Materials and weather

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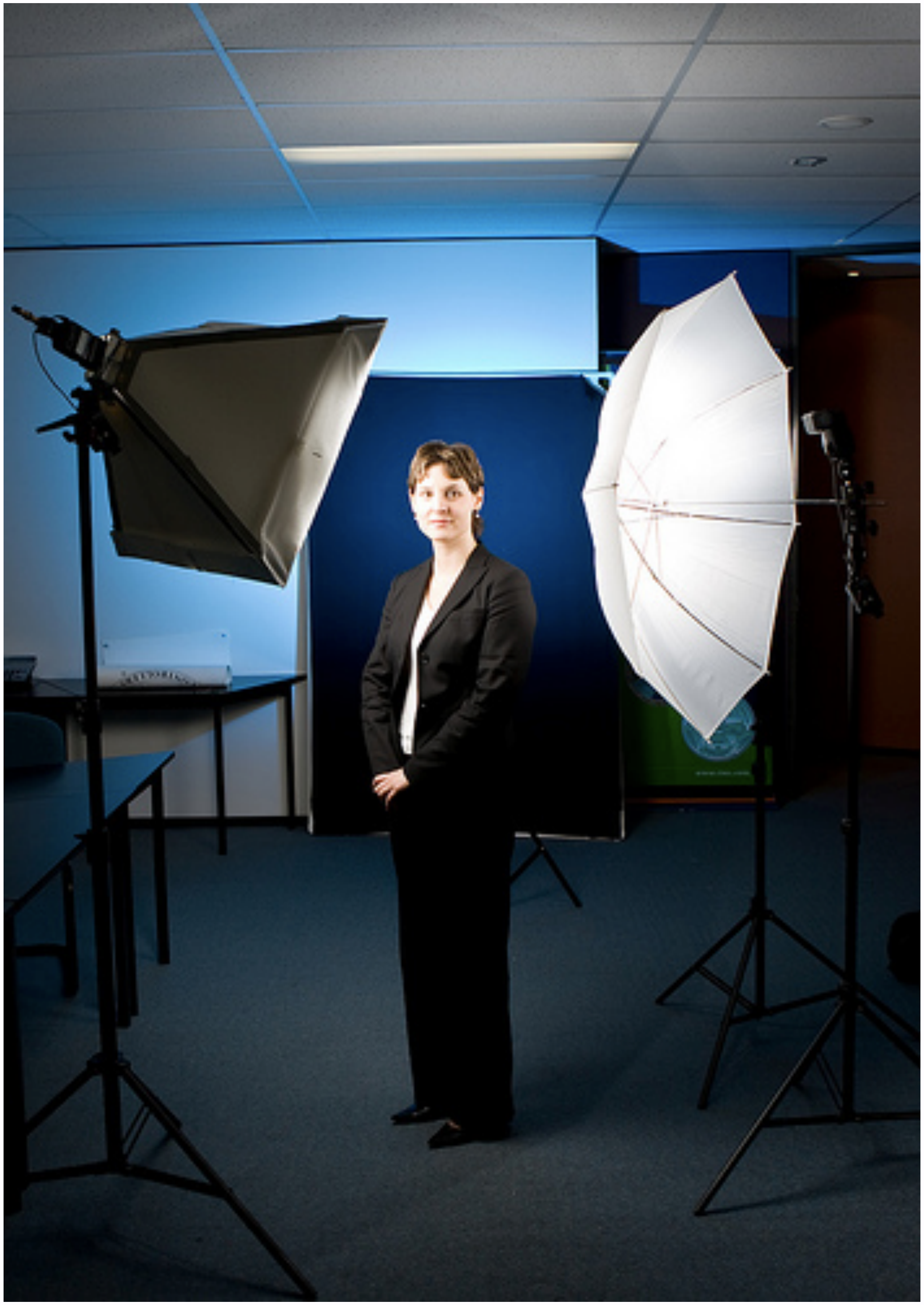
Key issues

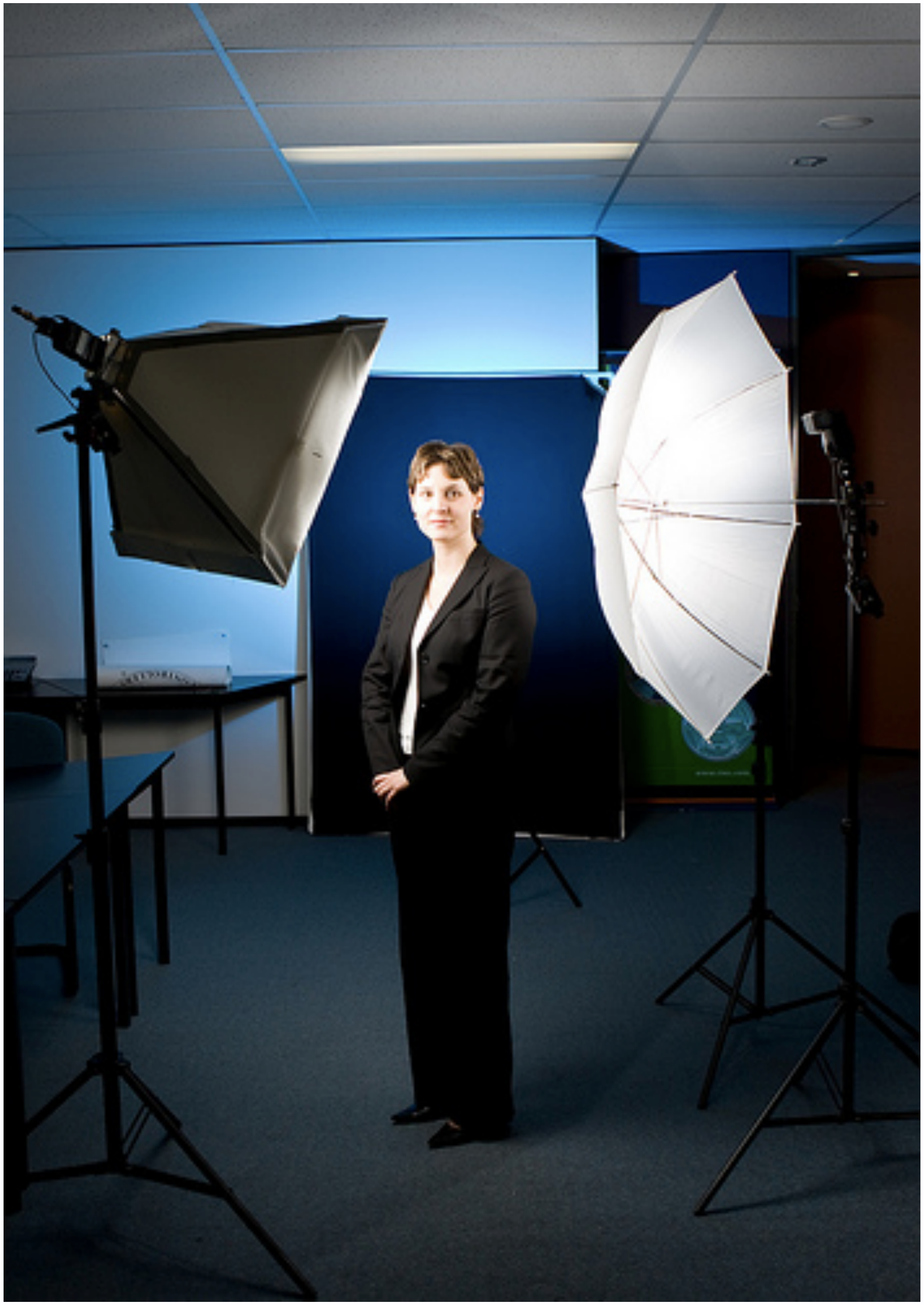
- Physical
  - what makes a pixel take its brightness values?
  - Effects
    - at surfaces
    - in volume
  - Human: what can people do?
    - which suggests problems we might be able to solve
- Sensing
  - can we sense in ways that reduce significance of effects?
  - sensor fusion, etc.
- Inference
  - what can we recover from the world using sensed values?

Effects at surfaces

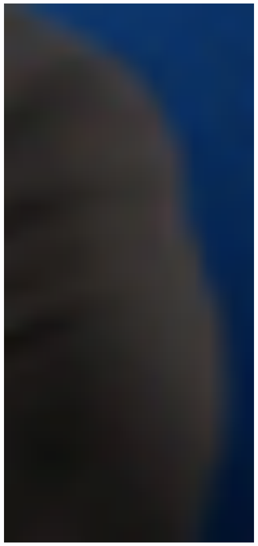
- We assume:
  - we see the world in a vacuum
    - or very clear air, no fog, nothing



nickwheeleroz



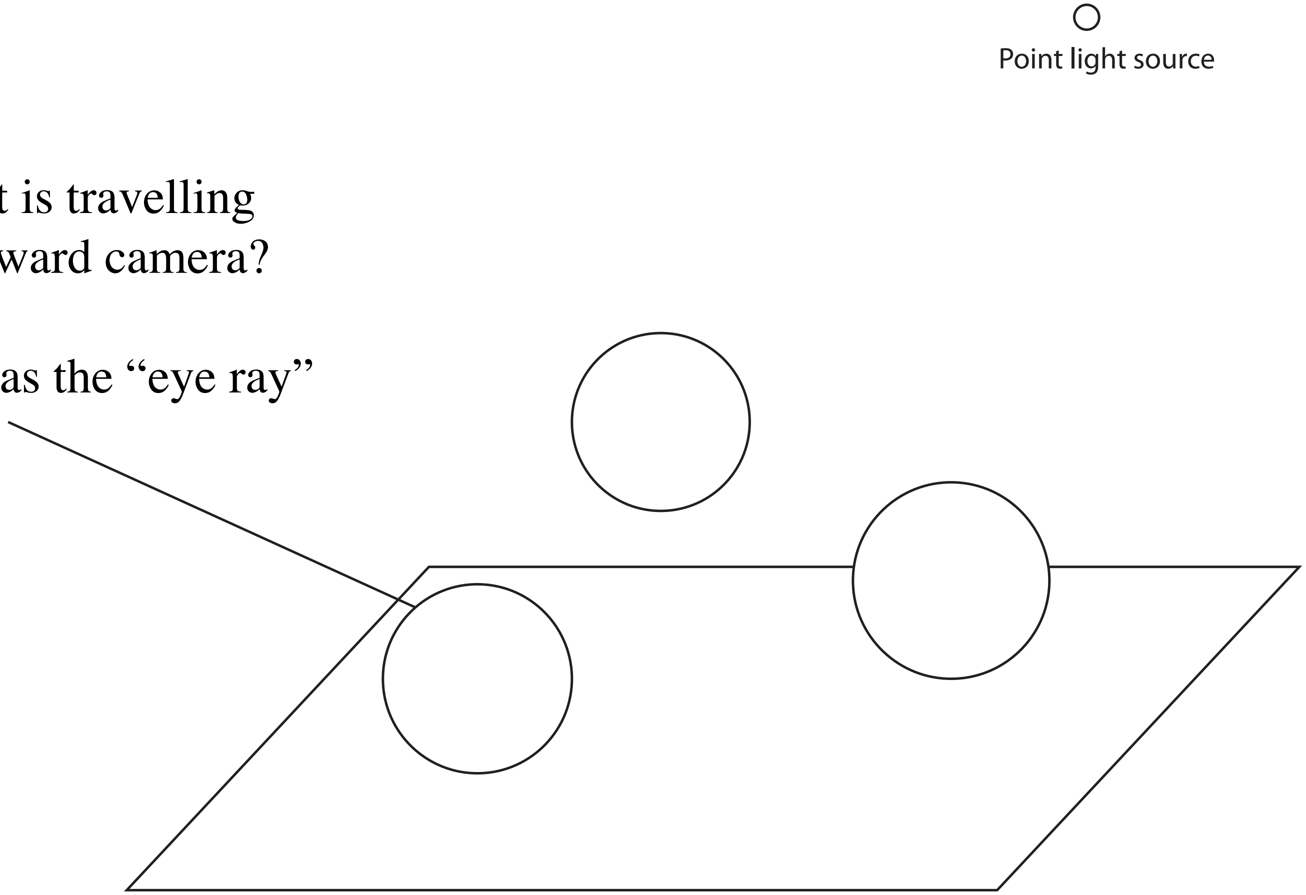
By nickwheeleroz, on Flickr



Very simple ray-tracing

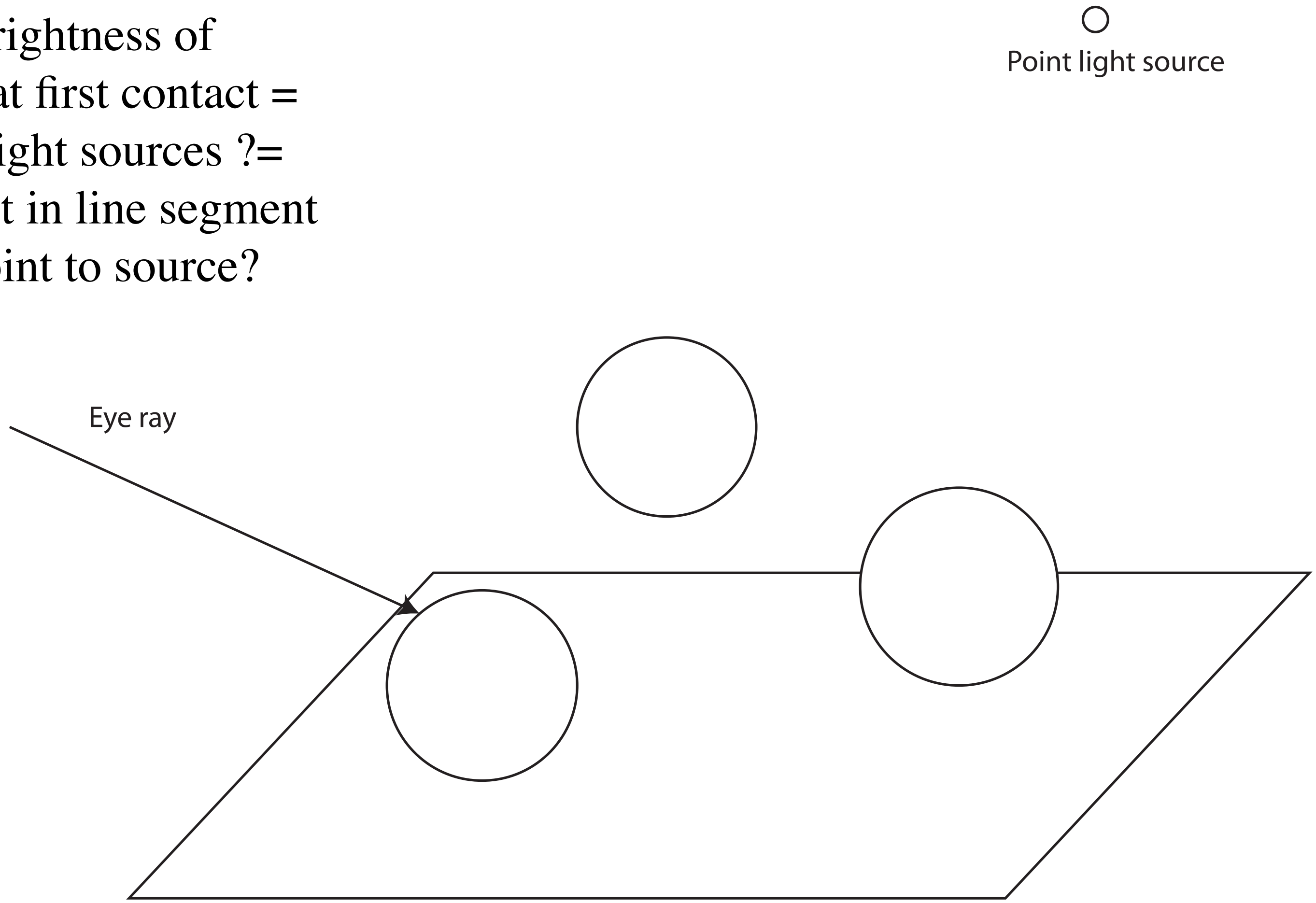
How much light is travelling down this ray toward camera?

sometimes known as the “eye ray”



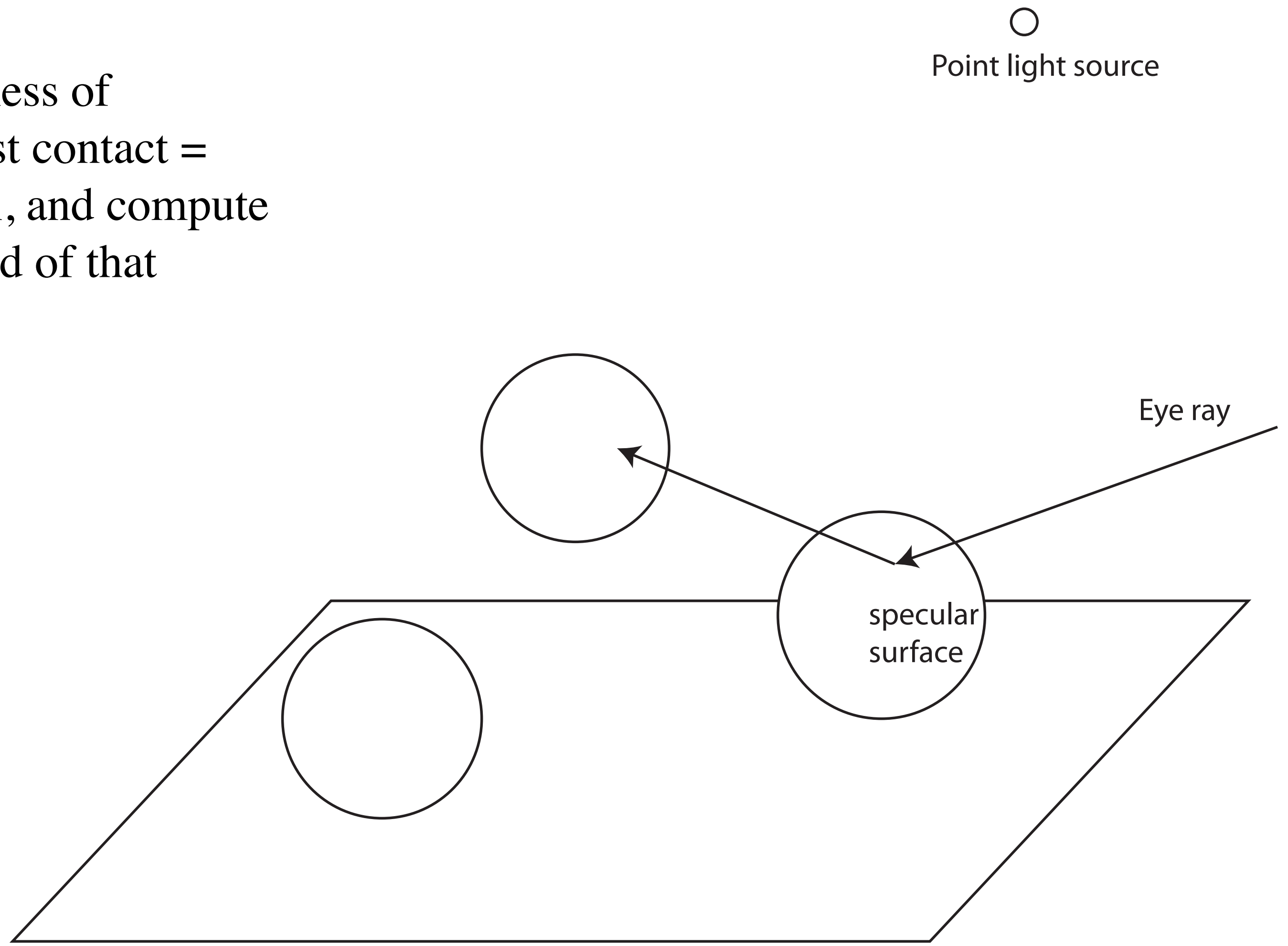
Eye ray strikes diffuse surface

Compute brightness of
diffuse surface at first contact =
Can it see the light sources ?=
Is there an object in line segment
connecting point to source?



Eye ray strikes specular surface

Compute brightness of
specular surface at first contact =
eye ray changes direction, and compute
brightness at the end of that

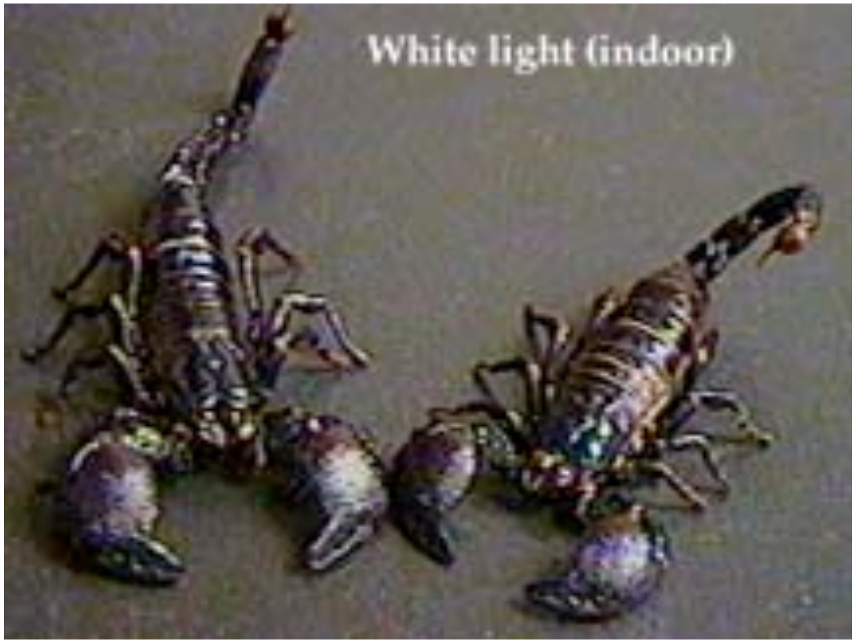


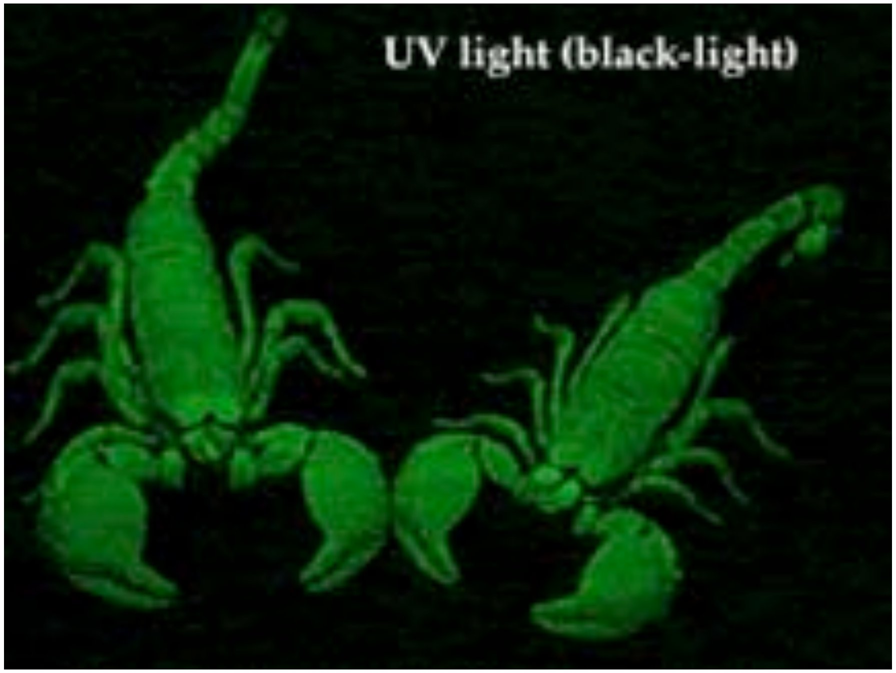
Lighting model

- Light arrives at a surface ONLY from a luminaire
  - this is an object that “makes light”
    - through chemical, mechanical, etc means
- Wild oversimplification, good for us right now
  - wait a few slides and it’ll get more complicated

Processes

- Cameras
  - film: non-linear
  - CCD: linear, with non-linearities made by electronics
- Light
  - is reflected from a surface
  - got there from a source
- Many effects when light strikes a surface -- could be:
  - absorbed; transmitted; reflected; scattered
  - Simplify
    - Assume that
      - surfaces don’t fluoresce
      - surfaces don’t emit light (i.e. are cool)
      - all the light leaving a point is due to that arriving at that point


White light (indoor)


UV light (black-light)

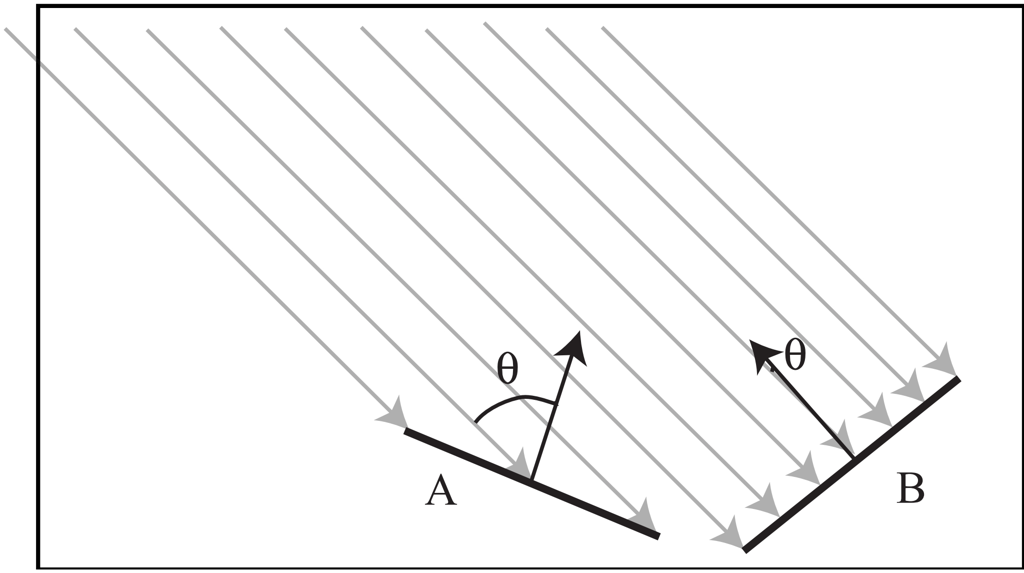
Diffuse reflection

- Light leaves the surface evenly in all directions
  - cotton cloth, carpets, matte paper, matte paints, etc.
  - most “rough” surfaces
  - Parameter: Albedo
    - percentage of light arriving that leaves
    - range 0-1
      - practical range is smaller
- Test:
  - surface has same apparent brightness when viewed from different dir’ns

Point source at infinity

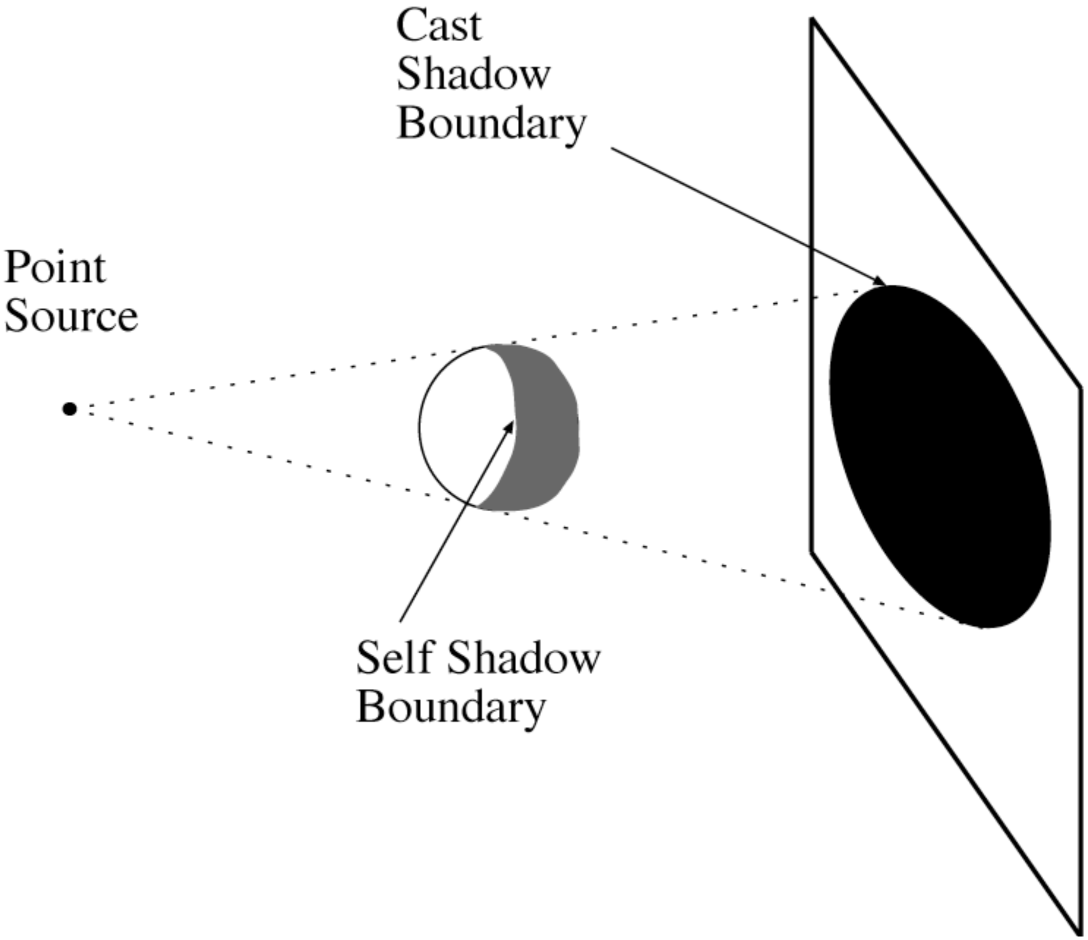
- E.g. the sun
  - energy travels in parallel rays
  - energy density received is proportional to cos theta
- Write:
  - p for albedo
  - S for source vector
    - from surface to source
    - length=intensity of source
  - N for normal
  - I for image intensity

$$I = \rho(N \cdot S)$$

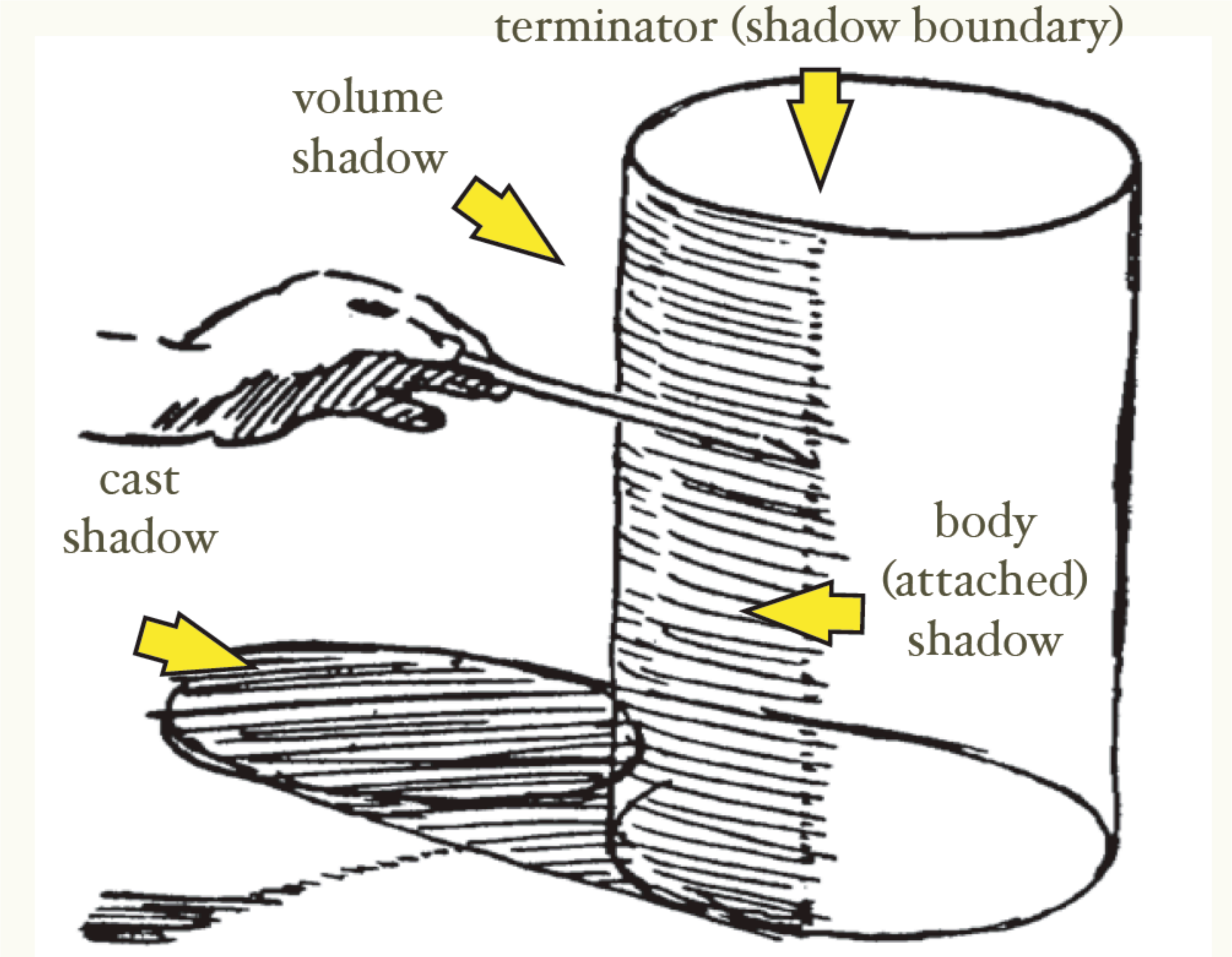


Shadows cast by a point source

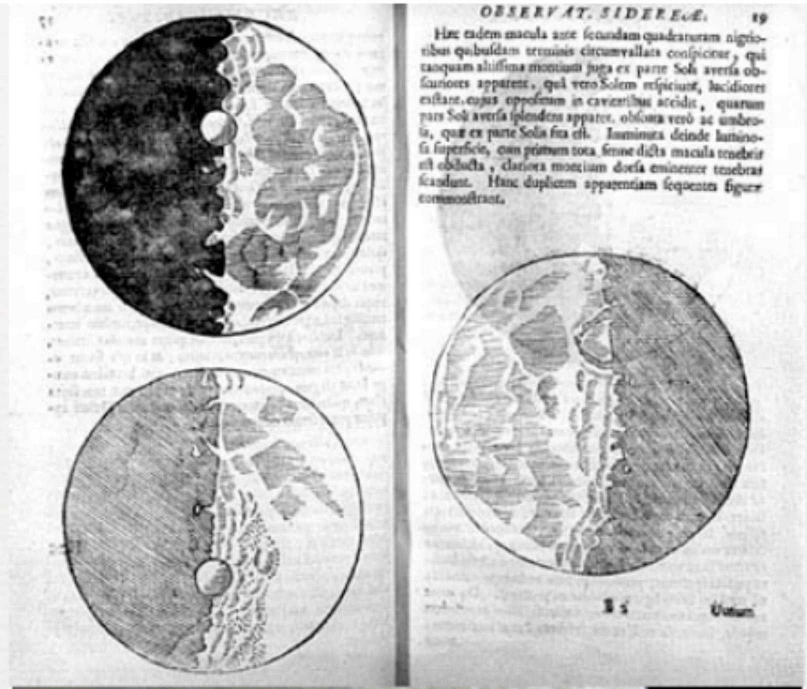
- A point that can't see the source is in shadow
- For point sources, the geometry is simple



Cues to shape - shadows



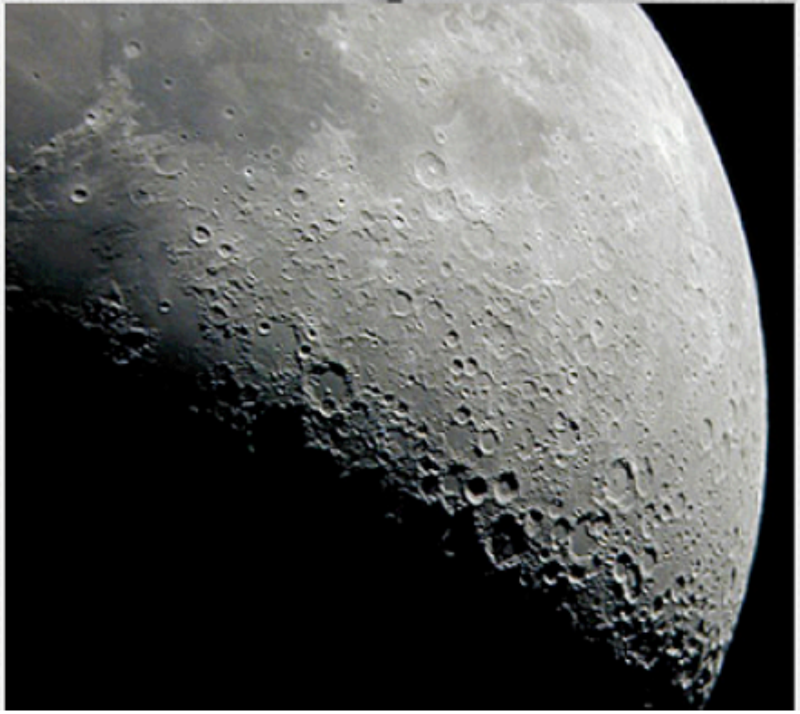
From Koenderink slides on image texture and the flow of light

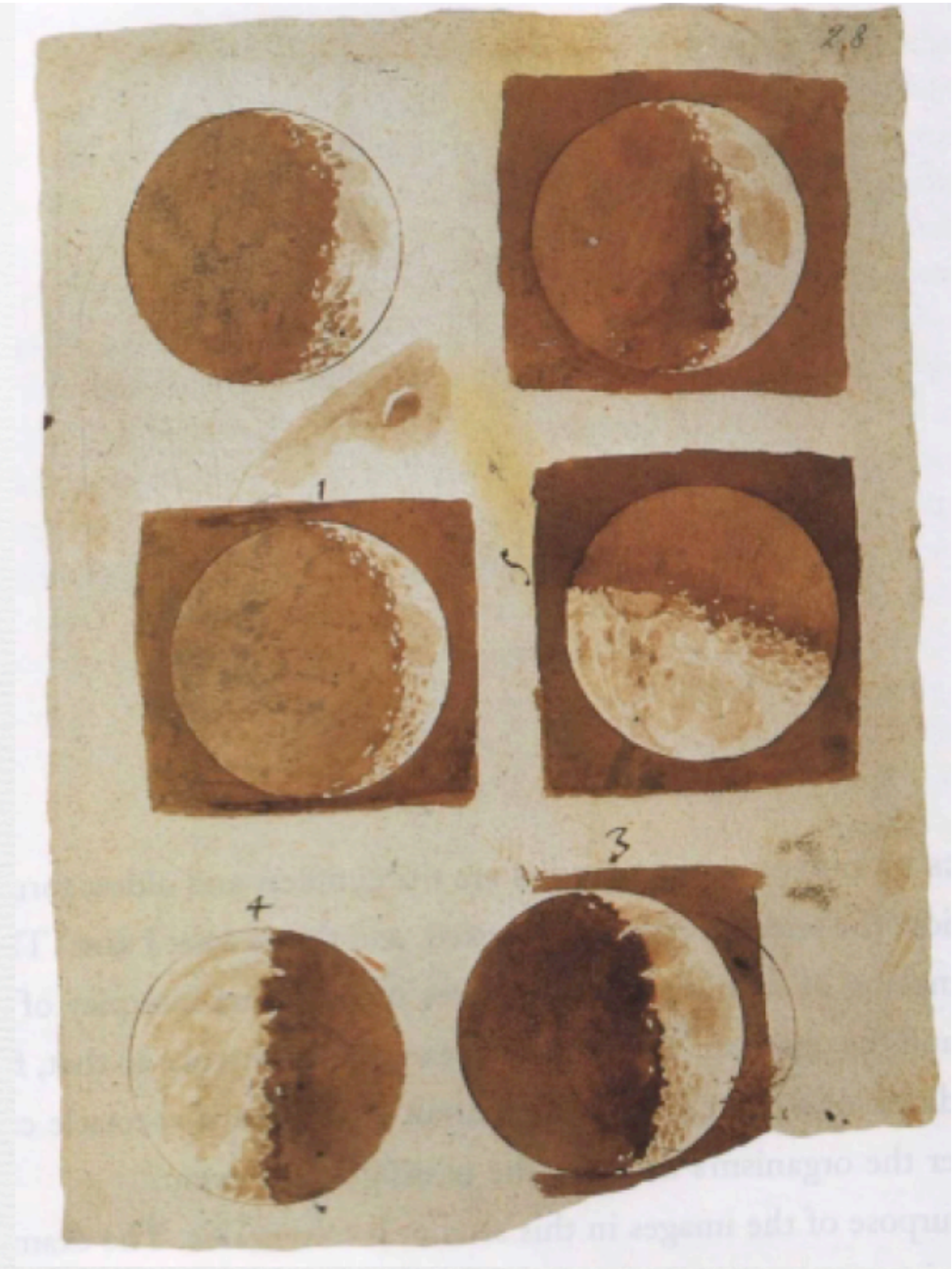


OBSERVAT. SIDEREÆ. 19

Hæc eadem macula ante ſecundam quadraturam nigrioribus quibuſdam terminis circumvallata conſpicitur, qui tanquam altiſſima montium iuga ex parte Soli averſa obſcuriores apparent, quà vero Solem reſpiciunt, lucidiores exſtare, cuius oppoſitum in cavitatibus accidit, quarum pars Soli averſa ſplendens apparet, obſcura verò ac umbroſa, quæ ex parte Solis ſita eſt. Imminuta deinde luminoſa ſuperficie, cum primum tota ferme dicta macula tenebris eſt obducta, clariora montium dorſa eminenter tenebras ſcandunt. Hanc duplicem apparentiam ſequentes figuræ commonſtrant.

