2nd Workshop on Computational Complexity and Economic Decision Making

Organised by the Leverhulme International Professorship in Neuroeconomics at the Faculty of Economics, University of Cambridge

19–20 May 2025
Newnham College, University of Cambridge

We gratefully acknowledge the generous support of the Leverhulme Trust and The Janeway Institute, Cambridge, which has made this workshop possible

Workshop programme

Monday, 19th of May

13:00-13:30	Welcome and coffee	
13:30-14:00	Adam Sanjurjo	Complexity in Choice
14:00-14:30	Michael Ungeheuer	A Cognitive Foundation for Perceiving Uncertainty
14:30-15:00	Duarte Goncalves	Revealed Complexity
15:00-15:30	Jean-Edouard Colliard	Measuring Regulatory Complexity
15:30-16:00	Coffee break	
16:00-16:30	Konstantinos Ioannidis	How computational complexity restores general equilibrium in markets with indivisible goods
16:30-17:00	Stefan Bucher	Cognitive Economic Curves: Quantifying Clear and Conspicuous Disclosure
17:00-17:30	Juan Pablo Franco Ulloa	Characterising the computational complexity of optimal choice via Fitness Landscape Analysis
18:00	Drinks reception (by invitation)	
19:00	Dinner (by invitation)	

Tuesday, 20th of May

9:00-9:30	Ferdinand Vieider	Loss-Sensitivity versus Loss-Aversion
9:30-10:00	Rafal Bogacz	Striatal dopamine reflects individual long-term learning trajectories
10:00-10:30	William R. Stauffer	Neural Correlates of Combinatorial Reasoning
10:30-11:00	Coffee break	
11:00-11:30	Fabian Grabenhorst	Neural mechanisms for complex decisions in the primate amygdala
11:30-12:00	Wolfram Schultz	Experimental economics at the single-neuron level
12:00-12:30	Peter Bossaerts	The Role of Markets in Resolving Complexity
12:30-13:30	Buffet Lunch	

List of Abstracts

Complexity in Choice

Adam Sanjurjo[1]

[1] Department of Economics, University of Alicante, Spain [1]

(Updates expected)

In computer science, the computational complexity of a problem is often measured by its space complexity, which quantifies the working memory resources required by an algorithm or machine to solve the problem. I implement this measure in a canonical multiattribute choice problem, in which each attribute of each alternative is first processed sequentially, in any order. I quantify the space complexity when varying the size of the problem, the processing order, and the information structure, and characterize the minimum complexity algorithms. I then introduce a choice model that incorporates space complexity as an input and test it using human choices from an existing experiment. A simple one-parameter version of the model closely tracks a complicated pattern of choice errors across six treatments. Lastly, I provide a novel structural explanation for the appeal of two well-known choice heuristics: satisficing and elimination-by-aspects.

A Cognitive Foundation for Perceiving Uncertainty

Michael Ungeheuer[1]

[1] Department of Finance, Aalto University, Finland

We propose a framework where perceptions of uncertainty are driven by the interaction between cognitive constraints and the way that people learn about it—whether information is presented sequentially or simultaneously. People can learn about uncertainty by observing the distribution of outcomes all at once (e.g., seeing a stock return distribution) or sampling outcomes from the relevant distribution sequentially (e.g., experiencing a series of stock returns). Limited attention leads to the overweighting of unlikely but salient events—the dominant force when learning from simultaneous information—whereas imperfect recall leads to the underweighting of such events—the dominant force when learning sequentially. A series of studies show that, when learning from simultaneous information, people are overoptimistic about and are attracted to assets that mostly underperform, but sporadically exhibit large outperformance. However, they overwhelmingly select more consistently outperforming assets when learning the same information sequentially, and this is reflected in beliefs. The entire 40-percentage point preference reversal appears to be driven by limited attention and memory; manipulating these factors completely eliminates the effect of the learning environment on choices and beliefs, and can even reverse it.

