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# Efficient Rendering of Heterogeneous Polydisperse Granular Materials

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# Efficient Rendering of Heterogeneous Polydisperse Granular Materials





# Efficient Rendering of Heterogeneous Polydisperse Granular Materials



Larry Hoffman – CC BY 2.0





# Efficient Rendering of Heterogeneous Polydisperse Granular Materials



Krissie Camealy – CC BY 2.0





# Efficient Rendering of Heterogeneous Polydisperse Granular Materials



\*Micky - CC BY-SA 2.0





# Efficient Rendering of Heterogeneous Polydisperse Granular Materials



Marco Verch – CC BY 2.0





# Efficient Rendering of Heterogeneous Polydisperse Granular Materials

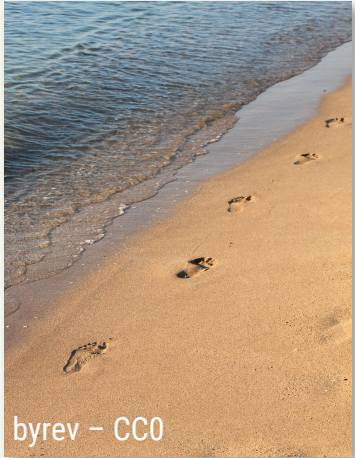


yeowatzup - CC BY 2.0





# THE APPEARANCE OF GRANULAR MATERIALS



byrev – CC0



yeowatzup – CC BY 2.0



\*Micky – CC BY-SA 2.0



Krissie Camealy – CC BY 2.0



Larry Hoffman – CC BY 2.0





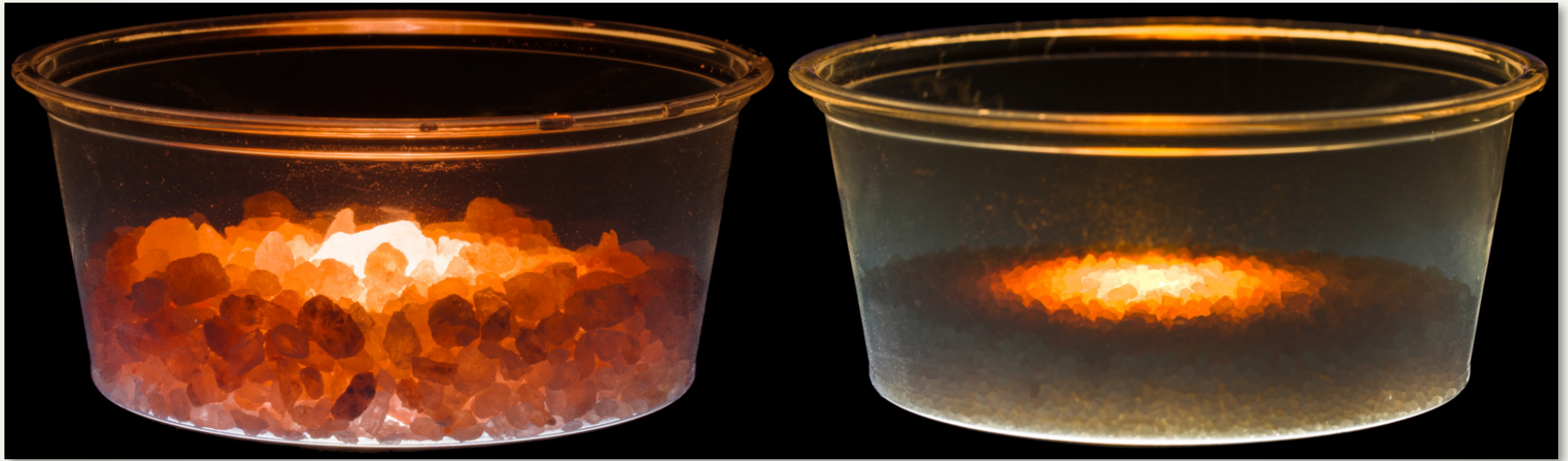




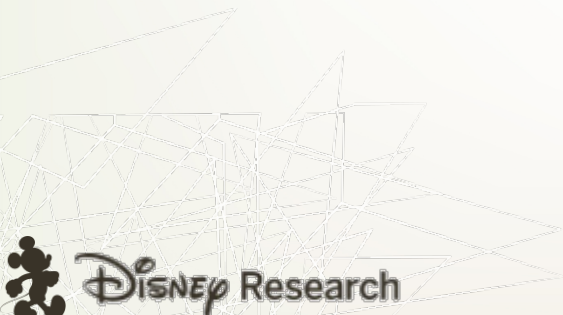




# DECOMPOSITION OF GRANULAR APPEARANCE



[Meng et al. 2015]