B 2 Unum





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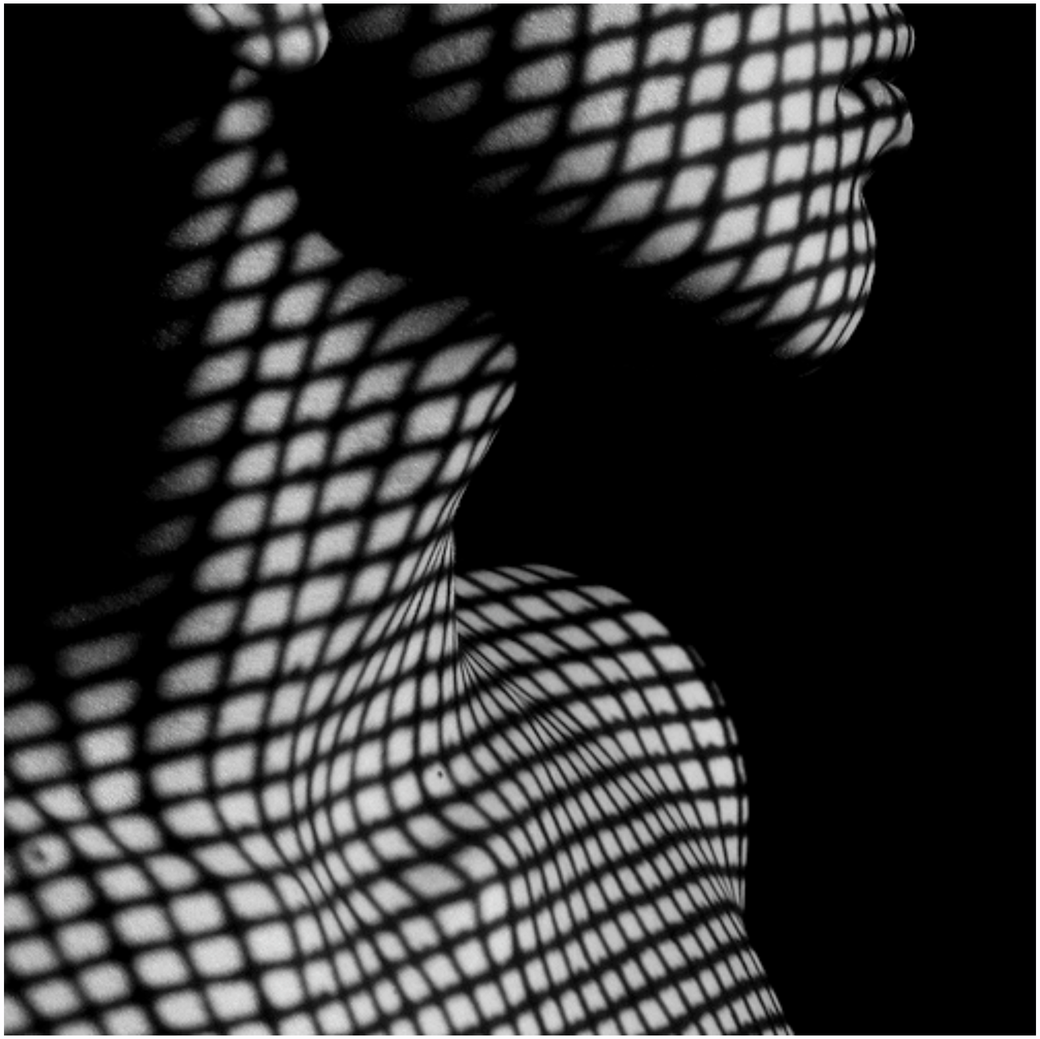
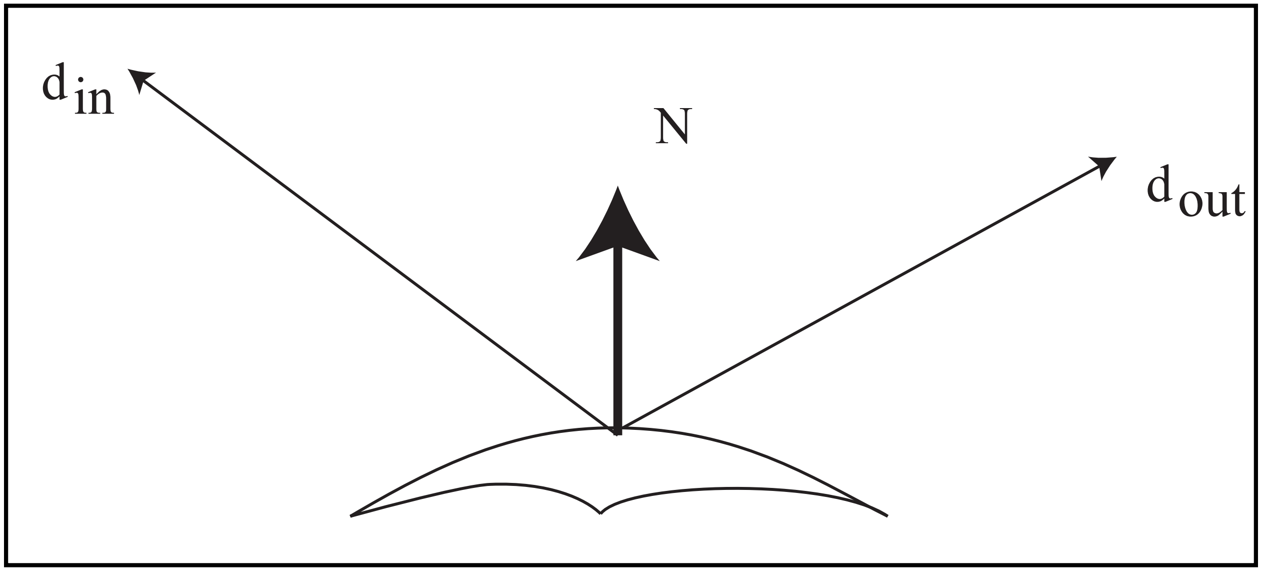
Shadow geometry can be very nasty



From Hel Des, on Flickr

Specularities

- For some surfaces, reflection depends strongly on angle
    - mirrors (special case)
        - incoming direction, normal and outgoing direction are coplanar
        - angle din, normal and angle dout, normal are the same
    - specular surfaces
        - light reflected in a “lobe” of directions
        - eg slightly battered metal surface
        - can see light sources specularly reflected
            - specularities



Flickr, by suzysputnik

Flickr, by piratejohnny

- Specularities are relatively easy to detect
  - small and bright (usually)

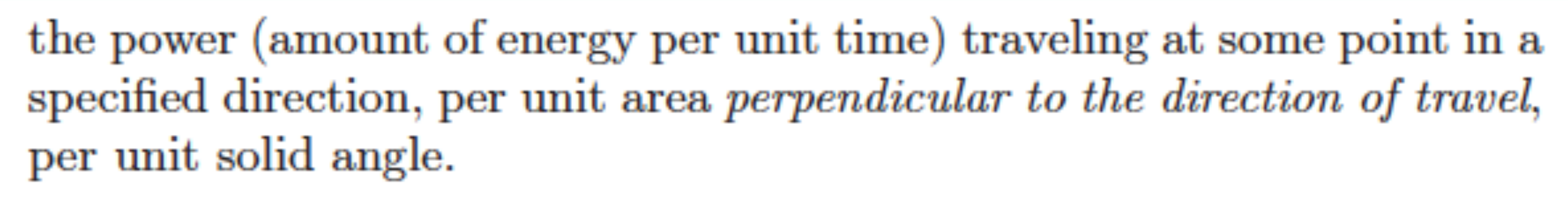
Key idea - how bright is this point?

Radiometry

- Questions:
  - how “bright” will surfaces be?
  - what is “brightness”?
    - measuring light
    - interactions between light and surfaces
- Core idea - think about light arriving at a surface
  - around any point is a hemisphere of directions
  - what is important is what a source “looks like” to a receiver
    - receiver can’t know anything else about source

Radiance

- Measure the “amount of light” at a point, in a direction

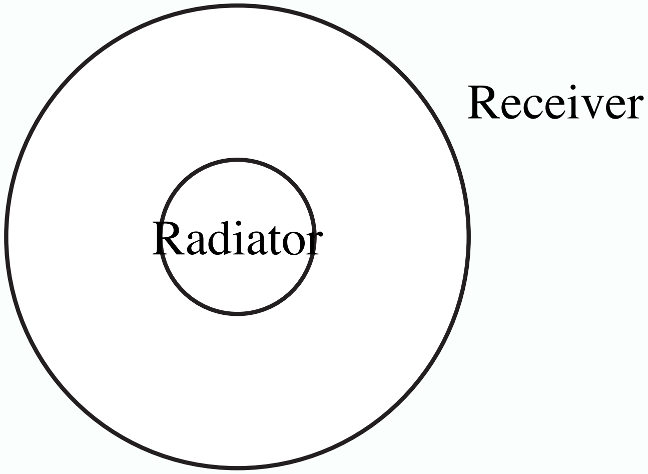


the power (amount of energy per unit time) traveling at some point in a specified direction, per unit area *perpendicular to the direction of travel*, per unit solid angle.

- Units: watts per square meter per steradian (wm-2sr-1)
- Crucial property:
  - In a vacuum, radiance leaving p in the direction of q is the same as radiance arriving at q from p
  - hence the units

Why not watts/square meter?

- Consider sphere radiating 1 W into vacuum
  - Radius 1, center at origin
  - Vacuum neither creates nor consumes power
- There's another sphere around it
  - Radius R, center at origin
  - Area - 4 pi R^2
  - It can't collect more power than first sphere radiates so
    - watts/square meter must go down with distance….!!! (ew)



Surfaces and the BRDF

- Many effects when light strikes a surface -- could be:
  - absorbed; transmitted. reflected; scattered
- Assume that
  - surfaces don’t fluoresce
  - surfaces don’t emit light (i.e. are cool)
  - all the light leaving a point is due to that arriving at that point
- Can model this situation with the Bidirectional Reflectance Distribution Function (BRDF)
- the ratio of the radiance in the outgoing direction to the incident irradiance

$$\rho_{bd}\left(\underline{x},\vartheta_o,\varphi_o,\vartheta_i,\varphi_i,\right) = \frac{L_o\left(\underline{x},\vartheta_o,\varphi_o\right)}{L_i\left(\underline{x},\vartheta_i,\varphi_i\right)\cos\vartheta_i d\omega}$$

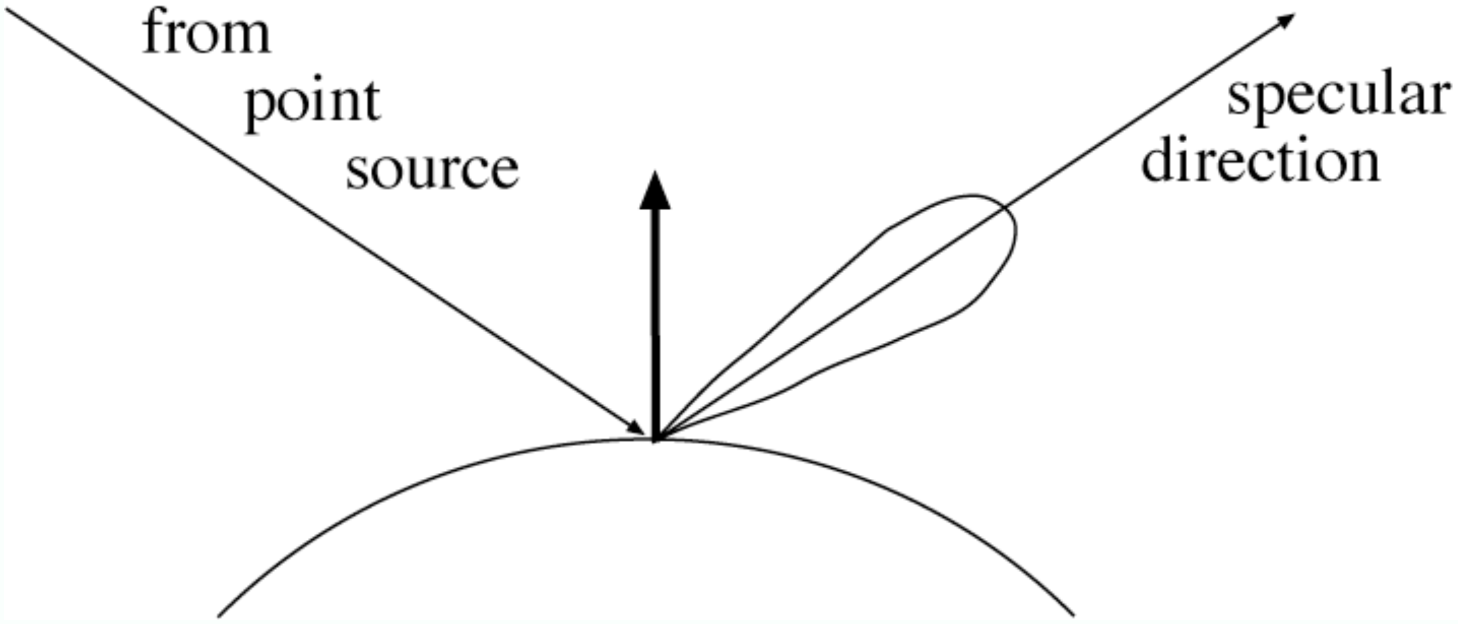
Lambertian surfaces and albedo

- For some surfaces, the BRDF is independent of direction
  - cotton cloth, carpets, matte paper, matte paints, etc.
  - radiance leaving the surface is independent of angle
  - Lambertian surfaces (same Lambert) or ideal diffuse surfaces
  - Use radiosity as a unit to describe light leaving the surface
  - percentage of incident light reflected is diffuse reflectance or albedo
- Useful fact:

$$\rho_{brdf} = \frac{\rho_d}{\pi}$$

Specular surfaces

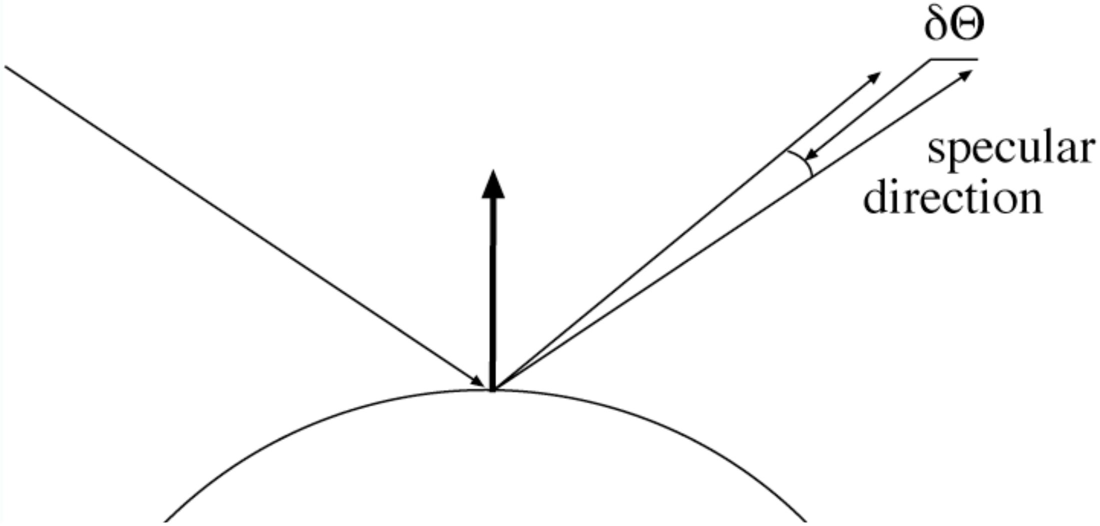
- Another important class of surfaces is specular, or mirror-like.
  - radiation arriving along a direction leaves along the specular direction
  - reflect about normal
  - some fraction is absorbed, some reflected
  - on real surfaces, energy usually goes into a lobe of directions
  - can write a BRDF, but requires the use of funny functions



Phong's model

- There are very few cases where the exact shape of the specular lobe matters.
- Typically:
  - very, very small --- mirror
  - small -- blurry mirror
  - bigger -- see only light sources as "specularities"
  - very big -- faint specularities
- Phong's model
  - reflected energy falls off with

$$\cos^n(\delta\vartheta)$$



Lambertian + specular

- Widespread model
  - all surfaces are Lambertian plus specular component
- Advantages
  - easy to manipulate
  - very often quite close true
- Disadvantages
  - some surfaces are not
    - e.g. underside of CD's, feathers of many birds, blue spots on many marine crustaceans and fish, most rough surfaces, oil films (skin!), wet surfaces
  - Generally, very little advantage in modelling behaviour of light at a surface in more detail -- it is quite difficult to understand behaviour of L+S surfaces

The Rendering Equation- 1

- We can now write

Angle between normal and incoming direction

$$L_o(\mathbf{x}, \omega_o) = L_e(\mathbf{x}, \omega_o) + \int_\Omega \rho_{bd}(\mathbf{x}, \omega_o, \omega_i) L_i(\mathbf{x}, \omega_i) \cos \theta_i d\omega_i$$

BRDF

Incoming radiance

Average over hemisphere

Radiance emitted from surface at that point in that direction

Radiance leaving a point in a direction

Radiance is constant along straight lines, so this is what we want to know

The Rendering Equation - II

- This balance works for
  - each wavelength,
  - at any time, so
- So

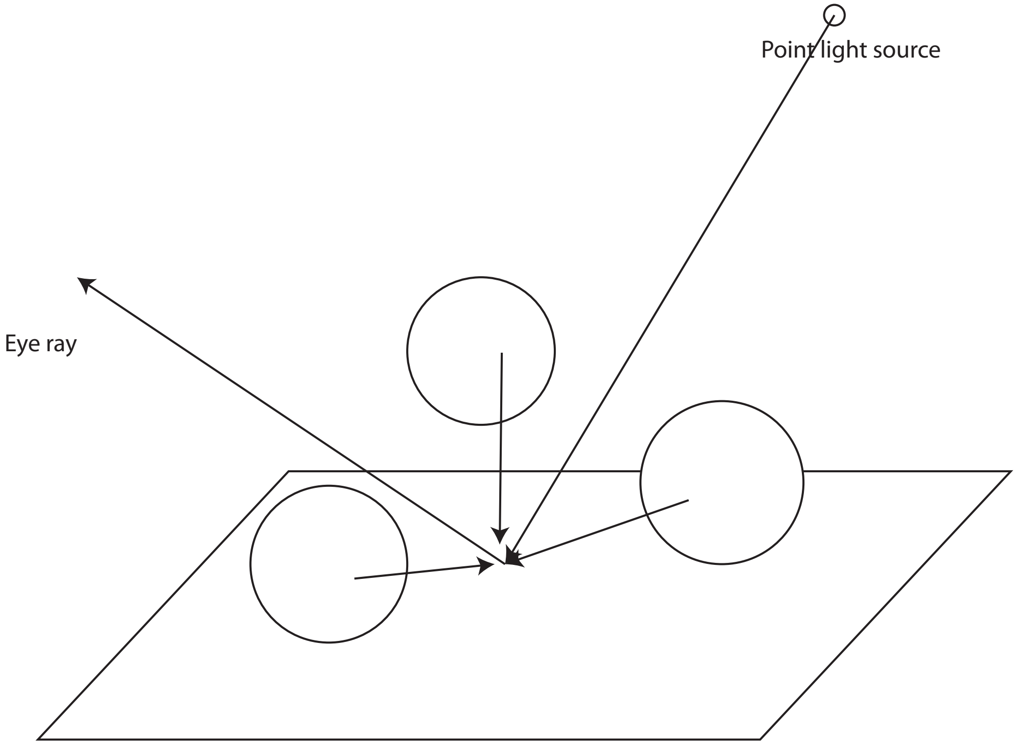
$$\begin{aligned} L_o(\mathbf{x}, \omega_o, \lambda, t) &= L_e(\mathbf{x}, \omega_o, \lambda, t) + \\ &\int_\Omega \rho_{bd}(\mathbf{x}, \omega_o, \omega_i, \lambda, t) L_i(\mathbf{x}, \omega_i, \lambda, t) \cos\theta_i d\omega_i \end{aligned}$$

Global illumination

$$L_o(\mathbf{x}, \omega_o) = L_e(\mathbf{x}, \omega_o) + \int_\Omega \rho_{bd}(\mathbf{x}, \omega_o, \omega_i) L_i(\mathbf{x}, \omega_i) \cos\theta_i d\omega_i$$

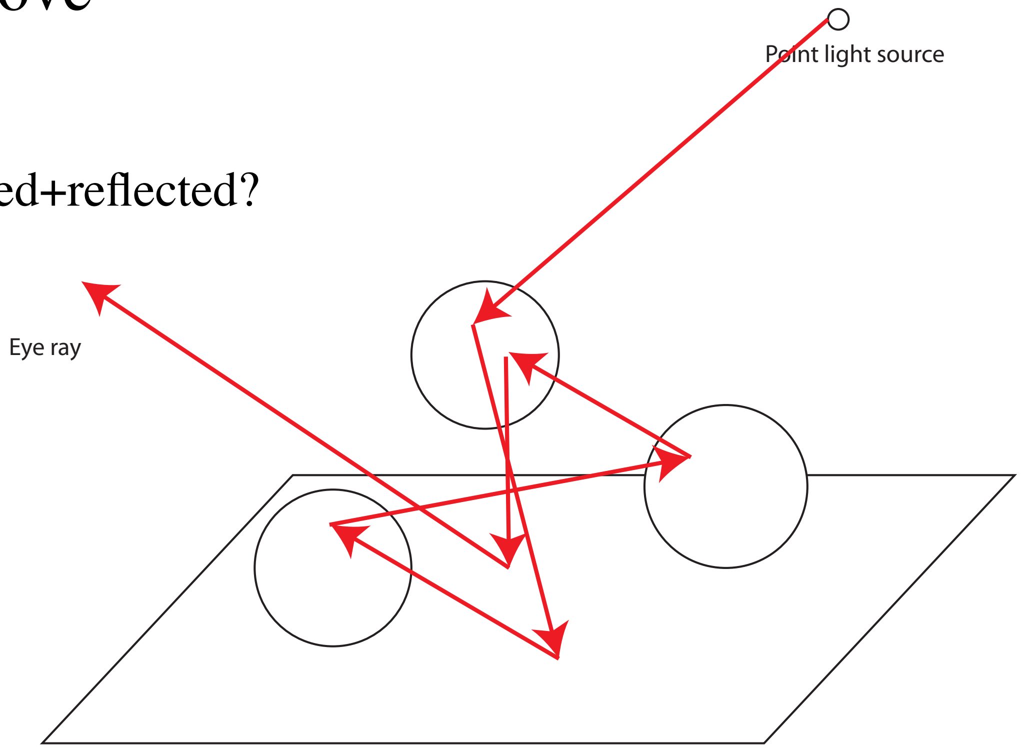
Incoming radiance |

- Incoming radiance isn't just from luminaires
  - the reason you can see surfaces is they reflect light
  - other surfaces don't distinguish between reflected light and generated light



Light paths

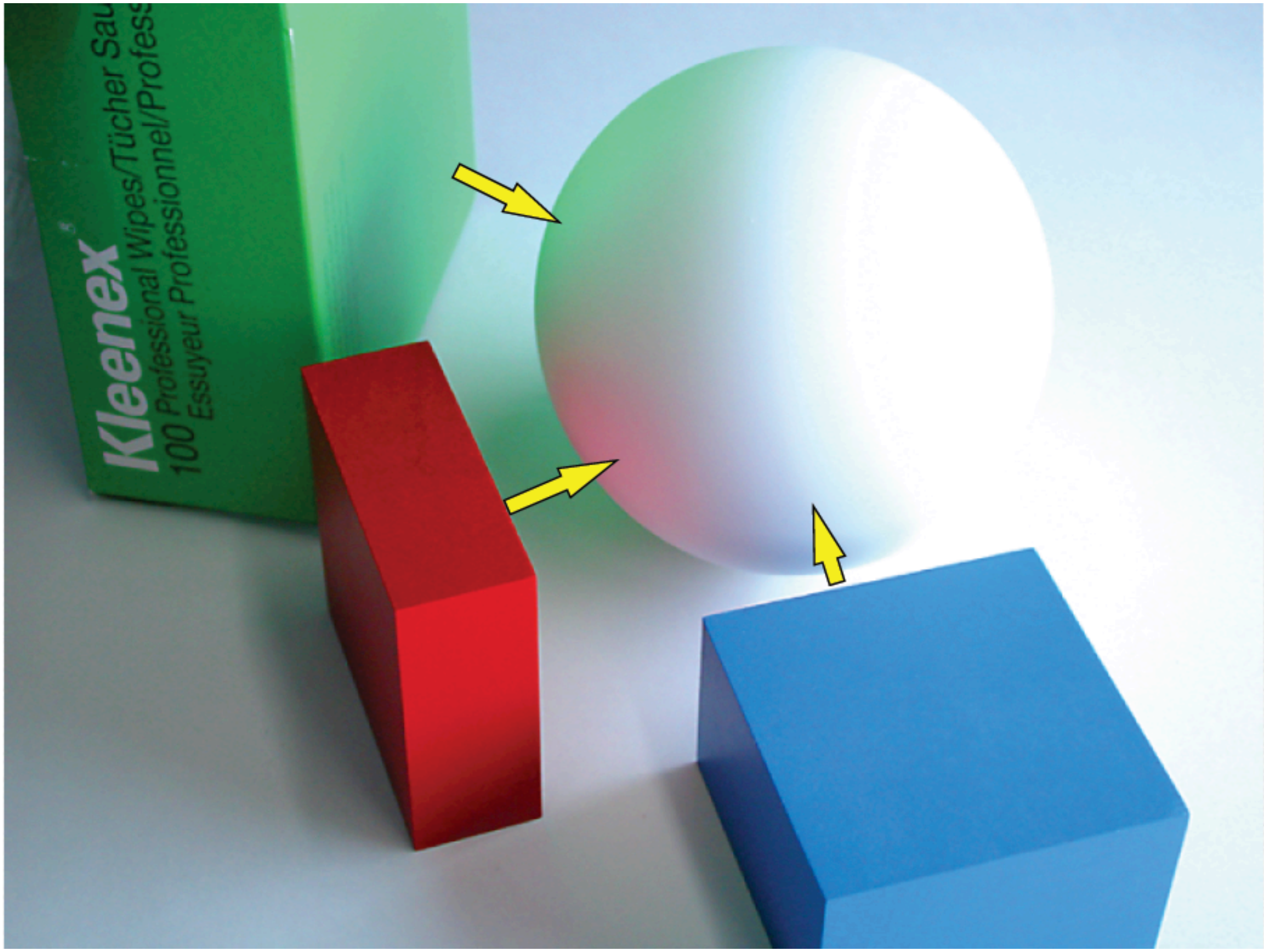
- Recursively expand, as above
  - sample the incoming directions
    - what radiance is coming in?
    - go to far end - what is emitted+reflected?
    - recur
-



Interreflections

- Issue:
  - local shading model is a poor description of physical processes that give rise to images
    - because surfaces reflect light onto one another
  - This is a major nuisance; the distribution of light (in principle) depends on the configuration of every radiator; big distant ones are as important as small nearby ones (solid angle)
  - The effects are easy to model
  - It appears to be hard to extract information from these models

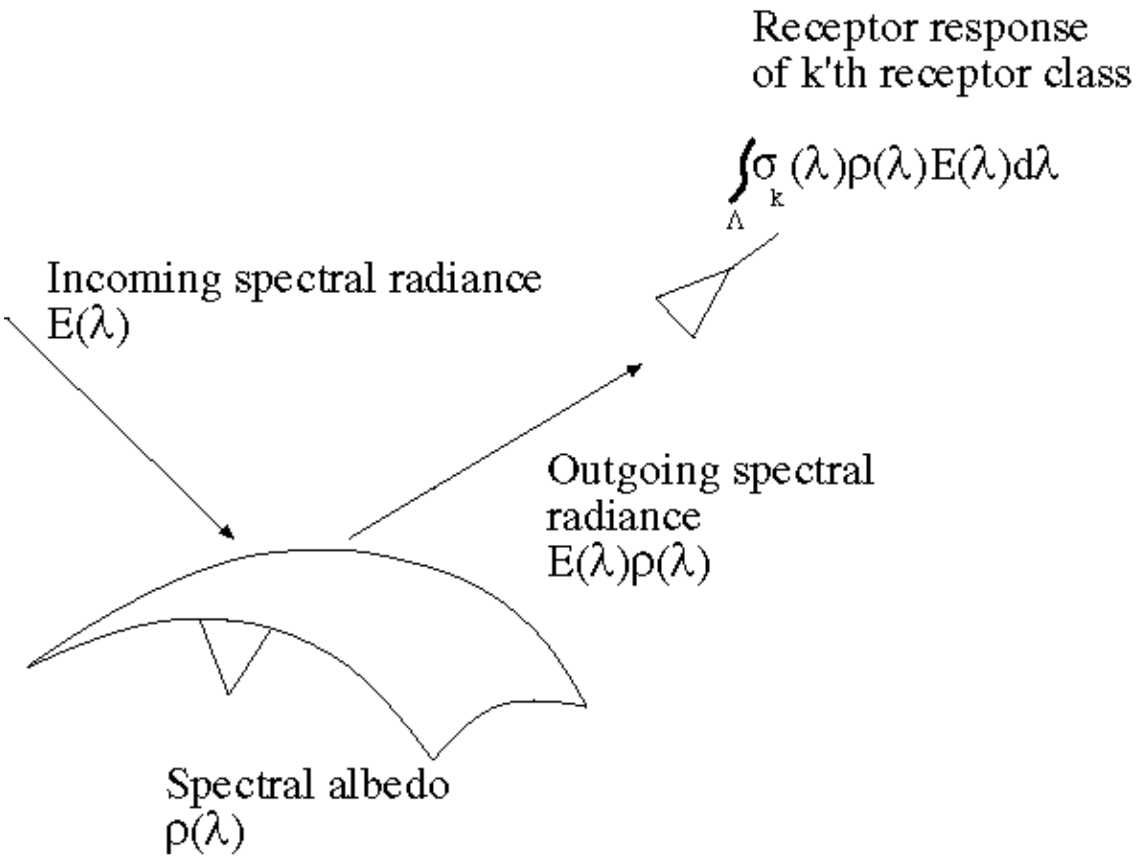
Interreflections


Kleenex
100 Professional Wipes/Tücher Sau
Essuyeur Professionnel/Profess

From Koenderink slides on image texture and the flow of light

The color of objects

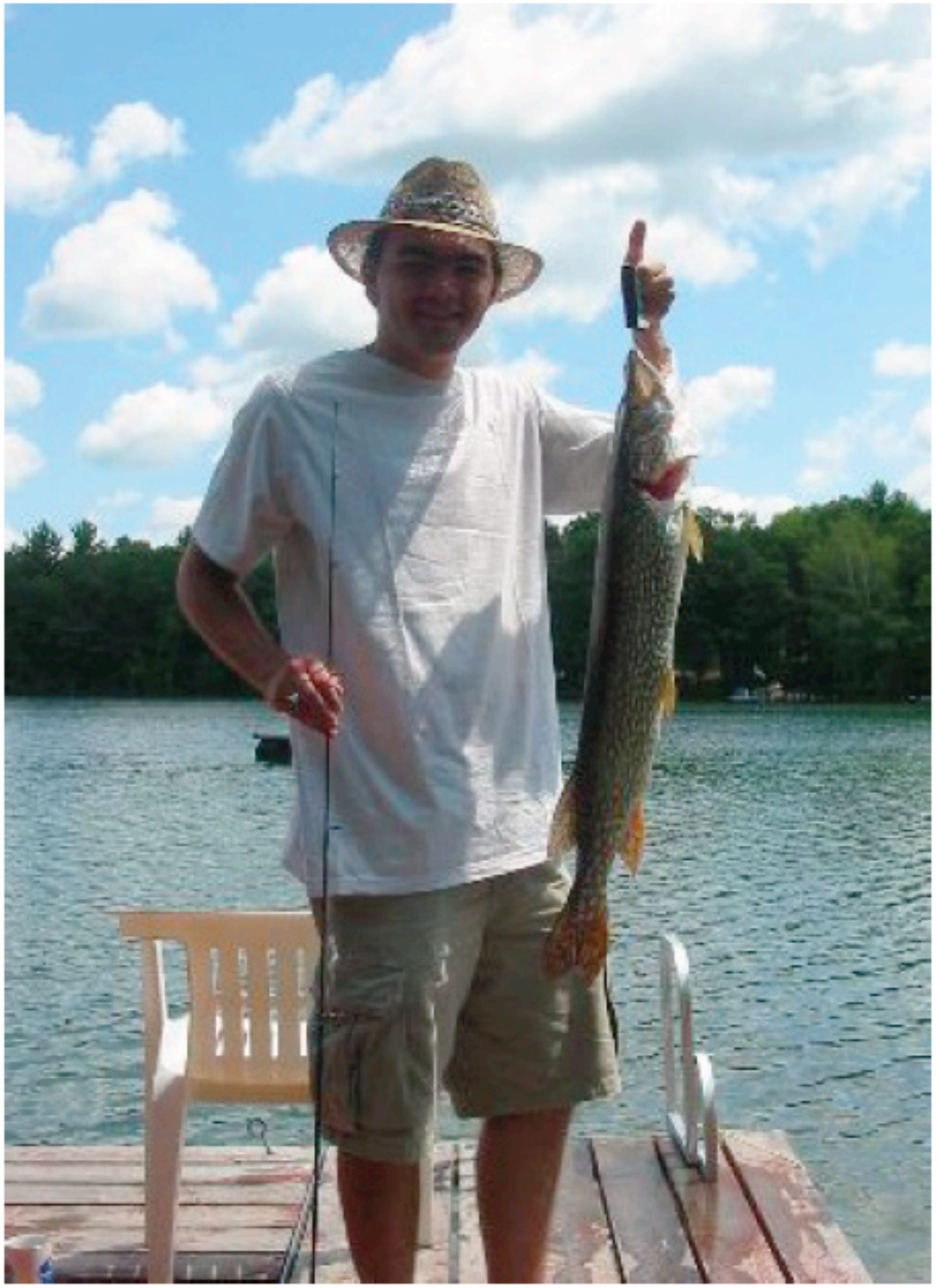
- Colored light arriving at the camera involves two effects
  - The color of the light source
  - The color of the surface
  - Changes caused by different colored light sources can be large

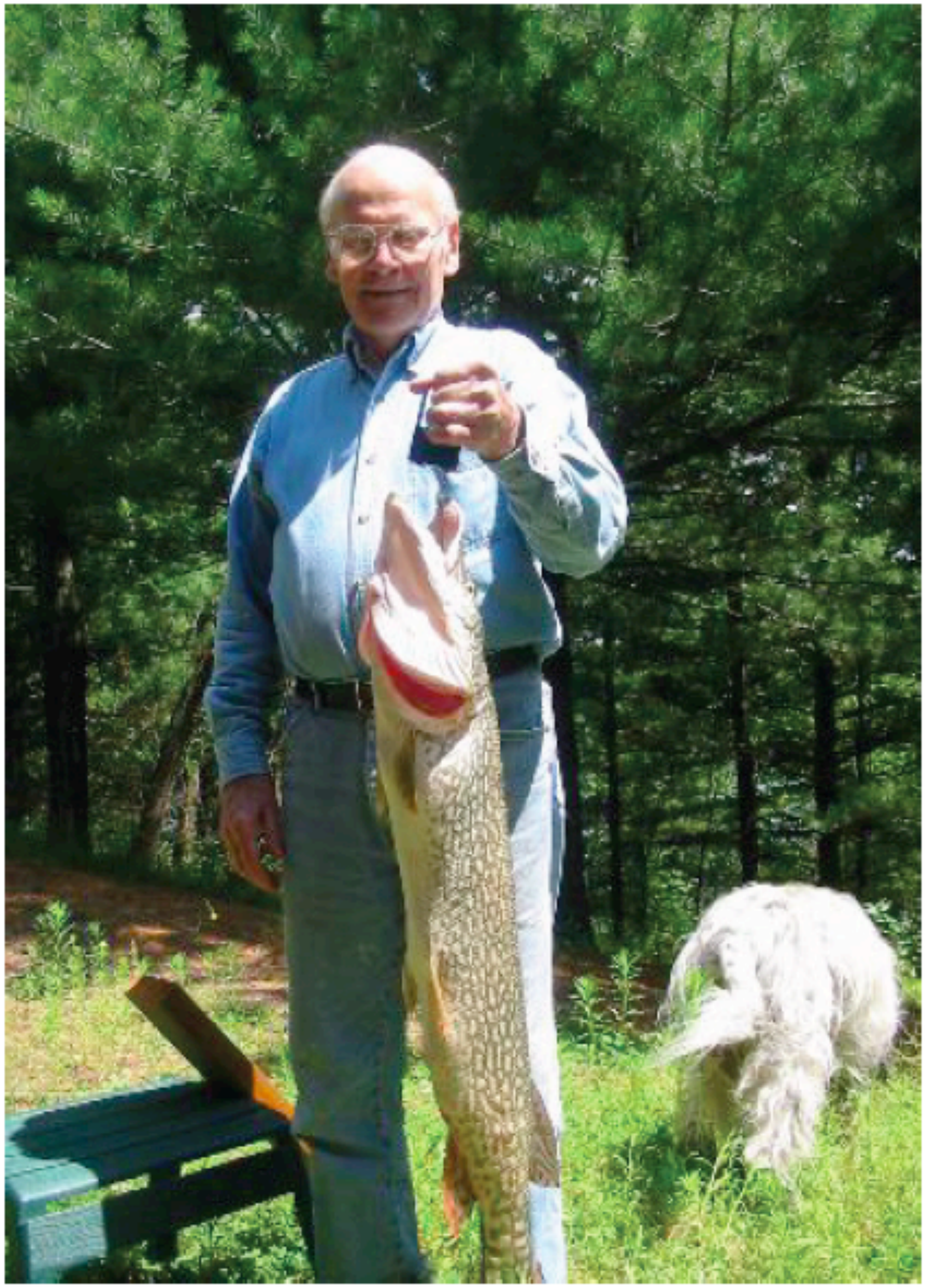

Receptor response
of k'th receptor class
$\int_\Lambda \sigma_k(\lambda)\rho(\lambda)E(\lambda)d\lambda$
Incoming spectral radiance
$E(\lambda)$
Outgoing spectral
radiance
$E(\lambda)\rho(\lambda)$
Spectral albedo
$\rho(\lambda)$

Constancy

- You perceive objects in terms of their properties
  - rather than what they look like in an image
- Examples:
  - size constancy
    - distant objects are small in pictures, nearby objects bigger
      - but you don’t think of them as changing size
  - lightness constancy
    - dark things in bright rooms can be brighter than light objects in dark rooms
      - but you perceive their lightness (=albedo)
  - color constancy
    - image color changes when lighting color changes
      - but you perceive the surface color
  - object constancy

Which fish is bigger?





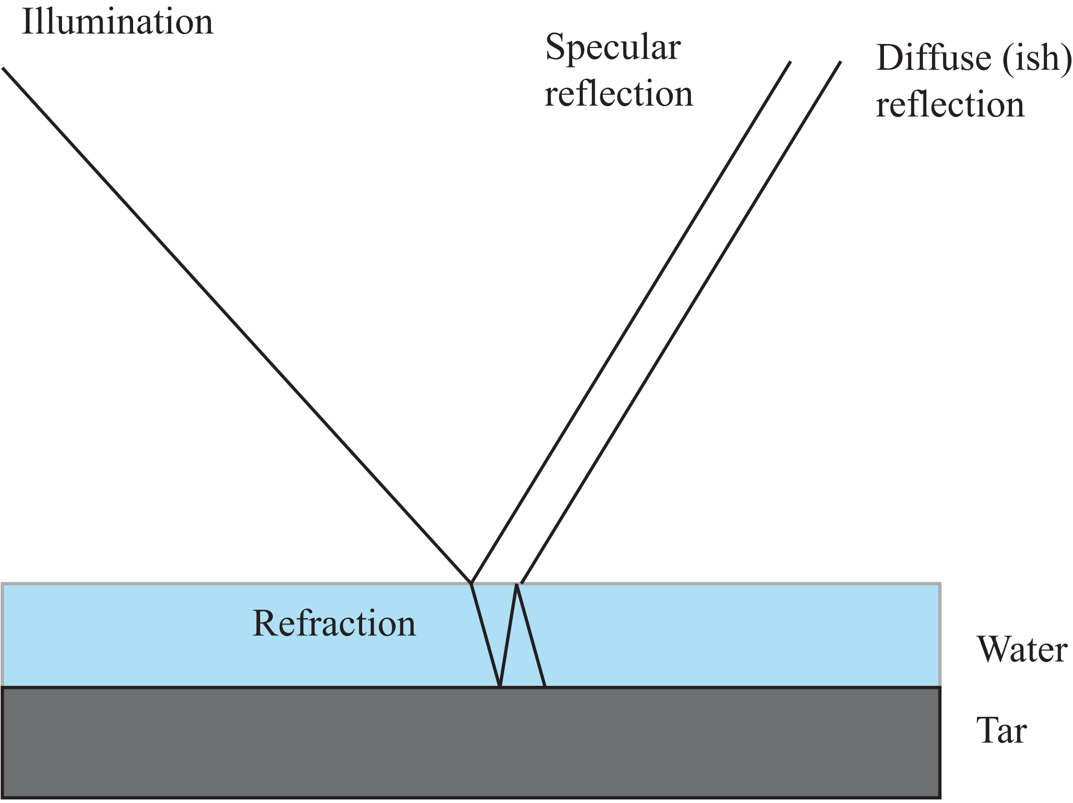
More complicated effects at surfaces

Refraction

- Light striking an interface changes direction
  - between translucent surfaces with different speed-of-light
  - (refraction)
- At critical angle, total internal reflection

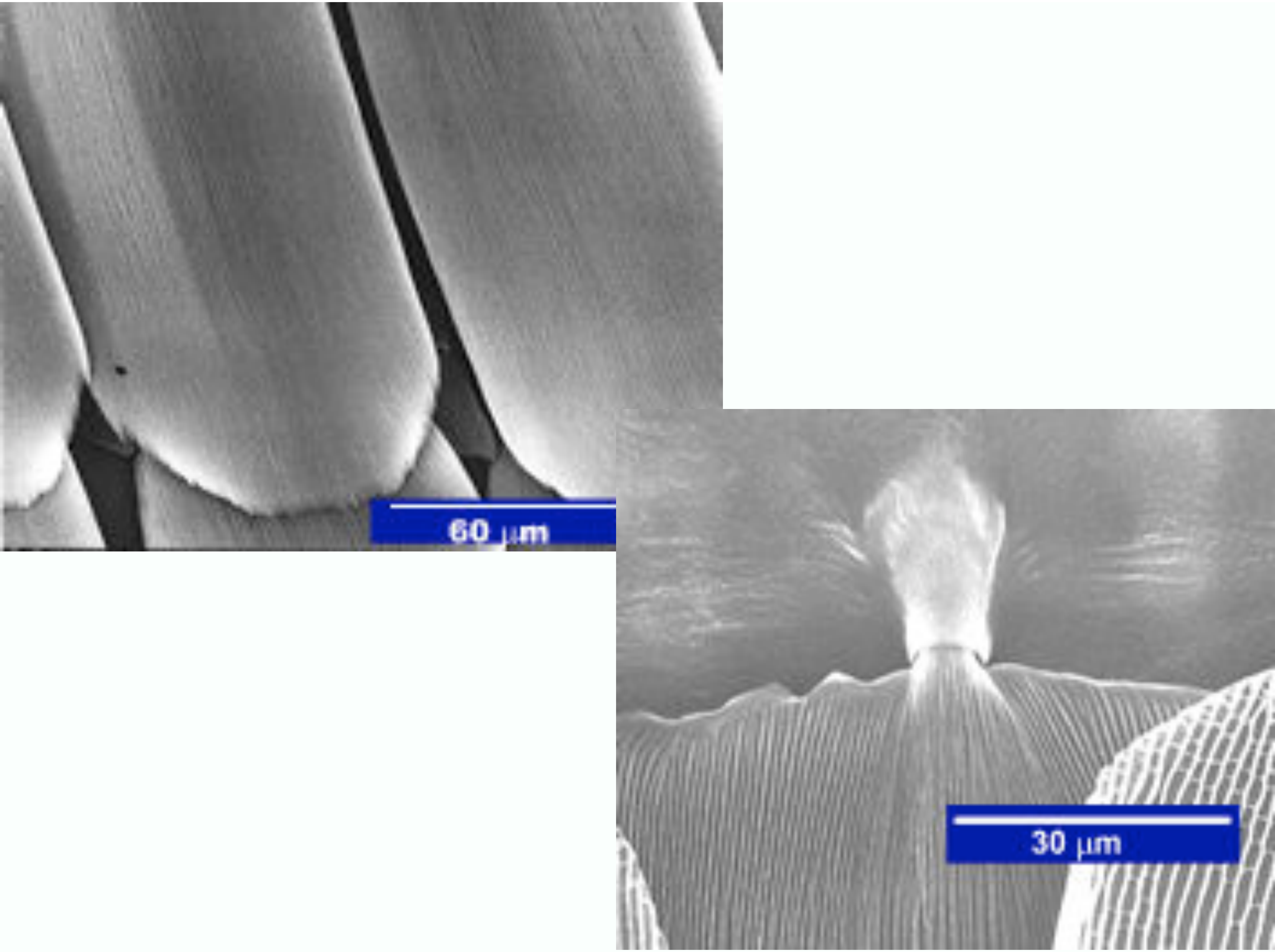
Films on surfaces

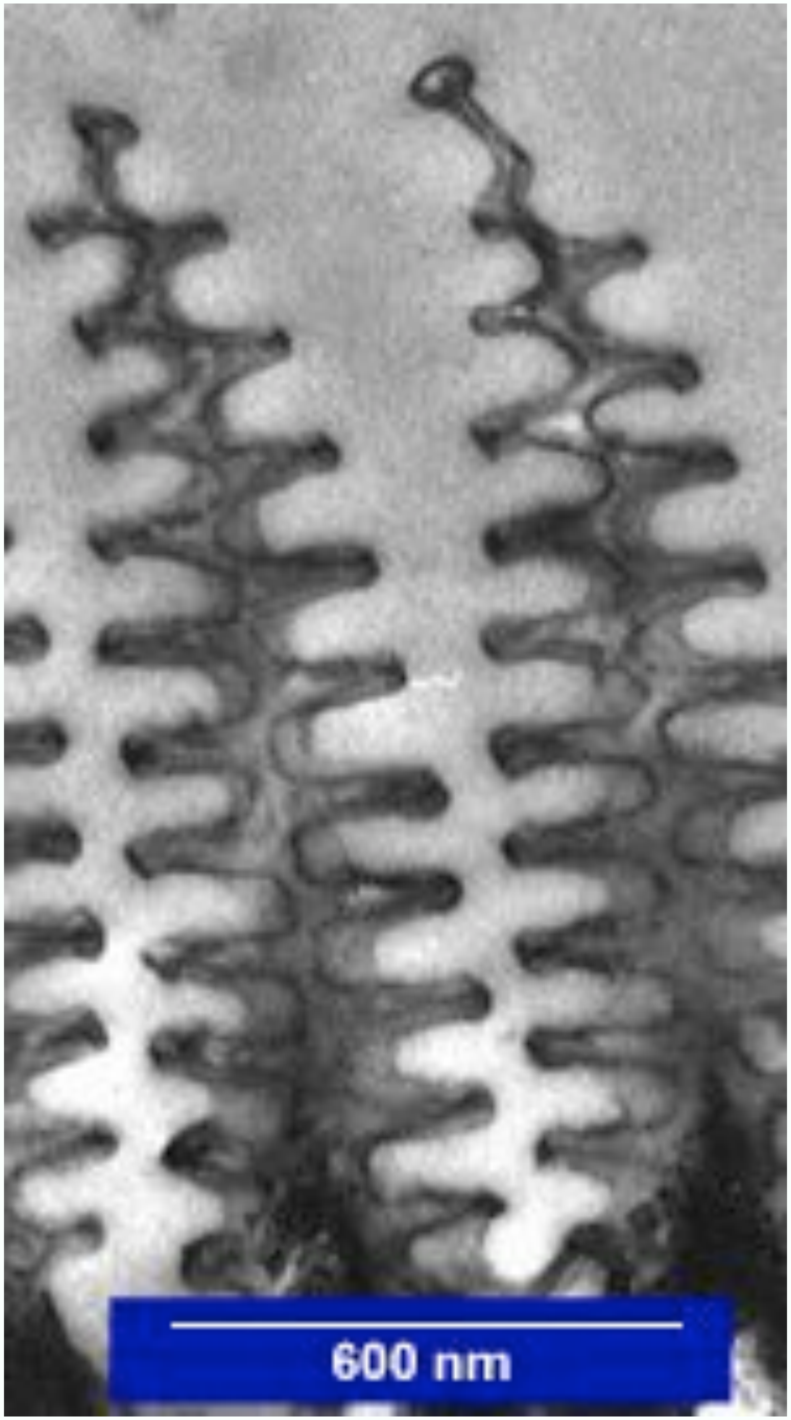
- eg water
- Assume:
  - film is thin
- You see:
  - specular reflection+diffuse term



