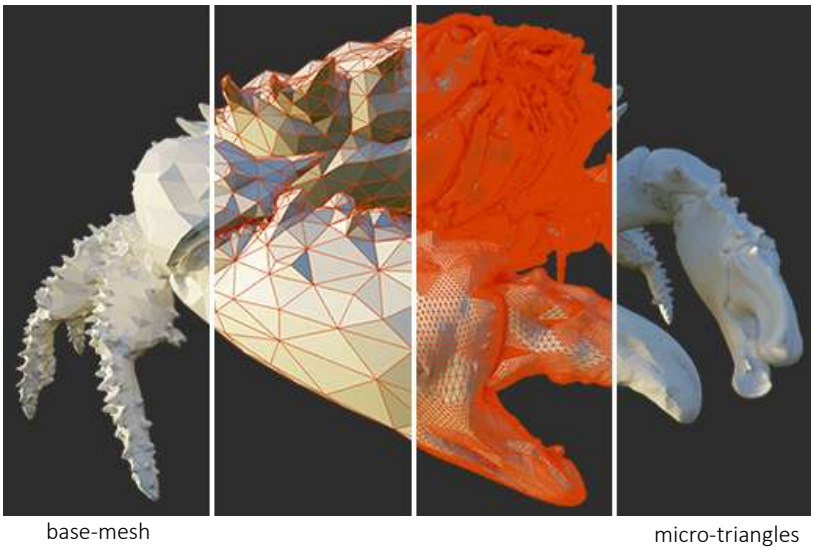
μ-meshes (micro-meshes)





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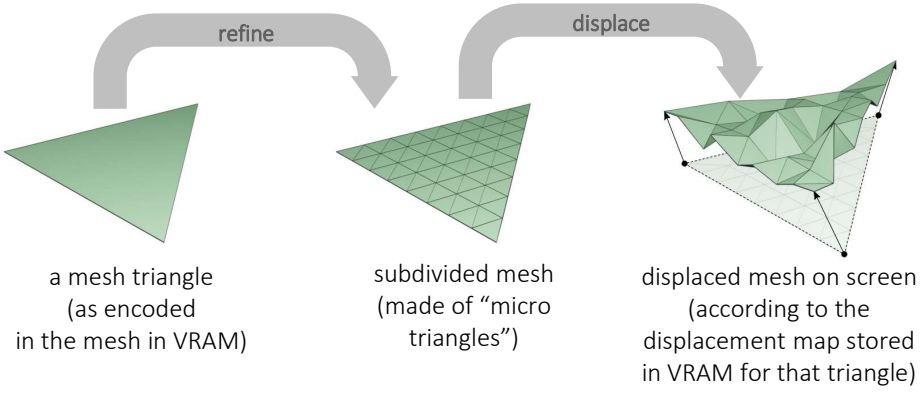
Micro-meshes (μ-meshes)



- A mesh with a specially formatted scalar displacement map
- Displacement map stored per triangle: no UV-map necessary
- During rendering, in GPU: refine + displace
- Proprietary by NVIDIA

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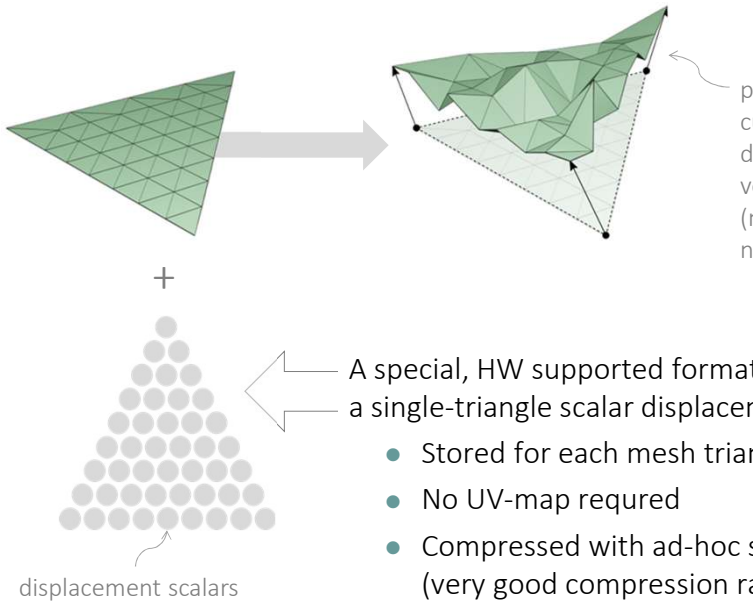
μ-meshes displacement