Revealed Complexity

Duarte Gonçalves[1]

[1] Department of Economics, University College London, UK

Understanding the complexity of economic problems is key to reducing errors and improving decision-making. While simple problems allow for straightforward choices, more complex ones pose greater cognitive demands and are more prone to mistakes. Building on the sequential sampling framework in Gonçalves (2024), we experimentally examine a behavioural marker of complexity: increased responsiveness to subsidies. Using tasks where we can exogenously and unambiguously vary complexity, we show that participants perform worse and respond more to subsidies as complexity increases. We also confirm other theoretical predictions, such as response times being single-peaked in complexity---longest for problems of intermediate difficulty. Finally, we extend our approach to a belief-updating task involving dimensions that cannot be easily ranked in complexity, demonstrating the broader applicability of our method. Our findings offer a tractable way to study problem complexity and suggest that responsiveness to incentives may help identify decision environments prone to errors.

Measuring Regulatory Complexity

Jean-Edouard Colliard[1]

[1] Department of Finance, HEC Paris, France

We propose a framework to study regulatory complexity, based on concepts from computer sci ence. We distinguish different dimensions of complexity, classify existing measures, develop new ones, compute them on three examples — Basel I, the Dodd-Frank Act, and the European Banking Authority's reporting rules — and test them using experiments and a survey on compliance costs. We highlight two measures that capture complexity beyond the length of a regulation. We offer a quantitative approach to the policy trade-off between regulatory complexity and precision. Our toolkit is freely available and allows researchers to work on other texts and test alternative measures.

How computational complexity restores general equilibrium in markets with indivisible goods

Konstantinos Ioannidis[1]

[1] Department of Economics, University of Cambridge, UK

We study whether and how markets reach general equilibrium when goods are indivisible. When goods are indivisible, consumers are facing an NP-hard optimisation problem. We develop a new equilibrium concept, namely the complexity compensating equilibrium, which exists even when consumer budgets are too low for general equilibrium to exist. We provide experimental evidence supporting our equilibrium.

Cognitive Economic Curves: Quantifying Clear and Conspicuous Disclosure

Stefan Bucher[1]

[1] Department of Economics, University of Cambridge, UK

Regulators demand consumer disclosures to be clear and conspicuous, yet there has been no metric to gauge disclosure clarity. We introduce cognitive economic curves, an empirically-driven method that ranks disclosures by assessing their impact on consumer decision-making and welfare. These curves plot consumers' probability of making optimal decisions as stakes increase, explicitly quantifying the cognitive load imposed by disclosures. Through incentivized experiments using privacy policies—known for complexity and jargon—we show that simplified, succinct disclosures significantly enhance decision quality. We further uncover how extraneous information leads consumers to wrongly reject beneficial options, while verbose language prompts acceptance of poor ones. Cognitive economic curves thus offer regulators and organizations a powerful, scientifically-grounded tool to measure and improve the clarity of disclosures.

Characterising the computational complexity of optimal choice via Fitness Landscape Analysis

Juan Pablo Franco Ulloa[1]

[1] Centre for Brain, Mind and Markets, University of Melbourne, Australia

Human decision-making often involves tackling computationally challenging optimisation problems. Yet, to date, there is no general theory to granularly characterise the complexity of optimisation problems and its effect on human decision quality. Here, we address this gap by introducing generic, task-independent complexity metrics using Fitness Landscape Analysis (FLA), a method from operations research. We evaluate the effectiveness of these metrics through an online experiment where participants solve instances of the knapsack optimisation problem, each varying in difficulty as determined by FLA. Our findings reveal that these complexity metrics account for a significant portion of the variance in human performance, highlighting FLA as a promising framework for understanding the intrinsic complexity of cognitive tasks. This study provides insights into human information-processing limitations and offers a modelling tool to enhance current decision-making models.

