

## Prelude

A typical dissertation will be structured according to (somewhat) standard sections, described in what follows. However, it is hard and perhaps even counter-productive to generalise: the goal is *not* to be prescriptive, but simply to act as a guideline. In particular, each page count given is important but *not* absolute: their aim is simply to highlight that a clear, concise description is better than a rambling alternative that makes it hard to separate important content and facts from trivia.

You can use this document as a L<sup>A</sup>T<sub>E</sub>X-based [?, ?] template for your own dissertation by simply deleting extraneous sections and content; keep in mind that the associated **Makefile** could be of use, in particular because it automatically executes to deal with the associated bibliography.

You can, on the other hand, opt *not* to use this template; this is a perfectly acceptable approach. Note that a standard cover and declaration of authorship may still be produced online via

<http://www.cs.bris.ac.uk/Teaching/Resources/cover.html>



DEPARTMENT OF COMPUTER SCIENCE

# Efficient Path Tracing using Reinforcement Learning Methods

Callum Pearce

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A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of Master of Engineering in the Faculty of Engineering.

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Monday 1<sup>st</sup> April, 2019

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# Declaration

This dissertation is submitted to the University of Bristol in accordance with the requirements of the degree of MEng in the Faculty of Engineering. It has not been submitted for any other degree or diploma of any examining body. Except where specifically acknowledged, it is all the work of the Author.

Callum Pearce, Monday 1<sup>st</sup> April, 2019



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# Contents

<b>1</b>	<b>Contextual Background</b>	<b>1</b>
<b>2</b>	<b>Technical Background</b>	<b>3</b>
<b>3</b>	<b>Project Execution</b>	<b>5</b>
3.1	Example Section . . . . .	5
<b>4</b>	<b>Critical Evaluation</b>	<b>11</b>
<b>5</b>	<b>Conclusion</b>	<b>13</b>
<b>A</b>	<b>An Example Appendix</b>	<b>15</b>



---

# List of Figures

3.1 This is an example figure. . . . .	6
--	---





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# List of Tables

3.1 This is an example table. . . . .	6
---------------------------------------	---

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# List of Algorithms

3.1 This is an example algorithm. . . . .	7
---	---



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# List of Listings

3.1 This is an example listing. . . . .	7
---	---



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# Executive Summary

**A compulsory section, of at most 1 page**

This section should précis the project context, aims and objectives, and main contributions (e.g., deliverables) and achievements; the same section may be called an abstract elsewhere. The goal is to ensure the reader is clear about what the topic is, what you have done within this topic, *and* what your view of the outcome is.

The former aspects should be guided by your specification: essentially this section is a (very) short version of what is typically the first chapter. Note that for research-type projects, this **must** include a clear research hypothesis. This will obviously differ significantly for each project, but an example might be as follows:

My research hypothesis is that a suitable genetic algorithm will yield more accurate results (when applied to the standard ACME data set) than the algorithm proposed by Jones and Smith, while also executing in less time.

The latter aspects should (ideally) be presented as a concise, factual bullet point list. Again the points will differ for each project, but an might be as follows:

- I spent 120 hours collecting material on and learning about the Java garbage-collection sub-system.
- I wrote a total of 5000 lines of source code, comprising a Linux device driver for a robot (in C) and a GUI (in Java) that is used to control it.
- I designed a new algorithm for computing the non-linear mapping from A-space to B-space using a genetic algorithm, see page 17.
- I implemented a version of the algorithm proposed by Jones and Smith in [6], see page 12, corrected a mistake in it, and compared the results with several alternatives.

## 0.0.1 Plan

1. Path tracing is a ray-tracing method for rendering computer generated photo-realistic images by accurately approximating global illumination. Traditionally it has been thought to trade off rendering speeds with image quality.
2. The goal is to design and implement modified path-tracing algorithms which reduces the number of zero-contribution light paths in its estimation of global illumination. This will lead to less noisy image with the same number of samples per pixel. I have integrated different reinforcement learning algorithms into the path-tracing rendering pipeline, which was initially motivated by Nvidia's promising results when integrating Q-learning
3. More specifically, the task of the reinforcement learning AI agent is to learn for any given point in the scene the light power contribution from all incident angles. This is known as the Irradiance Distribution, the term introduced by (cite The Irradiance Volume). It is then possible to importance sample scattering directions from the learned irradiance distribution at a given point in the scene to dramatically reduce the number of rays scattered in directions giving zero-light power contribution, also known as zero-contribution light paths.