A special, HW supported format for a single-triangle scalar displacement-map

- Stored for each mesh triangle
- No UV-map requred
- Compressed with ad-hoc schema (very good compression rates)

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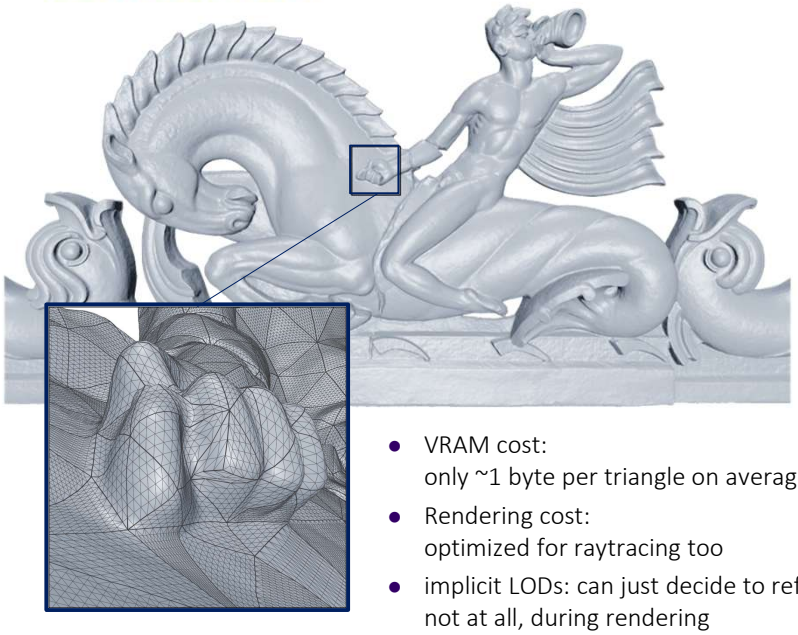
MicroMeshes



- VRAM cost:
  only ~1 byte per triangle on average!
- Rendering cost:
  optimized for raytracing too
- implicit LODs: can just decide to refine less, or not at all, during rendering

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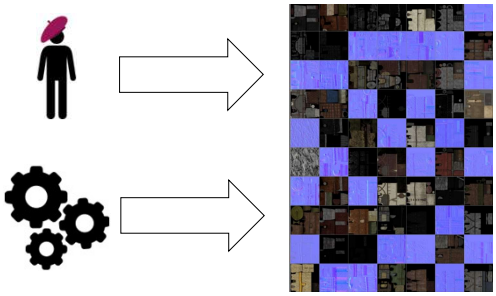
Something about authoring textures

- How are textures authored / created?
  - As a part of asset production pipelines
  - Let's see the basics on authoring of color-maps (or other material), normal maps, and more



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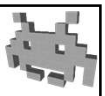
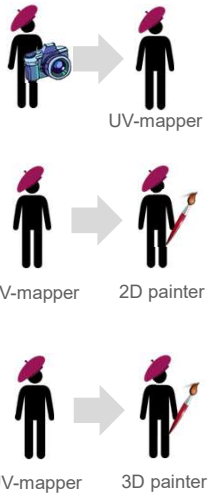
RGB-maps authoring: when (and how)?



- Image *first, then* UV-map
  - e.g., images that are photos
  - e.g., tileable images
- UV-map *first, then* paint in 2D
  - paint with 2D app (e.g. photoshop)
- UV-map *first, then* paint in 3D
  - paint with-in 3D modelling software,
  - Paint strokes (e.g. brushes) done on the model, recorded in the texture



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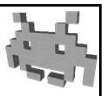
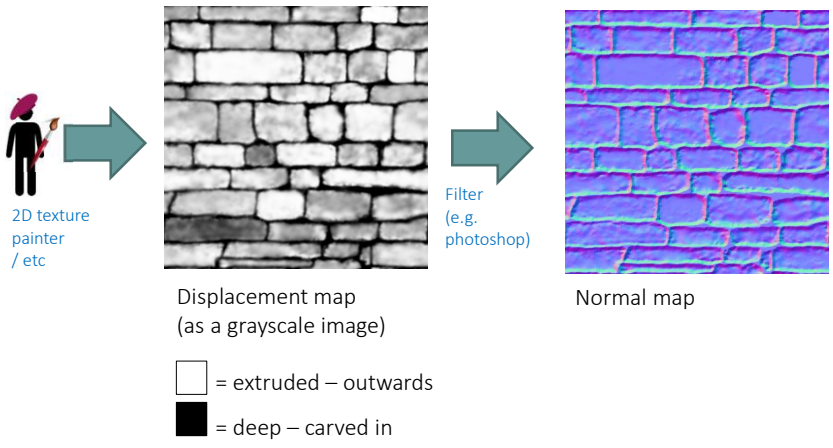
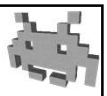
How are normal-maps obtained? (1/5) from a displacement map





