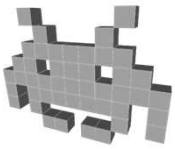
3D Videogames 2021/2022
Univ. degli Studi di Milano



Materials (and lights) In videogames

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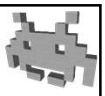
Course Plan



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

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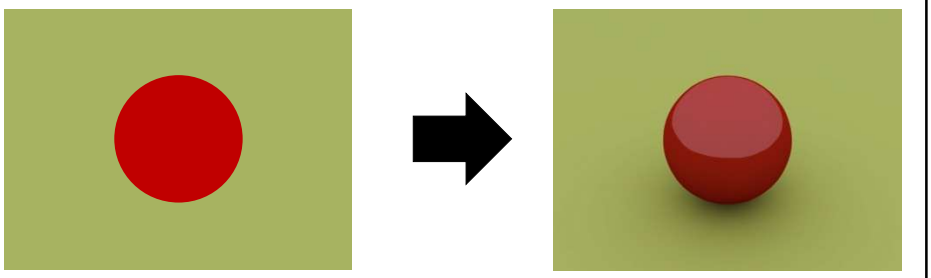
Lighting



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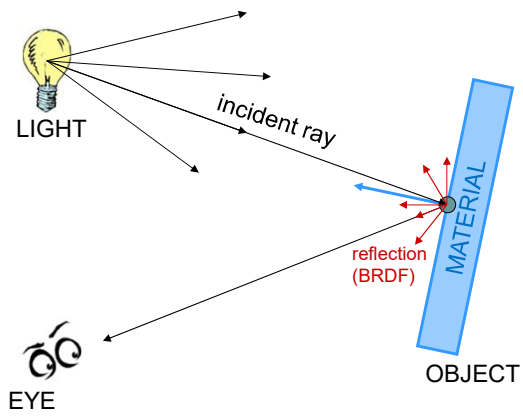
Local lighting



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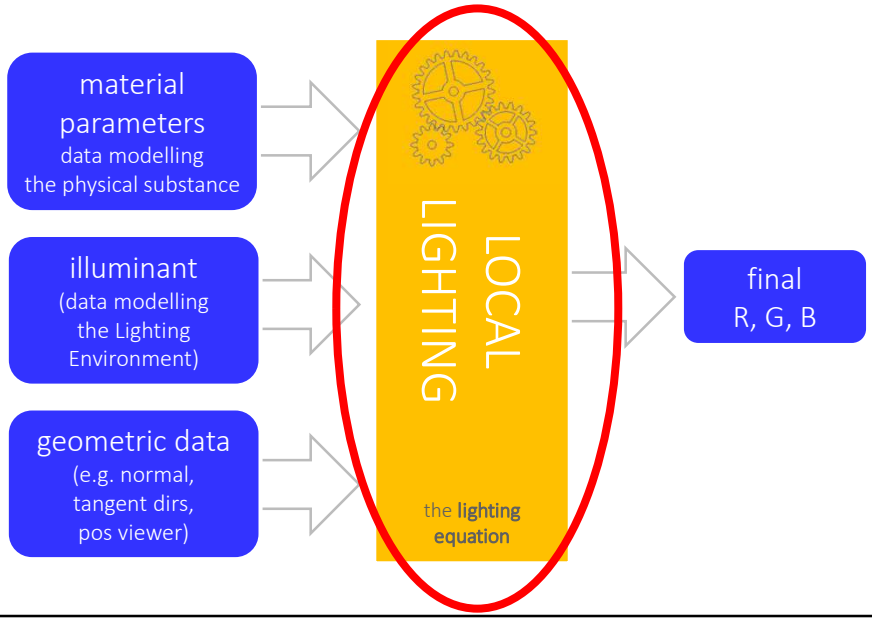
Local lighting



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Lighting equations

- Different equations can be employed…
  - Phong — the basic model, historically used in games for decades
  - Beckmann
  - Heidrich–Seidel
  - Cook–Torrance
  - Ward (anisotropic)
  - …
  - + additional Fresnel effect
- with a varying levels of
  - computational complexity
  - realism
  - material parameters required
  - richness of simulated effects