# LOW ORDER AND HIGH ORDER

Low order



=

+



Full image

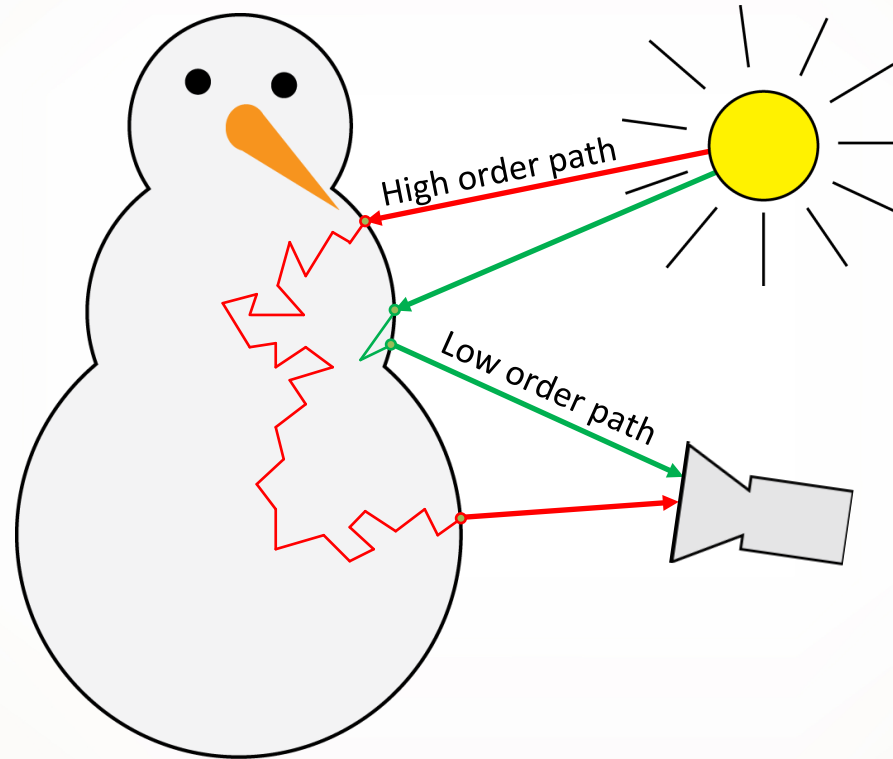
High order





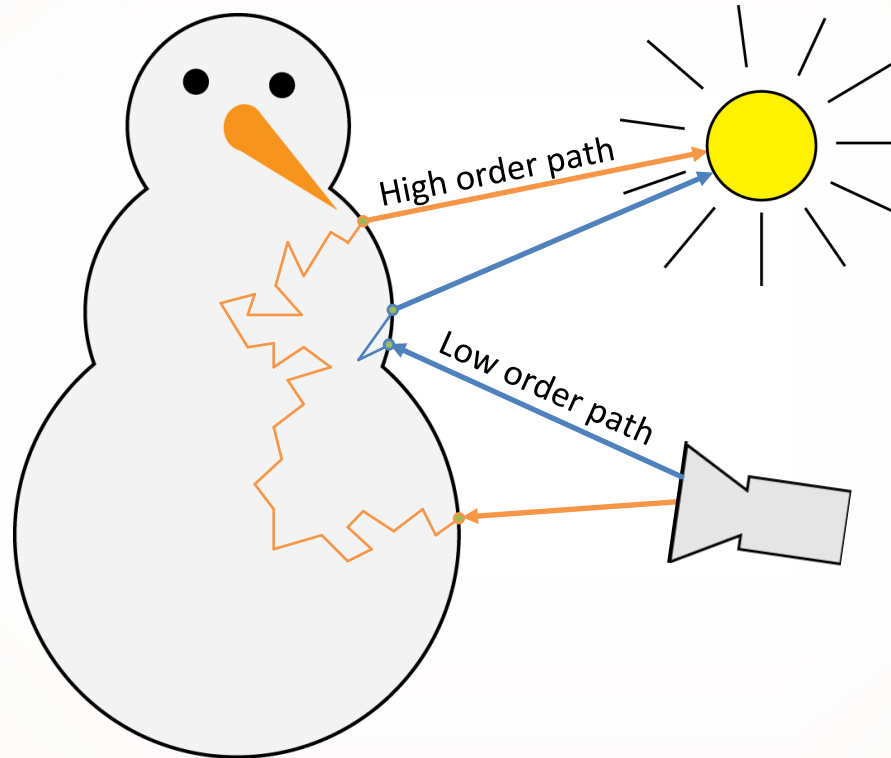


# LOW ORDER AND HIGH ORDER – INDIVIDUAL PHOTONS





# LOW ORDER AND HIGH ORDER – PATH TRACING



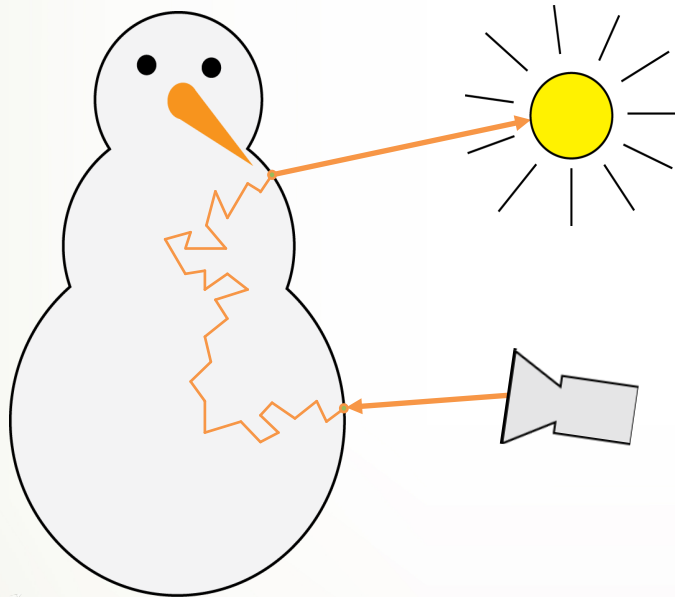




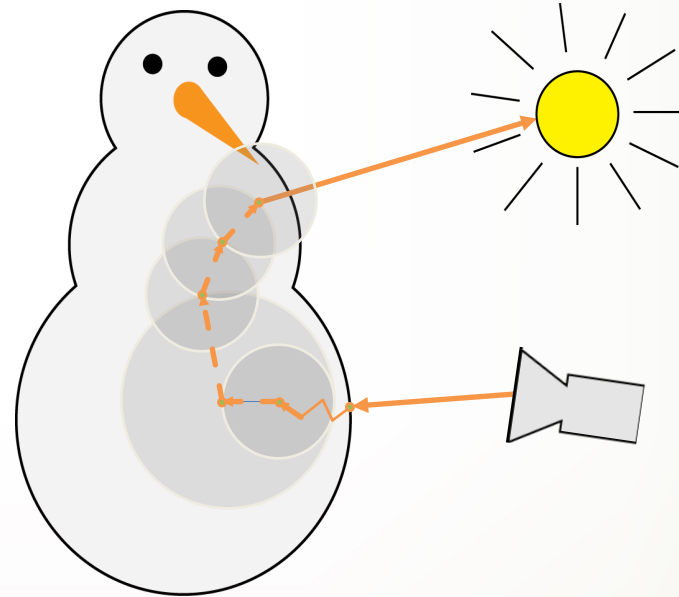
# ACCELERATING HIGH ORDER WITH SHELL TRACING



### Explicit Path Tracing



### Shell Tracing [Moon et al. 2007]

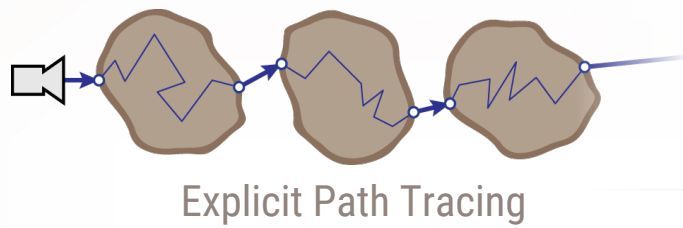




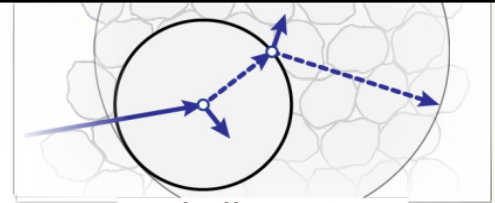
## Low order

## High order

Moon et al. 2007:



Explicit Path Tracing



Shell Tracing

- Per-grain material precomputation
- Only homogeneous

Meng et al. 2015:

Ours:







## Meng et al. 2015:



Grains



Continuous volume



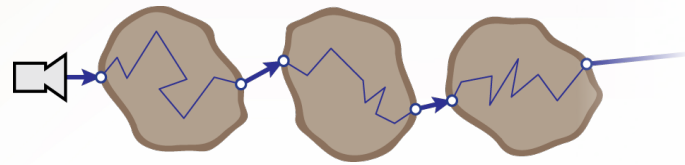


# METHODS OVERVIEW

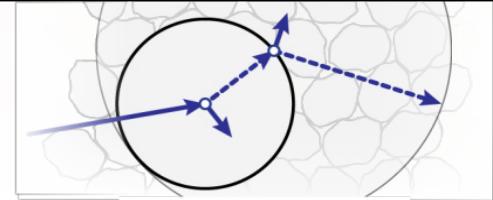
## Low order

## High order

Moon et al. 2007:



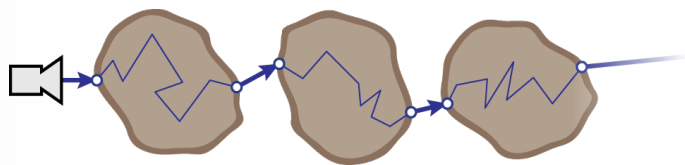
Explicit Path Tracing



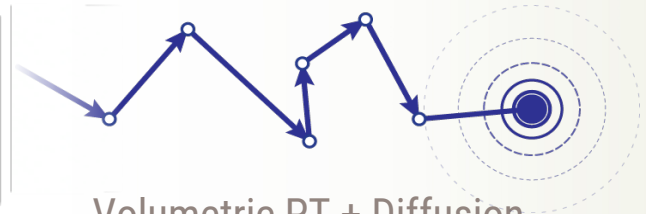
Shell Tracing

- Per-grain material precomputation
- Only homogeneous

Meng et al. 2015:



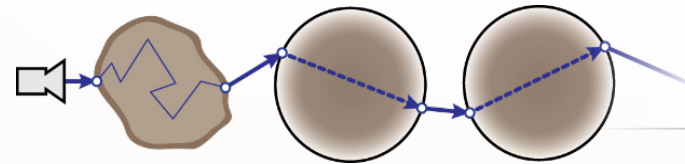
Explicit Path Tracing



Volumetric PT + Diffusion

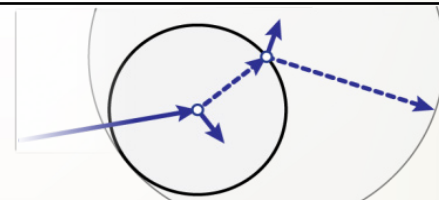
- Per-grain type precomputation
- Only homogeneous & monodisperse

Ours:



(Explicit PT +) Proxy PT

- Per-grain type precomputation



Volumetric Shell Tracing

- One-time global precomputation



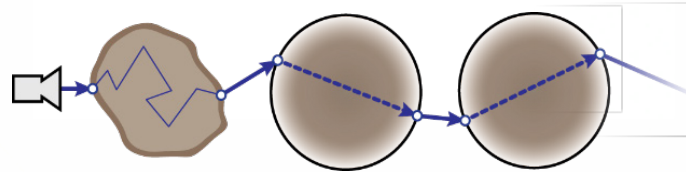




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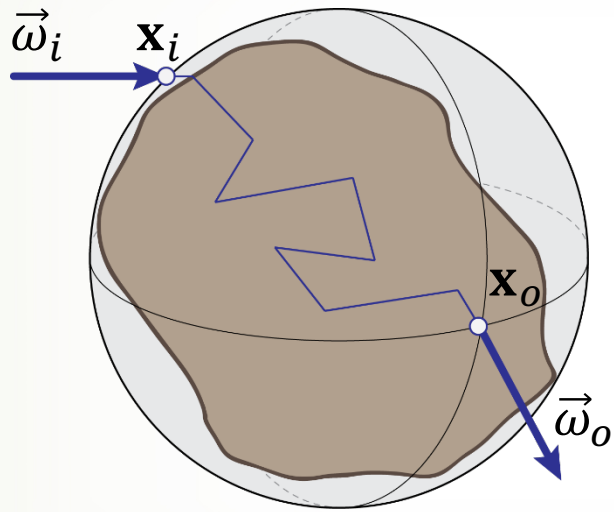
# Proxy Path Tracing

For accelerating low order light transport

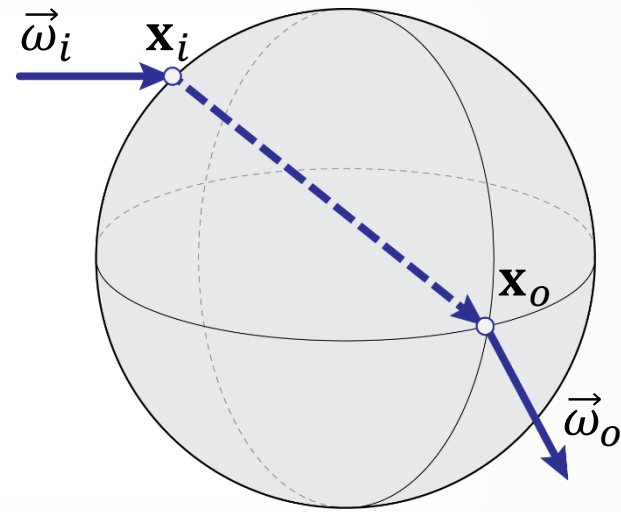




# PROXY REPRESENTATION OF GRAINS



**Grain**



**Spherical proxy**





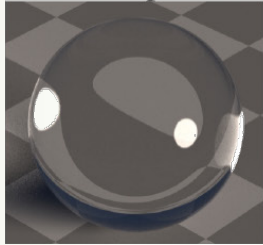


# DIMENSIONALITY REDUCTION OF PROXY REPRESENTATION

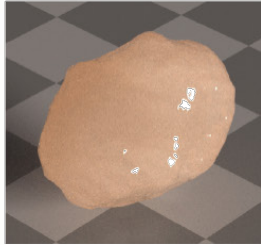


8D

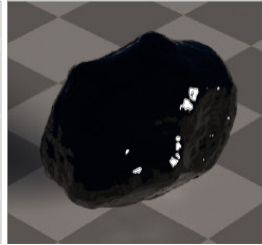
Glass sphere



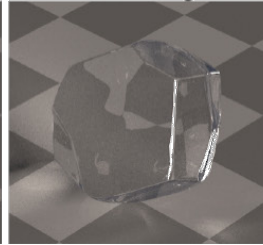
Brown sand



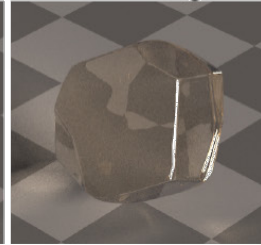
Black sand



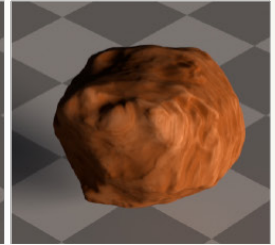
White sugar



Brown sugar



Cinnamon





# DIMENSIONALITY REDUCTION OF PROXY REPRESENTATION



	Glass sphere	Brown sand	Black sand	White sugar	Brown sugar	Cinnamon
8D						
5D						







# DIMENSIONALITY REDUCTION OF PROXY REPRESENTATION



	Glass sphere	Brown sand	Black sand	White sugar	Brown sugar	Cinnamon
8D						
5D						
3D						





# DIMENSIONALITY REDUCTION OF PROXY REPRESENTATION



	Glass sphere	Brown sand	Black sand	White sugar	Brown sugar	Cinnamon
8D						
5D						
3D						







# PROXY PATH TRACING RESULTS – SMALL SCALE

Explicit PT (reference):  
**369 hours**



Proxy Path Tracing (ours):  
**34.3 hours (10.7x)**





# PROXY PATH TRACING RESULTS – SMALL SCALE

Explicit PT (reference):

**369 hours**



Proxy Path Tracing (ours):