111

How are normal-maps obtained? (1/5) from a displacement map



- Input: a scalar displacement map
  Output: a normal map
  - a texel at coords *u,v* corresponds to a 3D point (*u* , *v* , height[*u*,*v*])
- Algorithm (2D image processing):
  - ∀ texel **t** of displacement map, compute best fitting plane around **t**
    - Consider all 3D points in a 3×3 patch surrounding **t**
      - or 5×5, or 7×7…
    - Find plane minimizing the summed squared distance from them
    - It's a least-squares minimization problem
  - The normal of this plane is the normal for **t**
- Resulting normal map is expressed in tangent-space
  - By definition! (one big advantage of Tangent Space NM)
  - Can be converted into Object-Space if needed (for a given UV-mapped mesh – injective maps only of course)

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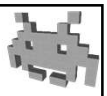
How are normal-maps obtained? (2/5) painting (sculpting?) on 3D



- Direct painting of normal- on the model
  - (can be done, e.g., with Z-brush, Blender…)
  - Similar to: 3D painting of color-maps
    - but artist paints geometric surface orientations, not colors
  - Similar to: mesh sculpting
    - but, for each stroke, the system updates the normal on the texture-map, not the geometry on the mesh

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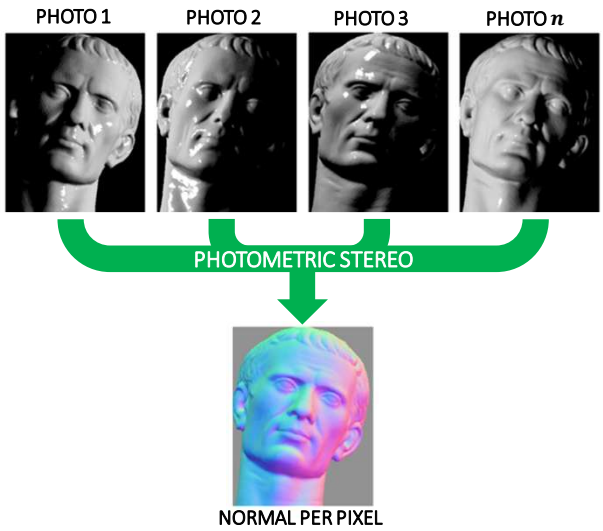
How are normal-maps obtained? (3/5) captured from reality



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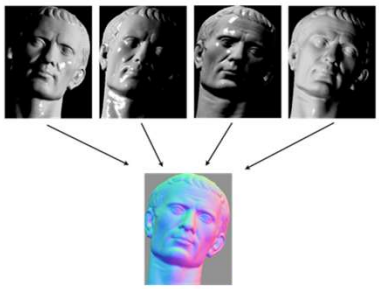
How are normal-maps obtained? (3/5) captured from reality

- Example: "Photometric Stereo"
  - a form of "inverse lighting"
  - Aka: "shape from shading"
  - a computer vision technique
- Input: *n* real images
  - Exact same viewpoint
  - Different illumination
  - (possibly, controlled and known)
- Output: a Normal Map
  - expressed in… image space
  - can be converted in object space, then in tangent space



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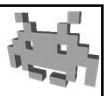
How are normal-maps obtained? (3/5) captured from reality



- Normal map estimation from images
  - Traditionally, many pictures are required in input
  - Traditionally, controlled illumination is required (I must place lights in known position)
  - With Machine Learning, it's becoming possible to use a single image with natural illumination
- Basic Idea:
  - input: a photo of a brick wall
  - output: a diffuse map + a normal map + a specular map etc. In short, an entire Material
- Emerging area. Many (commercial) tool already exists.