Interference effects

- Sometimes seen on films
    - if the film is the right number of wavelengths thick
        - waves will interfere destructively (resp constructively)
        - can give rise to intense colors
            - oil films on water often do this

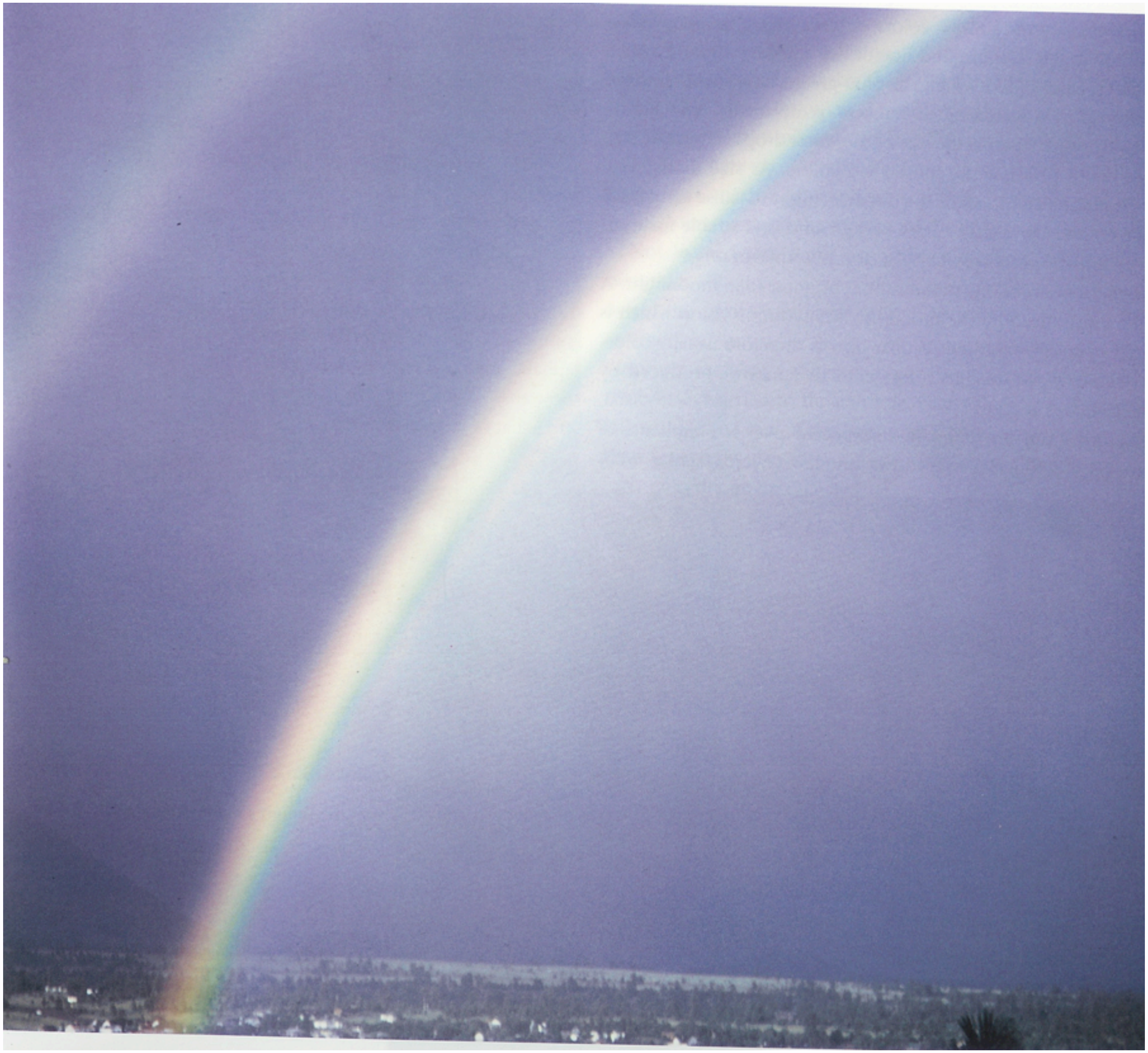

60 µm
30 µm


600 nm

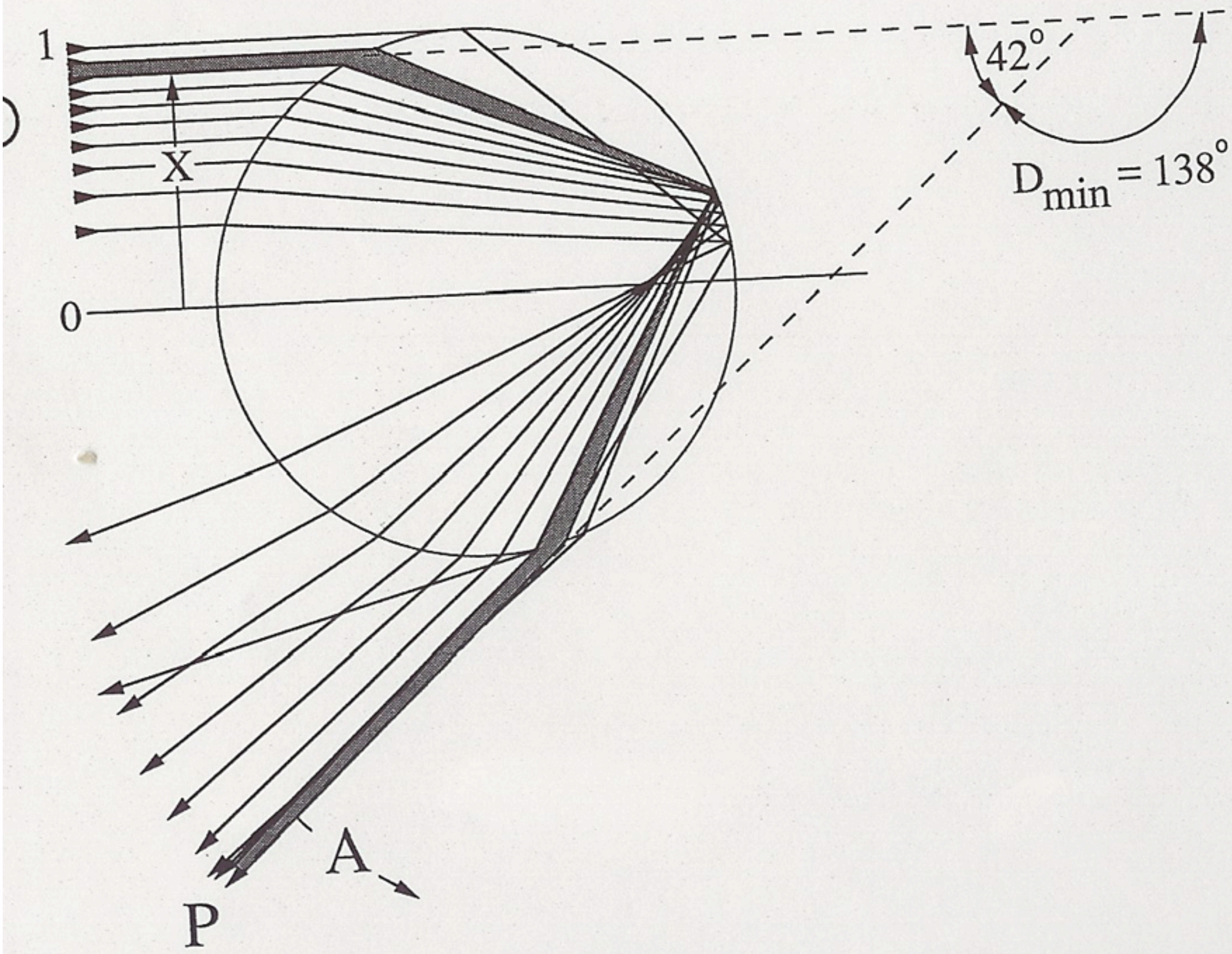
Effects in air

Refraction

- Light striking an interface changes direction
  - between translucent surfaces with different speed-of-light
  - (refraction)
- At critical angle, total internal reflection



From Lynch and Livingstone, Color and Light in Nature



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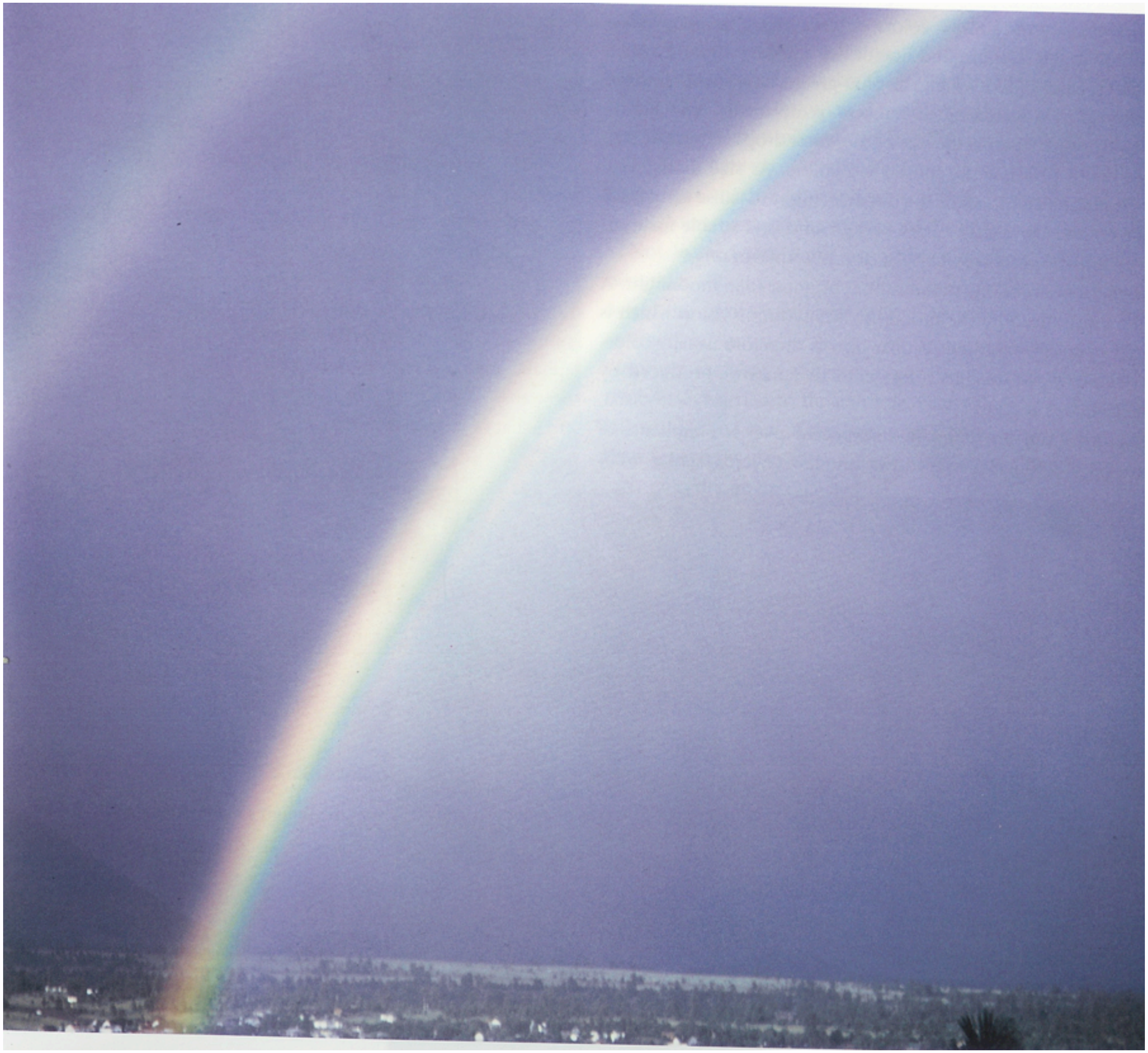

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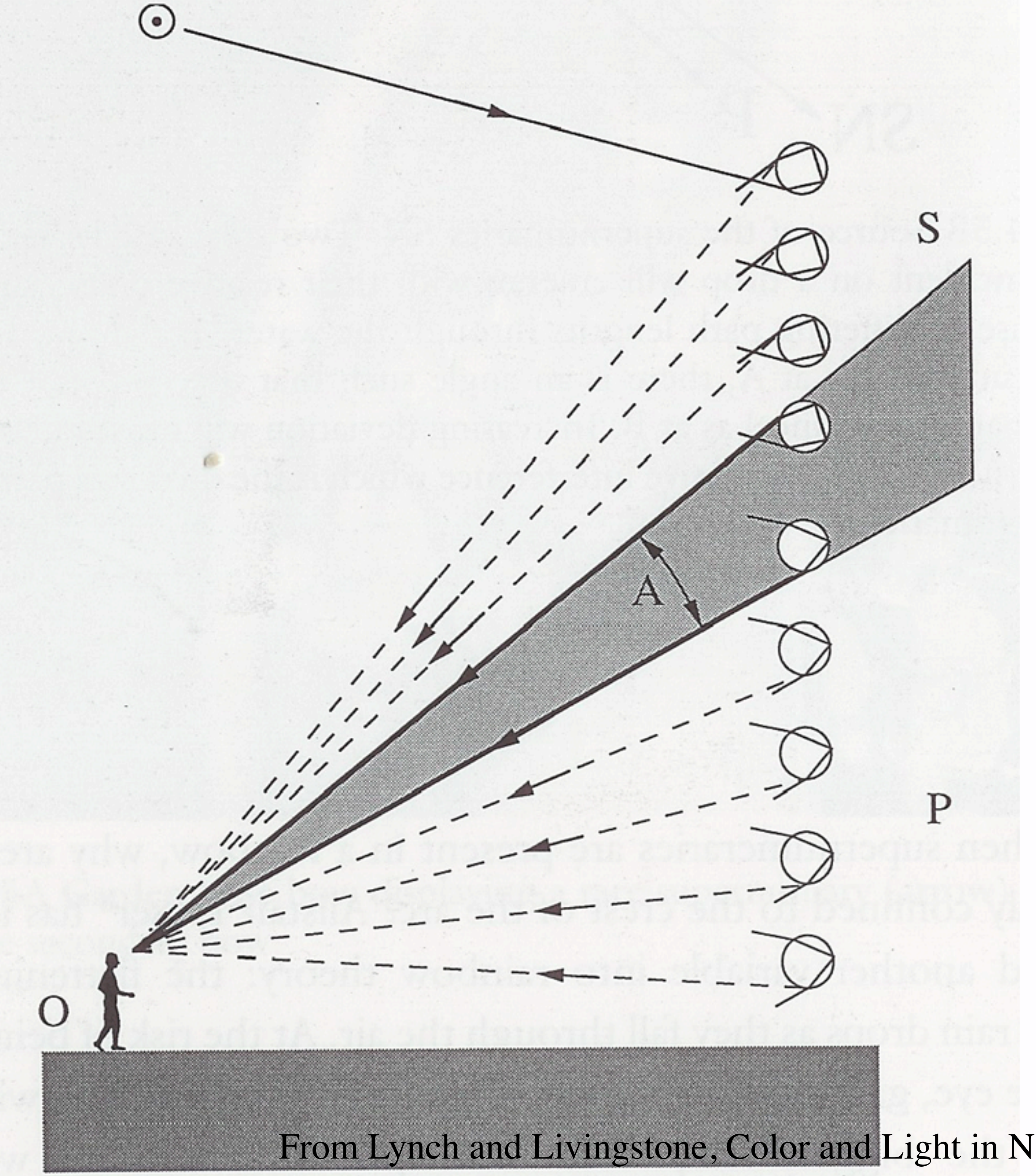

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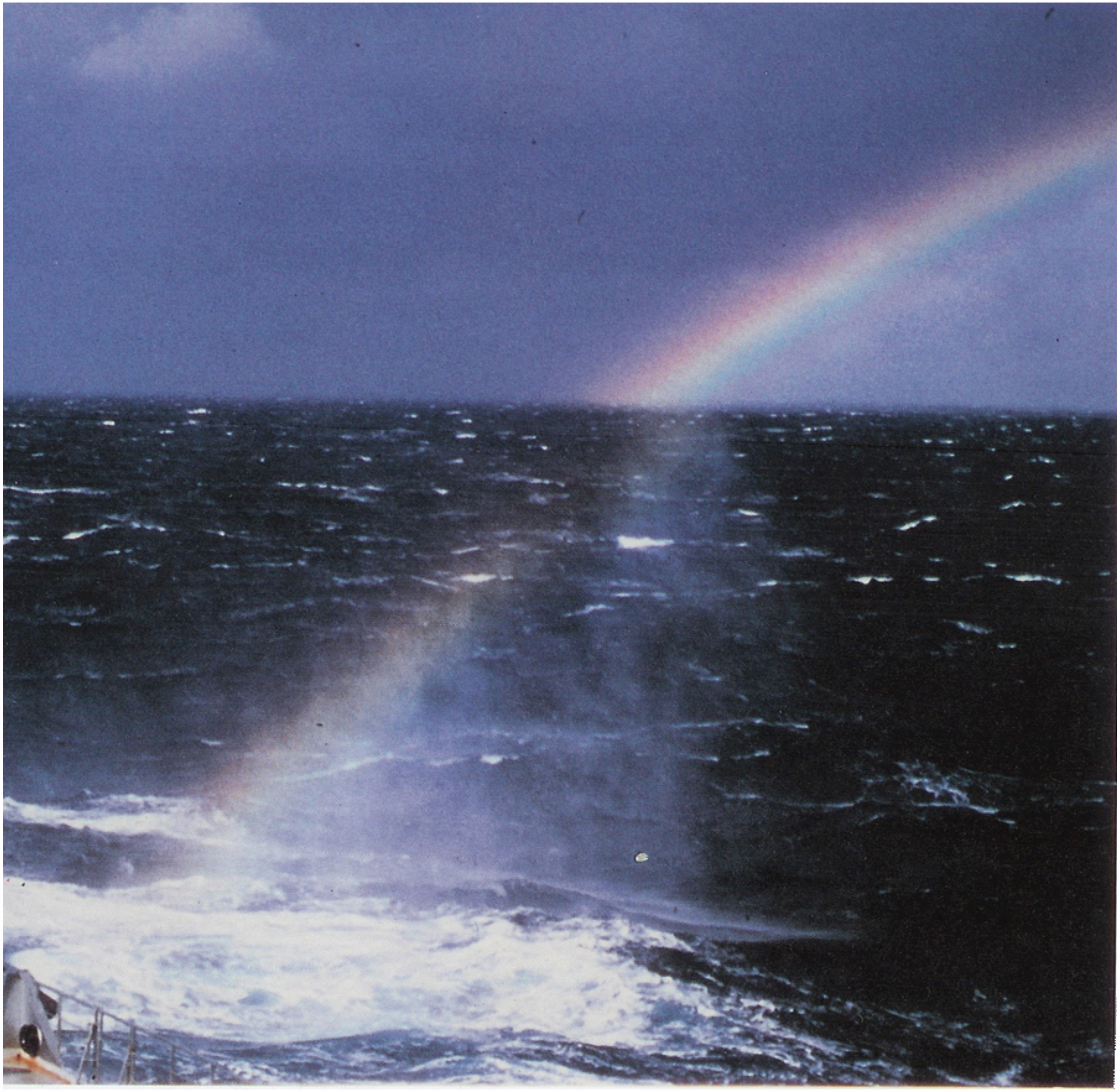

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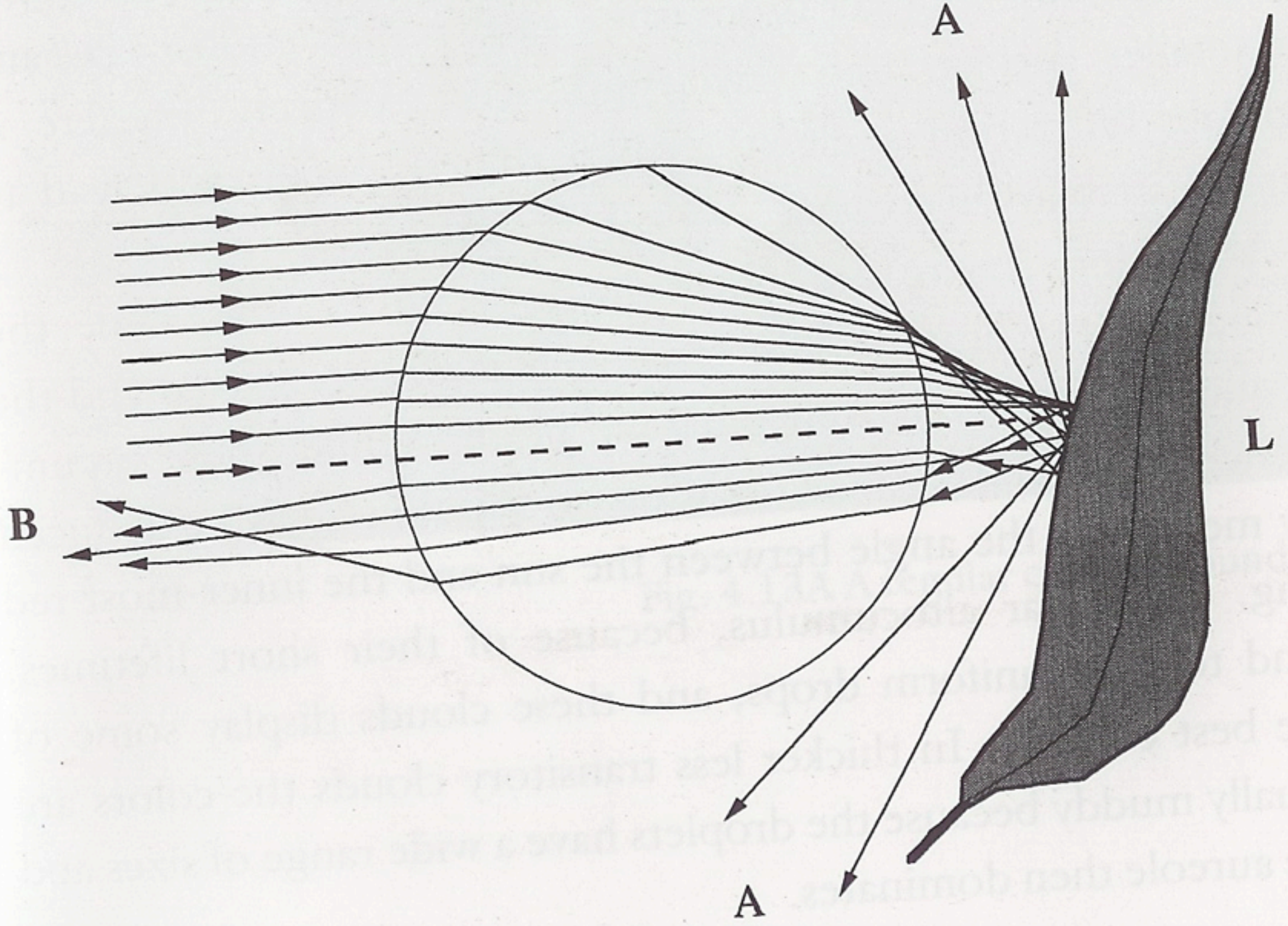

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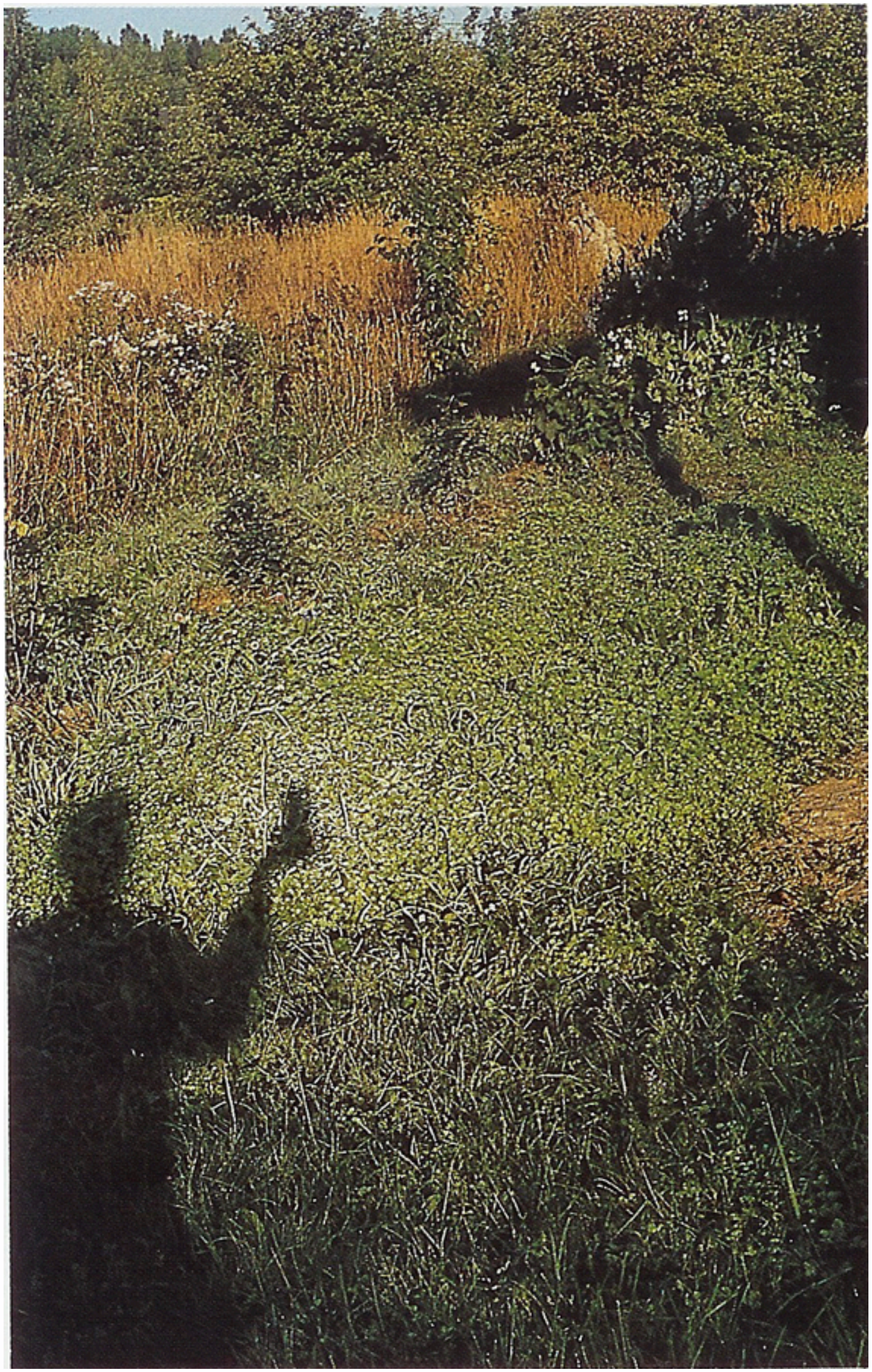


Minnaert, Light and Color in the outdoors
Heiligenschein

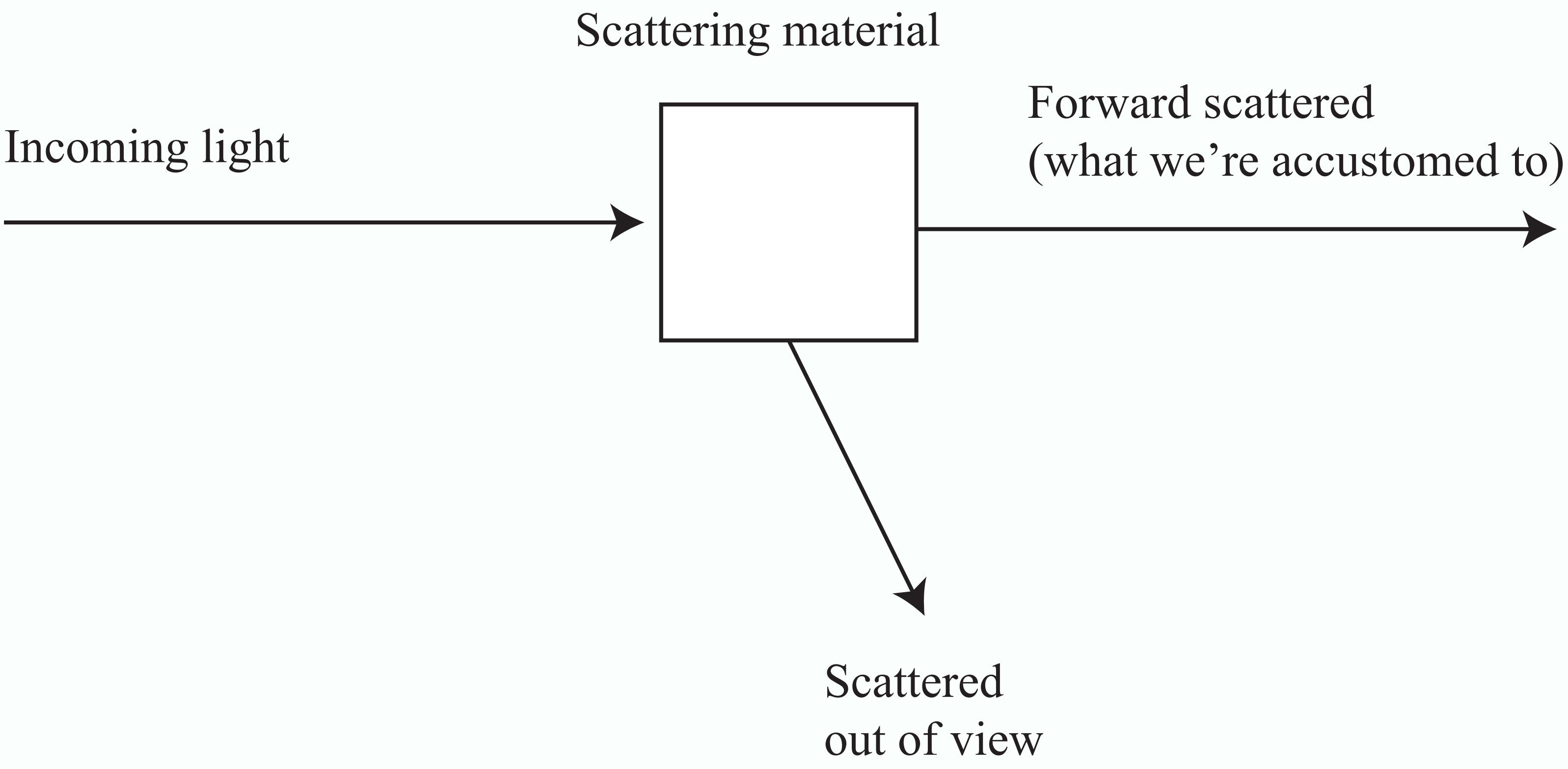
Scattering

- Fundamental mechanism of light/matter interactions
- Visually important for
  - slightly translucent materials (skin, milk, marble, etc.)
  - participating media

Participating media

- for example,
  - smoke,
  - wet air (mist, fog)
  - rain
  - dusty air
  - air at long scales
- Light leaves/enters a ray travelling through space
  - leaves because it is scattered out
  - enters because it is scattered in
- New visual effects

Light hits a small box of material



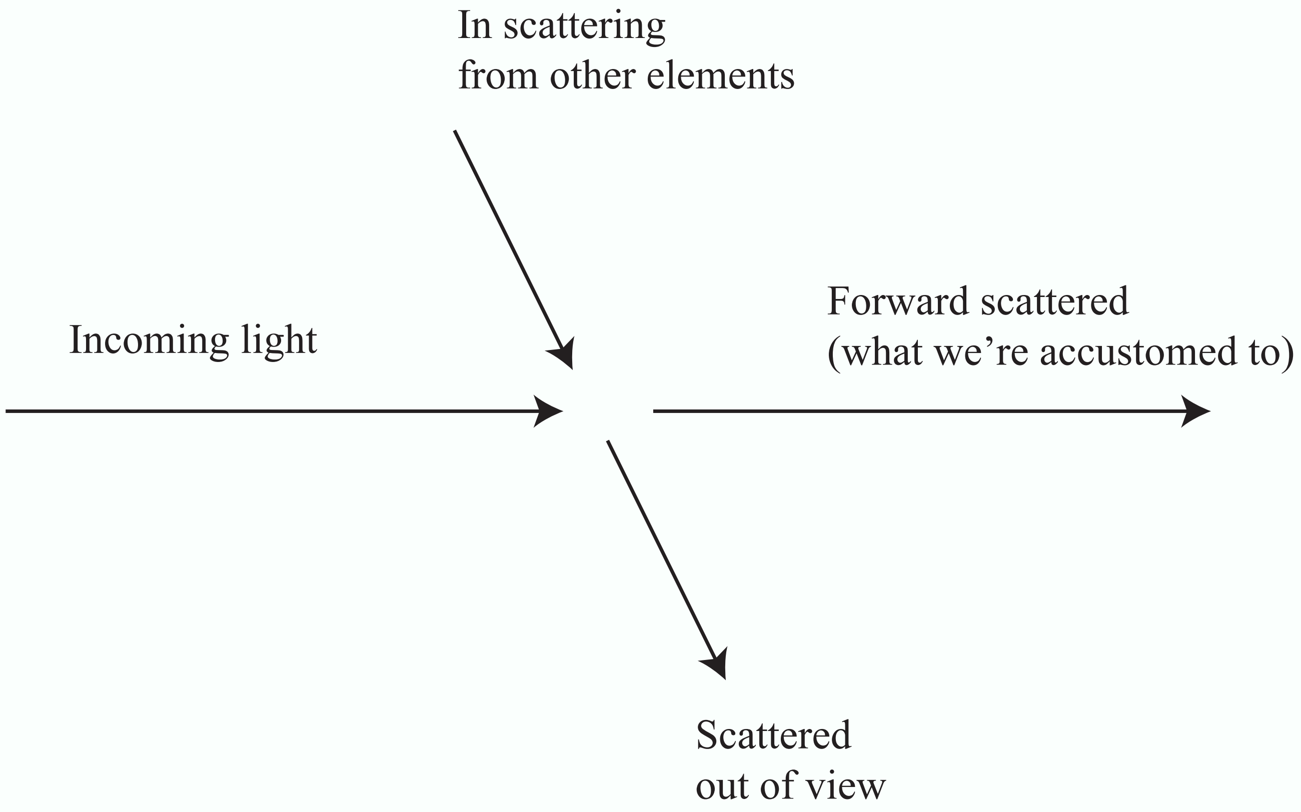
Scattering material

Incoming light

Forward scattered
(what we’re accustomed to)

Scattered
out of view

A ray passing through scattering material



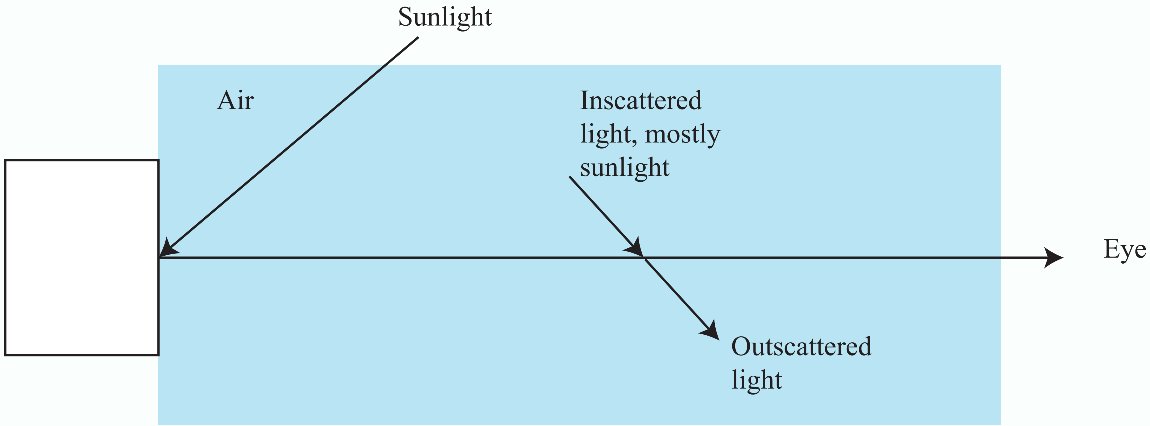
In scattering
from other elements

Incoming light

Forward scattered
(what we're accustomed to)

