Transient Rendering

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Motivation

There is growing interest in time-of-flight based computer vision applications and we want some general, physical explanation of measurements we make.

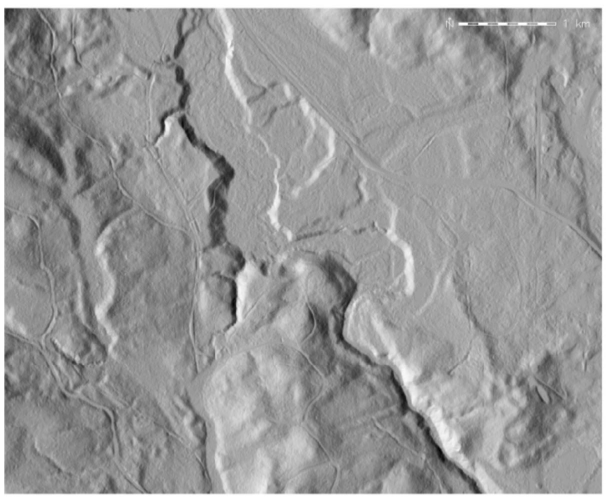
Our contribution:
a formal model that let's us do just that

Background

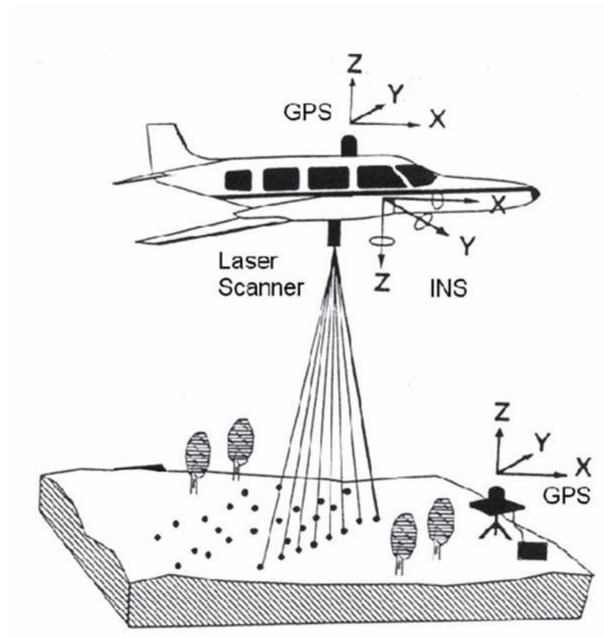
- We want
  - Rigorous analysis
  - Specific to light
  - Transient effects
- What's out there
  - LIDAR
  - SONAR
  - Rendering Equation

LIDAR

- NO: Rigorous analysis
- YES: Specific to light
- YES: Transient effects



(UC Davis)

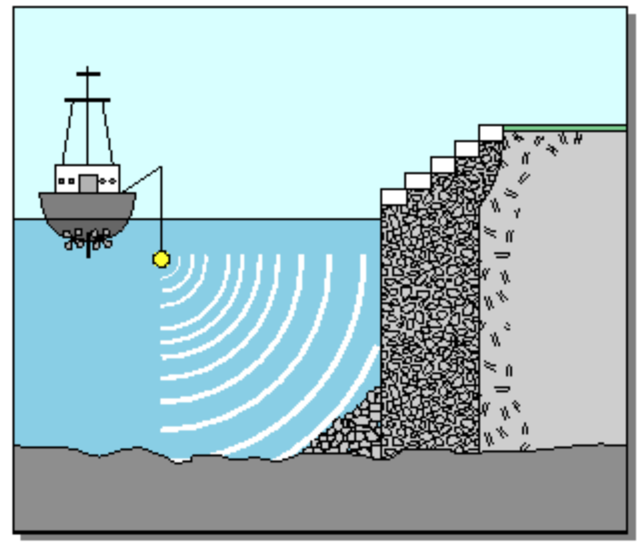


(UC Santa Cruz)

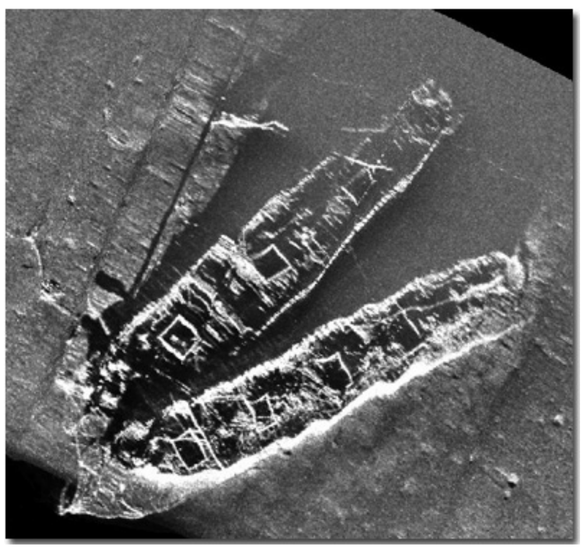
SONAR

- YES: Rigorous analysis
- NO: Specific to light
- YES: Transient effects

Overview (Transponder in yellow)



