Computer Graphics

- Introduction to Ray Tracing -

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RENDERING

Rendering

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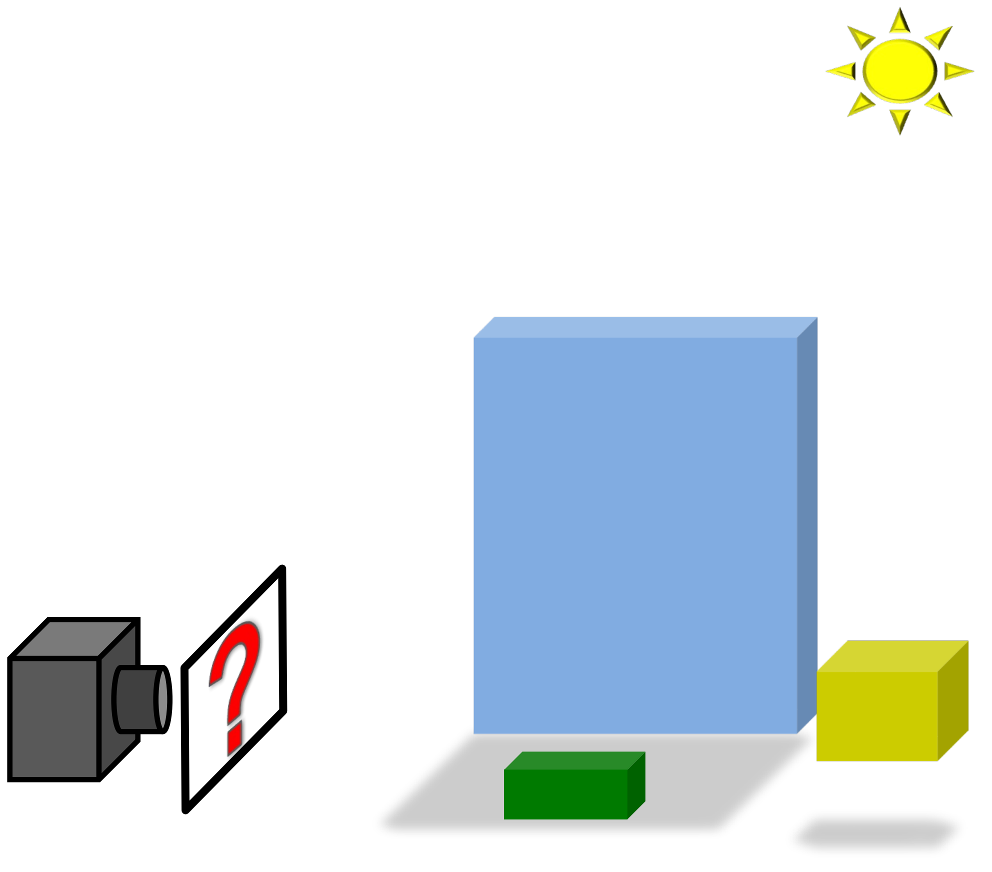
Rendering

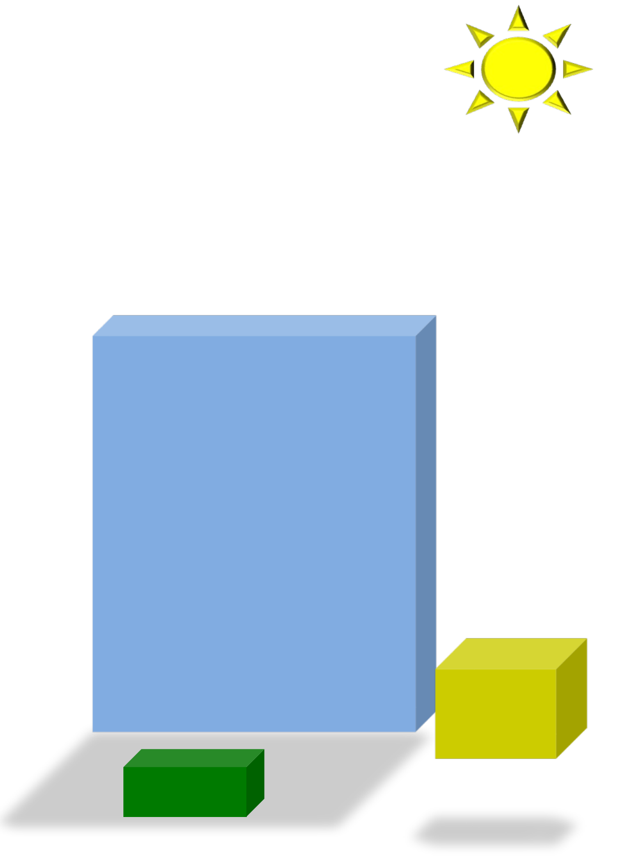
3D scene
camera
→ 2D image



Rendering

Ingredients: 3D scene

Set of objects in $\mathbb{R}^3$ defined by:



Rendering

Ingredients: 3D scene

Set of objects in $\mathbb{R}^3$ defined by:

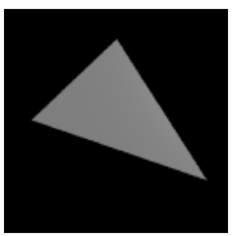
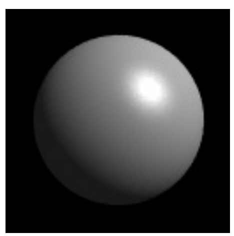
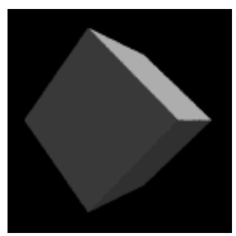
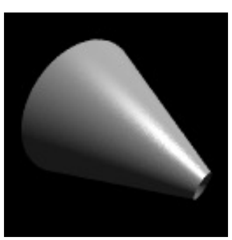
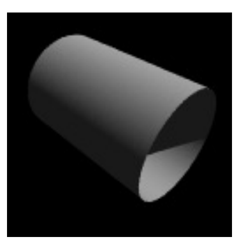
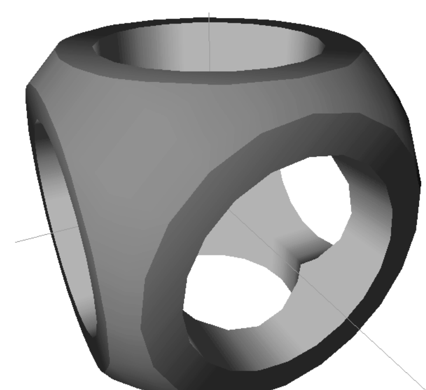
– Shape:

» primitives: spheres, boxes, triangles, …

» implicit functions: quadrics, noise functions, ...

» boolean operations on other shapes

» ...

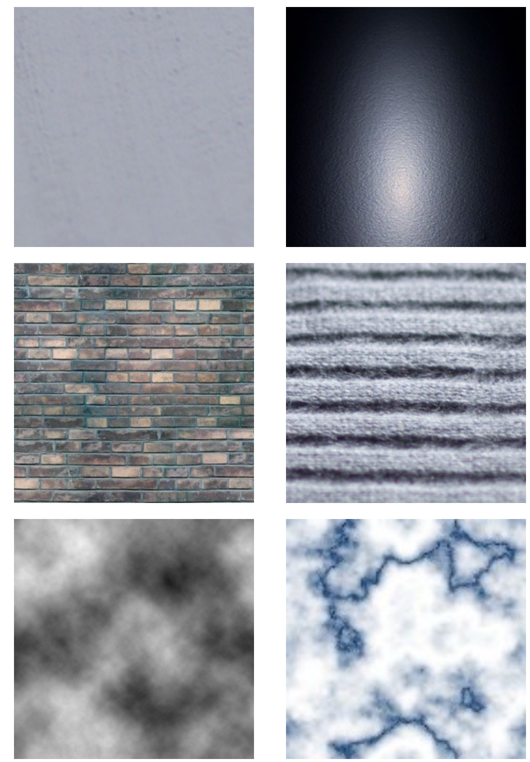







Rendering

Ingredients: 3D scene

Set of objects in $\mathbb{R}^3$ defined by:

- Shape:
  - » primitives: spheres, boxes, triangles, …
  - » implicit functions: quadrics, noise functions, ...
  - » boolean operations on other shapes
  - » ...
- Material: light reflectance and emission
  - » functions: diffuse, specular
  - » texture
  - » noise functions
  - » transparency properties

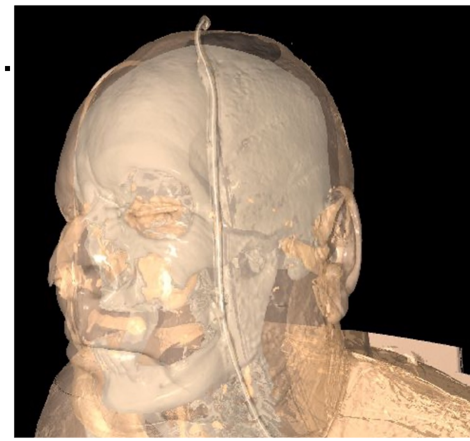


Rendering

Ingredients: 3D scene

Set of objects in $\mathbb{R}^3$ defined by:

- Shape:
  - primitives: spheres, boxes, triangles, …
  - implicit functions: quadrics, noise functions, …
  - boolean operations on other shapes
  - ...
- Material: light reflectance and emission
  - functions: diffuse, specular
  - texture
  - noise functions
  - transparency properties
- Advanced objects:
  - volumes
  - point clouds
  - ...

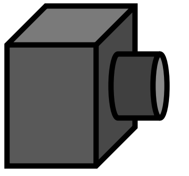


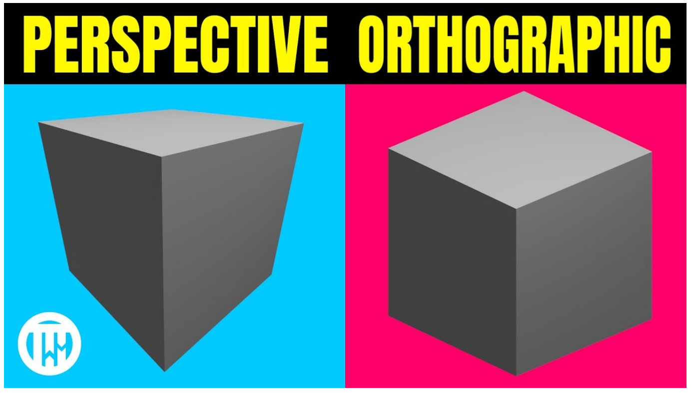
Rendering

Ingredients: camera

Defined in $\mathbb{R}^3$ by:

- Type:
  - » perspective, orthographic, fisheye ...
- Parameters:
  - » origin, direction, field-of-view ...





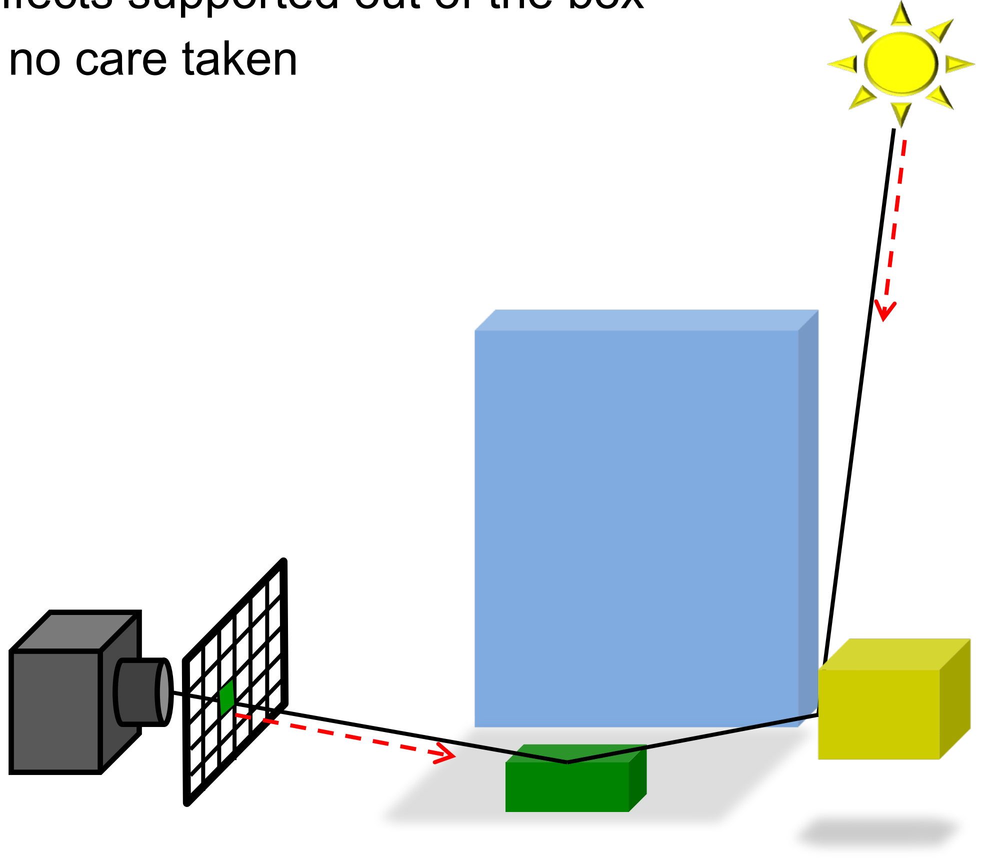
Rendering

Typical assumptions:

- Light reflected only off surfaces, objects
- Empty space is transparent
- No quantum effects
- No relativistic effects

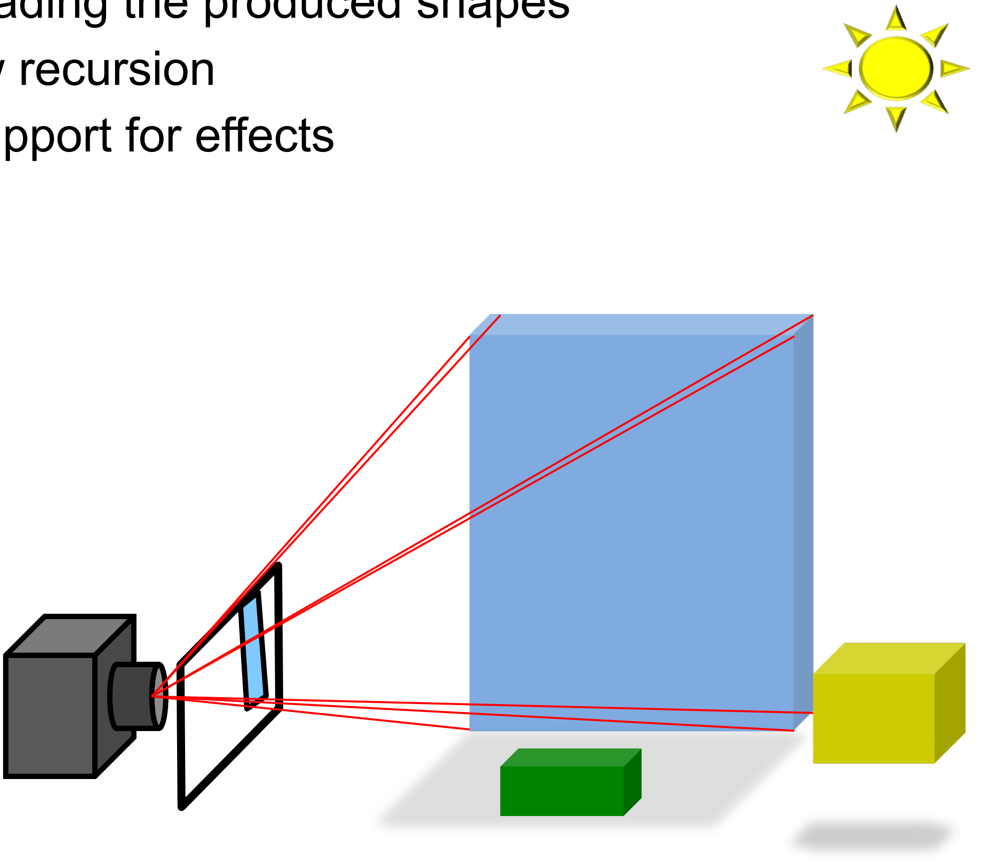
Rendering algorithms

- Ray Tracing
  - Physically-based simulation of light transport
  - Deep recursion
  - Many effects supported out of the box
  - Slow, if no care taken



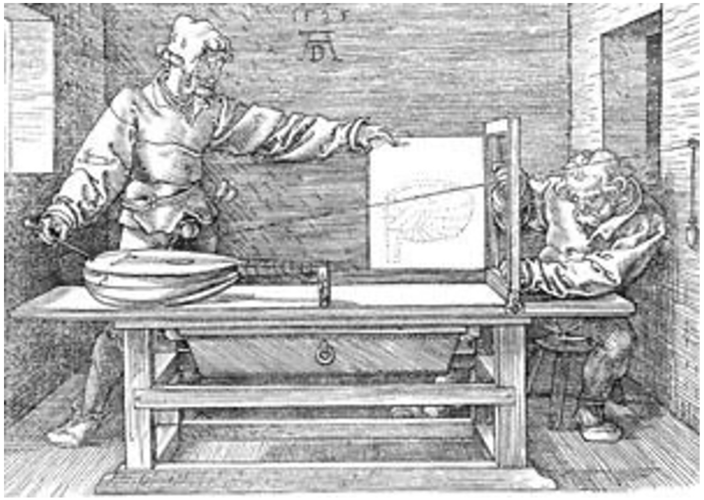
Rendering algorithms

- Rasterization
  - » Imperative drawing of scene
    - Projecting whole objects
    - Shading the produced shapes
  - » Shallow recursion
  - » Poor support for effects
  - » Fast



RAY-TRACING PRINCIPLES

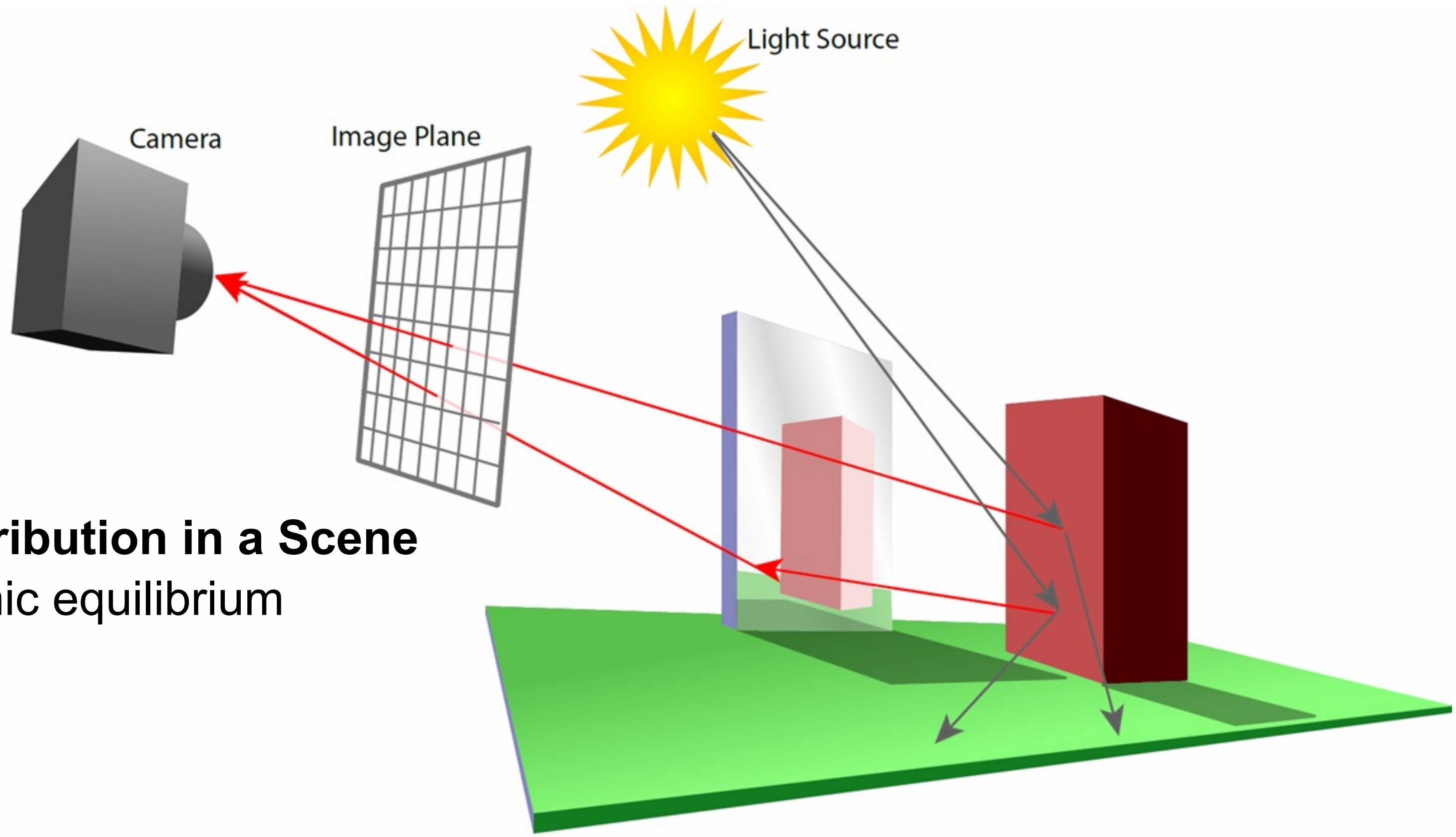
Ray Tracing Is…



Perspective Machine, Albrecht Dürer

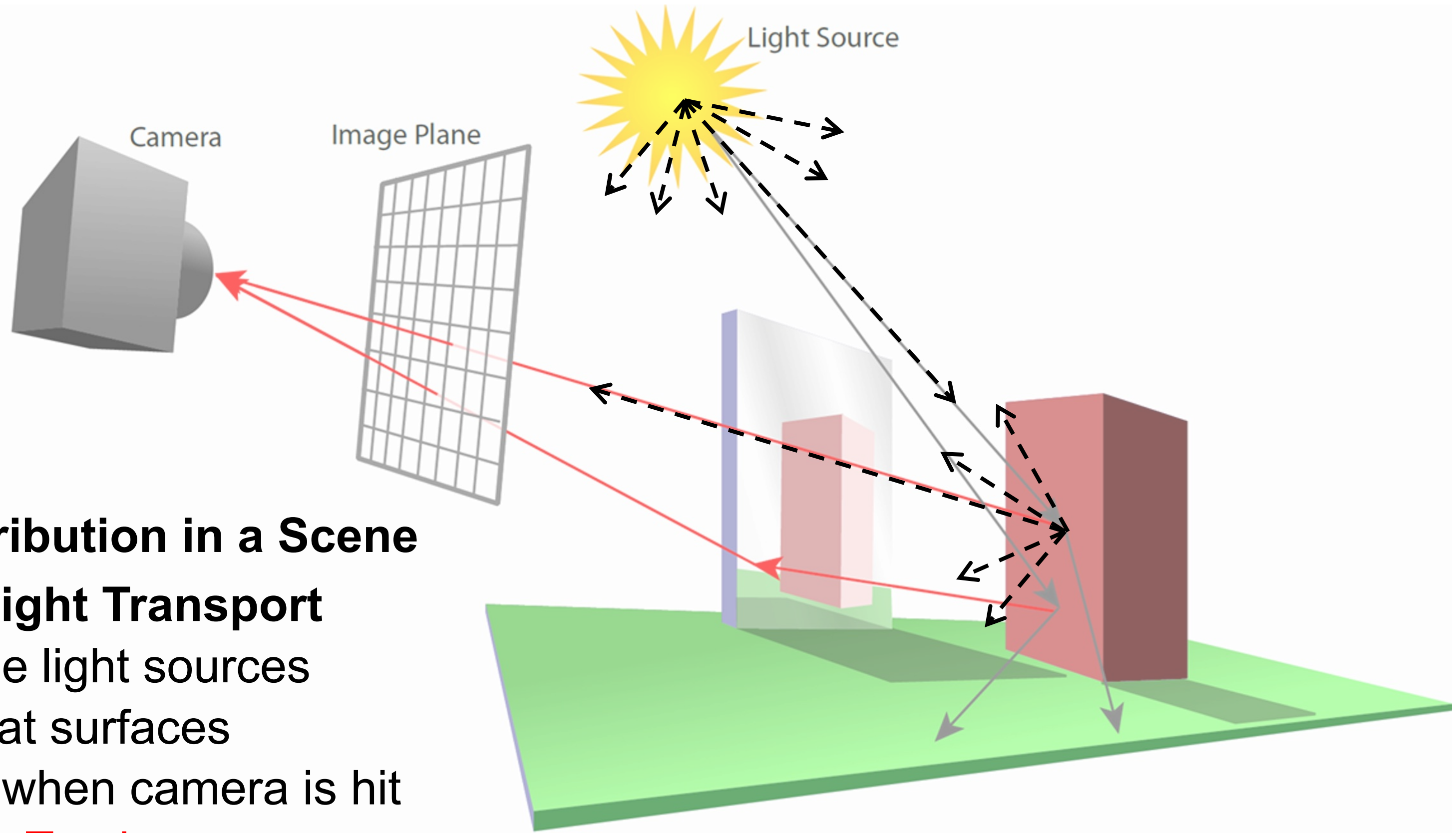
- **Fundamental rendering algorithm**
  - Simulates physical behavior of light
- **Automatic, simple and intuitive**
  - Easy to understand and implement
  - Delivers “correct“ images by default
- **Powerful and efficient**
  - Many optical global effects
  - Shadows, reflections, refractions, …
  - Efficient real-time implementation in SW and HW
  - Can work in parallel and distributed environments
  - Logarithmic scalability with scene size: O(log n) vs. O(n)
  - Output sensitive and demand driven
- **Concept of light rays is not new**
  - Empedocles (492-432 BC), Renaissance (Dürer, 1525), …
  - Uses in lens design, geometric optics, …