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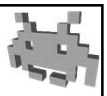
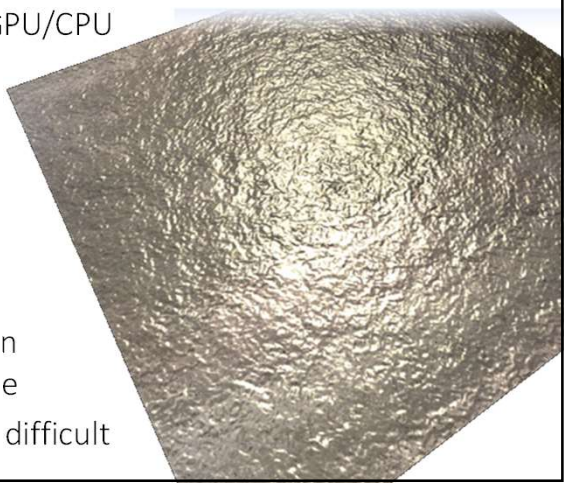
How are normal-maps obtained? (4/5) procedural generation (not frequent)



- Usual considerations about procedurality:
  - Saves RAM, costs GPU/CPU
  - Can be baked in preprocessing (becomes an asset)
  - Or, can be generated at run-time
  - Bonus: no repetition artifacts, animatable
  - Problem: control is difficult



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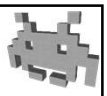
How are normal-maps obtained? (5/5) from a high-resolution model



Texture baking

- aka: detail recovery / “detail texture” synthesis

- input:
  - a hi-res mesh A with per-vertex attributes
  - a low-poly mesh B, with an injective UV-map
  - with A and B representing the same object
- output:
  - one or more textures for B storing the attributes of A
- a fully automatic process!

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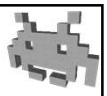
Texture baking: texture synthesis from hi-res models



- examples of inputs A & B:
  - low-poly mesh A obtained from a hi-res mesh B via automatic simplification or manual retopology
  - hi-res mesh B obtained from low-poly mesh A via sculpting
- examples of output:
  - attributes = normals → an object-space normal map is produced
  - attributes = base colors → a diffuse maps is produced
  - store distances between A and B (no attribute required) → a displacement map is produced
  - attributes = baked (global) lighting / AO → a light-map / AO-map is produced (see later)

then converted to tangent space (using mesh A)

common case!

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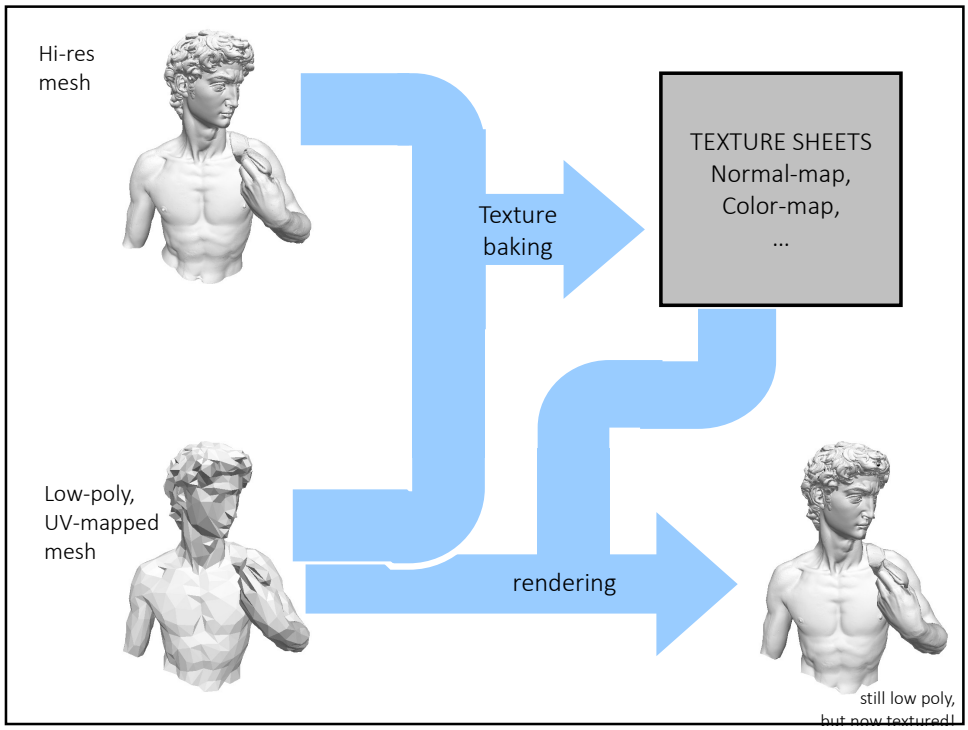
Hi-res
mesh
Texture
baking
TEXTURE SHEETS
Normal-map,
Color-map,
...
Low-poly,
UV-mapped
mesh
rendering
still low poly,
but now textured!