Loss-Sensitivity versus Loss-Aversion

Ferdinand Vieider[1]

[1] Department of Economics, Ghent University, Belgium

Using a representative sample of the UK (N = 1000), we document risk taking in mixed gain-loss choices to be strongly stake-dependent: while our respondents are risk seeking for mean-preserving spreads around zero for moderate stakes up to £10, they become increasingly risk averse as stakes increase. Such patterns are predicted by recent models of adaptive behaviour based on ‘noisy sampling’ and ‘noisy cognition’. We test the two adaptive models against each other and against traditional accounts based on diagnostic treatments for which they make opposite predictions. Prospect theory cannot account for the adaptive patterns we document. The evidence further supports the noisy cognition model over the sampling-based account. The reason is that the former is grounded in an optimization framework, whereas the latter is based on psychological intuition, which we show to be at the origin of the predictive differences between the two models.

Striatal dopamine reflects individual long-term learning trajectories

Rafal Bogacz[1]

[1] MRC Brain Network Dynamics Unit, University of Oxford, UK

Learning from naïve to expert occurs over long periods of time, accompanied by changes in the brain's neuronal signals. The principles governing behavioural and neuronal dynamics during long-term learning remain unknown. We developed a psychophysical visual decision task for mice that allowed for studying learning trajectories from naïve to expert. Mice adopted sequences of strategies that became more stimulus-dependent over time, showing substantial diversity in the strategies they transitioned through and settled on. Remarkably, these transitions were systematic; the initial strategy of naïve mice predicted their strategy several weeks later. Longitudinal imaging of dopamine release in dorsal striatum demonstrated that dopamine signals evolved over learning, reflecting stimulus-choice associations linked to each individual's strategy. A deep neural network model trained on the task with reinforcement learning captured behavioural and dopamine trajectories. The model's learning dynamics accounted for the mice's diverse and systematic learning trajectories through a hierarchy of saddle points. The model used prediction errors mirroring recorded dopamine signals to update its parameters, offering a concrete account of striatal dopamine's role in long-term learning. Our results demonstrate that long-term learning is governed by diverse yet systematic transitions through behavioural strategies, and that dopamine signals exhibit key characteristics to support this learning.

Neural Correlates of Combinatorial Reasoning

William R. Stauffer[1]

[1] Center for Neuroscience, University of Pittsburgh, USA

Combinatorial reasoning is a cognitive ability that supports decision making in computationally complex tasks such as budgeting, scheduling, and route planning. Behavioral impairments in tasks that rely on combinatorial reasoning often precede the onset of severe mental illness and age-related cognitive decline. Despite its significance, the neural mechanisms underlying this faculty remain poorly understood. We hypothesized that the dorsolateral prefrontal cortex (DLPFC)—a region that supports working memory, exhibits flexible coding schemes, and is known to degenerate in both psychosis and aging—would exhibit neural correlates of combinatorial reasoning. To test this, we trained rhesus monkeys to perform a combinatorial optimization task (the knapsack task) and recorded activity from well-isolated single units in the DLPFC during task performance. Our findings reveal that, during deliberation, individual neurons encode abstract computational elements analogous to those used in high-complexity combinatorial algorithms. These include neurons that track the best possible outcome given current information and update their activity as this upper bound changes, as well as neurons selectively tuned to specific combinations of items. Notably, the strength and specificity of this coding were enhanced on trials where the monkeys' behavior indicated engagement in high-complexity reasoning strategies. These results suggest that DLPFC neurons dynamically support the evaluation and construction of optimal solutions and may implement the computations that enable decision makers to determine what they value.

Neural mechanisms for complex decisions in the primate amygdala

Fabian Grabenhorst [1]

[1] Department of Experimental Psychology, University of Oxford, UK

Primates including humans encounter infinitely many rewards in the real world. Each reward consists of many features—such as the sensory and nutrient components of foods—and is governed by abstract variables including probability and risk, eliciting distinct preferences. Beyond evaluating rewards individually, primates' sophisticated social lives require grasping the reward valuations of social others to predict their choices. This complexity of many rewards, many features, and social contexts creates computational challenges for neural systems. Using evidence from single-neuron recordings and neural-network models, I will discuss how the primate amygdala implements solutions for these challenges.

