Group Name: Defenders of Metropolis
Intro to DAS - CAP3027
Fall 2017

Metropolis Light Transport

Group Presentation Final Script

Defenders of Metropolis (Slide 1)

Hello, we are the Defenders of Metropolis and are here to delve into Metropolis Light Transport: what it is and why you would use it.

We came together and realized that we are huge fans of Superman, defender of the city of Metropolis, and hence our group's name.

Introduction (Slide 2)

What is Metropolis Light Transport?

Metropolis Light Transport (or MLT) is an advanced, 3D rendering technique that uses the brightest areas of a 3-dimensional scene and builds millions of light paths targeting these regions. This resulting algorithm is more efficient than traditional random path building algorithms, such as bidirectional path tracing.

Why do you need to know about MLT? Why would you use it?

Let's say you have a 3D object that has been modeled and you would like to see how it would look in a photorealistic rendered environment.

You might consider using bidirectional path-tracing to render the image or 3D scene, but this will work only in certain situations. If the object you would like to render is in the direct path of your light source, then you need not worry because path tracing will be the most efficient rendering method to provide an accurate and visually pleasing image.

However, there are scenarios in which path tracing falls short (defracts - maybe a pun in there).

For example, in indirect lighting conditions, there is no direct path from the light source to your 3D object. Therefore, the reflected light, is the determinant of the quality of the image that can be rendered.

In path tracing, a few different light paths are sampled, which, in direct lighting can lead to a high quality overall image. There are not enough light paths sampled in indirect lighting situations, leaving you with an image in which the light ends up unevenly distributed throughout. The result is pockets of high light-intensity next to areas that are starkly contrasting / dark and an overall "noisy" image.

So, how do we clean up this noisy image?

Through convergence by way of the Metropolis Light Transport technique.

Because of the limitations of traditional random path-building algorithms, there arose a need for a more efficient algorithm to handle more complex lighting situations.

Monte Carlo Algorithm (Slide 3)

In an effort to find the best solution to global illumination problems, two researchers from Stanford, Veach and Guibas, proposed a method that utilized the Monte Carlo algorithm along with Markov chains- an algorithm known as the Metropolis algorithm. Remember, the goal is to use an algorithm that runs in acceptable time on real models and yields images that are physically possible and visually pleasing.

The Monte Carlo algorithm is known for its simplicity and adaptability. It's also known to support unbiased solutions. To say a solution is unbiased is to say that it calculates its solution by computing an average from a sample. In terms of images, this would result in noise. Now I know it sounds weird to say noise is acceptable in an image, but the alternative, a biased solution, tends to generate images with discontinuities and blurring.

Monte Carlo Example (Slides 4-7)

As I just mentioned, Monte Carlo deals with calculating a solution from a sample. An example of this is estimating the value of Pi by super-imposing a circle onto a square. Randomly generate points within the square, and calculate the ratio between the points in the square and outside and you multiply that by 4, for reasons I won't get into. But just understand that the more points that are sampled, the closer the result is closer to Pi.

Metropolis Sampling Method (Slide 8)

Now in coming up with a solution, they realized they needed to efficiently sample the transport paths from the light to the lens. They kept in mind, and this is important, that most paths do not contribute to the image. They may strike surfaces with low reflectivity, or go through solid objects. Why let these paths occupy space?

When sampling multiple states, or in the case of MLT, paths, the Metropolis algorithm only stores one state: the current one. Subsequent states depend on the current one. This process involves a contribution function, a transition function, and an acceptance probability.

The contribution functions determines the effectiveness of a state. The transition function, or mutation strategy, determines how a state is changed. It produces a probability of a state changing depending on the current one.

Each state has a probability of being accepted or rejected and this is dependent on the acceptance probability.

Collectively these functions and the acceptance probability contribute to what is known as detailed balance, or a state of equilibrium within the composition of the image.

Metropolis Light Transport (Slide 9 - 10)

I will be going into more detail on the generation of images using light paths and the overall MLT algorithm with some implementation considerations

Overview of the MLT algorithm(Slide 11 - 16)

In creating an image from a 3D space using light paths we need to start with a 3D scene.

From there we define a reference point for the image, which is the camera placement. And a light source.

We then draw a light path through the space from the camera to the light source. This path is composed of sub-paths with vertices on objects that the light has bounced off.

To evaluate the path drawn, we start with the power of the light source. This is interpolated into a brightness value based on the reflective properties of the surface vertices.