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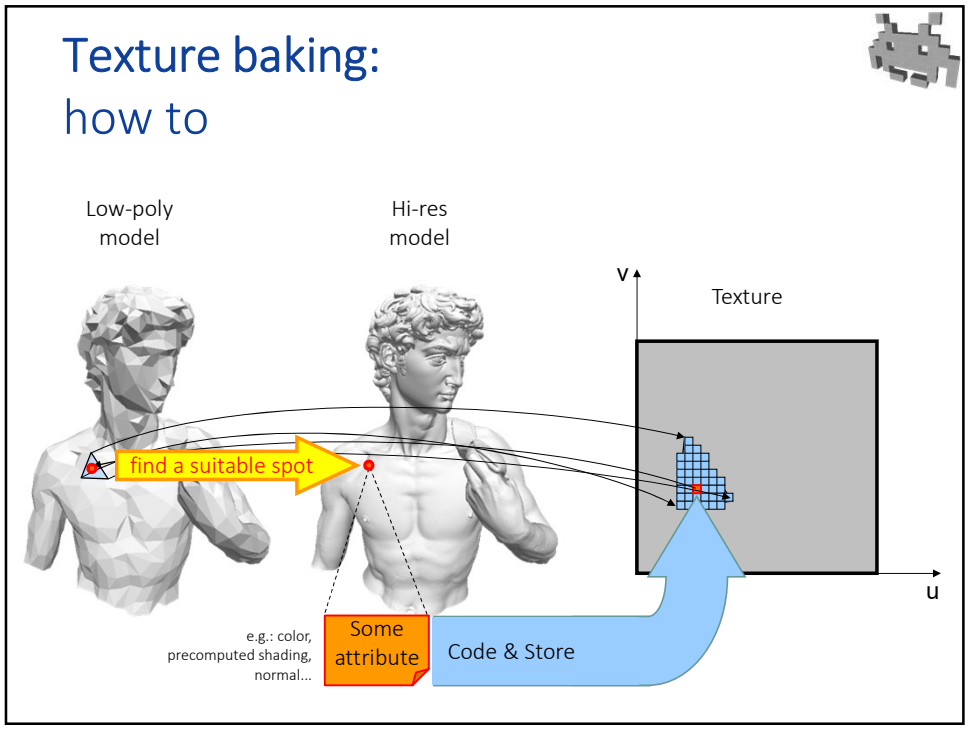