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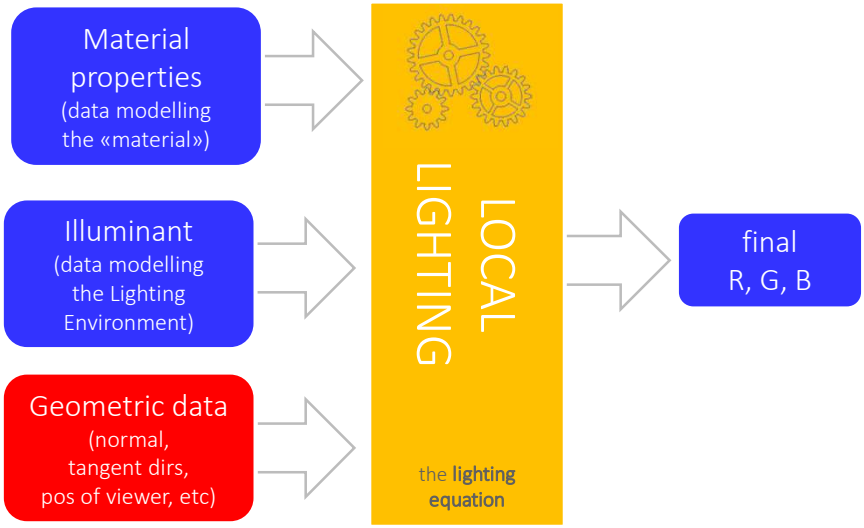
Geometric Data



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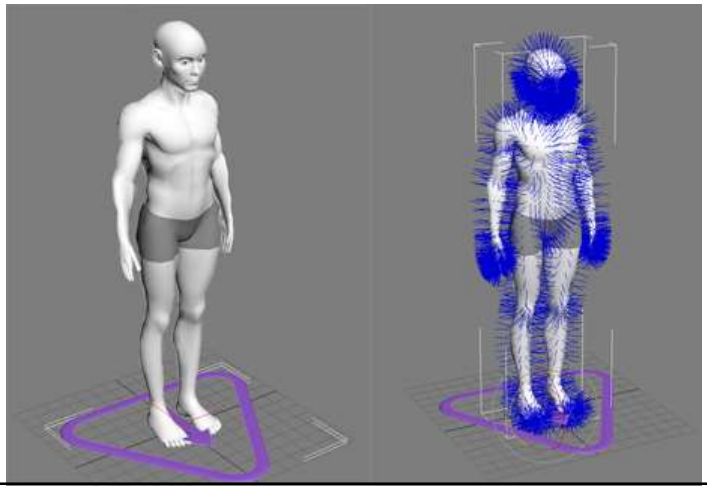
The geometry in lighting: normals

- Per-vertex attribute of meshes, and/or stored in normal maps



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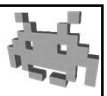
View-dependent lighting. Anisotropic lighting.



- A view-dependent lighting equation (or material) is one which uses the view direction $\hat{v}$
  - Consequence: its results cannot be backed! (why?)
  - Which terms of the lighting equations above are view-dependent"?
  - Otherwise, it's view-independent
- An anisotropic lighting equation (or material) is one which uses the tangent directions
  - Simulates real-world materials such as: satin, velvet, fabric
  - Otherwise, it's isotropic

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Tangent directions are used for anisotropic materials

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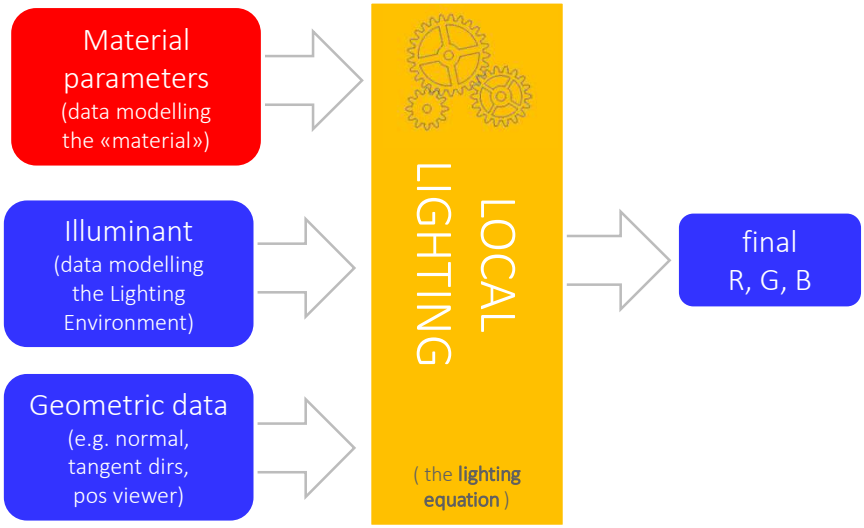
Material model



