King Abdullah University of Science and Technology
KAUST

CS 247 – Scientific Visualization
Lecture 15: Volume Rendering, Pt. 2

Markus Hadwiger, KAUST

Reading Assignment #8 (until Mar 21)

Read (required):

- Real-Time Volume Graphics, Chapter 1 (*Theoretical Background and Basic Approaches*), from beginning to 1.4.4 (inclusive)
- Real-Time Volume Graphics, Chapter 4 (Transfer Functions) until Sec. 4.4 (inclusive)

- Look at:
  Nelson Max, Optical Models for Direct Volume Rendering, IEEE Transactions on Visualization and Computer Graphics, 1995
  `http://dx.doi.org/10.1109/2945.468400`

Quiz #2: Mar 23

Organization

- First 30 min of lecture
- No material (book, notes, ...) allowed

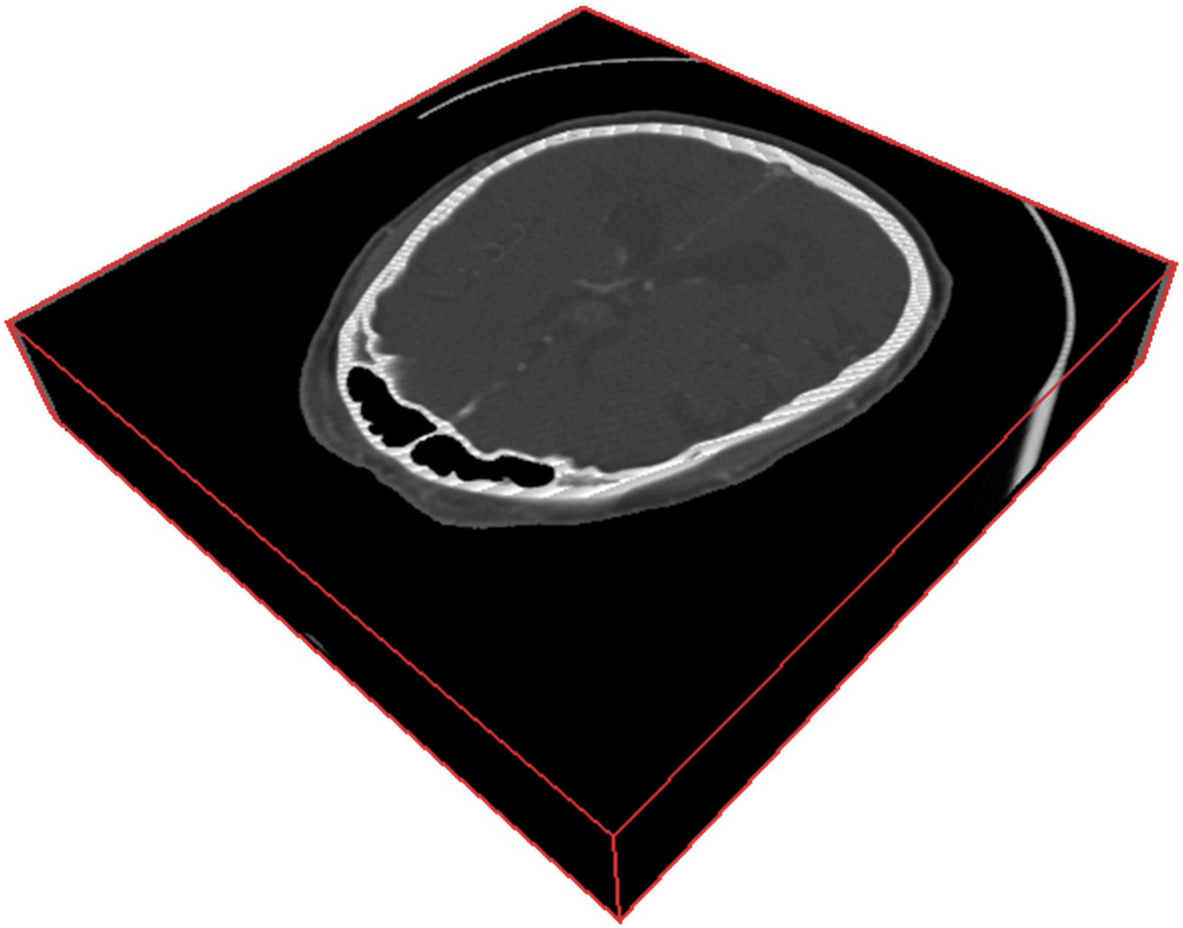
Content of questions

- Lectures (both actual lectures and slides)
- Reading assignments (except optional ones)
- Programming assignments (algorithms, methods)
- Solve short practical examples