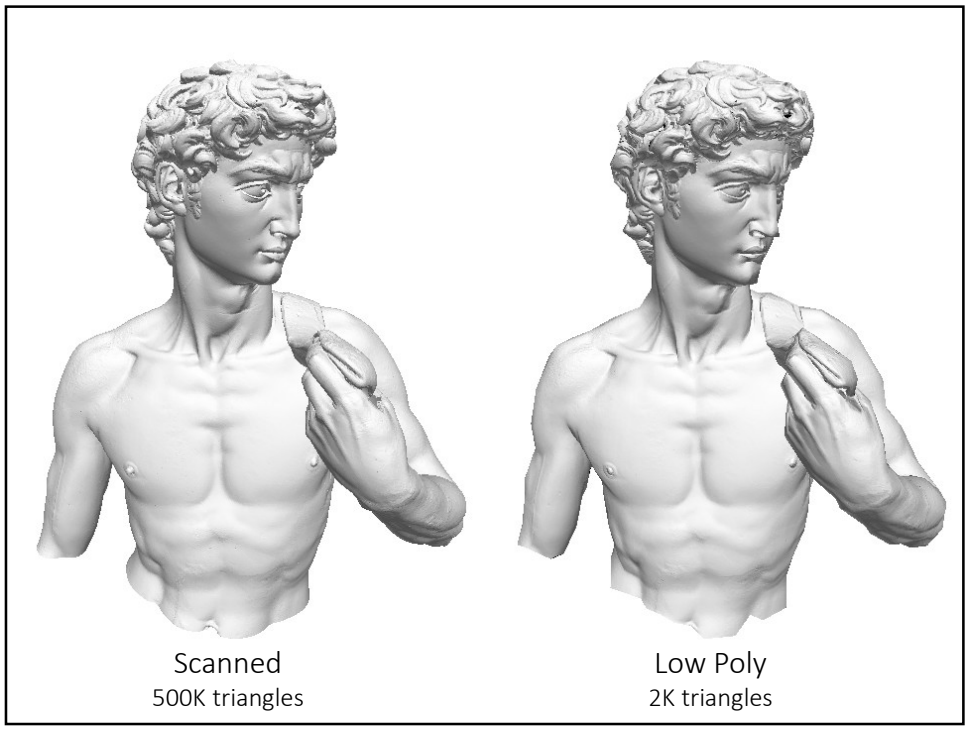
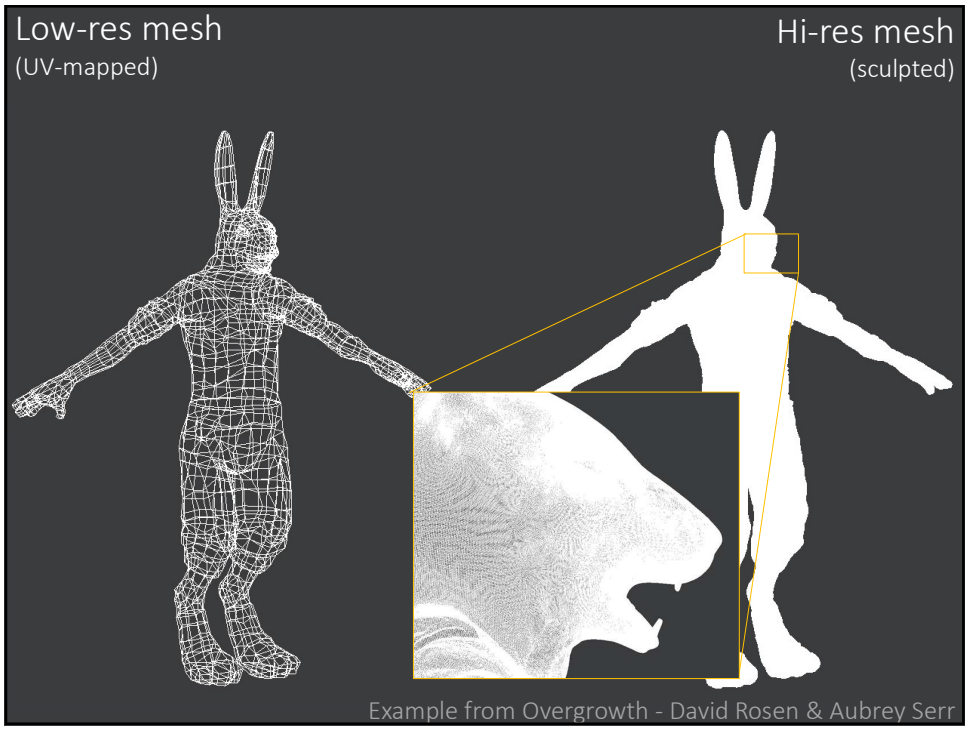