Light Transport



- **Light Distribution in a Scene**
  - Dynamic equilibrium

Light Transport

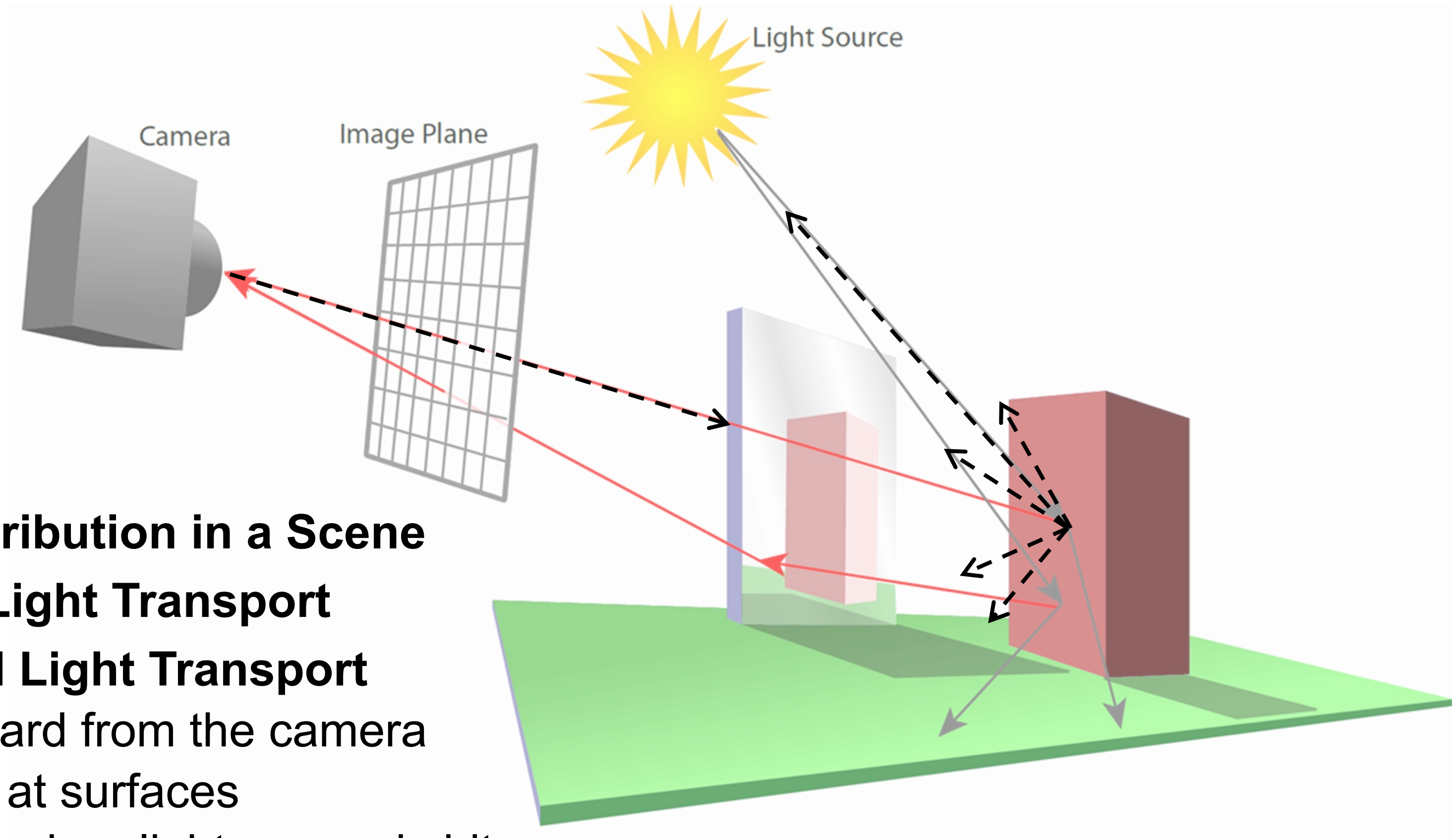


- **Light Distribution in a Scene**
- **Forward Light Transport**
  - from the light sources
  - reflect at surfaces
  - record when camera is hit
  - Particle Tracing

  Most photons will not reach the camera

  Intermediate results useful in more advanced algorithms

Light Transport

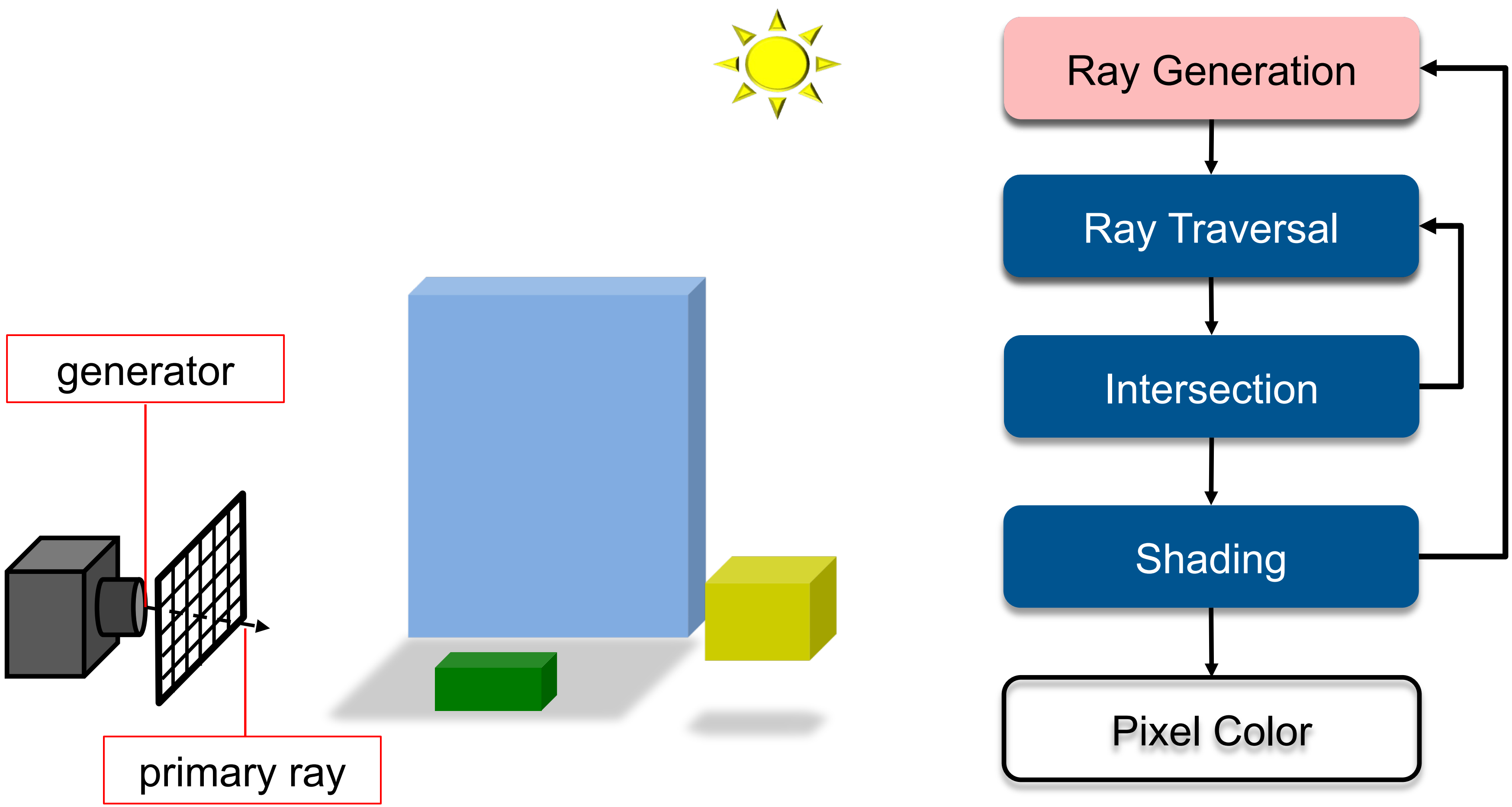


- **Light Distribution in a Scene**
- **Forward Light Transport**
- **Backward Light Transport**
  - backward from the camera
  - reflect at surfaces
  - record when light source is hit
  - Ray Tracing

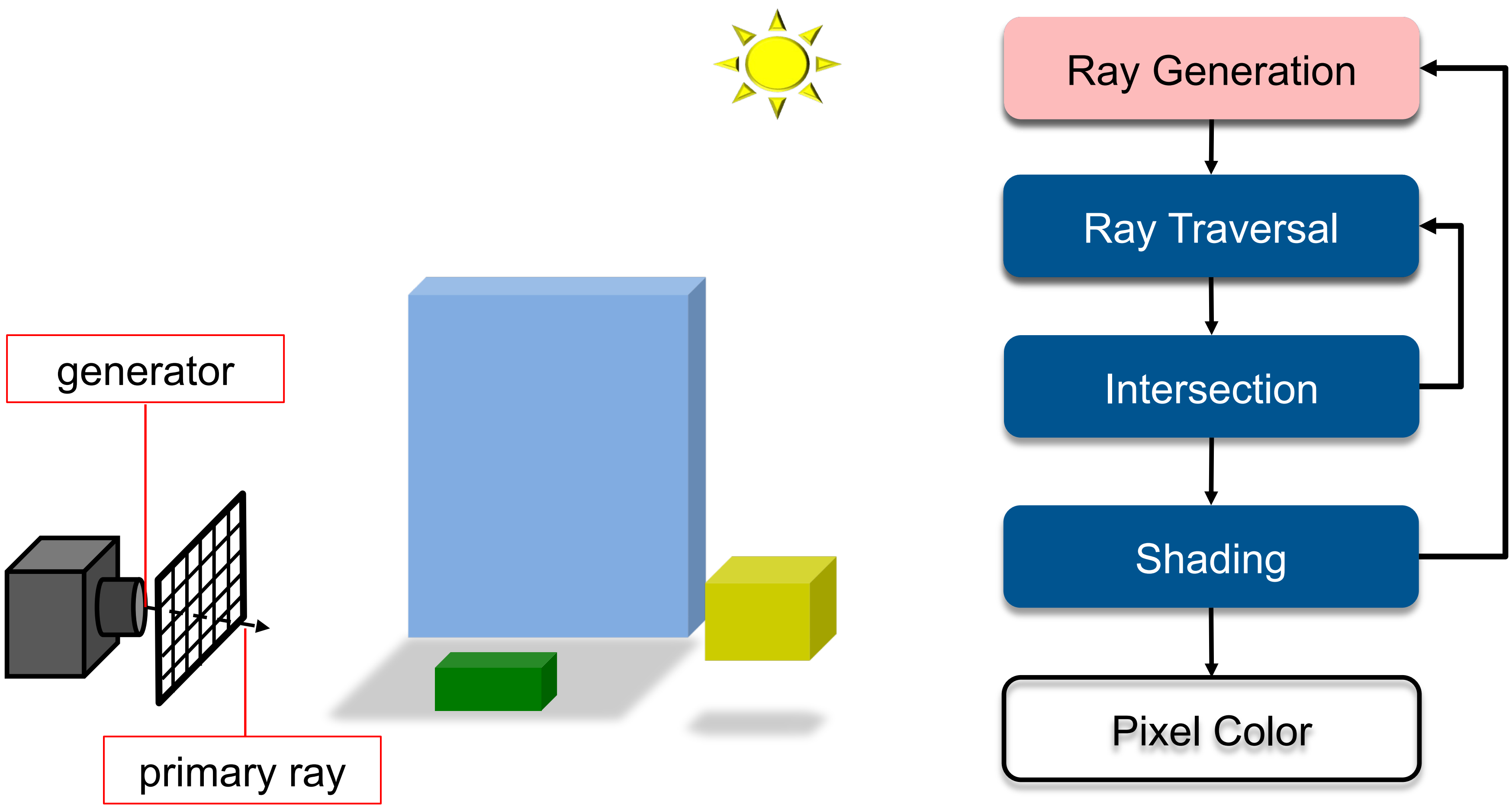
  Shoot shadow rays to hit light explicitly