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Material models

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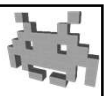
⚠ Terminology: «material» has 2 different meanings



- in Computer Graphics: the material *model*
  - a set of parameters describing the behavior of a physical substance (such as plastic or wood) to light
  - a part of the input of the (local) lighting equation
  - for example, its diffusive color or its level of shininess
- in game engines: the material *asset*
  - an asset combining:
    - a set of textures (e.g., diffuse + specular + normal map)
    - a set of shaders (e.g., vertex + fragment shader)
    - a set of global parameters (e.g., glossiness, ambient factors…)
    - a set of rendering flags, such as… back-face culling ON/OFF;
  - basically, it corresponds to the status of the rendering engine when a mesh is drawn

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Material *asset*

Describes a material model, but also:

- How are the parameters stored, for example
  - …in the texels of a texture?, or,
  - …as a global parameter (uniform material)?, or,
  - …as attributes of the currently rendered mesh?
- How is the lighting computed for the material, that is
  - The "shaders" that gather the parameters, and compute the lighting equation (see last lecture)
  - Settings and flags for the GPU rendering (e.g. back-face culling, depth test)
  - Which rendering passes must be done
- It includes bump-maps (any kind, e.g. normal-maps):
  - which technically, describe the shape, not the material

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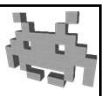
Material Asset = status of renderer



To render a mesh…

- Load…
  - make sure all data is ready in GPU RAM
    - Geometry + Attributes
    - Connectivity
    - Pose
    - Textures
    - Shaders
    - Material Global Params
    - Rendering Settings
- …and Fire!
  - issue the Draw Call

THE MESH ASSET

THE ANIMATION FRAME

THE MATERIAL **ASSET**

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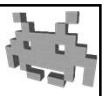
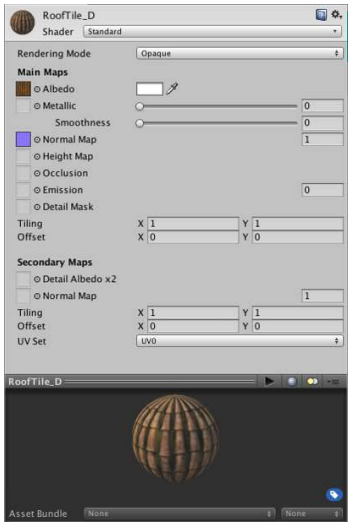
Material Assets





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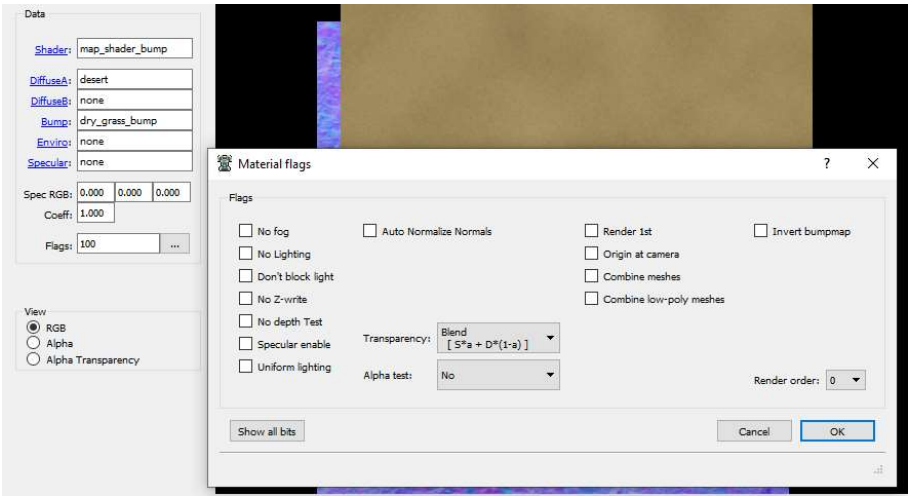
Material Assets