Scattered
out of view

Airlight as a scattering effect



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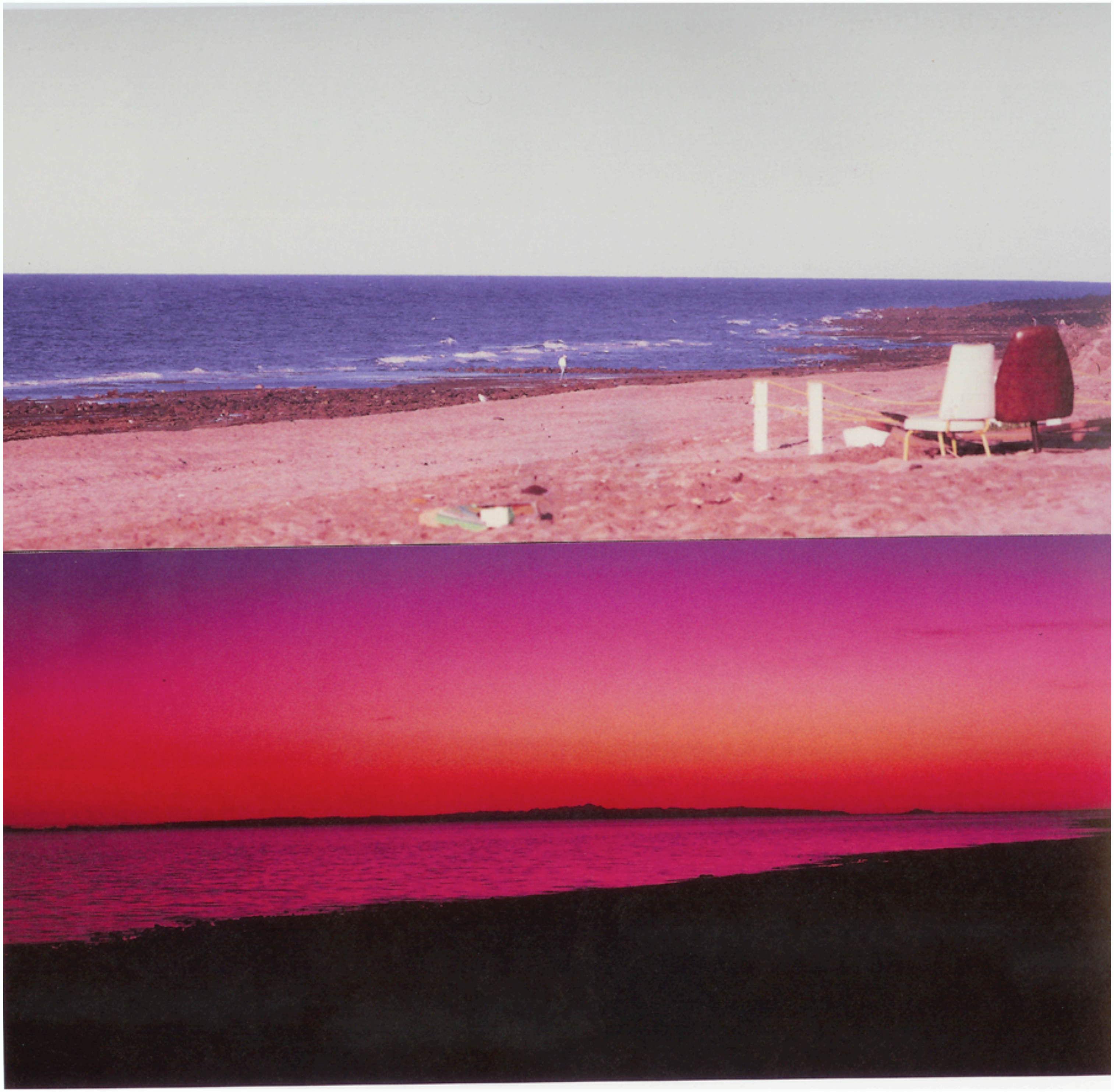
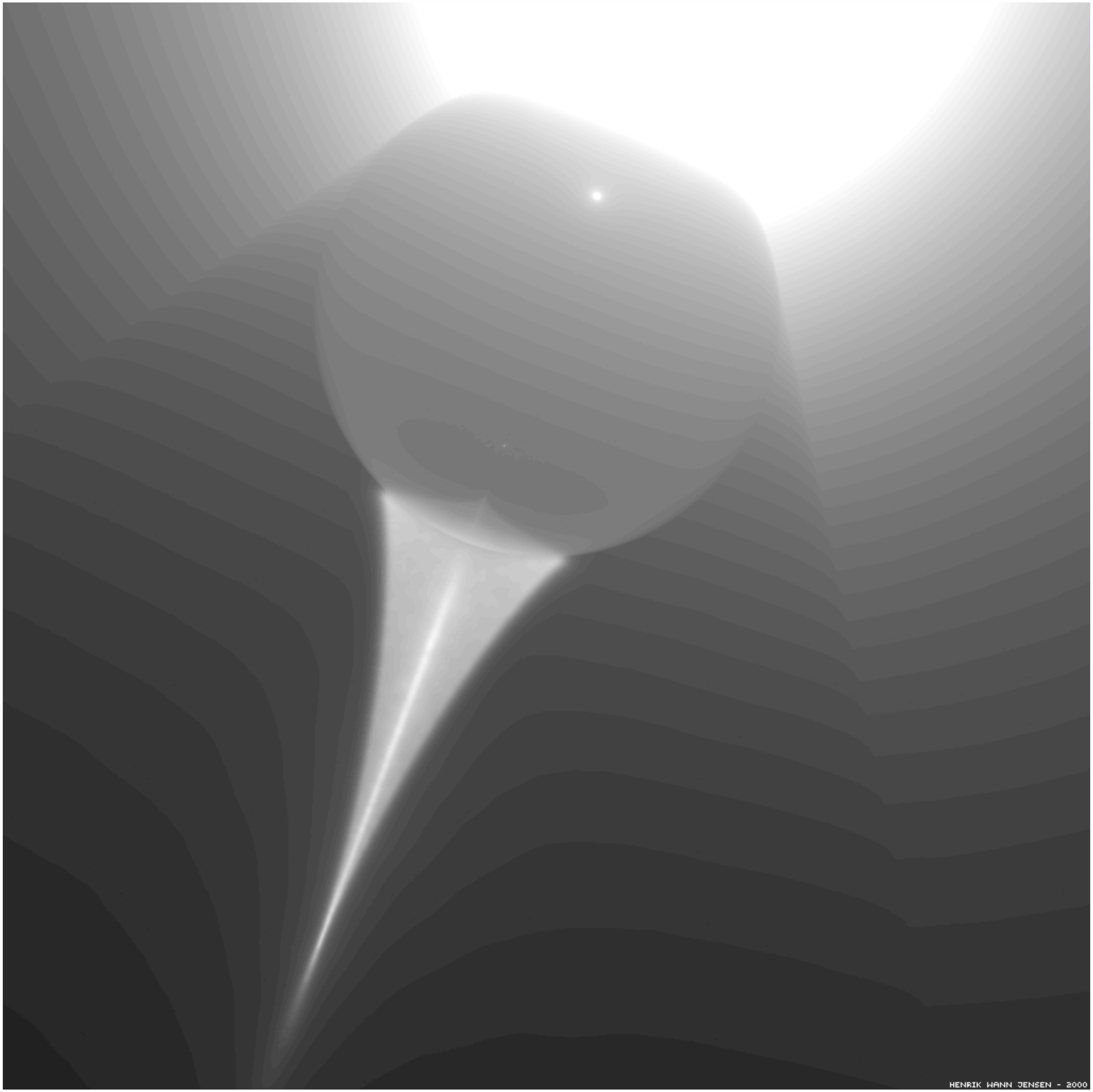
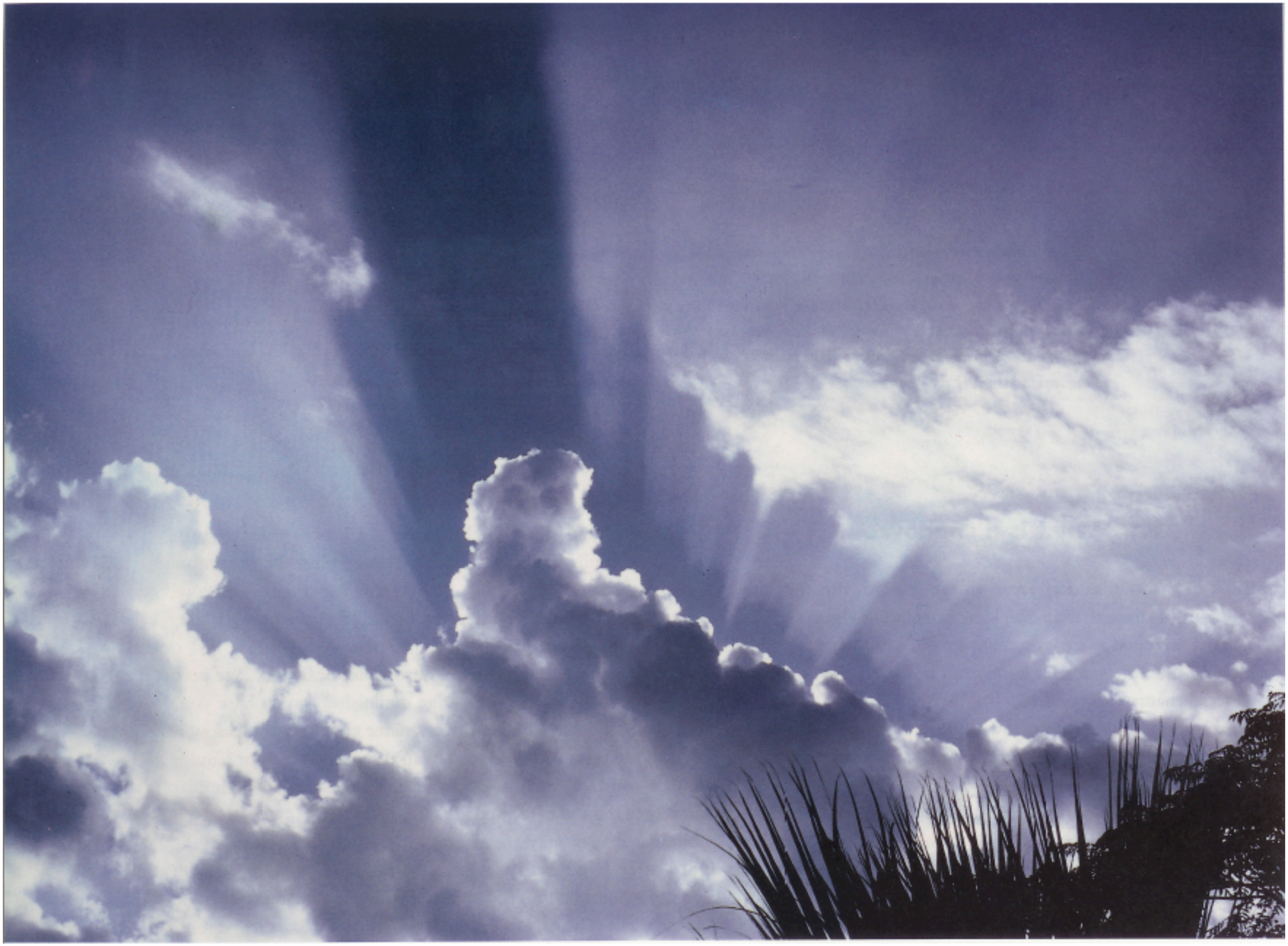


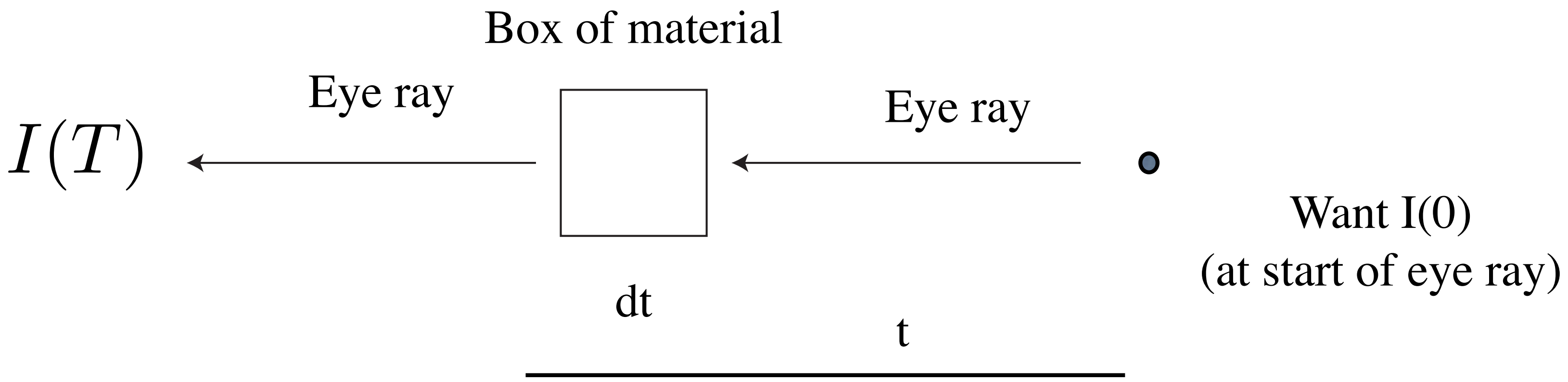
From Lynch and Livingstone, Color and Light in Nature


HENRIK WANN JENSEN - 2000

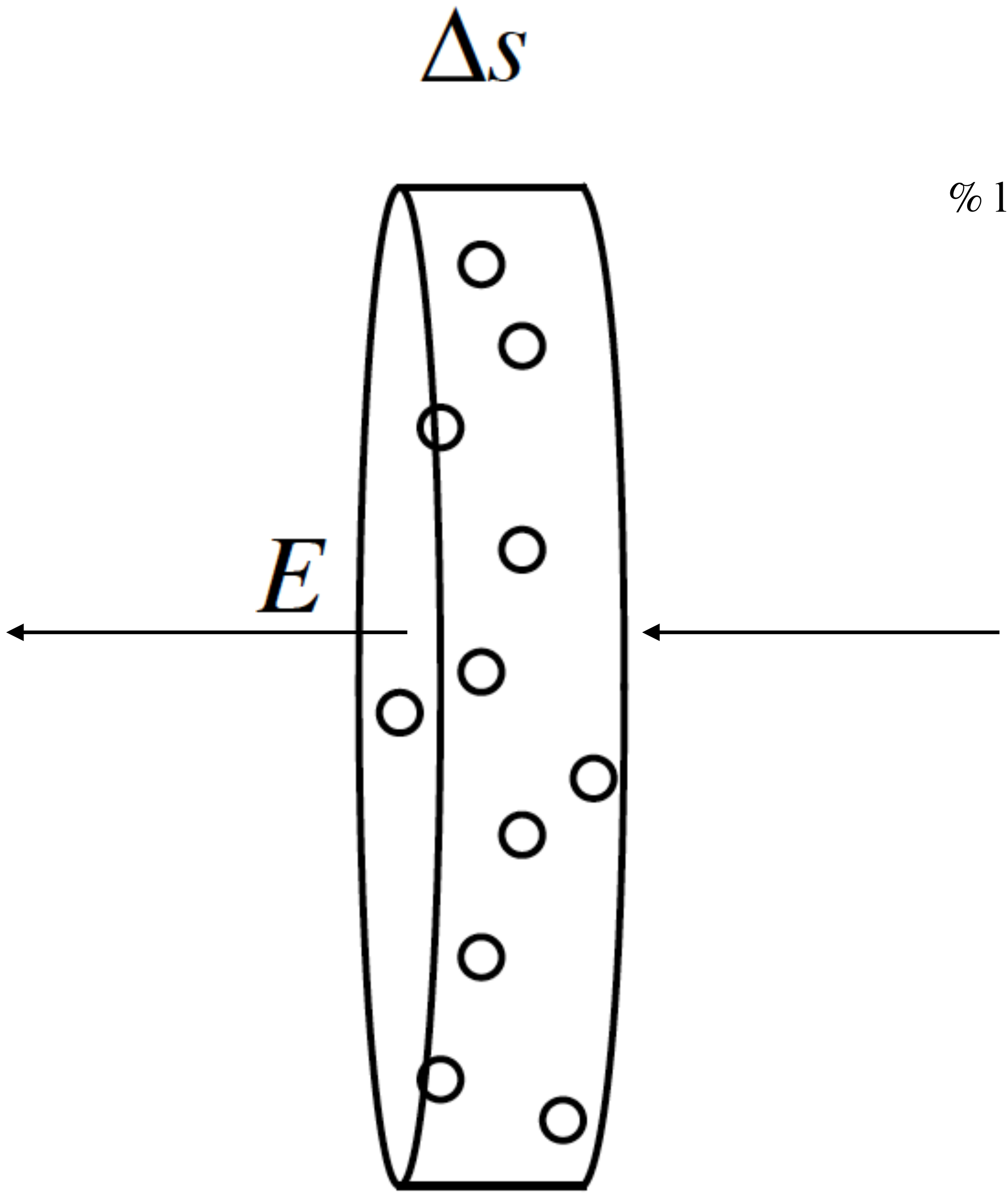


From Lynch and Livingstone, Color and Light in Nature

Absorption



- Ignore in-scattering
  - only account for forward scattering
- Assume there is a source at t=T
  - of intensity I(T)
  - what do we see at t=0?



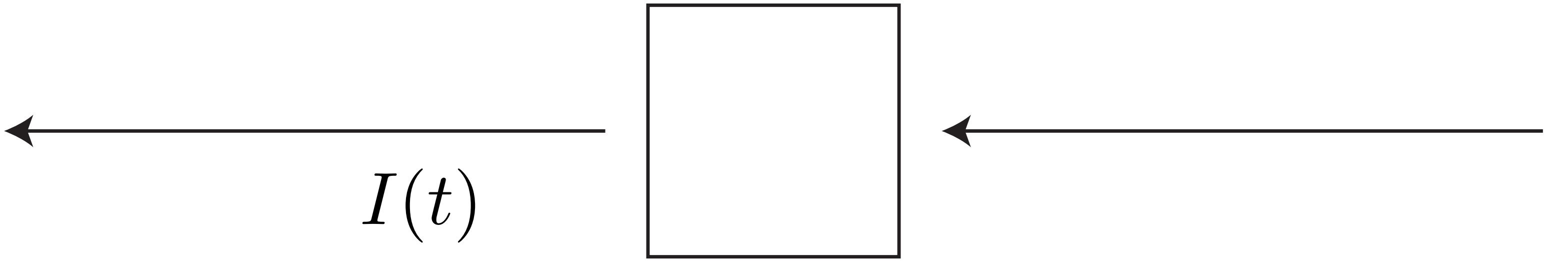
Cross sectional area of “slab” is E
Contains particles, radius r, density rho

Too few to overlap when projected

% light absorbed = (area of projected particles)/
(area of slab)

This is:

$$\frac{(\rho E \Delta s)\pi r^2}{E} = \sigma(s)\Delta s$$



$$I(t-\delta t) = I(t) - \underset{\substack{\uparrow \\ \text{Extinction} \\ \text{coefficient}}}{\sigma(t)} I(t)\delta(t)$$

$$\frac{dI}{dt} = \sigma(t)I(t)$$

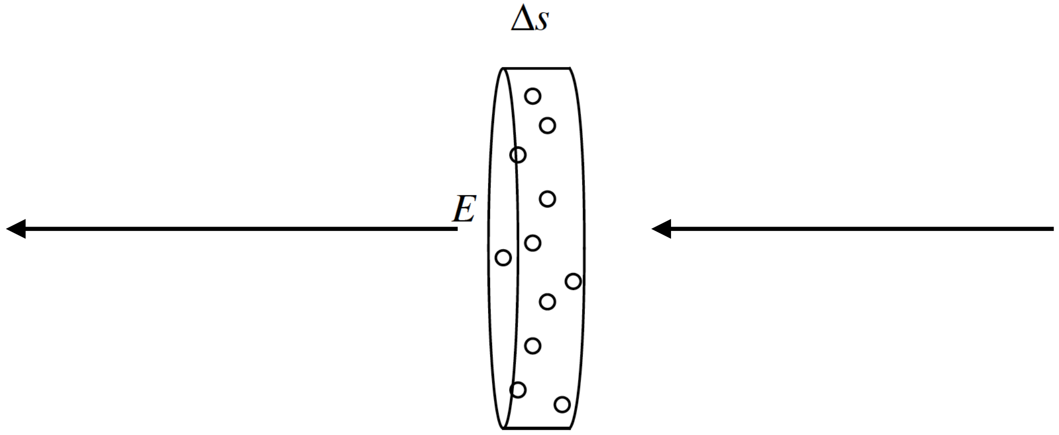
$$\frac{d\log I}{dt} = \sigma(t)$$

$$I(T) = I(0)e^{\int_0^T \sigma(t)dt}$$

$$\underset{\substack{\uparrow \\ \text{Eye is at 0}}}{I(0)} = \underset{\substack{\uparrow \\ \text{Intensity at T}}}{I(T)} e^{-\int_0^T \sigma(t)dt}$$

More interesting…

- Intensity is “created along the ray”
  - by (say) airlight
  - Model - the particles glow with intensity C(x)



Cross sectional area of “slab” is E
Contains particles, radius r, density rho

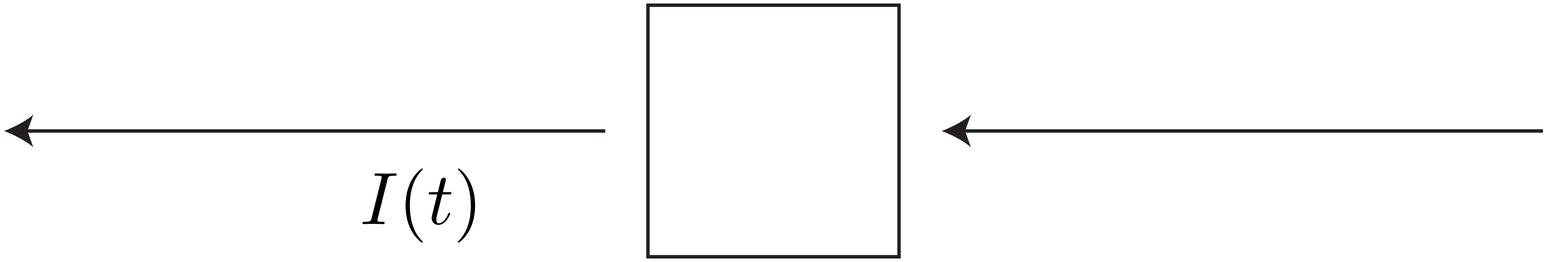
Too few to overlap when projected

Light out = Light in -
Light absorbed+
Light generated

Light generated: C x (area fraction
of proj. particles)

which is

$$C(\mathbf{x}(s))\frac{(\rho E \Delta s)\pi r^2}{E} = C(\mathbf{x}(s))\sigma(s)\Delta s$$



$$I(t - \delta t) = I(t) - \sigma(t) I(t) \delta t + \mathbf{c}(\mathbf{x}(t)) \sigma(t) \delta t$$

Absorption

Generation

$$I(0) = \int_0^T \mathbf{c}(\mathbf{x}(s)) \sigma(s) e^{-\int_0^s \sigma(u) du} ds$$

$$I(0) = \underset{\text{Accumulate along ray}}{\int_0^T} \underset{\text{Made at s}}{\underline{\mathbf{c}(\mathbf{x}(s))\sigma(s)}}\, \underset{\substack{\text{Absorbed in transit}\\ \text{from s to 0}}}{\underline{e^{-\int_0^s \sigma(u)du}}}\, ds$$

Dehazing and airlight

Airlight color at p

$$I(p) = J(p) \times T(p) + A(p) \times (1 - T(p))$$

Image color at p

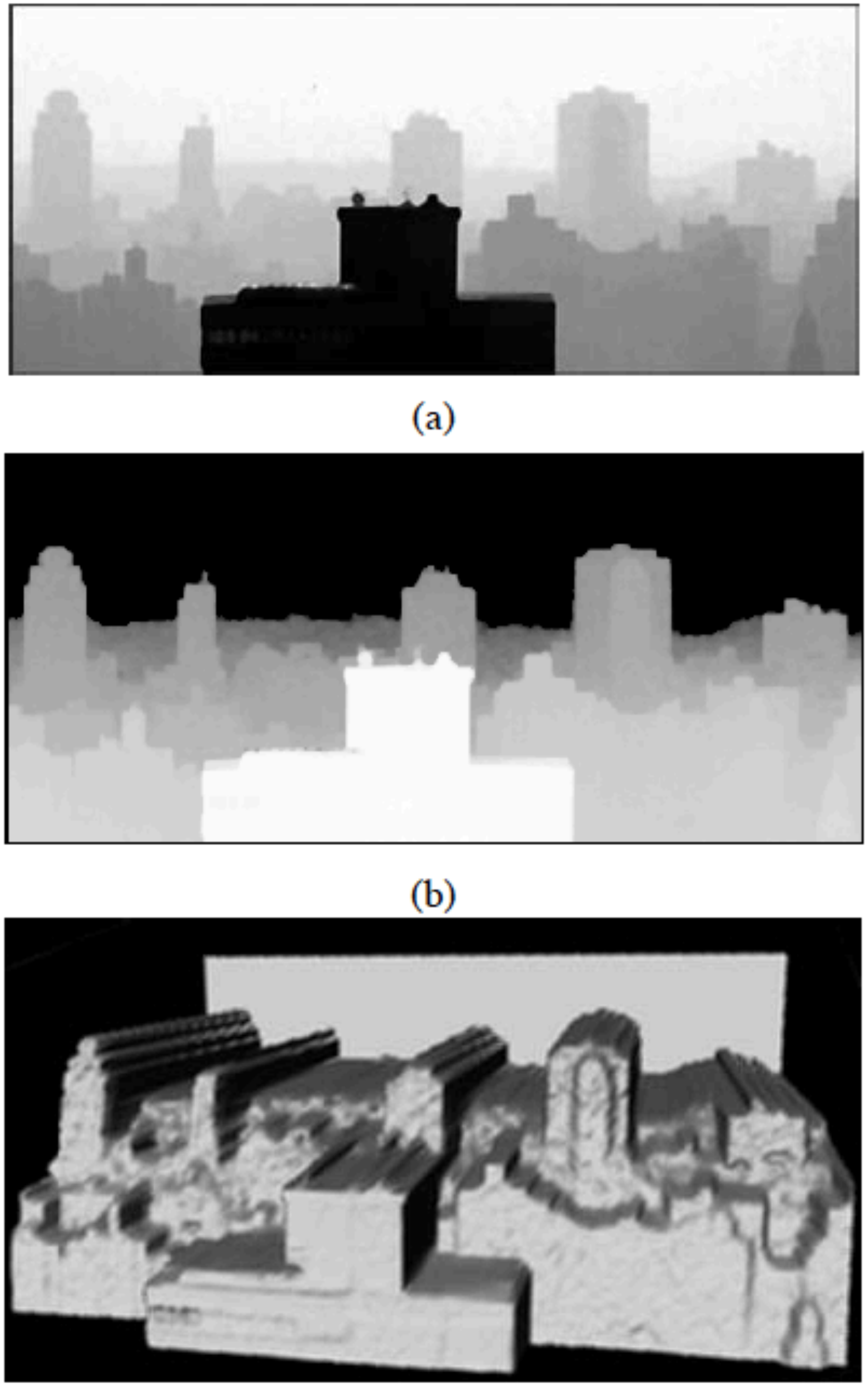
Surface radiance color at p

Absorption term, exponential in depth, at p

- Consequences
  - Brightness is a depth cue
  - Reasoning about airlight color yields dehazed image

Airlight yields a depth cue

- Assume that airlight is dominant
  - (i.e. most of light arriving at camera is airlight)
  - then you can recover depth from a single image
- Disadvantages
  - requires significant fog (but not too much) or large scales



(a)

(b)

(c)

Nayar and Narasimhan, 1999

Model

$$\underset{\substack{\uparrow \\ \text{Observed}}}{I(p)} = \underset{\substack{\uparrow \\ \text{Shading x albedo}}}{J(p)} \times \underset{\substack{\uparrow \\ \text{Independent of shading}}}{T(p)} + \overset{\substack{\text{Airlight color - same at all points} \\ \downarrow}}{A(p)} \times (1 - T(p))$$

- With work, this yields
  - neighboring pixels with same albedo yield
    - constraints on shading and T
  - assume shading and T independent
    - estimate A to yield “most independent” shading and T
  - result: J(p)

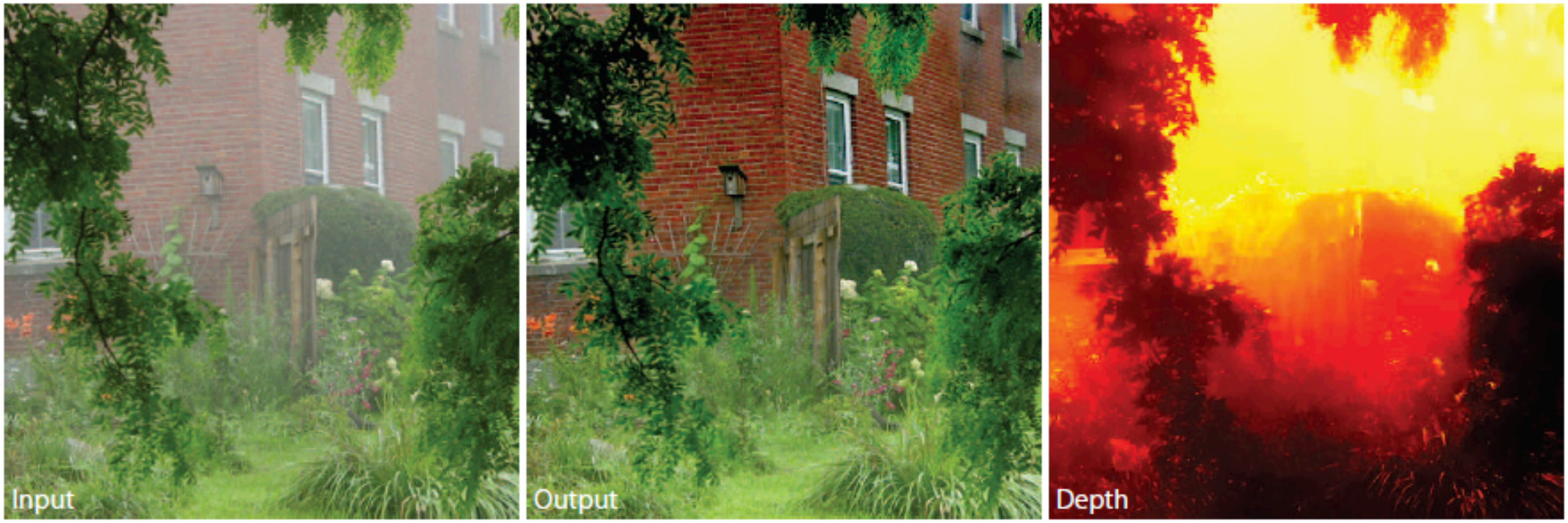


Figure 1: Dehazing based on a single input image and the corresponding depth estimate.

Fattal, 08 - note depth map AND dehaze; note also slightly odd colors

Improved estimation by cleaner model

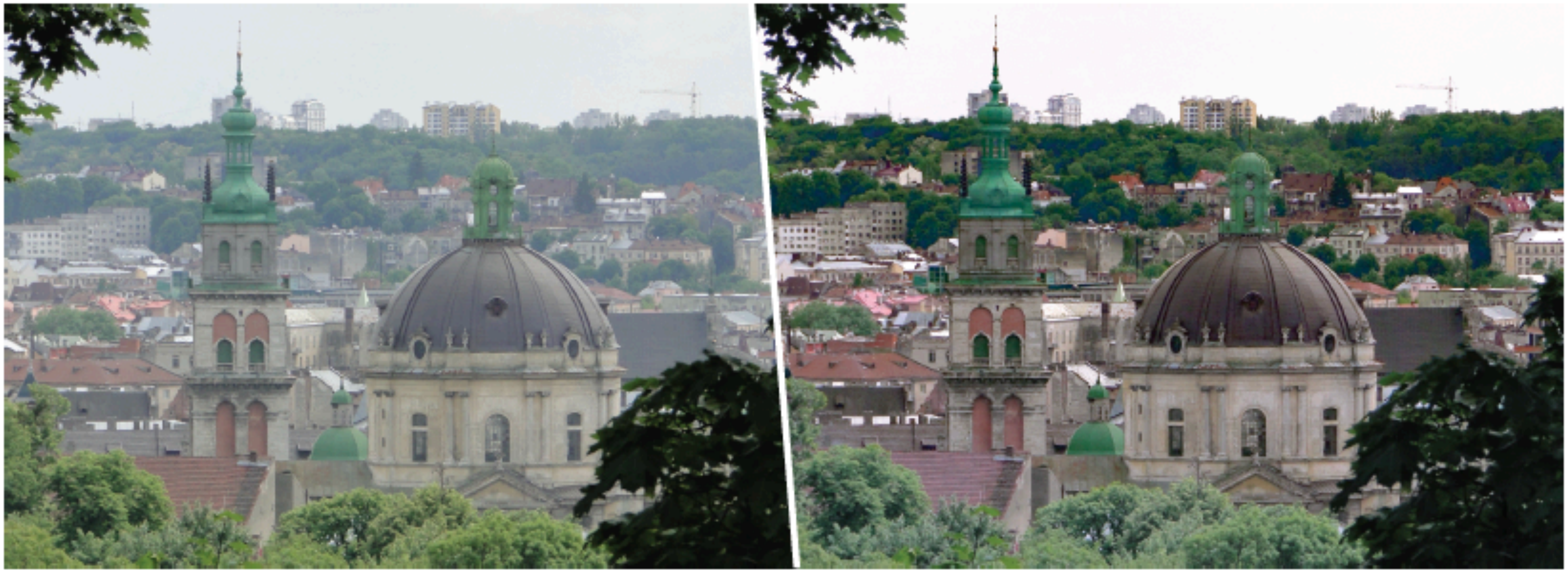


Fig. 1. Old Town of Lviv. Input image on the left, our result on the right.

Fattal, 08 - note depth map AND dehaze; note also slightly odd colors

Simple learning

- Idea:
    - recover transmission map from image
    - you could train by
        - get real images
        - make fake transmission maps, and combine
        - now have (hazy image, transmission map) pairs - train CNN

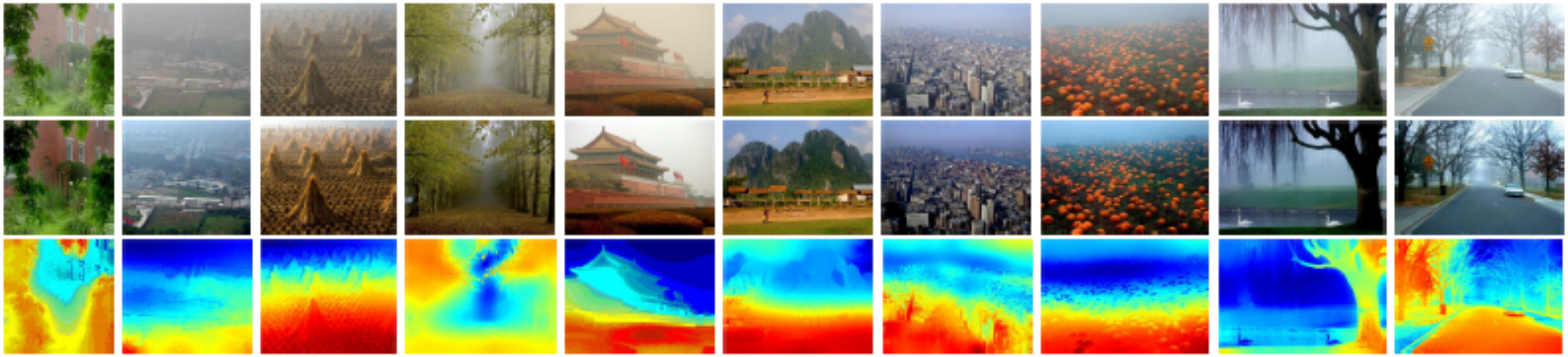


Fig. 11. The haze-free images and depth maps restored by DehazeNet

Cai et al 16 (DeHazeNet)

Paired datasets

- Idea:
  - obtain pairs (hazy image, clear image)
- Strategy:
  - Fake fog model on real image
    - Foggy cityscapes
      - https://people.ee.ethz.ch/~csakarid/SFSU_synthetic/
  - Render synthetic images fog/no-fog
    - RESIDE
      - https://arxiv.org/pdf/1712.04143.pdf
  - Take photos outdoors; introduce fog; repeat
    - NH-HAZE
      - https://data.vision.ee.ethz.ch/cvl/ntire20/nh-haze/

Single image dehazing

- Essentially
  - obtain images with/without haze (with haze by synthetic)
  - train network to reproduce without haze image from with haze

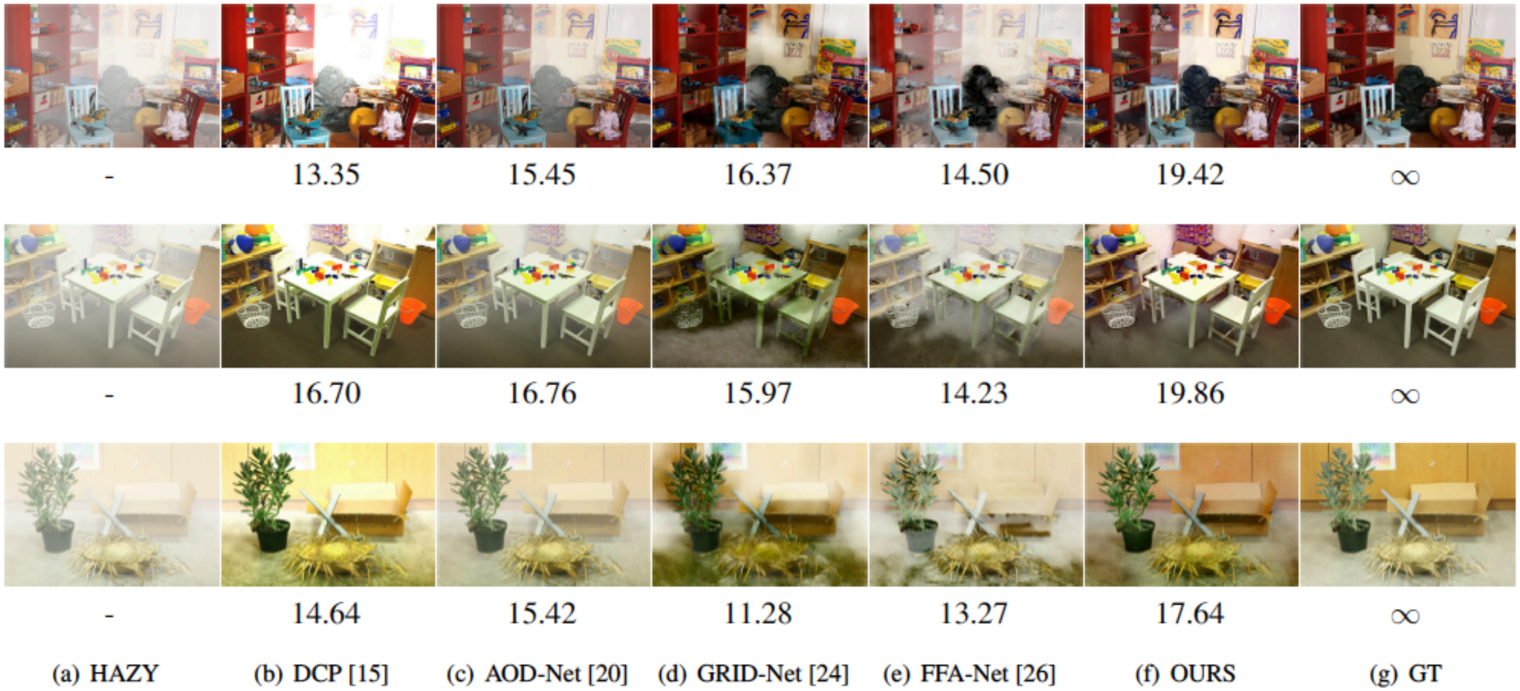
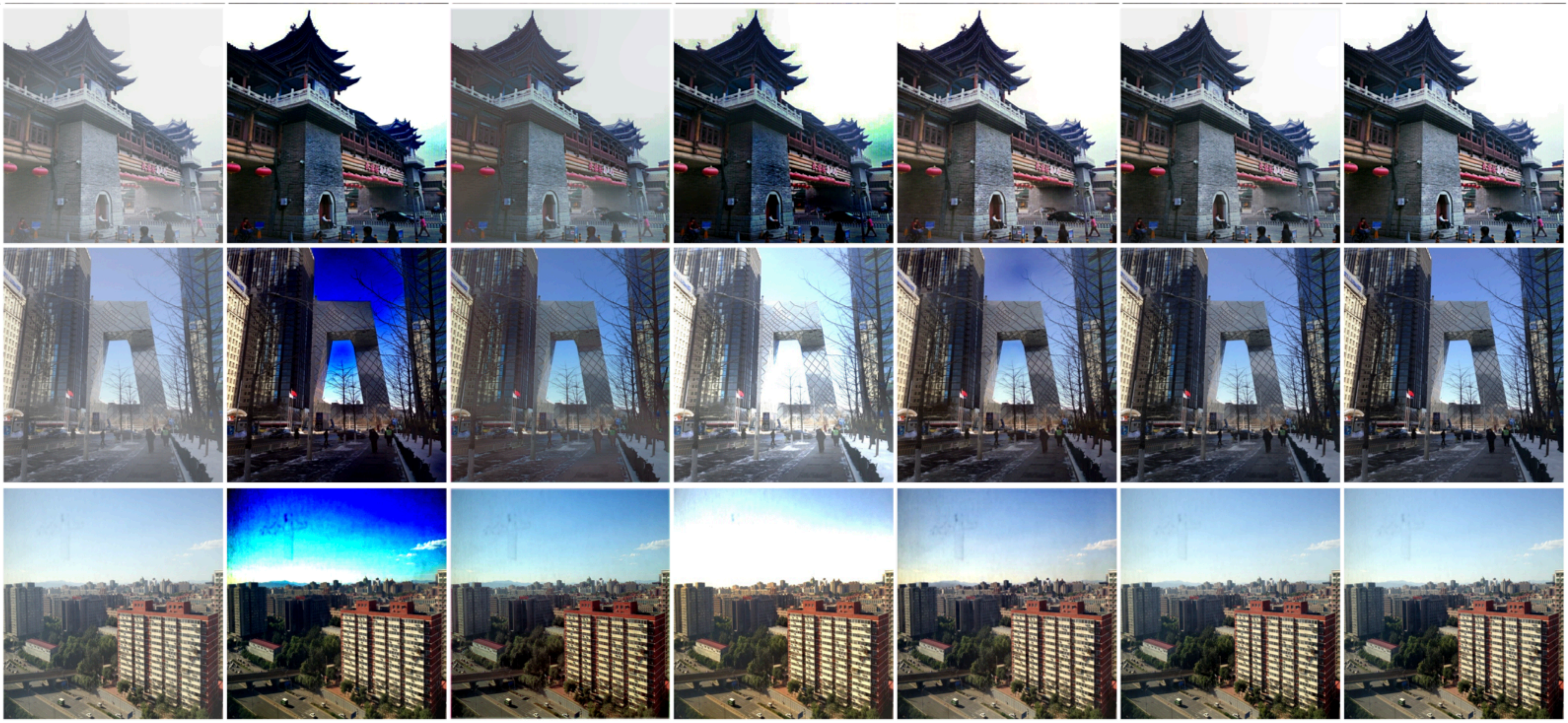


Figure 6. Qualitative comparisons with different state-of-the-art dehazing methods for indoor synthesis hazy images. The top two rows are from SOTS, the third row is from TestA dataset and the bottom three rows are from MiddleBury dehazing dataset. The numbers below image are PSNR (dB) value of each image.

Shen et al 19



(a)Hazy inputs (b)DCP (c)AOD-Net (d)DehazeNet (e)GCANet (f)Ours (g) GT

Qin et al 19 - Use feature attention

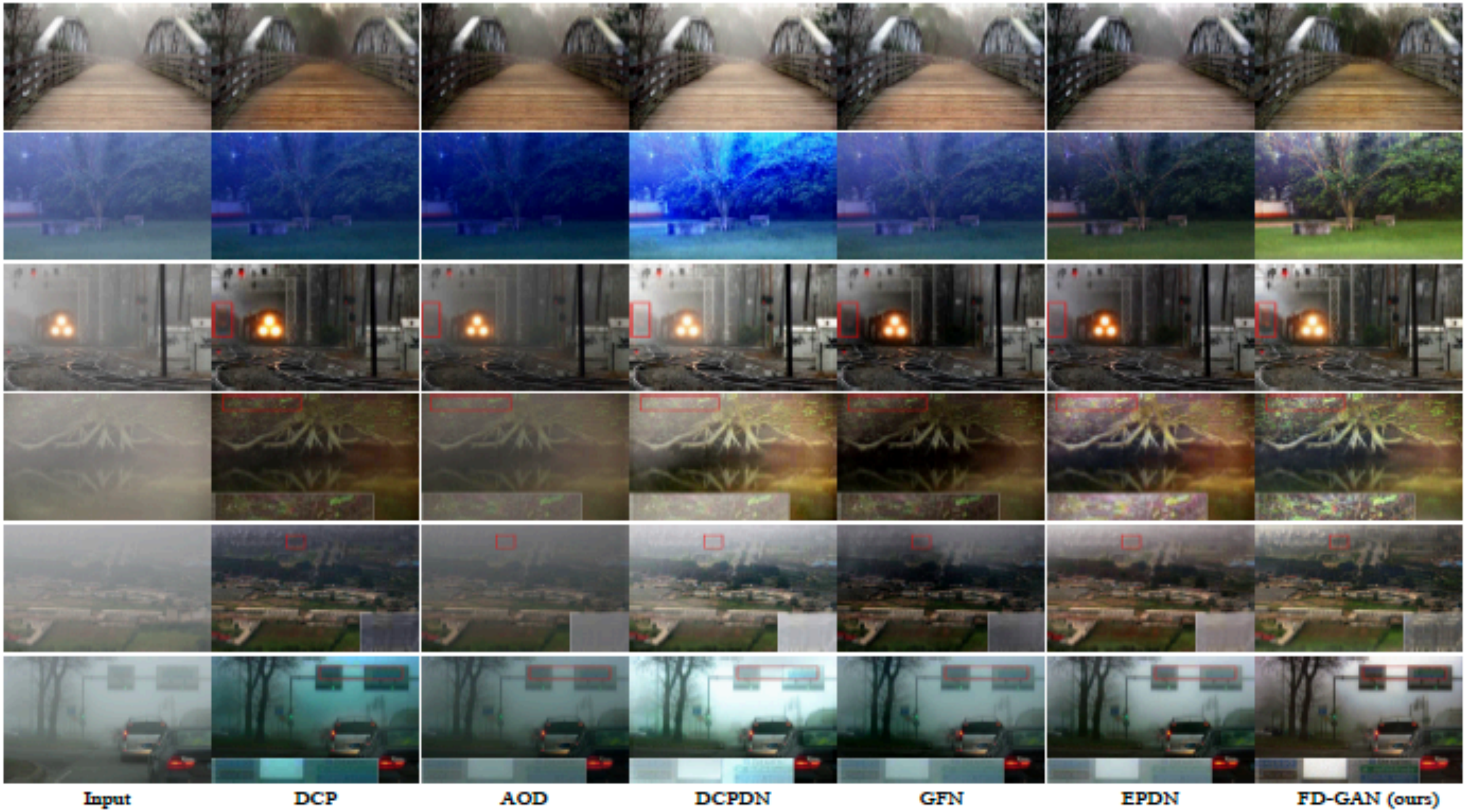
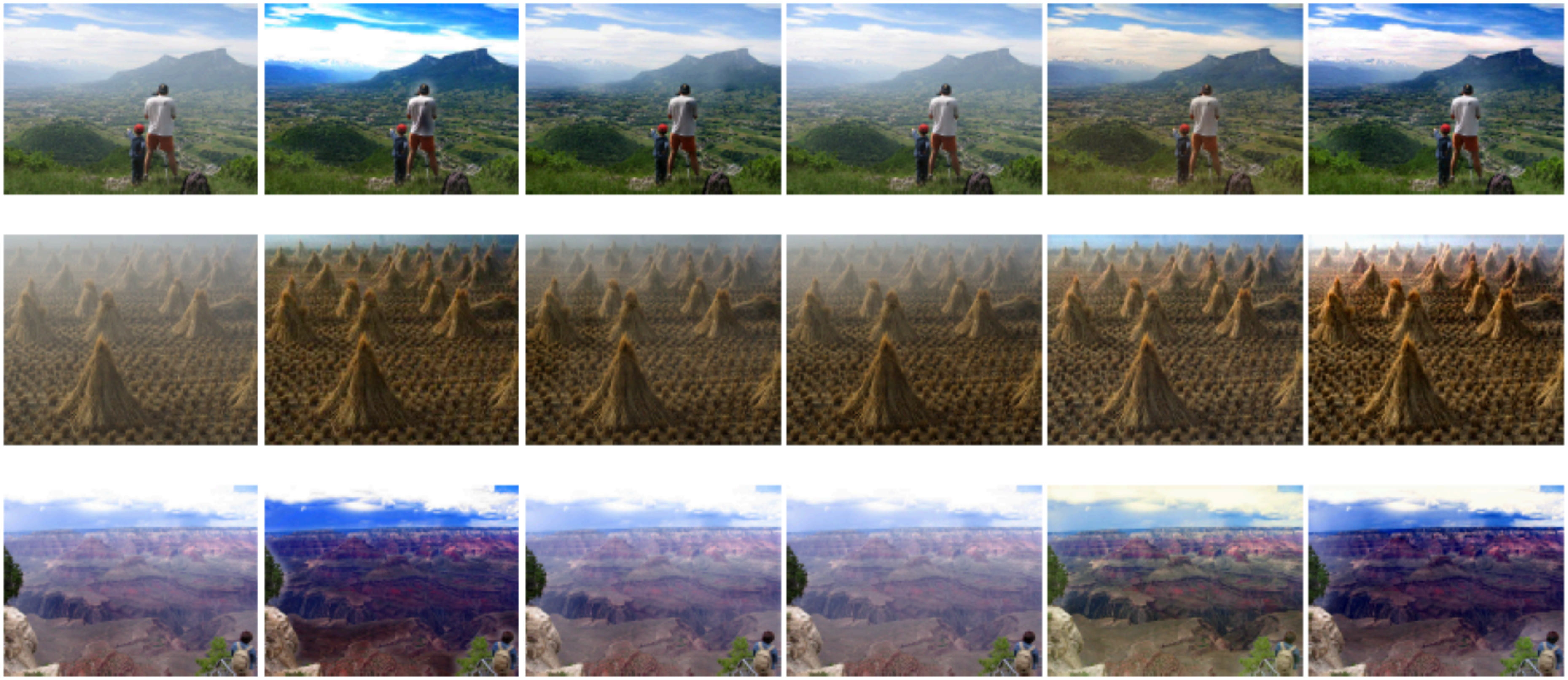


Figure 5: Visual comparisons on real-world hazy images. Our model can generate more natural and visual pleasing dehazed results with less color distortion. Please see the details in red rectangles. Zoom in for best view.