(USGS)



Height field of two sunken ships

(NOAA)

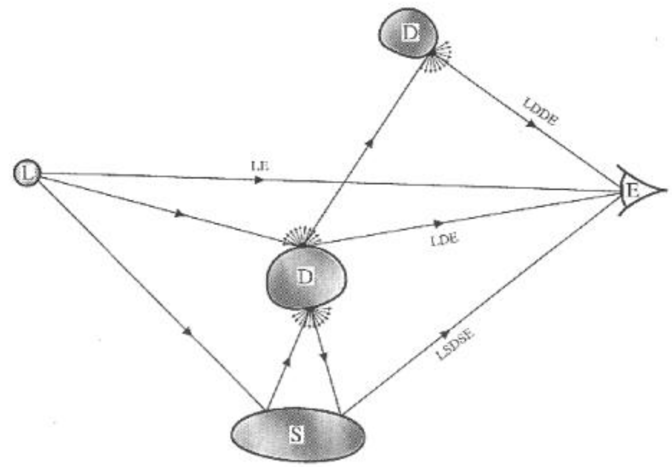
Rendering Equation

- YES: Rigorous analysis
- YES: Specific to light
- NO: Transient effects

$$L = L_0 + G \circ L$$

where

- L is total light
- L_0 is emitted light
- G is global transport (single bounce)



(Stanford)

The rendering equation is

$$I(x,x') = g(x,x')\left[\epsilon(x,x') + \int_S \rho(x,x',x'')I(x',x'')dx''\right].$$

where:

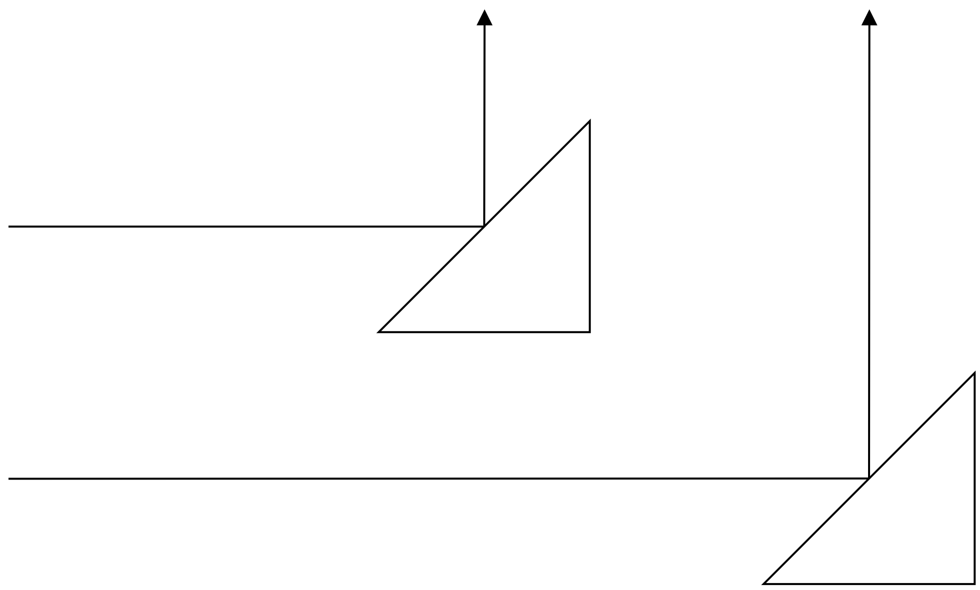
$I(x,x')$	is the related to the intensity of light passing from point x' to point x
$g(x,x')$	is a "geometry" term
$\epsilon(x,x')$	is related to the intensity of emitted light from x' to x
$\rho(x,x'x'')$	is related to the intensity of light scattered from x'' to x by a patch of surface at x'

(Kajiya, 1986)