  Shoot more rays to find more paths and light sources

Ray Tracing Pipeline



Ray Tracing Pipeline



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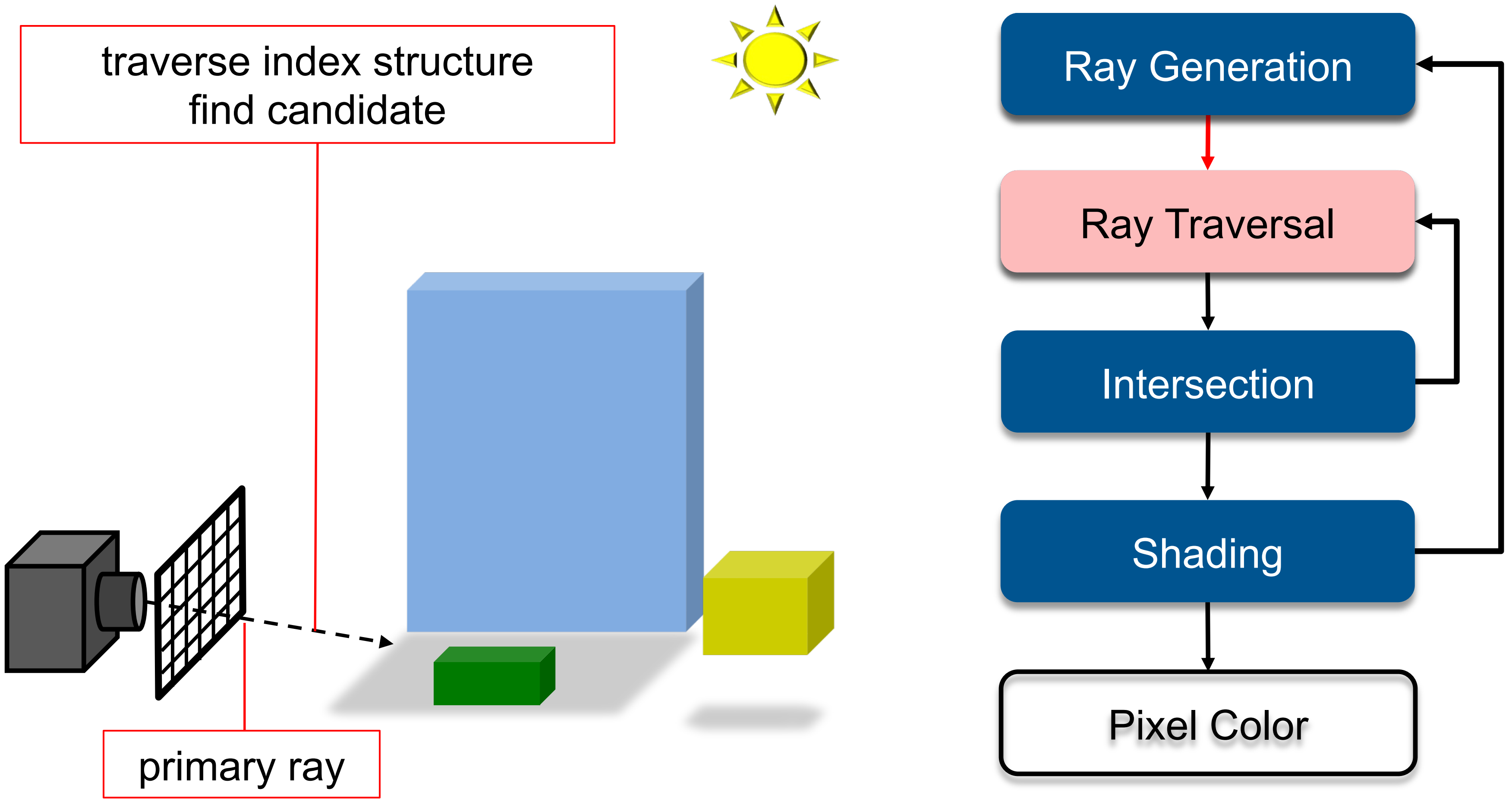

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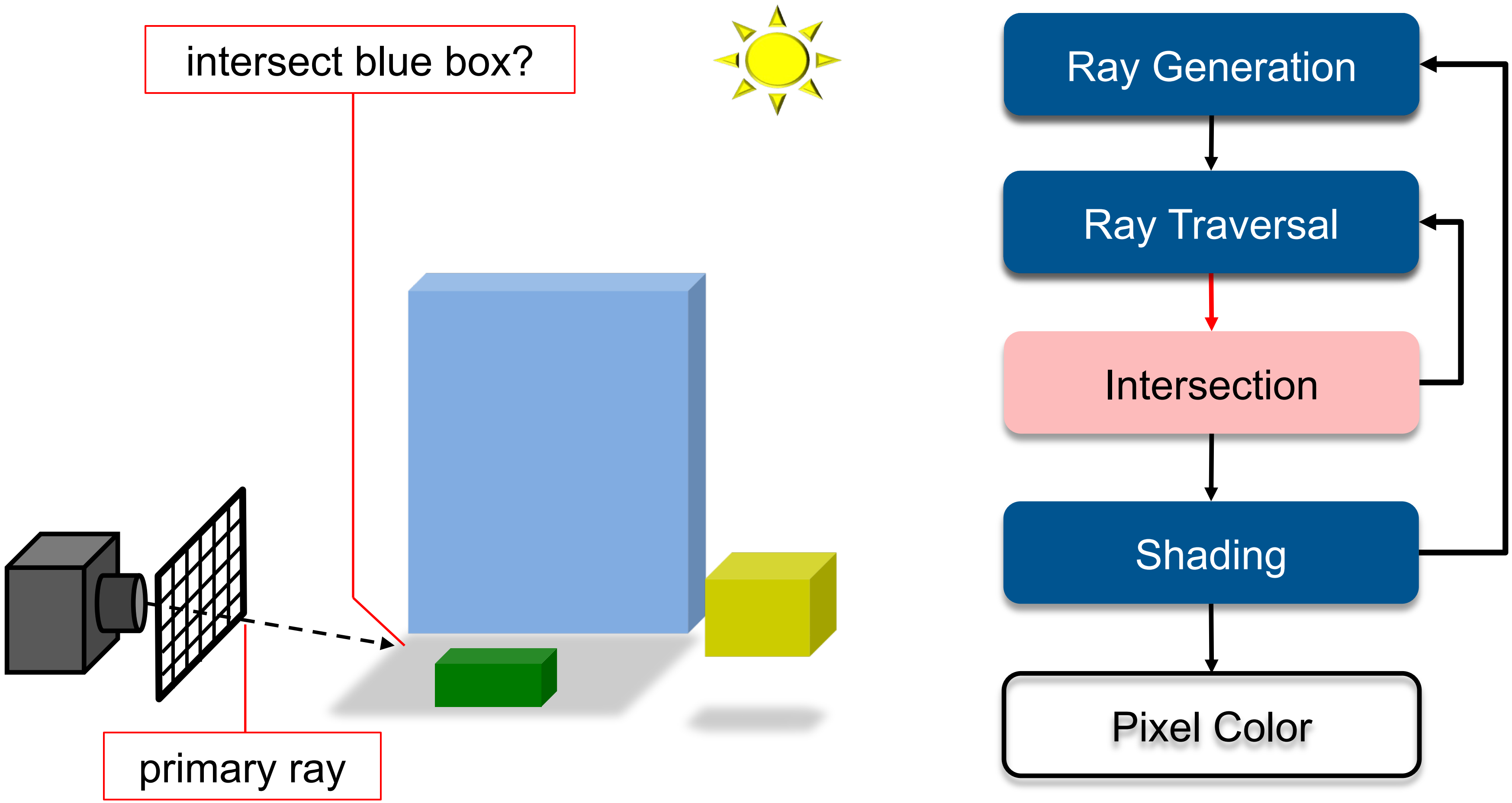

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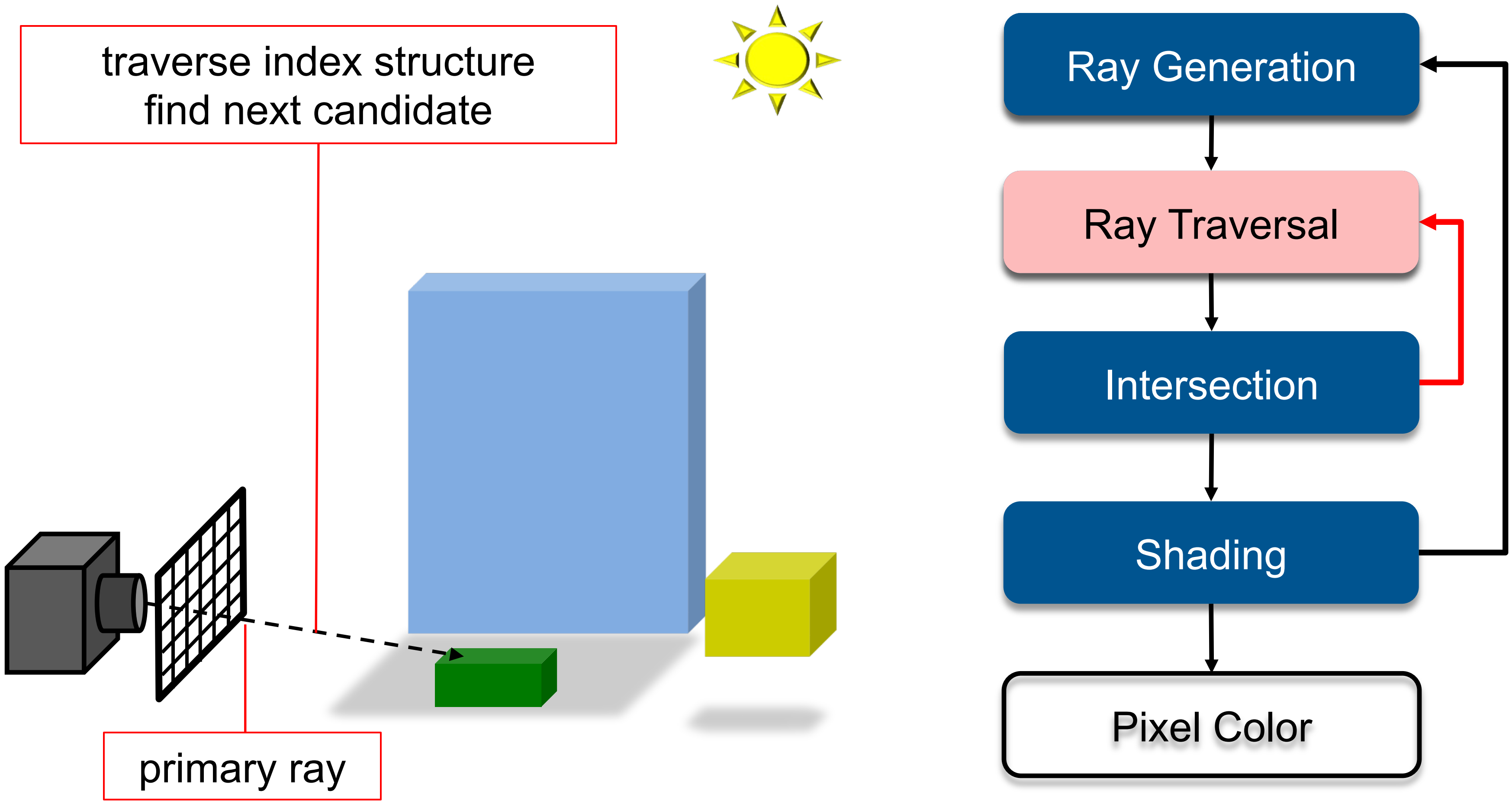

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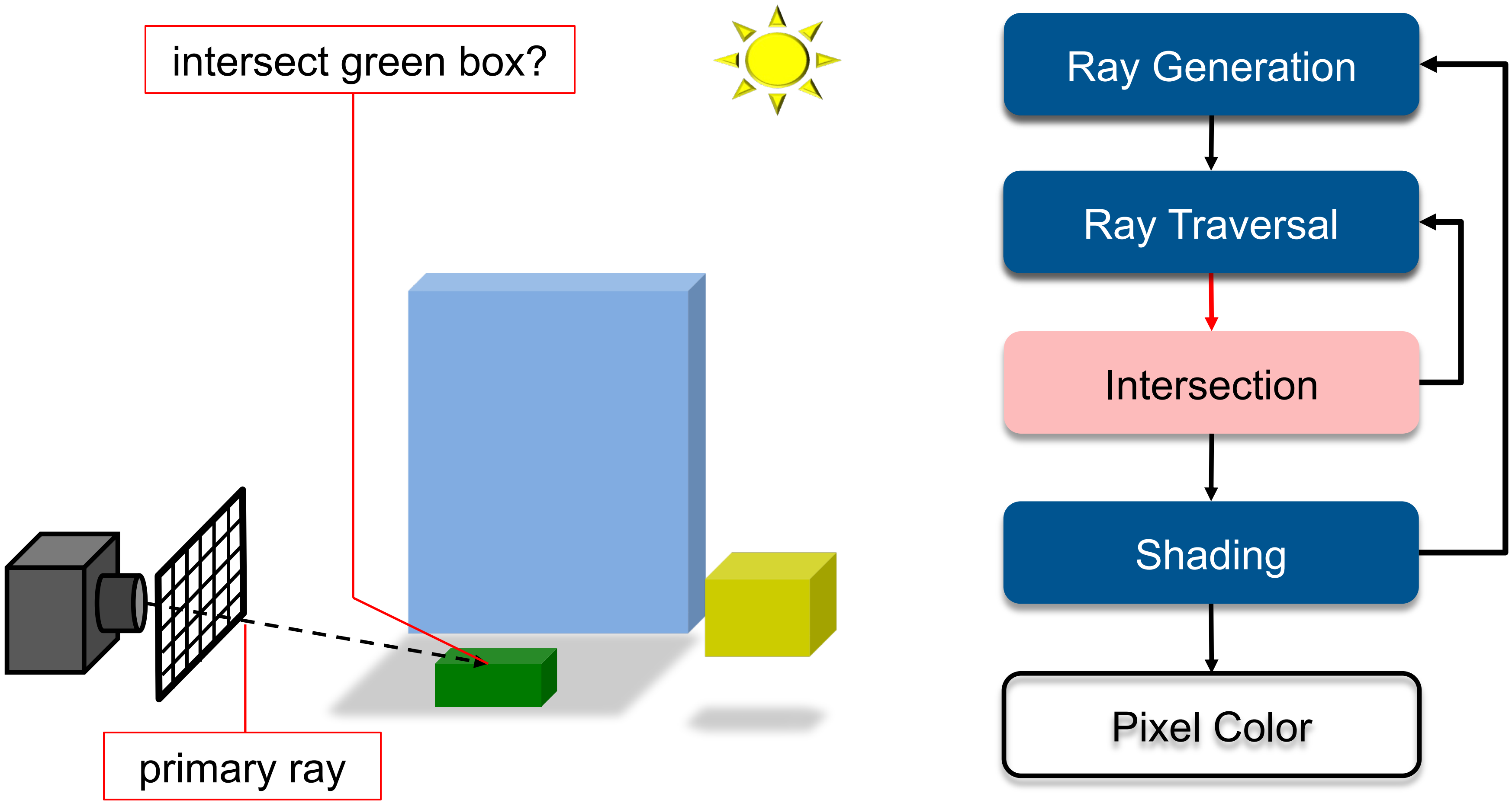

