Stochastic Sampling and Distributed Ray Tracing, Robert L. Cook

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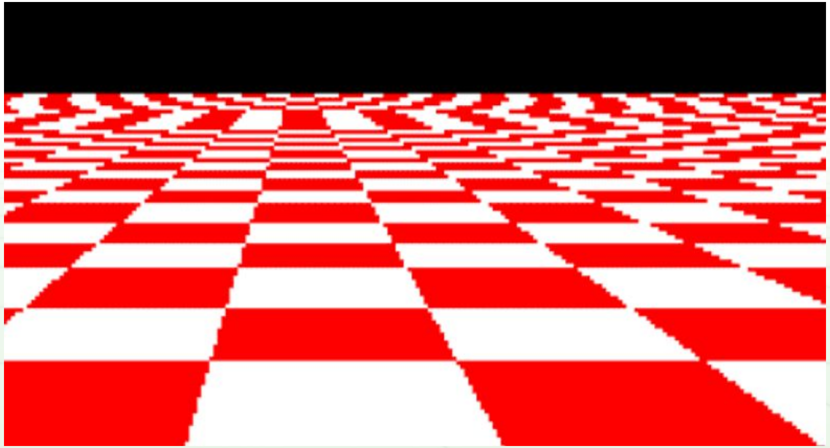
Overview

- Discrete pixel sizes gives an *upper limit* to the frequencies that can be displayed
  - Restricted by the *Nyquist limit*
- Displaying higher frequencies can result in artifacts
  - *Aliasing, e.g. Moiré patterns*
- Problem for ray tracing
  - Regularly spaced sample points
- Can be mitigated with
  - *Supersampling*
  - *Adaptive supersampling*
  - *Stochastic sampling*

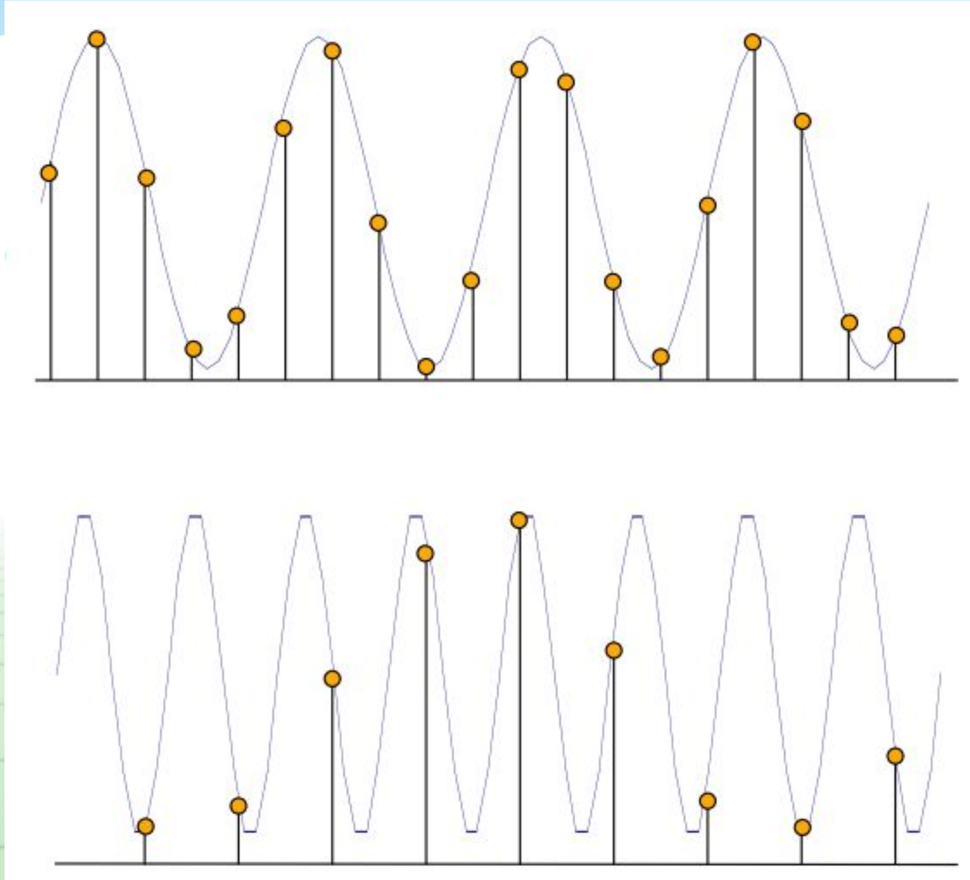


The Nyquist Theorem

To reconstruct a signal accurately, the sampling rate must be >= 2 times the highest frequency in a signal