The Important Distinction

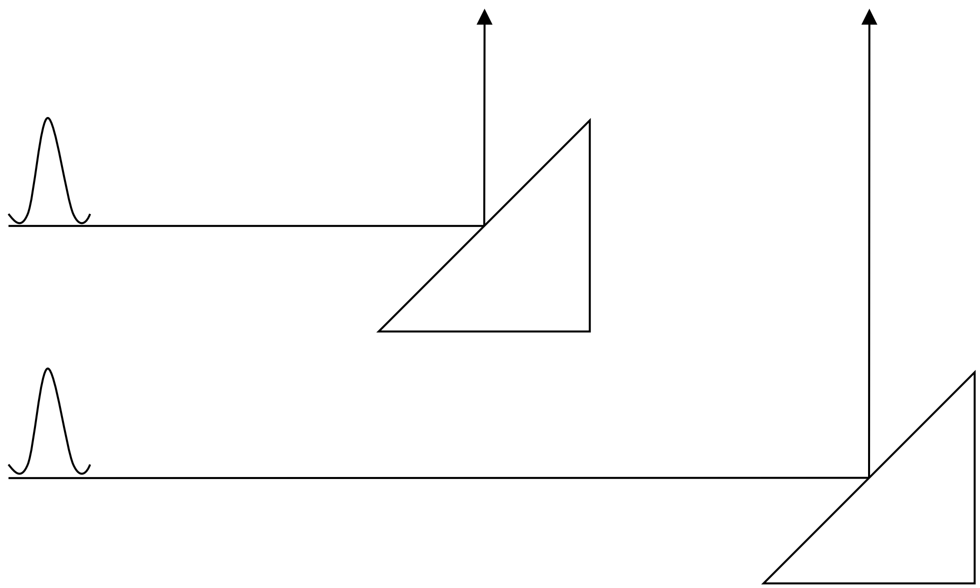
Steady state vs. transient light transport

Visualization



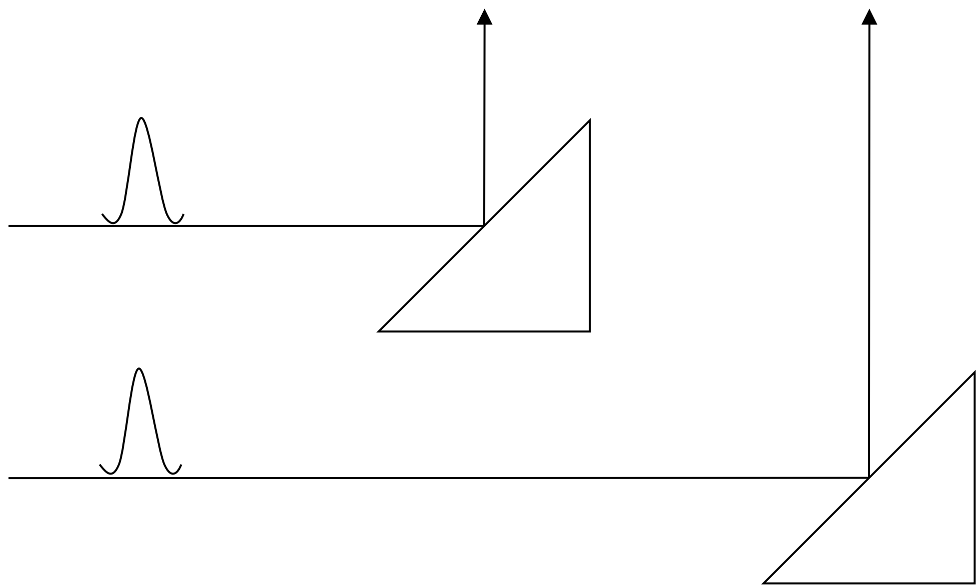
- Steady state: Where the light comes out

Visualization



- Transient: **When** the light comes out

Visualization



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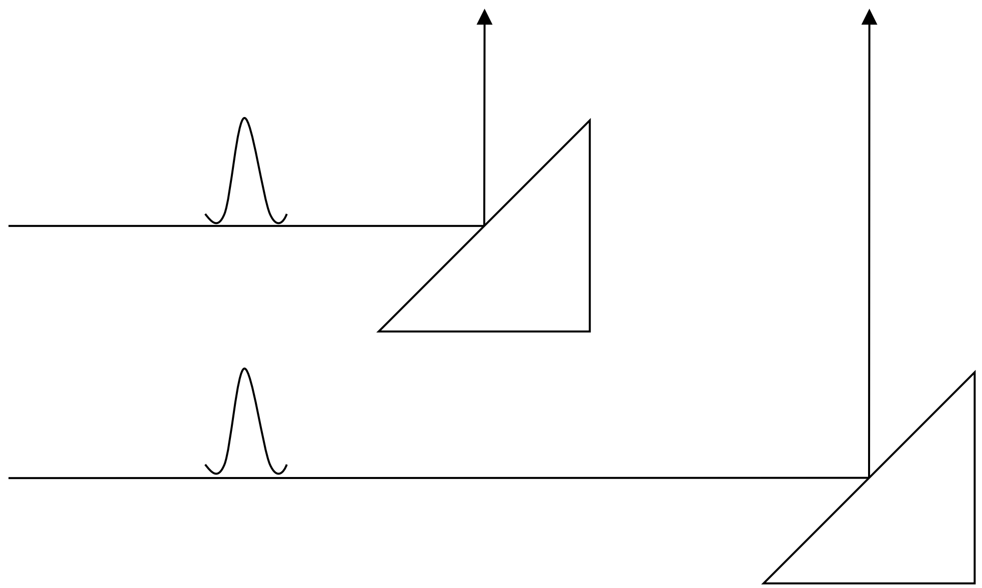