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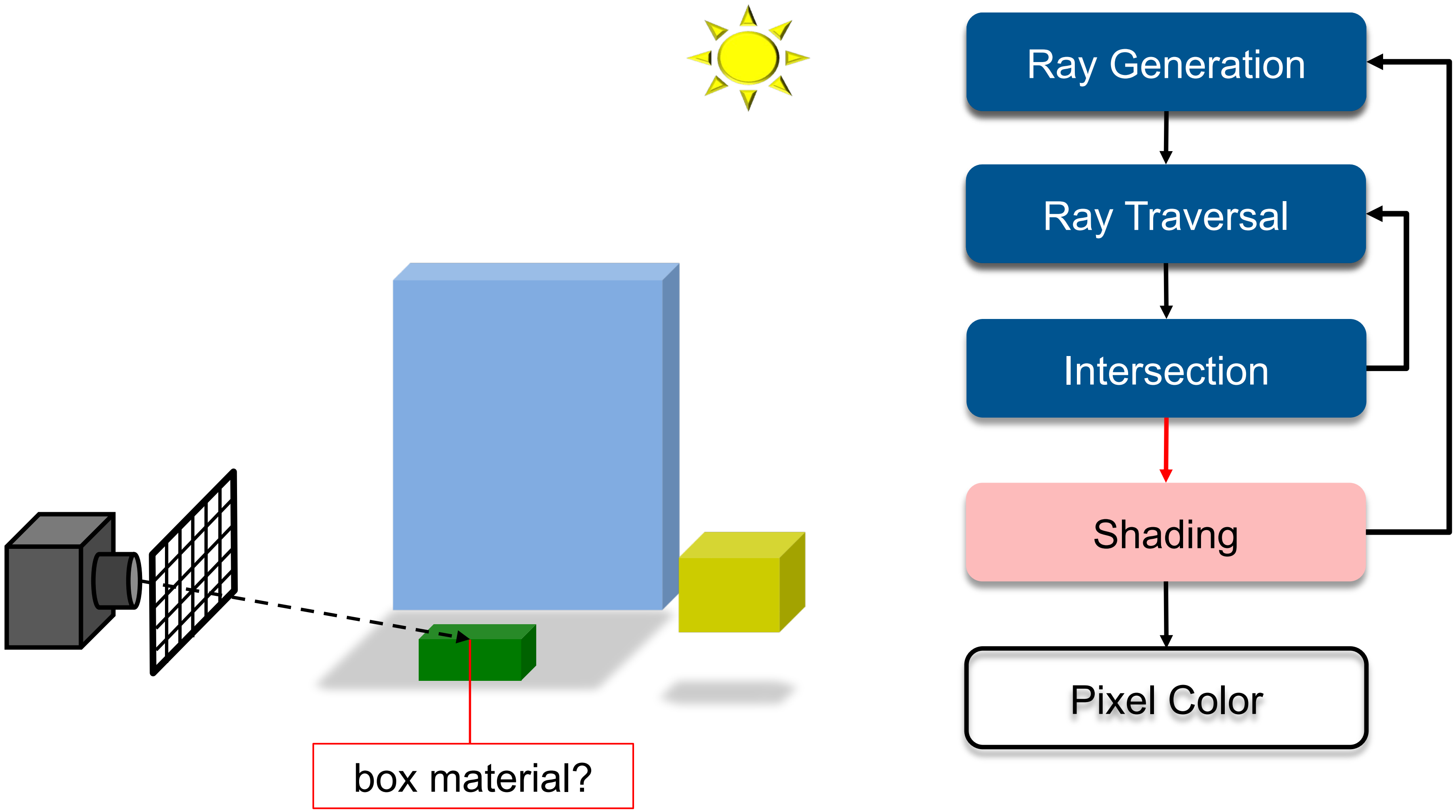

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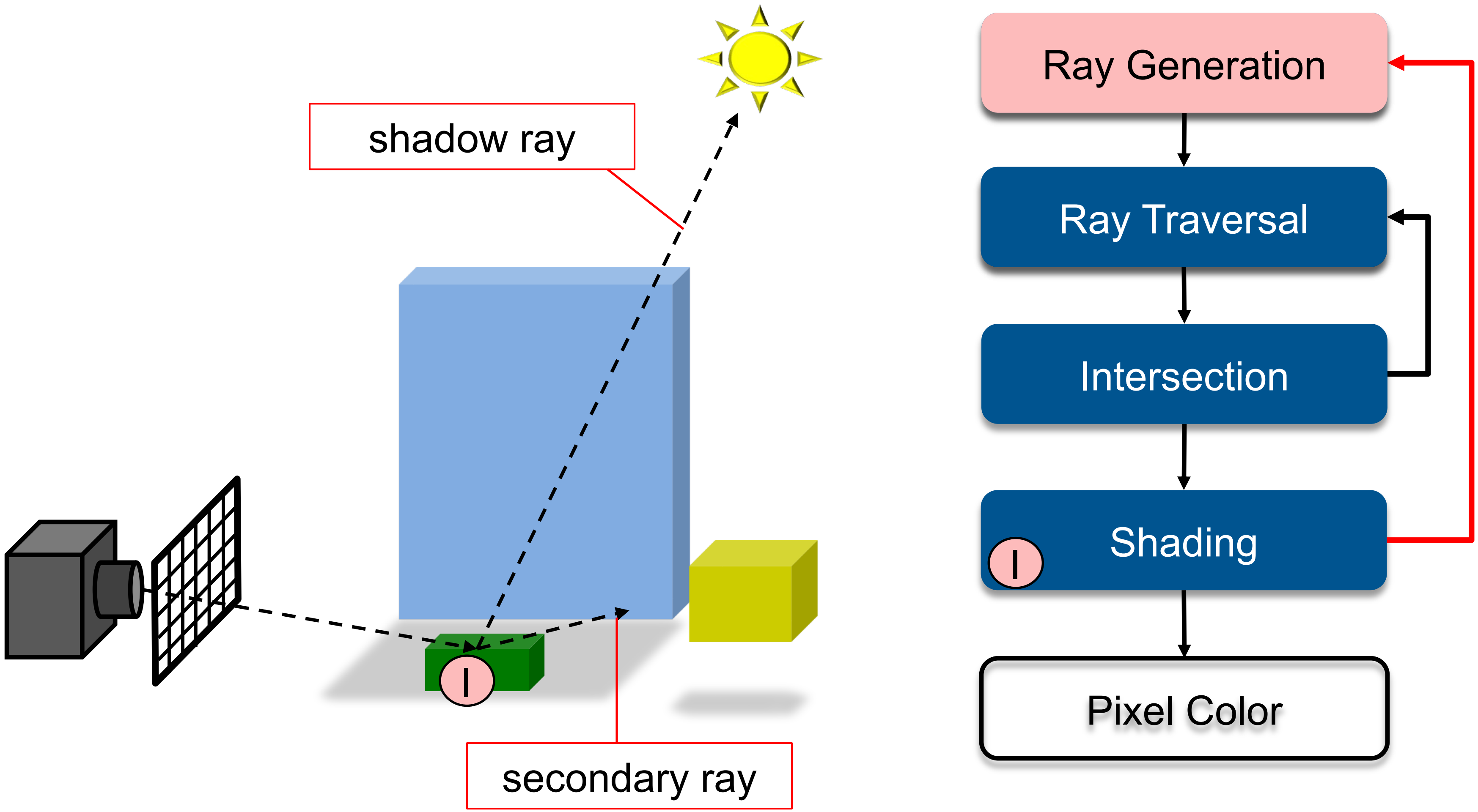

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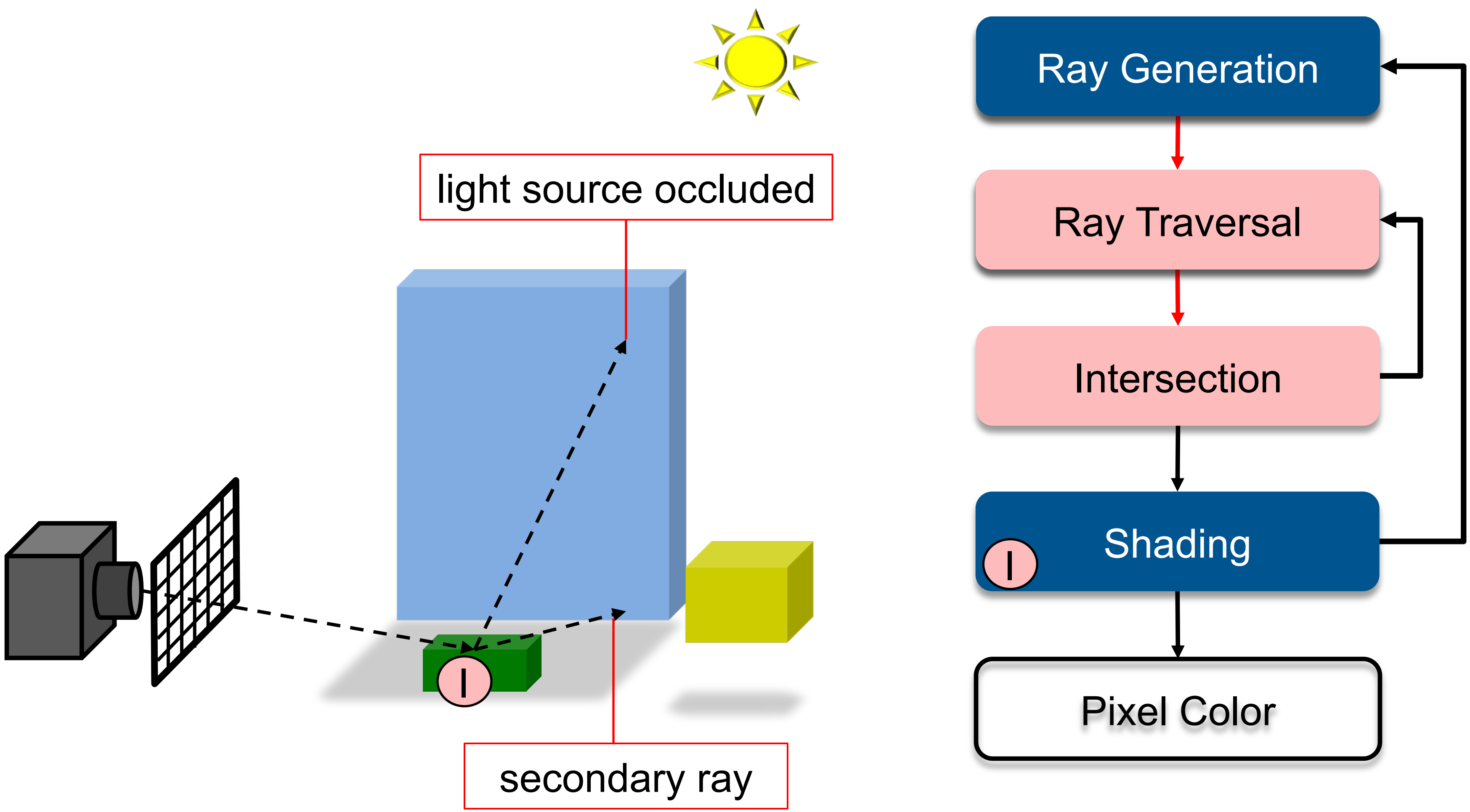