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4. I have assessed different on-line reinforcement learning techniques for learning the irradiance distribution for any point in a scene by comparing metrics such as average path length, number of ray paths connecting to a light - generalization
  5. I have spent x hours researching into reinforcement learning for Dynamic Programming methods, Monte Carlo methods, Temporal Difference methods, Deep reinforcement learning methods including monte-carlo and temporal difference learning approaches
  6. I have spent x hours researching into the newly emerging field of learning light transport
  7. I have created my own path-tracing graphics engine which supports naive path-tracing, reinforcement learning approach introduced by Ken Dahm, and my newly proposed deep reinforcement learning scheme for learning the irradiance distribution for any point in the scene



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# Supporting Technologies

**A compulsory section, of at most 1 page**

This section should present a detailed summary, in bullet point form, of any third-party resources (e.g., hardware and software components) used during the project. Use of such resources is always perfectly acceptable: the goal of this section is simply to be clear about how and where they are used, so that a clear assessment of your work can result. The content can focus on the project topic itself (rather, for example, than including “I used L<sup>A</sup>T<sub>E</sub>X to prepare my dissertation”); an example is as follows:

- I used the Java `BigInteger` class to support my implementation of RSA.
- I used a parts of the OpenCV computer vision library to capture images from a camera, and for various standard operations (e.g., threshold, edge detection).
- I used an FPGA device supplied by the Department, and altered it to support an open-source UART core obtained from <http://opencores.org/>.
- The web-interface component of my system was implemented by extending the open-source WordPress software available from <http://wordpress.org/>.

## 0.0.2 Plan

1. SDL2 for displaying the rendered images and saving the images as `.bmp` format
2. OpenGL mathematics library to support my ray-tracing calculations and includes GPU accelerated implementations of each function
3. CUDA Toolkit 10.1 parallel computing platform for accelerating the path tracer implementations
4. Nvidia 1070Ti graphics card for rendering images, this was my own personal graphics card
5. Dynet neural network framework for the implementation of deep reinforcement learning within the path tracing rendering pipeline



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# Notation and Acronyms

**An optional section, of roughly 1 or 2 pages**

Any well written document will introduce notation and acronyms before their use, *even if* they are standard in some way: this ensures any reader can understand the resulting self-contained content.

Said introduction can exist within the dissertation itself, wherever that is appropriate. For an acronym, this is typically achieved at the first point of use via “Advanced Encryption Standard (AES)” or similar, noting the capitalisation of relevant letters. However, it can be useful to include an additional, dedicated list at the start of the dissertation; the advantage of doing so is that you cannot mistakenly use an acronym before defining it. A limited example is as follows:

AES	:	Advanced Encryption Standard
DES	:	Data Encryption Standard
	:	
$\mathcal{H}(x)$	:	the Hamming weight of $x$
$\mathbb{F}_q$	:	a finite field with $q$ elements
$x_i$	:	the $i$ -th bit of some binary sequence $x$ , st. $x_i \in \{0, 1\}$



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# Acknowledgements

**An optional section, of at most 1 page**

It is common practice (although totally optional) to acknowledge any third-party advice, contribution or influence you have found useful during your work. Examples include support from friends or family, the input of your Supervisor and/or Advisor, external organisations or persons who have supplied resources of some kind (e.g., funding, advice or time), and so on.

## **0.0.3 Plan**

1. Carl Henrik Ek - Validating my understanding of deep reinforcement learning
2. Neill Campbell - Deep reinforcement learning strategy



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# Chapter 1

## Contextual Background

**A compulsory chapter, of roughly 5 pages**

This chapter should describe the project context, and motivate each of the proposed aims and objectives. Ideally, it is written at a fairly high-level, and easily understood by a reader who is technically competent but not an expert in the topic itself.

In short, the goal is to answer three questions for the reader. First, what is the project topic, or problem being investigated? Second, why is the topic important, or rather why should the reader care about it? For example, why there is a need for this project (e.g., lack of similar software or deficiency in existing software), who will benefit from the project and in what way (e.g., end-users, or software developers) what work does the project build on and why is the selected approach either important and/or interesting (e.g., fills a gap in literature, applies results from another field to a new problem). Finally, what are the central challenges involved and why are they significant?