In other words:

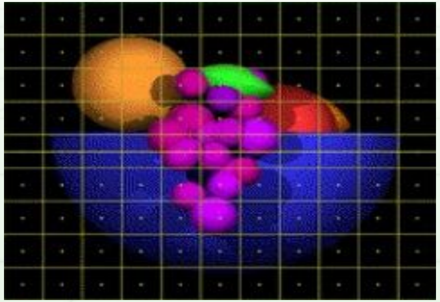
Nyquist limit = 2 * max_freq



Images as functions

- What does this have to do with graphics?
- An image can be seen as a luminosity function F(x,y) of values defined at the pixel centres
  - For grayscale image, F(x,y) is the intensity of pixel at (x,y)
  - A row of pixels can be seen as a function of the variable x

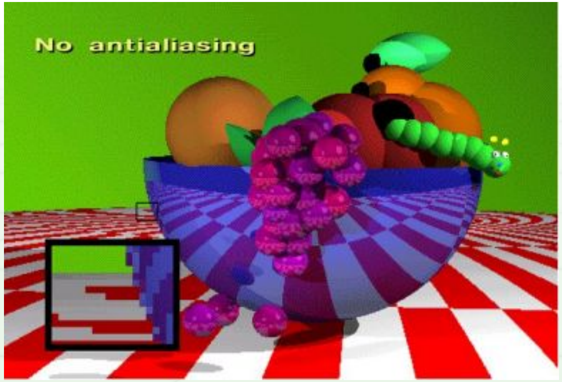
Sampling at pixel centers



Sampled signal

Sampling theory and graphics

- When the pixel distance is higher than the Nyquist limit of the sampled frequencies one becomes *jaggies*
- Jaggies are high frequencies appearing as low frequencies, resulting in regular patterns



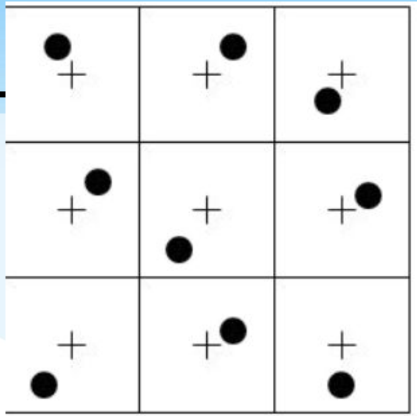
Anti-aliasing

- Try to avoid the side-effects of aliasing
- Supersampling
  - Raising the Nyquist limit
  - Expensive
- Adaptive supersampling
  - Increase samples only if necessary
    - When is “necessary”?
  - More involved

Stochastic sampling

- A Monte Carlo technique
- Sample at nonuniformly spaced locations
- Aliasing replaced by noise of correct average intensity
    - **Aliasing artifacts replaced by noise**
    - **Our visual systems tolerate noise quite well**
- Can be used to evaluate complex integrals
    - *Monte Carlo integration*

Jittering a regular grid



- Adding noise to the sample locations
- Can result in
  - Attenuation of high frequencies
  - Lost energy *appearing as uniform noise*.
  - No change in the basic composition of the spectrum
- *Subpixel jittering*
  - Divide pixel into a grid of subpixels
  - Randomly perturb center of each subpixel
- Approximation to a Poisson disk distribution

DISTRIBUTED/PROBABILISTIC RAY TRACING

Estimating integrals

- Use stochastic sampling to evaluate complex integrals:

$$L_o(x, \vec{\omega}_r) = L_e(x, \vec{\omega}_r) + \int_\Omega L_i(x, \vec{\omega}_i) f(x, \vec{\omega}_i, \vec{\omega}_r)(\vec{\omega}_i \cdot \vec{n}) d\vec{\omega}_i$$

- Simulate *fuzzy* fenomenas
- Stochastically distribute the rays in extra dimensions, given by variables of integration