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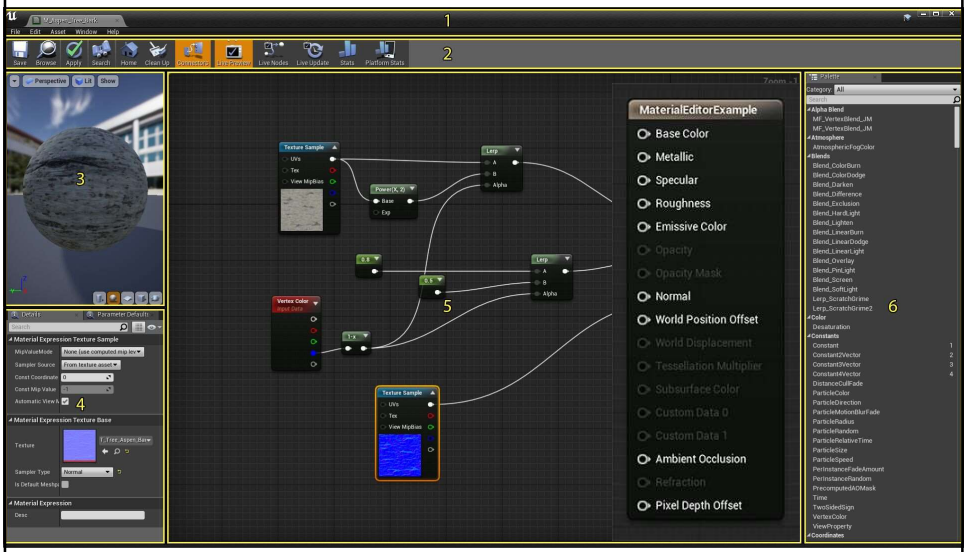
Material Assets



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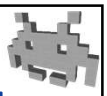
Material *Model* = a description of how a physical surface / substance reacts to light



- Q: which set of parameters is a «material»?
- A: it is determined by the chosen lighting equation

material model = the arguments of the lighting equation accounting for the physical substance that the surface is locally made of

- whichever is the answer, each parameter can be stored:
  - per Material Assets, as global parameters, or — uniform mat
  - per Vertex of a Mesh, as attributes, or — non-uniform, aka "spatially varying", material
  - per Texel of a texture sheet (maximal freedom) — non-uniform, aka "spatially varying", material

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(Local) Material Model: which physical characteristics does it reflect?

1) The physical substance (of a point on the surface)
   - Does it absorb photons, does it bounce them away?
   - Is it transparent to photons? (i.e. can photons pass through it?)
   - How does that depend on the frequency, that is, color of the photon? (that's what gives objects their "color"!)
   - These things depend, in turn, on electric conductivity, etc
   - E.g.: metals look shiny, because (⚠ over-simplification warning ⚠) light bounces off a cloud of shared electrons surrounding them
2) The micro-shape of the surface (around a point), e.g.
   - A polished (smooth, at a micro-scale) surface looks more shiny
   - A wet surface (water layer is very smooth!) looks more shiny
   - A waxed surface (wax layer is smooth!) looks more shiny
   - A rough, unpolished surface looks dull / not shiny

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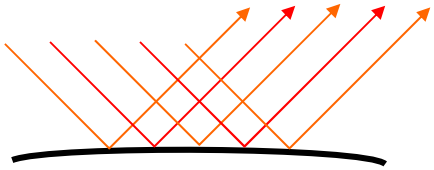
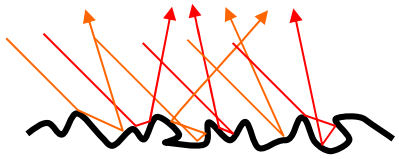
Material model and microshape





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The simplest choice for Material-model & lighting-equation:

A simple file-format for material assets, part of OBJ specification

- see: "OpenGL material", or OBJ material (.MTL files)
- This Lighting Equation is the sum of 4 terms:
  - "Ambient" + "Diffuse" + "Specular" + "Emission"
- The material is… a color multiplier for each term, therefore:
  - distinct multipliers for R, G and B
  - "Ambient" color
  - "Diffuse" color (aka "Base" color, aka "Albedo") — technically, only if it's gray-scale
  - "Specular" color (aka "Highlight" color)
  - "Emission" color — Often omitted, as it's zero for most materials
    (only for stuff *emitting* light – otherwise 0,0,0)
  - plus, one "Specular Exponent", aka "glossiness" or "shininess" (≥ 1, <128)