The chapter should conclude with a concise bullet point list that summarises the aims and objectives. For example:

The high-level objective of this project is to reduce the performance gap between hardware and software implementations of modular arithmetic. More specifically, the concrete aims are:

1. Research and survey literature on public-key cryptography and identify the state of the art in exponentiation algorithms.
2. Improve the state of the art algorithm so that it can be used in an effective and flexible way on constrained devices.
3. Implement a framework for describing exponentiation algorithms and populate it with suitable examples from the literature on an ARM7 platform.
4. Use the framework to perform a study of algorithm performance in terms of time and space, and show the proposed improvements are worthwhile.

### 1.0.1 Plan

1. Path-tracing in industry/ray-tracing in general, why is it important and how is the current field moving. Why should we optimise it algorithmically. Why should the reader care about path-tracing? - Usage in films, increasing interest for real-time simulations and gaming industry which is worth lots of money
2. High level overview of path-tracing: specifically must explain why it takes so long and why we care about the number of samples
3. In the path-tracing algorithm, a single pixel's colour is determined by firing multiple rays from the camera, through that pixel into the scene and building a colour value estimate for each one, then averaging their values to get the pixels colour. Each rays colour estimate is computed by estimating a solution to the recursive Rendering Equation (cite). The path-tracing algorithms estimate to this solution involves scattering the ray around the scene until it intersects with a light source. Therefore, if a ray is scattered in a direction with zero-light contribution, but other sampled rays are not, a

noisy estimate is achieved for the pixel value unless many rays are sampled to reduce the effect of this noise. Therefore, avoiding scattering rays in directions of zero-light power contribution can reduce the number of samples needed to achieve an accurate estimate of a pixels colour value.

4. Work was primarily motivated by Ken & Dahms paper for modelling the irradiance distribution in order to reduce the number of zero-contribution light transport paths traced. Nvidia are world leaders in GPU manufacturing and drive the computer graphics forward.
5. Literature around efficiently simulating light transport - it's applicability to all modern used off-line rendering techniques
6. Aims & Challenges:
  - (a) Implementing a path-tracer for diffuse surfaces from scratch using only maths and pixel libraries as helper functions which can handle imports of a custom scene
  - (b) Accelerating path-tracer on Cuda to get results in a reasonable time
  - (c) Implementing the irradiance volume data-structure and sampling technique which can adapt to any size scene
  - (d) Implementing Ken Dahms proposed path-tracing algorithm with nearest neighbour search of KD-Tree on a GPU efficiently
  - (e) Researching reinforcement learning: TD-Learning & deep reinforcement learning - never been taught before, so self taught with resources on-line
  - (f) Training a network on pre-computed Q values to check if it is possible for a neural network to learn the irradiance distribution function for a set of points in a scene
  - (g) Designing an algorithm to integrate deep reinforcement learning into the rendering pipeline for a path-tracer
  - (h) Choosing a set of metrics to evaluate the algorithms performances on
  - (i) Accelerating the algorithms via Cuda to run on Nvidia GPU



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## Chapter 2

# Technical Background

**A compulsory chapter, of roughly 10 pages**

This chapter is intended to describe the technical basis on which execution of the project depends. The goal is to provide a detailed explanation of the specific problem at hand, and existing work that is relevant (e.g., an existing algorithm that you use, alternative solutions proposed, supporting technologies).

Per the same advice in the handbook, note there is a subtle difference from this and a full-blown literature review (or survey). The latter might try to capture and organise (e.g., categorise somehow) *all* related work, potentially offering meta-analysis, whereas here the goal is simple to ensure the dissertation is self-contained. Put another way, after reading this chapter a non-expert reader should have obtained enough background to understand what *you* have done (by reading subsequent sections), then accurately assess your work. You might view an additional goal as giving the reader confidence that you are able to absorb, understand and clearly communicate highly technical material.

