Illumination by Randomized Integration

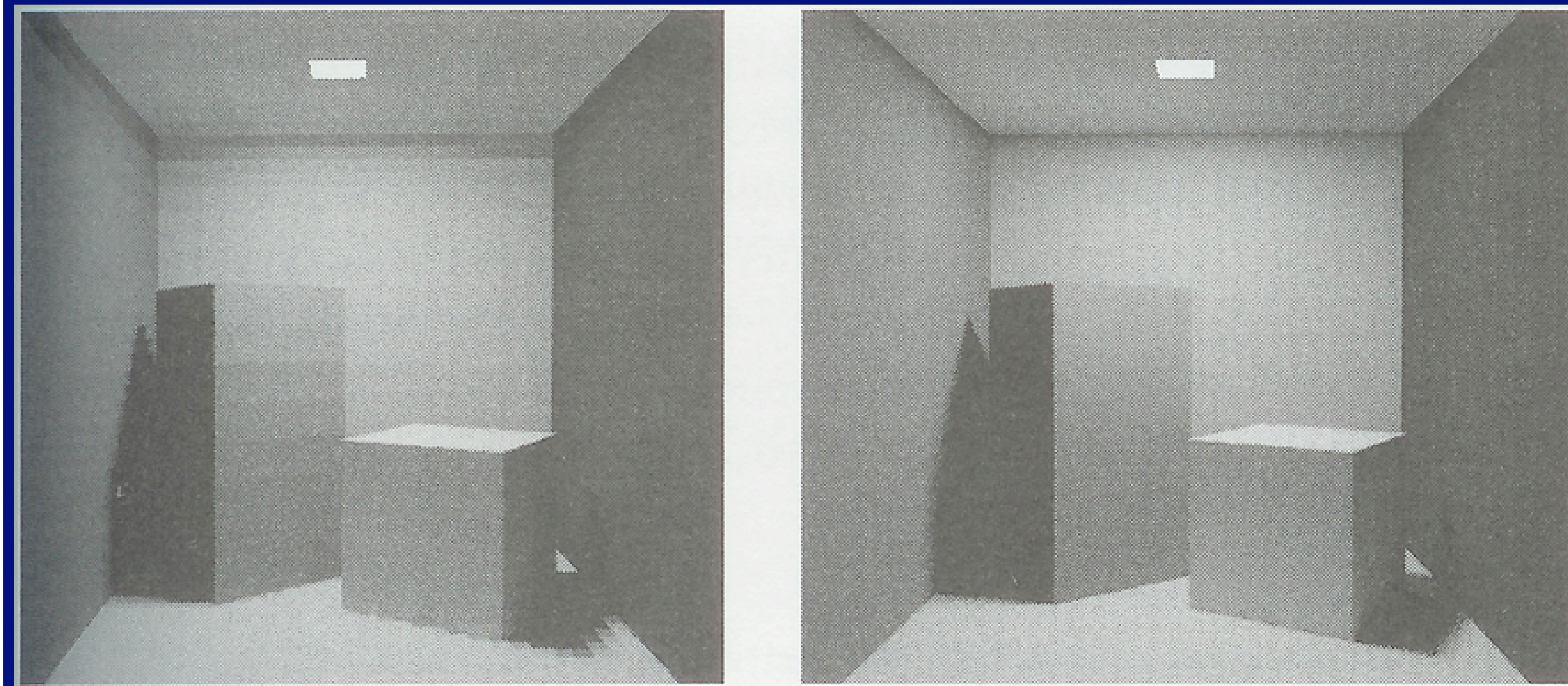
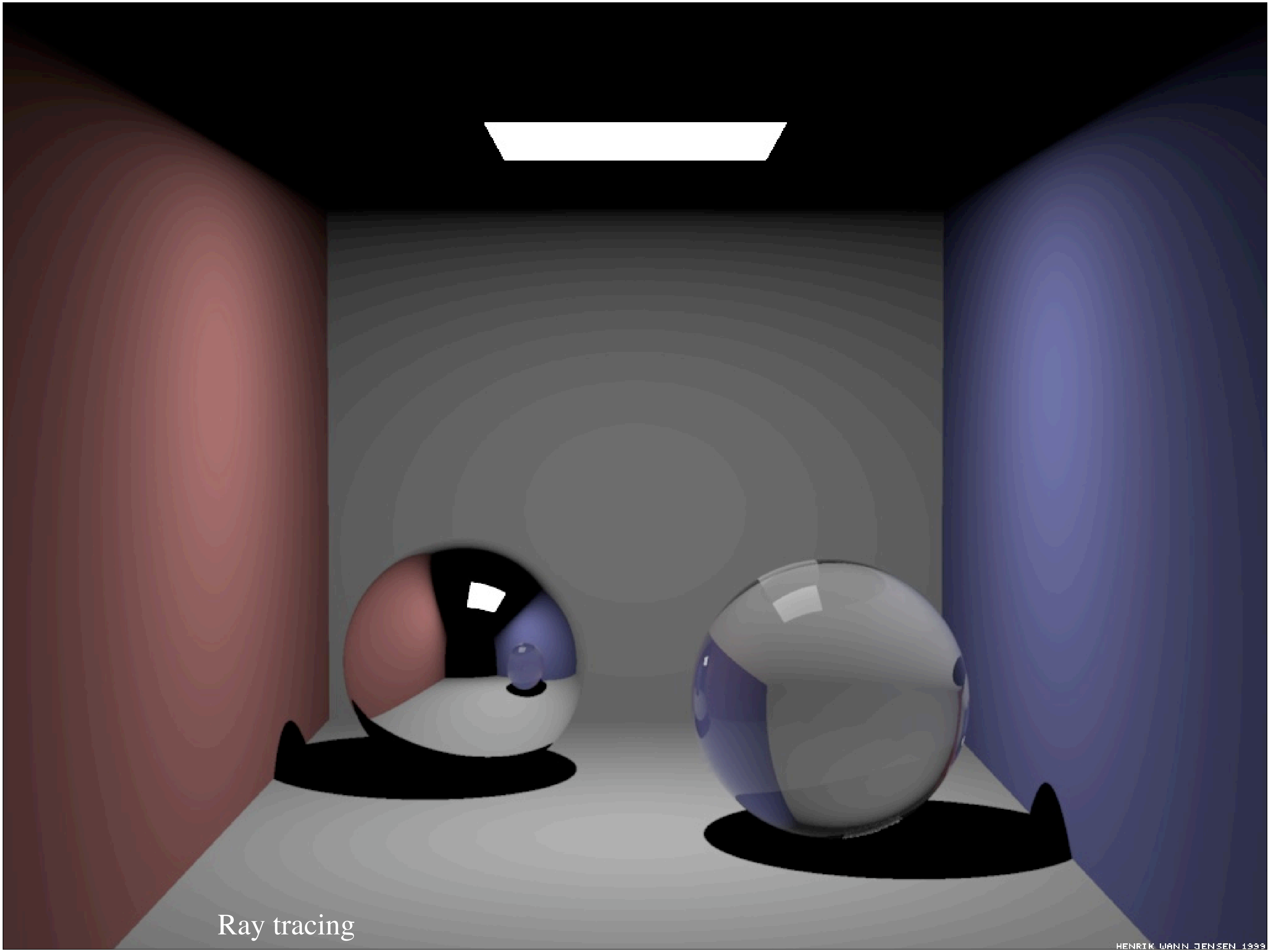
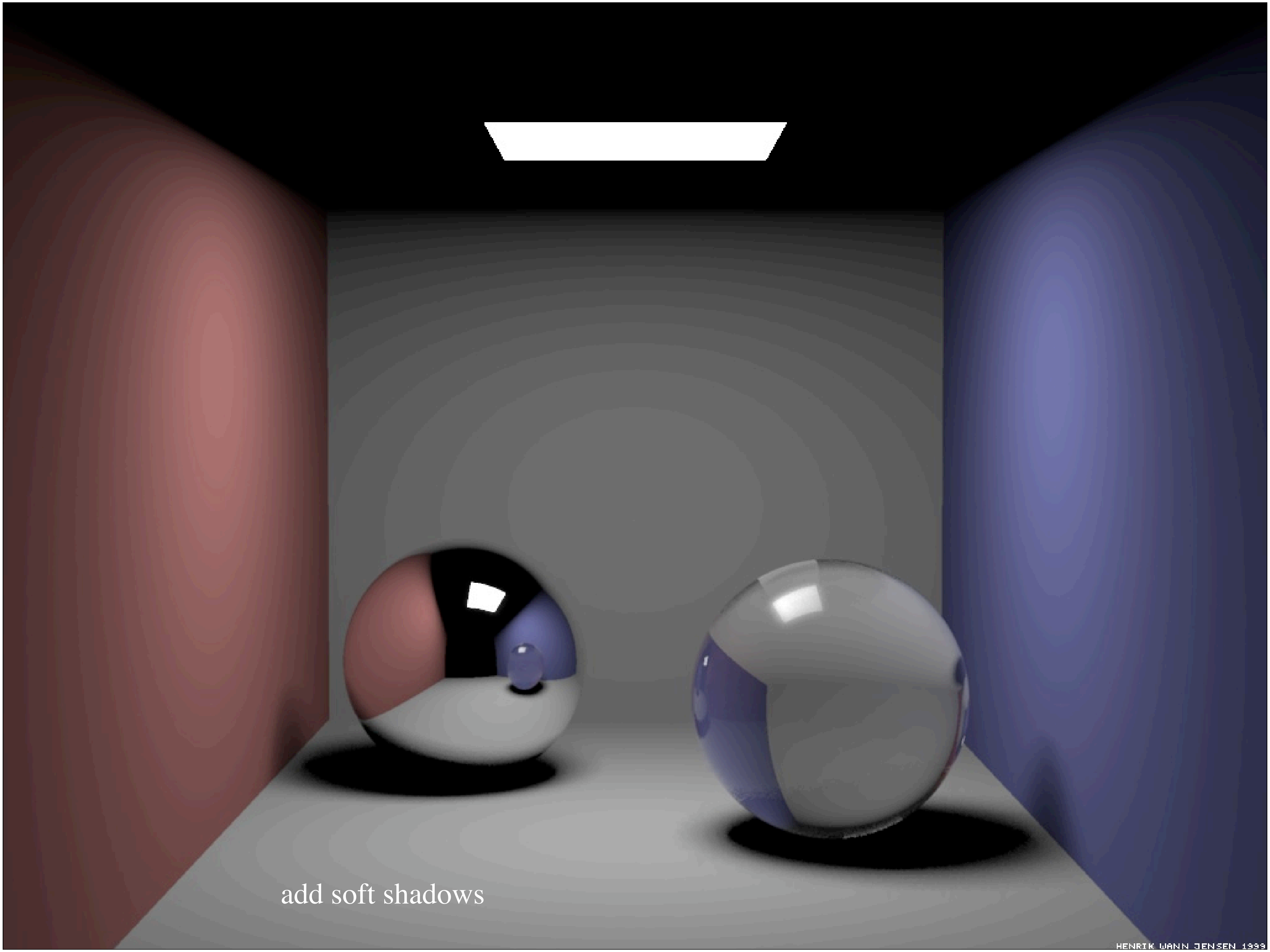