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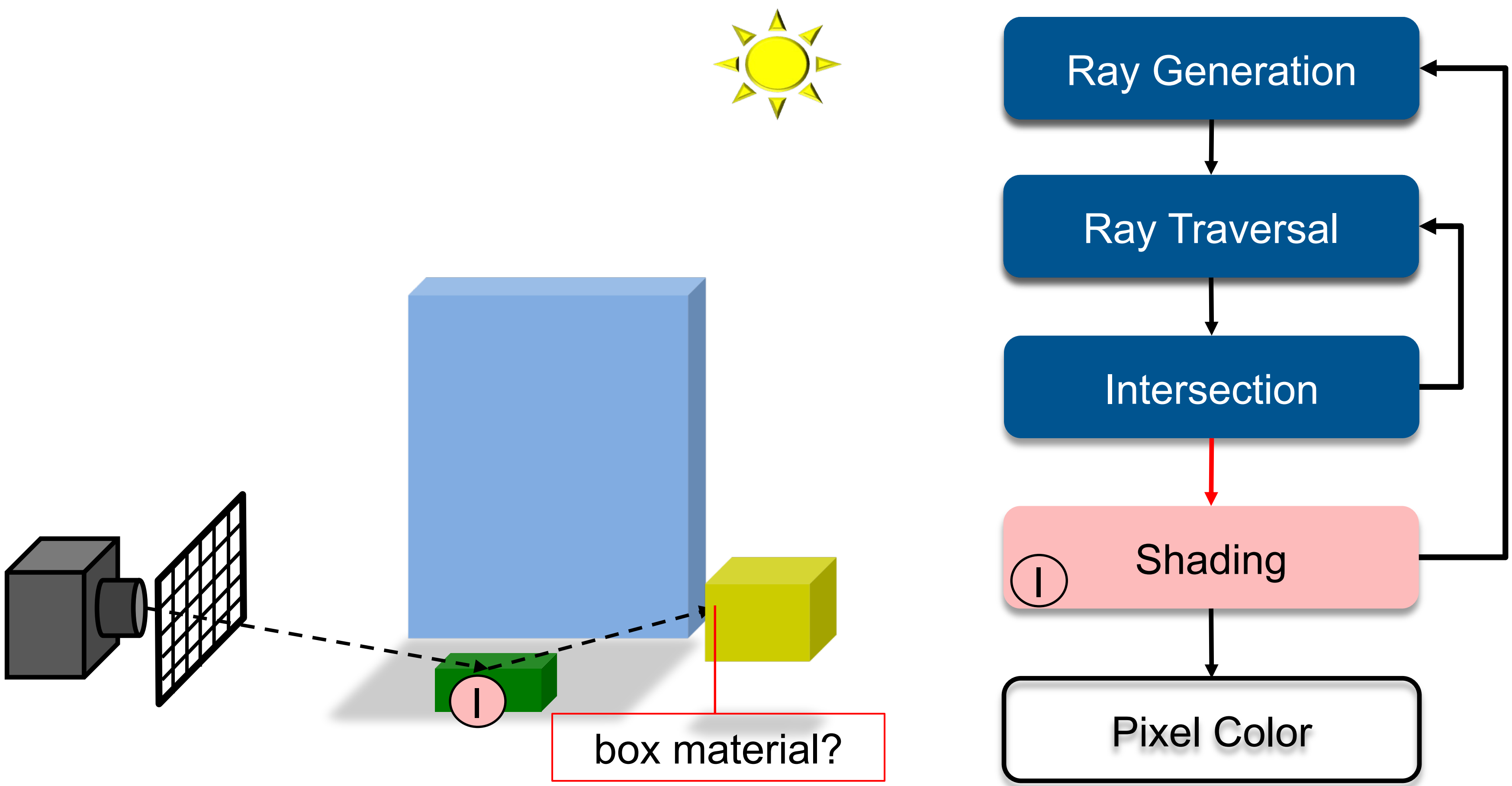

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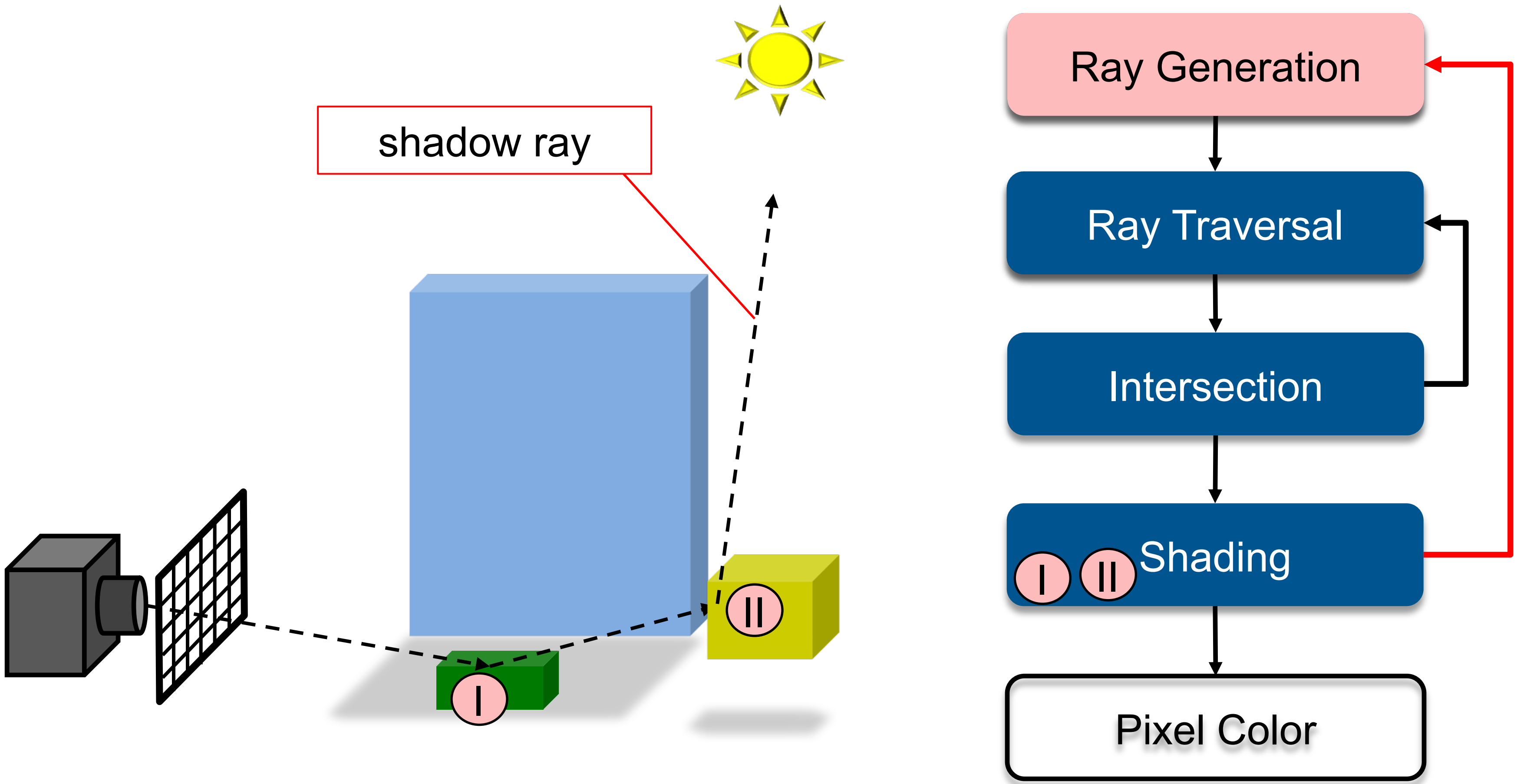

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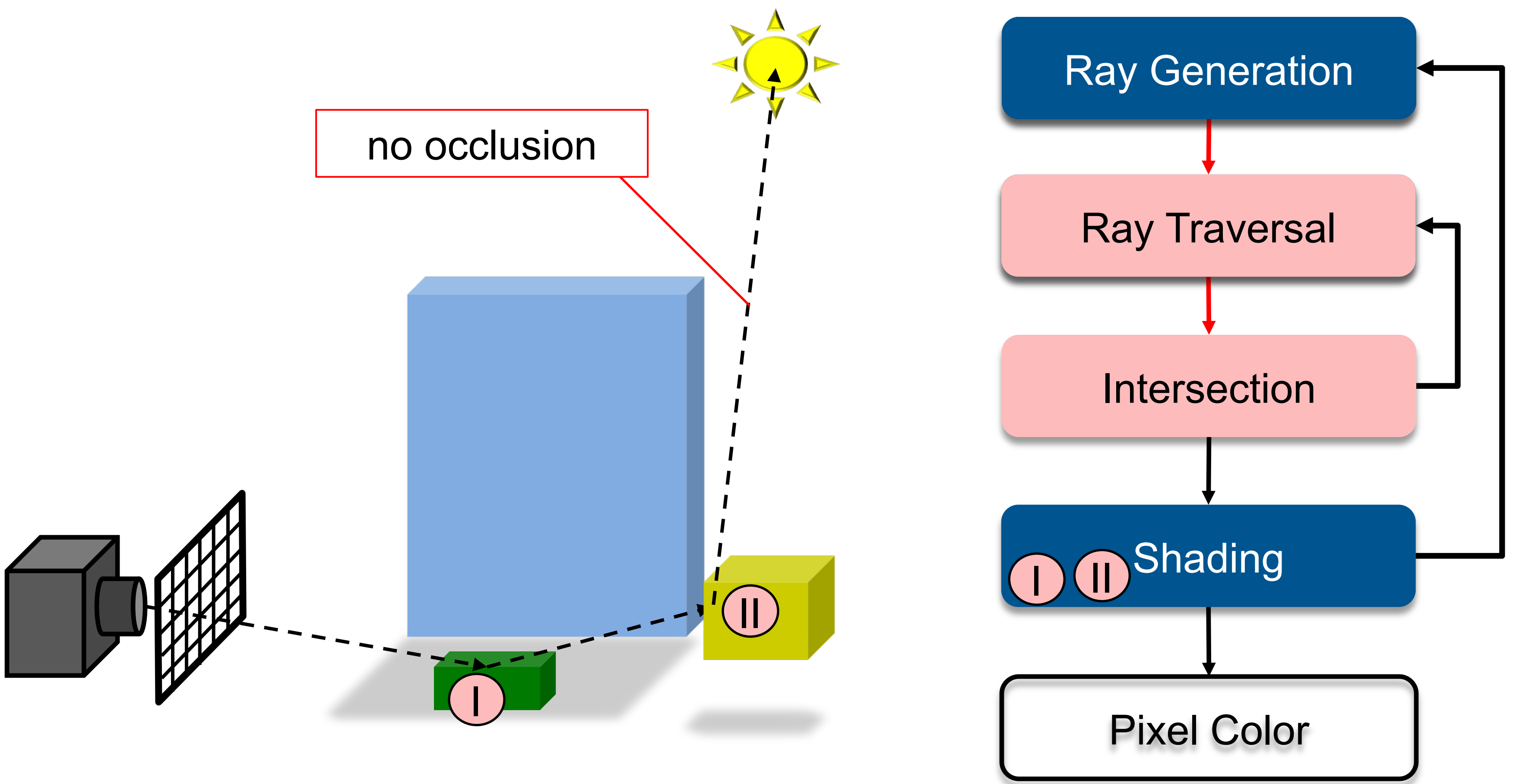

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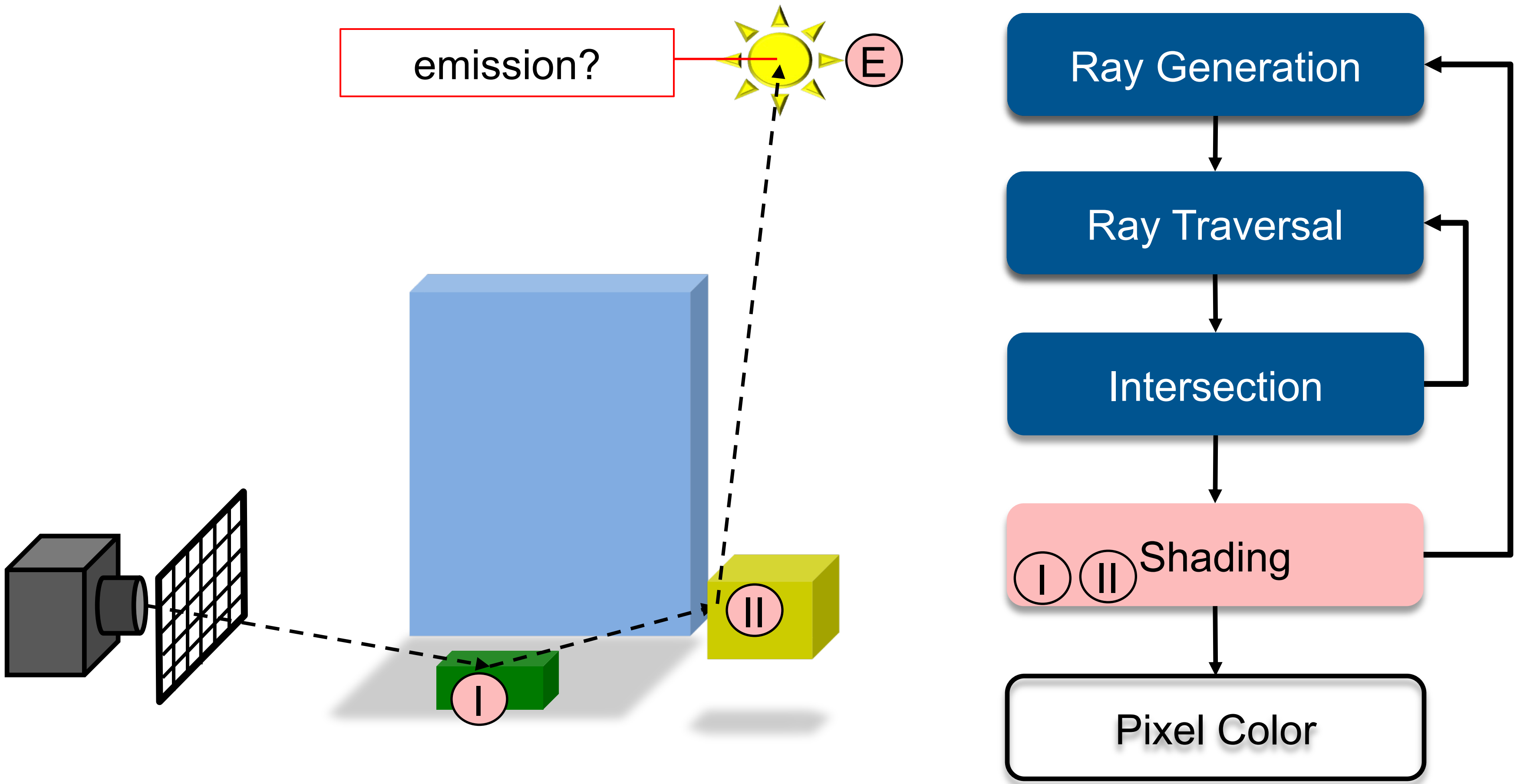