Experimental economics at the single-neuron level

Wolfram Schultz [1]

[1] Department of Physiology, Development & Neuroscience, University of Cambridge, UK

Rewards, and their maximisation, are crucial determinants for individual survival and evolutionary fitness. Rewards induce learning (positive reinforcement), approach behavior, economic choices and emotions (pleasure, desire).

We use behavioural tools derived from animal learning theory and machine learning (reinforcement learning) and economic decision theory (Expected Utility Theory, Revealed Preference Theory). We conceptualise rewards as probability distributions of value whose key parameters are expected (mean) value and forms of risk expressed as variance (spread) and skewness (asymmetry). Behavioural choices reveal distinct attitudes towards these risk forms and comply with predictions from estimated utility functions. The choices follow the gambles' first, second and third order stochastic dominance and thus are meaningful and rational in the sense of getting the best reward. Behavioural choices among multi-component rewards can be studied according to formal choice indifference curves of Revealed Preference Theory and provide further tests for reward maximisation, including Arrow's Weak Axiom of Revealed Preference Theory (WARP).

Using experimental tasks derived from these theories, we investigate the activity of individual reward neurons in specific brain structures. Dopamine neurons carry a two-component reward prediction error signal for the physical impact and value of rewards, respectively. The reward signal codes formal economic utility and is influenced by risk. Slower components of the same neurons signal motor activation. Neurons in the orbitofrontal cortex code the integrated or distinct values of multi-component rewards and follow Arrow's utility maximisation axiom. These neurophysiological mechanisms represent the physical implementation of theoretical constructs such as reward value (utility), preference, probability, risk and stochastic dominance. They inform and validate theories of economic decision making.

The Role of Markets in Resolving Complexity

Peter Bossaerts[1]

[1] Department of Economics, University of Cambridge, UK

Markets were initially thought of as means to efficiently allocate resources. In that setting, everyone is solving a personal resource allocation (budget) problem which, if goods are indivisible, is NP hard. Do markets select prices that make individuals' budget problems easier, thus facilitating rational behavior? Or do prices deliberately complicate budget decisions in order for supply and demand to equilibrate? In the latter case, the use of markets to solve societies' resource allocation problems may be counter-productive since it complicates members' lives.

Useful Information

Talks will be held at the **Lucia Windsor Room** at Newham College. It is located on the first floor, with lift access for ease of entry (please see *Location & Directions*, and *Newnham College Map* below).

Coffee breaks will be held near the **Lucia Windsor Room**. **Lunch** will be served in **College Hall,** with **dinner** there by invitation only.