Texture baking:
how to
Low-poly
model
Hi-res
model
v
Texture
find a suitable spot
u
e.g.: color,
precomputed shading,
normal...
Some
attribute
Code & Store

121


Scanned
500K triangles
Low Poly
2K triangles

122


Low-res mesh
(UV-mapped)
Hi-res mesh
(sculpted)
Example from Overgrowth - David Rosen & Aubrey Serr

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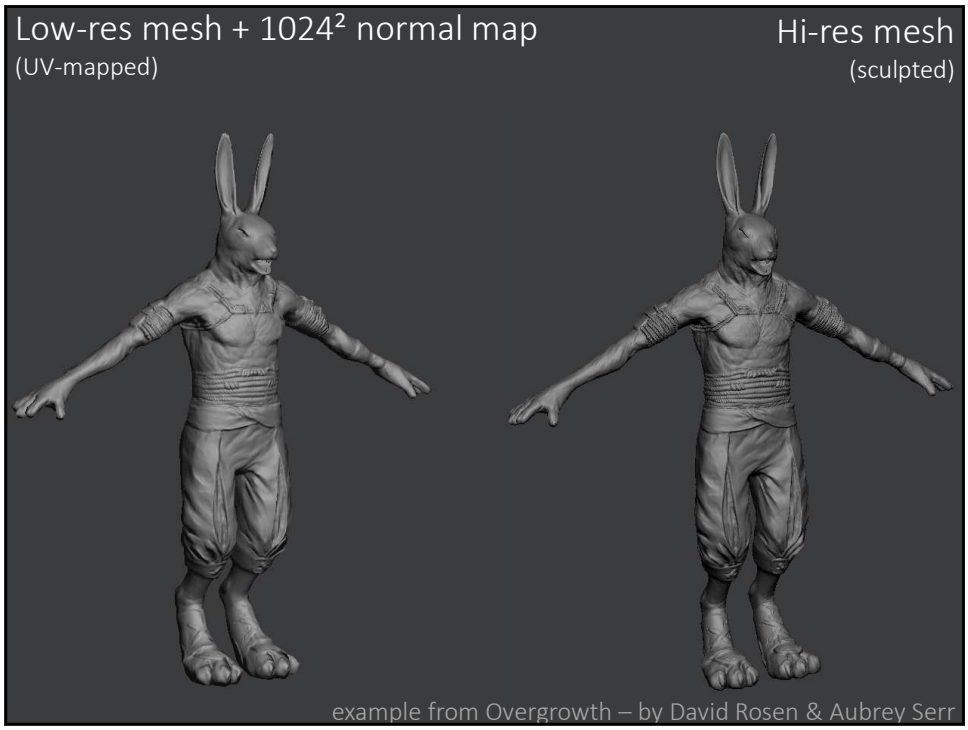

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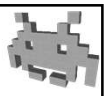
Signals typically stored in textures (in videogames) 4/4



Any type of texture can be backed (see the list)
But these types can only be baked!

Baked values:

- Each texel = a *baked* lighting value
  the one computed by the lighting function
  - The texture sheet is a (baked) "light-map"
  - Instead of computing lighting on the fly during rendering, we bake in preprocessing
  - During rendering, we access only the texture instead of computing the lighting. Fast!
  - Advantage: lighting now can be arbitrarily complex. Good for global lighting! (e.g. shadows, multiple reflections, etc)
- Each texel = an *computed* ambient occlusion map
  - The texture sheet is an "AO-map" (see below)

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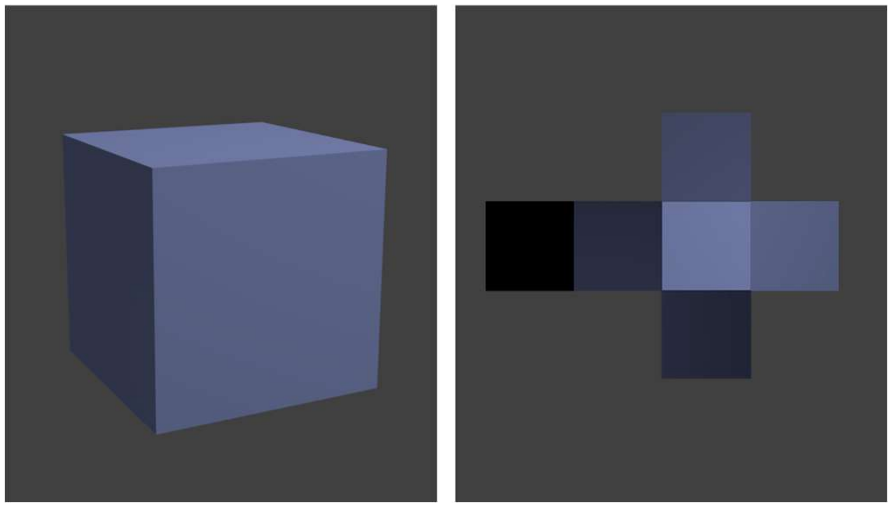
Light-map (a toy example)



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Lighting model (reprise):
Blocked lights (that is, shadows)

- In the lecture on materials, we considered "local" lighting models, where we assume that the rest of the 3D scene doesn't count
  - Only (1) the bit of surface being lit, (2) light sources, and (3) the observer, count
- In reality, the lighting equation can account for light "blockers"
  - One example of a "global" lighting effect
- The two "direct" terms (diffuse & specular) are negated (for each light source) when a "blocker" shadows the surface from that light
  - In all or in part: the two terms are multiplied by a "shadow factor" (in 0 to 1)
  - See Lecture on rendering (or courses on *Real Time Graphics Programming*) for rendering algorithms to compute this factor
- The ambient term is to be negated when the point on the surface is surrounded by many blockers
  - the term is multiplied by an "ambient occlusion" (AO) factor (in 0 to 1)
  - this term depends on the local arrangement of each point around the mesh
  - it can be backed into a texture: the AO-map!