**34.3 hours (10.7x)**



Explicit + Proxy PT (ours):

**73.7 hours (5x)**







# PROXY PATH TRACING RESULTS – LARGE SCALE



Explicit PT (reference)

**1588 hours**

Meng et al. 2015

**722 hours (2.2x)**

Proxy PT (ours)

**19.4 hours (82x)**





# PROXY PATH TRACING RESULTS – LARGE SCALE



➔ Explicit PT (reference) **1588 hours**  
Meng et al. 2015      **722 hours**

➔ Explicit PT (reference) **1588 hours**  
Proxy PT (ours)      **19.4 hours**







# PROXY PATH TRACING RESULTS – LARGE SCALE



Explicit PT (reference) **1588 hours**

Explicit PT (reference) **1588 hours**

➔ Meng et al. 2015

**722 hours**

➔ Proxy PT (ours)

**19.4 hours**



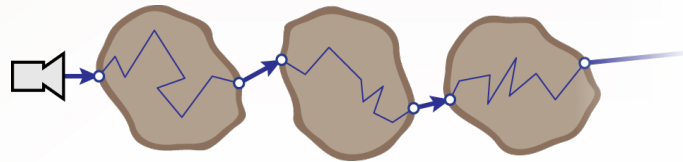


# METHODS OVERVIEW

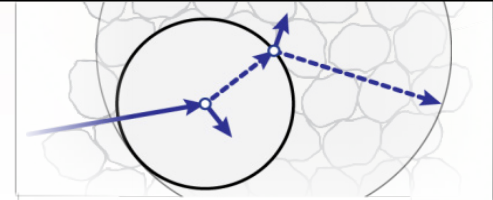
## Low order

## High order

Moon et al. 2007:



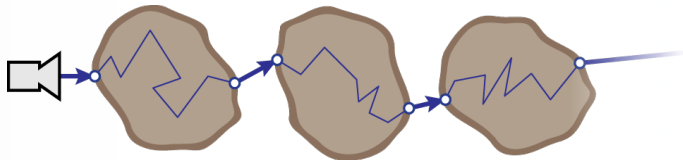
Explicit Path Tracing



Shell Tracing

- Per-grain material precomputation
- Only homogeneous

Meng et al. 2015:



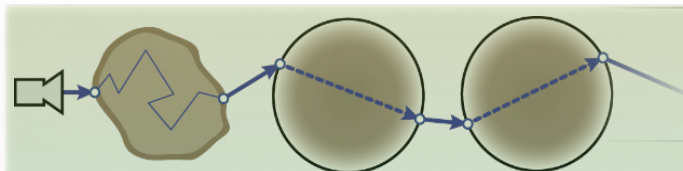
Explicit Path Tracing



Volumetric PT + Diffusion

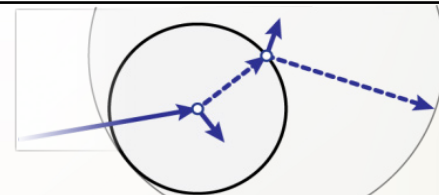
- Per-grain type precomputation
- Only homogeneous & monodisperse

Ours:



(Explicit PT + ) Proxy PT

- Per-grain type precomputation



Volumetric Shell Tracing

One-time global precomputation



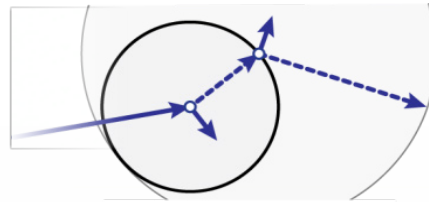


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# Volumetric Shell Tracing

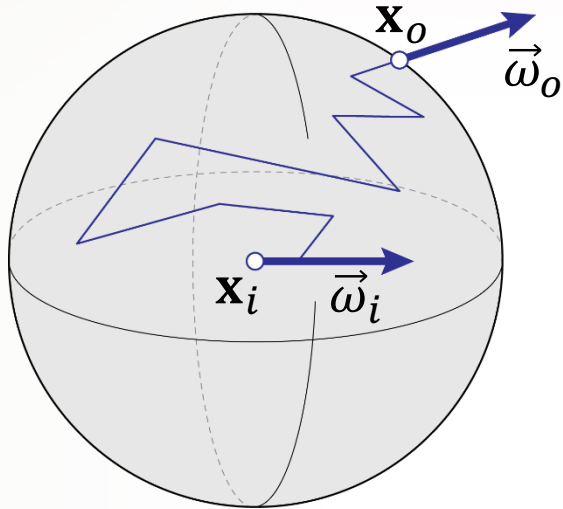
For accelerating high order light transport



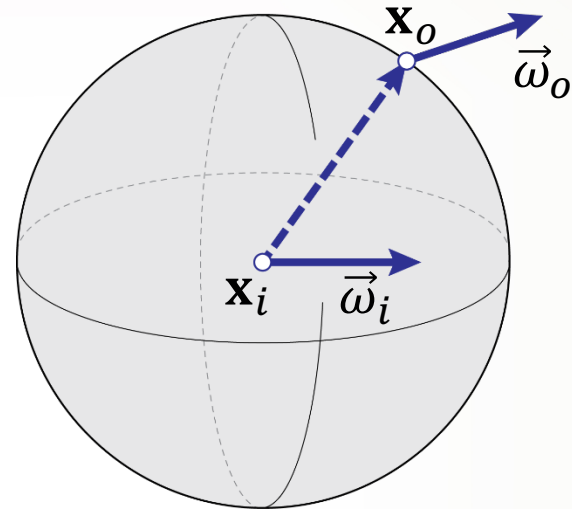




# SHELL TRANSPORT FUNCTION

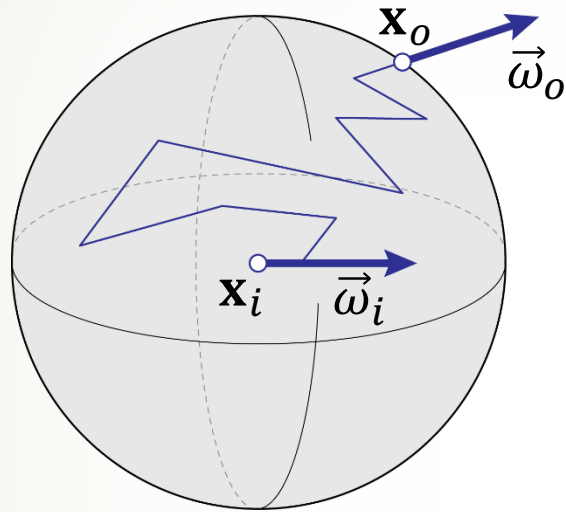


**Sphere filled  
with medium**



**Shell Transport  
Function**





**Sphere filled  
with grains**

**Moon et al. 2007:**

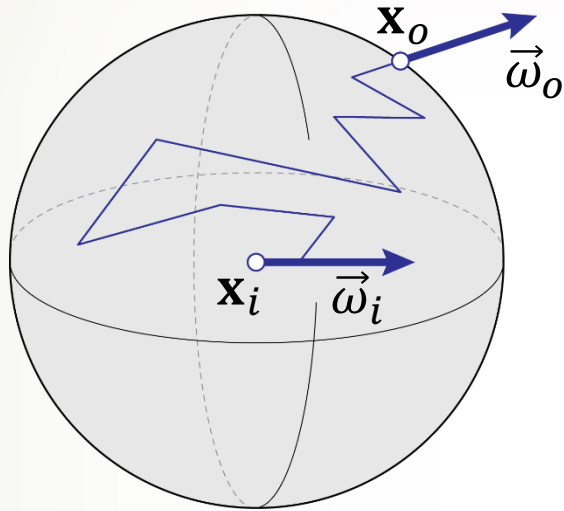


**Grains**





# SHELL TRANSPORT FUNCTION – OURS



**Sphere filled  
with continuous  
approximation**

**Ours:**



Continuous approximation [Meng et al. 2015]