Dong et al 21 - Use an adversarial loss



(a) INPUT (b) DCP [15] (c) GRID-Net [24] (d) FFA-Net [26] (e) FD-GAN [11] (f) OURS

Figure 7. Qualitative comparisons with different dehazing state-of-the-art methods for real hazy images.

Shen et al 20 - Use sequence model (resnet as implicit euler method)

Challenges

- NTIRE workshops and challenges
  - https://data.vision.ee.ethz.ch/cvl/ntire21/
  - https://data.vision.ee.ethz.ch/cvl/ntire20/

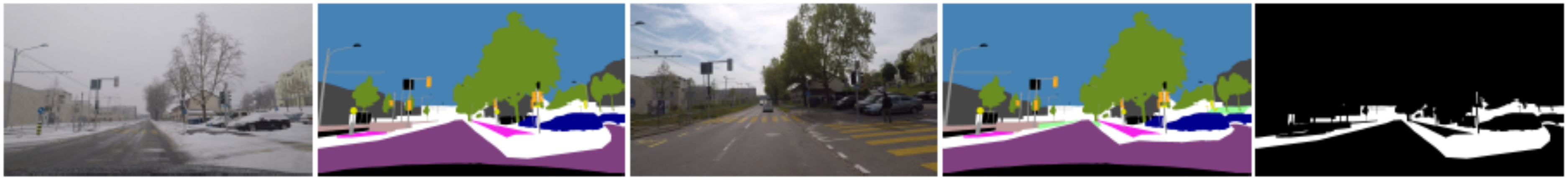
Image interpretation strategies

- Dehaze (derain; denighttime; etc) image, then apply
    - detector, segmenter, etc
    - issues:
        - dehazing (etc.) may create signal problems
- Simulate haze (rain; night; etc) existing labelled data, then train
    - detector, segmenter, etc.
    - issues:
        - simulator may not be accurate
- Collect paired data (good conditions/bad conditions)
- Multi-sensor fusion
    - different sensors are affected in different ways, so….

There's a review in Hnewa, 21

Paired data

- Collect data on good days, bad days
  - along the same routes, w/ GPS
  - use dynamic programming, GPS to compute alignment at the image level
- Now label
  - annotator labels bad image round 1
  - compares to good image; fixes labelling round 2

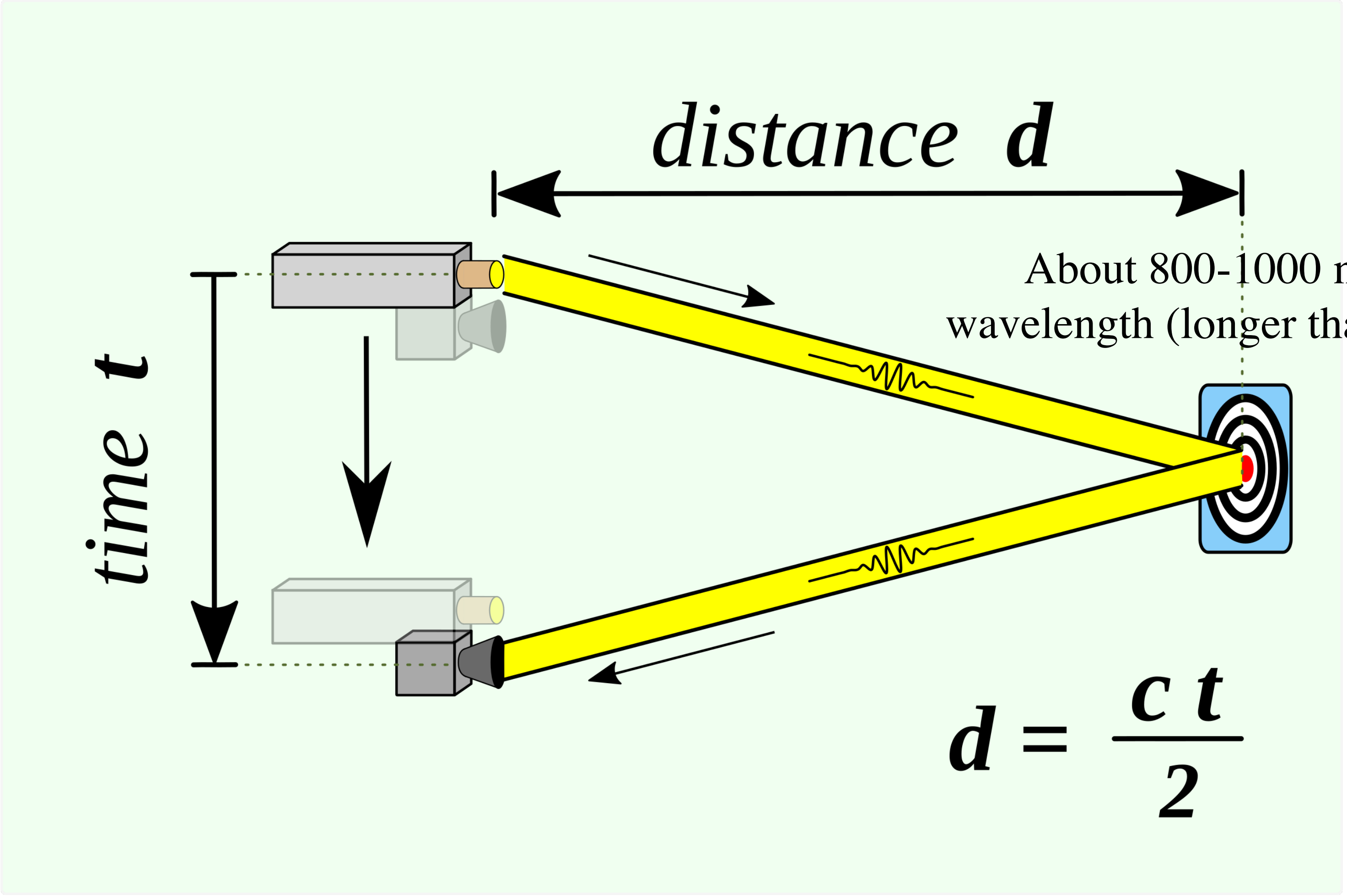


(a) Input image I (b) Stage 1 annotation (draft) (c) Corresponding image I' (d) Stage 2 annotation (GT) (e) Invalid mask J

Figure 2. **Illustration of annotation protocol for ACDC.** The color coding of the semantic classes matches Fig. 1. All annotations in (b), (d) and (e) pertain to the input image I in (a). A white color in (b) and (d) denotes unlabeled pixels.

Sakaridis et al, 21

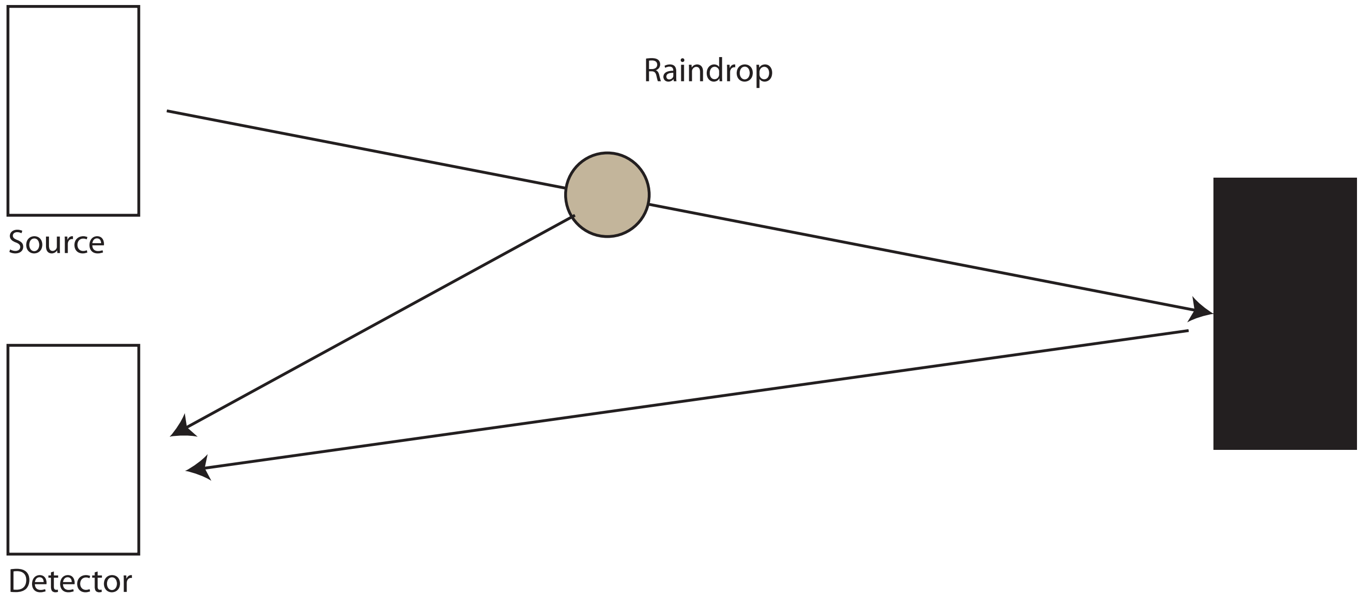
Fog and Lidar: Lidar



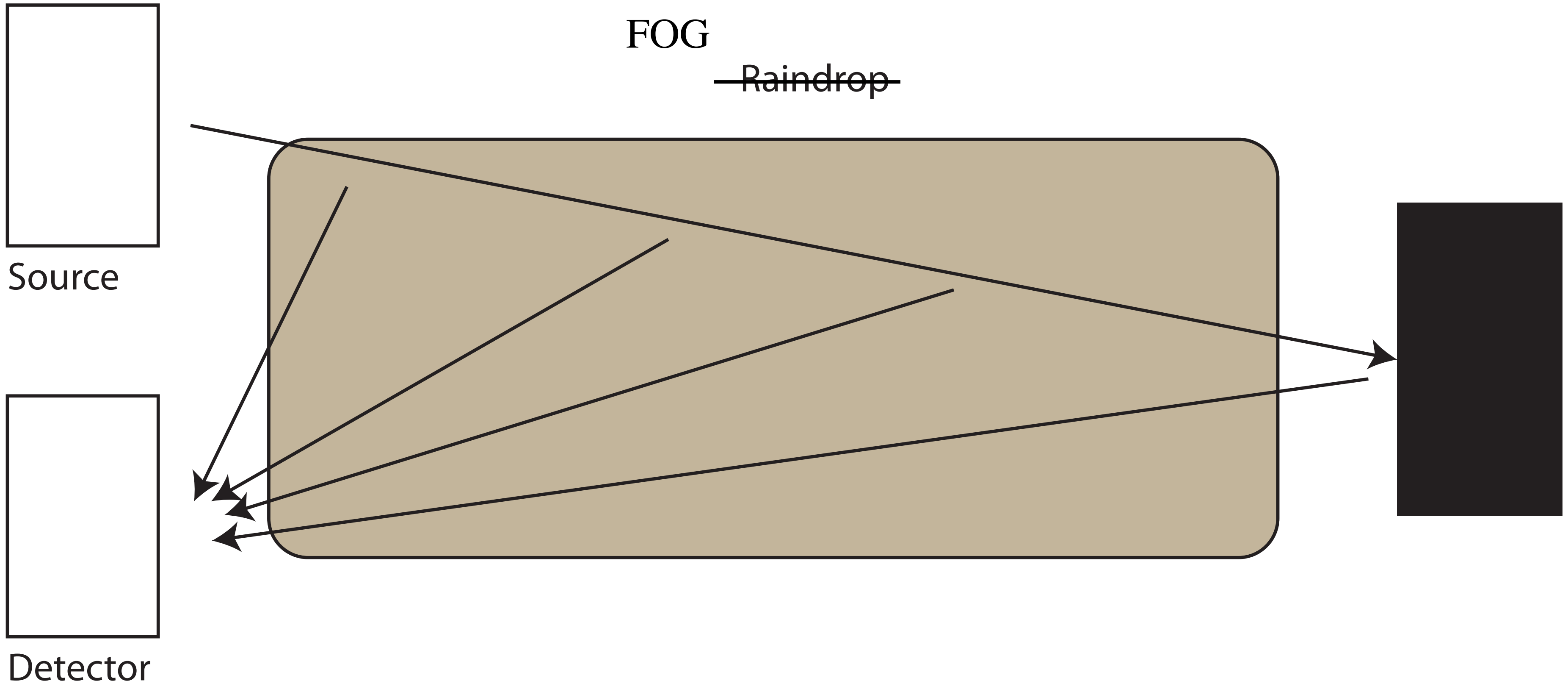
About 800-1000 nm
wavelength (longer than red)

Wikipedia

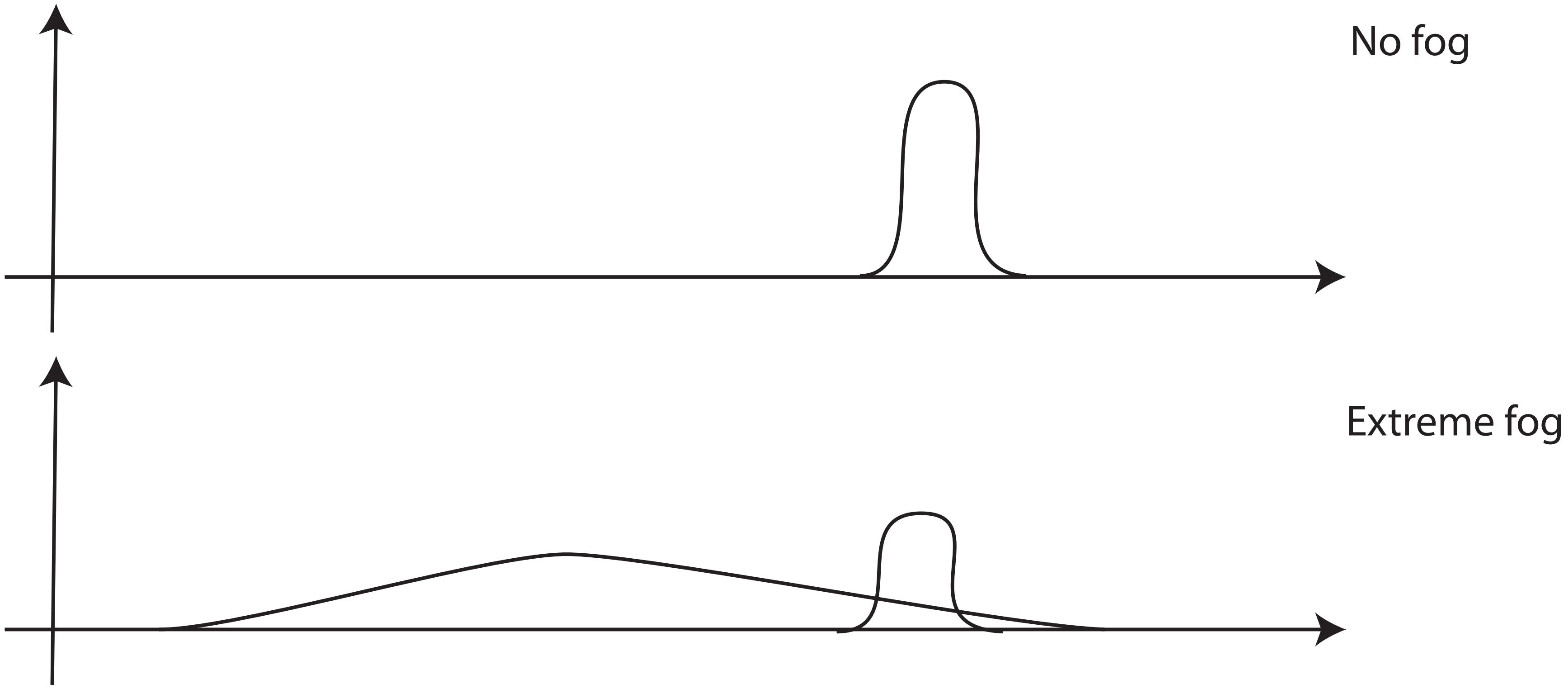
Raindrop backscatter

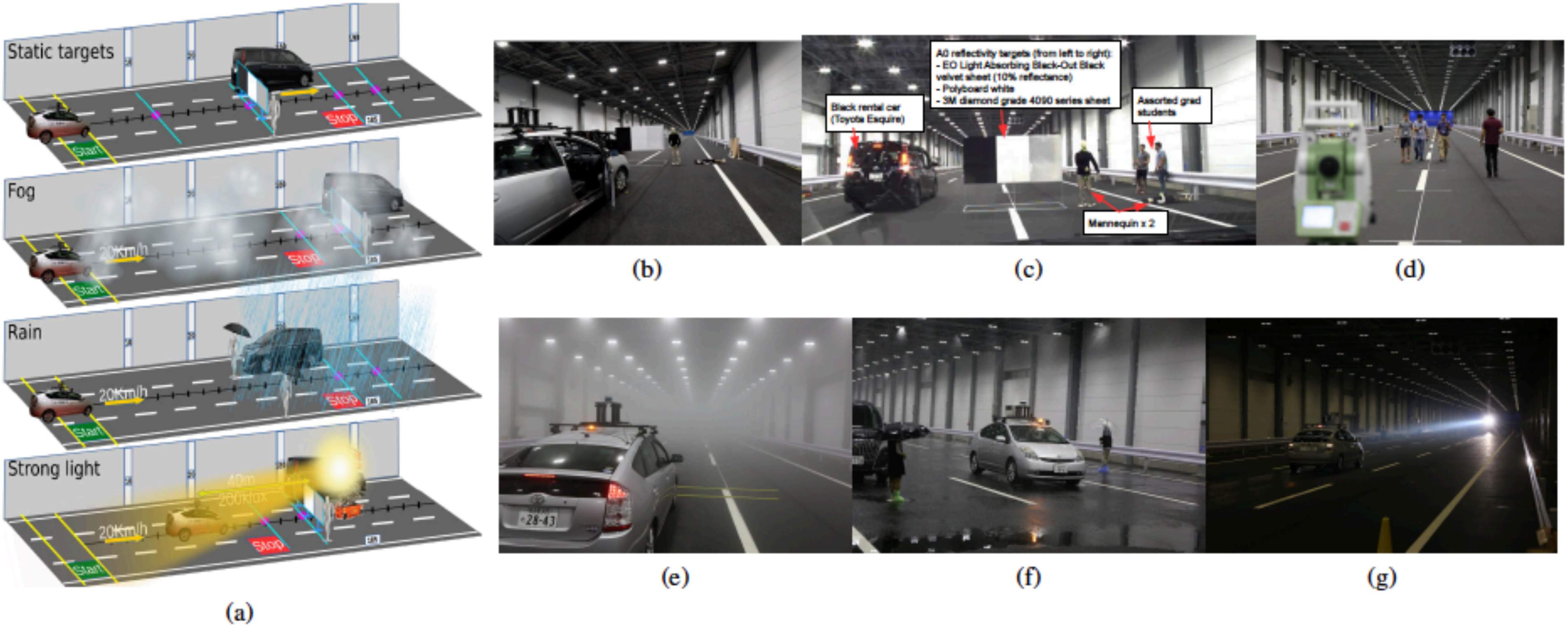


Fog scattering



What the sensor sees…

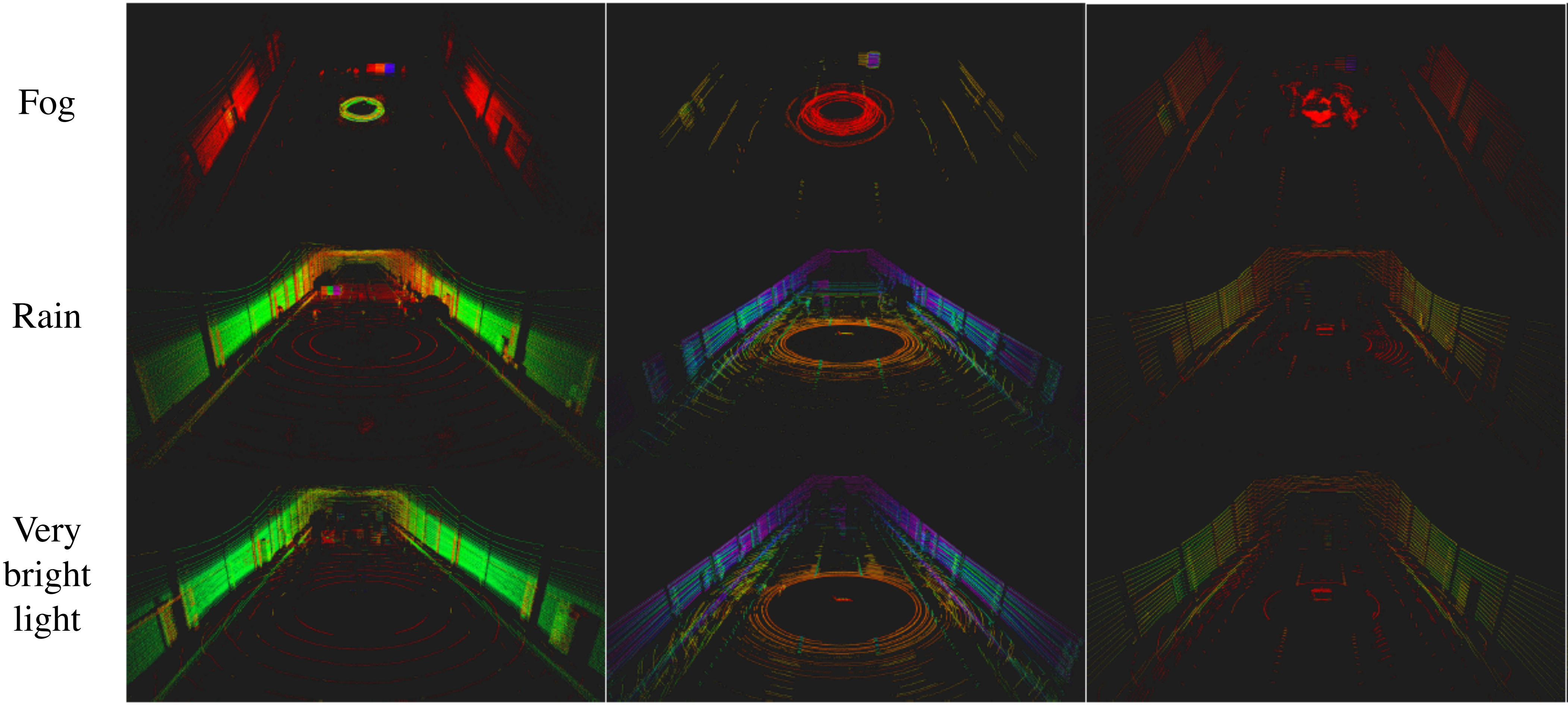



Static targets
Fog
Rain
Strong light
Start
Stop
20Km/h
40m
200Klux
Black rental car
(Toyota Esquire)
A0 reflectivity targets (from left to right):
- EO Light Absorbing Black-Out Black velvet sheet (10% reflectance)
- Polyboard white
- 3M diamond grade 4090 series sheet
Assorted grad students
Mannequin x 2

(a) (b) (c) (d) (e) (f) (g)

Fig. 5: Static targets and adverse weather experiments at JARI's weather chamber: (a) configuration of the different scenarios, (b) and (c) measurement, (e) to (g) sample adverse weather scenes, (d) setting up ground truth.

Carballo, 20



(a) VLS-128 (b) HDL-64S2 (c) HDL-32E

Carballo, 20

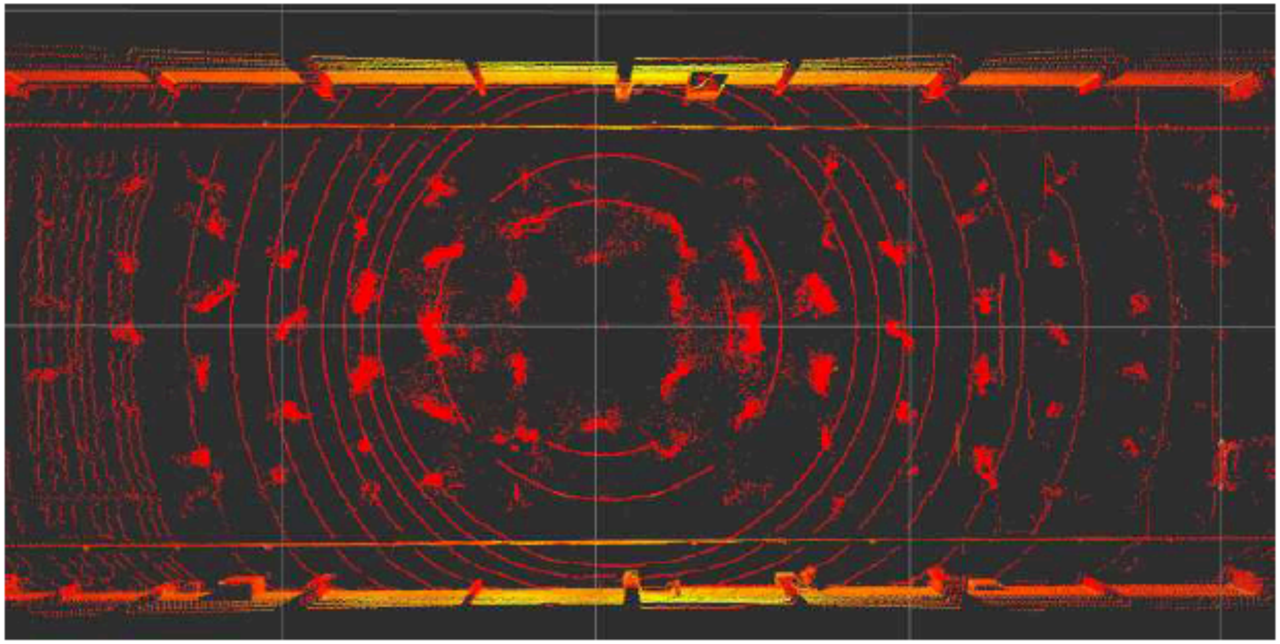
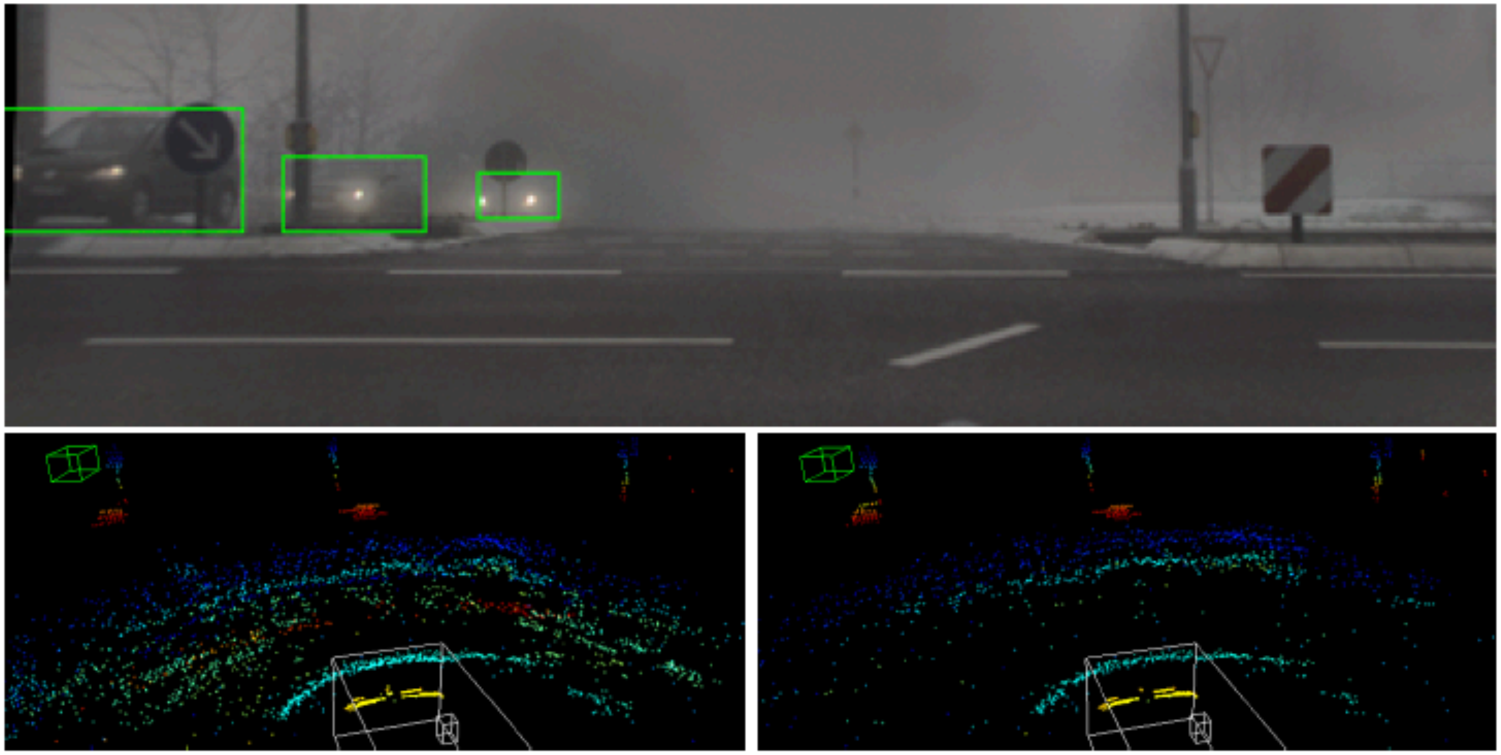


Fig. 9: “Rain pillars” as detected by a LiDAR.

- Qualitative effects
  - lost returns
  - fog torus
  - early returns
  - rain pillars
  - noise

Carballo, 20



(a) *strongest* returns

(b) *last* returns

Figure 1: LiDAR returns caused by fog in the (top) scene. (a) shows the *strongest* returns and (b) the *last* returns, color coded by the LiDAR *channel*. The returns of the ground are removed for better visibility of the points introduced by fog. Best viewed in color (red $\widehat{=}$ low, cyan $\widehat{=}$ high, 3D bounding box annotation in green, ego vehicle dimensions in gray).

Hahner 21

Radar is unaffected

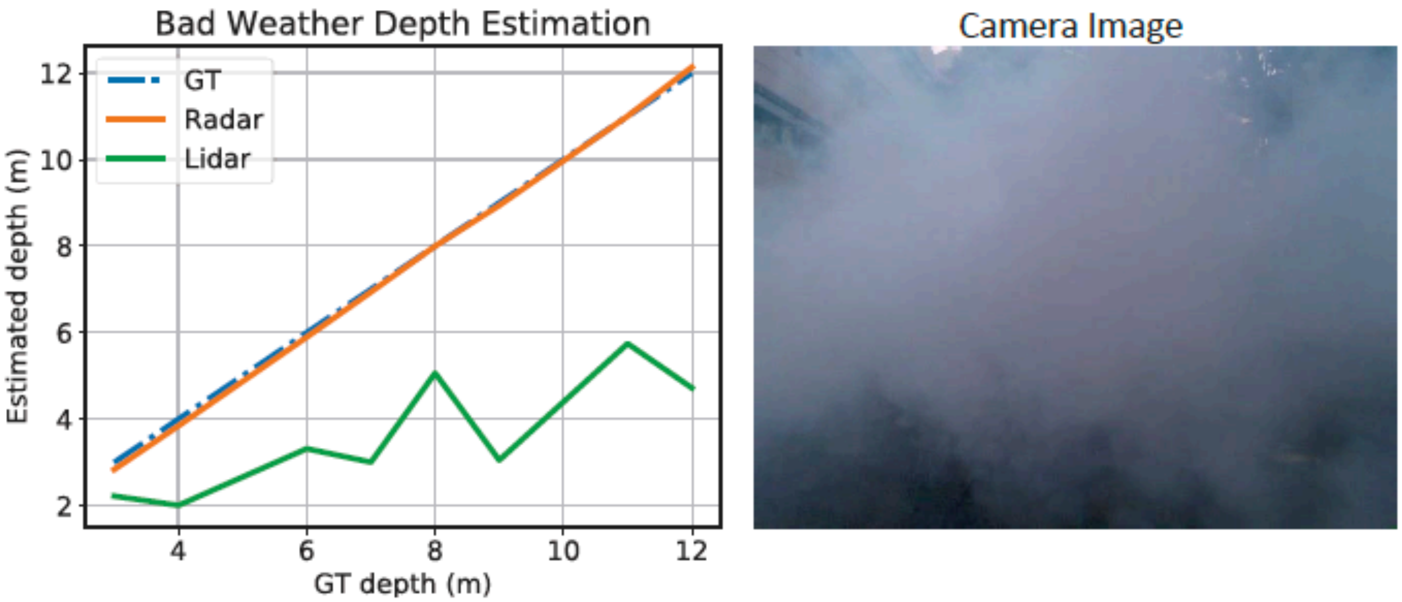
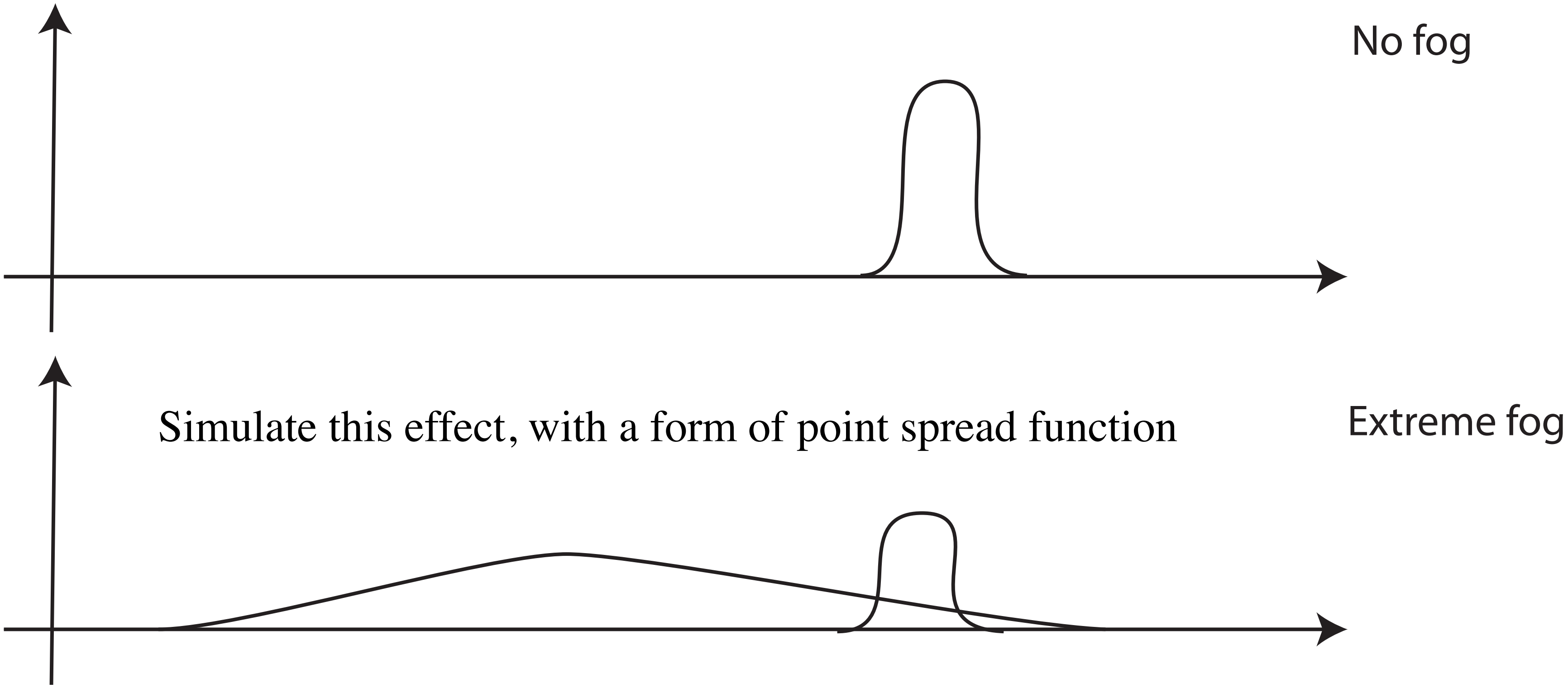


Figure 16: *Performance comparison of different sensors in the presence of adverse conditions. The left plot shows the depth estimation performance of Radar and LiDAR for an object directly in front of the sensor in the presence of fog. The right figure shows the camera image for the experiment.*

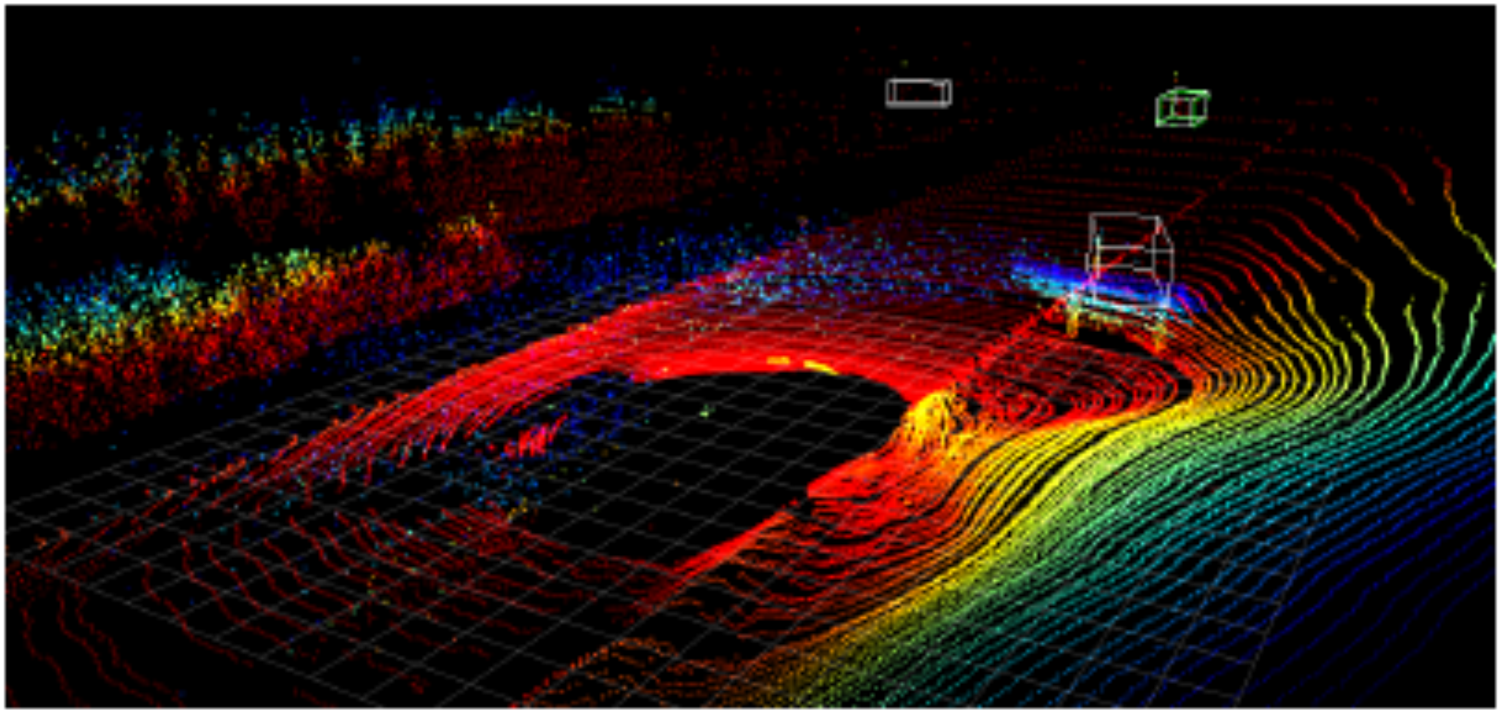
Bansal et al 20

What the sensor sees…



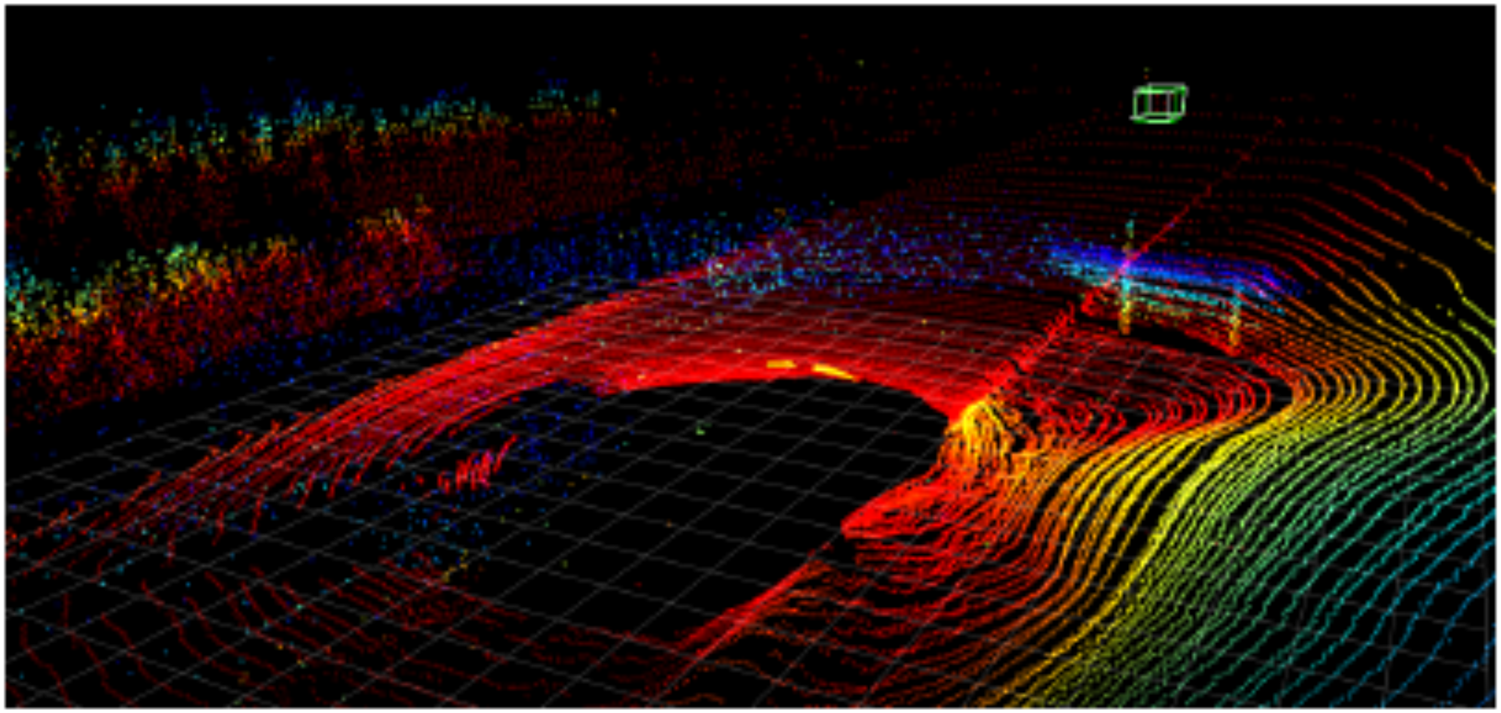
Simulate this effect, with a form of point spread function