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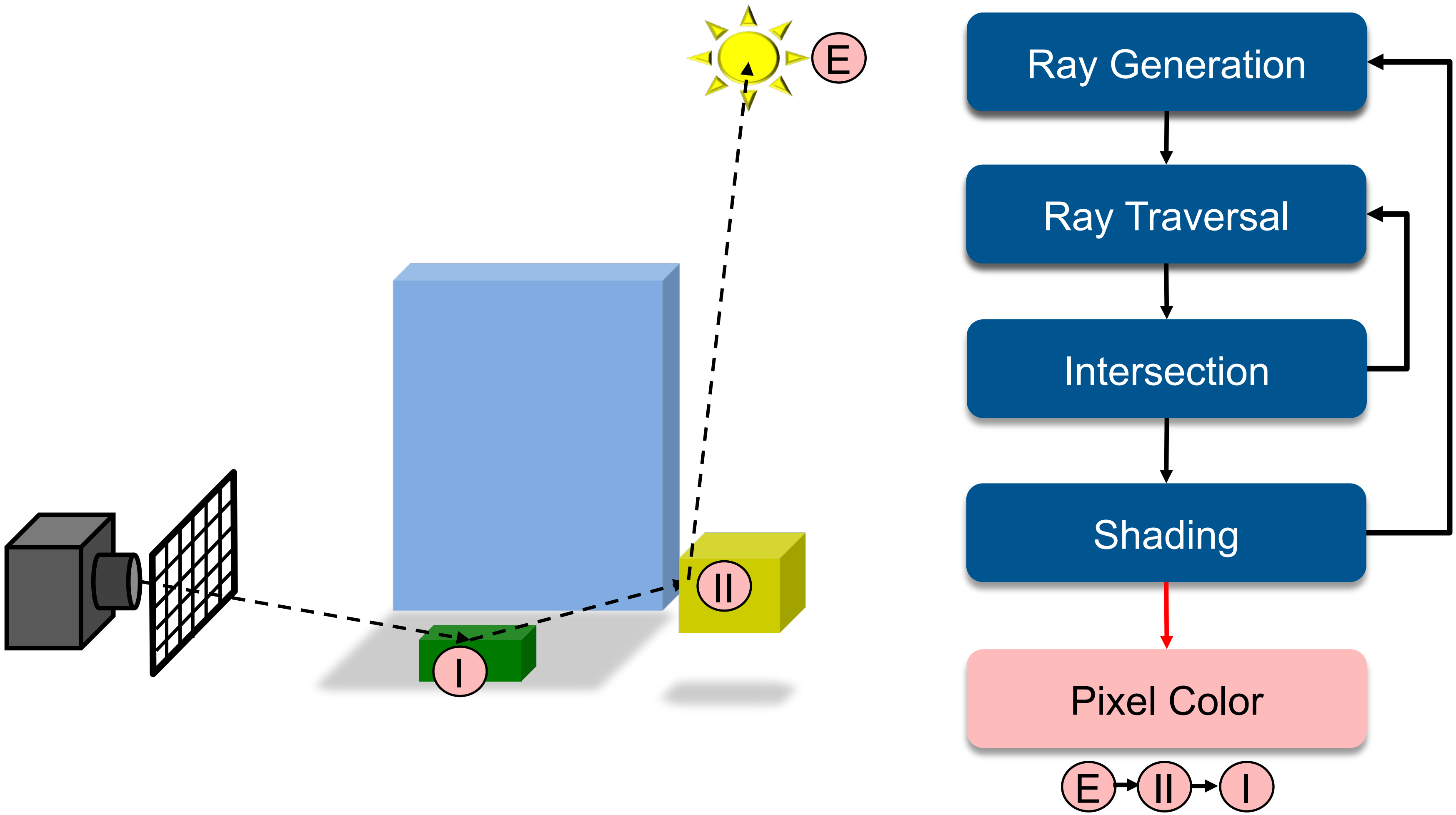


Ray Tracing Algorithm

```
render(camera, scene)
    foreach pixel in image
        ray = camera.generatePrimaryRay(pixel)
        color = trace(ray, scene)
        image[pixel] = color
    return image
```

Ray Tracing Algorithm

```
trace(scene, ray)
    hit = findIntersection(scene, ray)
    return shade(scene, ray, hit.coord, hit.obj)
```

```
findIntersection(scene, ray)
    bestHit = {none,infinite}
    foreach obj in scene
        hit = obj.intersect(ray)
        if hit succesful
            if hit.dist < bestHit.dist
                bestHit = hit
    return bestHit
```

Ray Tracing Algorithm

```
shade(scene, ray, coord, obj)
    material = obj.material
    color = material.emission

    foreach light in scene.lights
        shadowray = light-hit
        if shadowtrace(scene, shadowray, light)
            color += light.radianceAt(hit) * material.reflectance

    foreach secondaryRay in material.generateSecondaryRays()
        irradiance = trace(scene, secondaryRay)
        color += irradiance * material.reflectance

    return color
```

```
shadowtrace(scene, ray, light)
    hit = scene.findIntersection(ray)
    return (hit before light)
```

Ray Tracing Algorithm

?

```
camera.generatePrimaryRay
```

```
obj.intersect(ray)
```

```
material.emission
```

```
light.radianceAt
```

```
material.reflectance
```

```
material.generateSecondaryRays
```

RAY-TRACING FEATURES

Ray Tracing Features

- **Incorporates into a single framework**
  - Hidden surface removal
    - Front to back traversal
    - Early termination once first hit point is found
  - Shadow computation
    - Shadow rays/ shadow feelers are traced between a point on a surface and a light sources
  - Exact simulation of some light paths
    - Reflection (reflected rays at a mirror surface)
    - Refraction (refracted rays at a transparent surface, Snell's law)
- **Limitations**
  - Many reflections (exponential increase in number of rays)
  - Indirect illumination requires many rays to sample all incoming directions
  - Easily gets inefficient for full global illumination computations
  - Solution: Pick a single secondary ray at random (Monte Carlo)
    - Problem: Introduces noise that can require many samples to vanish

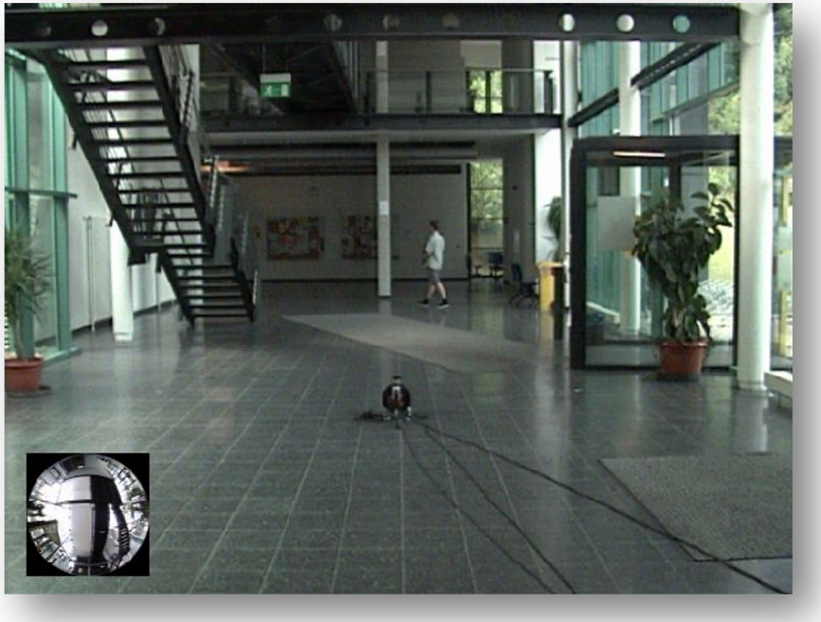
Ray Tracing Can…

- **Produce Realistic Images**
  - By simulating light transport
  - Test yourself: https://cgifurniture.com/3d-rendering-vs-product-photography-quiz/

What is Possible?

- **Models Physics of Global Light Transport**
  - Dependable, physically-correct visualization

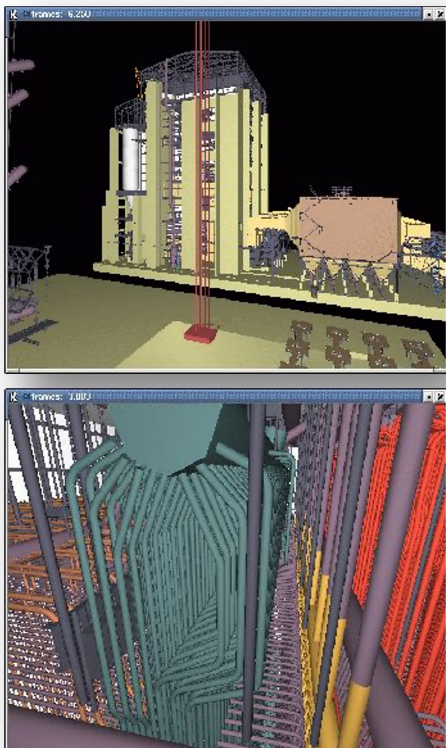
Realistic Visualization: VR/AR



Lighting Simulation

What is Possible?

