Multidimensional Lightcuts

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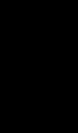
Problem



- Simulate complex, expensive phenomena
  - Complex illumination
  - Anti-aliasing
  - Motion blur
  - Participating media
  - Depth of field

$$\text{Pixel} = \int_{\text{Time}} \int_{\text{Pixel Area}} \int_{\text{Lights}} L(\mathbf{x}, \omega) \ldots$$

Problem

- Simulate complex, expensive phenomena
  - Complex illumination
  - Anti-aliasing
  - Motion blur
  - Participating media
  - Depth of field

$$\text{Pixel} = \int_{\text{Volume}} \int_{\text{Time}} \int_{\text{Pixel Area}} \int_{\text{Lights}} L(\mathbf{x}, \omega) \ldots$$

Problem

- Simulate complex, expensive phenomena
  - Complex illumination
  - Anti-aliasing
  - Motion blur
  - Participating media
  - Depth of field

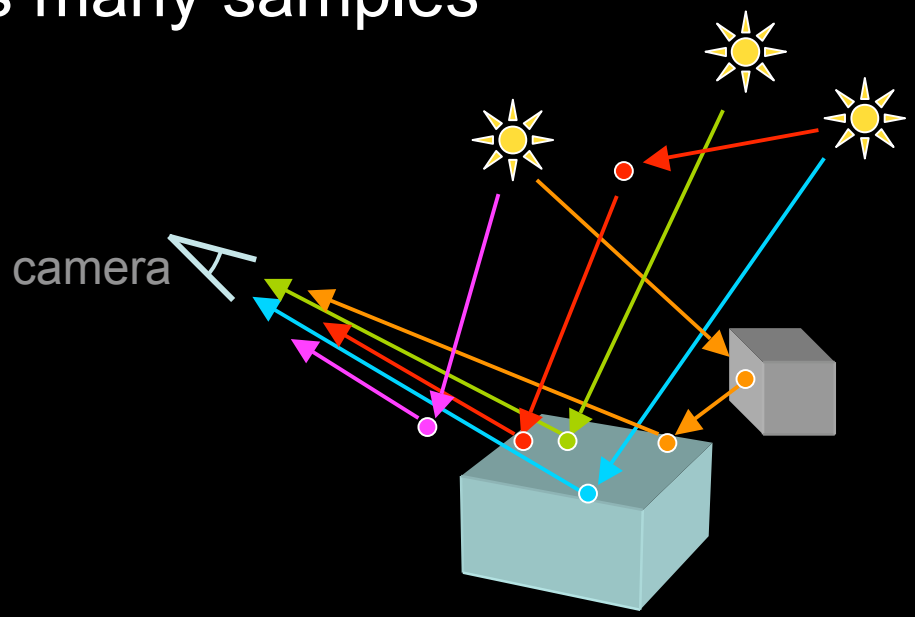
$$\text{Pixel} = \int_{\text{Aperture}} \int_{\text{Volume}} \int_{\text{Time}} \int_{\text{Pixel Area}} \int_{\text{Lights}} L(\mathbf{x}, \omega) \ldots$$

Problem

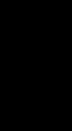
- Complex integrals over multiple dimensions

$$\text{Pixel} = \int_{\text{Aperture}} \int_{\text{Volume}} \int_{\text{Time}} \int_{\text{Pixel Area}} \int_{\text{Lights}} L(\mathbf{x},\omega)\ldots$$

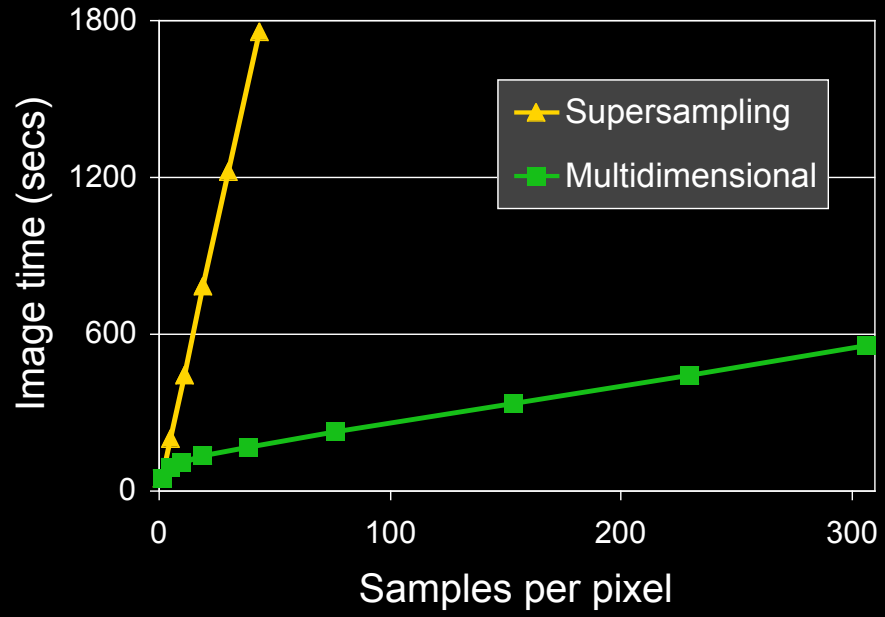
  - Requires many samples



Multidimensional Lightcuts



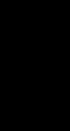
- New unified rendering solution
  - Solves all integrals simultaneously
  - Accurate
  - Scalable



Related Work

- Motion blur
  - Separable [eg, Korein & Badler 83, Catmull 84, Cook 87, Sung 02]
  - Qualitative [eg, Max & Lerner 85, Wloka & Zeleznik 96, Myszkowski et al. 00, Tawara et al. 04]
  - Surveys [Sung et al. 02, Damez et al. 03]
- Volumetric
  - Approximate [eg, Premoze et al. 04, Sun et al. 05]
  - Survey [Cerezo et al. 05]
- Monte Carlo
  - Photon mapping [Jensen & Christensen 98, Cammarano & Jensen 02]
  - Bidirectional [Lafortune & Willems 93, Bekaert et al. 02, Havran et al. 03]
  - Metropolis [Veach & Guibas 97, Pauly et al. 00, Cline et al. 05]

Related Work



- Lightcuts (SIGGRAPH 2005)
  - Scalable solution for complex illumination
  - Area lights
  - Sun/sky
  - HDR env maps
  - Indirect illumination

- Millions of lights → hundreds of shadow rays
  - But only illumination at a single point

Insight

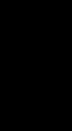
- Holistic approach
  - Solve the complete pixel integral

$$\text{Pixel} = \int_{\text{Aperture}} \int_{\text{Volume}} \int_{\text{Time}} \int_{\text{Pixel Area}} \int_{\text{Lights}} L(\mathbf{x},\omega)\ldots$$

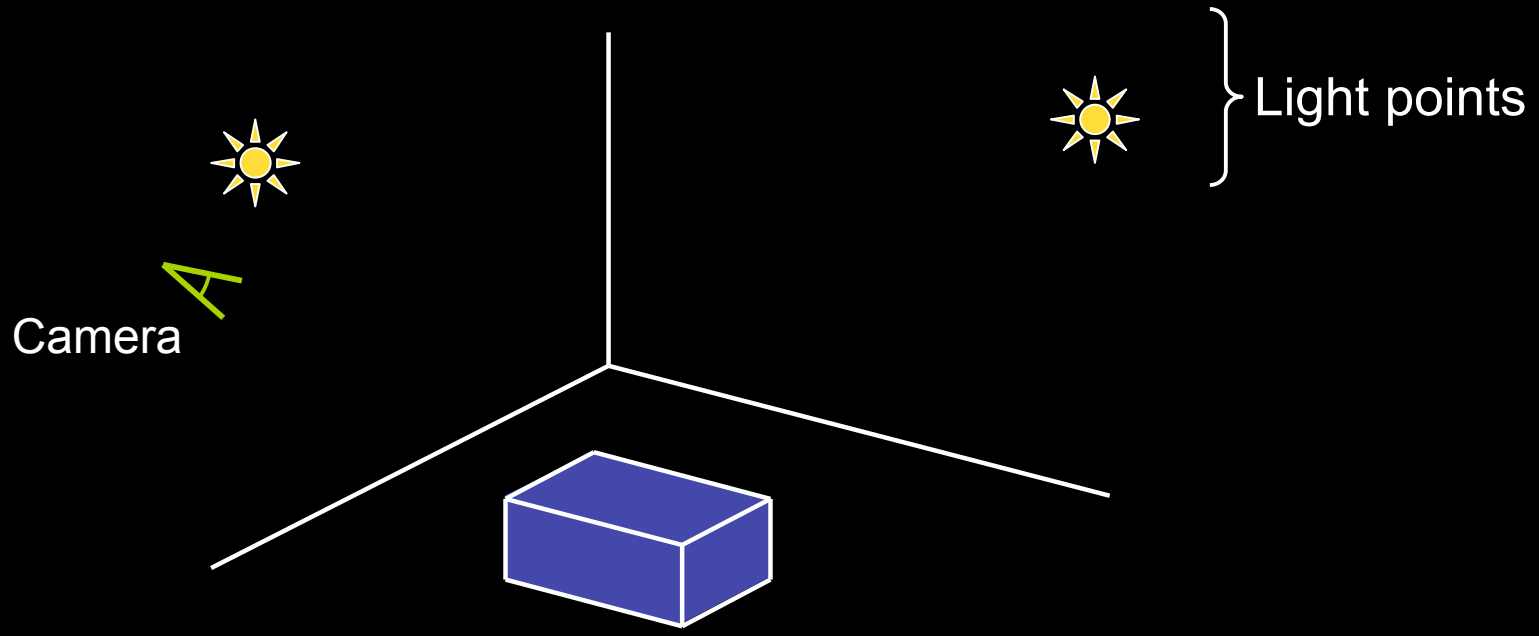
  - Rather than solving each integral individually


Direct only (relative cost 1x)
Direct+Indirect (1.3x)
Direct+Indirect+Volume (1.8x)
Direct+Indirect+Volume+Motion (2.2x)