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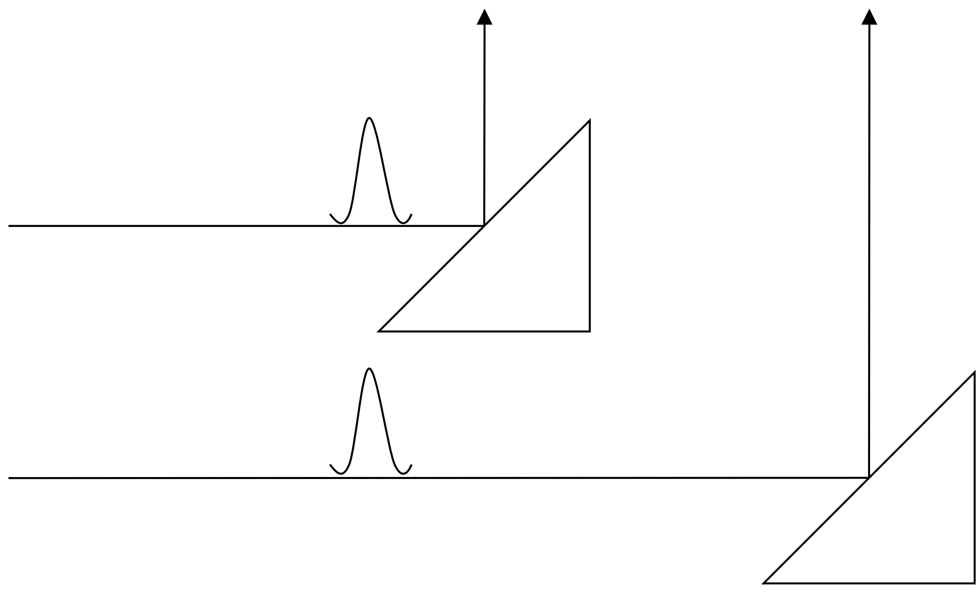

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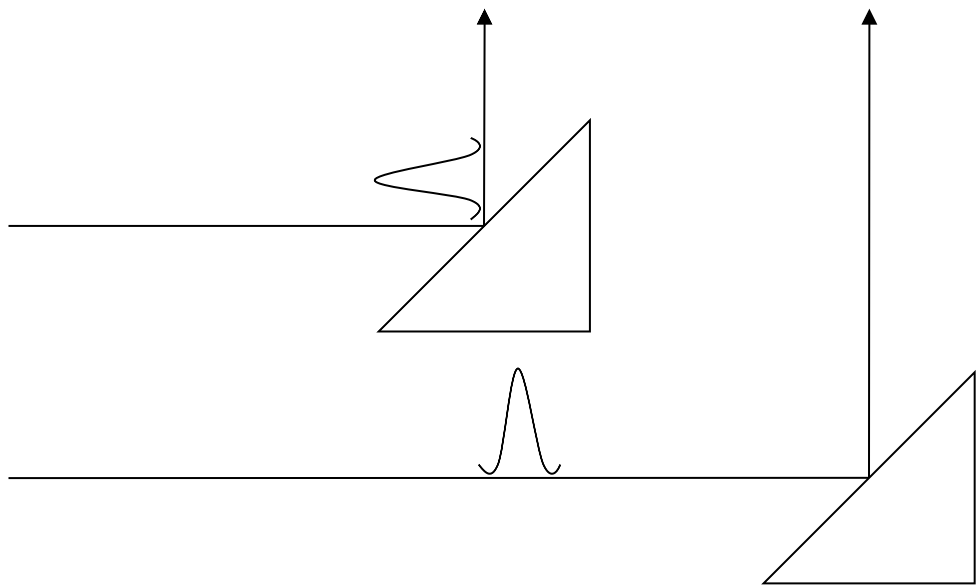