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Lighting model (reprise):
Ambient occlusion

CAST SHADOWS negate

AMBIENT OCCLUSION negates

direct light terms (per light) | ambient light

diffuse term | specular term | ambient term

$$(\hat{n}\cdot\hat{L})\begin{pmatrix}d_R\\d_G\\d_B\end{pmatrix}\otimes\begin{pmatrix}L_R\\L_G\\L_B\end{pmatrix}+(\hat{n}\cdot\hat{H})^{E}\begin{pmatrix}s_R\\s_G\\s_B\end{pmatrix}\otimes\begin{pmatrix}L_R\\L_G\\L_B\end{pmatrix}+\begin{pmatrix}a_R\\a_G\\a_B\end{pmatrix}\otimes\begin{pmatrix}A_R\\A_G\\A_B\end{pmatrix}$$

$\hat{H}$ = nlerp($\hat{V}$, $\hat{L}$, 0.5)

material parameter
light parameter
geometry

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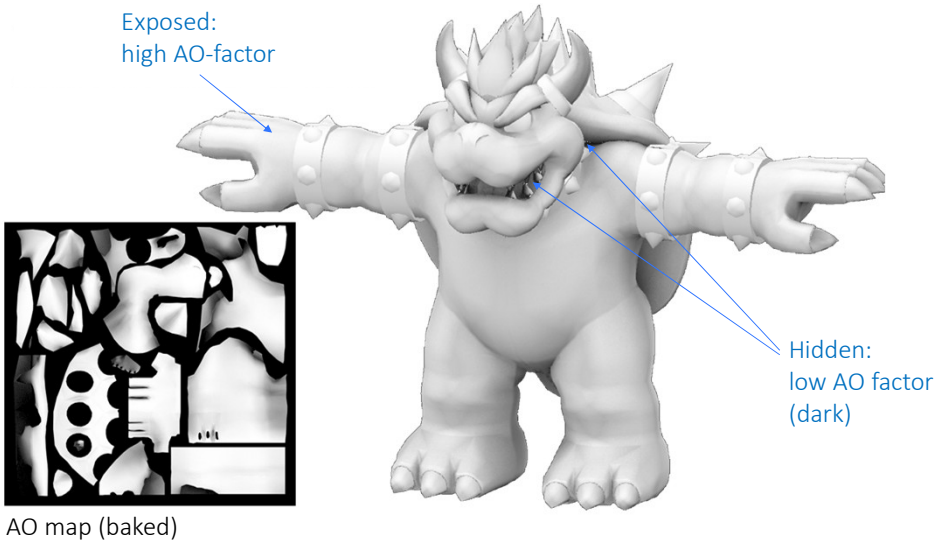
Baking AO-map for a model



AO map (baked)
NOTE: this requires UV unwrapping (injective UV-map), like any baked texture

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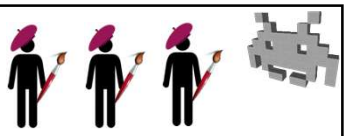
Asset production pipeline
(a general concept in game-dev)



- A sequence of stages used to produce assets. For each stage:
  - what is produced, starting from what
  - using which tool(s), by which artist(s)
  - storing which intermediate result(s), in which format, etc.
- Different pipelines for different classes of objects
  - E.g. characters ≠ sceneries (“props”) ≠ equippable armours ≠ …
  - Note: within a given game, all assets in a class are usually quite uniform (comparable resolution, same set of texture sheets, same formats, etc.)
- In the past lectures, we mentioned many possible steps
  - low poly modelling, sculpting, uv-mapping, LOD-ding…
  - texturing, geometric proxy construction, …
  - TODO: the parts about animations (skinning + rigging + animation…)
  - TODO: the parts about materials
- Identifying a good pipeline is not trivial!

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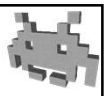
Asset production pipeline: for example



1. Concept drawings
   - by 2D artists
2. Low-poly model A
   - by 3D modelers, using low-poly editing tools
3. UV-mapping of A
   - by UV-mappers, or by automatic tools. output: an injective UV-map of A
4. Subdivision, then digital sculpting of Hi-Res model B
   - by a 3D modeler, using digital sculpting tools
5. Painting over B
   - using a 3D painter, and producing per-vertex colors
6. Texture baking
   - Automatic construction of three Textures for A with attributes from B:
     - Normals from B, (produces a normal map)
     - Colors from B (produces a diffuse map)
     - Baked lighting from B (produces a light-map)

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