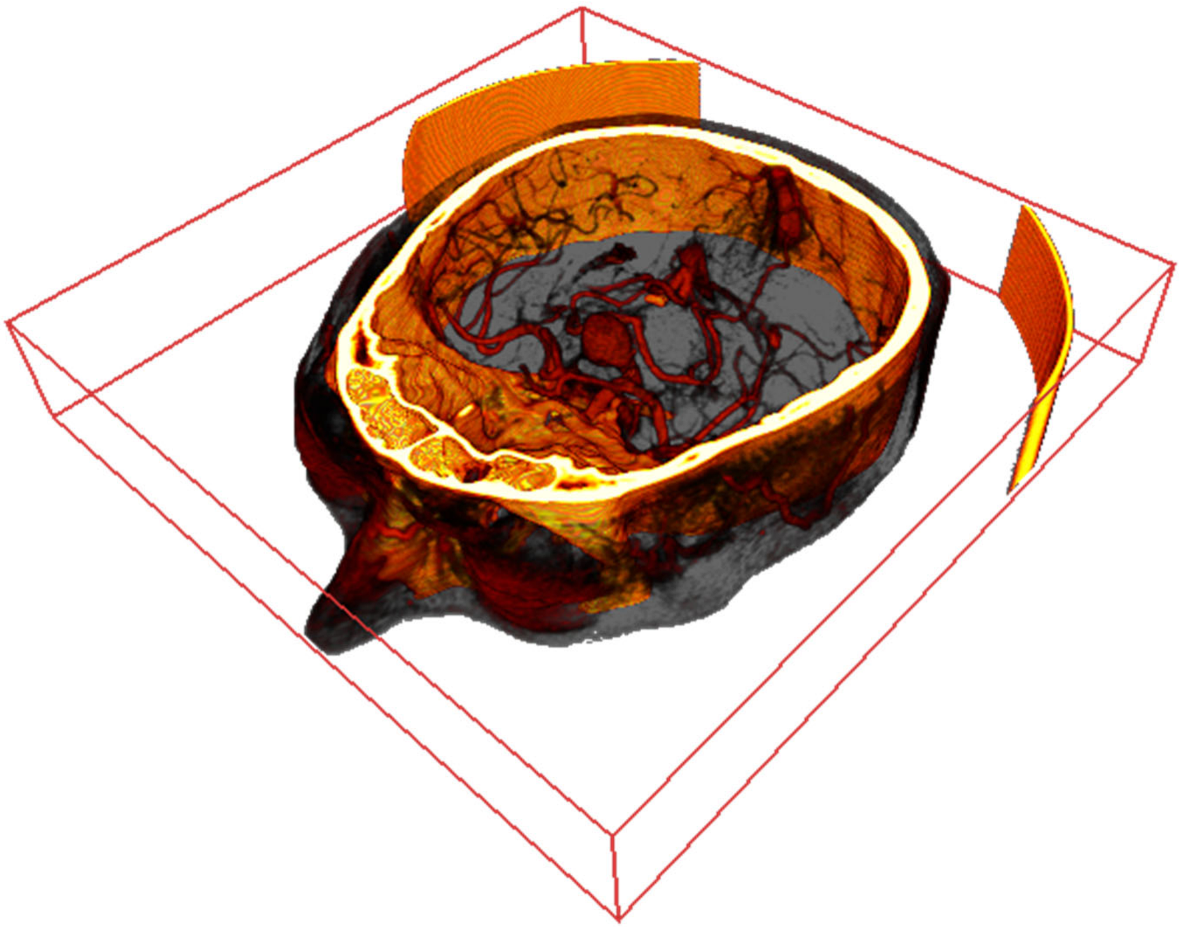
Volume Visualization

VolVis: Theory

Direct Volume Rendering

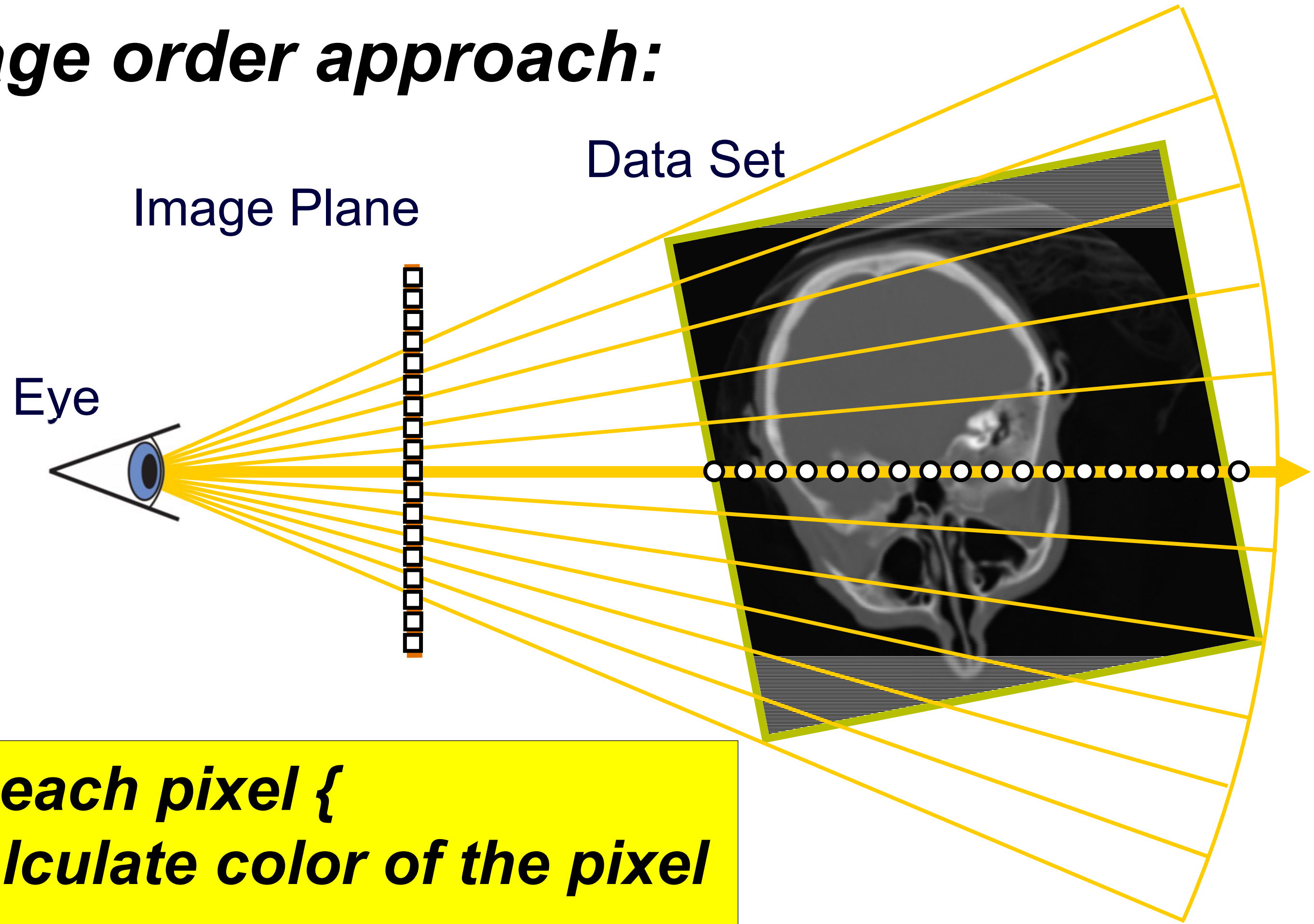


Direct Volume Rendering



Direct Volume Rendering

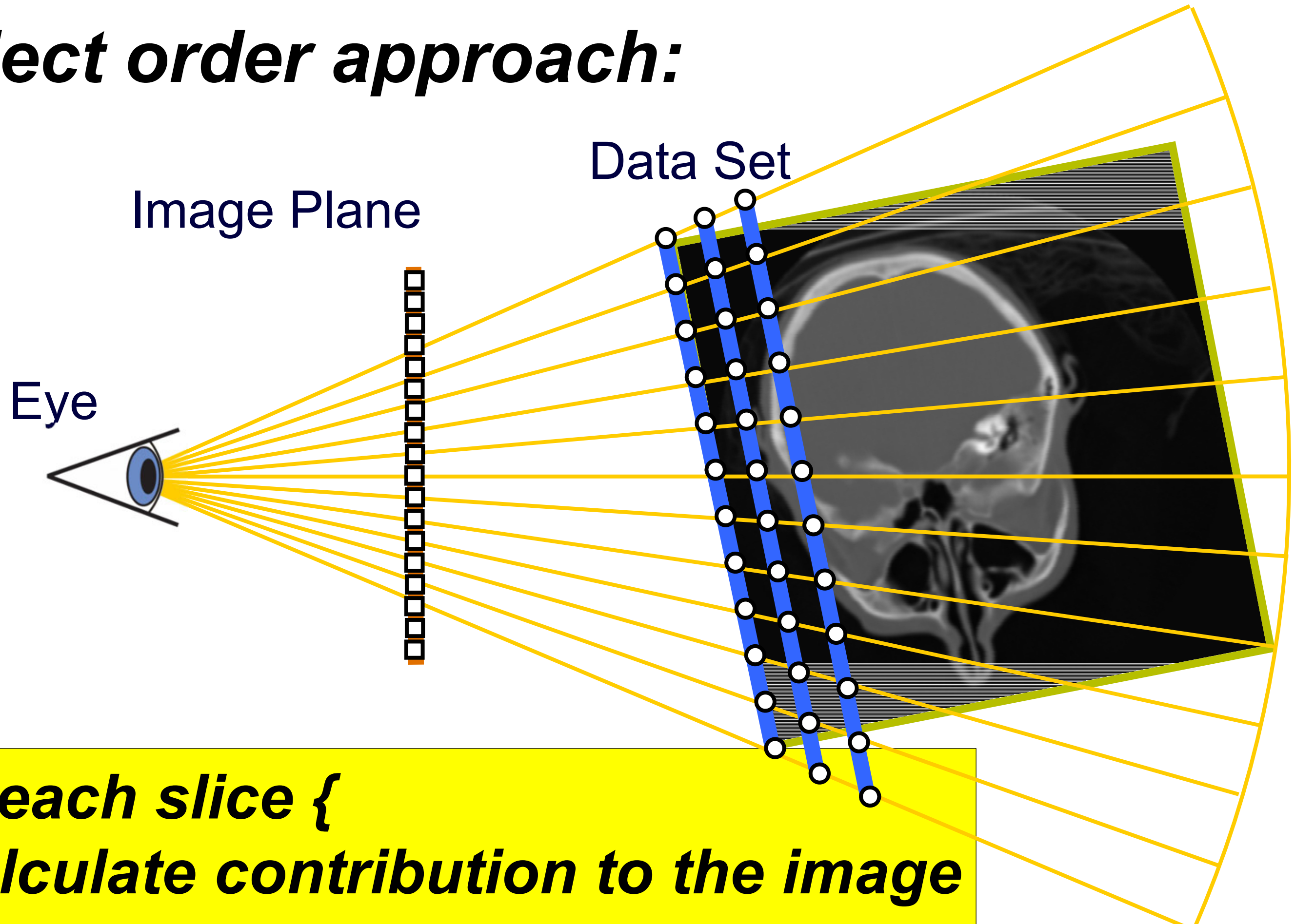
Image order approach:



For each pixel {
calculate color of the pixel
}

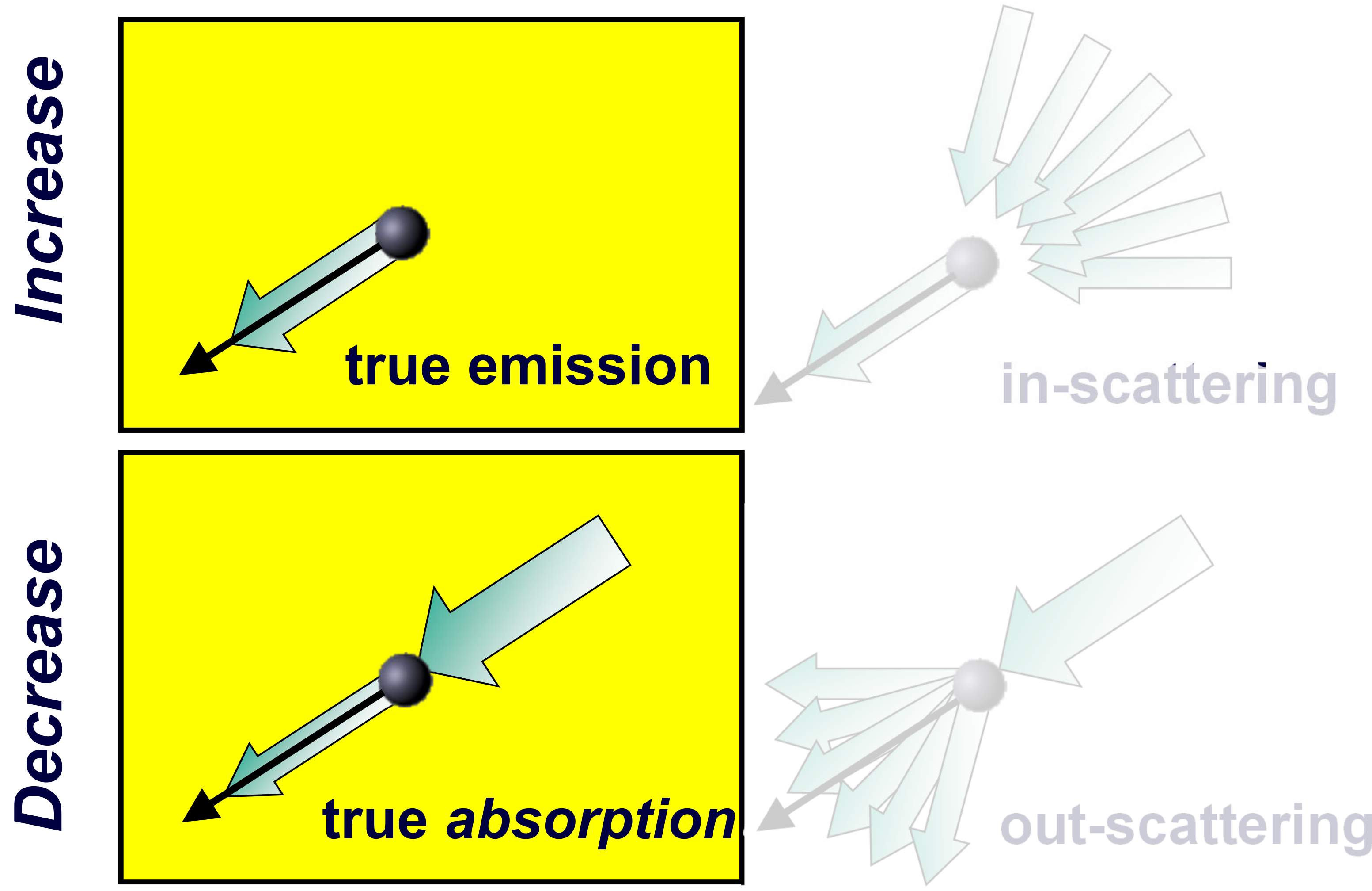
Direct Volume Rendering: Object Order

Object order approach:



For each slice {
calculate contribution to the image
}

Physical Model of Radiative Transfer



Volume Rendering Integral Summary

Volume rendering integral
for *Emission Absorption* model

$$I(s) \;=\; I(s_0)\, e^{-\tau(s_0,s)} + \int_{s_0}^{s} q(\tilde{s})\, e^{-\tau(\tilde{s},s)}\, \mathrm{d}\tilde{s}$$

Numerical solutions:

Back-to-front compositing

$$C'_i \;=\; C_i + (1 - A_i)C'_{i-1}$$

Front-to-back compositing

$$\begin{aligned} C'_i &= C'_{i+1} + (1 - A'_{i+1})C_i \\ A'_i &= A'_{i+1} + (1 - A'_{i+1})A_i \end{aligned}$$

here, all colors are associated colors!

Volume Rendering Integral

How do we determine the radiant energy along the ray?

Physical model: emission and absorption, no scattering

Initial intensity at s_0

$$I(s) = \boxed{I(s_0)}$$

Volume Rendering Integral

How do we determine the radiant energy along the ray?

Physical model: emission and absorption, no scattering

Initial intensity at s_0

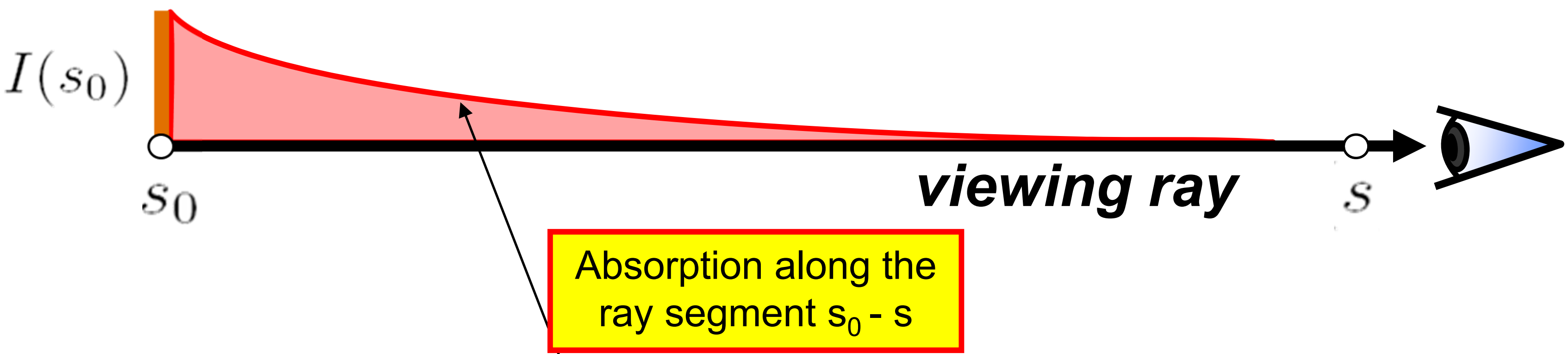
$$I(s) = \boxed{I(s_0)}$$

Without absorption all the initial radiant energy would reach the point ***s.***

Volume Rendering Integral

How do we determine the radiant energy along the ray?