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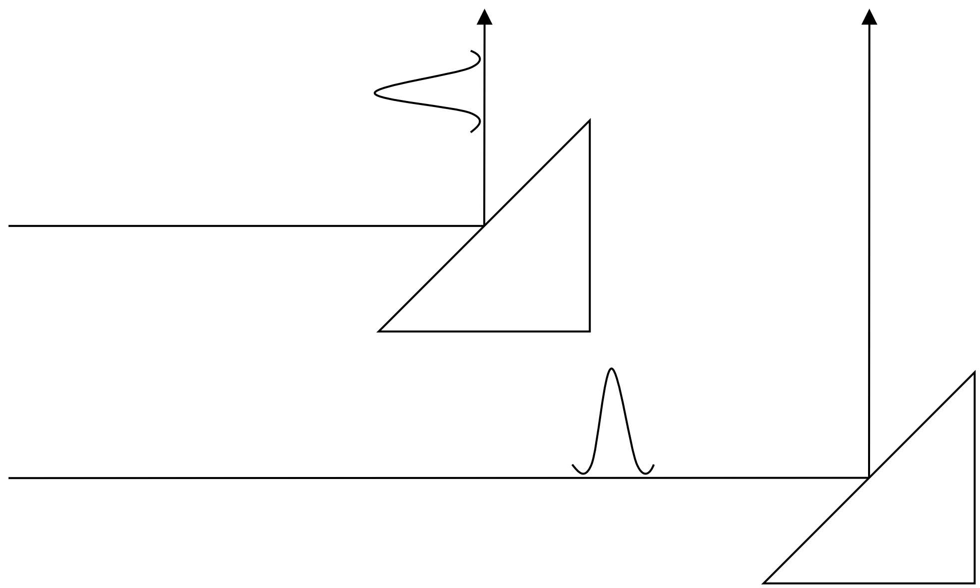

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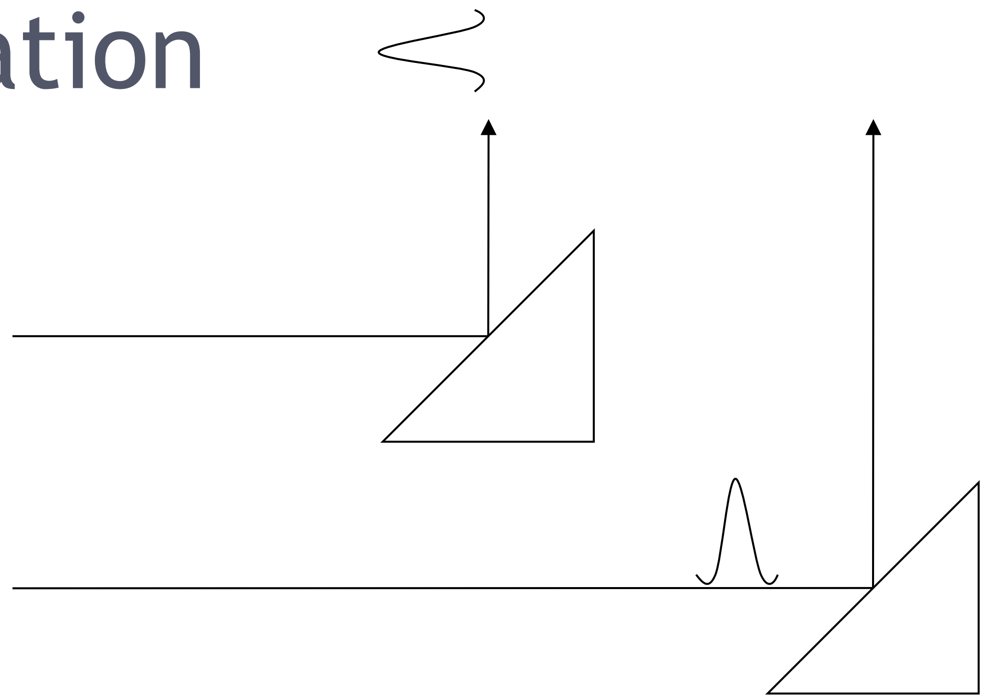


- Note: Top pulse wins the race!

Energy vs. Power

Steady State	Transient
Energy (Joules)	Power (Watts)
Number of photons received	Rate of photons received
Radiance	Radiant flux

Infinite vs. Finite

Steady State	Transient
$\text{Delay}(X, Y) = 0$	$\text{Delay}(X, Y) = \frac{\lvert X - Y \rvert}{c}$

- X, Y are points
- c is the speed of light

Functions

Steady State	Transient
$L = \mathrm{f}(X, \omega)$	$F = \mathrm{g}(X, \omega, t)$

- X is a point
- ω is a direction
- t is a time

Transient Rendering Equation

(our contribution)