Figure from Dutre, Bekaert, Bala 03; rendered by Suykens-De Laet



Ray tracing


add soft shadows
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Paths

- Recall we could do LDS*E with eye ray tracing
  - we can do LD*E with finite element radiosity methods
    - actually, can also do LD*S*E (how?)
- But there are many more paths
  - and surfaces might not be only S or D, too
- Model paths explicitly

Path tracing

- Paths start at eye
- At diffuse surface, choose ongoing direction uniformly at random across hemisphere
- Value of path is accumulated values of reflectance along path times Exitance at end

- But
  - where does a path stop?
    - when albedo is zero (many luminaires)

Issues

- Severe variance problems as described
  - or very very slow for nice solutions
- What about surfaces that aren’t diffuse?
  - and illumination at different wavelengths?

Russian roulette

- Increase probability of absorbtion of low weight paths, and reweight the paths
  - notice that ρ helps here a lot -
  - we could change the probability of absorbtion

Path tracing

- Path tracing
  - Path starts at eye
  - At a diffuse surface with albedo ρ, path is
    - continued with probability ρ
    - absorbed with probability 1- ρ
  - Value of path
    - E(x) if it arrives at luminaire
    - 0 otherwise
  - Direction along which path continues is uniform over exit hemisphere

This is a diffuse surface formulation.

Particle tracing

- Particle starts at source
- At a diffuse surface with albedo ρ, path is
  - continued with probability ρ
  - absorbed with probability 1- ρ
- In either case, it deposits power in a texel at that point
  - particle with power ϕ arriving at texel with area A_t
    - deposits power $\frac{\phi}{A_t}$
    -
- Direction along which path continues is uniform over exit hemisphere

This is a diffuse surface formulation.

Global illumination

- Account for all light transfer

$$L(\mathbf{x}, \mathbf{x} \rightarrow \mathbf{y}) = L_e(\mathbf{x}, \mathbf{x} \rightarrow \mathbf{y}) + \int \text{radiance due to irradiance} d\omega$$

- And this gets us

$$L(\mathbf{x}, \mathbf{x} \rightarrow \mathbf{y}) = L_e(\mathbf{x}, \mathbf{x} \rightarrow \mathbf{y}) + \int \rho_{bd}(\mathbf{x} \rightarrow \mathbf{y}, \mathbf{u} \rightarrow \mathbf{x}) L(\mathbf{x}, \mathbf{u} \rightarrow \mathbf{x}) \cos\theta d\omega$$


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Path tracing for general surfaces

- Path tracing
  - Path starts at eye
  - At a surface, path is
    - continued with probability α
    - absorbed with probability 1- α
  - Value of path
    - $L_e(\mathbf{x}_n, \mathbf{x}_n \rightarrow \mathbf{x}_{n-1})$ if it arrives at luminaire
    - 0 otherwise
  - Direction along which path continues
    - a draw from P(ω)
  - Weight path segment by

$$\frac{\rho_{bd}(\mathbf{x}_{n-1} \rightarrow \mathbf{x}_n, \mathbf{x}_n \rightarrow \mathbf{x}_{n+1}) \cos\theta}{P(\omega)\alpha}$$

    - and accumulate these weights

This will do anything,
but with very serious variance problems

Variance problems

- Paths may not find the light often
  - this could be fixed by clever choice of P to heavily emphasize directions toward the source
- Caustics will be poorly rendered, because the path to the source is obscure

Bidirectional path tracing

- Start paths at both eye and light and join them
- Notice:
  - a pair of eye-light paths generates many possible transfer paths
  - we can use each of these, if we compute weights correctly to get integral estimate right