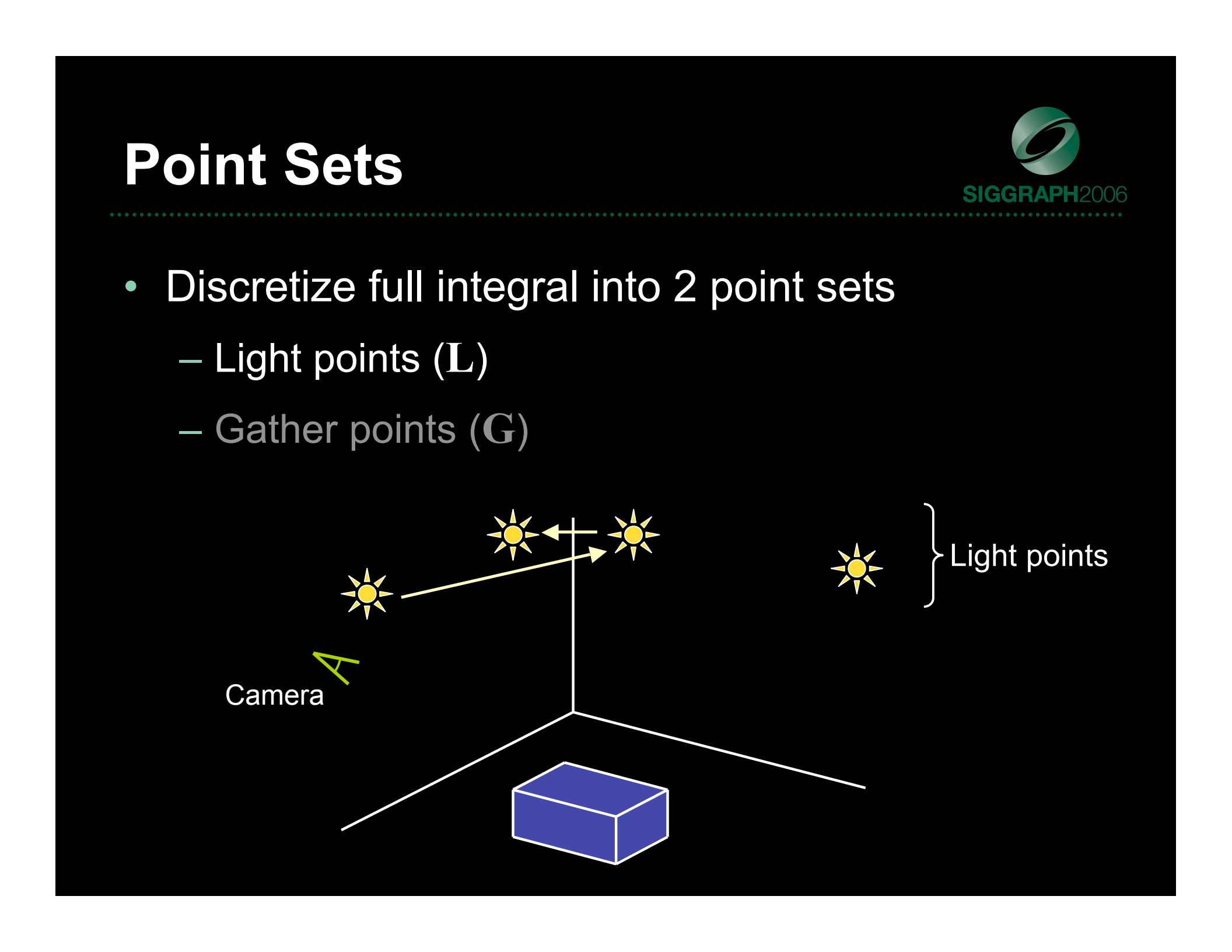
Point Sets



- Discretize full integral into 2 point sets
  - Light points ($\mathbf{L}$)
  - Gather points ($\mathbf{G}$)



Point Sets



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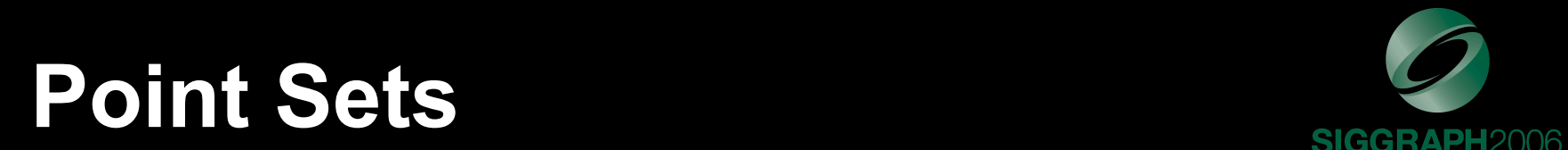

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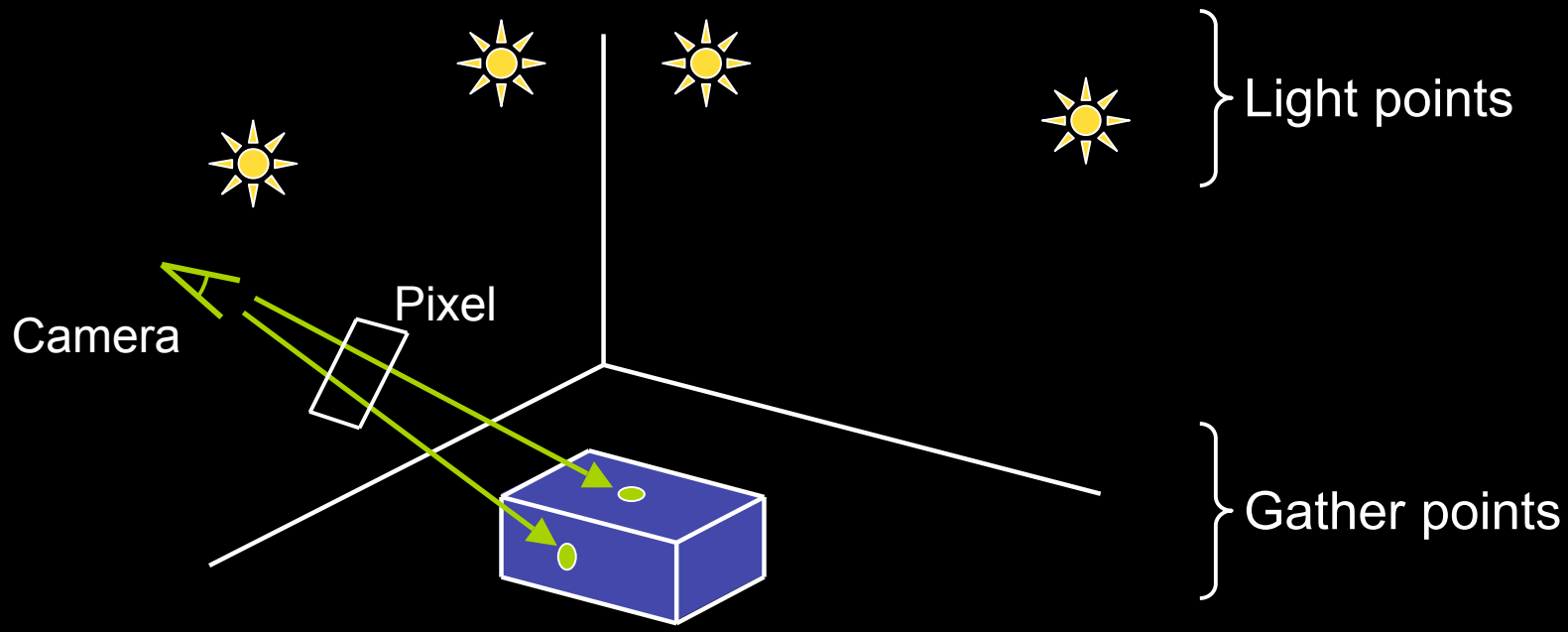

Point Sets

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  - Light points ($\mathbf{L}$)
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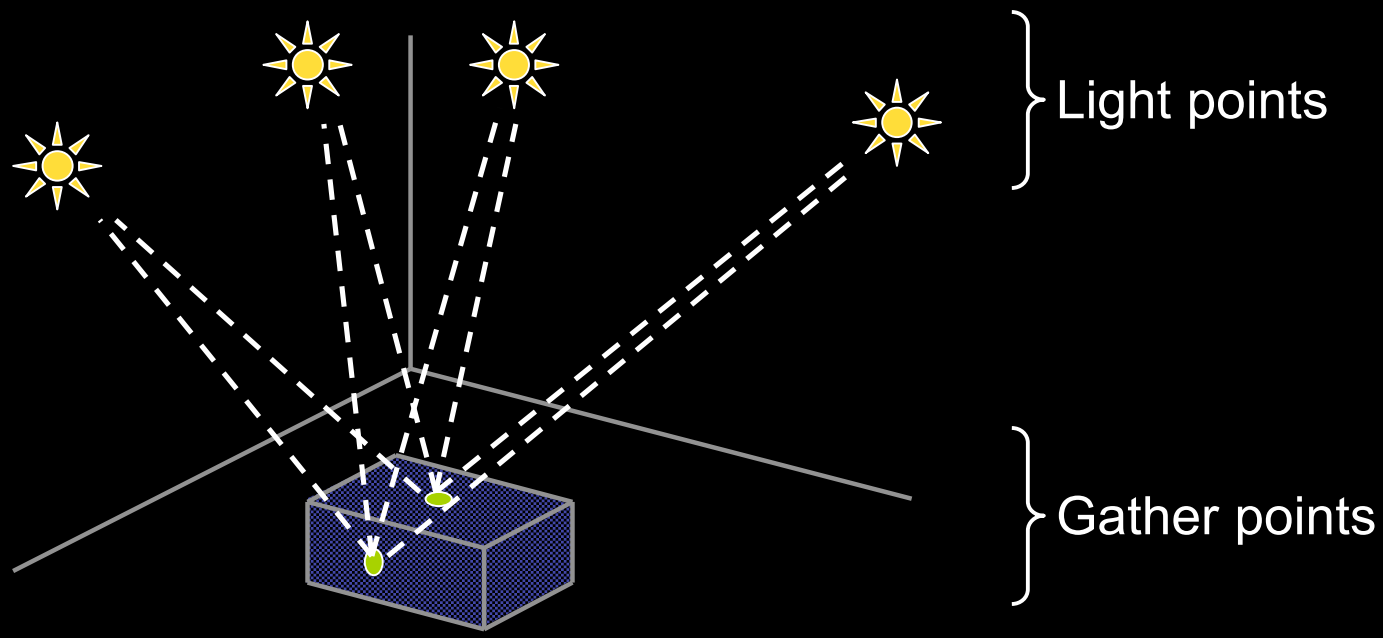