Hahner 21



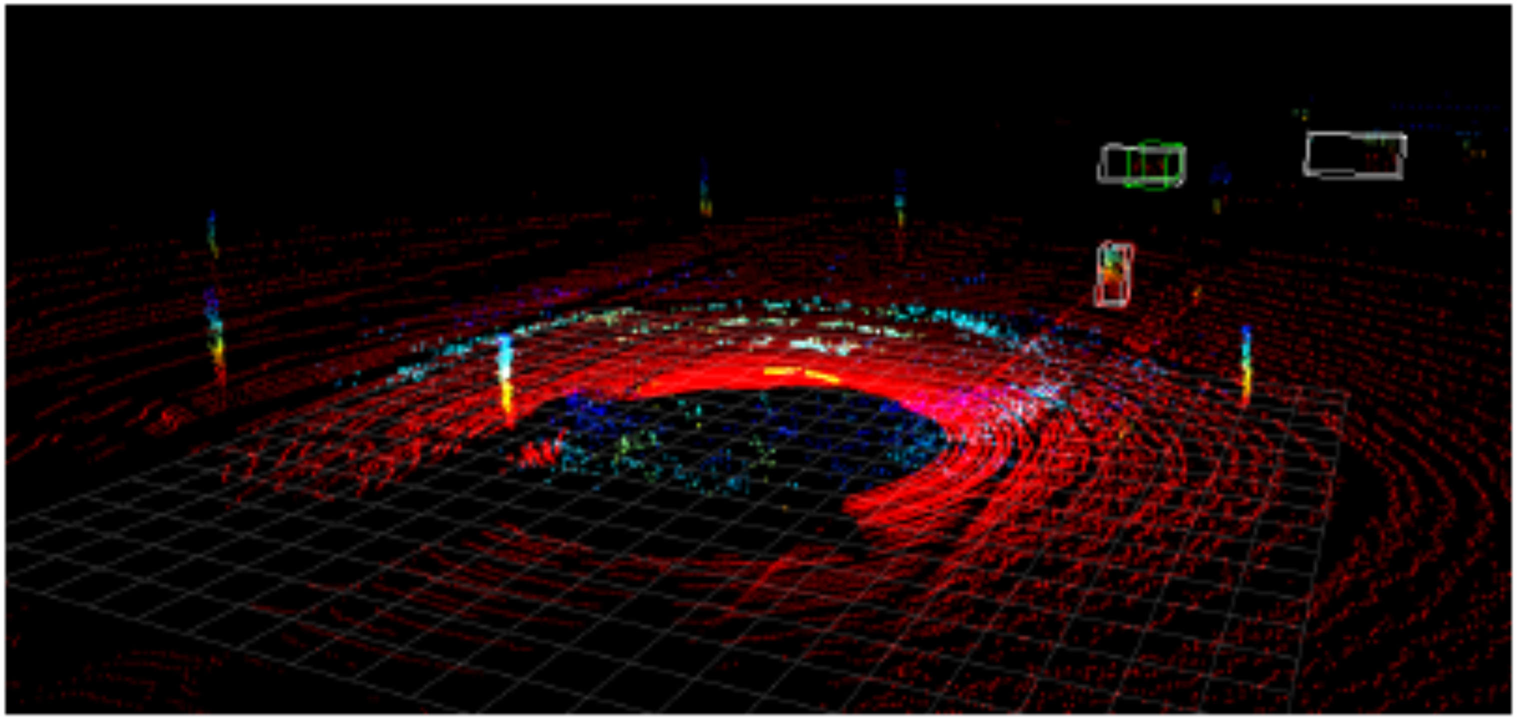
PV RCNN trained on
good weather lidar returns
only

Lidar captured in dense fog



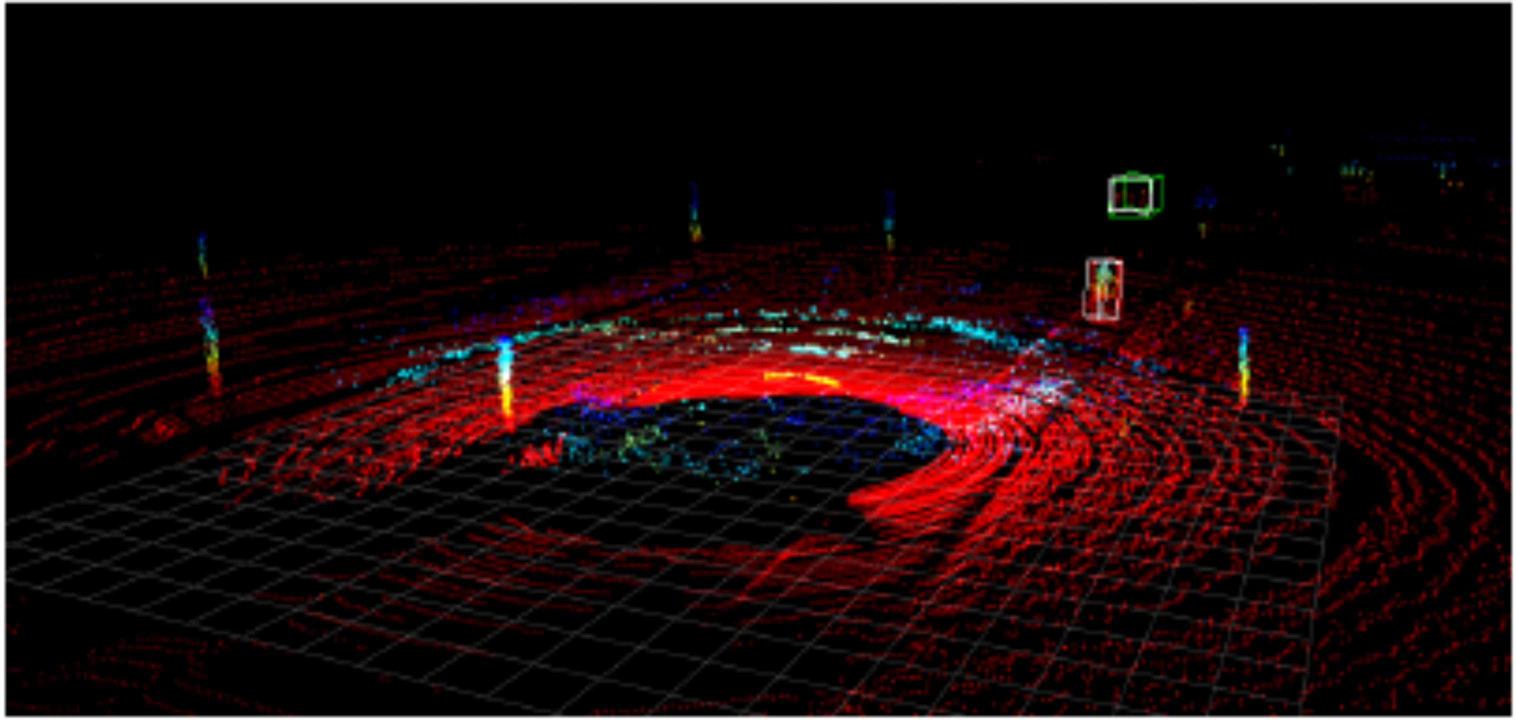
PV RCNN trained on
good and simulated bad
weather lidar returns
only

Hahner 21



PV RCNN trained on good weather lidar returns only

Lidar captured in dense fog



PV RCNN trained on good and simulated bad weather lidar returns only

Hahner 21

Multi sensor methods

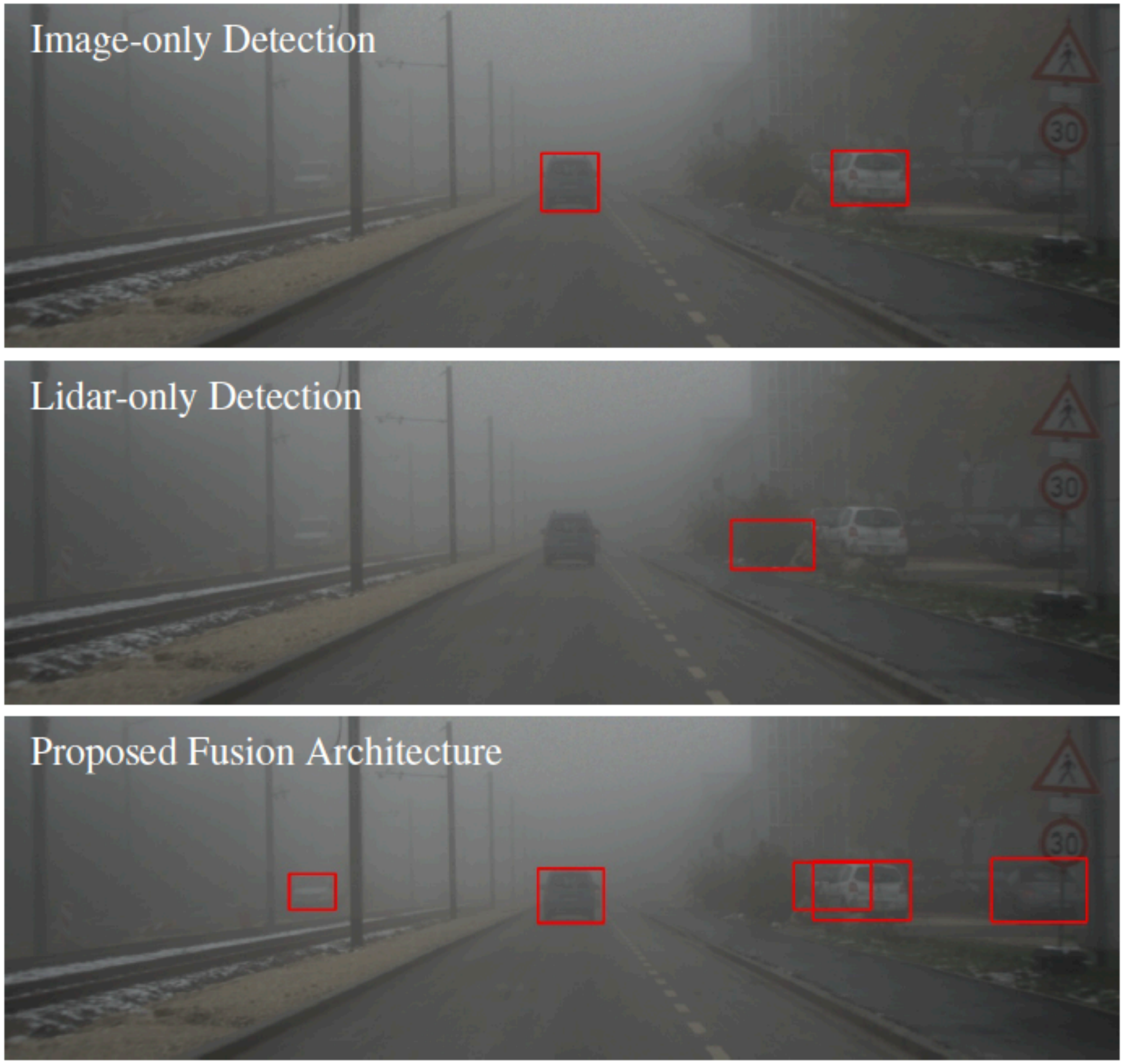


Image-only Detection

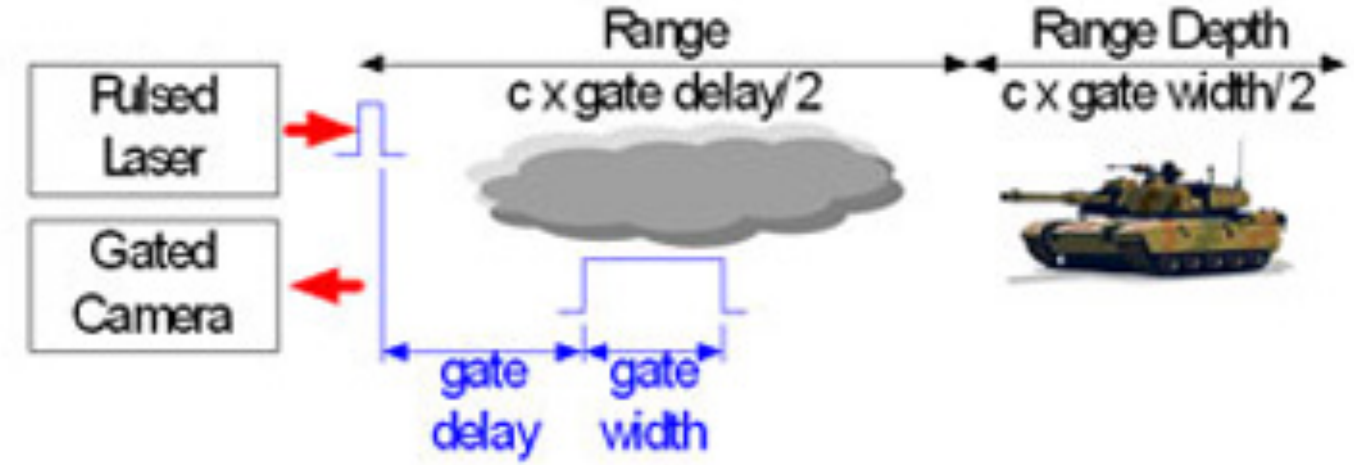
Lidar-only Detection

Proposed Fusion Architecture

Figure 1: Existing object detection methods, including efficient Single-Shot detectors (SSD) [41], are trained on automotive datasets that are biased towards good weather conditions. While these methods work well in good conditions [19, 59], they fail in rare weather events (top). Lidar-only detectors, such as the same SSD model trained on projected lidar depth, might be distorted due to severe backscatter in fog or snow (center). These asymmetric distortions are a challenge for fusion methods, that rely on redundant information. The proposed method (bottom) learns to tackle unseen (potentially asymmetric) distortions in multimodal data without seeing training data of these rare scenarios.

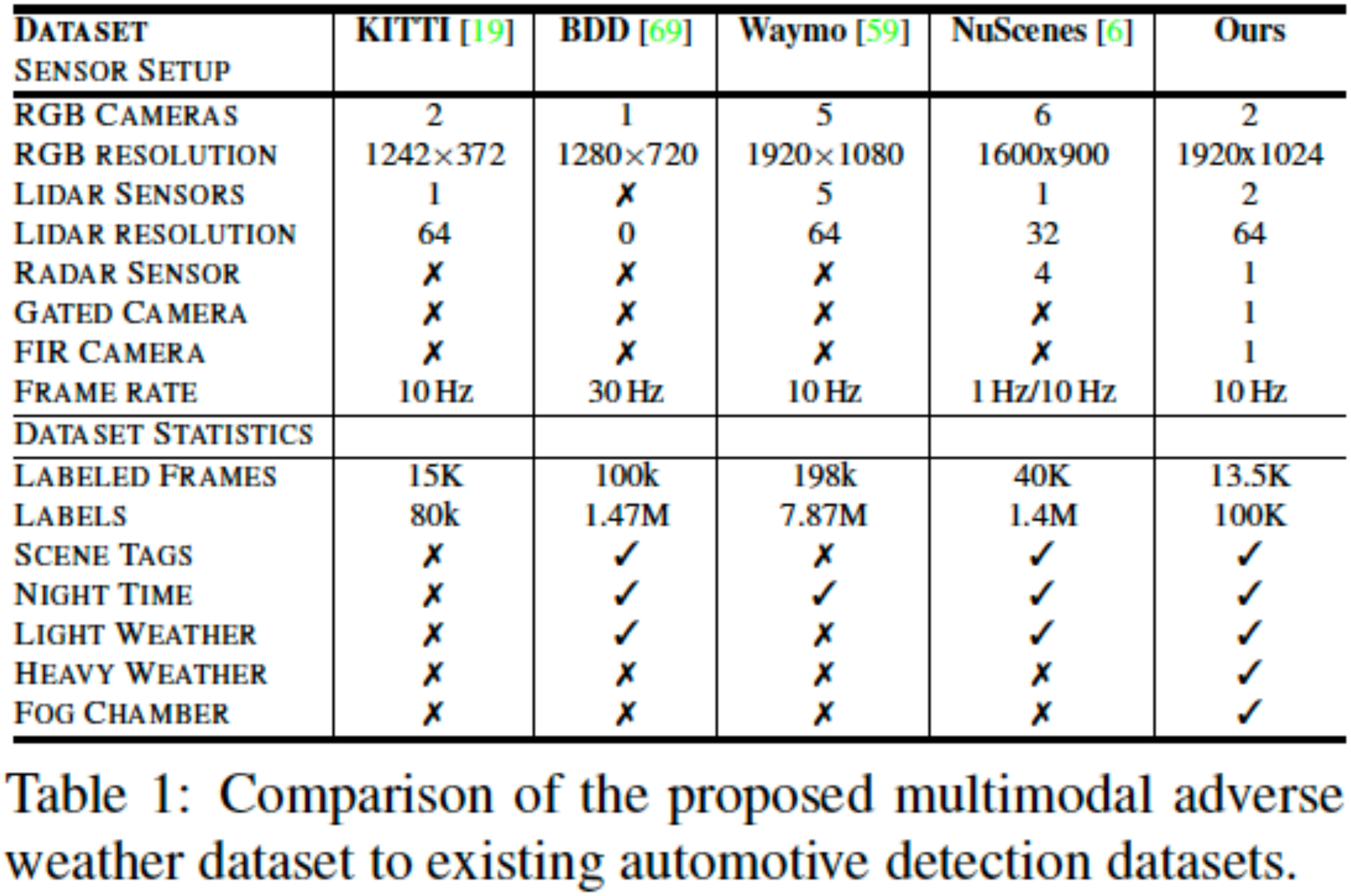
Bijelic et al 20

Gated cameras



From sensors unlimited website

Multi sensor bad weather data



DATASET SENSOR SETUP	KITTI [19]	BDD [69]	Waymo [59]	NuScenes [6]	Ours
RGB CAMERAS	2	1	5	6	2
RGB RESOLUTION	1242×372	1280×720	1920×1080	1600x900	1920x1024
LIDAR SENSORS	1	✗	5	1	2
LIDAR RESOLUTION	64	0	64	32	64
RADAR SENSOR	✗	✗	✗	4	1
GATED CAMERA	✗	✗	✗	✗	1
FIR CAMERA	✗	✗	✗	✗	1
FRAME RATE	10 Hz	30 Hz	10 Hz	1 Hz/10 Hz	10 Hz
DATASET STATISTICS					
LABELED FRAMES	15K	100k	198k	40K	13.5K
LABELS	80k	1.47M	7.87M	1.4M	100K
SCENE TAGS	✗	✓	✗	✓	✓
NIGHT TIME	✗	✓	✓	✓	✓
LIGHT WEATHER	✗	✓	✗	✓	✓
HEAVY WEATHER	✗	✗	✗	✗	✓
FOG CHAMBER	✗	✗	✗	✗	✓

Table 1: Comparison of the proposed multimodal adverse weather dataset to existing automotive detection datasets.

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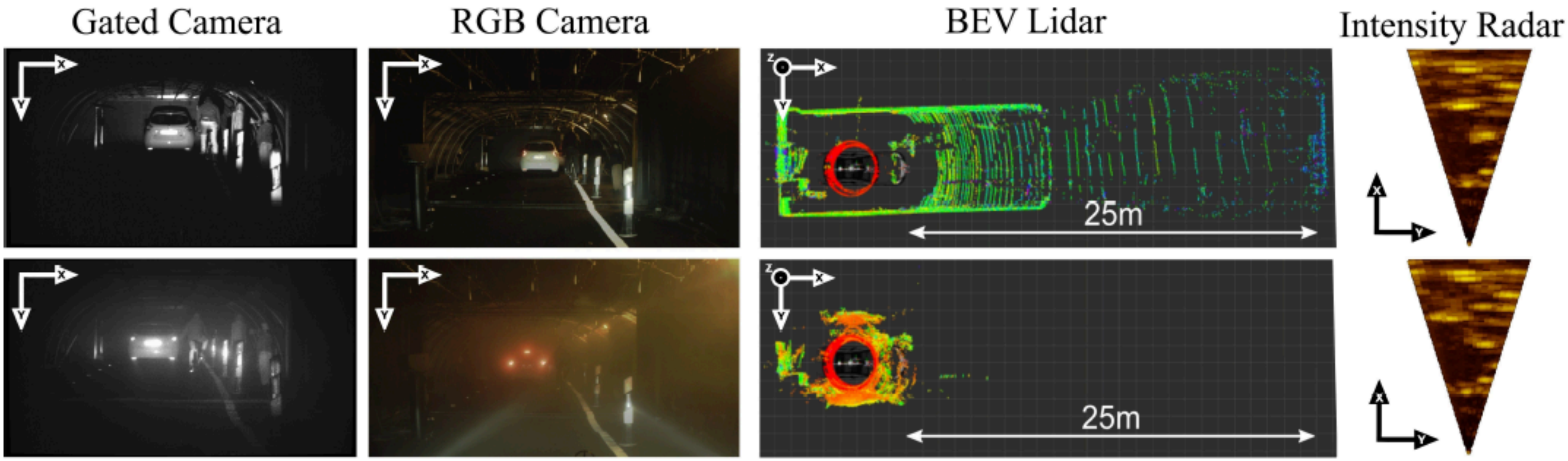


Figure 3: Multimodal sensor response of RGB camera, scanning lidar, gated camera, and radar in a fog chamber with dense fog. Reference recordings under clear conditions are shown in the first row, recordings in fog with visibility of 23 m are shown in the second row.

Bijelic et al 20

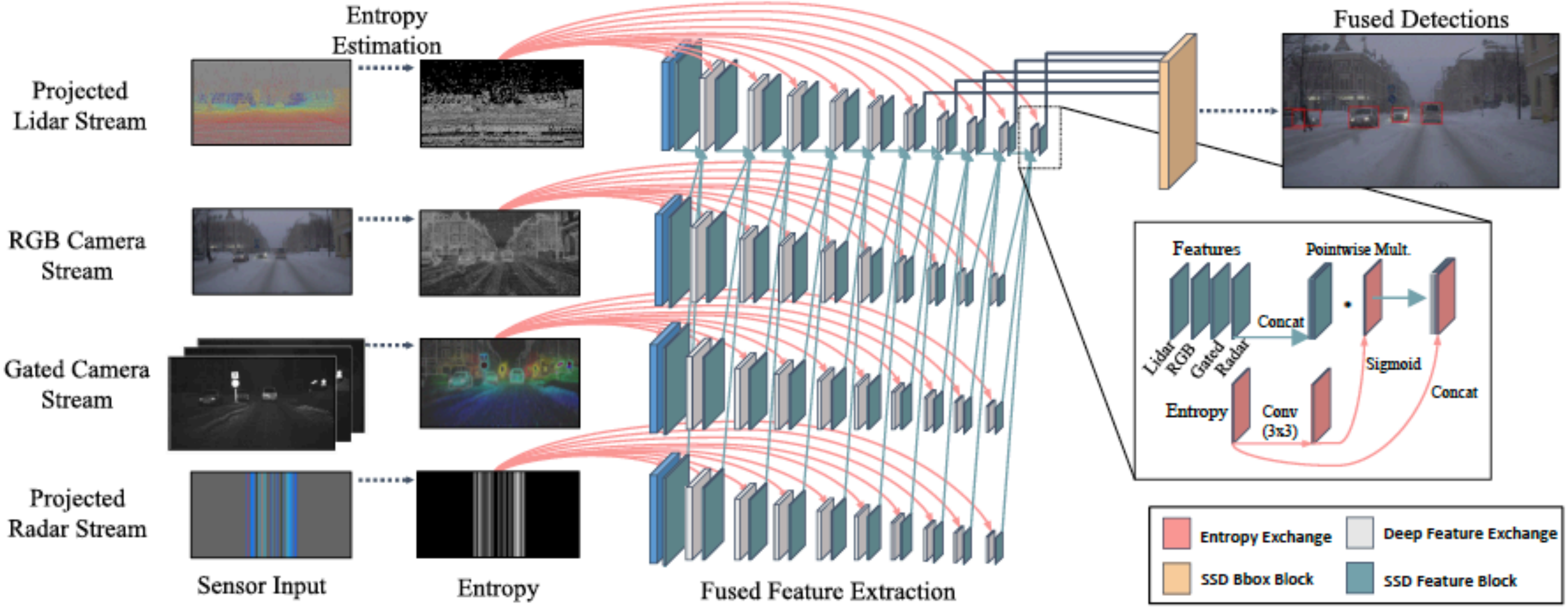


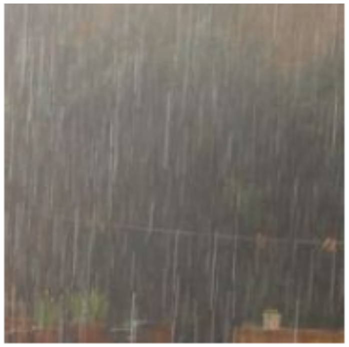
Figure 4: Overview of our architecture consisting of four single-shot detector branches with deep feature exchange and adaptive fusion of lidar, RGB camera, gated camera, and radar. All sensory data is projected into the camera coordinate system following Sec. 4.1. To steer fusion in-between sensors, the model relies on sensor entropy, which is provided to each feature exchange block *(red)*. The deep feature exchange blocks *(white)* interchange information *(blue)* with parallel feature extraction blocks. The fused feature maps are analyzed by SSD blocks *(orange)*.

Bijelic et al 20

Rain has multiple interesting effects

Blur from wet air

Puddles



Color shifts

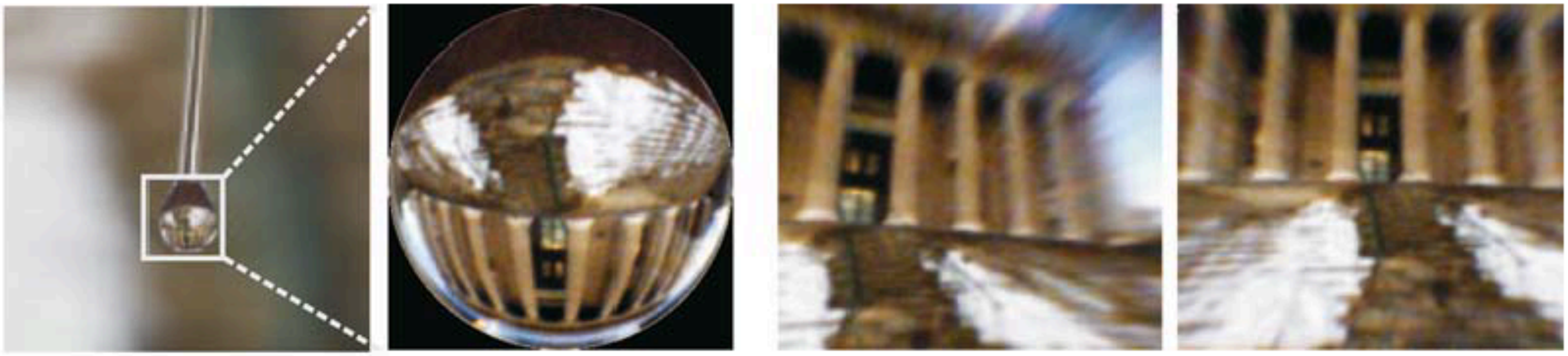
Streaks

These are often quite strongly coupled to scene geometry

Rain - multiple extrinsic phenomena,
including smoothing, raindrops, loss of saturation,
glossy/wet surfaces, etc. etc.

Rain - phenomena

Refraction causes each drop to contain a tiny image



(a) An image of a drop hanging from a pipette

(b) Perspective views created from (a)

Figure 7. Looking at the world through a raindrop. (a) An image of a drop hanging from a pipette and a magnified version. (b) Near-perspective views computed using the geometric mapping due to refraction. Note that, in the perspective views, straight lines in the scene are mapped to straight lines in the image.

Garg and Nayar 07

Backscatter

- Refraction in drops causes backscatter of headlight light
    - makes driving in rain at night harder
- Neat trick
    - (Tamburo et al 14)
    - Do not illuminate raindrops by
        - having headlights that are highly steerable (multiple micro mirrors)
        - very fast exposure with usual illumination identifies raindrops
            - too fast for driver to resolve
        - now direct light between drops

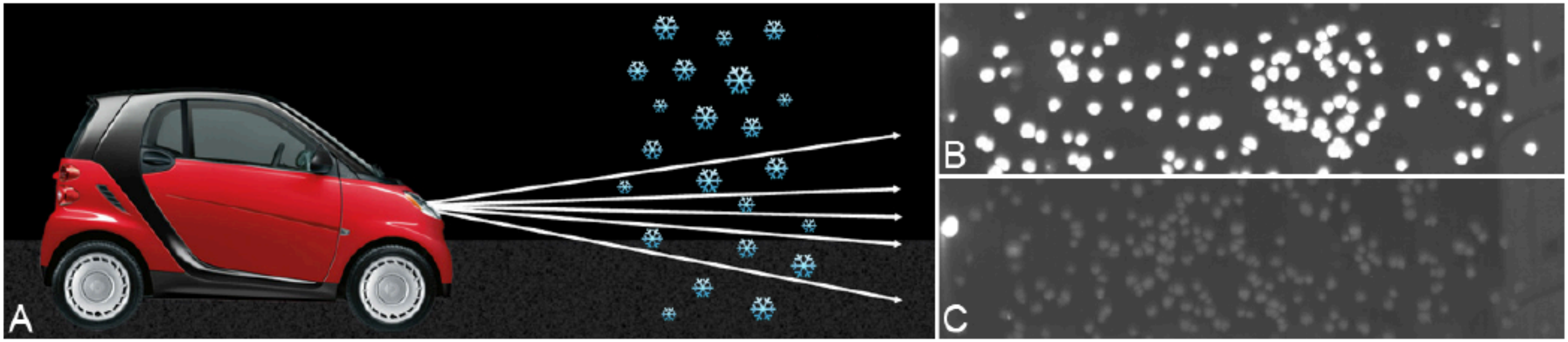
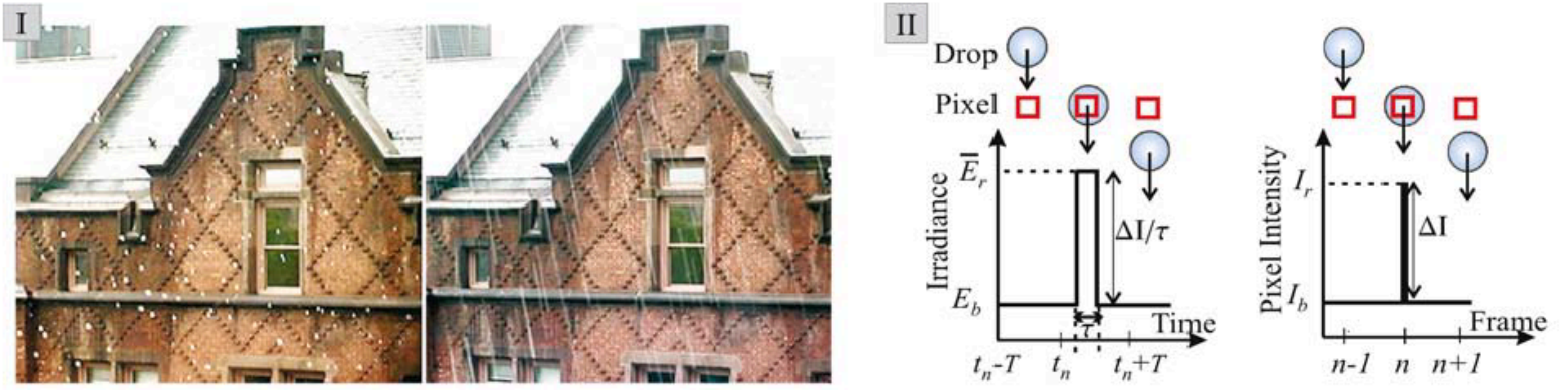


Fig. 7. A: Our headlight has unprecedented resolution over space and time so that beams of light may be sent in between the falling snow. Illustration adapted from [11]. B: Artificial snowflakes brightly illuminated by standard headlight. C: Our system avoids illuminating snowflakes making them much less visible.

Tamburo et al 14

Rain - phenomena

Drops move fast, and so create motion blur (streaks)



(a) Short exposure time (1 ms) (b) Normal exposure time (30 ms) (a) Average irradiance at a pixel (b) Intensity at a pixel

Figure 9. (I) Raindrops and motion-blur. An image of a scene taken in rain with (a) a short exposure time of 1 ms and (b) with typical exposure time of a camera (30 ms). (II) The intensities produced by motion-blurred raindrops. II (a) The average irradiance at the pixel due to the raindrop is $\bar{E}_r$ and that due to the background scene is E_b. Note that $\bar{E}_r > E_b$. The drop projects onto a pixel for time $\tau < 1.18$ ms, which is far less than the typical exposure time T of a camera. (b) Intensities of a pixel in three frames. A drop stays over the pixel in only a single frame and produces a positive intensity fluctuation of unit frame width.

Garg and Nayar 07

Rain - phenomena

Shallow free space - individual rain streaks
Deep free space - more bulk, fog-like effects

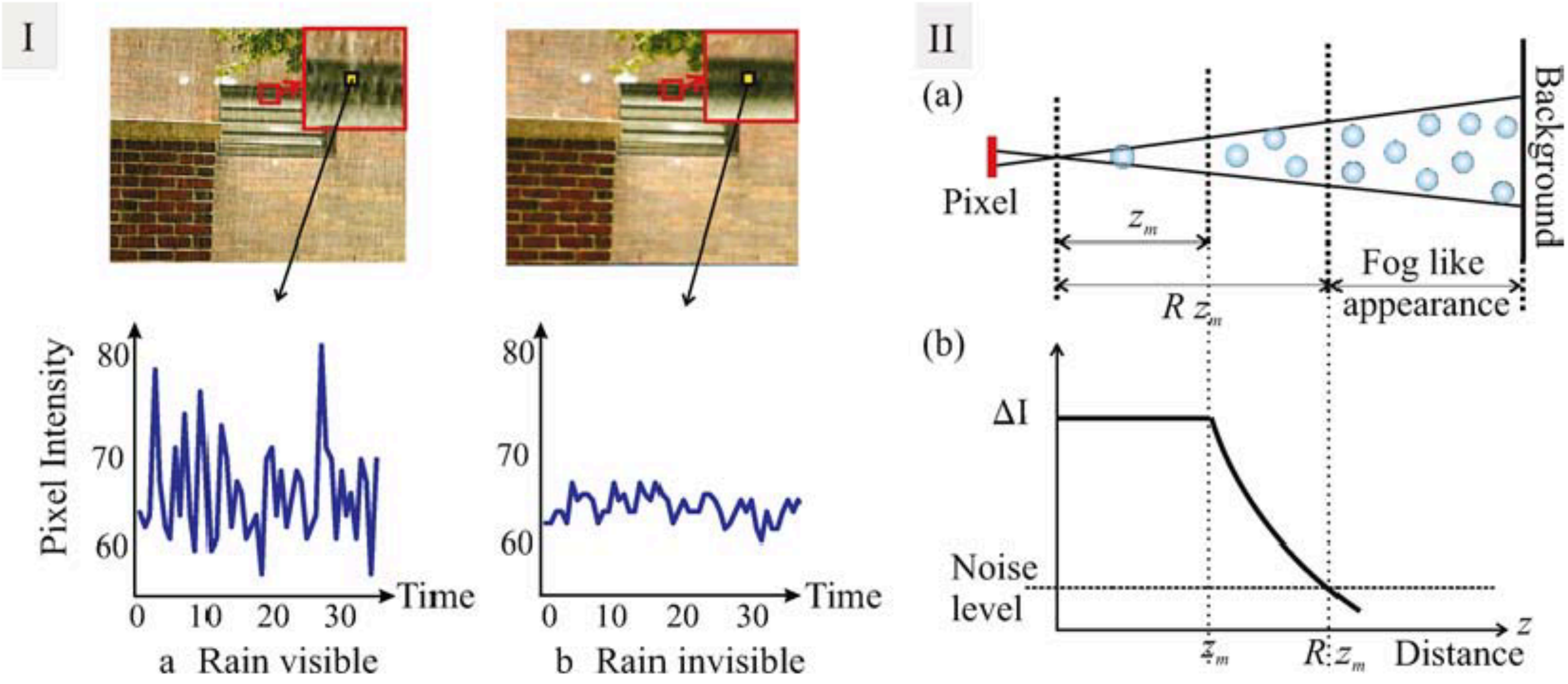
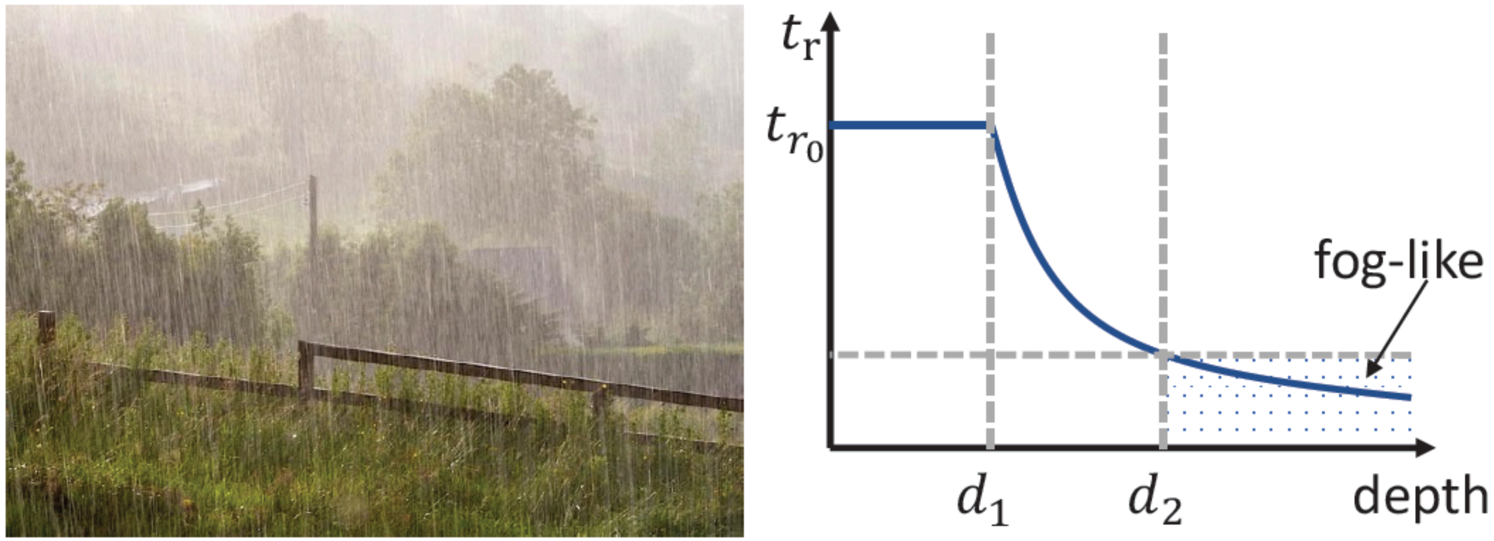


Figure 13. Dynamic weather and visibility: (I)(a) Frame from a video of a scene where rain is visible. The intensity variation due to rain is high. (b) Frame from a video of the same scene taken with camera parameters to reduce the visibility due to rain. The intensity at the same pixel shows low variance over time. (II) The change in intensity produced by a falling raindrop as a function of the drop's distance z from the camera. The change in intensity ΔI does not depend on z for drops that are close to the camera ($z < z_m$). While for raindrops far from the camera ($z > z_m$), ΔI decreases as $1/z$ and for distances greater than $R\,z_m$, ΔI is too small to be detected by the camera. Therefore, the visual effects of rain are only due to raindrops that lie close to the camera ($z < Rz_m$) which we refer to as the *rain visible region.*

Garg and Nayar 07

Rain - phenomena

Shallow free space - individual rain streaks
Deep free space - more bulk, fog-like effects

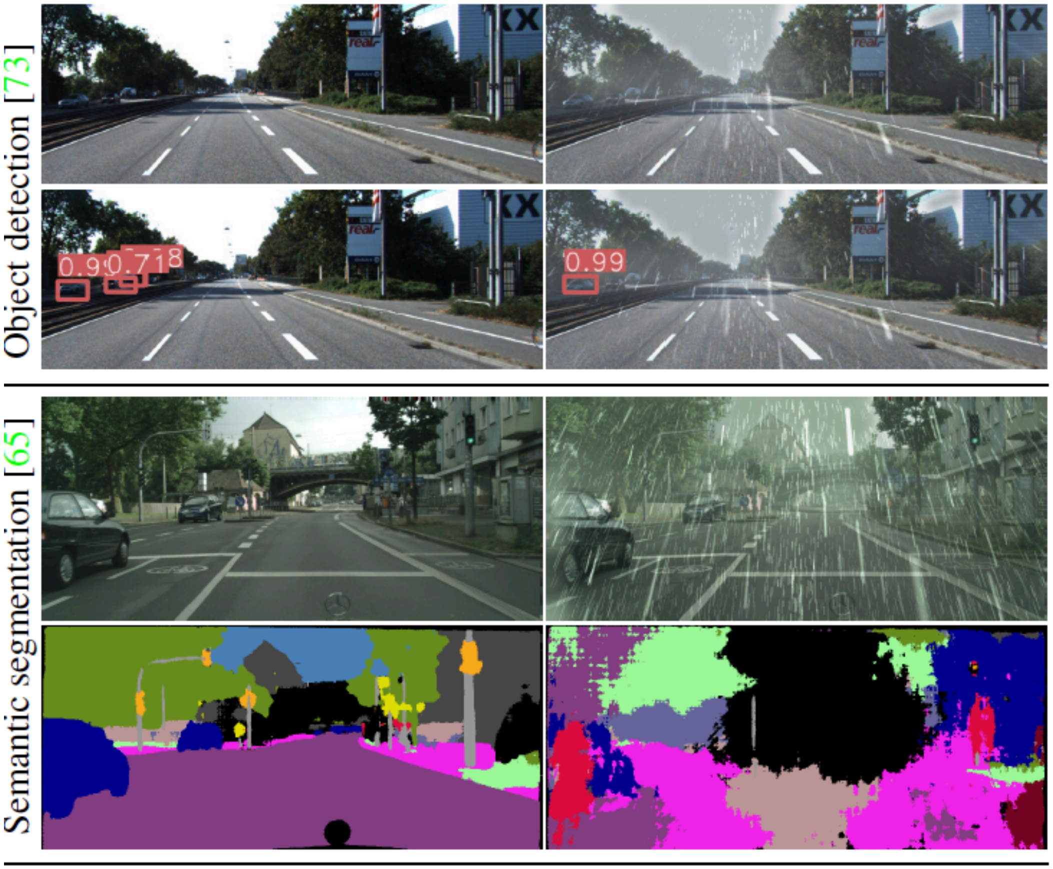


(a) input real photo (b) rain visibility & depth

Figure 1: (a) An example real photo that demonstrates the scene visibility variation with depth, and the presence of rain streaks and fog; and (b) a plot of rain streak intensity (t_r) against scene depth (d) based on the model in [13].