Different ways of distributing rays

- Distributing reflected rays
- Distributing transmitted rays
- Distributing shadow rays through the solid angle of each light source
- Distributing ray origins over camera lens area
- Distributing rays in time

Rough reflections & refractions

Integration of reflected light:

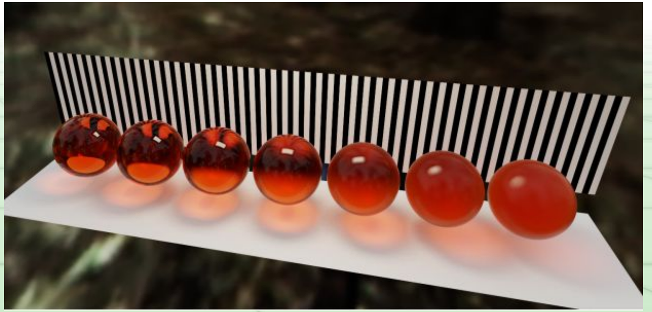
- Distribute rays about *mirror direction*
- Specular reflectance function

Integration of transmitted light:

- Distribute rays about *transmitted light direction*
- Specular transmittance function

Rough reflections

Rough refractions



Soft shadows

- Occurs where a light source is partially obscured
- Distribute shadow rays over light source region
  - Weighted according to e.g. projected area and brightness
- # rays should be proportional to the amount of the light's energy if completely unobscured.
- shadow = visible light / total unobscured light

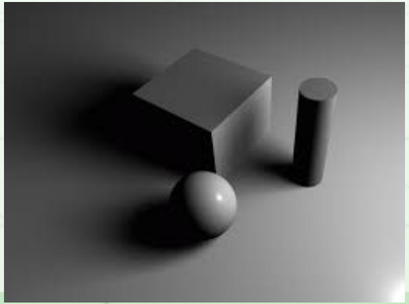
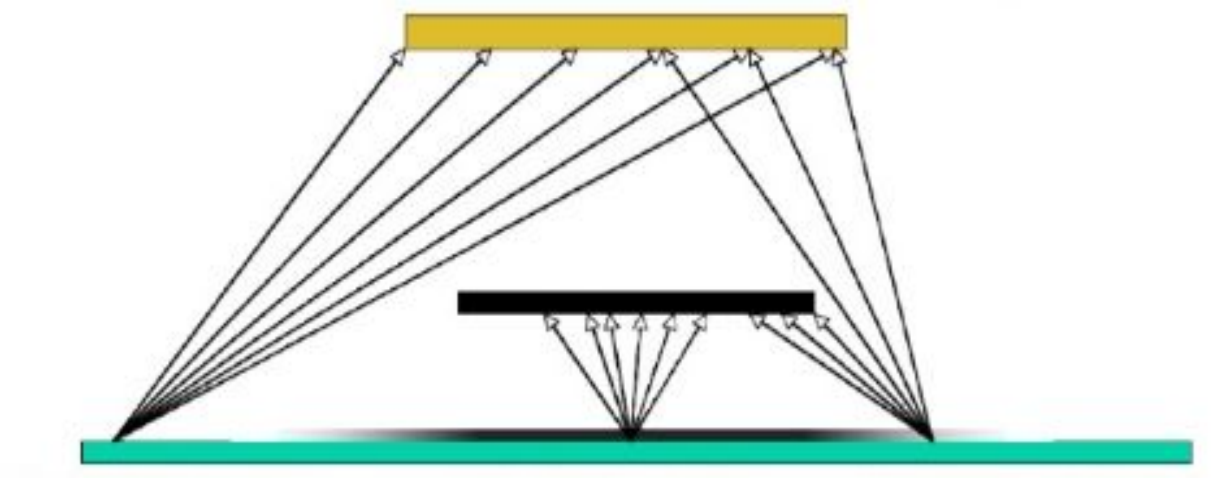


Illustration: soft shadows



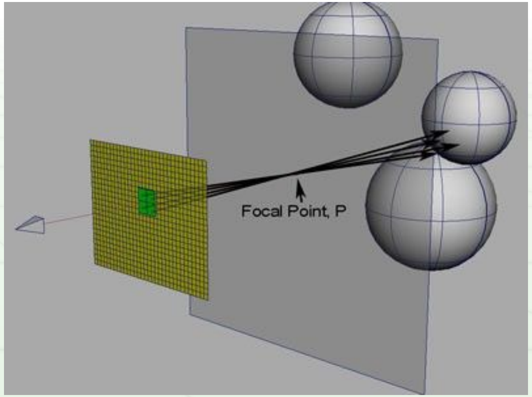
All shadow rays hit light source. Fully illuminated

No shadow rays hit light source. Fully shadowed.