Physical model: emission and absorption, no scattering



$$I(s) = I(s_0)\boxed{e^{-\tau(s_0,s)}}$$

Volume Rendering Integral

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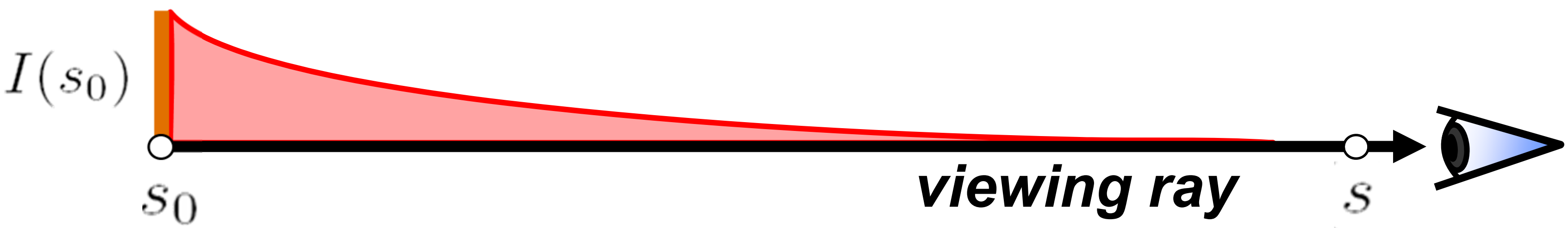
Physical model: emission and absorption, no scattering



$$I(s) \; = \; I(s_0)\; e^{-\tau(s_0,s)}$$

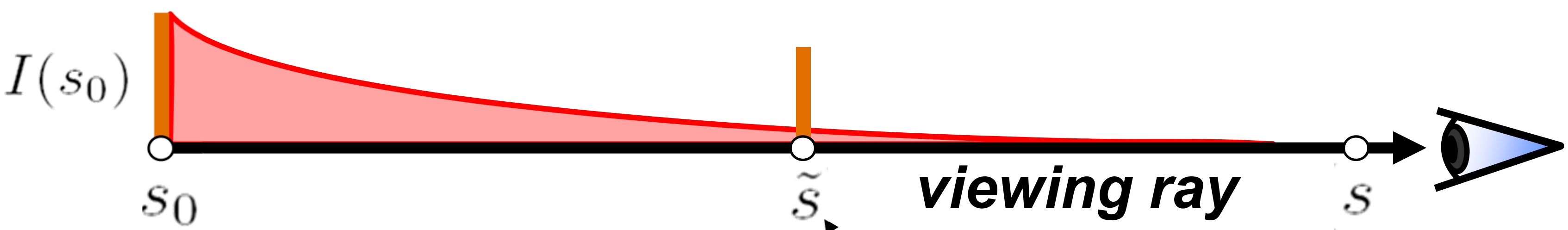
Optical depth τ
Absorption κ

$$\tau(s_1, s_2) \; = \; \int_{s_1}^{s_2} \kappa(s)\; ds.$$

Volume Rendering Integral

How do we determine the radiant energy along the ray?

Physical model: emission and absorption, no scattering



One point $\tilde{s}$ along the viewing ray emits additional radiant energy.

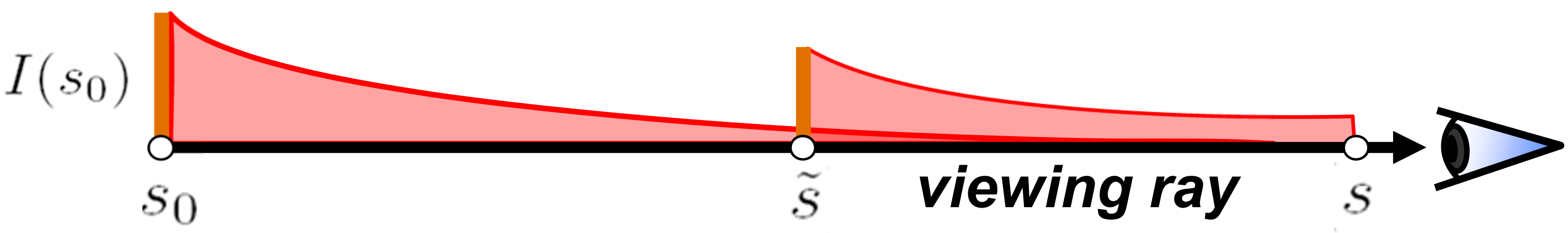
Active emission at point $\tilde{s}$

$$I(s) = I(s_0)\, e^{-\tau(s_0, s)} + \boxed{q(\tilde{s})}$$

Volume Rendering Integral

How do we determine the radiant energy along the ray?

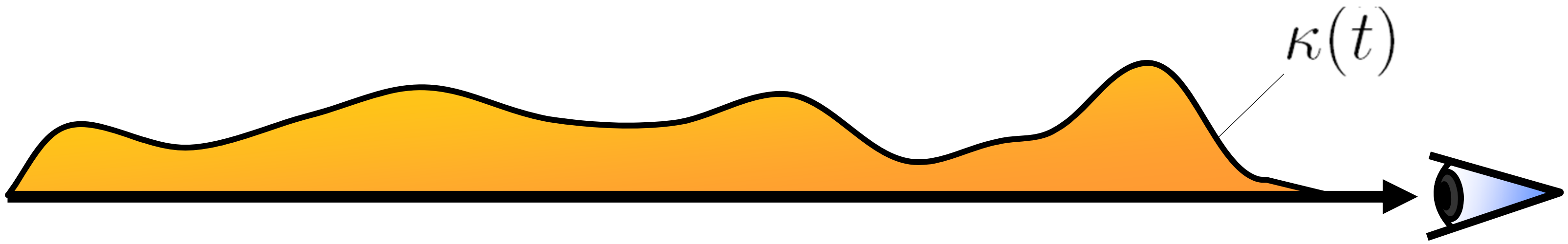
Physical model: emission and absorption, no scattering



Every point $\tilde{s}$ along the viewing ray emits additional radiant energy

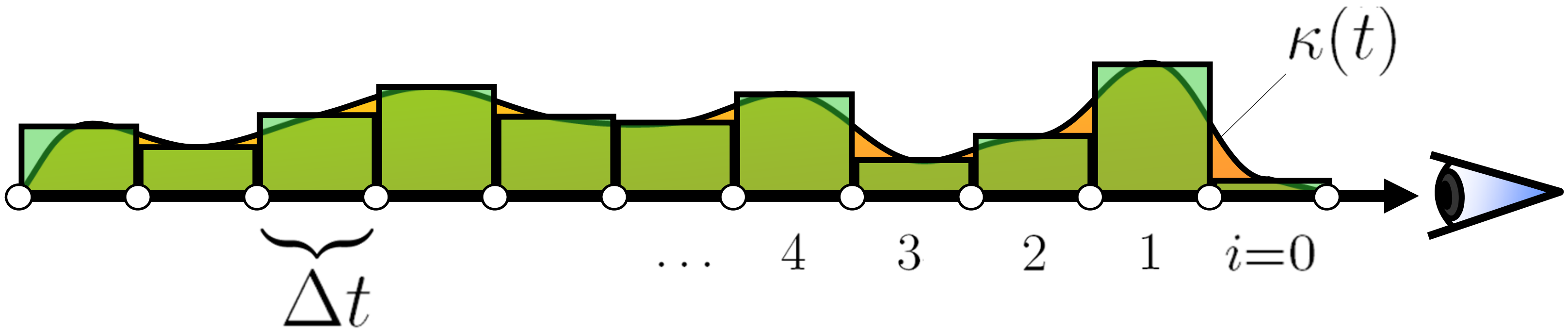
$$I(s) \;=\; I(s_0)\, e^{-\tau(s_0,s)} \;+\; \int_{s_0}^{s} q(\tilde{s})\, e^{-\tau(\tilde{s},s)}\, d\tilde{s}$$

Volume Rendering Integral: Numerical Solution



Optical depth: $\tau(0,t) \quad = \quad \int_0^t \kappa(\hat{t})\, d\hat{t}$

Volume Rendering Integral: Numerical Solution

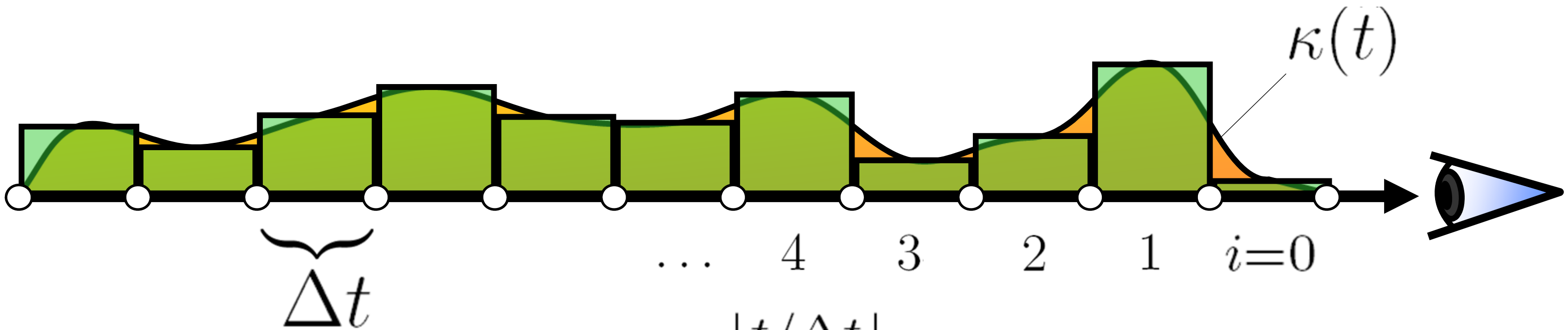


Optical depth: $\tau(0,t) \;=\; \int_0^t \kappa(\hat{t})\, d\hat{t}$

Approximate Integral by Riemann sum:

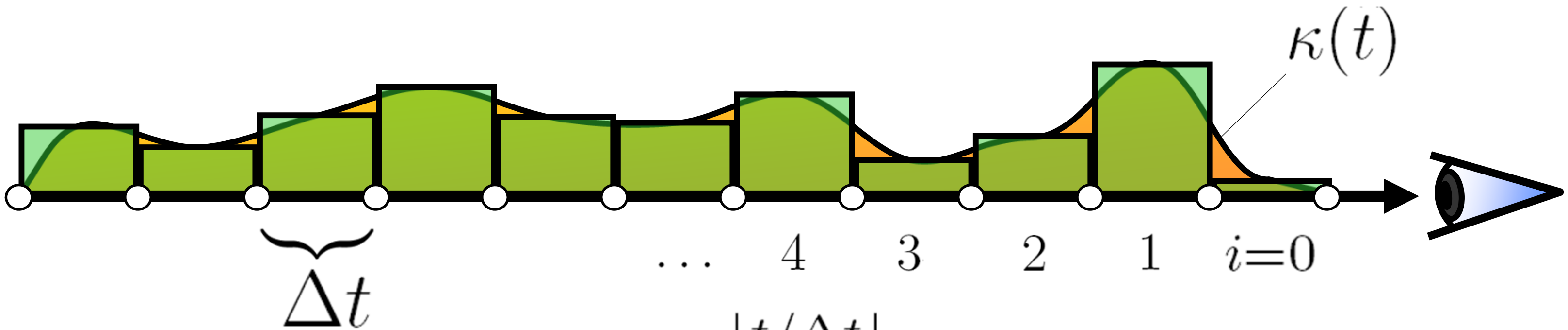
$$\tau(0,t) \;\approx\; \sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i \cdot \Delta t)\, \Delta t$$

Volume Rendering Integral: Numerical Solution



$$\tau(0,t) \approx \tilde{\tau}(0,t) = \sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i \cdot \Delta t)\,\Delta t$$

Volume Rendering Integral: Numerical Solution



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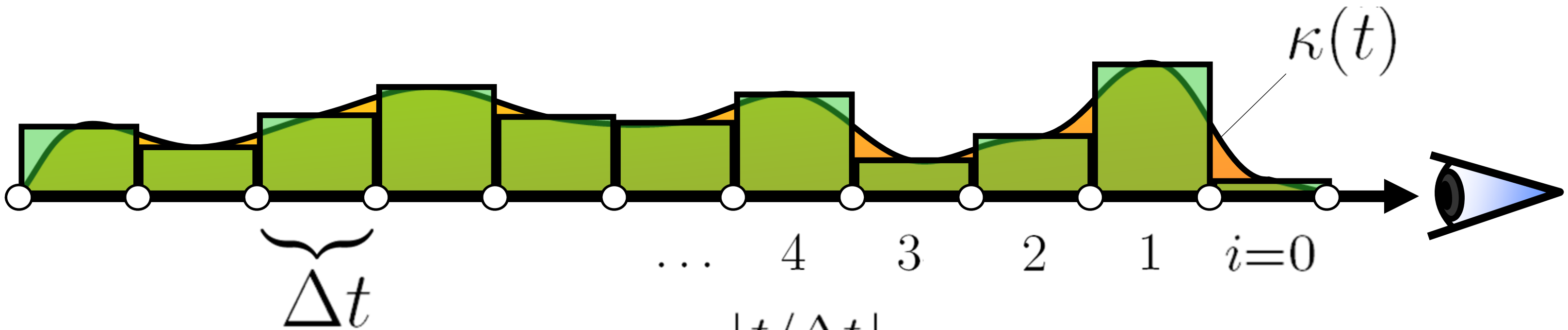
$$e^{-\tilde{\tau}(0,t)} = e^{-\sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i \cdot \Delta t)\, \Delta t}$$

Volume Rendering Integral: Numerical Solution



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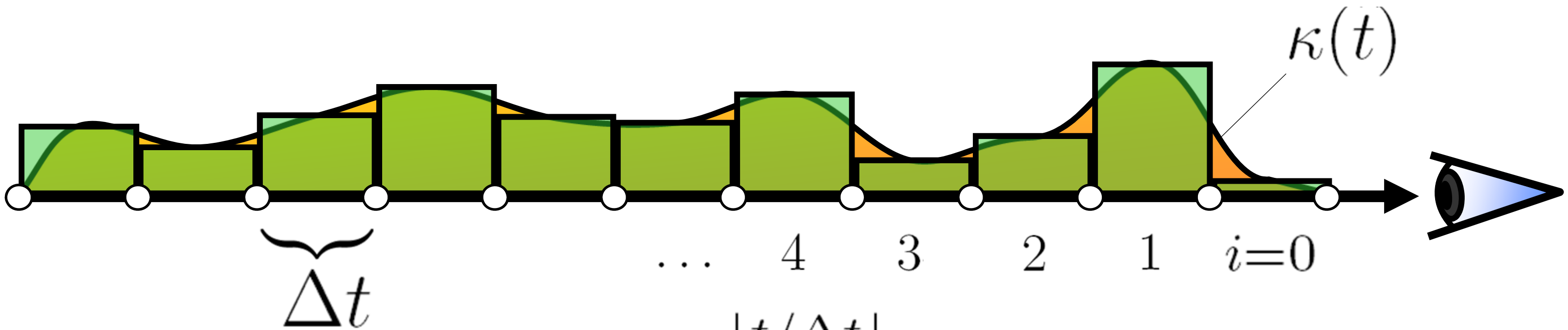

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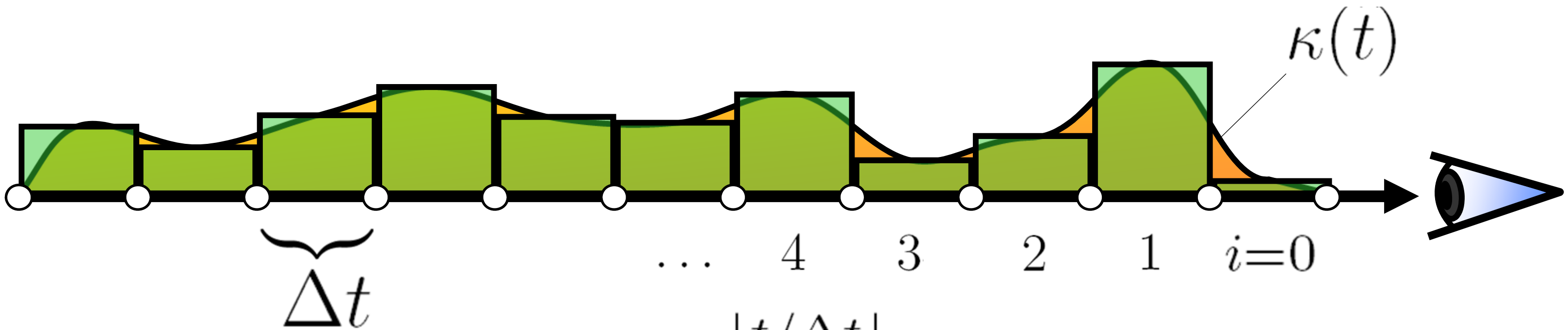
Now we introduce *opacity*:

$$A_i = 1 - e^{-\kappa(i \cdot \Delta t)\, \Delta t}$$

Volume Rendering Integral: Numerical Solution



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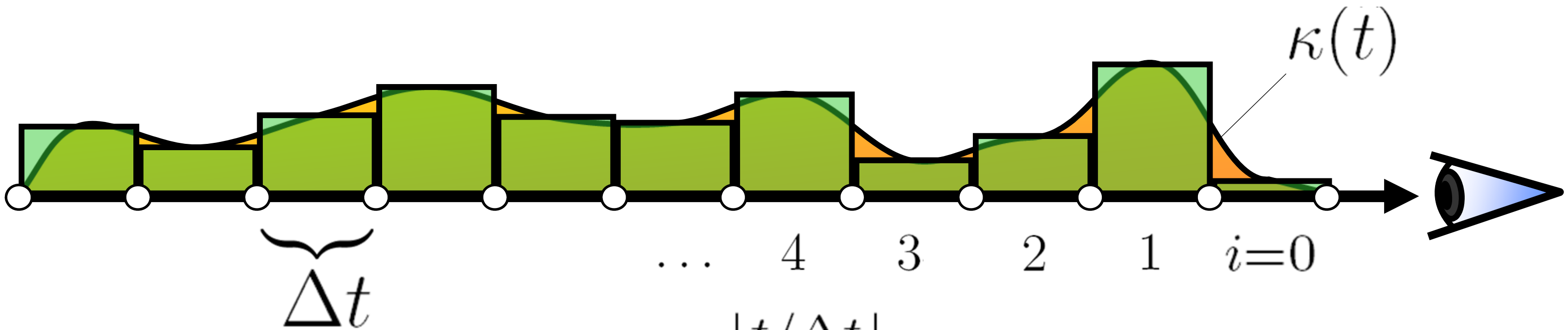

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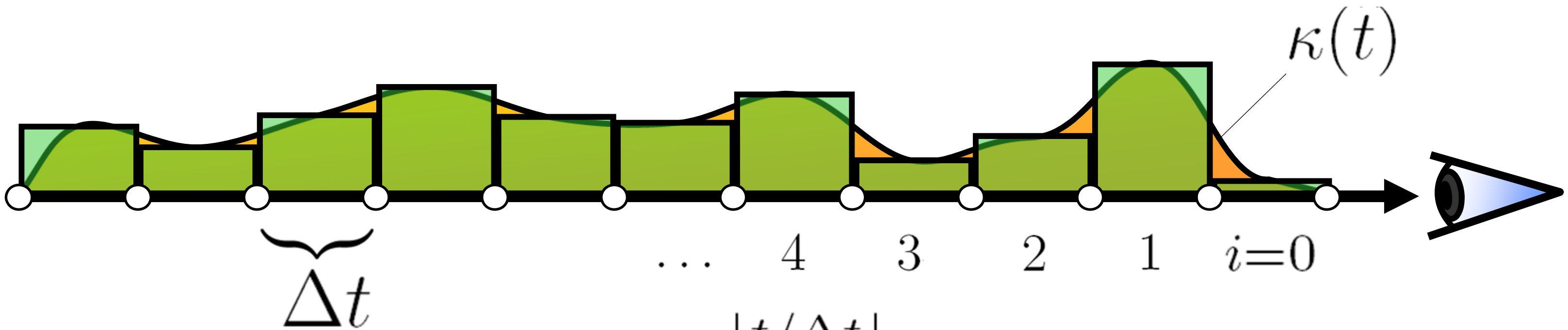

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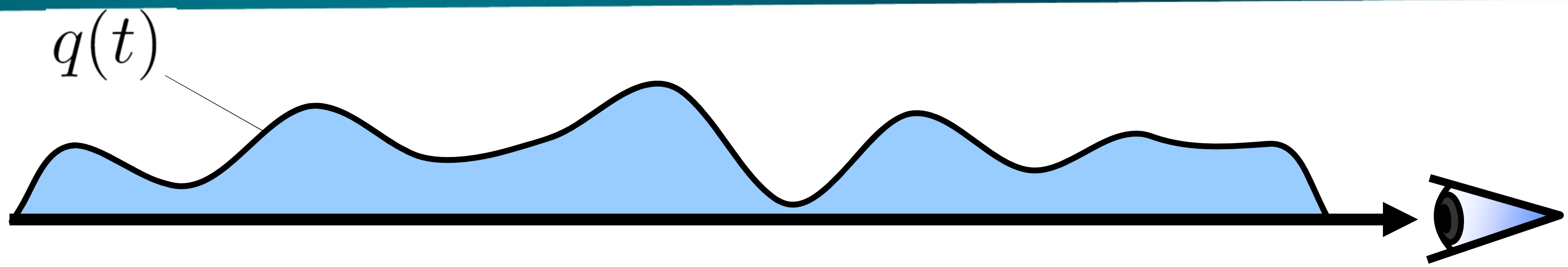

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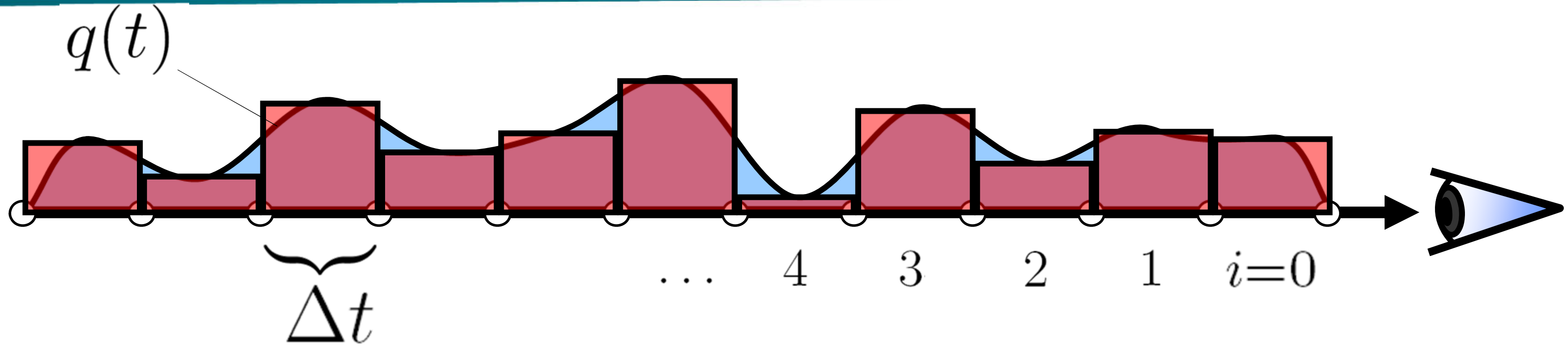
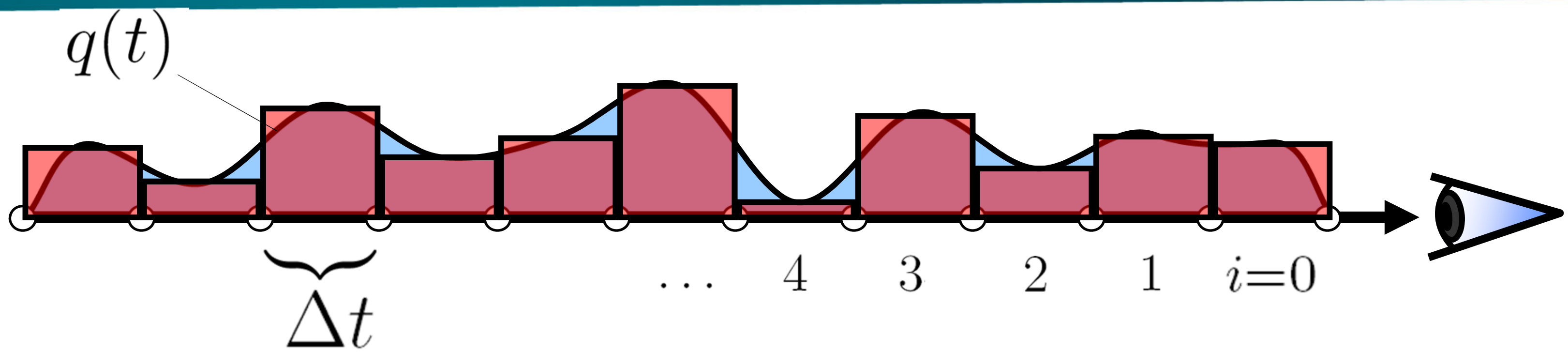