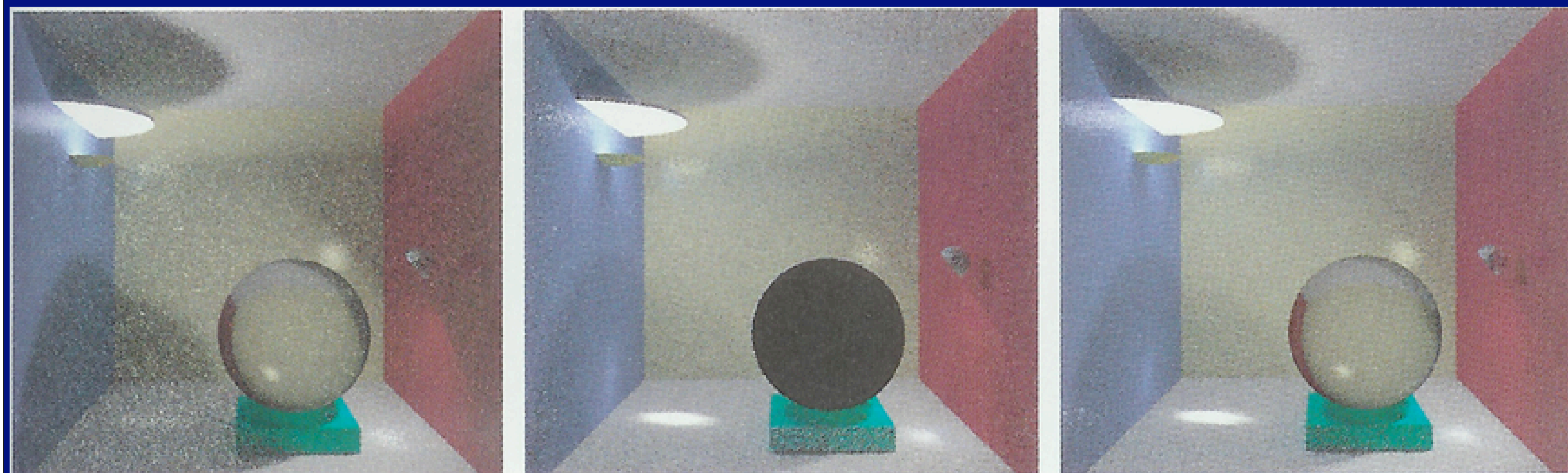


Figure from Dutre, Bekaert, Bala 03; rendered by Suykens-De Laet

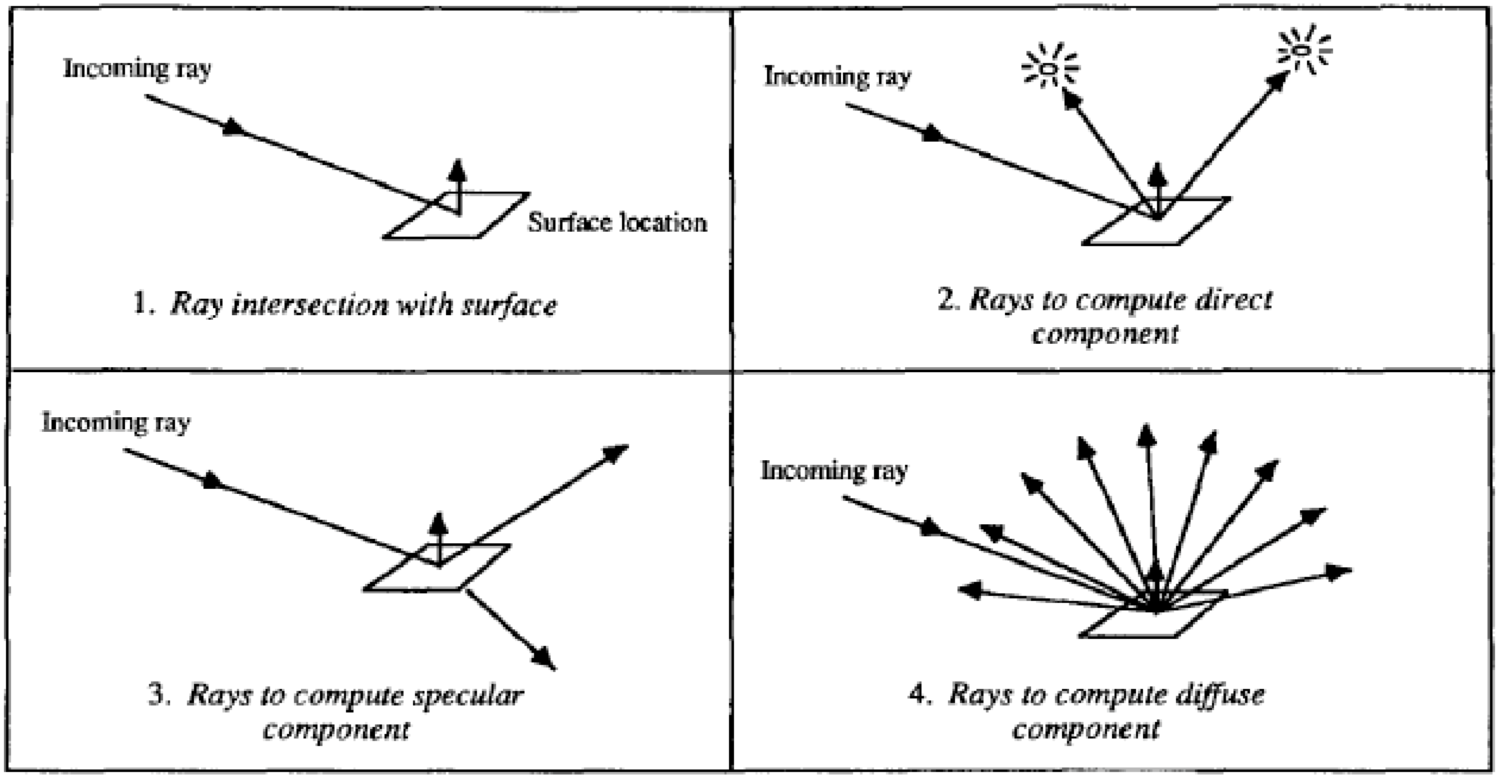


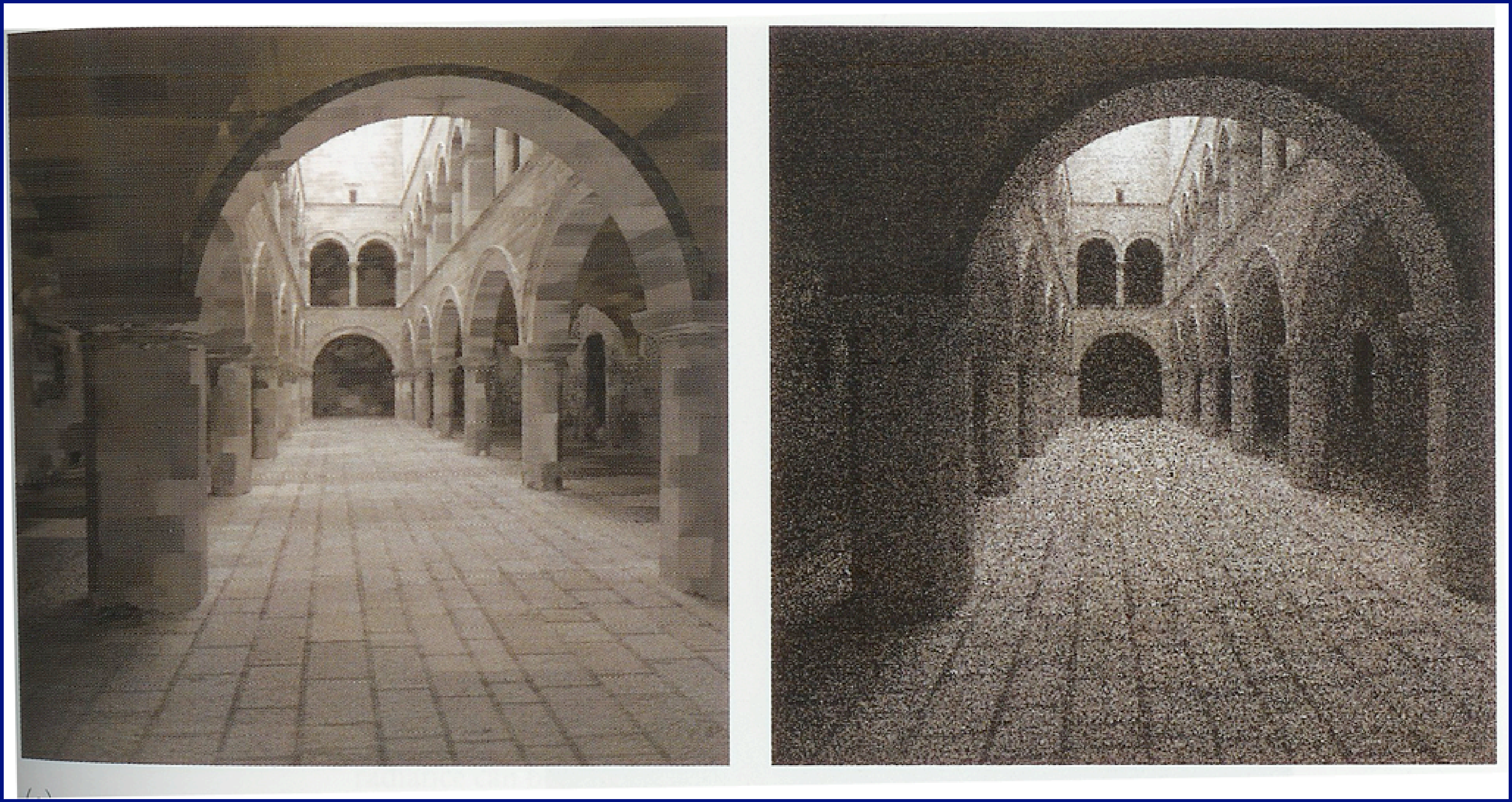
Figure 1: The four steps of ray tracing.

Figure from Ward et al, “A Ray-tracing solution for diffuse interreflection”, 1988

Irradiance caching

- The indirect term varies slowly over space
  - cache and interpolate
- Cache by
  - storing irradiance samples in octree with normal
- Interpolate by
  - obtaining all samples with error smaller than α
    - error is:
      - (distance term)+(normal term)
    - not enough samples?
      - generate new ones and cache them
  - forming weighted sum using extrapolated illumination values

Powerful standard method in
almost every modern rendering system



Irradiance cache vs path tracing, from Pharr + Humphreys

Cache sample locations from Pharr + Humphreys

Irradiance caching: samples

- Obtaining samples:
  - evaluate irradiance at sample point by:
    - direct term:
      - sample each source directly, as before