- **Huge Models**
  - Logarithmic scaling in scene size

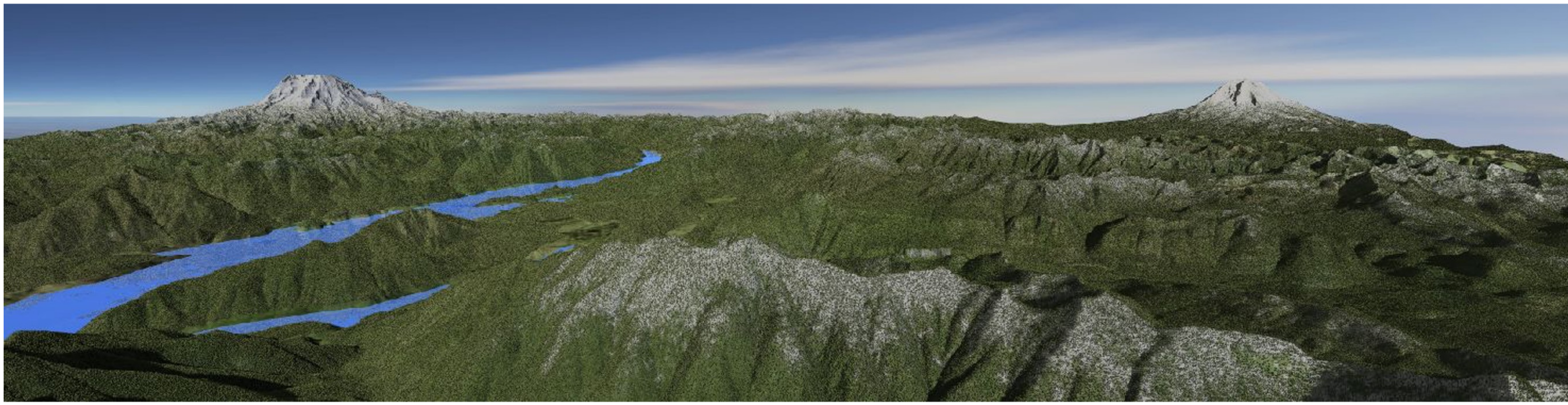


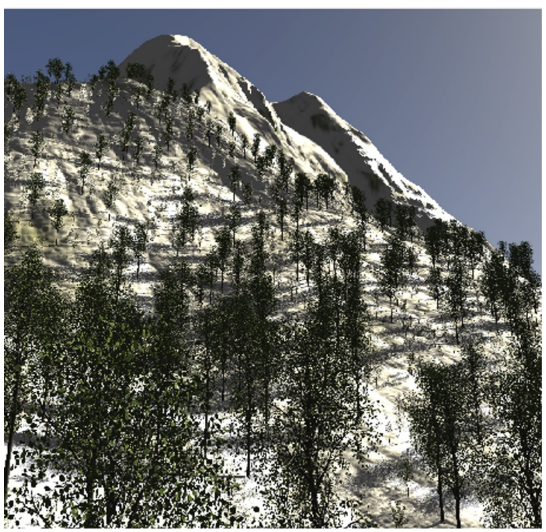
12.5 Million Triangles

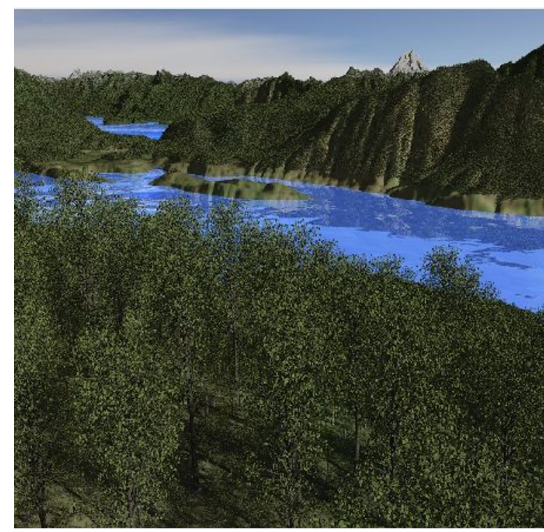
~1 Billion Triangles

Outdoor Environments

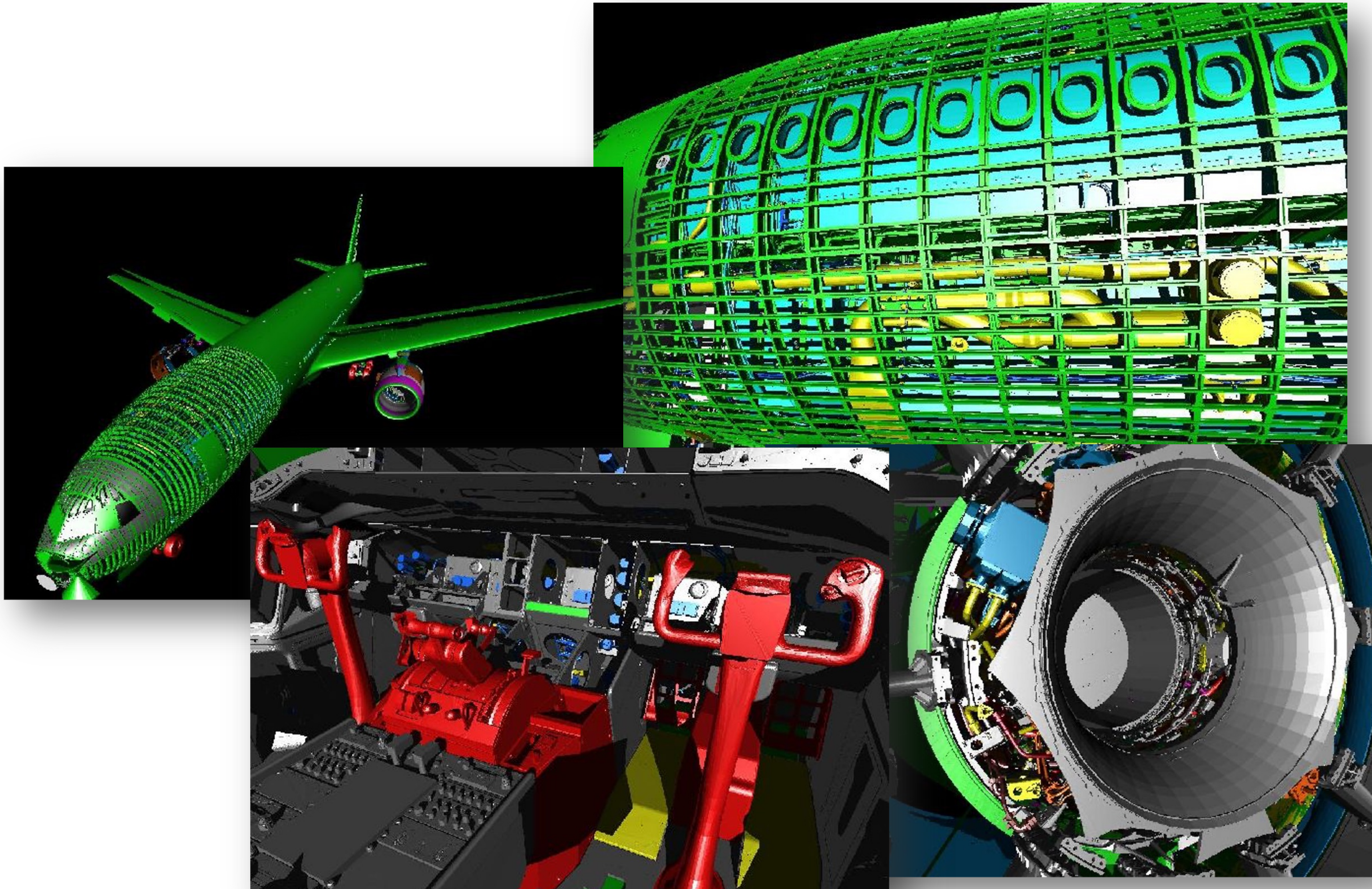
90 x 10^12 (trillion) triangles







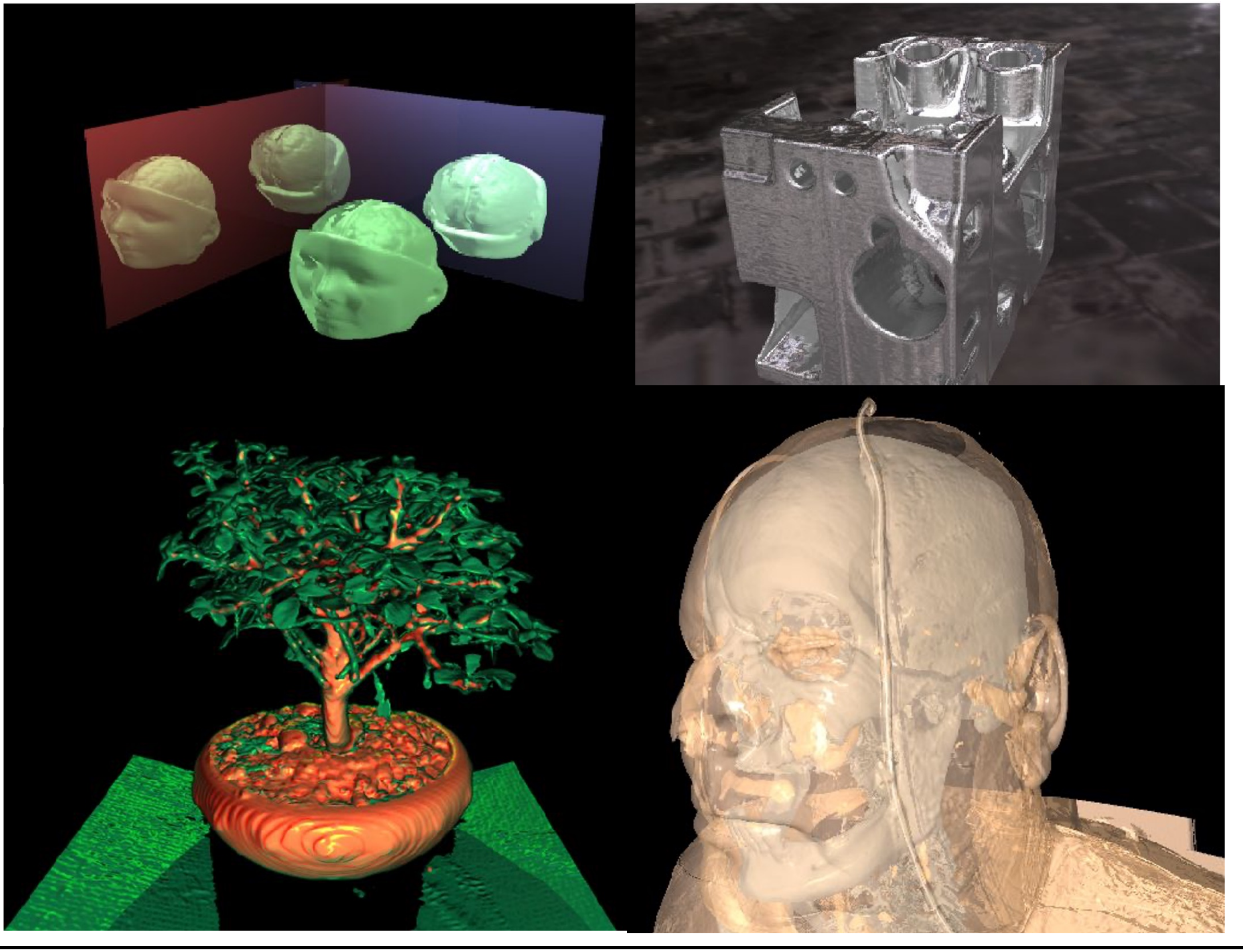
Boeing 777



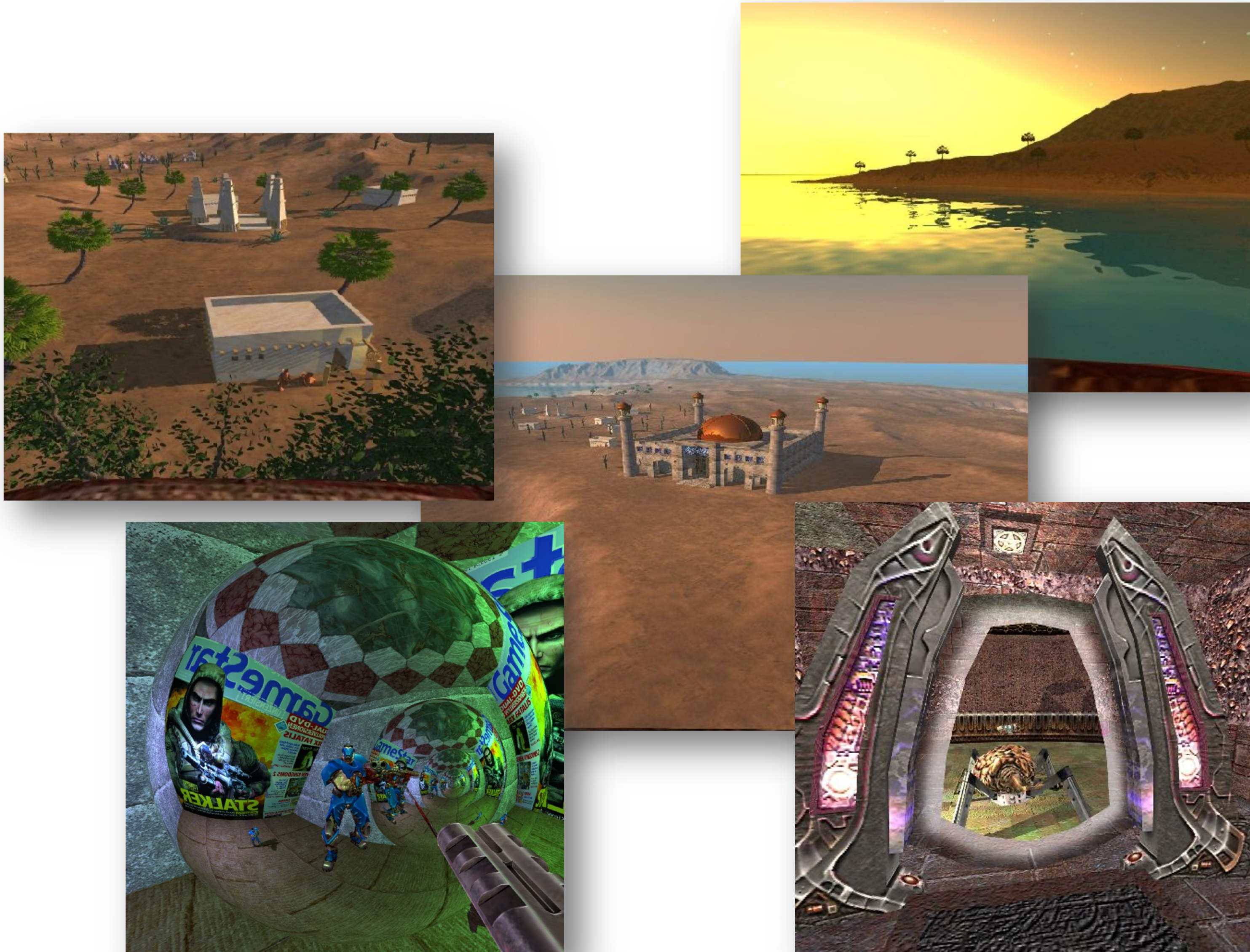
Boeing 777: ~350 million individual polygons, ~30 GB on disk

Volume Visualization

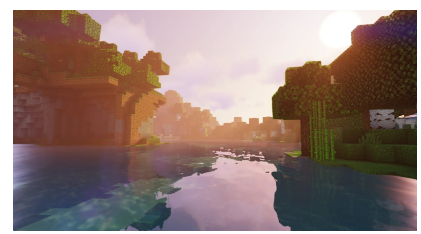
Iso-surface rendering



Games?



Games!



Ray Tracing in CG

- **In the Past (until end of 80ies)**
  - Was computationally very demanding (minutes to hours per frame)
  - Tried hard to speed it up, but always too slow → only off-line use
- **“Lost generation” (1990ies)**
  - Believed ray tracing would not be suitable for HW implementations
  - Believed ray tracing would always be slower than rasterization
- **More Recently**
  - Interactive ray tracing on supercomputers [Parker, U. Utah‘98]
  - Interactive ray tracing on PCs [Wald‘01]
  - Distributed real-time ray tracing on PC clusters [Wald’01]
  - RPU: First full HW implementation [Siggraph 2005]
  - Commercial tools: Embree (Intel/CPU), OptiX (Nvidia/GPU)
  - Complete film industry has switched to ray tracing (Monte-Carlo)
- **Own conference**
  - Symposium on Interactive RT, now High-Performance Graphics (HPG)
- **Ray tracing systems**
  - Research: PBRT (offline, physically-based, based on book, OSS), Mitsuba-2 renderer (EPFL), Rodent (SB), …
  - Products: Blender (OSS), V-Ray (Chaos Group), Arnold & VRED (Autodesk), Corona (Render Legion), MentalRay/iRay (MI), …

Ray Casting Outside CG

- **Tracing/Casting a ray**
  - Special type of query
    - "Is there a primitive along a ray"
    - "How far is the closest primitive"
- **Other uses than rendering**
  - Visibility computation
  - Volume computation
  - Collision detection
  - Acoustics
  - Radar
  - …