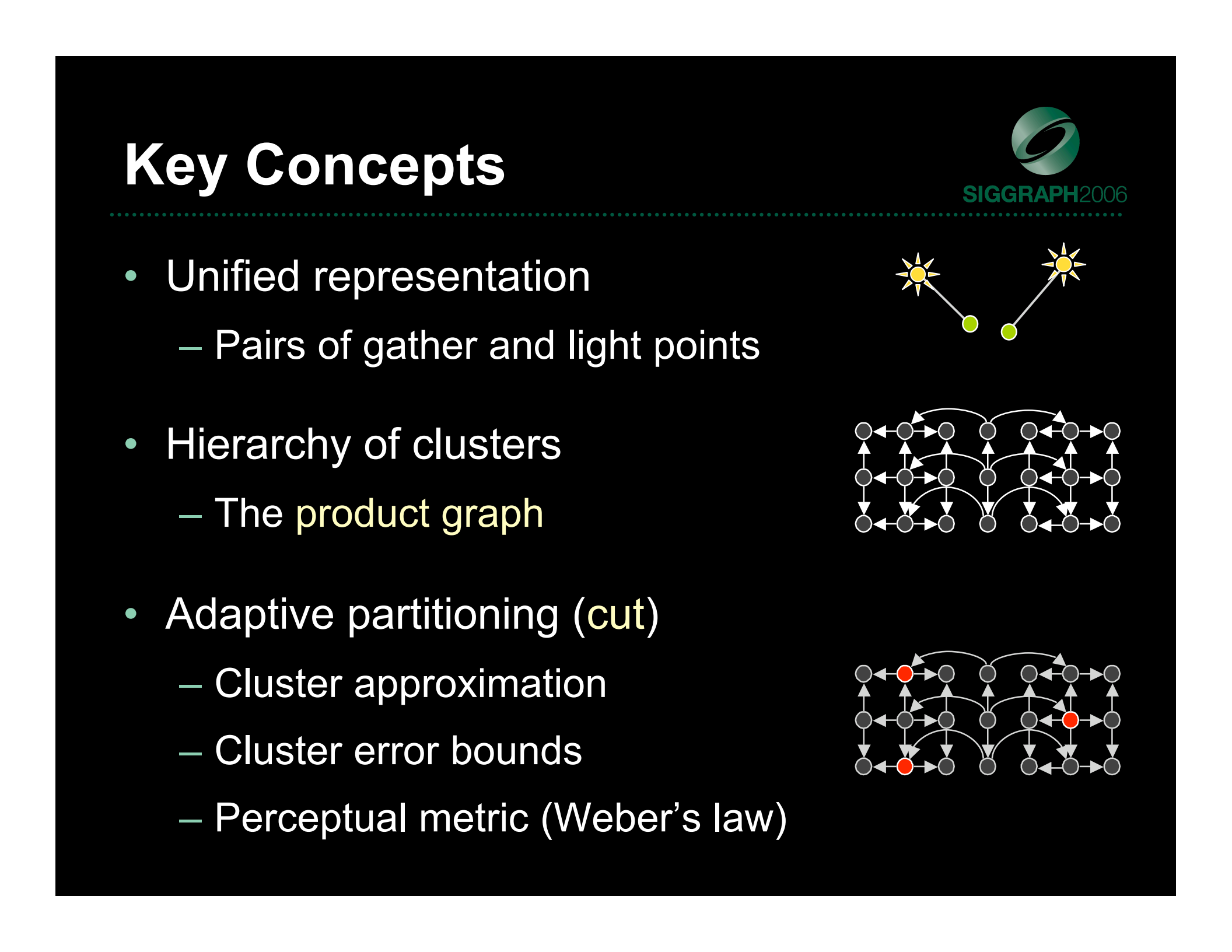
Discrete Equation

- Sum over all pairs of gather and light points
  - Can be billions of pairs per pixel

$$\text{Pixel} = \sum_{(j,i)\in G\times L} S_j \, M_{ji} \, G_{ji} \, V_{ji} \, I_i$$

- S_j: Gather strength
- M_{ji}: Material term
- G_{ji}: Geometric term
- V_{ji}: Visibility term
- I_i: Light intensity

Key Concepts



- Unified representation
  - Pairs of gather and light points

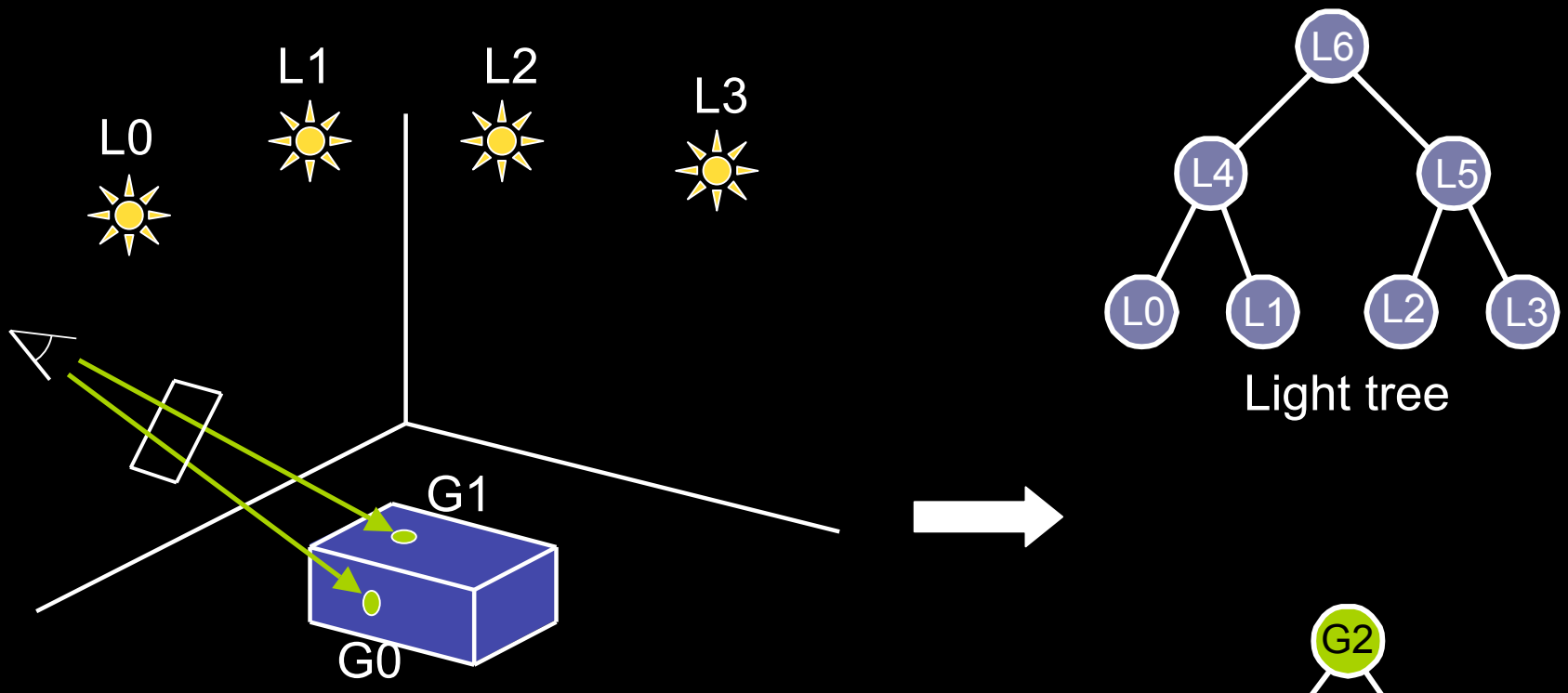
- Hierarchy of clusters
  - The product graph

- Adaptive partitioning (cut)
  - Cluster approximation
  - Cluster error bounds
  - Perceptual metric (Weber's law)

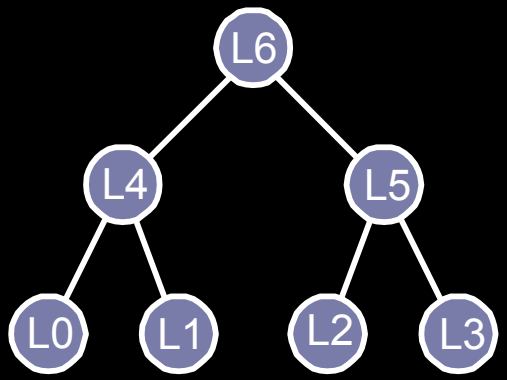
Product Graph

- Explicit hierarchy would be too expensive
  - Up to billions of pairs per pixel
- Use implicit hierarchy
  - Cartesian product of two trees (gather & light)