$$e^{-\tilde{\tau}(0,t)} = \prod_{i=0}^{\lfloor t/\Delta t \rfloor} (1 - A_i)$$

$$q(t) \approx C_i = c(i \cdot \Delta t)\, \Delta t$$

Volume Rendering Integral: Numerical Solution



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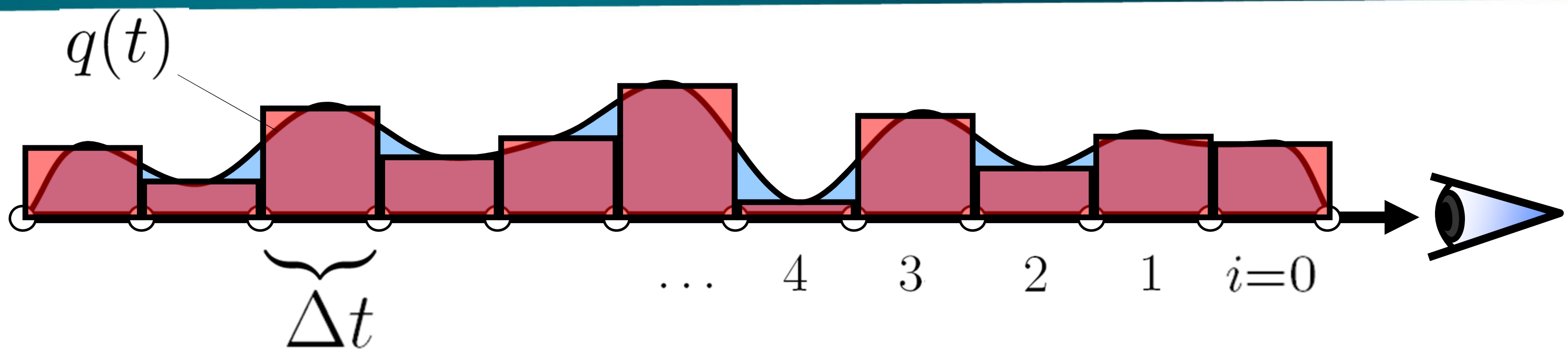
$$\tilde{C} = \sum_{i=0}^{\lfloor T/\Delta t \rfloor} C_i \, e^{-\tilde{\tau}(0,t)}$$

Volume Rendering Integral: Numerical Solution



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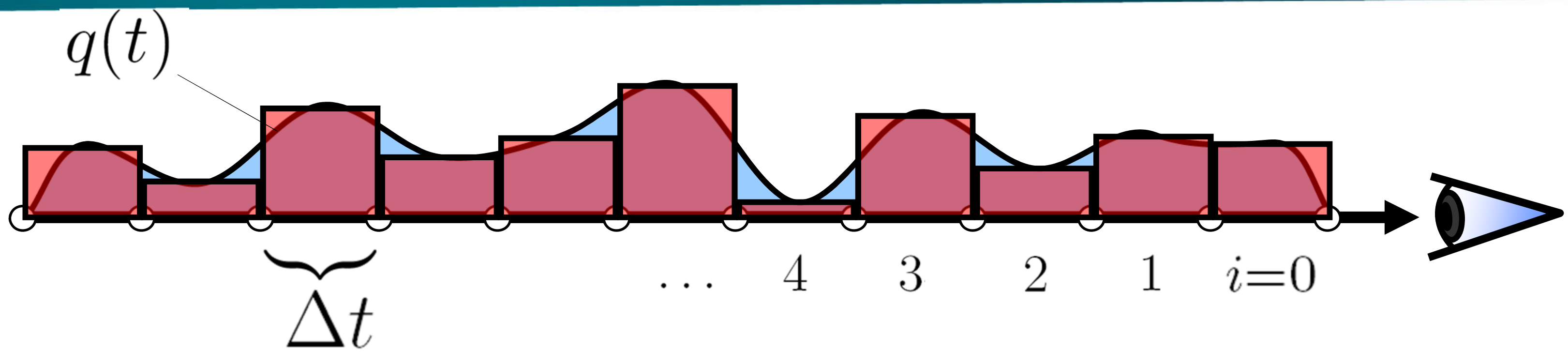

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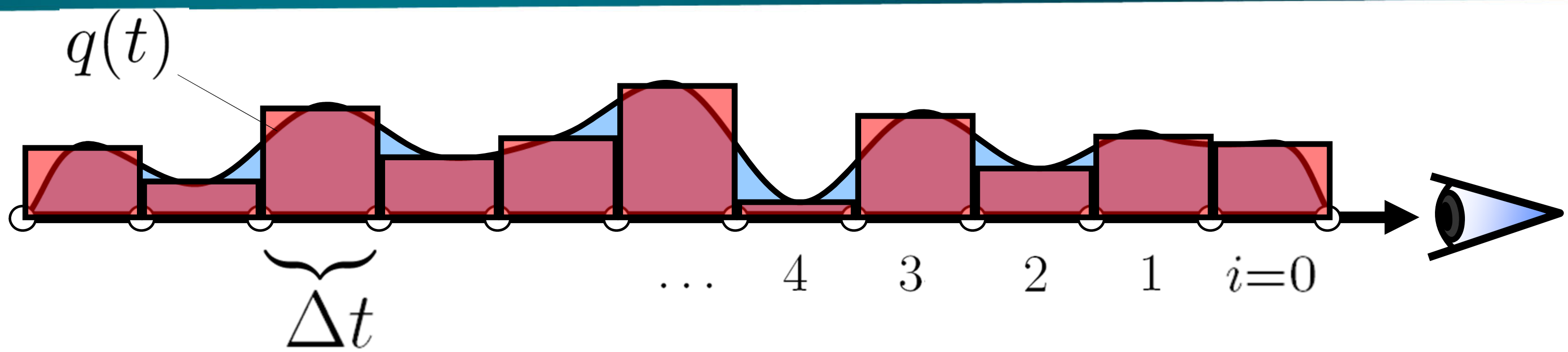

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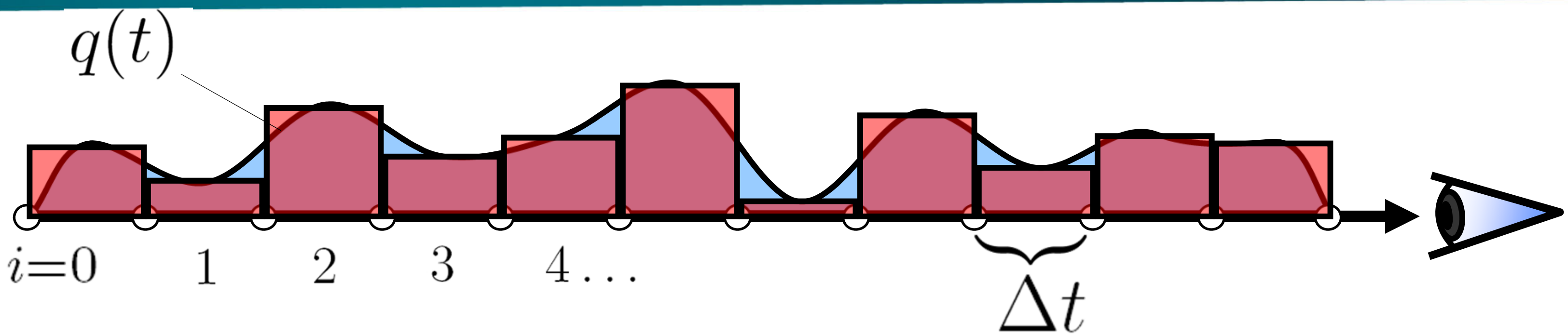
can be computed recursively/iteratively!