    - indirect term:
      - sample non-source directions with probability $P(\omega)$
      - form estimate

$$\frac{1}{N}\sum_j \frac{L_i(\mathbf{x}, \omega_j)\cos\theta_j}{P(\omega_j)}$$

      - Notice that the incoming radiance might be computed from the cache, if there are samples

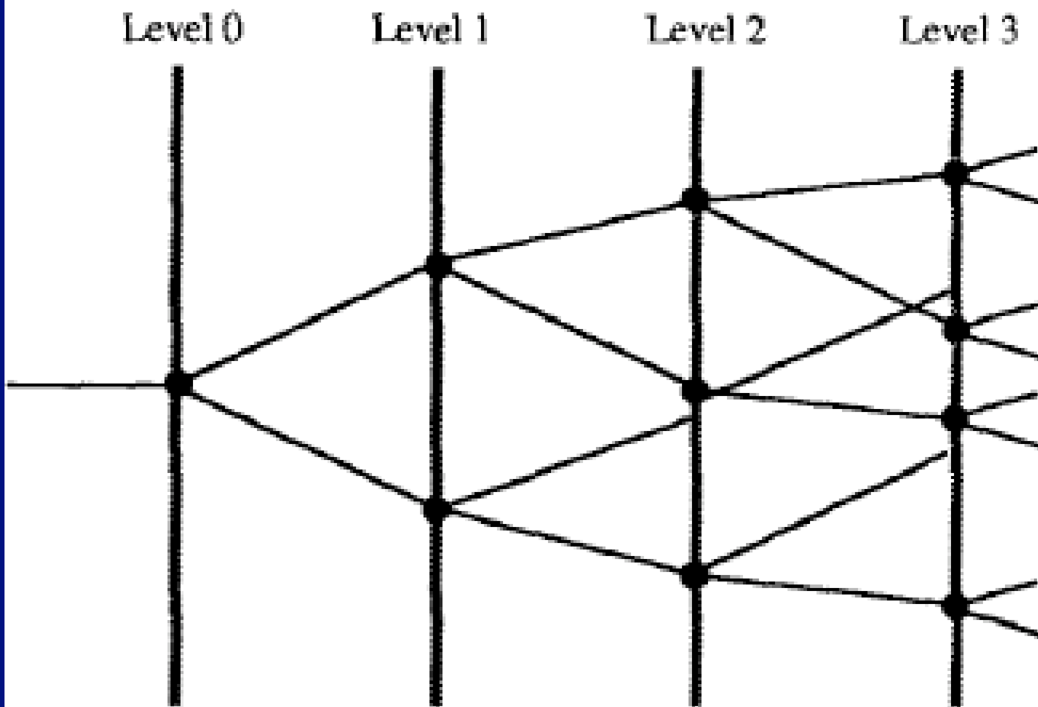


Figure 7: The lines represent rays, and the points represent primary evaluations. The rays that reuse computed values do not propagate.

Note:
Russian roulette prevents the tree getting out of hand
Fairly quickly, the cache fills up

Figure from Ward et al, "A Ray-tracing solution for diffuse interreflection", 1988

Irradiance caching: reconstruction

- Query octree for possible samples
  - Do not want to use:
    - samples that are too far away
      - this is a function of how samples were obtained
    - samples with a bad normal
    - samples that lie closer to the eye than current point
- Reconstruct by
  - weighted sum of samples
  - interpolation process can use:
    - distances
    - gradients