Product Graph

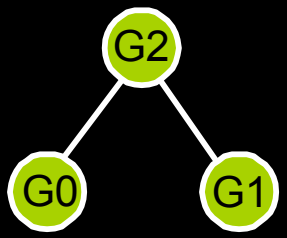


Product Graph



Light tree

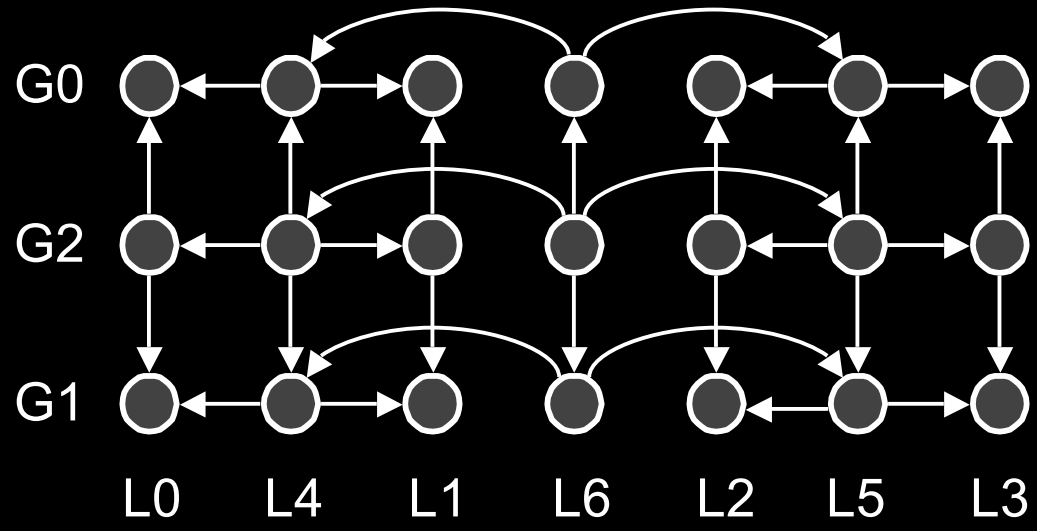
X



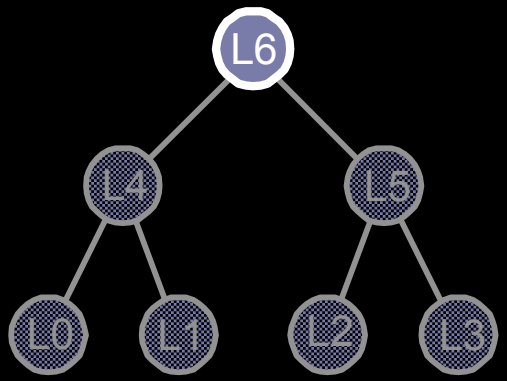
Gather tree

=

Product Graph

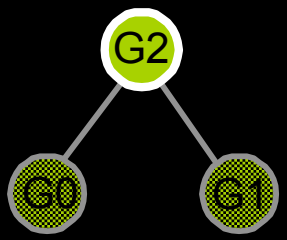


Product Graph



Light tree

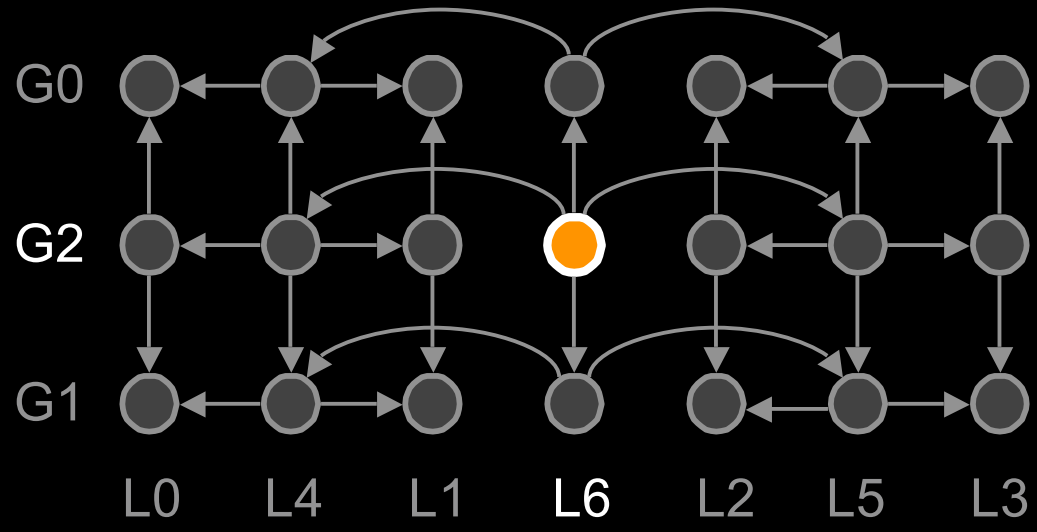
X



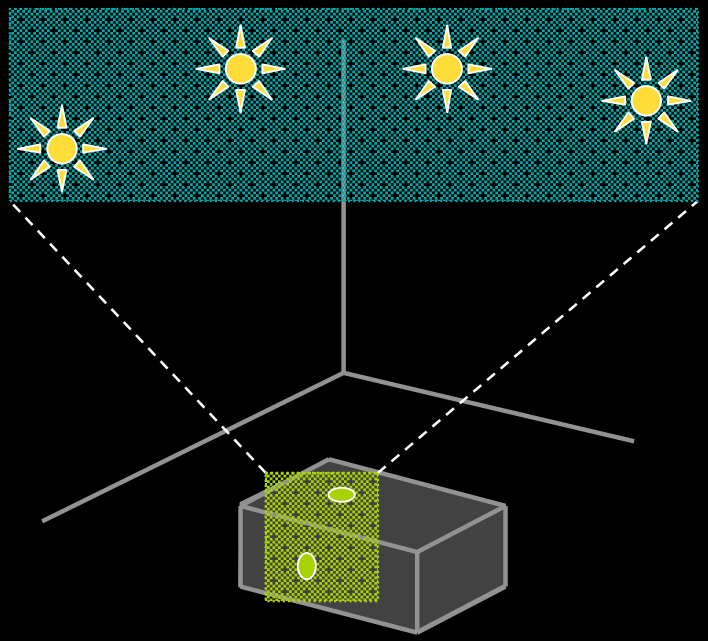
Gather tree

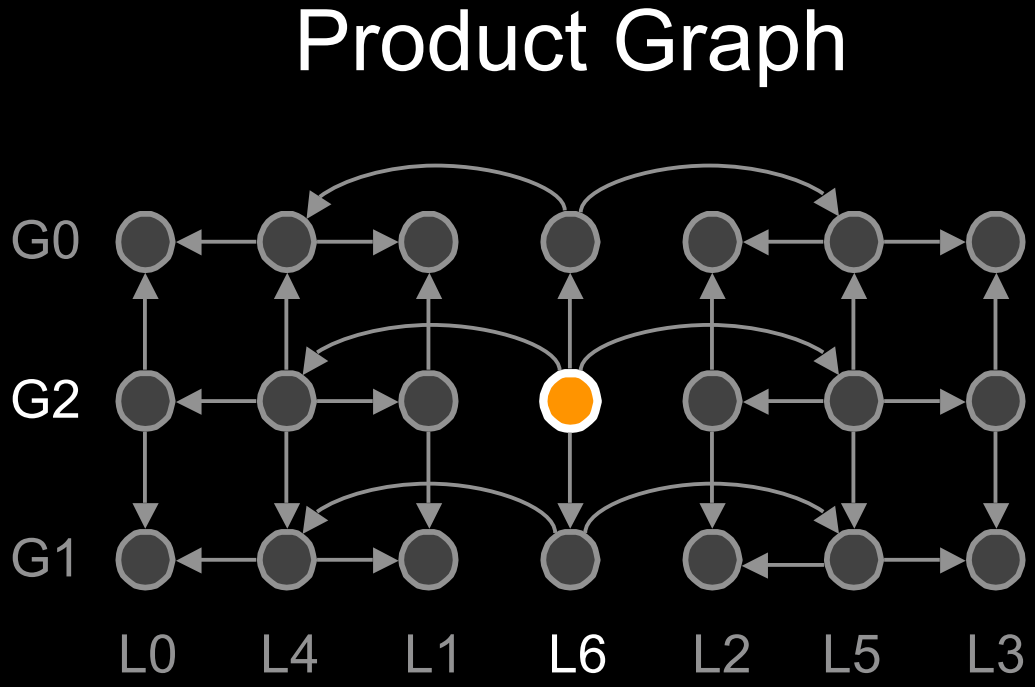
=

Product Graph



Product Graph





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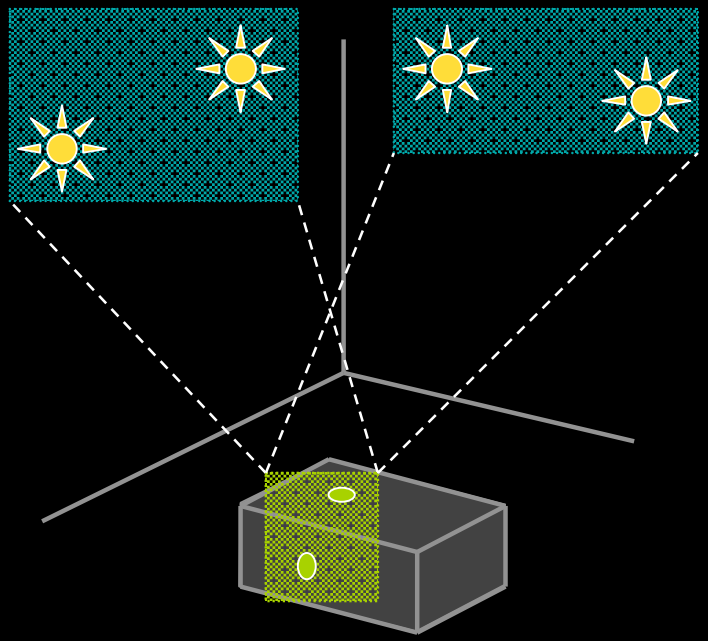
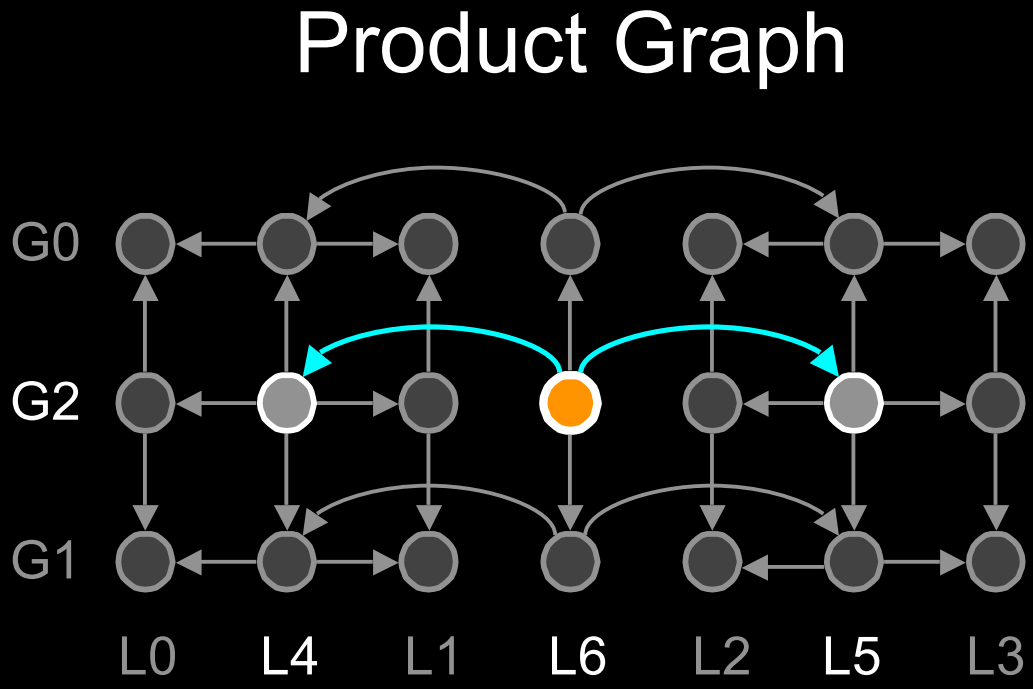
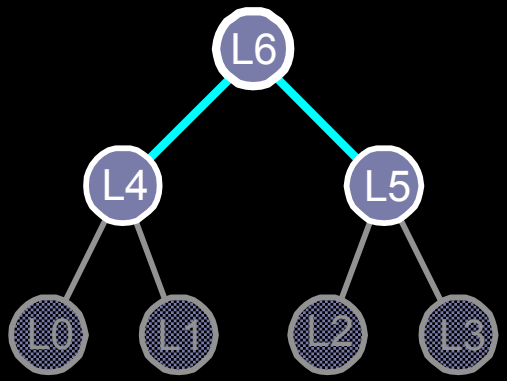