The overall strategy of MLT is to generate and sample paths according to a probability that is proportional to the evaluation function. These paths are in a sequence where the next path is generated by mutating the previous path.

The path mutation is based on a mutation strategy. Generally, a mutation strategy outlines a set of mutations. One mutation is randomly selected from that set, with each mutation equally weighted.

Each mutation has a probability that it will be rejected. This rejection is based on the relative contribution of the previous and mutated paths to the image. Here we have a simple example of a path that passes through a wall. This would be rejected as it will not contribute to the overall image.

When a path is accepted, the pixel location on the image is determined and that section of the image is filled in with the corresponding brightness evaluated from the path.

Basic MLT Algorithm(Slide 17 - 18)

Start with an initial path
Start with an empty image
For the number of samples desired
    Mutate X

Determine the acceptable probability based on the initial path and mutated path

Generate a random number - check against the acceptance probability

Make the mutated path the new initial path

Either record mutated path or re-record initial path which will not change the image

Return the completed image once N samples have been run

Initialization Phase (Slide 19)

Trying to initialize the MLT algorithm using only a single sample does not work practically.

It is quite likely that a single initial sample would be a path that does not contribute to the overall image. Mutating from this sample has a high likelihood of generating exclusively useless paths and results in a completely black image.

The solution is to run many copies of the algorithm in parallel and accumulate the samples into one image.

We sample a moderately large number of initial light paths. This provides a suitably extensive starting point to run the algorithm on many points in parallel.

The initialization phase can be thought of as a method for determining the overall brightness across the image. This allows the iterative metropolis phase to determine the relative pixel intensities of the image.

Spectral Sampling (Slide 20)

Spectral sampling enables generation of images that are in color. Up to this point the images that would be generated using the MLT algorithm are in black and white. The previous path evaluations and acceptance functions utilize a brightness value that would color the images in black to white.

To achieve color images, paths must be evaluated for the color that is delivered to the lens and the luminance of that color. Each path contributes some amount of energy to the lens at each of the sampled wave lengths. The resulting spectrum can then be converted into a color value.

The color value can be used to determine the overall luminance. Luminance values are now used to determine the acceptable probability of a path's mutation and the color is recorded to the final image

MLT Algorithm: With Color (Slide 21 - 22)

The mutated path and initial paths are evaluated for color and luminance

Luminance is used to determine the Acceptable Probability of the mutation. The color value is recorded to the final image based on the path's location.

Designing Mutation Strategies (Slide 23-32)

Different mutation strategies lead to specific results that may be beneficial for certain scenes

The idea is to estimate the acceptance probability for each mutation before they are actually tried

- The probabilities for each mutation strategy is then weighted by a factor based on the acceptance probability.

- It is not possible to know the exact acceptance probabilities prior to a mutation

- So instead, we give the different mutation strategies nearly equal probabilities

  - This will work in a wide variety of situations

  - There will be a lot of rejections of the mutation strategies

Properties of good mutation strategies

- High acceptance probability

  - If acceptance probability is too low, it will cause light paths to clump

  - Computation time is wasted on mutating the same path repeatedly

Large path changes

- Needs to change image location

  - Small changes cause clumping

  - Large change ex: deleting or adding vertices

Ergodocity

- Important all paths have a probability above 0

  - Some paths may be missed due to another path that seemed more promising

Stratification

Domain of light paths uniformly distribute samples into sub-domains

Use as few ray tracing options as possible

Probability of deletion is calculated using 2^-L where L is length (exception: length at 1=0.25, length at 2=0.5

Bidirectional Mutations (Slide 32-34)

Must efficiently sample the transport paths from the light sources to the lens
Splits path into 2 halves
Deletion probability goes through each path
Connects subpaths from each half
Keep in mind that for some environments, most paths do not contribute to the image
They may strike surfaces with low reflectivity, or go through solid objects

Perturbations (Slide 35-36)

The general idea of perturbations are to make very small changes to the path by moving path vertices slightly.
They handle very special cases of light rendering
Small and complex geometric scenes
Caustics
Anything that has high frequency features within a scene

Two main kinds of Perturbations:

1. Caustic Perturbations
2. Lens Perturbations

Caustic Perturbations

Path originates from light source

Lens Perturbations

Path originates from camera/viewer

Lens Subpath mutation strategy and many more (Slides 38-39)

Lens subpath mutation ensures entire image is processed and that stratification is fully utilized because subpaths are re-used a fix number of times

There are many other mutation strategies that can be implemented into MLT

These mutation strategies yield certain advantages and disadvantages to the MLT algorithm compared with other rendering techniques

Advantages and Disadvantages of MLT (Slide 40)

I'll start by briefly reviewing the general advantages and disadvantages of MLT

MLT's strengths include:

1) Its EFFICIENCY
    - Metropolis Light Transport operates on importance sampling; the algorithm samples paths and explore them locally according to the relative contribution they make to the ideal scene image.

