

# **Decision-making in quantum environments:**

from model-free to model aware learning of quantum controls

by  
MATIAS BILKIS

*This page is intentionally left blank*

Universitat Autònoma de Barcelona

**Decision-making in quantum environments:**  
from model-free to model aware learning of quantum controls

by  
MATIAS BILKIS

under the supervision of  
Prof. PROF JOHN CALSAMIGLIA COSTA  
and  
PhD.

A thesis submitted in partial fulfillment for the degree of  
Doctor of Philosophy in Physics

Física Teòrica: Informació i Fenòmens Quàntics  
Departament de Física, Facultat de Ciències



Bellaterra, Defense date

This work is licensed under a [Creative Commons](#) “Attribution-NonCommercial-ShareAlike 3.0 Unported” license.



*To the ones I love.*

*This page is intentionally left blank*

---

# Resum

---





---

# Resumen

---



---

# Abstract

---

*This page is intentionally left blank*

---

# Declaration

---

I declare that the thesis has been composed by myself and that the work has not been submitted for any other degree or professional qualification. I confirm that the work submitted is my own, except where work which has formed part of jointly-authored publications has been included. My contribution and those of the other authors to this work have been explicitly indicated below. I confirm that appropriate credit has been given within this thesis where reference has been made to the work of others.



---

## List of Publications

---

*This page is intentionally left blank*



---

# Acknowledgments

---

*This page is intentionally left blank*

---

# Contents

---

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Preliminaries</b>	<b>3</b>
2.1	This is the first section . . . . .	3
2.1.1	This is the first . . . . .	3
2.1.2	This is the second . . . . .	3
<b>3</b>	<b>Results</b>	<b>9</b>
<b>4</b>	<b>Conclusions</b>	<b>11</b>
<b>A</b>	<b>Technicalities</b>	<b>13</b>



---

# Notation

---

$U_{\text{SB}}(t)$  =system-bath unitary evolution  
 $H_{\text{SB}}$  =system-bath Hamiltonian evolution  
 $H_{\text{int}}, V$  =interaction hamiltonians  
 $S^\alpha$  =system coupling operator  
 $B^\alpha$  =bath coupling operator  
 $\rho, \sigma$  =these are states  
 $f, g$  =general functions  
 $x, y, z$  =general variables  
 $X, Y, Z$  =general matrices  
 $\sigma_l^x, \sigma_l^y, \sigma_l^z$  =Pauli operators  
 $t, t', \tau, t_1, t_2,$  =these are times  
 $N, L$  =number of particles, spins  
 $\Lambda, \mathcal{L}, \mathcal{E}(t)$  =Lindblad and evolution operators  
 $J_k, A_k$  =Jump operators, Kraus operators

$\Pi(E), P(E)$  =projectors and POVM elements  
 $\mathcal{P}, \mathcal{Q}, \mathcal{I}$  =projections and identity map  
 $\varepsilon_k, E_i, E$  =energies  
 $r, R$  =random number and Random matrix  
 $\lambda$  =weak-coupling constant  
 $\mu, \sigma$  =mean and standard deviation  
 $\mathcal{U}_S, \mathcal{U}_B$  =system, bath internal energy  
 $dW, dQ$  =differential work and heat  
 $p(a, b), q(a, b)$  =probability distributions  
 $\mathcal{S}, \mathcal{S}_{\text{vN}}, \mathcal{S}_B, \mathcal{S}_{\text{obs}}$  =entropies  
 $\gamma, \kappa$  =dissipation rates in extended and normal spaces  
 $\mathcal{H}$  =Hilbert space  
 $\mathcal{D}(\rho||\sigma)$  =relative entropy  
 $\omega, \Omega$  =system and bath frequencies  
 $C(t), \hat{C}(\omega)$  =bath correlation function  
 $\mathcal{T}_+$  =time-ordering operator

*At the beginning there was only Chaos.*

— Aristophanes

# 1

---

## Introduction

---

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy

---

pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.