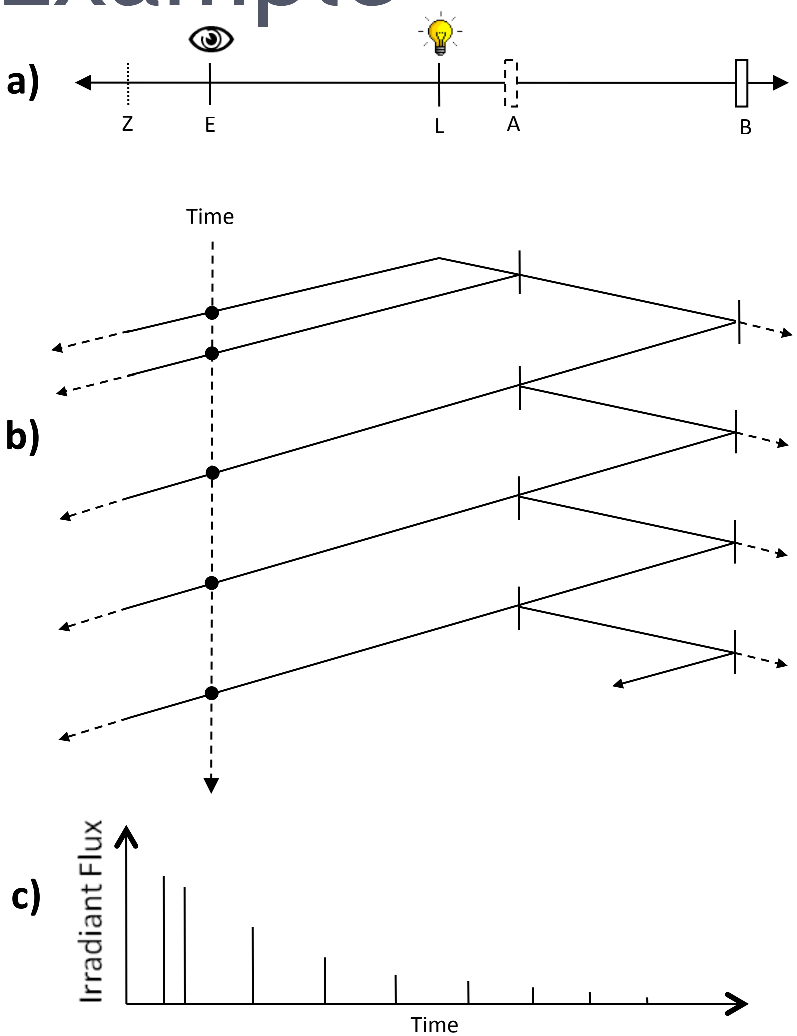
$$F(t) = F_0(t) + G \circ F(t)$$

Transient Rendering Equation

- Global light transport *G* is the composition of two physical processes
  - propagation, *P*
    - delays light over distances
  - scattering, S
    - same as traditional rendering

$$G \circ F(t) = S \circ P \circ F(t)$$

Example



a) 1-d world with two surfaces A and B, eye E and light L
b) result of transient rendering
c) light seen at E over time

- Input: positions, scattering kernels, initial light emission
- Output: received light power at every point, every direction, and every time

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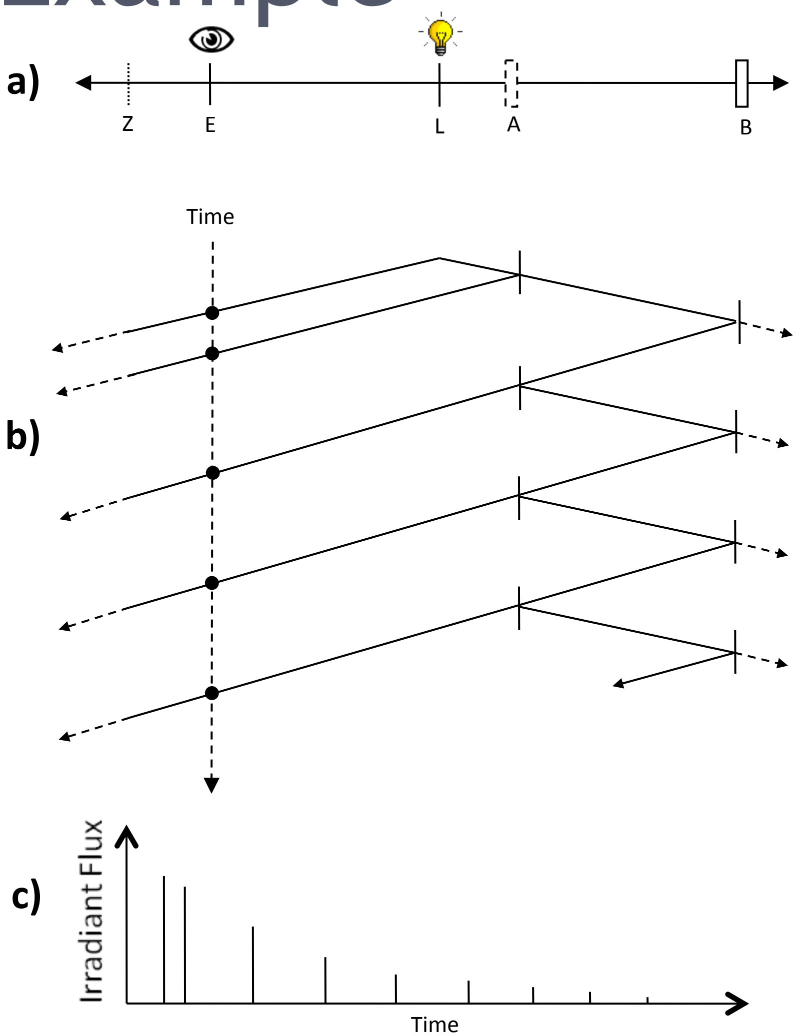