2) Its MUTATION STRATEGY
    - Serves as a single, adaptable control structure that can be designed to handle varying, difficult illumination/lighting situations.

3) The COST
    - Average cost of sample is small, and when an important path with large relative contribution is explored locally, the cost expense is amortized.
    - Mutation Set/Strategy is easily extended to include mutation strategies that cover all lighting possibilities to increase robustness for a small cost tradeoff:

4) MEMORY
    - Low memory requirements (scene rep, rendered image rep, current sampled path)

The main disadvantages are:

1) There are some cases where biased algorithms (path tracing and bidirectional) and other methods actually yield better results more efficiently, such as basic direct lighting scenes.
2) Although the mutation strategy for an MLT implementation is very adaptable, the strategy must be designed carefully, or inconsistencies could appear in the final image.

MLT Uses Cases (Slide 41)

Traditional methods, including path and bidirectional path tracing are only optimized for narrow lighting situations.

MLT is ideal for many hard sampling/illumination problems, especially…

Indirect Lighting (Slide 42)

Indirect Lighting...

Caustics (Slide 43)

Caustics...

Non-Diffuse Surfaces (Slide 44)

Specular and Glossy Surfaces

Method Comparison (Slide 45)

So let's go ahead compare MLT to traditional methods, and then later we will compare MLT to other global illumination techniques.

(Slide 46)

This illuminated scene actually contains two rooms. The room on the opposite side of the wall that we are facing supplies an indirect light source that passes through the narrow doorway aperture to the right.

This is a rendered image of the illuminated scene using bidirectional path tracing for a specified render time.

Notice the low-quality handling of the different surface types of the teapots and the overall static-like quality of the scene due to the hard illumination problem of indirect lighting.

(Slide 47)

This is the same scene rendered with an implementation of MLT for the same specified render time.

In comparison, notice how MLT handles the glossy, diffuse, and specular surfaces of the teapots, wall, and floor tiles much better than bidirectional.

This is an example where MLT efficiently samples, preserves and mutates useful paths from a major contributing path that makes it through the doorway from the indirect light source.

(Slide 48)

This scene's main focus is the small pool with caustics produced by water ripples in the water. This image was rendered using standard path tracing for a specified render time.

(Slide 49)

This is the same image rendered using MLT.

Perturbations are the key mutation responsible for efficiently handling the hard illumination demand of the caustics

MLT clearly diminishes the noise in the bright areas of the region produced by the caustics.

If you look closely, there is actually increased noise in the dimmer regions of the image rendered with MLT. Path tracing actually diminishes noise in dimmer regions.

Compared to Ray Tracing (Slide 50)

Some other groups have/will be talking about other global illumination techniques, so we WON'T discuss the specifics of these methods.

I will start with Ray Tracing.

Ray Tracing's advantage is that it handles realistic rendering of reflections, refractions, and shadows. If you have a desired scene that features many of these aspects, this would be the ideal technique.

The main disadvantages of Ray Tracing, however, are that:

- It is computationally heavy, whereas MLT handle complex illumination problems relatively efficiently and modestly in terms of cost and time expenses.
- Also, it has difficulty handling advanced lighting effects produced by caustics, which as we know is an especially strong advantage of MLT.

Compared to Radiosity (Slide 51)

Let's move on to Radiosity

The strengths of Radiosity are that:

- The method is simple to explain and implement,
- And many renderers already support implementation.

Although the components of MLT are also relatively simple if understood, very few implementations of MLT exist or are supported.

On the other hand, radiosity typically only handles multiple diffuse bounces and has trouble with specular or glossy surfaces. This is a specific strength of MLT where it converges to a solution of the rendering equation faster than other global illumination methods.

Conclusion (Slide 52)

Overall, Metropolis Light Transport serves as a comprehensive solution to global illumination problems. Thank you.

Questions (Slide 53)