*There is nothing more practical than a good theory*  
— Kurt Lewin

# 2

---

## Preliminaries

---

This is chapter 1

### 2.1 This is the first section

The first section of chapter one has also two subsections.

#### 2.1.1 This is the first

There are many interesting works! [aksin; angenendt; bertram; baez/article; sigfridsson]

#### 2.1.2 This is the second

What is Lorem Ipsum? Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem

Ipsium passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum. This is an amazing equation!

$$x = y + \mathcal{Q}p - \mathbf{q} + \int_0^\pi d\tau \sigma(\xi) \quad (2.1)$$

Why do we use it? It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

Where does it come from? Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, *consectetur*, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "de Finibus Bonorum et Malorum" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "Lorem ipsum dolor sit amet..", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "de Finibus Bonorum et Malorum" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham.

Where can I get some? There are many variations of passages of Lorem Ipsum available, but the majority have suffered alteration in some form, by injected humour, or randomised words which don't look even slightly believable. If you are going to use a passage of Lorem Ipsum, you need to be sure there isn't anything embarrassing hidden in the middle of text. All the Lorem Ipsum generators on the Internet tend to repeat predefined chunks as necessary, making this the first true generator on the Internet. It uses a dictionary of over 200 Latin words, combined with a handful of model sentence structures, to generate Lorem Ipsum which looks reasonable. The generated Lorem Ipsum is therefore always free from repetition, injected humour, or non-characteristic words etc. What is Lorem Ipsum? Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem

Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum.

Why do we use it? It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

Where does it come from? Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, *consectetur*, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "*de Finibus Bonorum et Malorum*" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "*Lorem ipsum dolor sit amet..*", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "*de Finibus Bonorum et Malorum*" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham.

Where can I get some? There are many variations of passages of Lorem Ipsum available, but the majority have suffered alteration in some form, by injected humour, or randomised words which don't look even slightly believable. If you are going to use a passage of Lorem Ipsum, you need to be sure there isn't anything embarrassing hidden in the middle of text. All the Lorem Ipsum generators on the Internet tend to repeat predefined chunks as necessary, making this the first true generator on the Internet. It uses a dictionary of over 200 Latin words, combined with a handful of model sentence structures, to generate Lorem Ipsum which looks reasonable. The generated Lorem Ipsum is therefore always free from repetition,

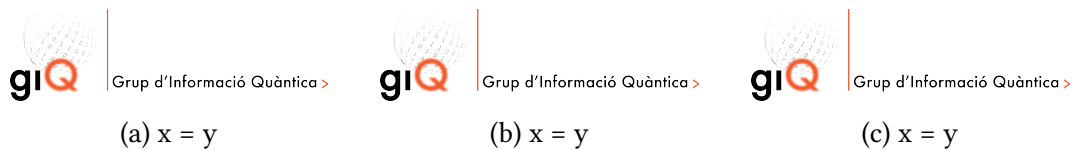


Figure 2.1: this is the big caption

injected humour, or non-characteristic words etc. What is Lorem Ipsum? Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum.

Why do we use it? It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

Where does it come from? Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, *consectetur*, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "de Finibus Bonorum et Malorum" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "Lorem ipsum dolor sit amet..", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "de Finibus Bonorum et Malorum" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham.

Where can I get some? There are many variations of passages of Lorem Ipsum



Figure 2.2: Caption

available, but the majority have suffered alteration in some form, by injected humour, or randomised words which don't look even slightly believable. If you are going to use a passage of Lorem Ipsum, you need to be sure there isn't anything embarrassing hidden in the middle of text. All the Lorem Ipsum generators on the Internet tend to repeat predefined chunks as necessary, making this the first true generator on the Internet. It uses a dictionary of over 200 Latin words, combined with a handful of model sentence structures, to generate Lorem Ipsum which looks reasonable. The generated Lorem Ipsum is therefore always free from repetition, injected humour, or non-characteristic words etc.



# 3

---

## Results

---

---



---

## Conclusions

---

---



---

## Technicalities

---