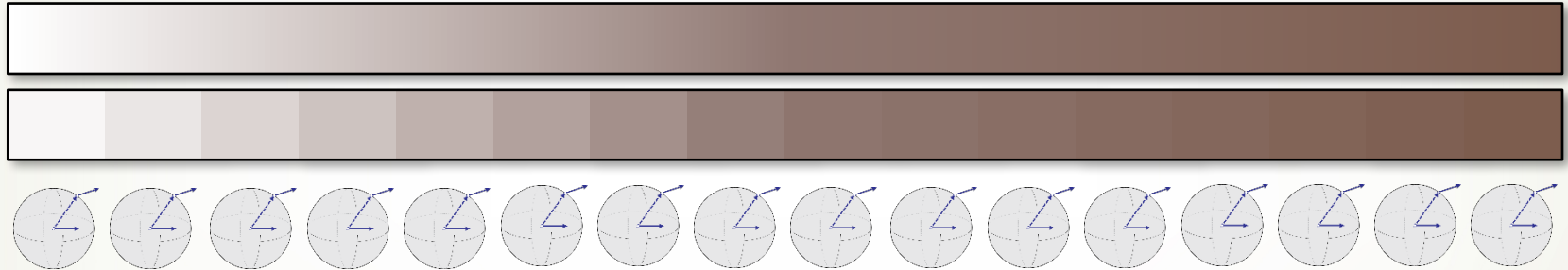




## Why continuous volumes?

- Significantly faster pre-computation (**~1000x**)
- Enables dense dictionary of shells!

RTE parameter space (HG phase function)

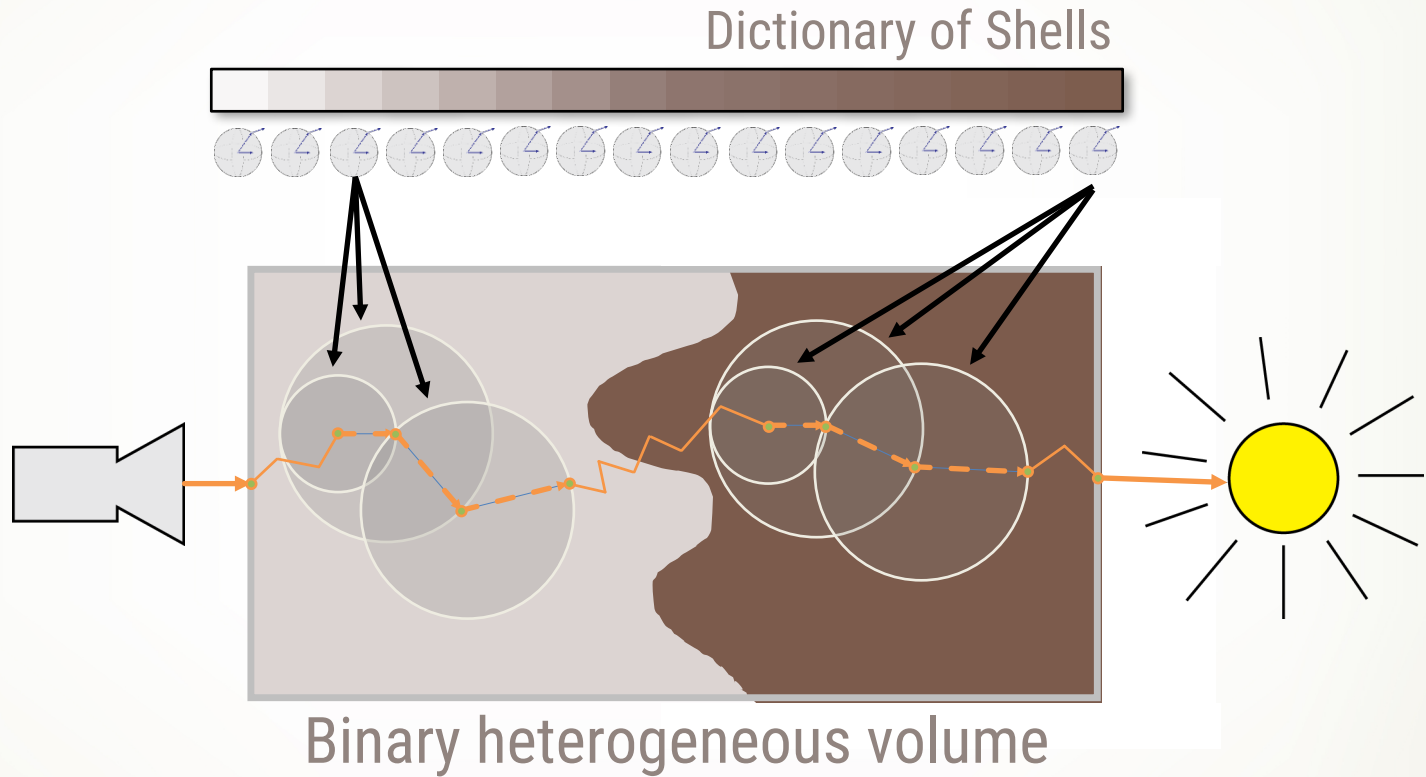


High-resolution dictionary of shells over full RTE space  
**(240 MB, 10h precomputation on workstation)**