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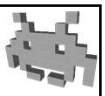
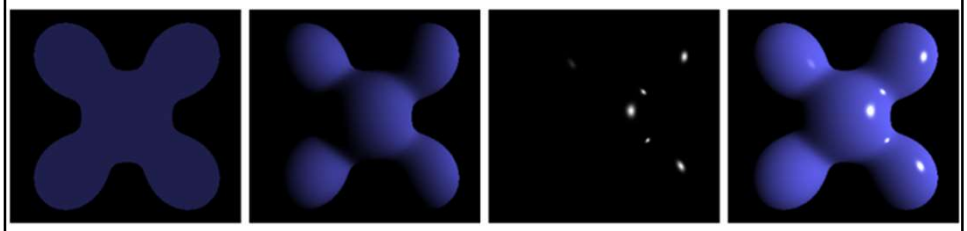
A lighting equation
(referred to as basic or «Phong» lighting equation)



- It's the sum of 3 terms:



ambient + diffuse (or "Labertian") + specular (or "Phong") = final

plus a constant additional term ("emission"), only for objects emitting light

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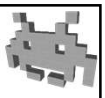
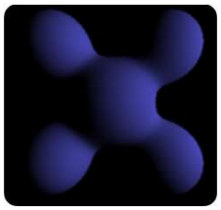
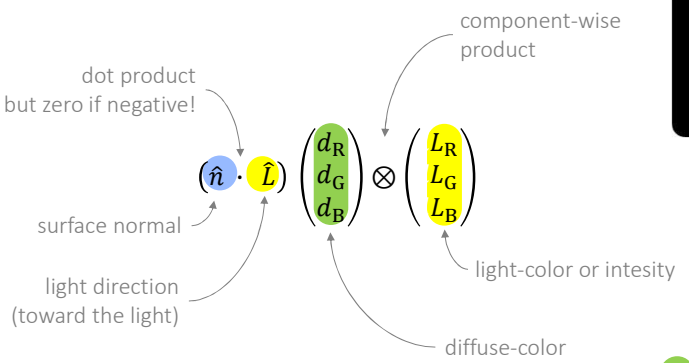
A basic lighting equation: diffuse term («Lambertian»)



- In formulas:





See CG course!

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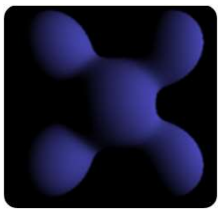
A basic lighting equation: diffuse term (aka «Lambertian»)



- info:
  - it's physically based
  - exhibited by dull materials (e.g., plasters, untreated wood)
  - used in any lighting equation
- material parameters used:
  - base color, (albedo, when grayscale), aka diffuse color, Lambertian color, or sometimes just color
  - with non uniform materials, the texture used to specify it is called diffuse-map or color map or just RGB map

implementation note: (applies to all formulas)
the versors in the dot-product must be in the same space! -- e.g., object space or world space

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The intuition behind the diffuse-term formula

The local orientation of the surface $\hat{n}$

The dot product between versors is a measure of their similarity!

The direction $\hat{L}$ the light is coming *from*

- When the normal direction is similar to the light direction, then the surface is oriented directly toward the light, so, it looks brighter
  - … from any viewing direction!
  - this is a view-independent effect: the view-direction is not involved in the formula

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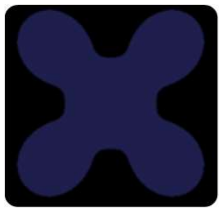
A basic lighting equation: ambient term

- In formulas:



$$\begin{pmatrix} a_R \\ a_G \\ a_B \end{pmatrix} \otimes \begin{pmatrix} A_R \\ A_G \\ A_B \end{pmatrix}$$

component-wise product

ambient light color or intesity

ambient-color

material parameter

light parameter

geometry

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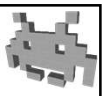
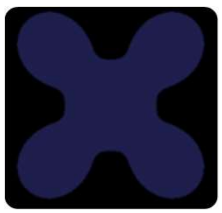
A basic lighting equation: ambient term: info