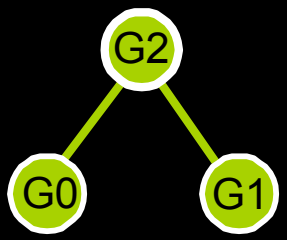


Product Graph



Light tree

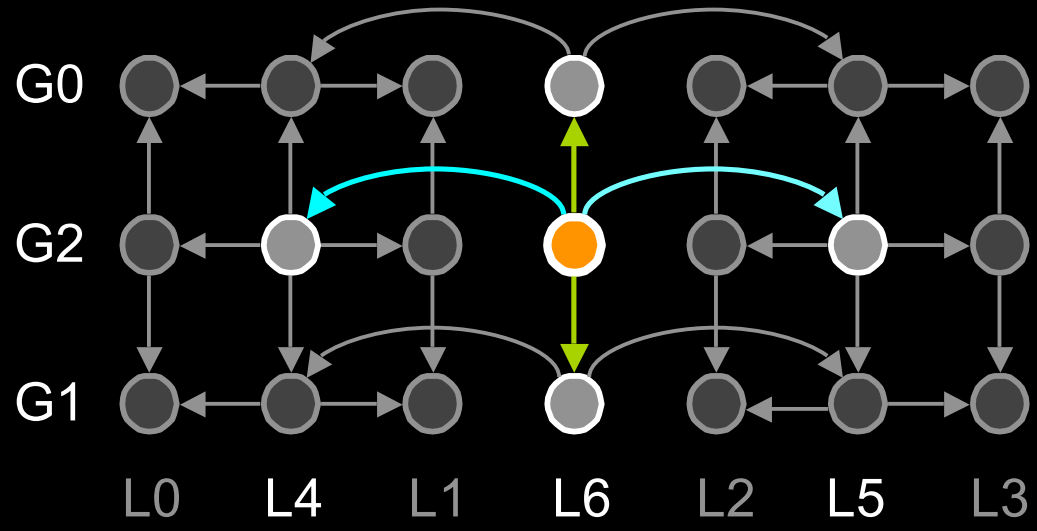
X



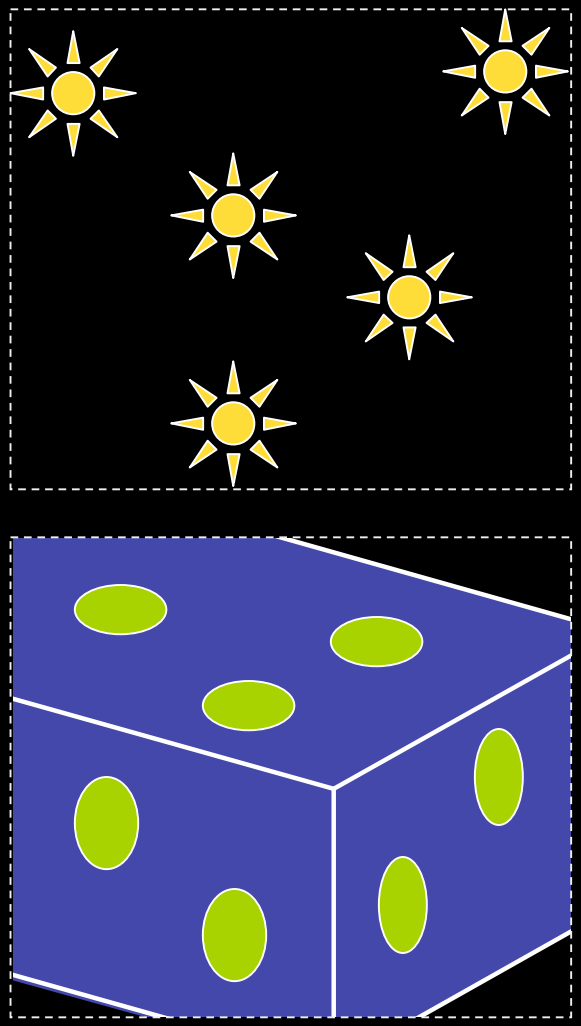
Gather tree

=

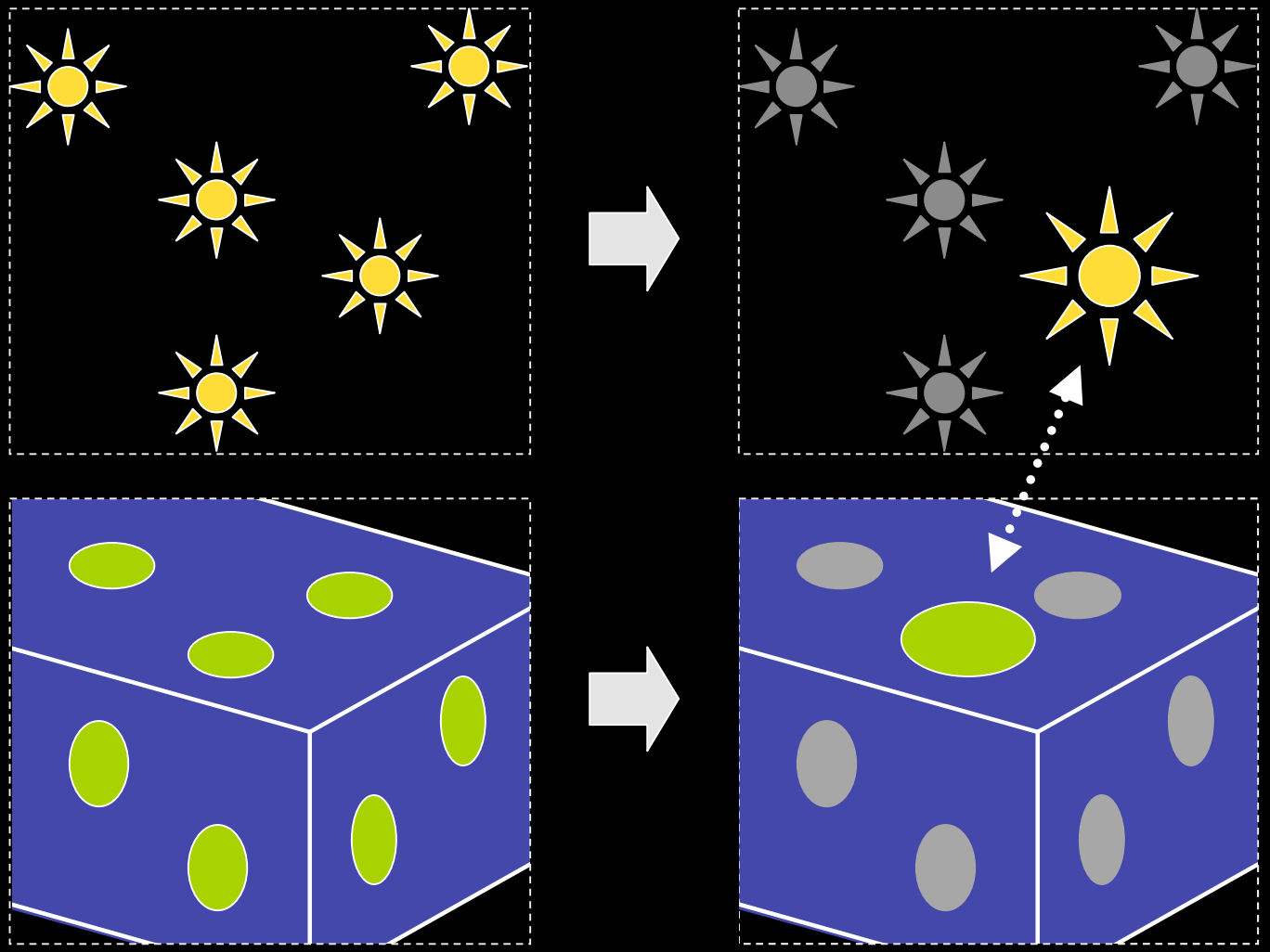
Product Graph



Cluster Representatives

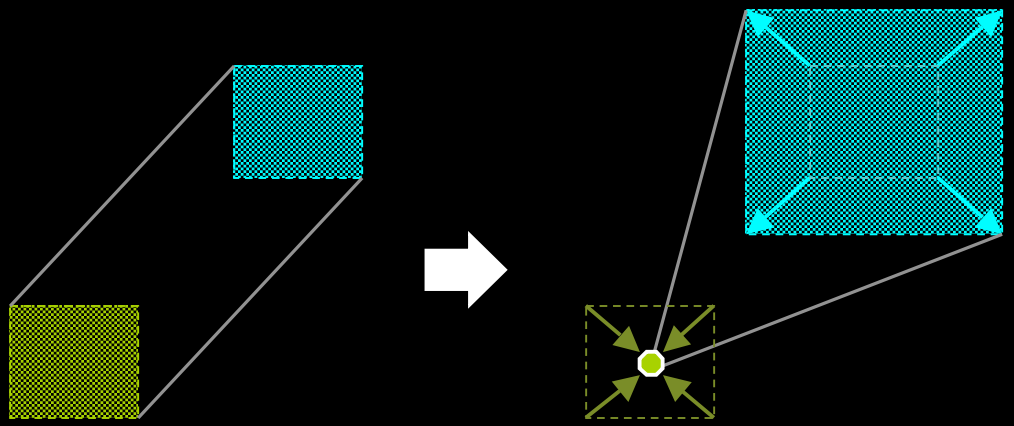


Cluster Representatives

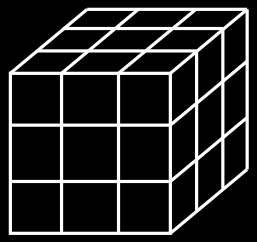


Error Bounds

- Collapse cluster-cluster interactions to point-cluster
  - Minkowski sums
  - Reuse bounds from Lightcuts