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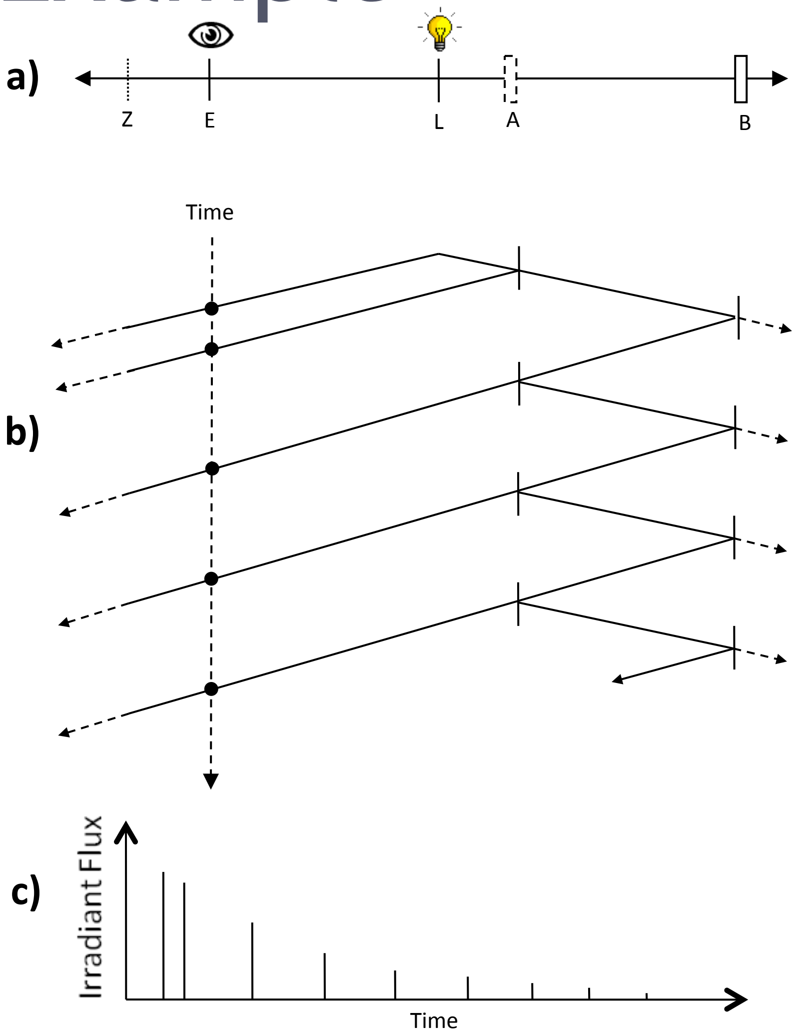

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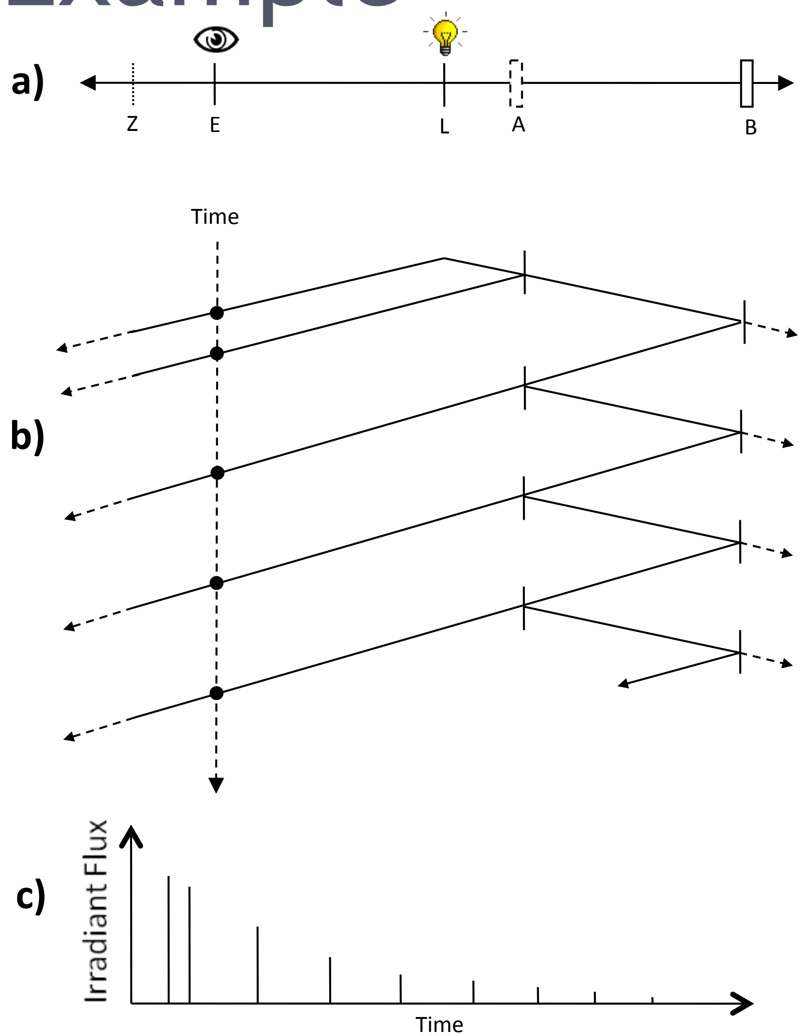