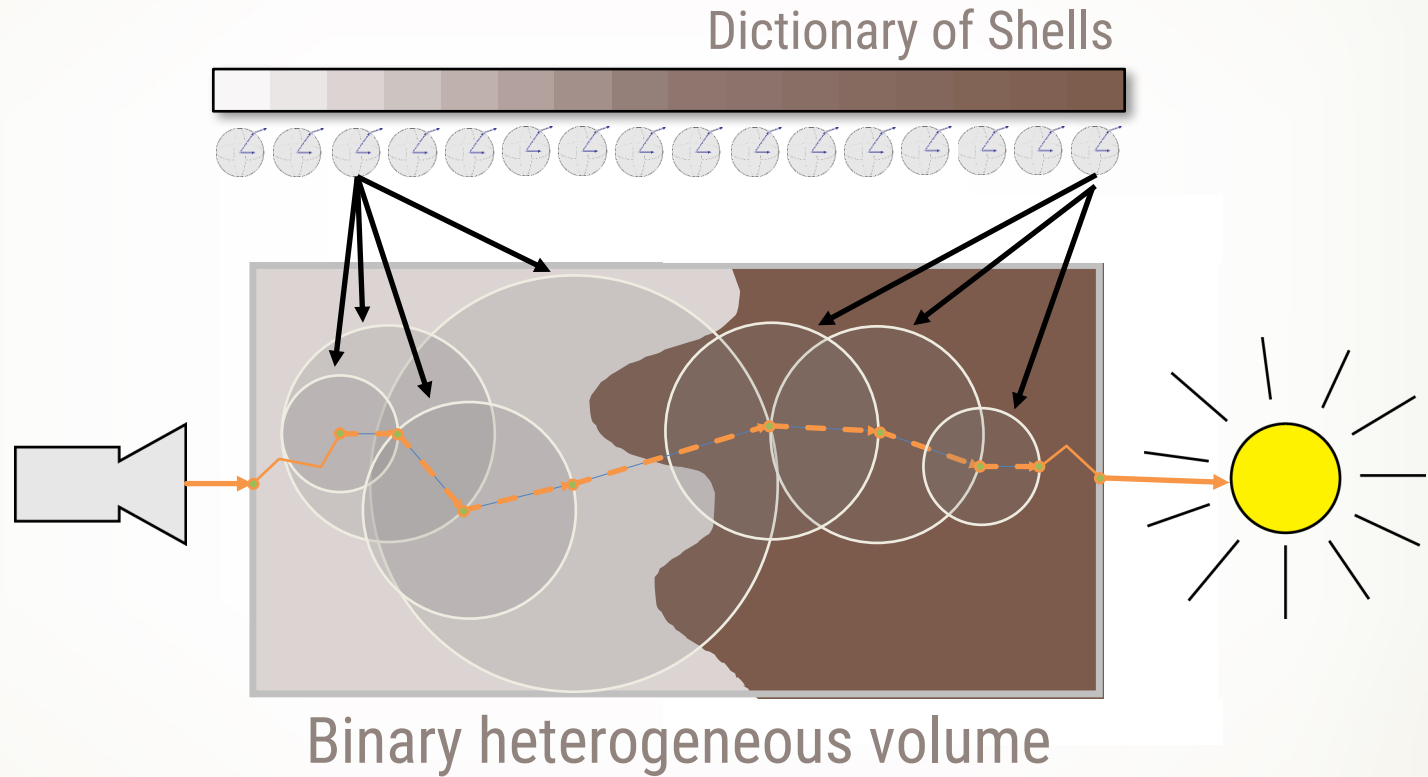


# SHELL TRACING IN HETEROGENEOUS VOLUMES (CONSERVATIVE)





# SHELL TRACING IN HETEROGENEOUS VOLUMES (GREEDY)

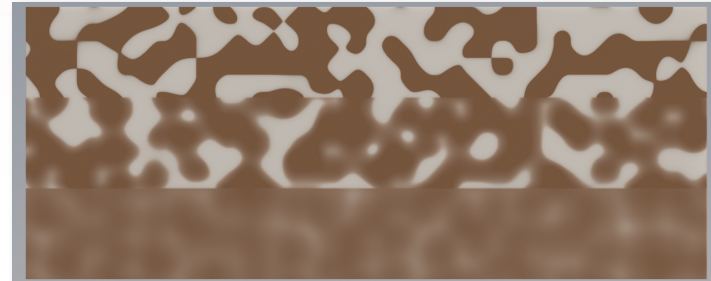




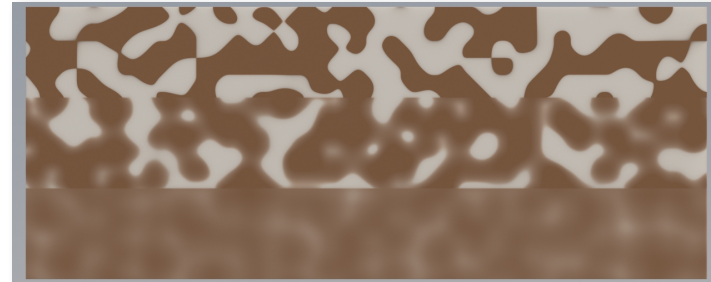


# SHELL TRACING: GREEDY VS. CONSERVATIVE (THICK MEDIUM)

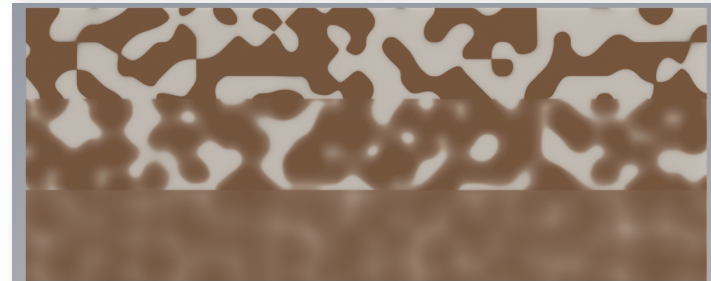
Volumetric PT (reference):  
**802 hours**



Cons. Shell Tracing (ours):  
**173 hours (4.6x)**



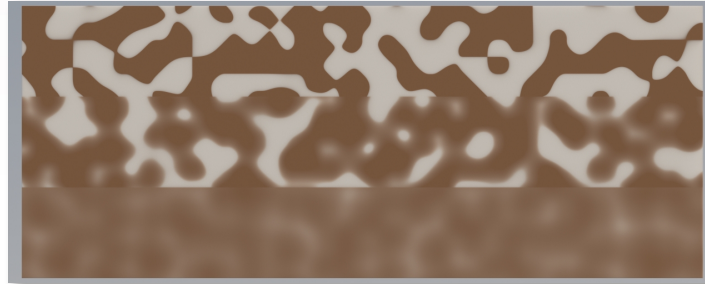
Greedy Shell Tracing (ours):  
**155 hours (5.2x)**



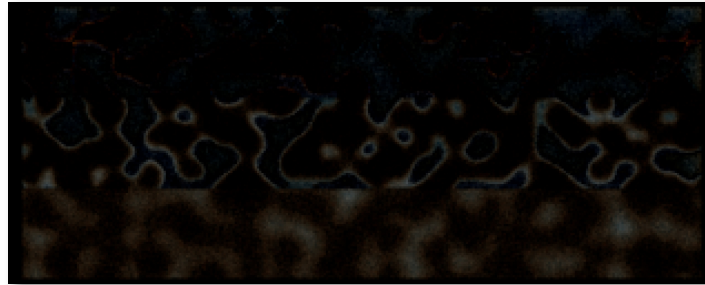


# SHELL TRACING: GREEDY VS. CONSERVATIVE (THICK MEDIUM)

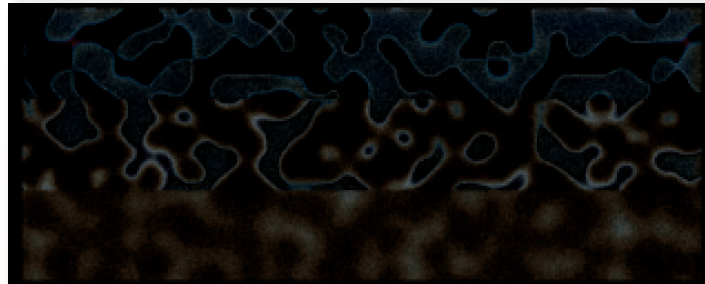
Volumetric PT (reference):  
**802 hours**