- Compute maximum over multiple BRDFs
  - Rasterize into cube-maps

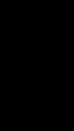


- More details in the paper

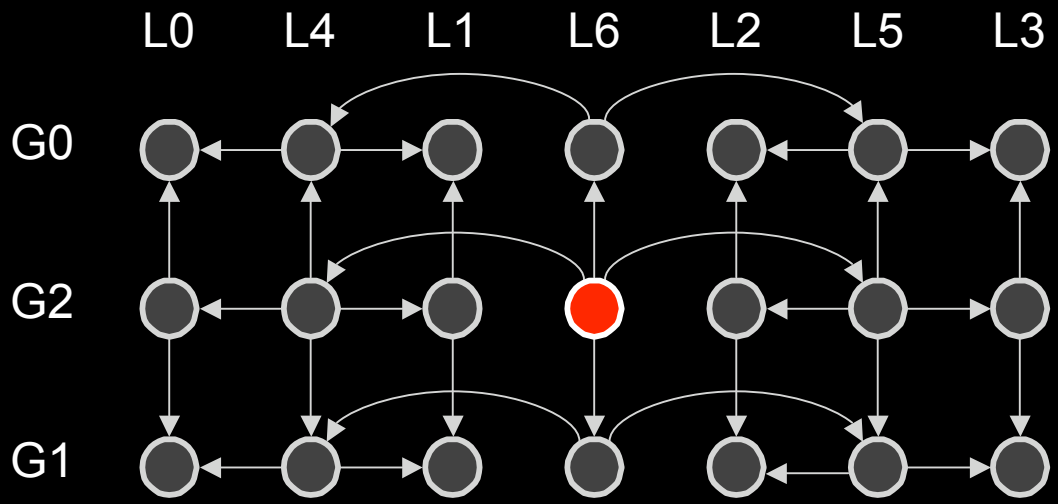
Algorithm Summary

- Once per image
  - Create lights and light tree
- For each pixel
  - Create gather points and gather tree for pixel
  - Adaptively refine clusters in product graph until all cluster errors < perceptual metric

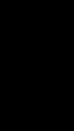
Algorithm Summary



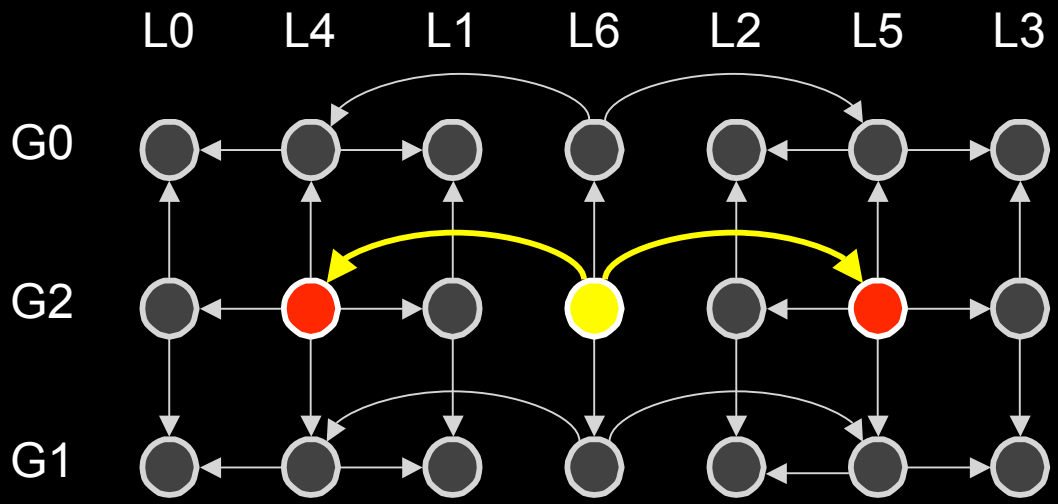
- Start with a coarse cut
  - Eg, source node of product graph



Algorithm Summary



- Choose node with largest error bound & refine
  - In gather or light tree



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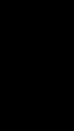

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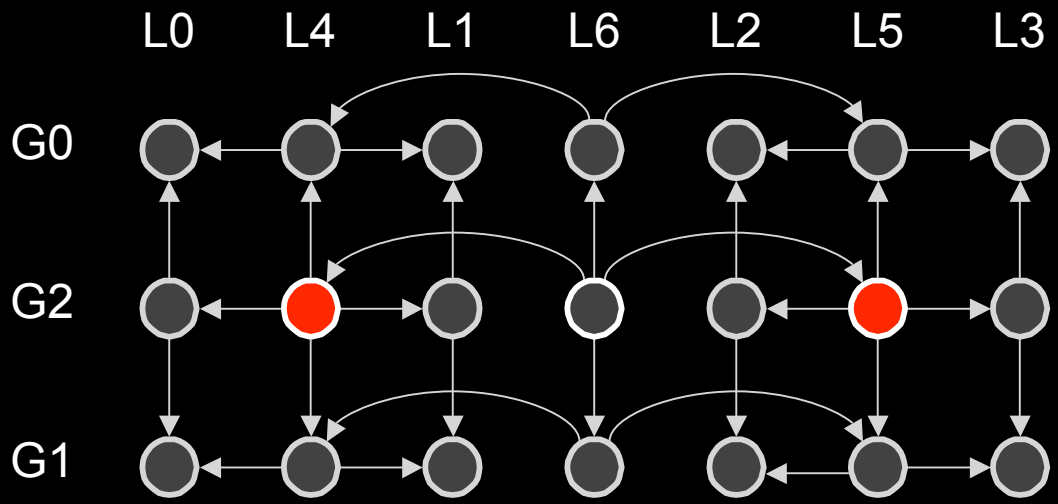

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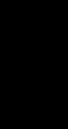
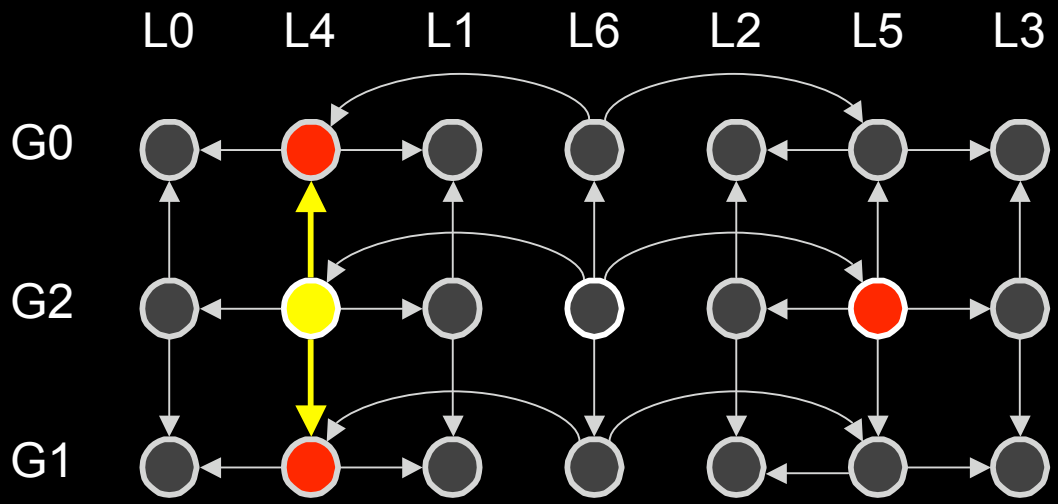


- Repeat process



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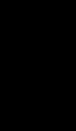
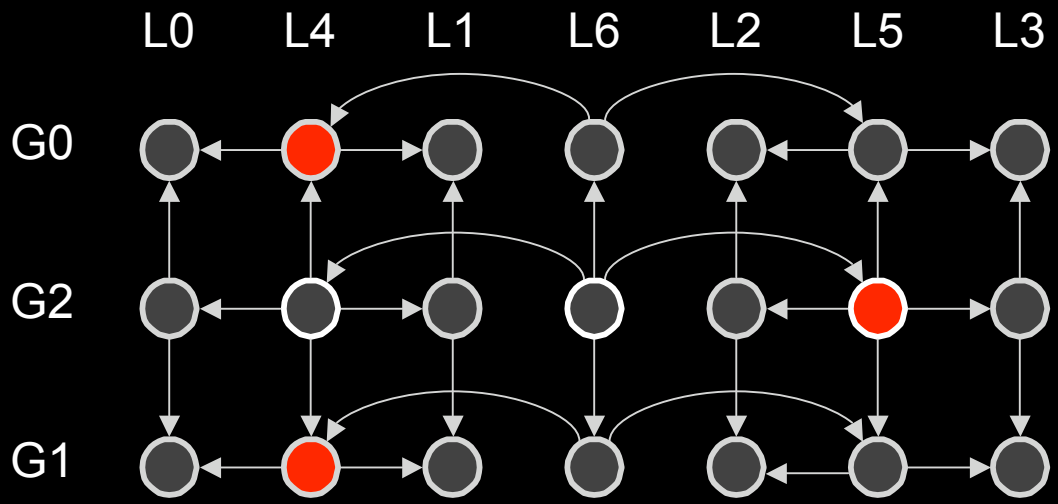


- Until all clusters errors < perceptual metric
  - 2% of pixel value (Weber's law)



Results

- Limitations
  - Some types of paths not included
    - Eg, caustics
  - Prototype only supports diffuse, Phong, and Ward materials and isotropic media

Roulette

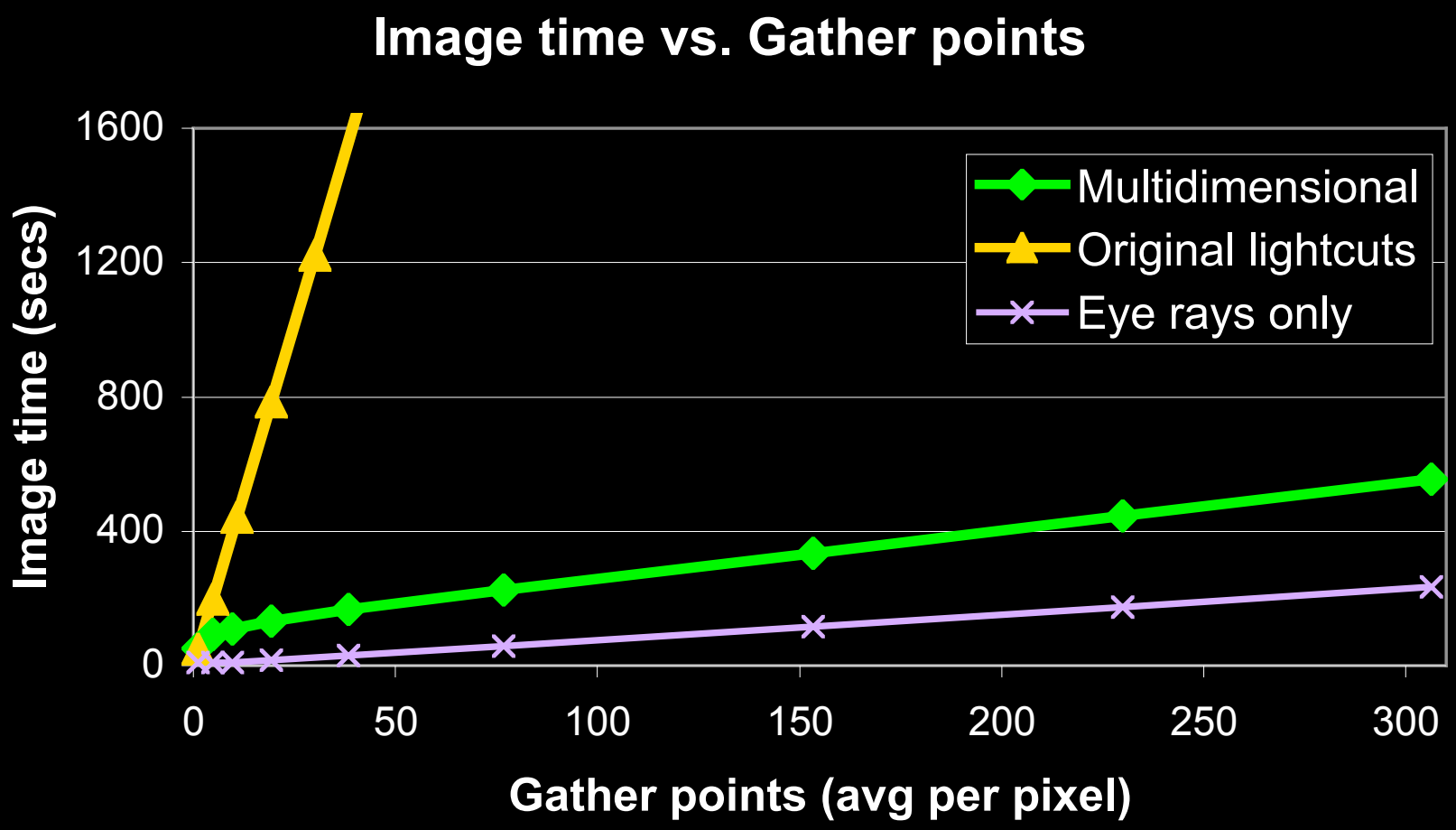
7,047,430 Pairs per pixel Time 590 secs
Avg cut size 174 (0.002%)