- based on the assumption: "a bit of light reaches the object from every direction"
  - e.g., from light bounces,
  - e.g. from unmodelled light sources
- without it, things not directly lit by lights are black (and it looks ugly)
  - it's very simple to compute, so why not
- uses parameters in the material:
  - ambient-color (RGB)
  - or, ambient-factor (scalar), then ambient-color = diffuse-color · ambient-factor
  - also called Ambient Occlusion factor (AO)
- as all parameters can be :
  - stored in textures: AO map (typically baked)
  - stored in vertices as attributes
  - it can also be computed on the fly (see SSAO, last lecture)

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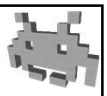
The intuition behind the ambient-term formula



- A bit of light will reach this point of the surface from *all* directions (so, surface normal does not count from this)
- In first approximation, this is proportional to:
  how exposed is this point of the surface (a constant), and
  how much light is around overall (another constant)

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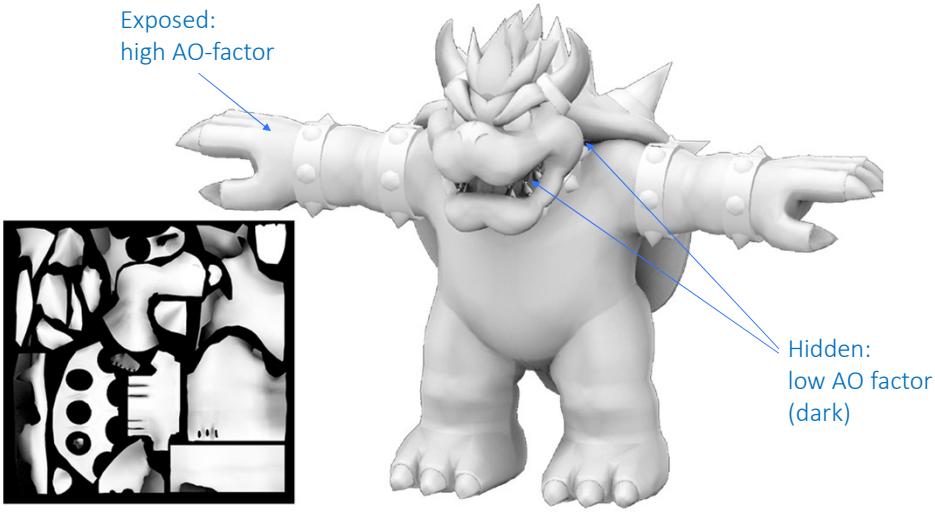
Baking AO map for a model



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

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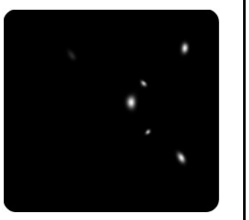
A basic lighting equation: specular term (aka «Blinn-Phong» term)



- In formulas:

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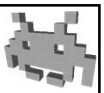
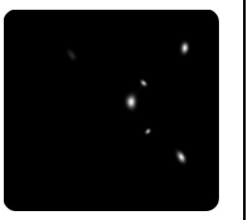
A basic lighting equation: specular term (aka «Blinn-Phong» term)





- info:
  - not physically based
  - not even energy conserving
  - basically, just a trick
  - simulates reflections ("highlights")
- material parameters used:
  - specular color
    determines the intensity and color of the highlight
    sometimes: it's diffuse color x a constant
    often > 1 – oversaturated highlight
  - specular exponent (or "glossiness")
    determines the SIZE of the highlight
    larger numbers → smaller highlight
- textures:
  - specular map and glossiness map
  - e.g., a 4-channel texture can store: RGB spec color + glossiness

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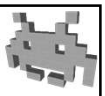
The intuition behind the specular-term formula

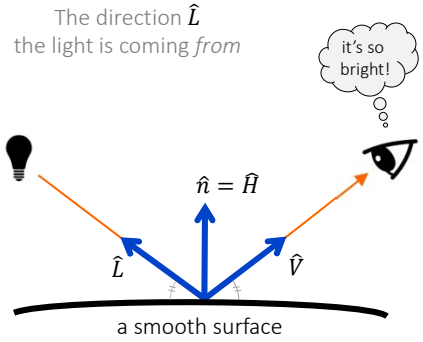


The local orientation of the surface $\hat{n}$

- When the normal direction matches the average of light direction and view direction, the light is reflected straight toward the eye, so, we see a bright reflection on the object
- By exponentiating the factor, I reduce it quickly toward 0, unless it was 1 or close
  - So, I only keep the really good matches