Cons. Shell Tracing (ours):  
**173 hours (4.6x)**



Greedy Shell Tracing (ours):  
**155 hours (5.2x)**



Relative Squared Error x64



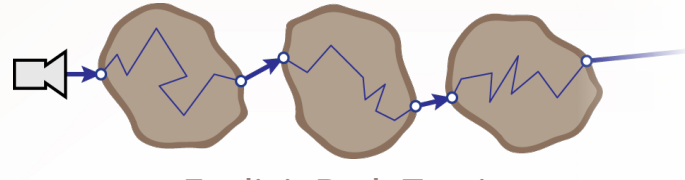


# METHODS OVERVIEW

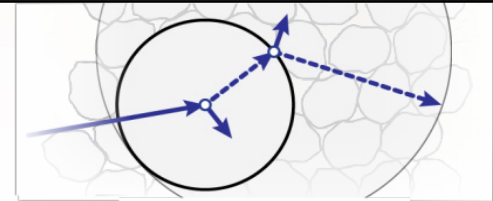
## Low order

## High order

Moon et al. 2007:



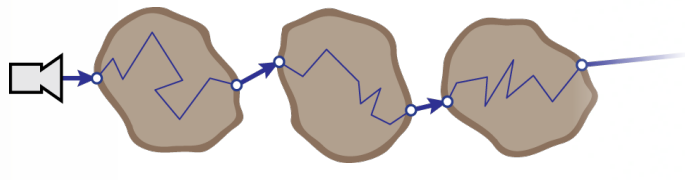
Explicit Path Tracing



Shell Tracing

- Per-grain material precomputation
- Only homogeneous

Meng et al. 2015:



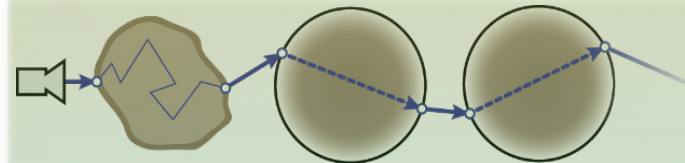
Explicit Path Tracing



Volumetric PT + Diffusion

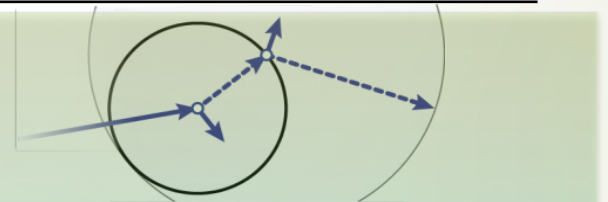
- Per-grain type precomputation
- Only homogeneous & monodisperse

Ours:



(Explicit PT + ) Proxy PT

- Per-grain type precomputation



Volumetric Shell Tracing

- One-time global precomputation







# OUR FULL METHOD VS. MENG ET AL. 2015 (HOMOGENEOUS)



Explicit Path Tracing  
**13,480 hours**



Meng et al. 2015  
**93 hours (145x)**



Our full method  
**5 hours (2,696x)**





# OUR FULL METHOD VS. MENG ET AL. 2015 (HOMOGENEOUS)

Relative Squared Error x8



Explicit Path Tracing  
**13,480 hours**



Meng et al. 2015  
**93 hours (145x)**



Our full method  
**5 hours (2,696x)**





# OUR FULL METHOD VS. MENG ET AL. 2015 (HOMOGENEOUS)



➔ Explicit PT (reference) **13,480 hours**  
Meng et al. 2015 **93 hours**

➔ Explicit PT (reference) **13,480 hours**  
Our full method **5 hours**







# OUR FULL METHOD VS. MENG ET AL. 2015 (HOMOGENEOUS)



Explicit PT (reference) **13,480 hours**

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**93 hours**



Explicit PT (reference) **13,480 hours**

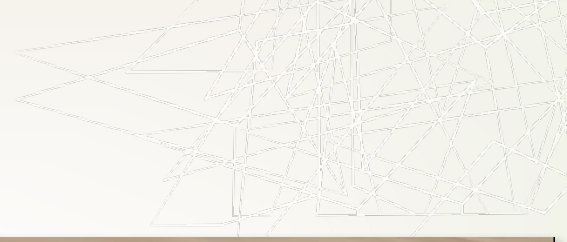
➔ Our full method

**5 hours**





# OUR FULL METHOD (HETEROGENEOUS)



© Disney





# MORE RESULTS AND VALIDATION

## Test Suite Overview

We present equal-time and equal-variance comparisons between brute-force reference techniques, the method of Meng et al. [2015], and ours. Due to the way we render images on a cluster we can not show images with exactly equal render times and variance. Thus, we always give our methods the disadvantage by displaying images with lowest render times in equal-time comparisons and lowest variances in equal-variance comparisons.

For each rendering technique we report time to unit variance (TTUV), the mean relative squared error (MRSE), and an estimate of the absolute bias. We compute the latter by subtracting a variance estimate of both images from the mean squared error (MSE) and then taking the square root.