### 2.0.1 Plan

1. Define what a ray-tracing rendering algorithm consists of and the difference between global and direct illumination. Acknowledge other ray-tracing algorithms like bi-directional path-tracers, Renderman's algorithm, photon mapping.
2. Define terms like BRDF, radiance, irradiance and the rendering equation
3. Explain the details of the path-tracing algorithm in depth. It should be completely clear the relation between path-tracing and the rendering equation. It should be clear where the Monte Carlo approach comes in and why importance sampling within path-tracing can yield less noisy and more accurate results, potentially in the same fixed time-budget
4. Introduce the concept of importance sampling in computing global illumination with some early examples of its success, use in industry and recent papers on efficient light transport simulation. State the reasoning behind why it still continues to accurately simulate global illumination, in other words, why zero-contribution light paths do not contribute to the image.
5. Introduce reinforcement learning: Markov Decision Process, Bellman Equation, Temporal Difference Learning and its strong points and weaknesses, how does it differ to traditional monte-carlo (might not be relevant). Proved to converge on the true valuation function for a given state-action pair when run infinitely
6. State the derived learning rule supplied by Ken Dahm and visualize the matching terms as well as a justification why each parameter matches. What is the value and the incentive, diminishing return for rewards far in the future etc
7. State new on-line algorithm proposed by Ken Dahm and details for discretizing the state and action space into the Irradiance Volume data-structure which was previously introduced
8. Introduce the concept of deep reinforcement learning, describing how DeepMind used the technique for playing Atari games. Given a state give me the state-action values for all actions possible in that state. Then how we can apply this to our scene to model the state space and continuous.



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## Chapter 3

# Project Execution

A topic-specific chapter, of roughly 15 pages

This chapter is intended to describe what you did: the goal is to explain the main activity or activities, of any type, which constituted your work during the project. The content is highly topic-specific, but for many projects it will make sense to split the chapter into two sections: one will discuss the design of something (e.g., some hardware or software, or an algorithm, or experiment), including any rationale or decisions made, and the other will discuss how this design was realised via some form of implementation.

This is, of course, far from ideal for *many* project topics. Some situations which clearly require a different approach include:

- In a project where asymptotic analysis of some algorithm is the goal, there is no real “design and implementation” in a traditional sense even though the activity of analysis is clearly within the remit of this chapter.
- In a project where analysis of some results is as major, or a more major goal than the implementation that produced them, it might be sensible to merge this chapter with the next one: the main activity is such that discussion of the results cannot be viewed separately.

Note that it is common to include evidence of “best practice” project management (e.g., use of version control, choice of programming language and so on). Rather than simply a rote list, make sure any such content is useful and/or informative in some way: for example, if there was a decision to be made then explain the trade-offs and implications involved.

### 3.1 Example Section

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Figure 3.1: This is an example figure.

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Table 3.1: This is an example table.

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### 3.1.1 Example Sub-section

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```
for i = 0 upto n do
  | ti ← 0
end
```

**Algorithm 3.1:** This is an example algorithm.