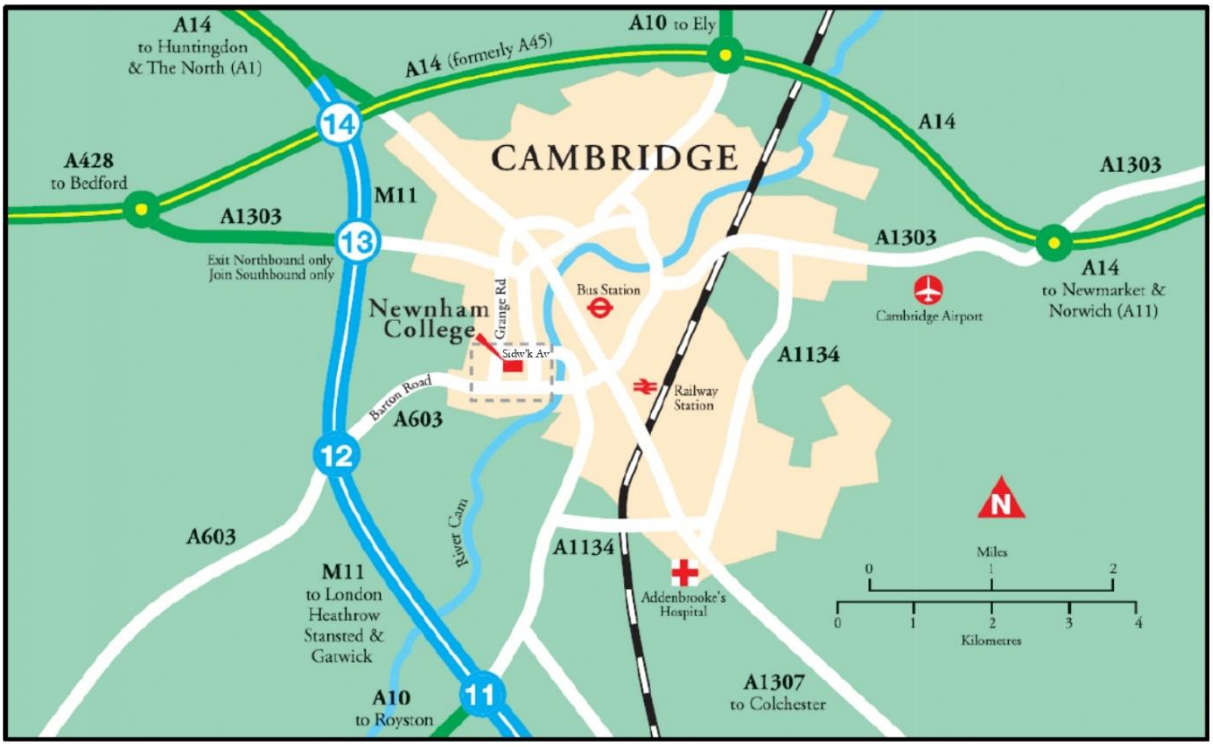
Wi-Fi will be available throughout the conference, with instructions for network access provided on site.