Roulette

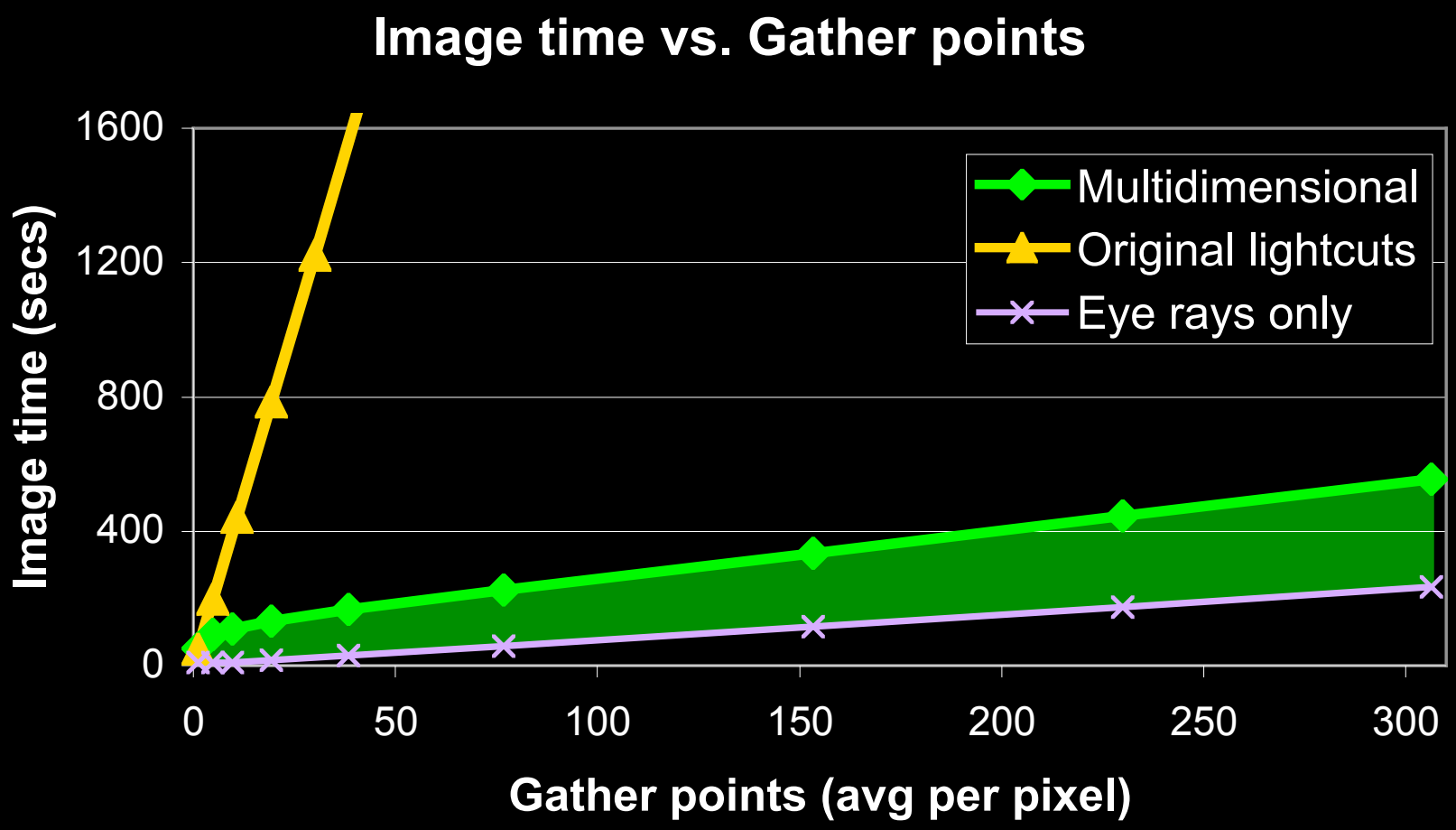
Roulette

Polygons:	151,752
Light Points:	23,000
Gather Points:	306
Gather/Light Pairs:	7,047,430
Cut Size:	174 (0.002%)

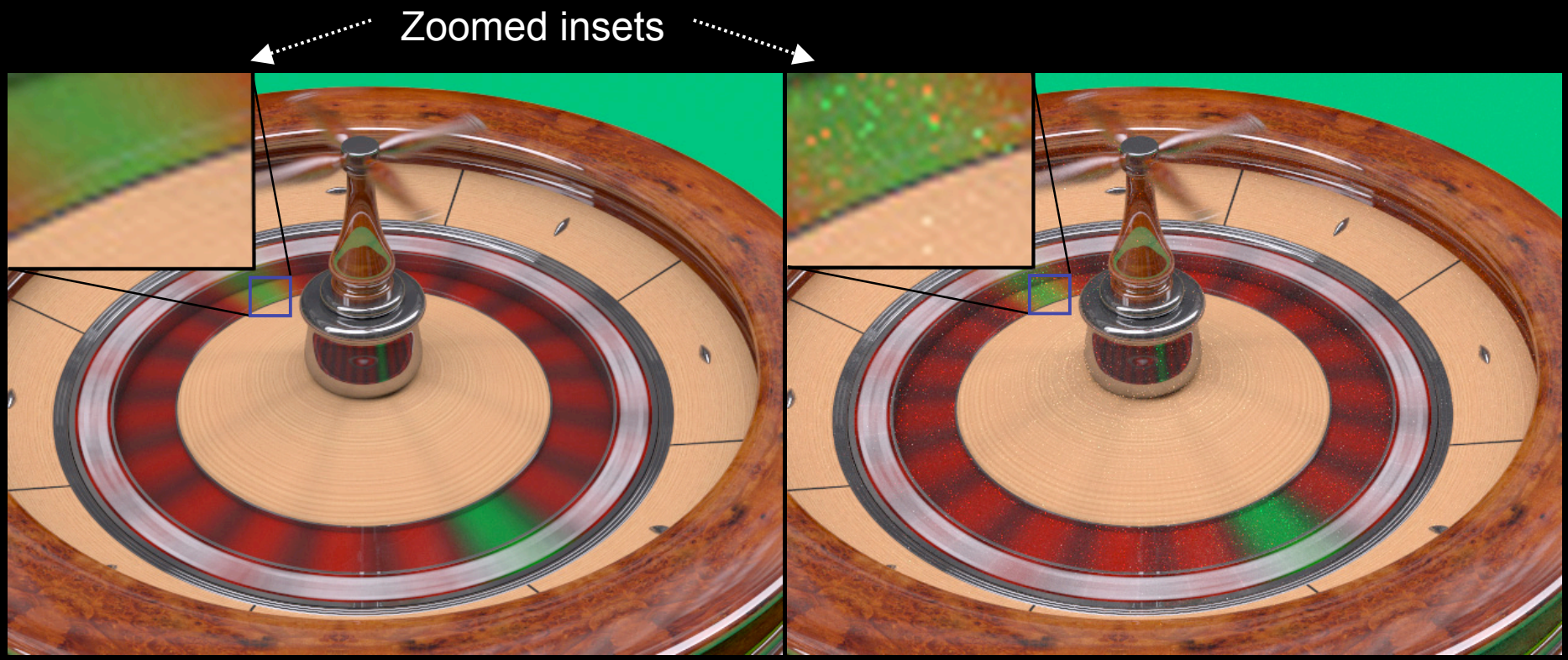
Scalability



Scalability



Metropolis Comparison



Our result
Time 9.8min

Metropolis
Time 148min (15x)
Visible noise
5% brighter (caustics etc.)