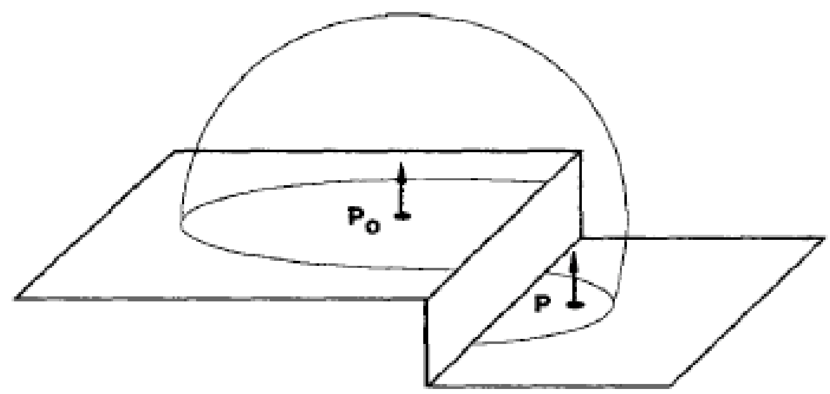
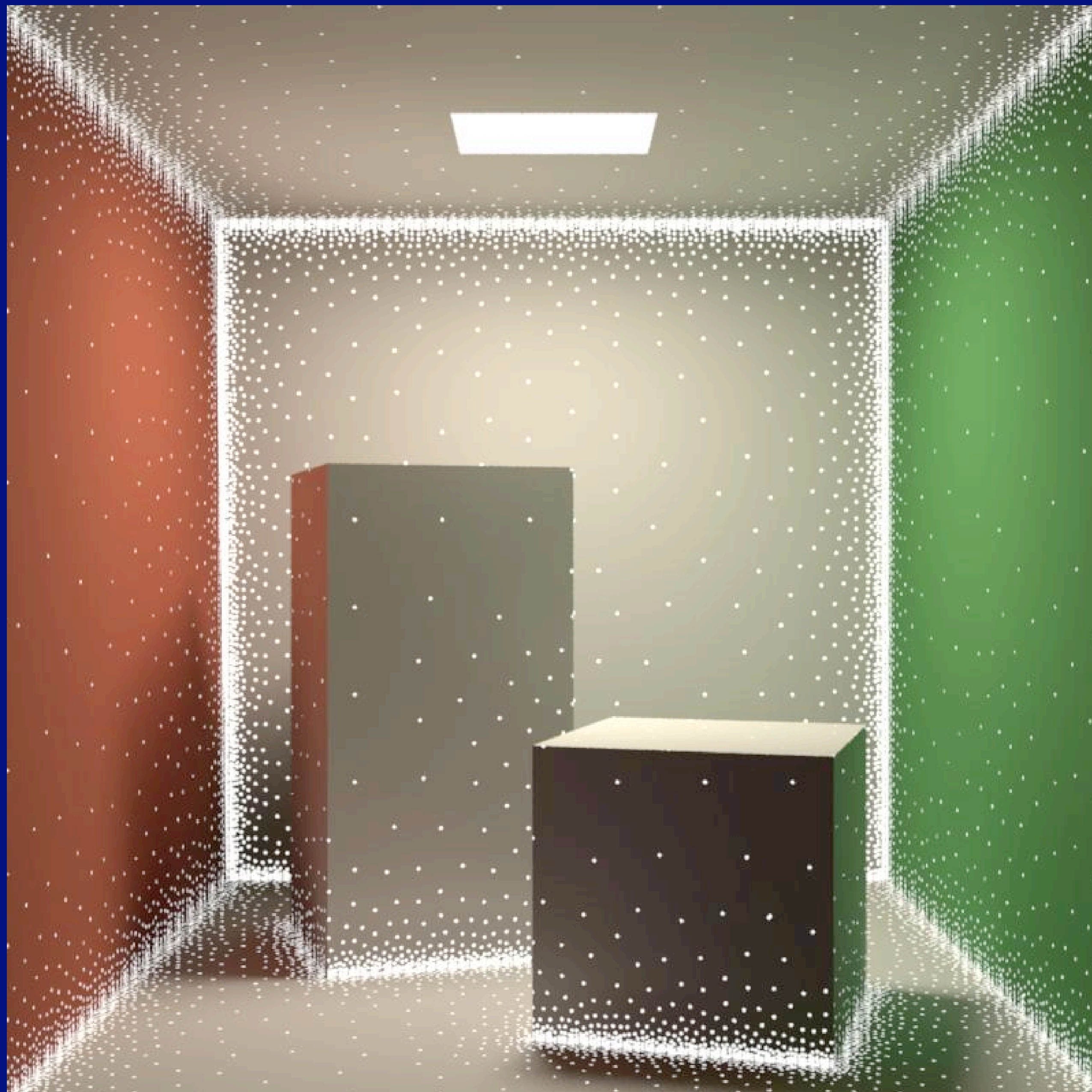


Figure 4: $\vec{P}_0$ sees few close-by surfaces, so its estimated error at $\vec{P}$ is small. But $\vec{P}$ is shadowed by the surface under $\vec{P}_0$, and the true illuminance is different.

Figure from Ward et al, "A Ray-tracing solution for diffuse interreflection", 1988



Typical sample locations for
irradiance cache

Photon maps

- Drop the requirement of an unbiased estimate of illumination
  - accept some bias for better variance properties
- Propagate photons from source, cache when they arrive at surfaces
- Interpolate illumination value by averaging over k-nearest neighbours
- Caustic variance
  - use two classes of photon: sample specular, refractive directions separately
- How many photons?
  - keep trying till it looks good

Photon propagation

- Photons carry Power
  - scale photons from source by number emitted
- reflected
  - diffuse
    - store in map when it arrives, propagate
      - prob proportional to cos theta
      - power scaled by albedo
        - or use russian roulette
  - specular
    - do not store in map, propagate
      - along specular direction
      - power scaled by reflectivity
        - or use russian roulette
  - arbitrary BRDF
    - inportance sample outgoing direction

Photon propagation

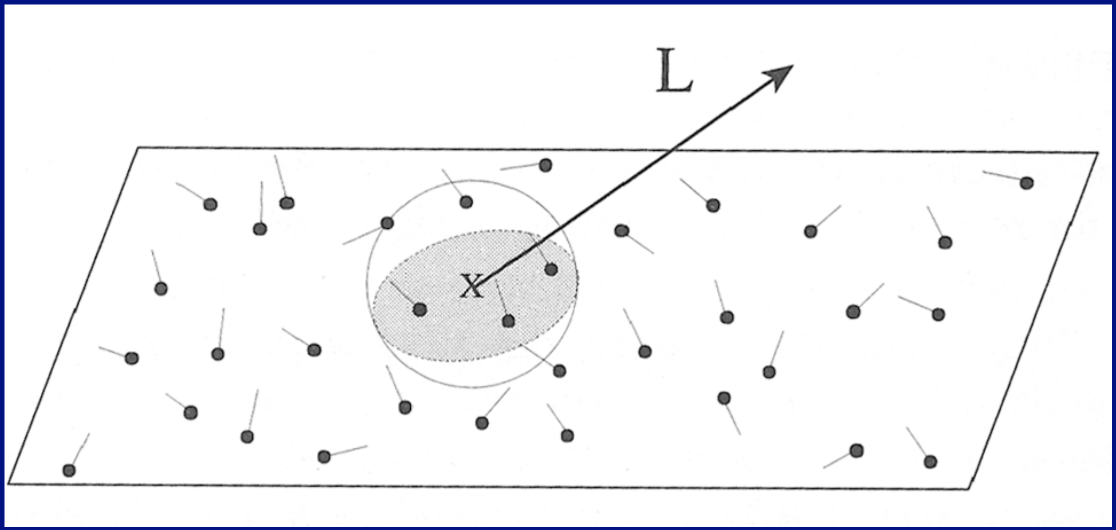
- When a photon arrives at complex surface, multiple photons could be generated
  - eg specular + diffuse
    - russian roulette to decide whether
      - specular
        - reflected/absorbed
      - diffuse
        - reflected/absorbed
- Photons are stored at diffuse (non-specular!) surfaces only
- Stored as:
  - Power, Location, Normal