Some shadow rays hit light source. Partially shadowed.

Depth of field & Motion Blur

- Motion blur
  - Distribute rays over time to simulate object movement
  - Need to be able to calculate position of object at specific time
- Depth of Field
  - Distribute rays across a discrete camera aperture



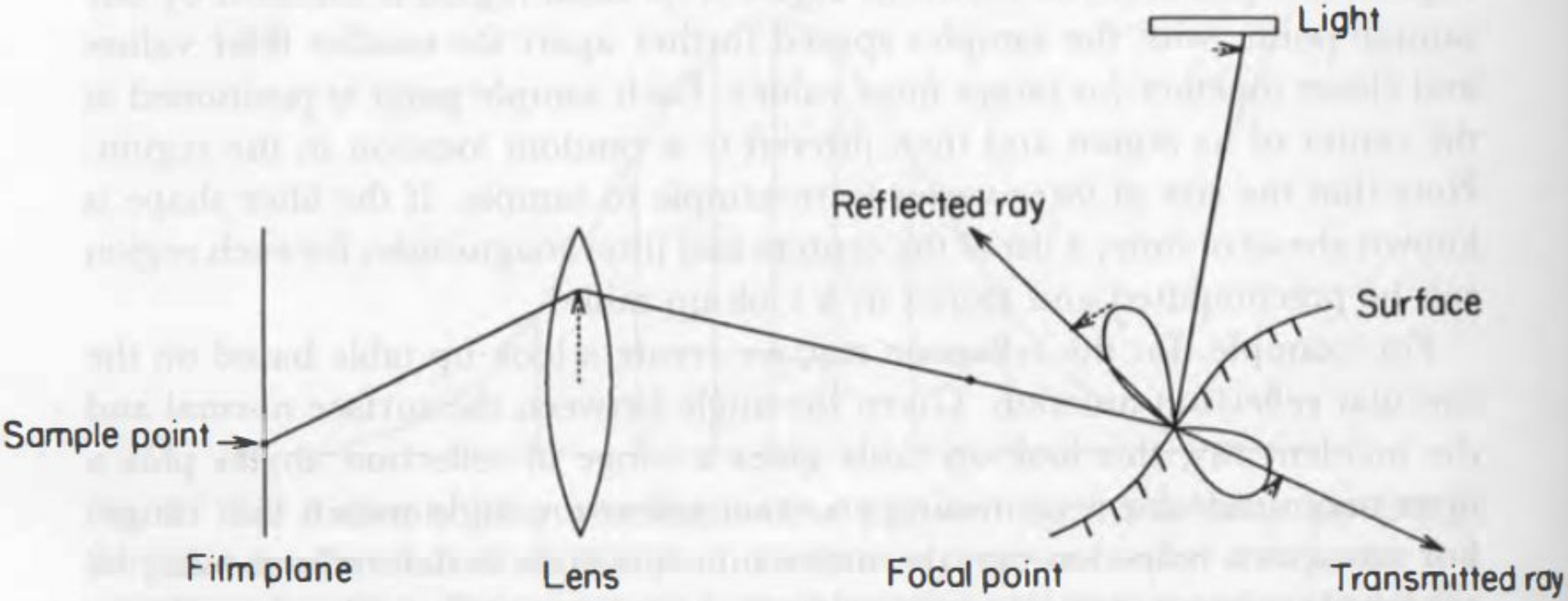


Fig. 10. Typical distributed ray path.

Conclusion

- Existing solutions usually try to work around the Nyquist limit
- Aliasing can be minimized by replacing it by noise
  - High frequencies appear as noise instead of aliasing
- Stochastic sampling allows for many fuzzy fenomenas
  - Distributed/probabilistic ray tracing
- Do sampling based on the relevant properties
  - Importance sampling

Questions?