Volume Rendering Integral: Numerical Solution



Note: we just changed the convention from i=0 is at the front of the volume (previous slides) to i=0 is at the back of the volume !

can be computed recursively/iteratively:

$$C'_i \;=\; C_i + (1 - A_i)C'_{i-1}$$

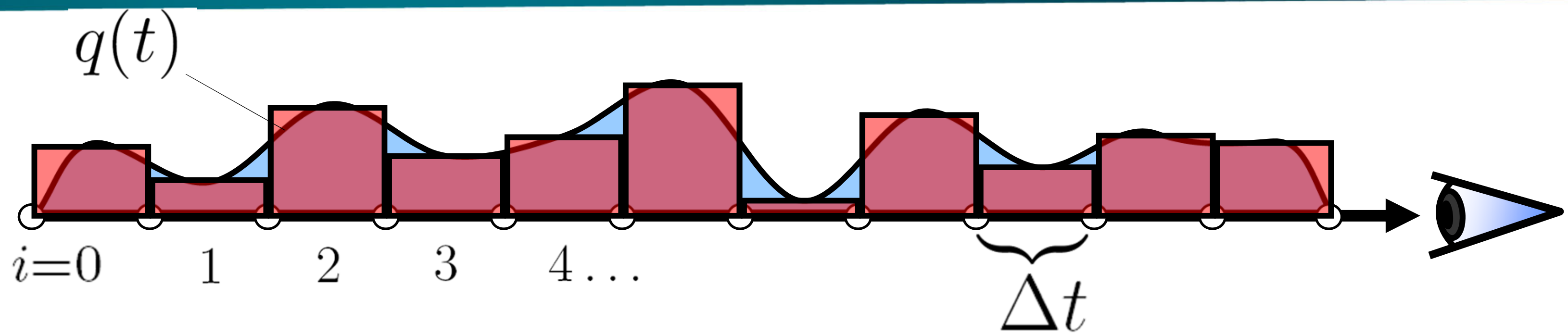
Radiant energy observed at position ***i***

Radiant energy emitted at position ***i***

Absorption at position ***i***

Radiant energy observed at position ***i–1***

Volume Rendering Integral: Numerical Solution



Back-to-front compositing

$$C_i' = C_i + (1 - A_i)C_{i-1}'$$

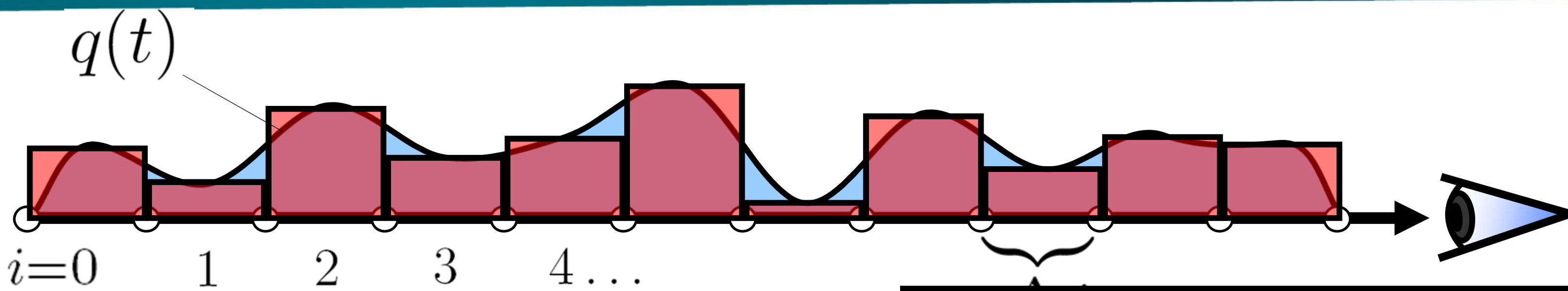
Iterate from *i*=0 (back) to *i*=max (front): *i* increases

Front-to-back compositing

$$\begin{aligned} C_i' &= C_{i+1}' + (1 - A_{i+1}')C_i \\ A_i' &= A_{i+1}' + (1 - A_{i+1}')A_i \end{aligned}$$

Iterate from *i*=max (front) to *i*=0 (back) : *i* decreases

Volume Rendering Integral: Numerical Solution



Back-to-front compositing

$$C'_i \quad = \quad C_i + (1$$

Iterate from *i*=0 (back

Early Ray Termination:
Stop the calculation when

$$A'_i \approx 1$$

Front-to-back compositing

$$\begin{aligned} C'_i &= C'_{i+1} + \boxed{(1 - A'_{i+1})} C_i \\ A'_i &= A'_{i+1} + (1 - A'_{i+1}) A_i \end{aligned}$$

Iterate from *i*=max (front) to *i*=0 (back) : *i* decreases

Volume Rendering Integral Summary

Volume rendering integral
for *Emission Absorption* model

$$I(s) \;=\; I(s_0)\, e^{-\tau(s_0,s)} + \int_{s_0}^{s} q(\tilde{s})\, e^{-\tau(\tilde{s},s)}\, \mathrm{d}\tilde{s}$$

Numerical solutions:

Back-to-front compositing

$$C'_i \;=\; C_i + (1 - A_i)C'_{i-1}$$

Front-to-back compositing

$$C'_i \;=\; C'_{i+1} + (1 - A'_{i+1})C_i$$
$$A'_i \;=\; A'_{i+1} + (1 - A'_{i+1})A_i$$

here, all colors are associated colors!

VolVis: Opacity Correction

[preview]

Opacity Correction

Simple compositing only works as far as the opacity values are correct… and they depend on the sample distance!

$$T_i = e^{-\int_{s_i}^{s_i+\Delta t} \kappa(t)\,dt} \approx e^{-\kappa(s_i)\Delta t} = e^{-\kappa_i \Delta t}$$

$$A_i = 1 - e^{-\kappa_i \Delta t} \qquad \tilde{T}_i = T_i^{\left(\frac{\Delta \tilde{t}}{\Delta t}\right)}$$

$$\boxed{\tilde{A}_i = 1 - (1 - A_i)^{\left(\frac{\Delta \tilde{t}}{\Delta t}\right)}}$$

opacity correction formula

Beware that usually this is done *for each different scalar value* (every transfer function entry), not actually at spatial positions/intervals *i*

Associated Colors

Associated (or “opacity-weighted” colors) are often used in compositing equations

Every color is *pre-multiplied* by its corresponding opacity

$$\begin{bmatrix} R \\ G \\ B \\ A \end{bmatrix} \Rightarrow \begin{pmatrix} R*A \\ G*A \\ B*A \\ A \end{pmatrix}$$

Our compositing equations assume associated colors!

Important: After opacity-correction, all associated colors must be updated! (or combined/multiplied correctly on-the-fly!)

Associated Colors in Volume Rendering

Standard emission-absorption optical model

- Only one kind of particle: the same particles that absorb light, emit light
- Aha! Therefore lower absorption means lower emission as well

Light observed from (in front of) segment *i* (without any light behind it):

$$C_i = \frac{q_i}{\kappa_i}\left(1 - e^{-\kappa_i \Delta t}\right) = \hat{C}_i A_i$$

$$q_i := \hat{C}_i \kappa_i$$

$$A_i := 1 - e^{-\kappa_i \Delta t}$$

$$\lim_{\kappa_i \to 0} q_i \frac{\left(1 - e^{-\kappa_i \Delta t}\right)}{\kappa_i} = \lim_{\kappa_i \to 0} \hat{C}_i \left(1 - e^{-\kappa_i \Delta t}\right) = 0$$

$$\lim_{\kappa_i \to \infty} q_i \frac{\left(1 - e^{-\kappa_i \Delta t}\right)}{\kappa_i} = \lim_{\kappa_i \to \infty} \hat{C}_i \left(1 - e^{-\kappa_i \Delta t}\right) = \hat{C}_i$$

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Thank you.

Thanks for material

- Helwig Hauser
- Eduard Gröller
- Daniel Weiskopf
- Torsten Möller
- Ronny Peikert
- Philipp Muigg
- Christof Rezk-Salama