Photon storage and querying

- Store in k-d tree
  - to look up r closest photons
  - tree represents free space close to surfaces

Evaluating Radiance

- Reflected radiance is: $$L_r(\mathbf{x},\omega) = \int_\Omega \rho_{bd}(\omega,\omega_i) L_i(\mathbf{x},\omega_i)\cos\theta d\omega$$
- Each photon carries known power, in known direction
  - assume the relevant photons all arrive at x
  - each contributes radiance (power/dA)
  - assume surface is flat around x, build a circle
    - photons in this circle contribute
    - area is known



$$L_r(\mathbf{x},\omega)\frac{1}{\pi r^2}\sum \rho_{bd}(\omega,\omega_j)P_j(\mathbf{x},\omega_j)$$

Figure from Jensen’s book

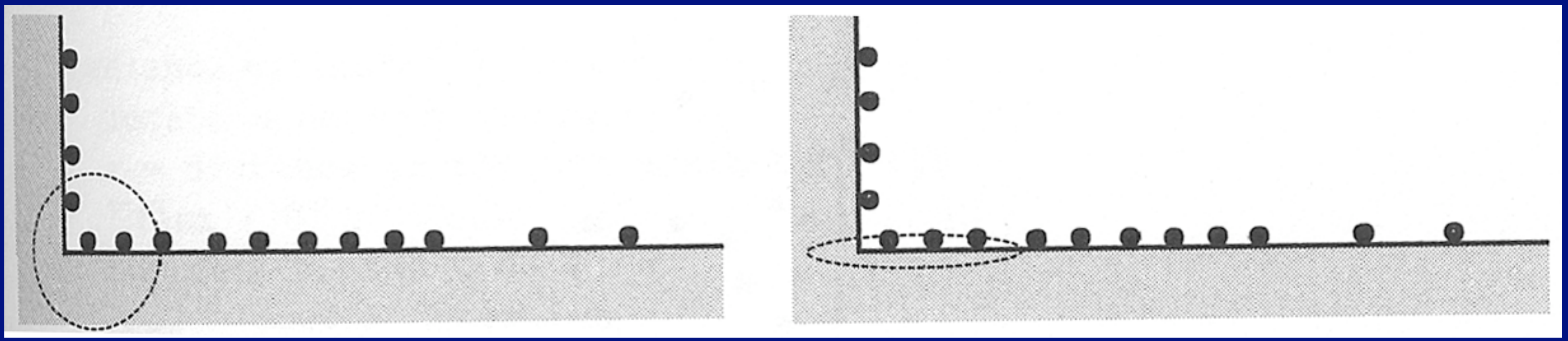


Figure from Jensen's book

A two pass renderer

- Propagate photons
  - two classes
    - caustic photons toward specular/glossy, refractive objects
      - large numbers
      - caustic map
    - global illumination photons toward diffuse objects
      - small numbers
- Gather
  - render using
    - direct term by area source sampling
    - specular term by ray-tracing
    - caustic term by direct query to photon map