Kitchen

5,518,900 Pairs per pixel Time 705 secs
Avg cut size 936 (0.017%)

Kitchen

Kitchen

Polygons:	388,552
Light Points:	55,189
Gather Points:	100
Gather/Light Pairs:	5,518,900
Cut Size:	936 (0.02%)

Tableau

Tableau

Polygons:	630,843
Light Points:	13,000
Gather Points:	180
Gather/Light Pairs:	234,000
Cut Size:	447 (0.2%)

Temple

Kalabsha Temple

Polygons:	2,124,003
Light Points:	94,168
Gather Points:	1,282
Gather/Light Pairs:	114,149,280
Cut Size:	821 (0.0007%)

Conclusions

- New rendering algorithm
  - Unified handling of complex effects
    - Motion blur, participating media, depth of field etc.
  - Product graph
    - Implicit hierarchy over billions of pairs
  - Scalable & accurate

Future Work

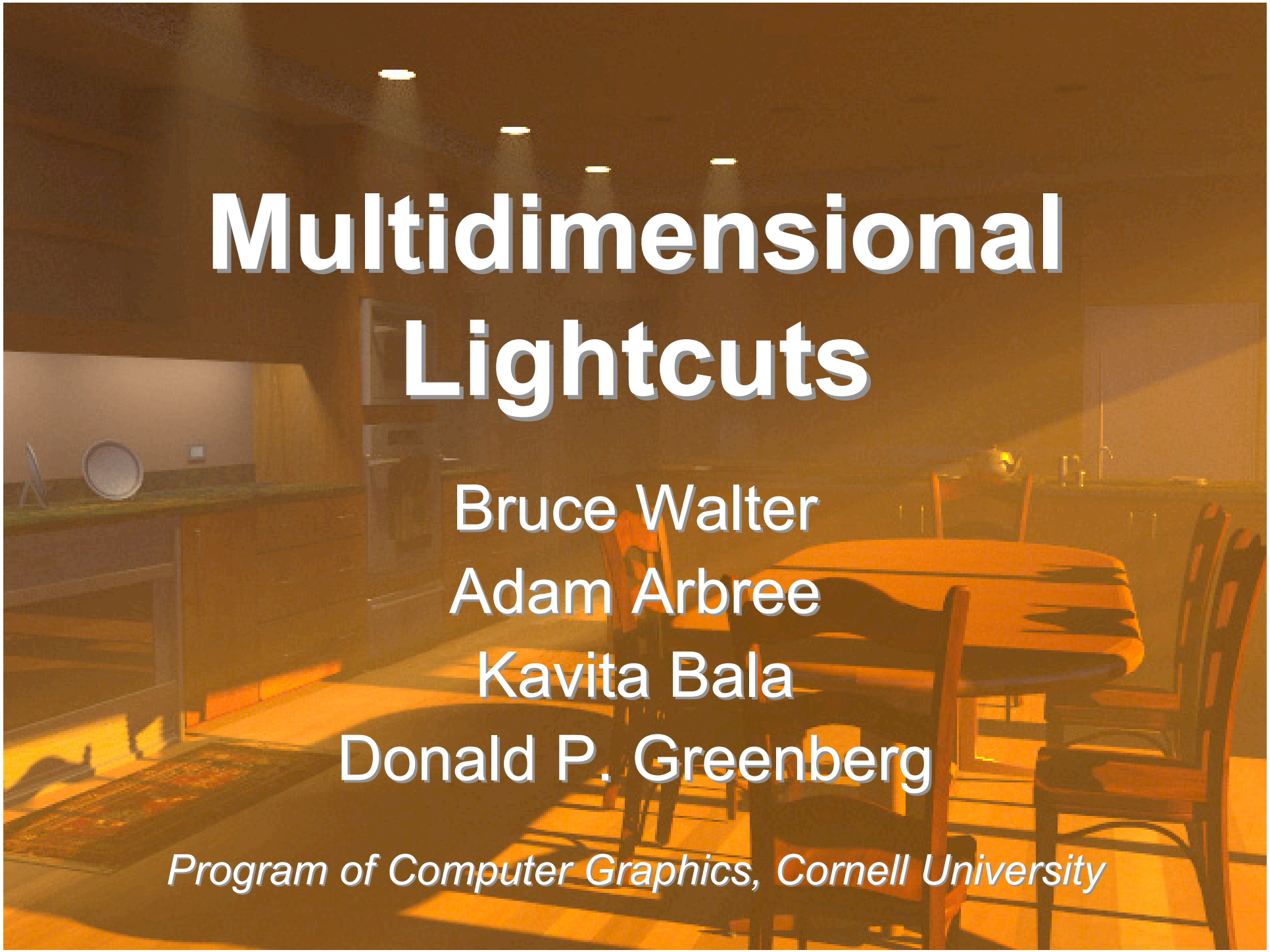
- Other types of paths
  - Caustics, etc.
- Bounds for more functions
  - More materials and media types
- Better perceptual metrics
- Adaptive point generation

Acknowledgements

- National Science Foundation grants ACI-0205438 and CCF-0539996
- Intel corporation for support and equipment
- The modelers
  - Kitchen: Jeremiah Fairbanks
  - Temple: Veronica Sundstedt, Patrick Ledda, and the graphics group at University of Bristol
  - Stanford and Georgia Tech for Buddha and Horse geometry

The End

- Questions?



Multidimensional Lightcuts

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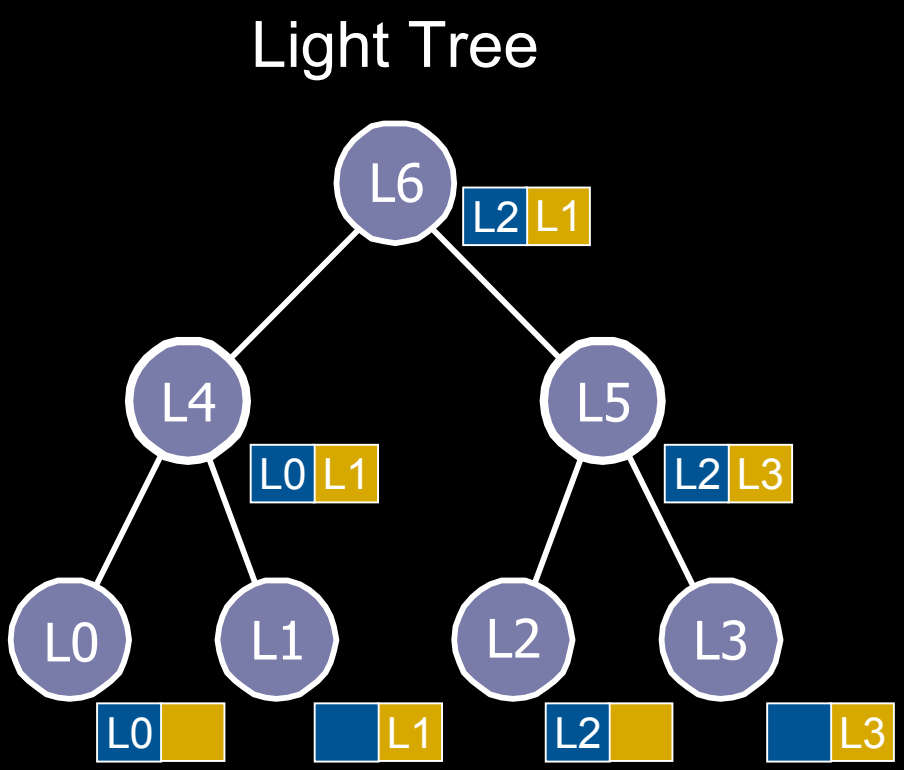
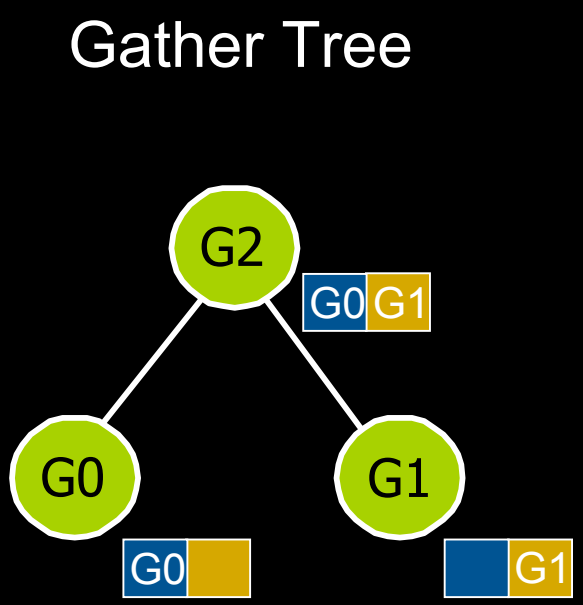
Program of Computer Graphics, Cornell University

Representatives

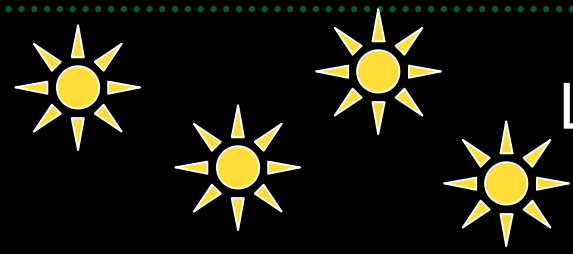




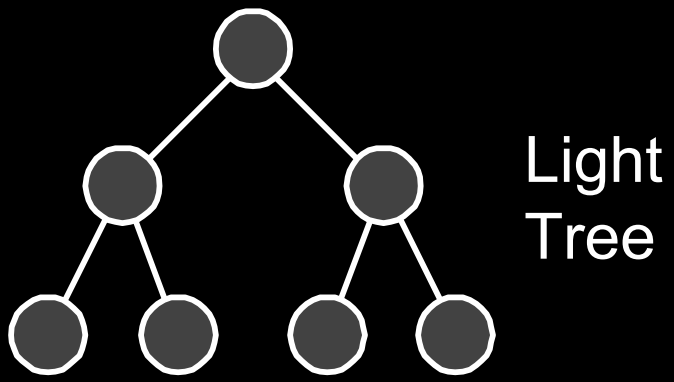
Exists at first or second time instant.

Lightcuts key concepts

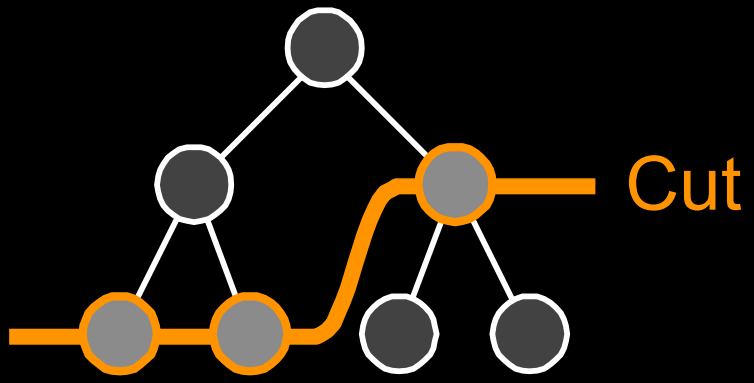
- Unified representation
  - Convert all lights to points



- Hierarchy of clusters
  - The *light tree*



- Adaptive *cut*
  - Partitions lights into clusters



180 Gather points X 13,000 Lights = 234,000 Pairs per pixel

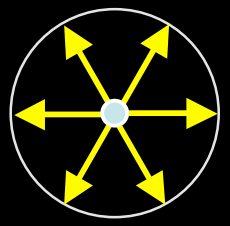
Avg cut size 447 (0.19%)

114,149,280 Pairs per pixel

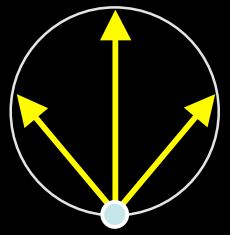
Avg cut size 821
Time 1740 secs

Types of Point Lights

- Omni
  - Spherical lights



- Oriented
  - Area lights, indirect lights



- Directional
  - HDR env maps, sun&sky