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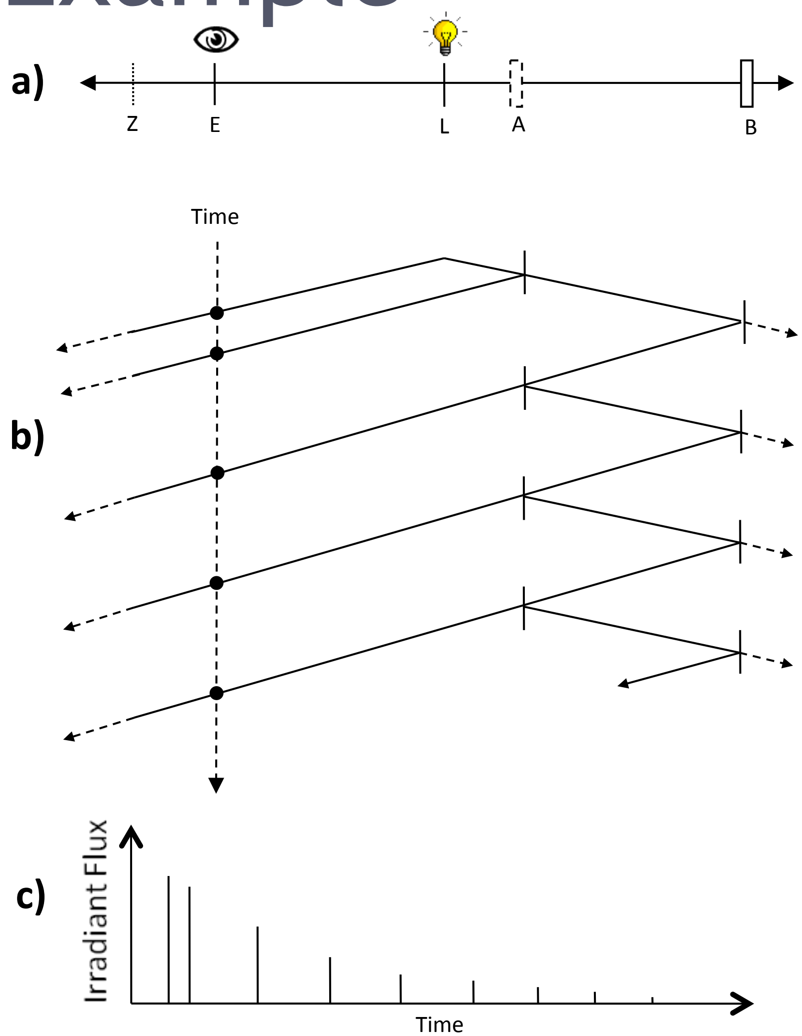

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Sensor Model

- Turns ideal worlds into ground truth sensor readings
- Takes into account:
  - Sampled function of time
  - Integration over shutter window
  - Light pulse envelope
  - Discrete photons
- Produces: sequence of energy measurements

New Research Directions

- Applications: do things we could not do before
- Building sensors: capture transient patterns directly
- Theory: generalize and compute

Some Applications

- 3.0D range finding (hidden surfaces)
- Subsurface scattering estimation from time instead of space samples
- Model-based LIDAR applications

Building Sensors

- Existing LIDAR hardware measures the data we need, but throws most of it away

Theory

- Generalize
  - Wavelength
  - Subsurface scattering
  - Phosphorescence
- Compute
  - Dependency calculation
  - Function representations
  - Augment a common raytracer

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Conclusion

We have taken initial steps into exploring the effects of the light propagation delay, and called this *Transient Rendering*.

We hope that transient rendering can serve as a principled foundation for future time-of-flight based computer vision techniques.