Hu et al 19

Simulating rain



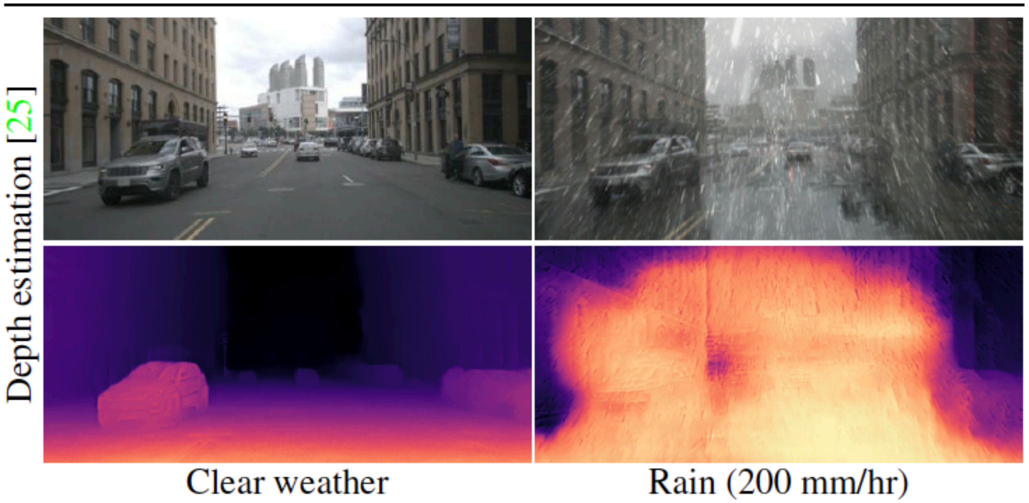


Fig. 1 Vision tasks in clear and rain-augmented images. Our synthetic rain rendering framework allows for the evaluation of computer vision algorithms in challenging bad weather scenarios. We render physically-based, realistic rain on images from the KITTI [23] (rows 1-2) and Cityscapes [13] (rows 3-4) datasets with object detection from mx-RCNN [73] (row 2), semantic segmentation from ESPNet [65] (row 4). We also present a combined data-driven and physic-based rain rendering approach which we apply to the nuScenes [9] (rows 5-6) dataset with depth estimation from Monodepth2 [25] (row 6). All algorithms are quite significantly affected by rainy conditions.

Tremblay et al 20

Simulating rain - issues

- Near field:
    - drops are bright, discrete, likely ballistic motion
        - how bright?
        - where?
        - how moving?
    - likely air is “wet”
        - so some fogging, depending on depth
- Far field:
    - fog like effects
- So we need to know
    - depth, environment map, falling drops, camera movement

Simulating rain

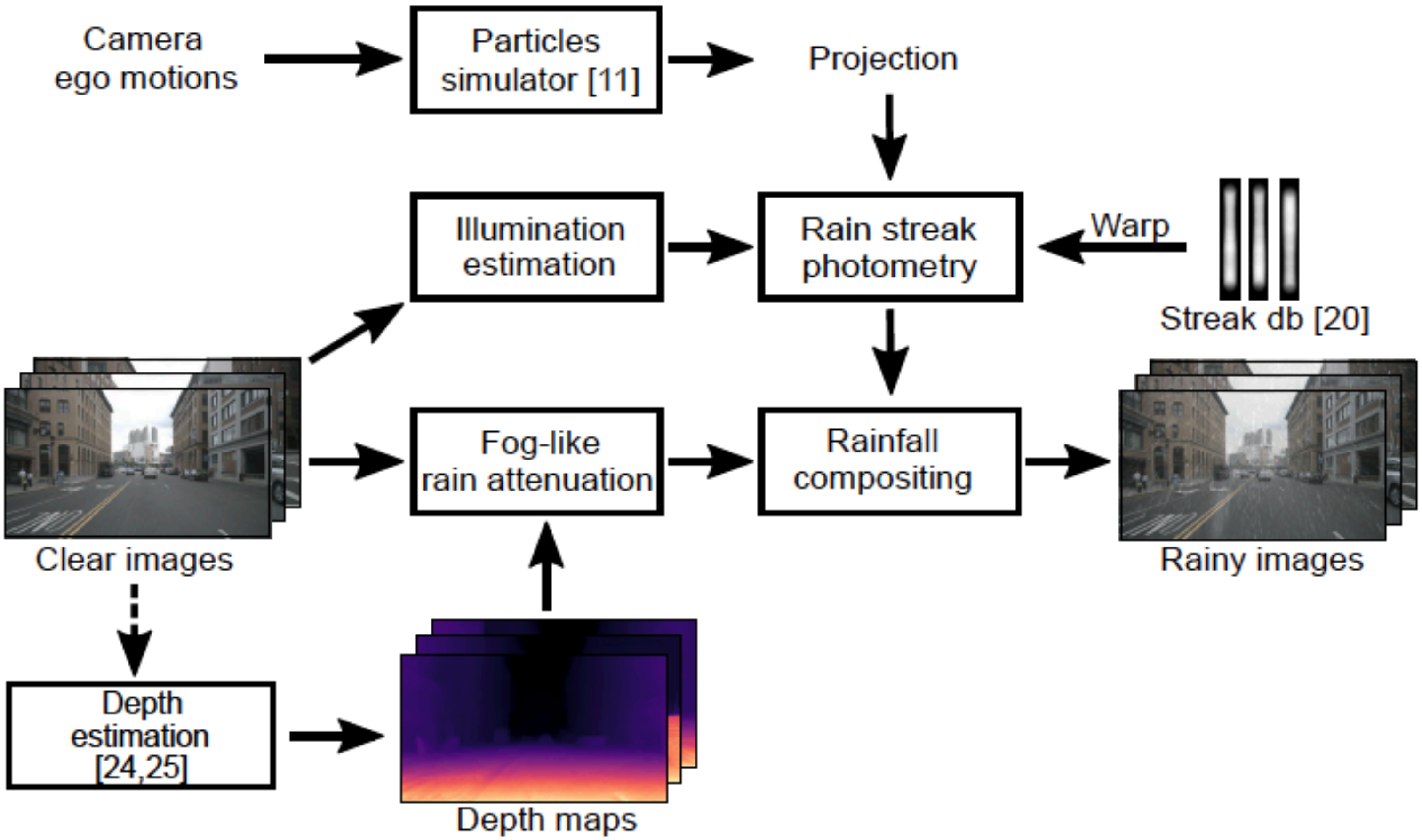
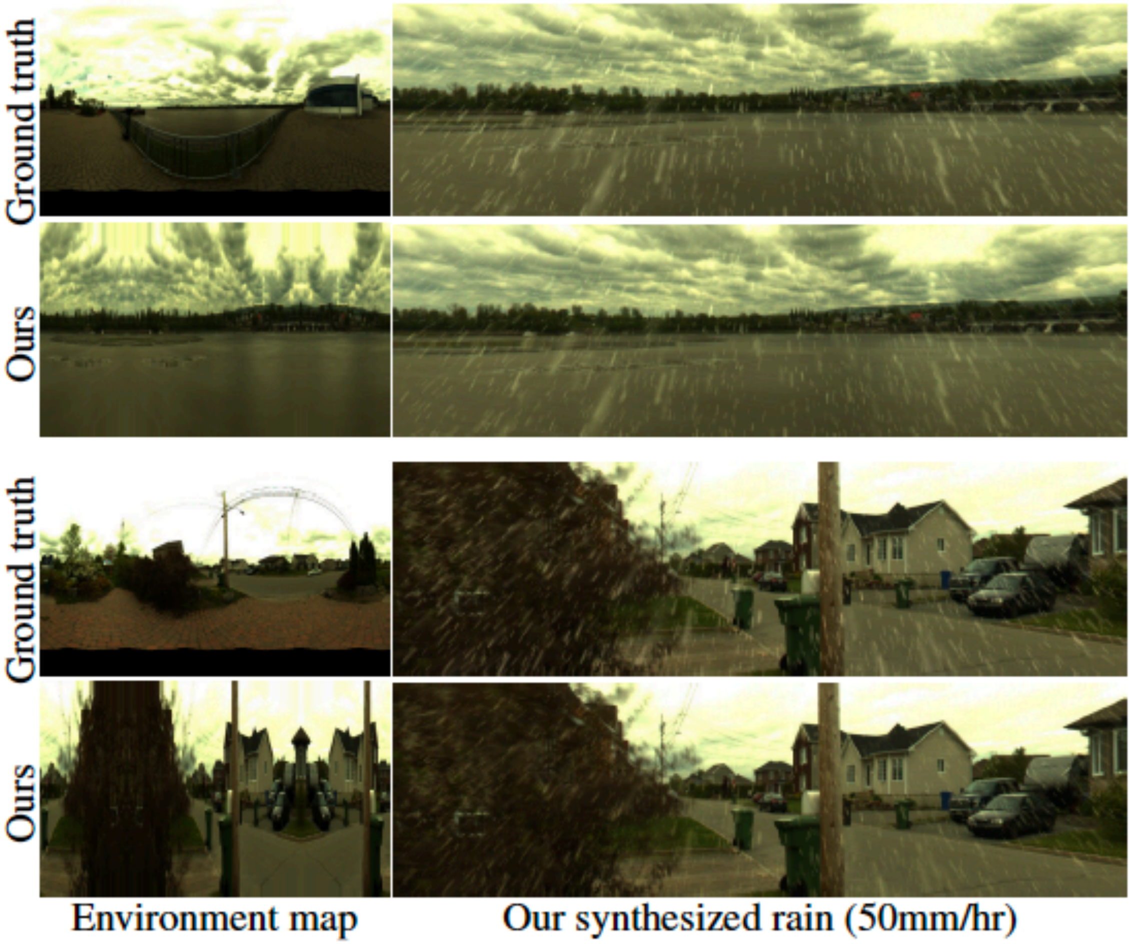


Fig. 2 Physics-Based Rendering for rain augmentation. We use particles simulation together with depth and illumination estimation to render arbitrarily controlled rainfall on clear images.

Tremblay et al 20

Simulating rain



Minor errors in environment map have no real effect on rain appearance

Tremblay et al 20

Simulating rain

- Trick:
  - rain causes color effects, specular effects etc.
    - CycleGAN is good at this, but bad at streaks
    - Physics based simulation is bad at this but good at streaks

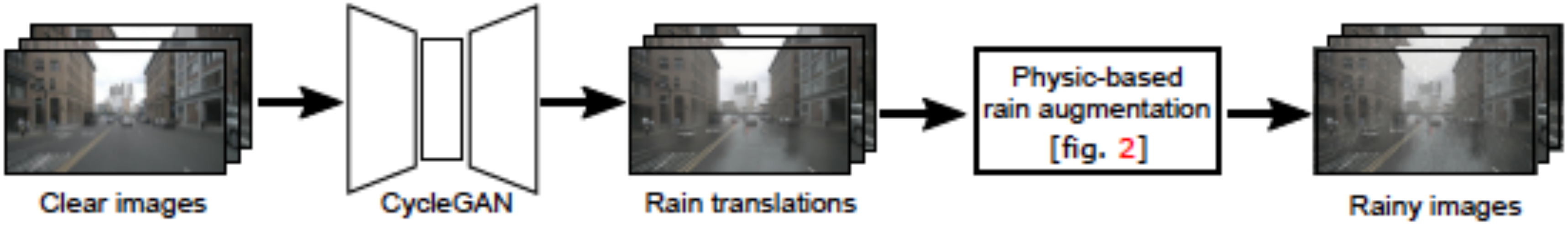
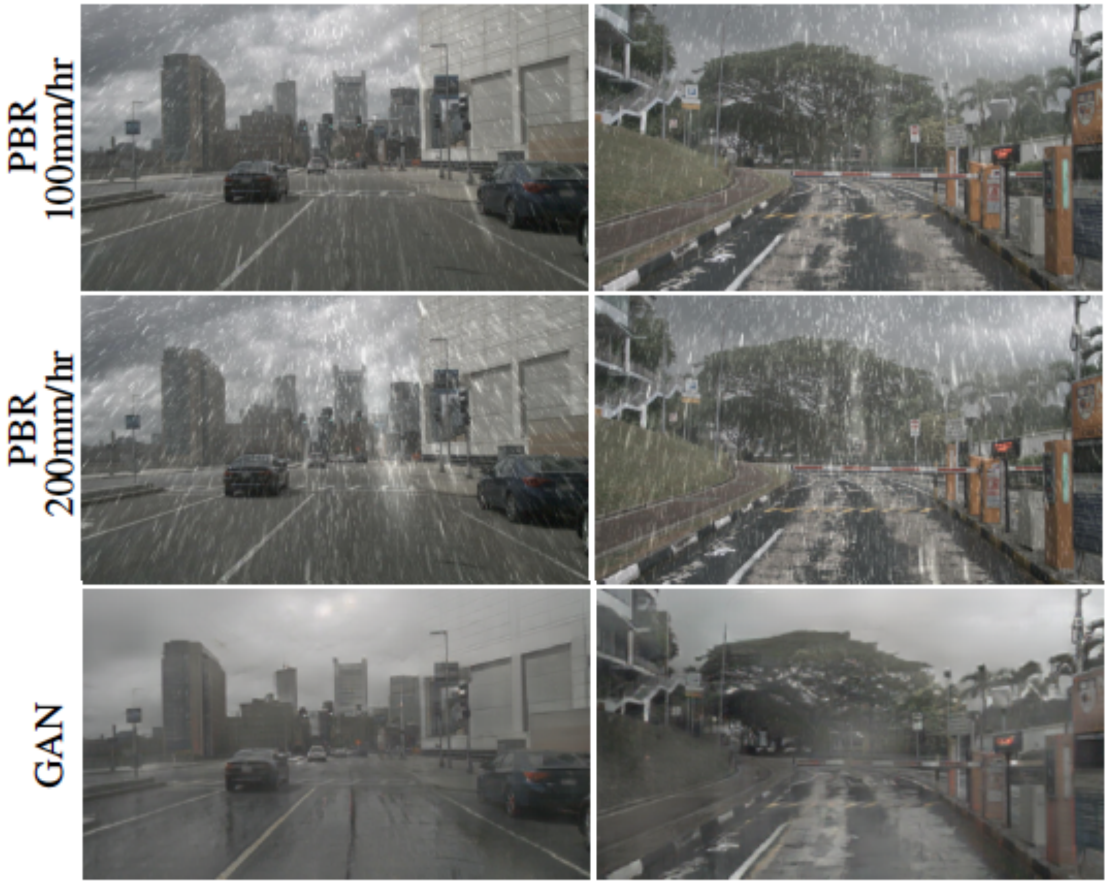


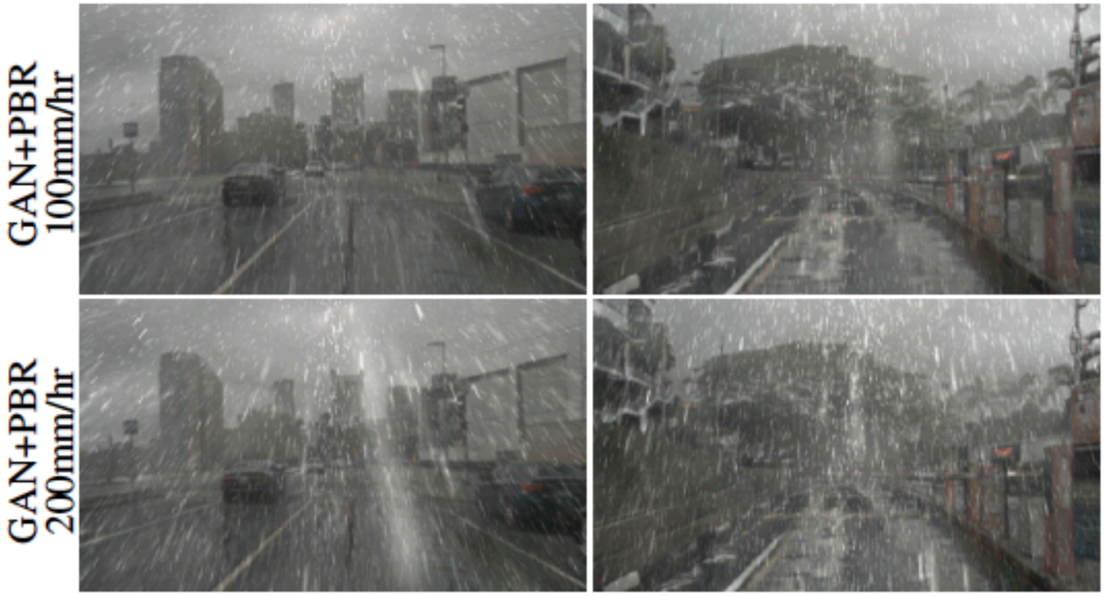
Fig. 5 GAN+PBR rain-augmentation architecture. In this hybrid approach, clear images are first translated into rain with CycleGAN [83] and subsequently augmented with rain streaks with our PBR pipeline (see fig. 2).

Tremblay et al 20

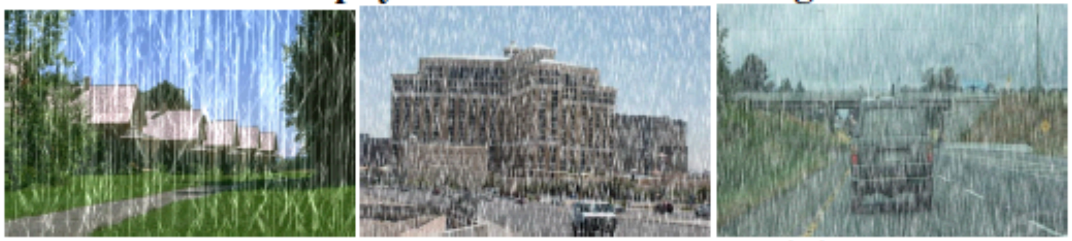


Tremblay et al 20

Rain photographs



Other physic-based rain rendering



rain100H [74] rain800 [79] did-MDN [78]

Tremblay et al 20

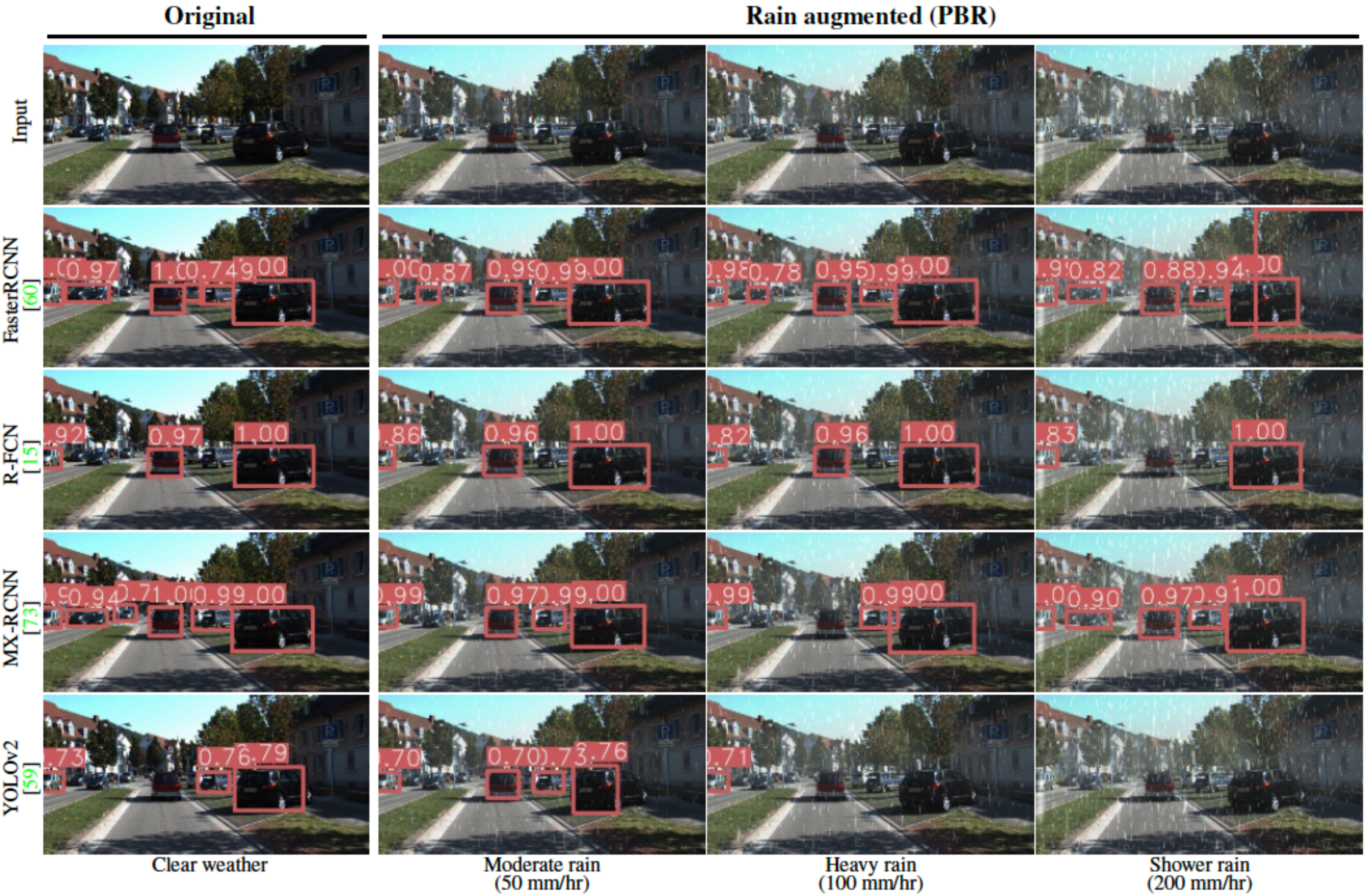


Fig. 11 Object detection on PBR rain augmentation of KITTI. From left to right, the original image (clear) and three PBR augmentations with varying rainfall rates. Images are cropped for visualization.

Tremblay et al 20

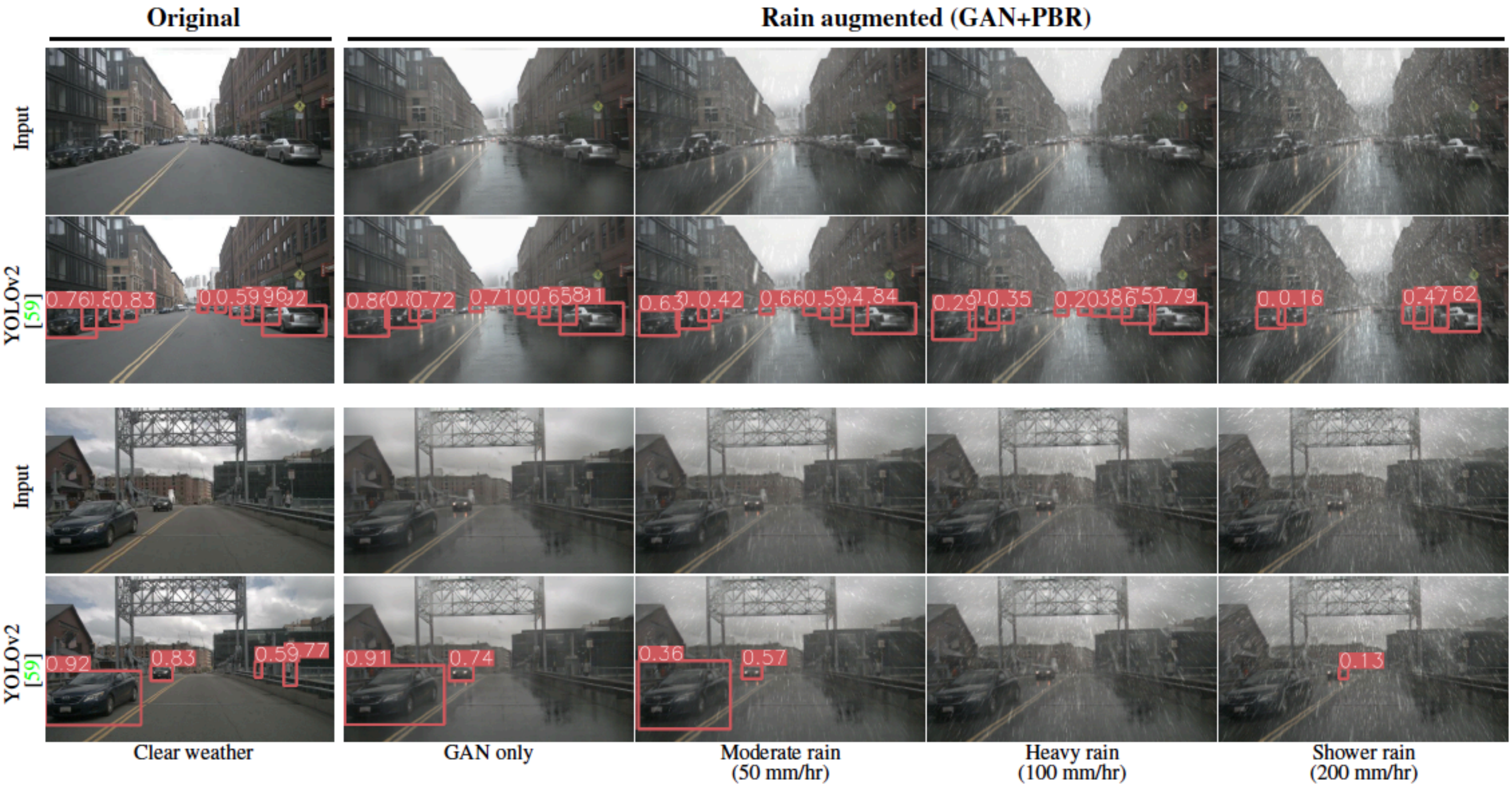


Fig. 15 Object detection on our GAN+PBR augmented nuScenes. From left to right, the original image (clear), the GAN augmented image and three GAN+PBR images.

Tremblay et al 20

Deraining - strategies

- Essentially
    - obtain images with/without rain (with rain by synthetic)
    - train network to reproduce without rain image from with rain
    - starts with Eigen et al 13

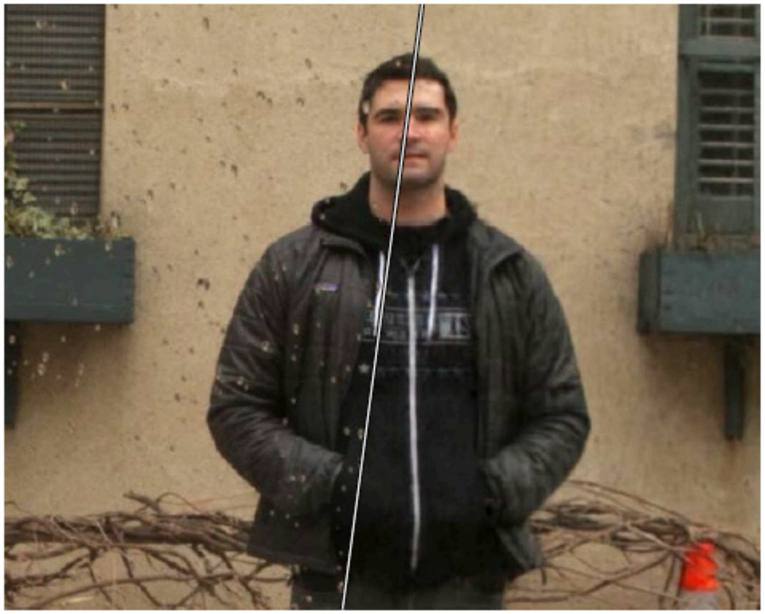
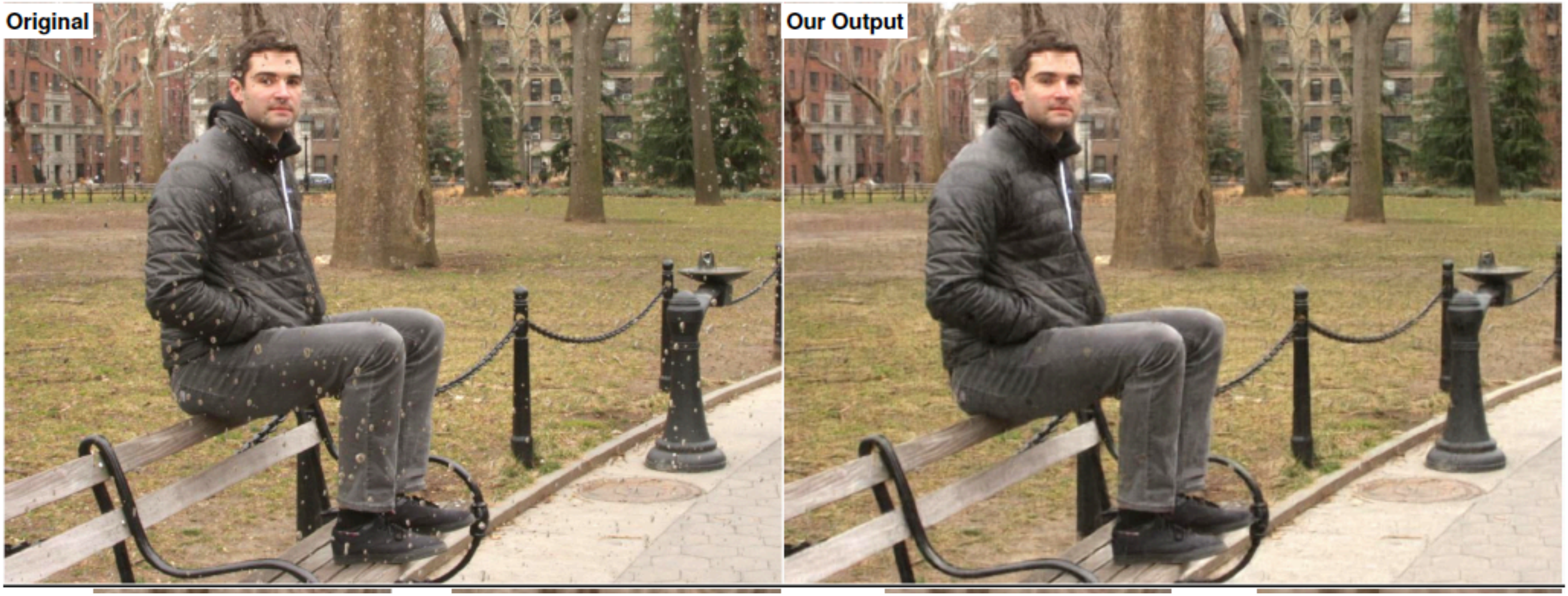


Figure 1. A photograph taken through a glass pane covered in rain, along with the output of our neural network model, trained to remove this type of corruption. The irregular size and appearance of the rain makes it difficult to remove with existing methods. This figure is best viewed in electronic form.

From Eigen et al. 13

Rainy windows



From Eigen et al. 13

Rain streaks

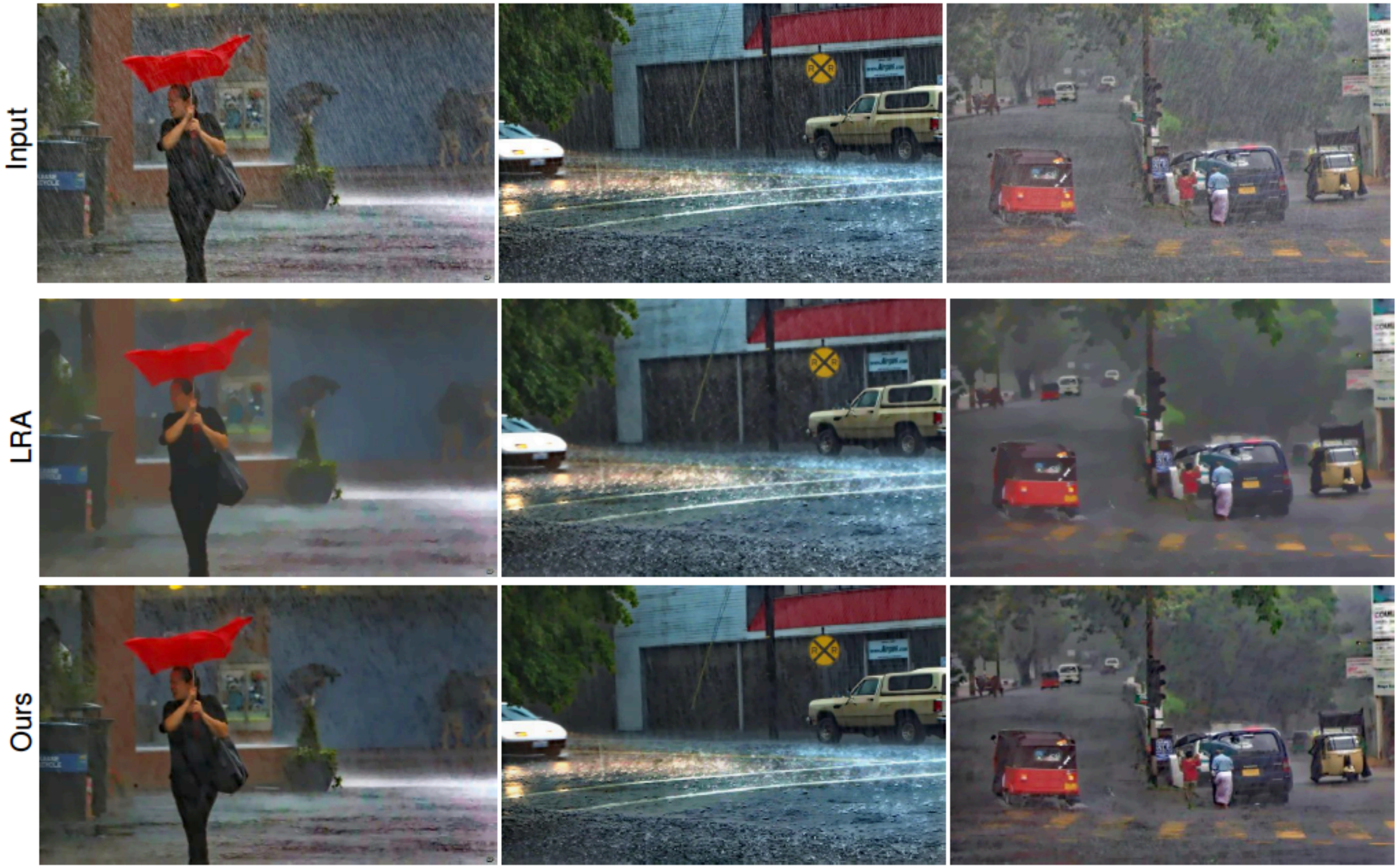


Figure 7: Visual comparison of different rain streak removal methods on real example images.

Li et al 16

Streaks

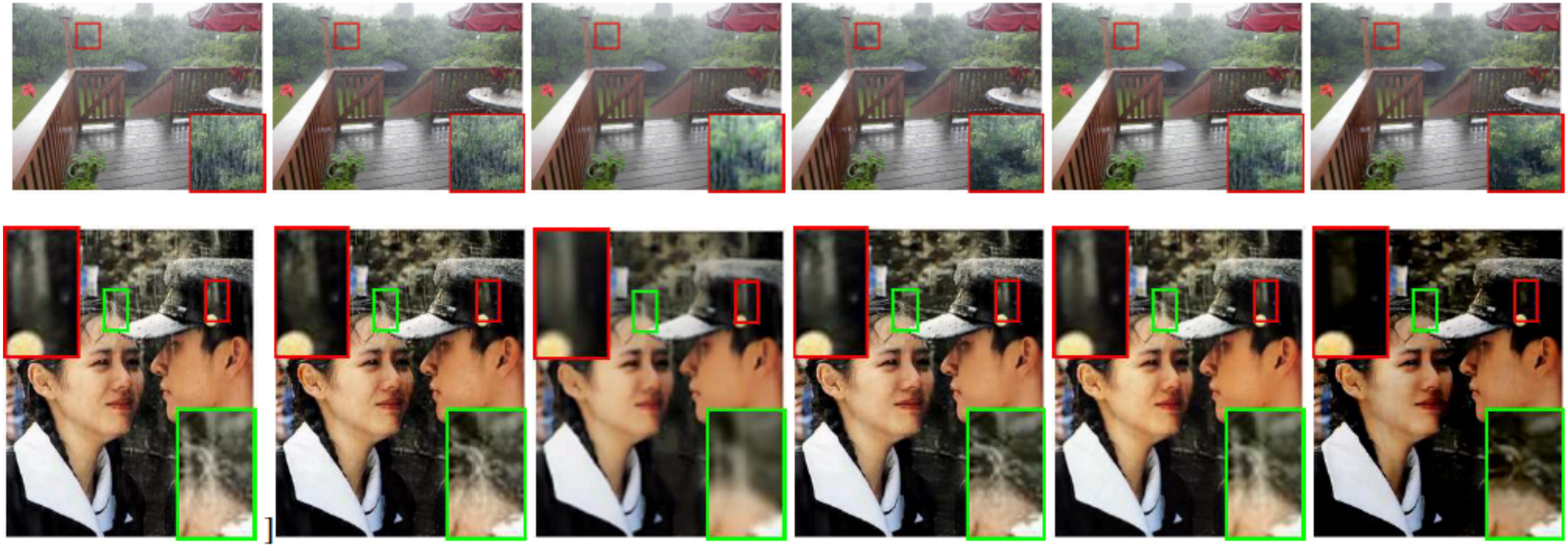


Figure 6: Real rain streaks removal experiments under different scenarios. From left to right are input image, results of DSC[26], LP [24], CNN [10], DID-MDN[31] and ours. Demarcated areas in each image are amplified at a 3 time larger scale.

Wei et al 19

Both rain streaks and haze

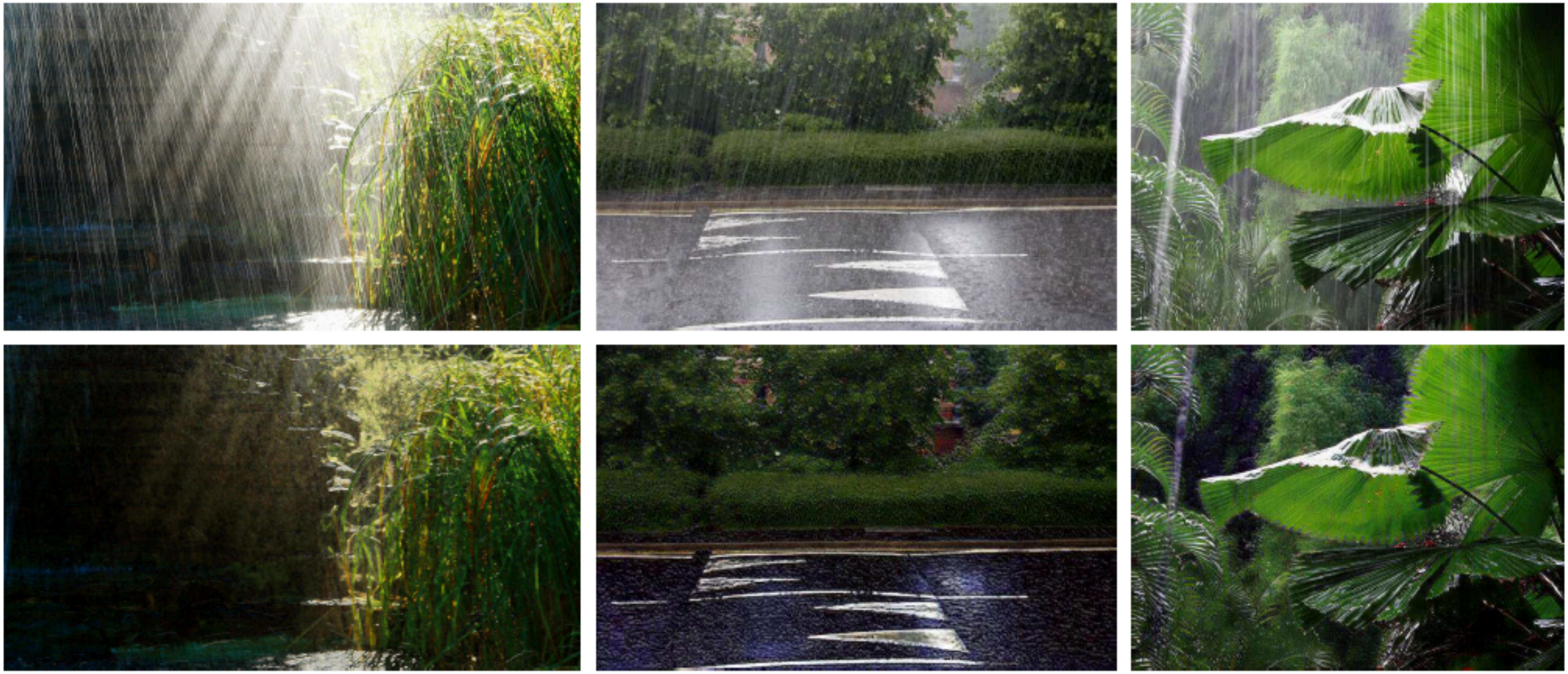
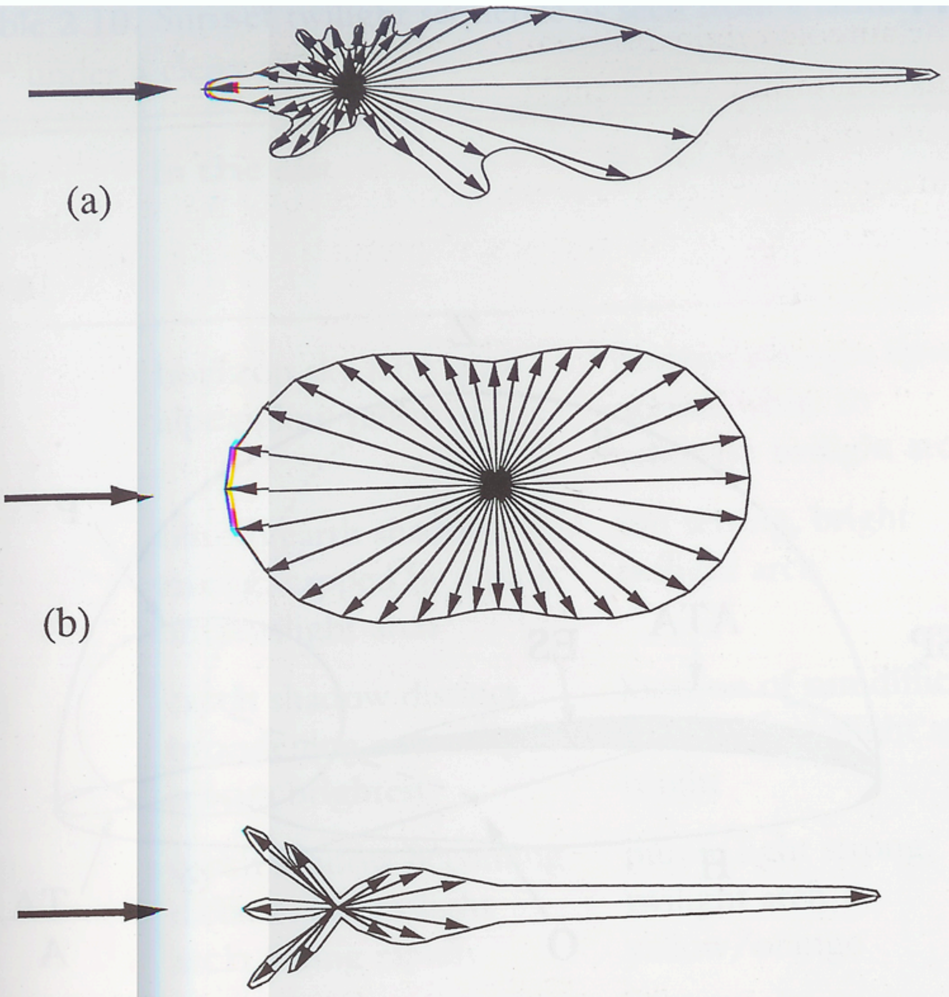


Figure 7. Examples of JORDER-R-DEVEIL on heavy rain (left two images) and mist images (right two images).

Yang et al 17

Scattering profiles can be complicated



Big (dust, smoke)

Air molecules

Water drops

Fig. 2.7C Scattering patterns for different particles. (a) Large irregular particles, like those comprising dust and smoke, are irregular in the sense that they are not symmetric. They do, however, have a strong forward scattering peak and a smaller though still pronounced backscattering peak. (b) Air molecules have a scattering function that is symmetric fore and aft: they scatter the same amount of light in both the forward and backward directions but lack both the forward and backscattering peak. (c) Large water drops have a strong forward and backscattering peak and also show strong enhancements at the primary and secondary rainbow angles.