The dot product between versors is a measure in 0 to 1 of their similarity

The direction $\hat{L}$ the light is coming *from*



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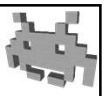
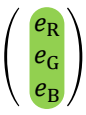
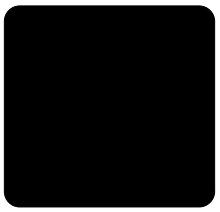
A basic lighting equation: emission term



- In formulas:



emission-color



most objects have no emission term

material parameter
light parameter
geometry

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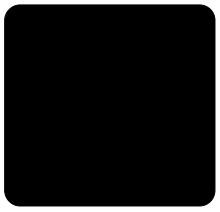
A basic lighting equation - emission term: info

- it models light that is…
  - …emitted from an object, and
  - …reaches the camera (directly!)
- useful for, e.g., small led lights, that are visible in the dark
  - for any other object (i.e, most of them), it is zero



zero, in this case

- note: the emitted light doesn't illuminate other objects
  - for this, you need to add lights to the scene
- the texture storing it (if there's one) is called emission map
- HDR values possible (that is, $e_{\mathrm{R,G,B}} > 1$) to get a "glow" effect (see HDR, last lecture)

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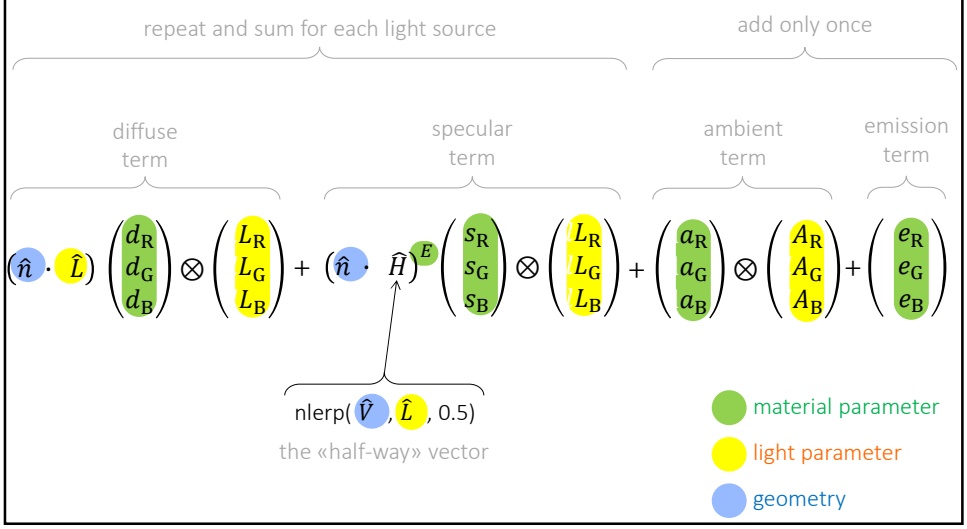
A basic lighting equation: the full equation



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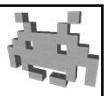
Lighting equation: some remarks



- Lighting is *additive*: the Diffuse and Specular components…
  - must be added for each light in the scene (for discrete lights – see later)
  - must be integrated on the light environment (for continuous light environment – see later)
  - the Ambient Light and Emission components are added once
- The Specular factor is nowadays too crude for the quality expected from modern games
  - The other factors are still used, as they are realistic
  - See later for the improvements
- The geometric vector used can be expressed in any space
  - but it must be the same space! (see later)

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Applying the Lighting equation

- It's computed for each pixel (in the fragment shader, see lecture on rendering)
  - most game engines support a good set of choices of different lighting equations
  - custom new equations can be programmed in fragment shaders
- Material + geometry parameters can be stored …
  - …in textures *(for highest-frequency variations inside 1 obj)*
  - …in vertex attributes *(smooth variations inside 1 obj)*
  - …as material asset parameters *(no variation for 1 obj)*
  - For example, where are
    - diffuse color
    - specular color
    - normals
    - tangent dirs

  typically stored?