    - global illumination term by gathering the photon map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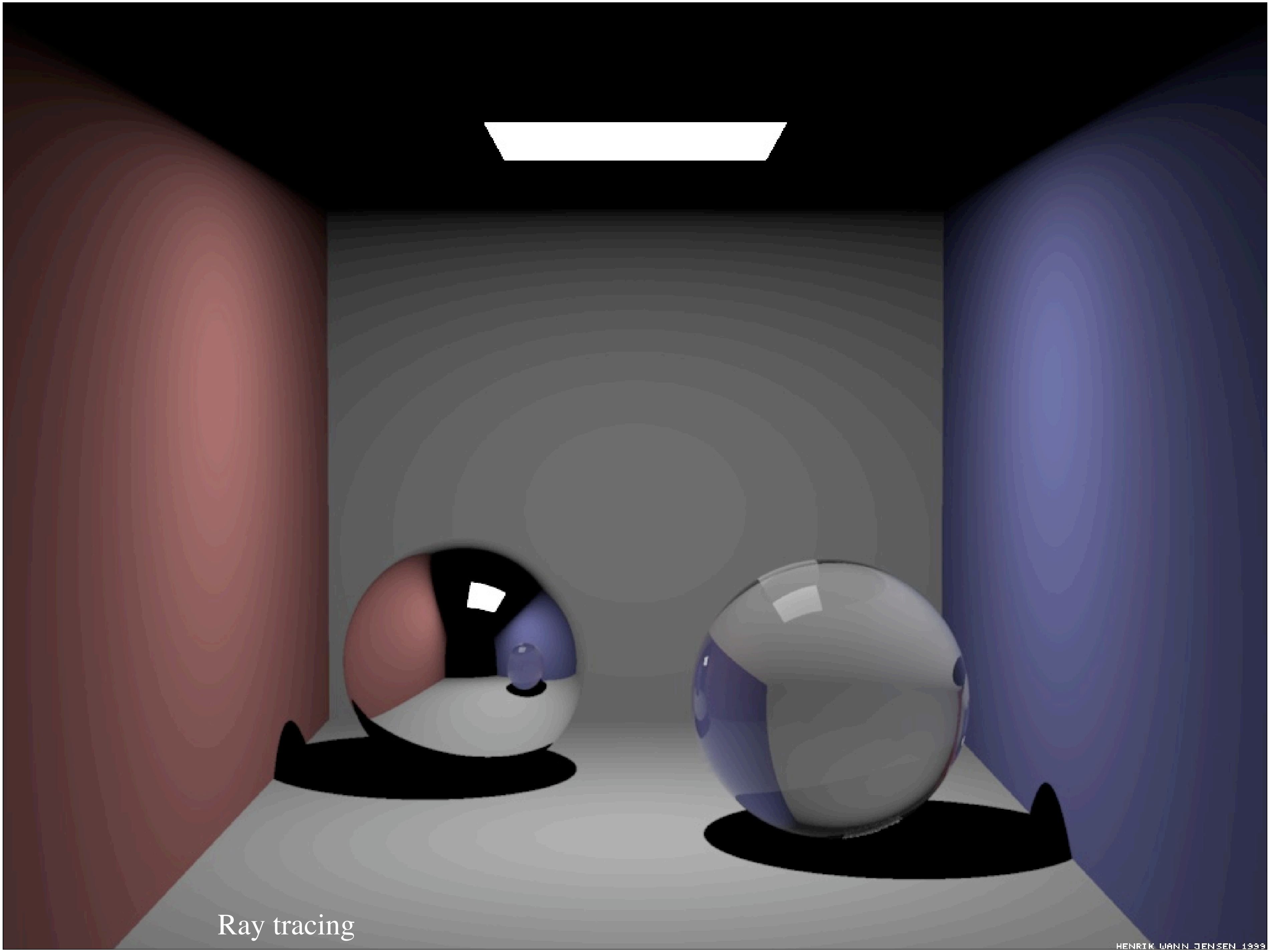
Ray tracing
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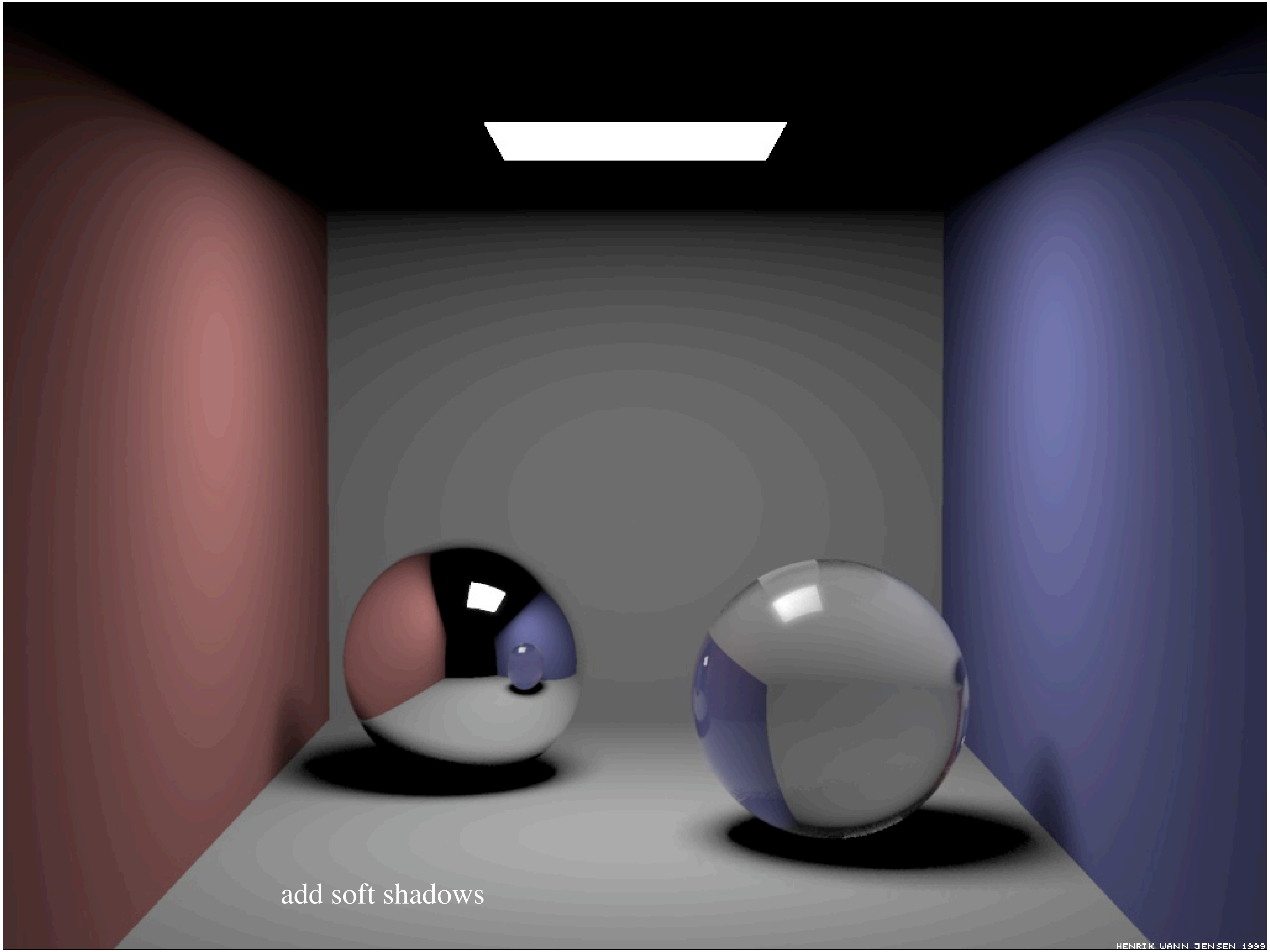
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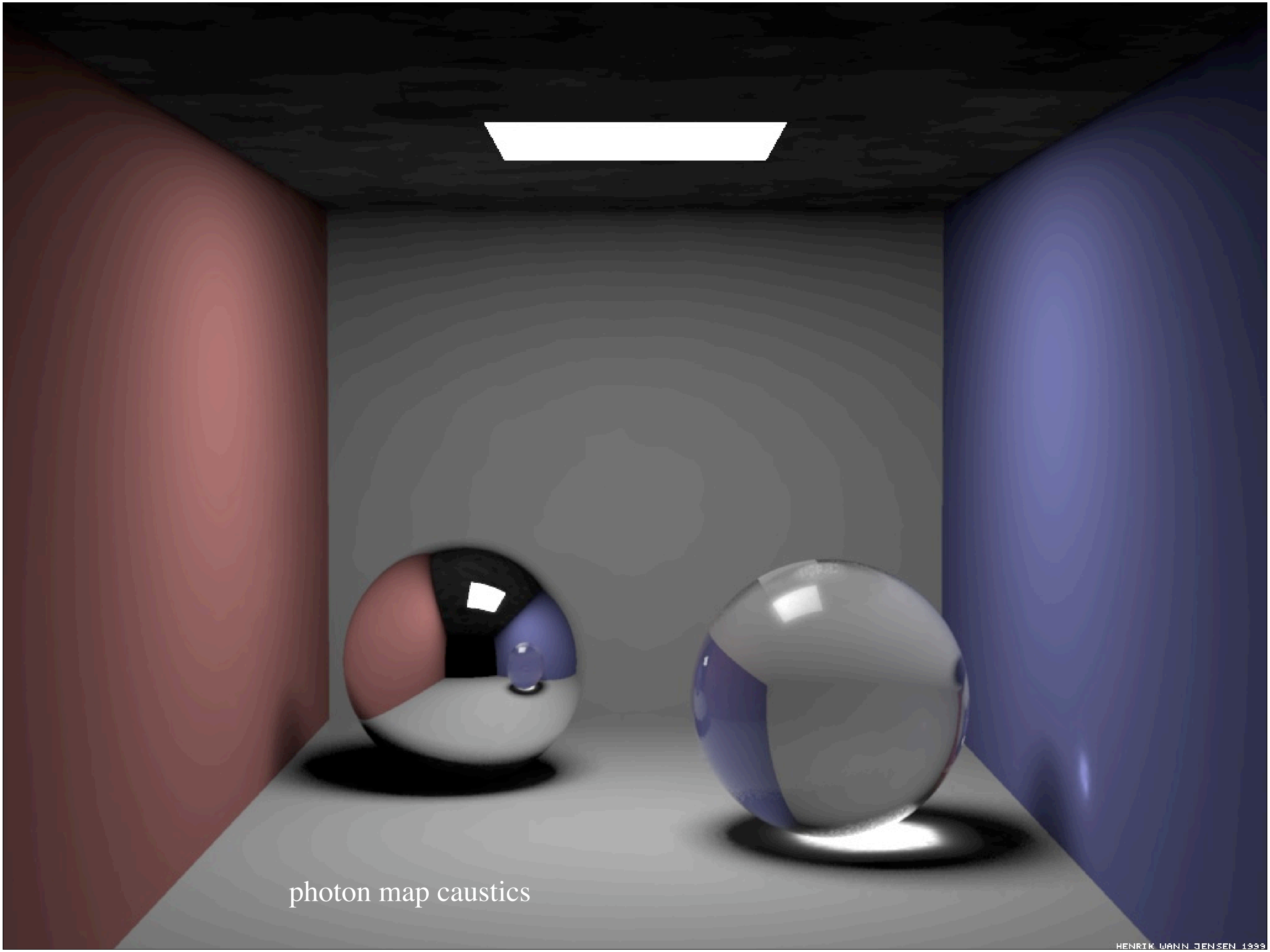
photon map caustics
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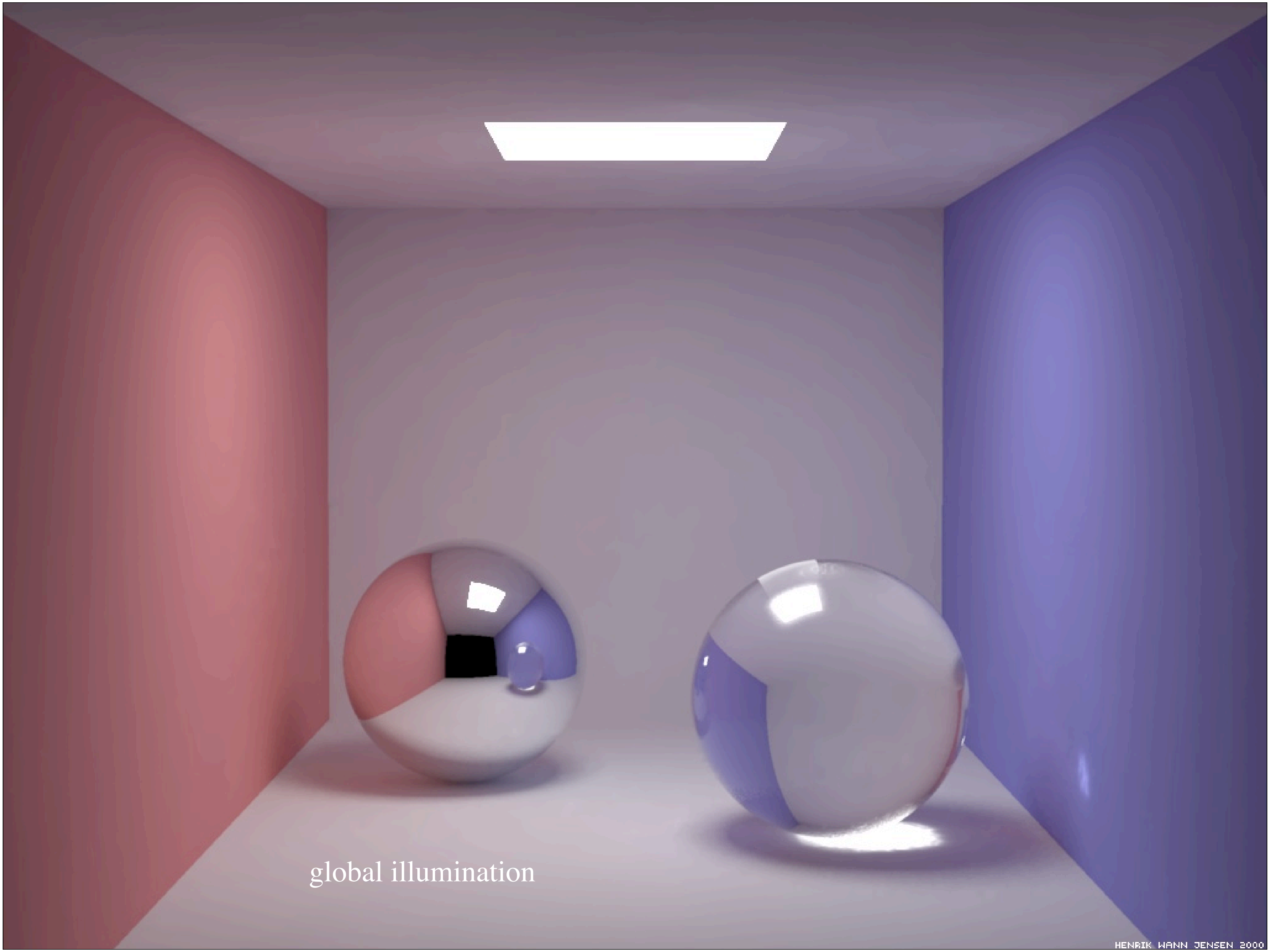
global illumination
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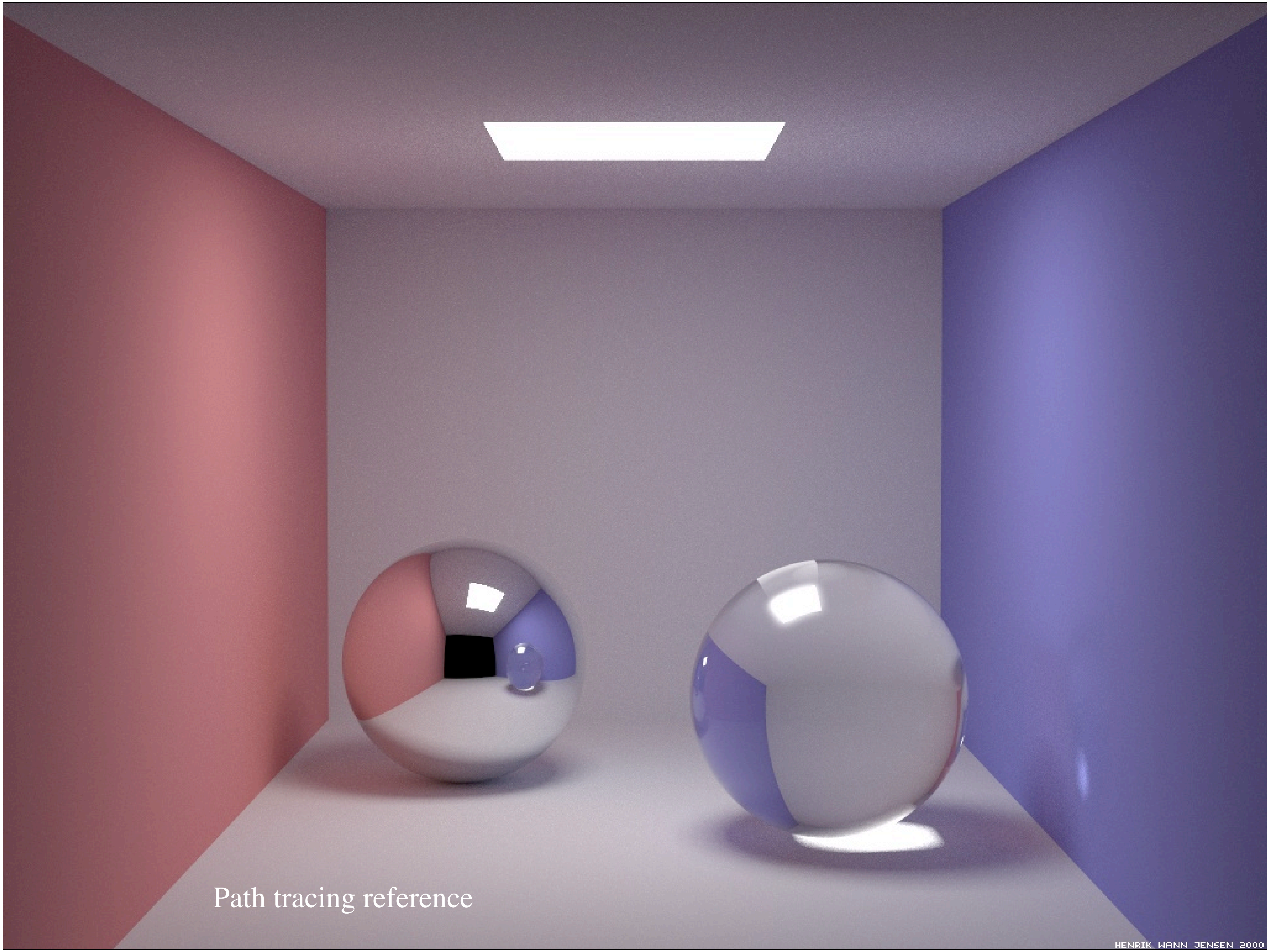
Path tracing reference
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