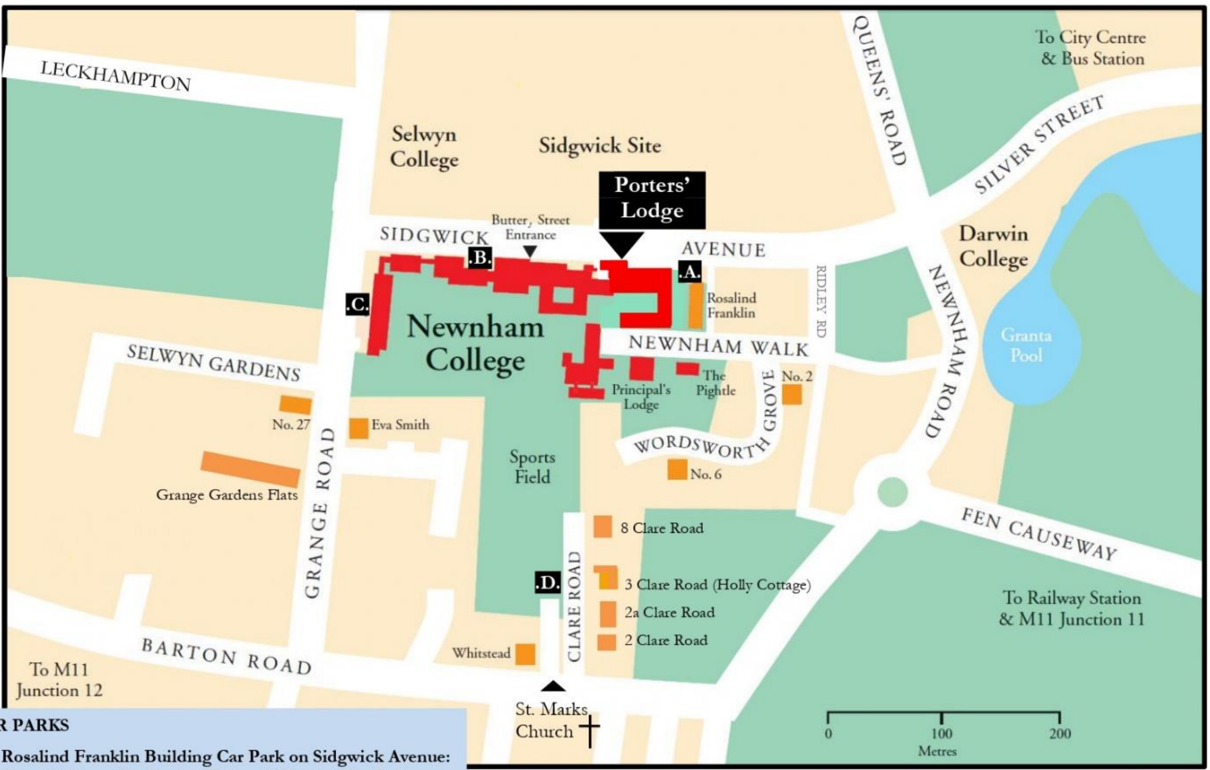
Lucia Windsor Room

College Hall

NEWNHAM COLLEGE
UNIVERSITY OF CAMBRIDGE

Location & Directions:





CAR PARKS

.A. Rosalind Franklin Building Car Park on Sidgwick Avenue: Drop Off Area, Pre-Booked Visitor & Disabled Car Park.

.B. Clough Car Park on Sidgwick Avenue: Fellows only Parking.

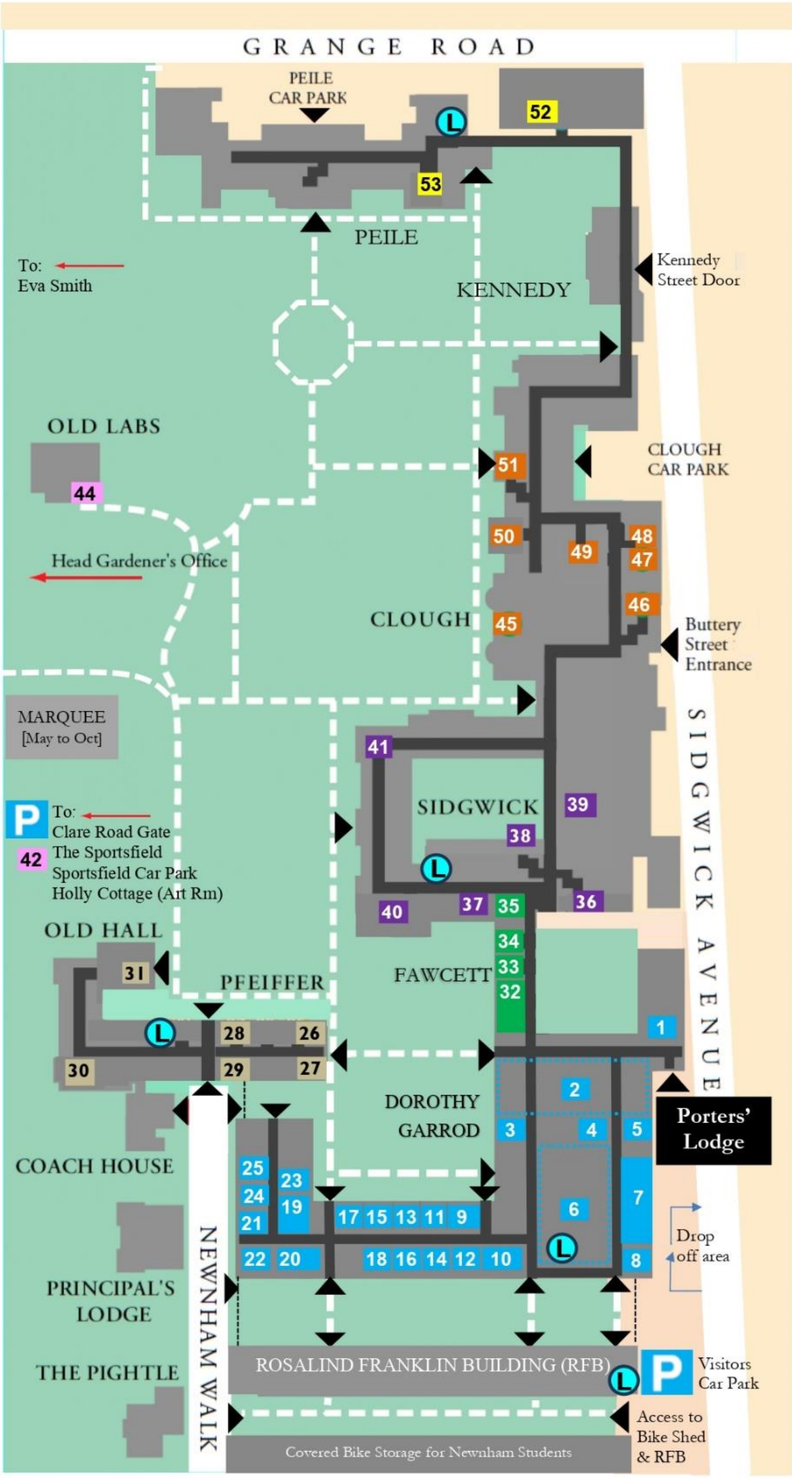
.C. Peile Car Park on Grange Road: Fellows & Staff Parking.