Bowl



Castle



Dunes



Spices



Pile



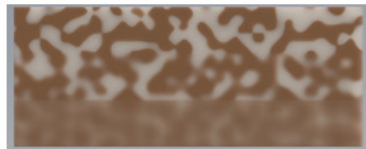
TwoPiles



Lucy



Snowman



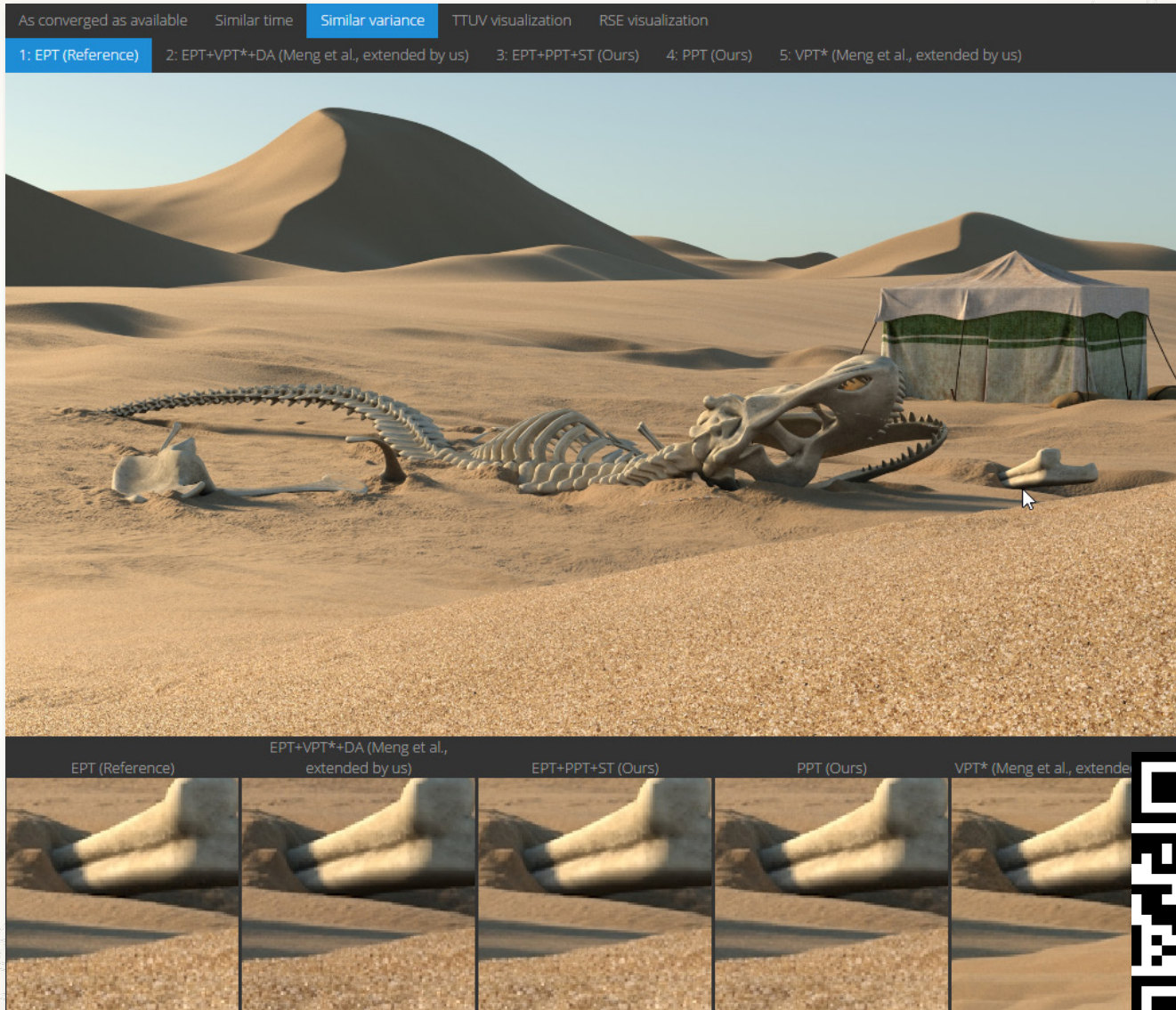
Wedge







# MORE RESULTS AND VALIDATION





# MORE RESULTS AND VALIDATION

	Reference	Approximate Solution				Approximation Error (RSE×12)			
	VPT TTUV: 3.54e-4 hrs	VPT+2D STFs TTUV: 1.99e-4 hrs	+HG Phase TTUV: 3.61e-4 hrs	+Tight Interp. TTUV: 2.90e-4 hrs	VPT+Diffusion TTUV: 2.14e-4 hrs	VPT+2D STFs MRSE: 2.16e-5	+HG Phase MRSE: 5.88e-5	+Tight Interp. MRSE: 1.07e-4	VPT+Diffusion MRSE: 8.21e-4
10 cm large									
1 m large									
10 m large									
100 m large									



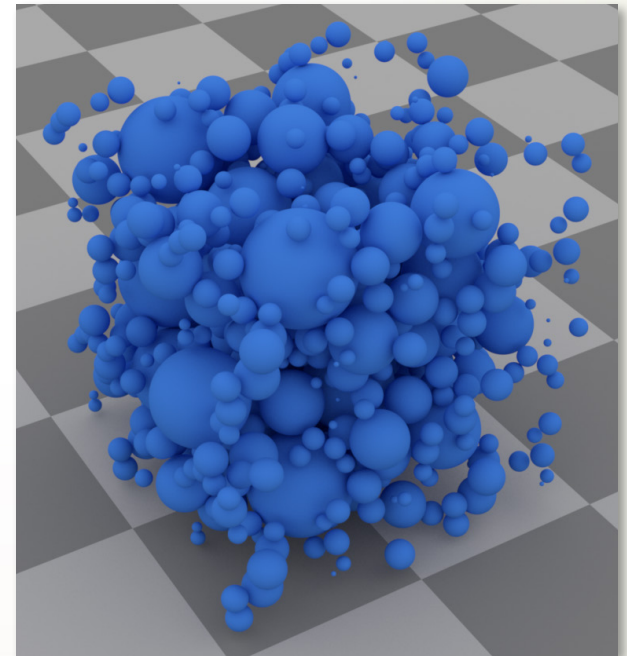


## LIMITATIONS OF BOUNDING SPHERE PACKING

- Limited packing density
- No anisotropy
- Uncorrelated grain orientations



[Meng et al. 2015]



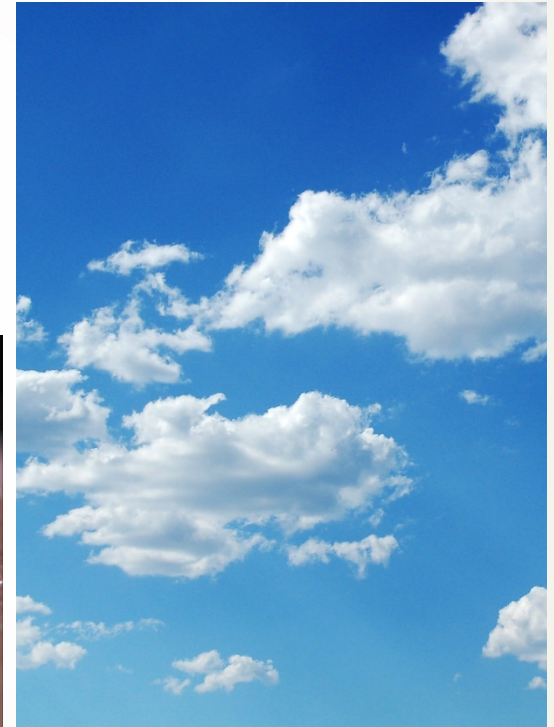
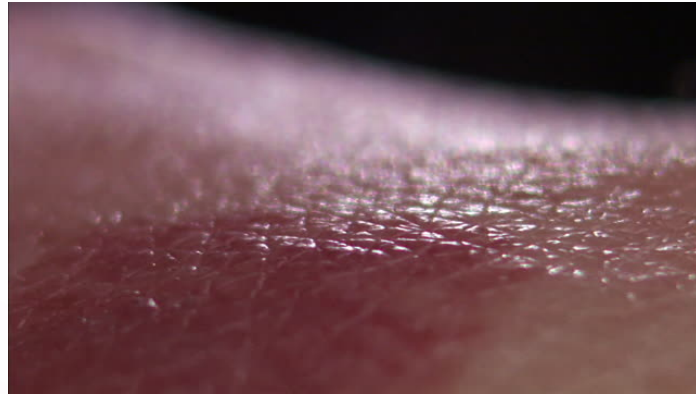




# FUTURE WORK FOR VOLUMETRIC SHELL TRACING



- Shell Tracing vs. Diffusion
- Shell Tracing in clouds
- Hair rendering





**THANK YOU FOR YOUR  
ATTENTION!**

Email: [muelltho@inf.ethz.ch](mailto:muelltho@inf.ethz.ch)

Web: <https://tom94.net>

## ACKNOWLEDGEMENTS

- Maurizio Nitti
- Alessia Marra
- Romain Prévost
- Stanford 3D Scanning Repository