From Lynch and Livingstone, Color and Light in Nature

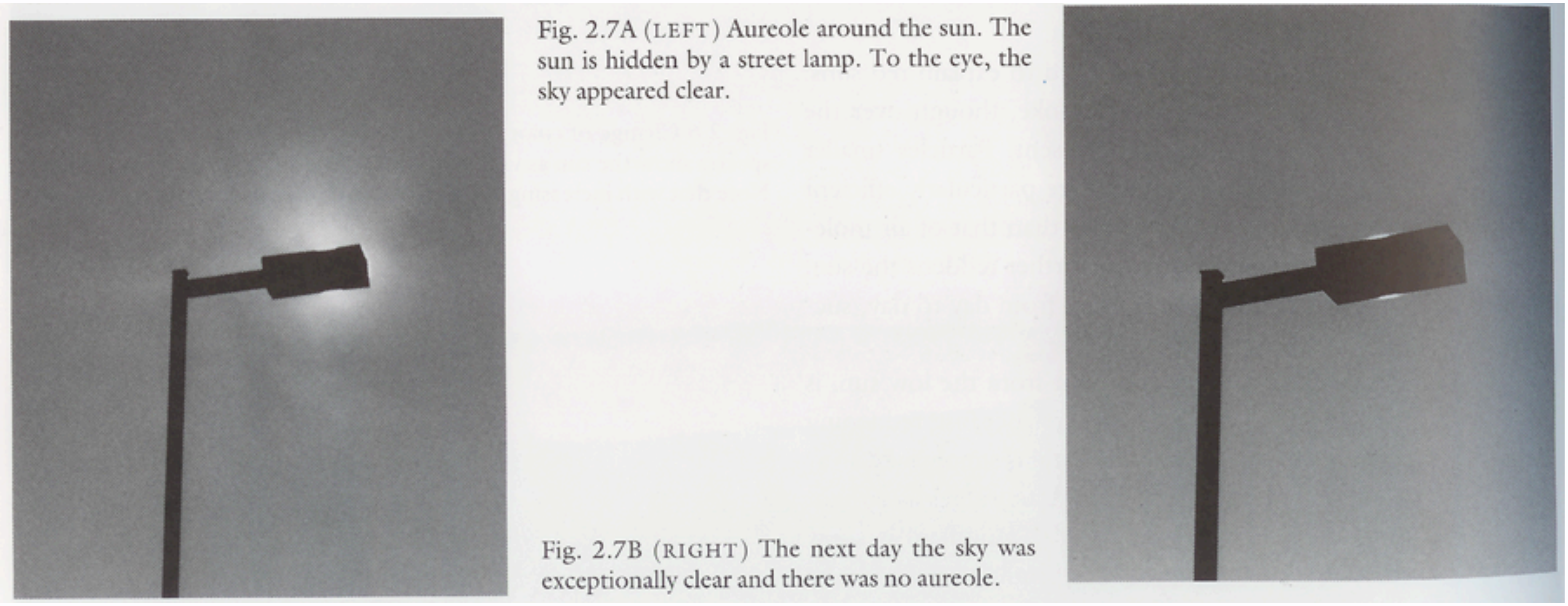
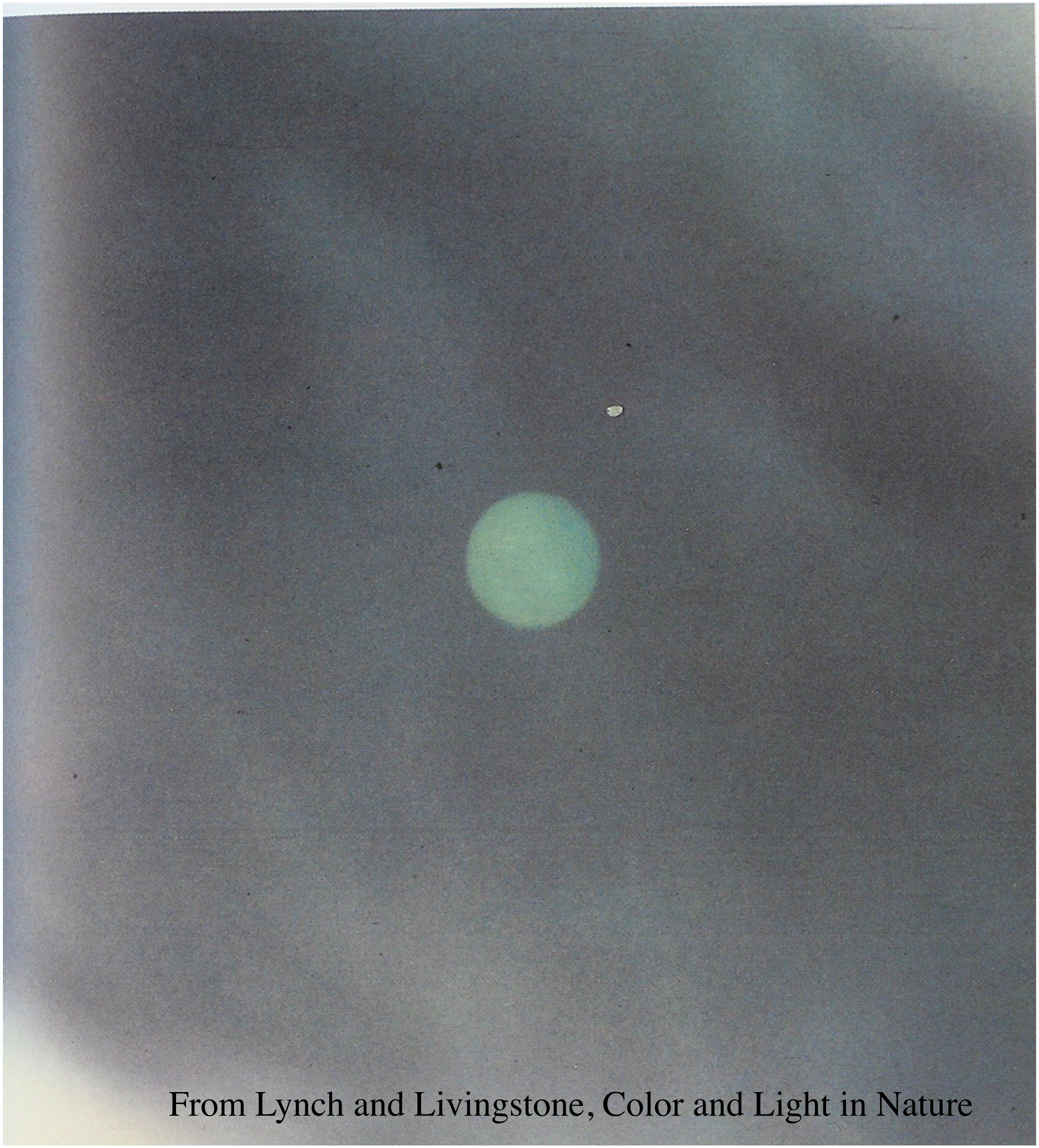


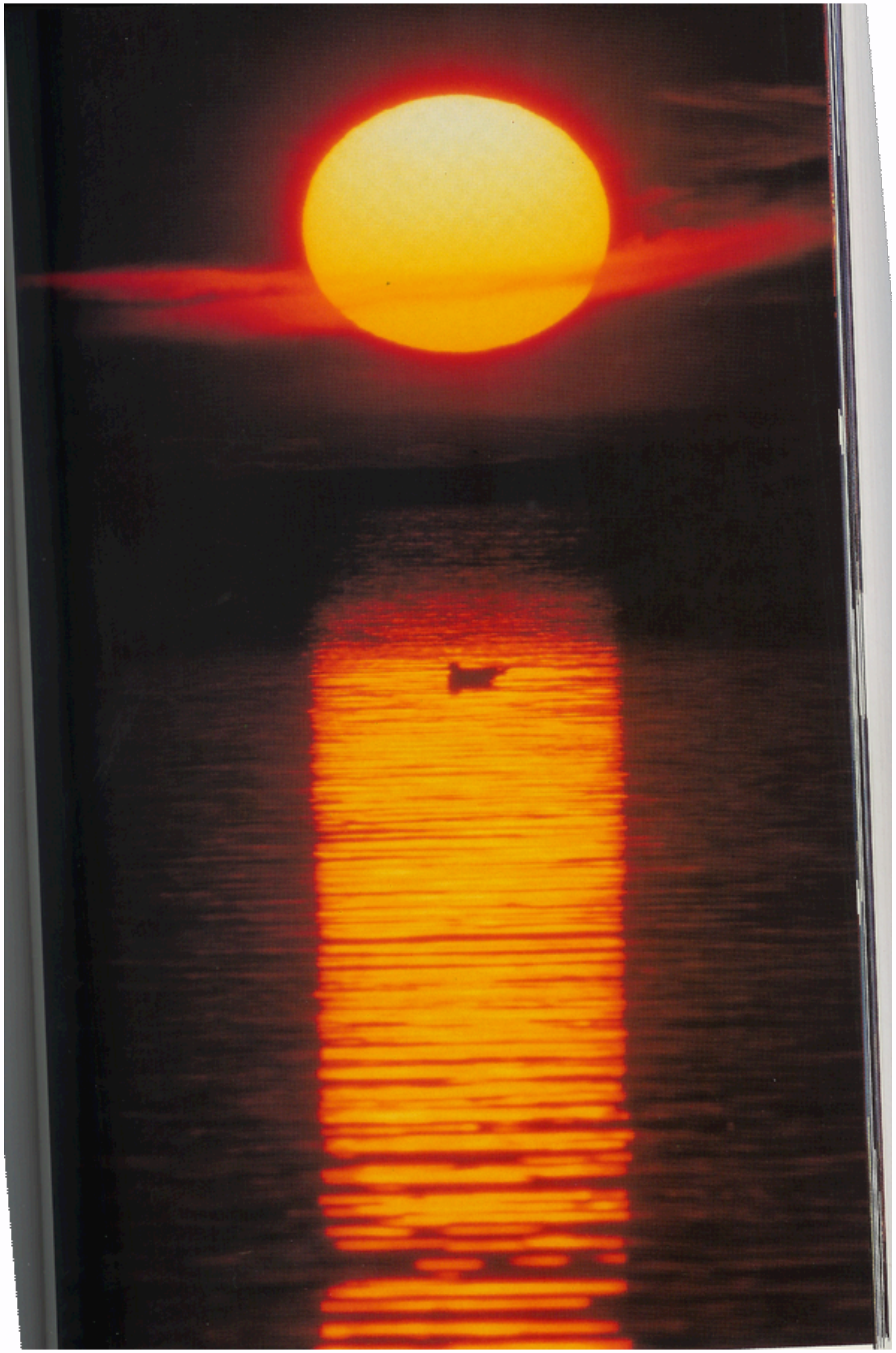
Fig. 2.7A (LEFT) Aureole around the sun. The sun is hidden by a street lamp. To the eye, the sky appeared clear.

Fig. 2.7B (RIGHT) The next day the sky was exceptionally clear and there was no aureole.

From Lynch and Livingstone, Color and Light in Nature

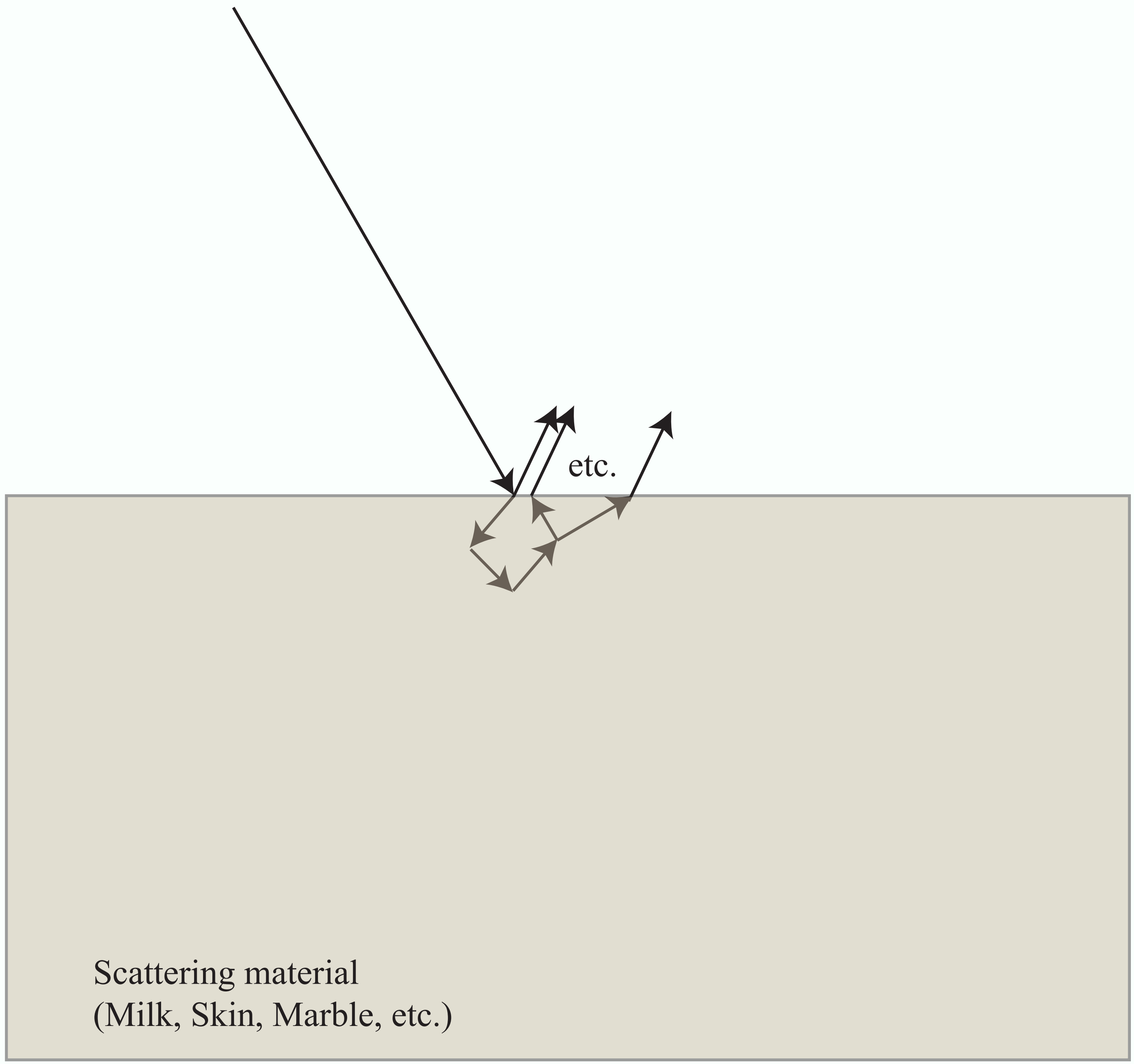


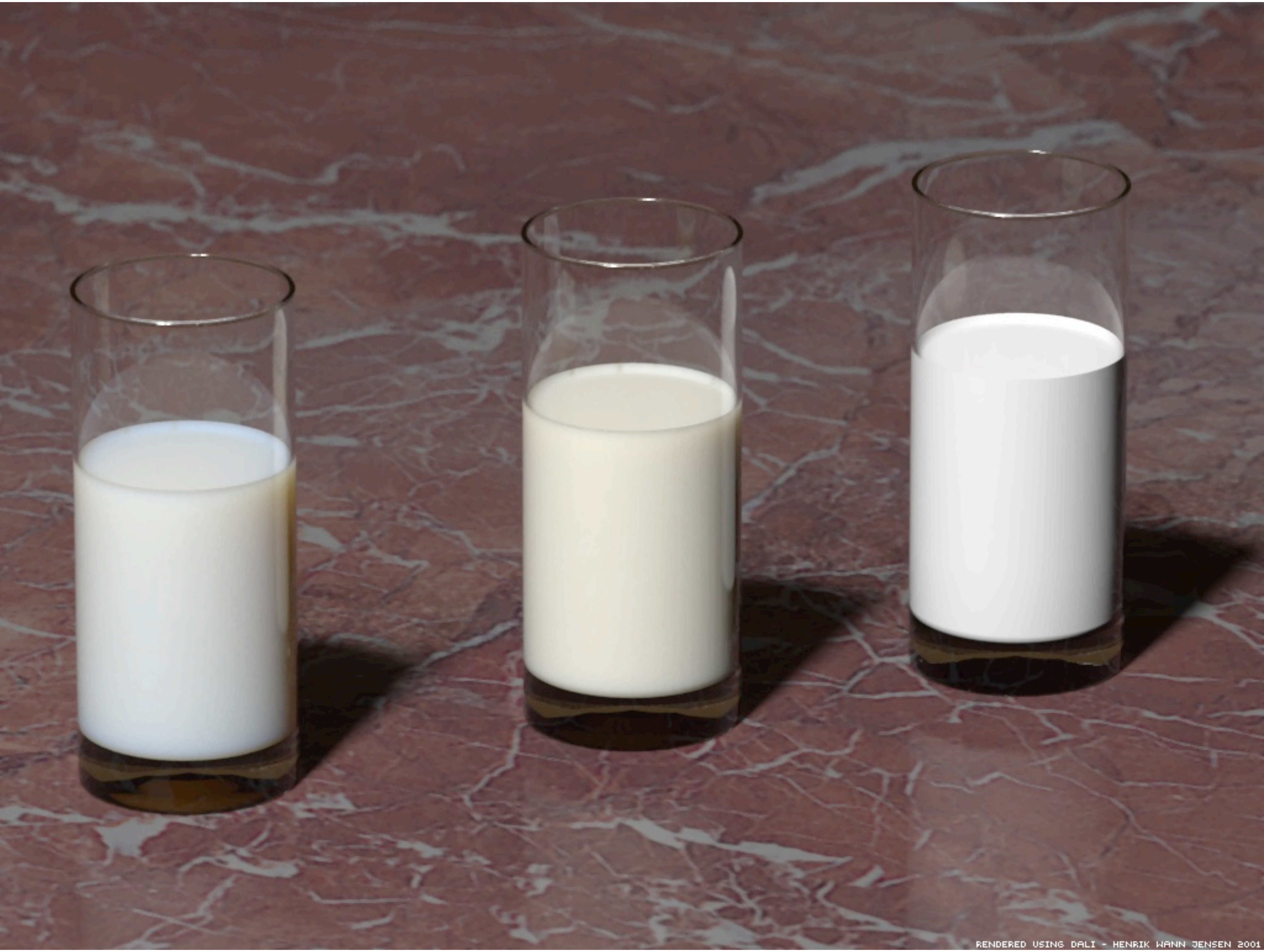
From Lynch and Livingstone, Color and Light in Nature



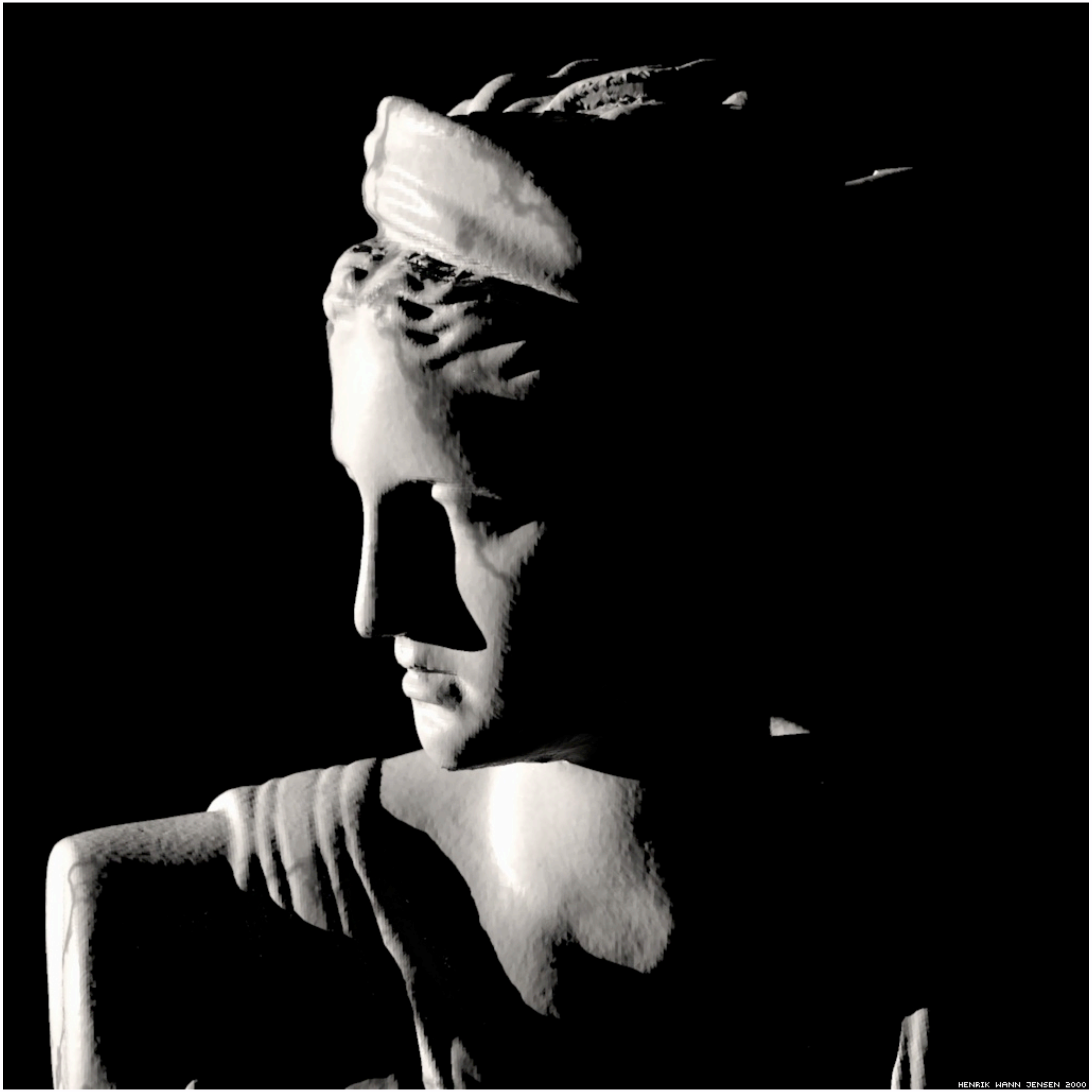
Minnaert, Light and Color in the outdoors

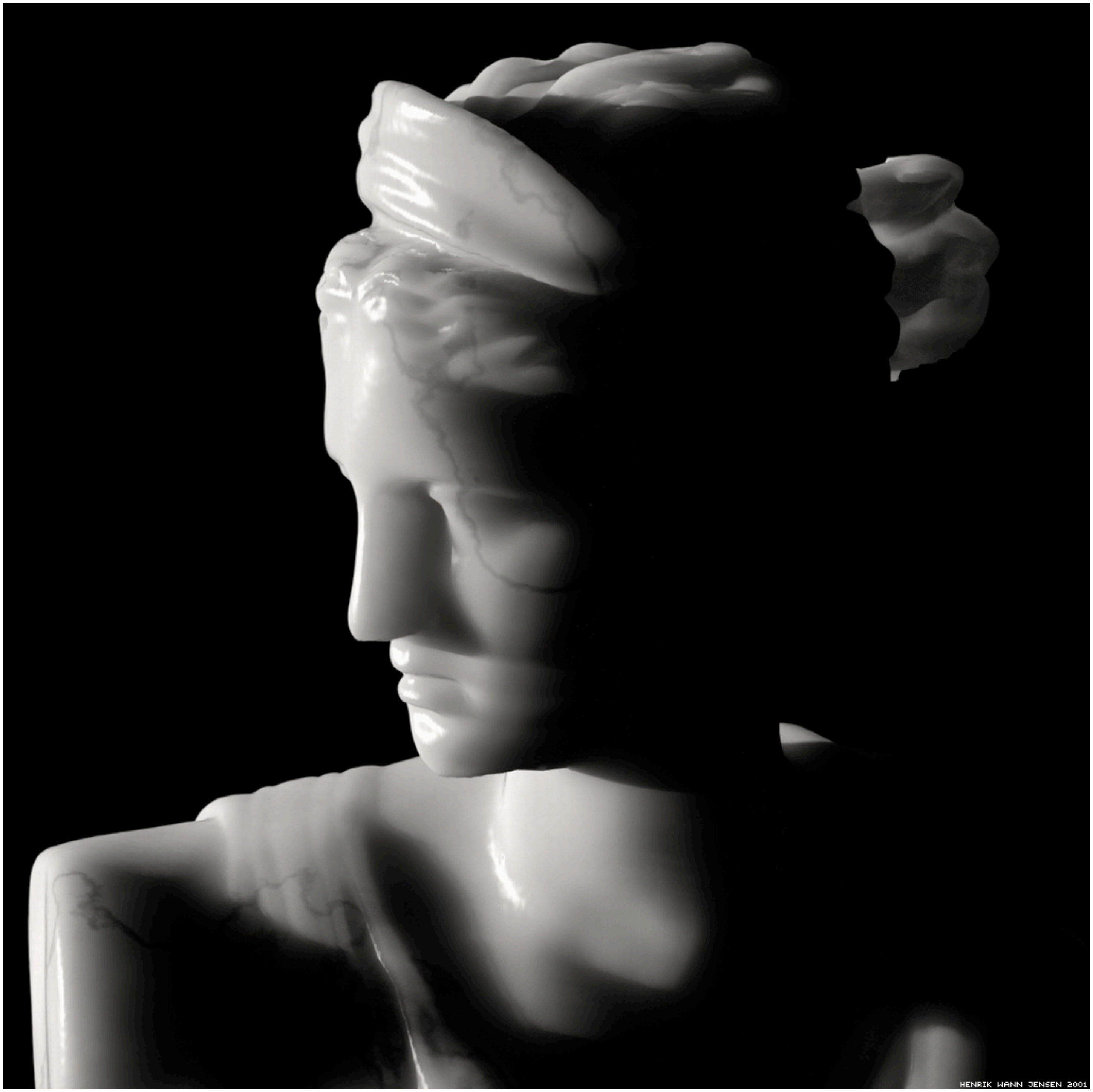
Notice flattened sun,
sparkles

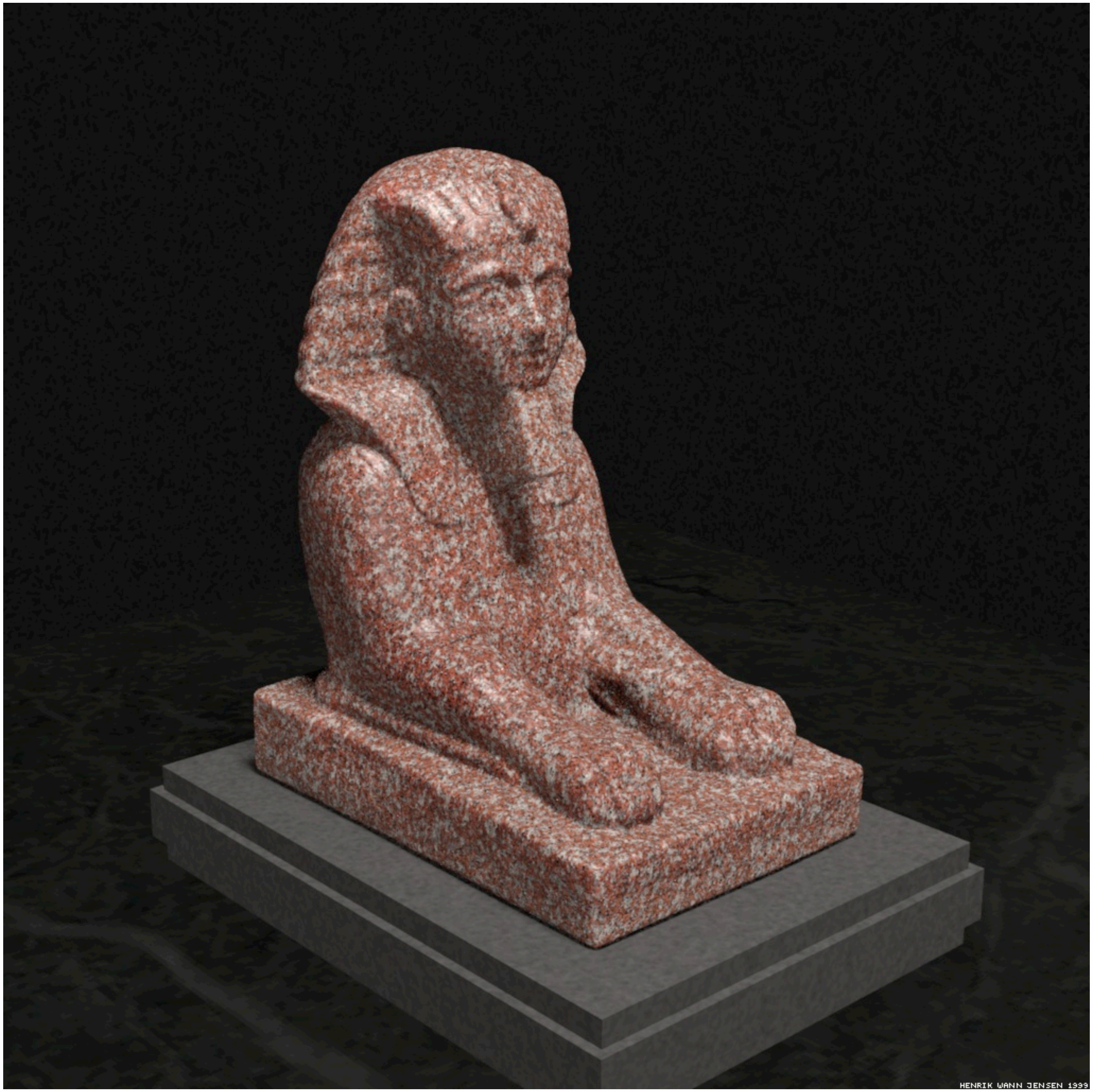

etc.
Scattering material
(Milk, Skin, Marble, etc.)



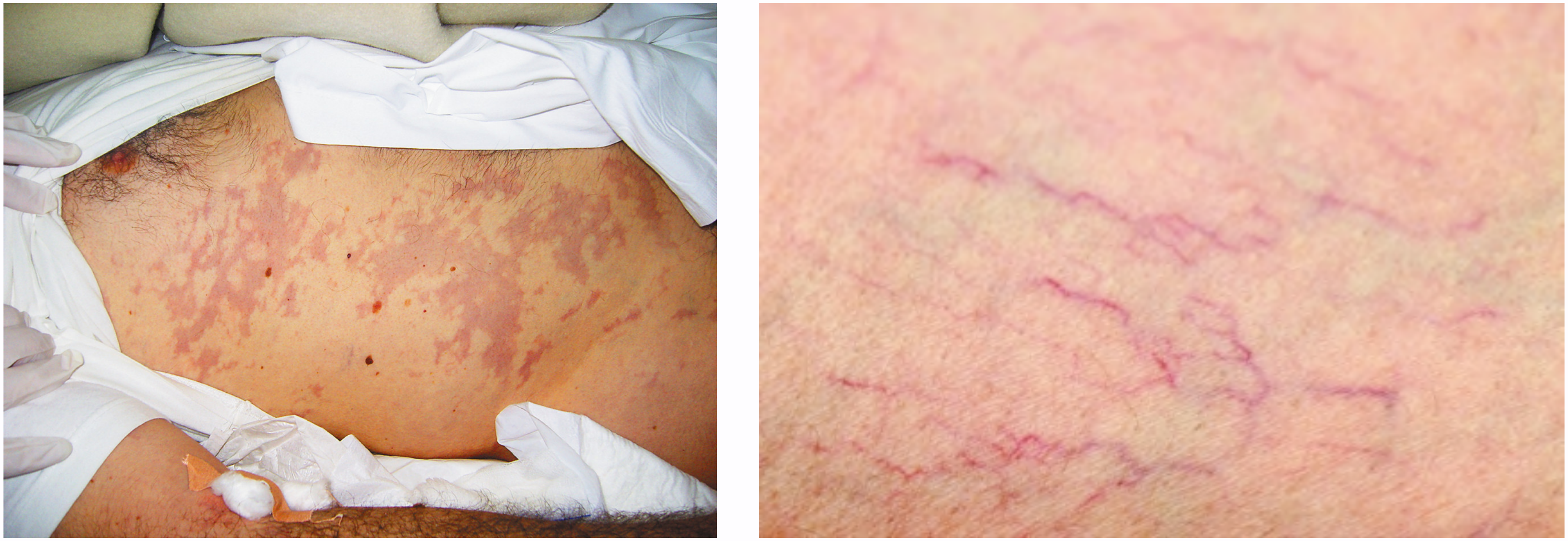
RENDERED USING DALI - HENRIK WANN JENSEN 2001


HENRIK WANN JENSEN 2000

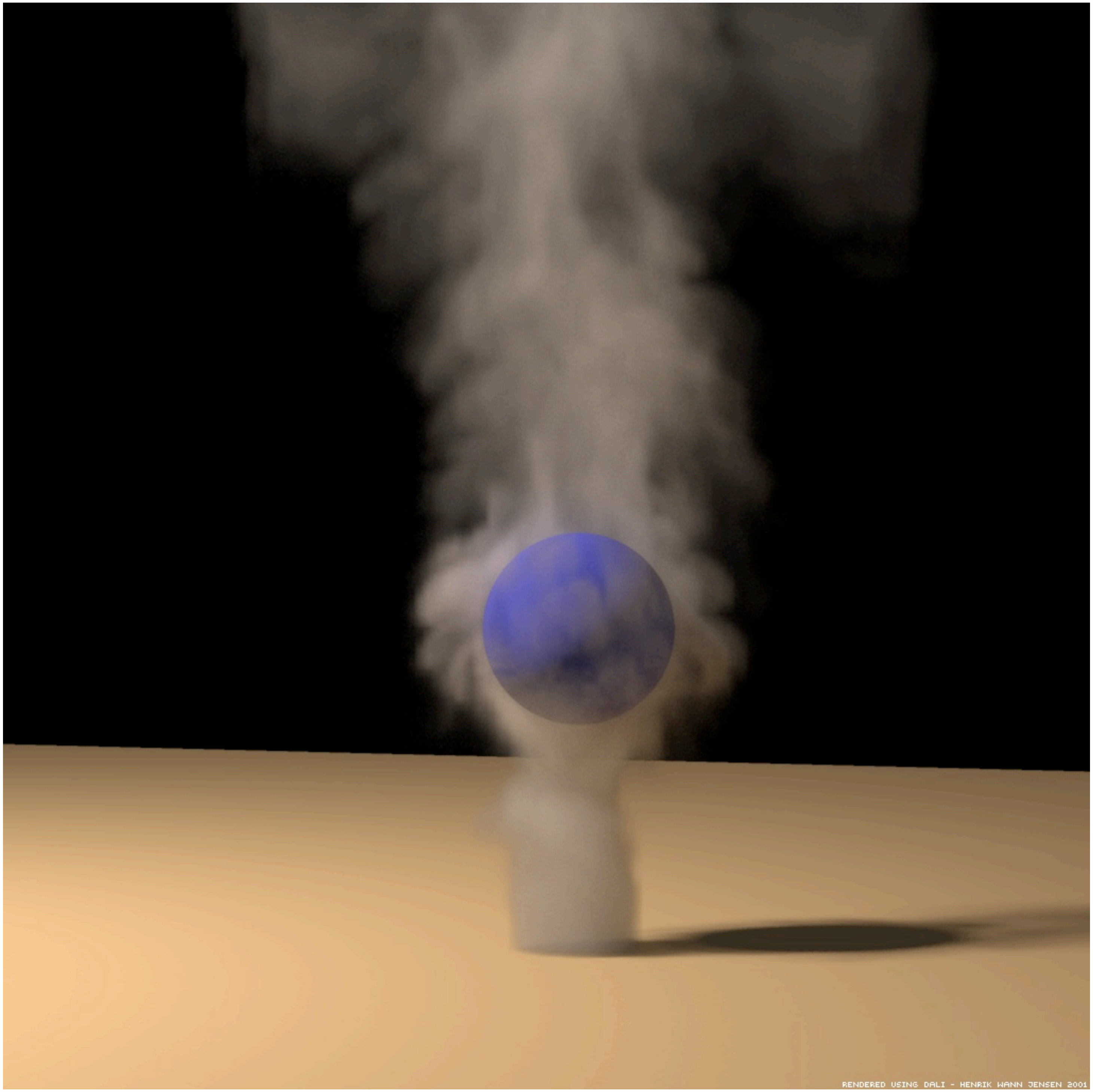

HENRIK WANN JENSEN 2001



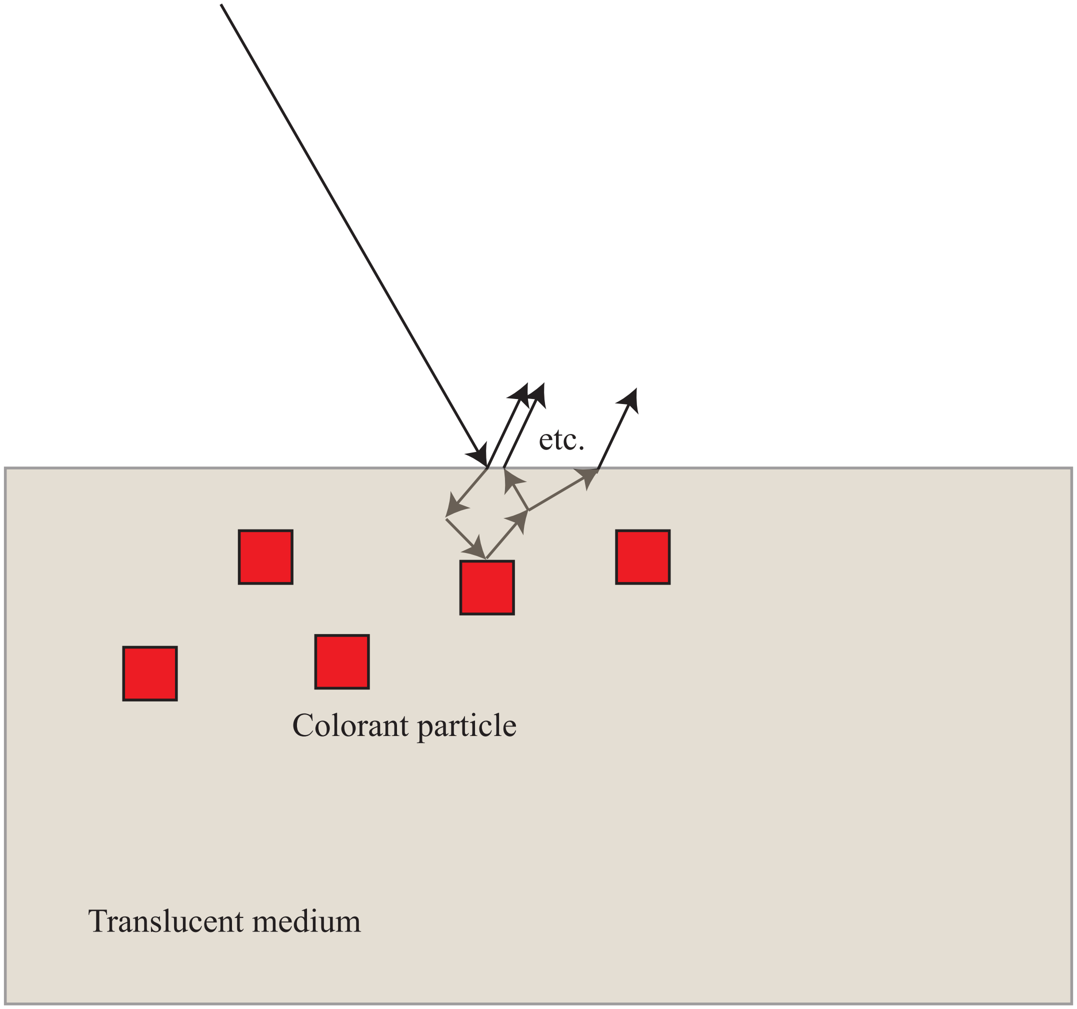
HENRIK WANN JENSEN 1999



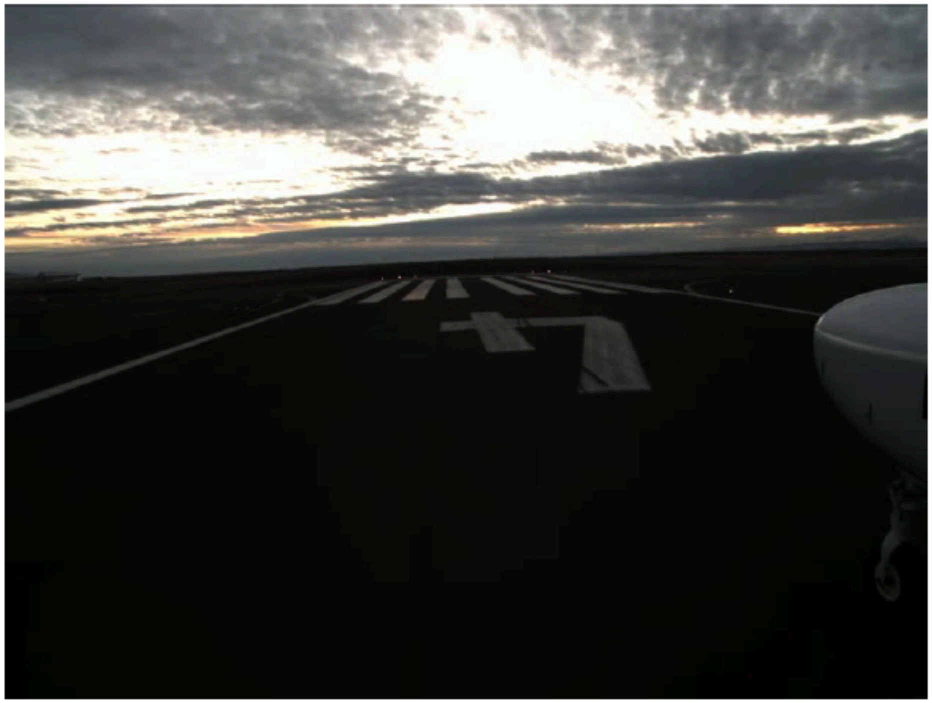
subsurface scattering in skin (not rendered!)

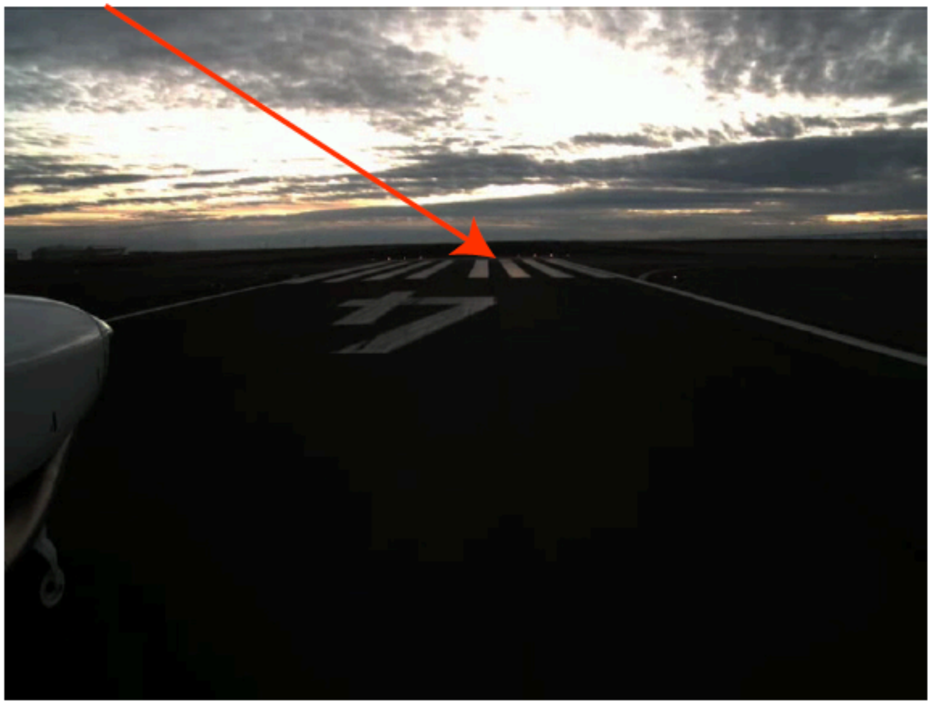

RENDERED USING DALI - HENRIK WANN JENSEN 2001

Paints are films with colored scatterers



Glowing paint from specular refl’ns





~~Boeing~~ Autonomy data