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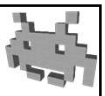
The tesk to defining material: Chapter 1 ('90s)



- The lighting equation above has been *standard way* for many years, because
  - It's cheap to compute
  - It's easy to control by material artists
  - Lighting was hardwired in graphics API (OpenGL and DirectX), and this was the only model which was provided
- Therefore, the material parameters it used has been the standard way to define materials (in videogames)
  - Via parameters or textures defining the various terms
- Unfortunately, it's also crude, not realistic, and all materials look similar
  - It's only realistic if the Specular component is zero
- We will see how more complex lighting modes

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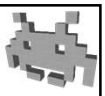
How to author a Phong material: (how to pick the parameters)



By hand! Questions a *material artist* must ask him/herself

- Diffuse color (aka Base color, aka Albedo):
  - "Which color is this stuff?"
  - i.e., "Which color does it look like, if I shine a white light on it?"
- Specular color (aka Highlight color)
  - "Which color and how bright are its reflections?"
  - if it's a factor (and Specular-color = Base-color · Specular-factor): "How bright are its reflection?"
- Specular exponent (aka Glossiness) (in 1 to 128)
  - "How concentrated are its reflections?"
  - Larger value (e.g., 100) ==> more concentrated highlights
  - Smaller value (e.g., 4) ==> larger highlights
- Ambient color / Ambient (Occlusion) factor (in 0 to 1)
  - How easy it is to reach this point of by ambient light
  - Small values: this point is difficult to reach by light
  - Larger values: this point is well exposed, easy to reach

Doesn't make any physical sense, it's just a crude way to simulate the effect. Real reflections don't work this way!

A way to remedy the fact that we are not modelling a realistic light environment

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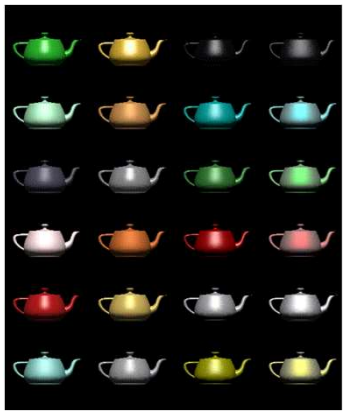
Defining material: Chapter 1 ('90s)

Material	GL_AMBIENT	GL_DIFFUSE	GL_SPECULAR	GL_SHININESS
Silver	0.19225 0.19225 0.19225 1.0	0.50754 0.50754 0.50754 1.0	0.508273 0.508273 0.508273 1.0	51.2
Polished Silver	0.23125 0.23125 0.23125 1.0	0.2775 0.2775 0.2775 1.0	0.773911 0.773911 0.773911 1.0	89.6
Emerald	0.0215 0.1745 0.0215 0.55	0.07568 0.61424 0.07568 0.55	0.633 0.727811 0.633 0.55	76.8
Jade	0.135 0.2225 0.1575 0.95	0.54 0.89 0.63 0.95	0.316228 0.316228 0.316228 0.95	12.8
Obsidian	0.05375 0.05 0.06625 0.82	0.18275 0.17 0.22525 0.82	0.332741 0.328634 0.346435 0.82	38.4
Pearl	0.25 0.20725 0.20725 0.922	1.0 0.829 0.829 0.922	0.296648 0.296648 0.296648 0.922	11.264
Ruby	0.1745 0.01175 0.01175 0.55	0.61424 0.04136 0.04136 0.55	0.727811 0.626959 0.626959 0.55	76.8
Turquoise	0.1 0.18725 0.1745 0.8	0.396 0.74151 0.69102 0.8	0.297254 0.30829 0.306678 0.8	12.8
Black Plastic	0.0 0.0 0.0 1.0	0.01 0.01 0.01 1.0	0.50 0.50 0.50 1.0	32
Black Rubber	0.02 0.02 0.02 1.0	0.01 0.01 0.01 1.0	0.4 0.4 0.4 1.0	10



not very expressive ☹

Still used (sometimes).
MTL files (OBJ file format) is basically this.

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Problem with the basic (aka Phong) material model

- It's not very expressive
- It's made-up (especially the specular component)
- It isn't realistic

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