```
for( i = 0; i < n; i++ ) {
  t[ i ] = 0;
}
```

Listing 3.1: This is an example listing.

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**Example paragraph.** This is an example paragraph; note the trailing full-stop in the title, which is intended to ensure it does not run into the text.

### 3.1.2 Plan

1. Decision on why implementing path-tracer with bare bones tools GLM and SDL rather than other packages or frameworks that perform a lot of functionality - we needed complete customizability of the algorithm to get all the data we needed and to modify the pipeline completely. Quick justification on why C++ was used
2. Implementing path-tracer and the specific algorithm used with pseudo-code. With a description of implementing it with CUDA and why the algorithm is embarrassingly parralleizable. Present results for different number of samples.

3. Q-value storage implementation using the Irradiance volume structure. Describe how the space was split up via sampling irradiance volumes uniformly over the state space. Visualize the scene discretization with hemispheres and the voronoi plot.
4. Describe how nearest neighbour search was used to find closest radiance volume but how this was tricky to convert into CUDA. Describe and state the new algorithm proposed by Ken and Dahm with the importance sampling and update steps involving the irradiance volumes nearest neighbour search.
5. Present results for expected SARSA approach and how it compares to the default path-tracer. Why is it better in terms of number of zero-contribution light paths included and show how this directly relates to a reduction in noise within the image. Also present the fall in avg path length.
6. Introduce state-action space for deep reinforcement learning approach and how it differs to expected SARSA approach. Introduce reasoning behind wanting to try the neural network approach vs discretized state space (not continuous)
7. Present findings to see if Q-values (irradiance distributions) can be learned by the neural network by using the previous methods converged irradiance volumes outputs as ground truth and train the network against a subset of them and test the network against a subset of them.
8. Introduced designed online algorithm to learn the Q-values for any given state-action pair. Explain discretization of action space. Explain neural network architecture and why the configuration was chosen. Describe the loss function and the newly derived update rule.
9. Go through implementation details with GPU and other decisions made





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## Chapter 4

# Critical Evaluation

A topic-specific chapter, of roughly 15 pages

This chapter is intended to evaluate what you did. The content is highly topic-specific, but for many projects will have flavours of the following:

1. functional testing, including analysis and explanation of failure cases,
2. behavioural testing, often including analysis of any results that draw some form of conclusion wrt. the aims and objectives, and
3. evaluation of options and decisions within the project, and/or a comparison with alternatives.

This chapter often acts to differentiate project quality: even if the work completed is of a high technical quality, critical yet objective evaluation and comparison of the outcomes is crucial. In essence, the reader wants to learn something, so the worst examples amount to simple statements of fact (e.g., “graph X shows the result is Y”); the best examples are analytical and exploratory (e.g., “graph X shows the result is Y, which means Z; this contradicts [1], which may be because I use a different assumption”). As such, both positive *and* negative outcomes are valid *if* presented in a suitable manner.

### 4.0.1 Plan

1. Show for about 4 different scenes the results for a  $n$  different numbers of samples; the images, average path length, number of light paths which actually contribute to the image which are sampled between all techniques. I will have to analyse which reduces the number of zero contribution paths the most, but also still assess if the image is photo-realistic.
2. Also analyse default Q-learning's ability on top of expected SARSA
3. Justify reasoning for choosing to analyse Q-Learning, Expected SARSA and DQN (because they have good results for other cases and TD learning fits the online learning procedure)
4. Assess the number of parameters required, configuration is important for these algorithms, if it is very difficult to get right, then the time spent configuring may not be worth it compared to actually rendering the image. E.g. default path-tracing there are not other parameters apart from the number of samples per pixel, expected SARSA requires the user to specify the memory which is allowed to be used by the program, this requires careful consideration, as well as the threshold the distribution cannot fall below, the deep Q-learning algorithm requires less config but potentially different neural network architectures should be investigated to further reduce the number of zero-contribution light paths.
5. Ease of implementation
6. Parallelisability of each algorithm, path-tracing is far easier to parallelise as it requires minimal memory accesses by the program to infer pixel values, as opposed to expected SARSA which requires many. Deep-q learning has more customizability in terms of parallelizing (needs more research)

7. Memory usage: Path-tracing is minimal, Expected SARSA is unbounded, Deep Q-Learning is bounded by the size of the neural network, but the memory it requires is still significant (needs more research)
8. DQN vs Expected Sarsa: Do not have to wait for an iteration to begin importance sampling on the newly learned Q values for a given point, neural network is continually trained and inferred from. Continuous state space vs discretized required for storage in expected SARSA.

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# Chapter 5

## Conclusion

**A compulsory chapter, of roughly 5 pages**

The concluding chapter of a dissertation is often underutilised because it is too often left too close to the deadline: it is important to allocation enough attention. Ideally, the chapter will consist of three parts:

1. (Re)summarise the main contributions and achievements, in essence summing up the content.
2. Clearly state the current project status (e.g., “X is working, Y is not”) and evaluate what has been achieved with respect to the initial aims and objectives (e.g., “I completed aim X outlined previously, the evidence for this is within Chapter Y”). There is no problem including aims which were not completed, but it is important to evaluate and/or justify why this is the case.
3. Outline any open problems or future plans. Rather than treat this only as an exercise in what you *could* have done given more time, try to focus on any unexplored options or interesting outcomes (e.g., “my experiment for X gave counter-intuitive results, this could be because Y and would form an interesting area for further study” or “users found feature Z of my software difficult to use, which is obvious in hindsight but not during at design stage; to resolve this, I could clearly apply the technique of Smith [7]”).

### 5.0.1 Plan

1. Summarise contributions:
  - (a) Implementing a path tracer from scratch to analyse in depth the difficulties and issues that come with Ken Dahm’s algorithm. Including memory usage, parallelisation and parameter usage.
  - (b) Analysis of different reinforcement learning approaches pitched together clearly on a variety of scenes
  - (c) Analysis of neural networks ability to learn the irradiance distribution function
  - (d) Online deep-reinforcement learning algorithms effectiveness of learning irradiance distribution function
2. If DQN does not work well provide some further analysis on potential other alternatives which could be used.
3. Future Work: Policy learning to model continuous action & state space
4. DDQN and other deep reinforcement learning strategies



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## Appendix A

# An Example Appendix

Content which is not central to, but may enhance the dissertation can be included in one or more appendices; examples include, but are not limited to

- lengthy mathematical proofs, numerical or graphical results which are summarised in the main body,
- sample or example calculations, and
- results of user studies or questionnaires.

Note that in line with most research conferences, the marking panel is not obliged to read such appendices.