.D. Sportsfield Car Park on Barton Road: Pre-Booked Visitor, Staff and Fellows Parking

[Please note that no parking is available on site without prior permission from the College]

NEWNHAM COLLEGE
UNIVERSITY OF CAMBRIDGE

Newnham College Map



41	Admissions Tutor (1st flr)
3	Anna Bateson Room
42	Art Room (Holly Cottage)
2	Bar/Café
30	Barbara White Room
52	Buildings Manager & Workshop
15	Bursar
10	Bursary
46	Buttery
2	Café/Bar
47	Catering Operations Manager (1st flr)
48	Catering Offices (1st flr)
51	Clough JCR (1st flr)
17	College Accountant
29	---
45	College Hall (Clough Dining Hall)
26	College Nurse
21	Communications Directors
32	Conference Offices
6	Cynthia Beerbower Room
20 /22	Development & Roll Offices (Grd flr)
23	Development Director
13	Domestic Bursar
18	Executive Assistant to the Principal
8	Gym (3rd flr X Staircase - Roof Level)
14	Information and Support Office
43	Head Gardener
11	Head of Tutorial & Academic Office
33	Housekeeping Manager
34	Housekeeping Office
12	HR Manager
14	Information and Support Office
19	I.T. Department
53	Jane Harrison Room
49	Kitchen (Executive Head Chef)
39	Library and Archives
35	Linen Room
44	Lucia Windsor Room (1st flr)
25	Margaret Anstee Centre (MAC)
5	Millicent Garrett Fawcett Room
31	MCR
44	Music Practice Rooms (Old Labs)
44	Old Labs
4	Party Room (Basement)
22	Pavilion Meeting Room (3rd flr Y staircase)
1	Porters' Lodge & Head Porter
38	Postgraduate Tutors Room (1st flr)
16	Principal
20/22	Roll & Development Offices (Grd flr)
50	SCR
28	Senior Tutor (1st flr)
37	Sidgwick Study Room (1st flr)
40	Sidgwick Hall & Sidgwick Alcove
36	Skilliter Centre (1st flr)
7	Supervision Rooms
9	Tutorial & Academic Office
24	Undergraduate Admissions Office
41	Vice-Principal (Grd flr)
27	Wellbeing Advisor
	Garden Paths (main routes)
	Entrances
L	Laundries (washing machines / driers)

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