

The Cavendish Laboratory under James Clerk Maxwell(1871-79)¹⁾

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맥스웰 시기의 캐브디쉬 연구소(1871-79)

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요 약

1874년에 문을 연 케임브리지 대학의 캐브디쉬 연구소는 영국 실험물리학의 중심지로서 많은 우수한 과학자들을 배출해 냈다. 이 논문의 목적은 캐브디쉬 연구소가 초대 소장이었던 맥스웰의 지도하에 어떻게 새로운 전통들을 수립해 나갔는가를 보이고자 하는 데에 있다. 저자는 우선 지금까지 알려져 왔던 바와는 달리 초창기에 연구소의 전망이 그렇게 밝지만은 않았다는 점을 보일 것이다. 그리고 “19세기 후반” “케임브리지 대학”이라는 독특한 환경하에서 연구의 전통, 정밀관측의 전통, 그리고 대학원으로서의 역할 등이 연구소에 점차적으로 정착되어 가는 과정을 밝히고자 한다. 마지막으로 맥스웰이 소장으로서 재직할 당시 성공한 일과 실패한 일이 어떤 것이었으며, 그 원인은 무엇이었는가 하는 점도 자세히 다룰 것이다.

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1) This paper is based on a chapter of my thesis, *The Emergence of the Cavendish School : The History of the Cavendish Laboratory, 1871-1900*. Following abbreviations are employed : CUR(Cambridge University Reporter), CUL MS(Cambridge University Library Manuscripts), MT(Mathematical Tripos), NST(Natural Science Tripos), *Proc.Roy.Soc.* (Proceedings of the Royal Society of London), *Phil.Mag.* (Philosophical Magazine).

The Cavendish Laboratory, built in 1874, was the first physics laboratory at the University of Cambridge. Under three distinguished scientists, Maxwell, Rayleigh and J. J. Thomaon, the Laboratory succeeded to plant a new research tradition in this old University. Since the end of the 19th century, it had become the center of experimental physics for British Empire, producing many celebrated discoveries. However, the future of the Laboratory was not so rosy in the beginning. In this paper, I will try to show how Maxwell endeavored to introduce his advanced idea of physics laboratory, and how far he succeeded or failed to realize it during his tenure.

I. Foundation of the Professorship of Experimental Physics and the Establishment of the Cavendish Laboratory

The much debated subjects of heat, electricity and magnetism were finally added to the new scheme of examination for Honours in the Mathematical Tripos in 1868, which was first given in 1873. The University, however, had no means of teaching these experimental subjects, and the next step was to find a way to offer instruction in them. For this purpose, a syndicate was appointed on 25 November 1868, “to consider the best means of giving instruction to students in physics, especially in Heat, Electricity and Magnetism, and the methods of providing apparatus for this purpose.”²⁾

On 27 February 1869, after three months of thorough study, the Physical Science Syndicate issued a detailed report³⁾ It started by pointing out the lack of means to teach these experimental subjects in the University, and justified its inquiry by quoting the Report of the Royal Commission of 1850: “no reason can be assigned why other great branches of Natural Science should not become equally objects of attention, or why Cambridge should not become a great school of physical and experimental as it is already of mathematical and classical instruction.”⁴⁾ To secure these aims, the Report recommended the foundation of a new professorship whose main duty was “to teach and illustrate the law of Heat, Electricity and Magnetism, to apply himself to the advancement of the knowledge of such subjects and to promote their study in the University.”⁵⁾ and to establish “a well appointed Laboratory.”⁶⁾ It also recommended the appointment of a special syndicate “whthout delay”⁷⁾ to investigate the means of financing these enterprises. The Report was signed by twelve prominent figures in the University, among whom there were Dr. H. W. Cookson(Master of St. Peter’s College), G. G. Stokes(Lucasian Professor), G. M. Humphry(Professor of Anatomy), G. D. Liveing(Professor of Chemistry), and E. J. Routh(famous mathematical coach).

2) R. T. Glazebrook, *James Clerk Maxwell and Modern Physics* (New York, 1896), p. 61.

3) *CUR*, (Nov. 16, 1870), pp. 93–97.

4) *Ibid.*, p. 94.

5) *Ibid.*, p. 95.

6) *Ibid.*, p. 94.

7) *Ibid.*, p. 96.

Some aspects of the Report should be noted. First, throughout the whole Report, emphasis was laid on the Professor's role as a lecturer, not as a researcher. The Professorship was to provide "the large amount of additional teaching"⁸⁾ needed to train the candidates of several examinations: the Mathematical Tripos(MT), the Natural Science Tripos(NST), the optional branch of Mechanism and Applied Science or that of Chemistry for the Ordinary Degree, and later the first examination for the M.B. Degree. The laboratory and its equipments were required "to render the Professor's teaching practical."⁹⁾ The Professor was to give at least eighteen lectures every term, and the course of lectures was to be approved by the Board of Mathematical Studies. The burden of delivering a total of fifty four lectures a year, in addition to directing the laboratory, was certainly very heavy. The Report therefore recommended the appointment of a Demonstrator "whose principal duty shall be to give personal instruction in the Laboratory,"¹⁰⁾ and that of an assistant for the preparation of lecture room and laboratory. In short, research was not yet regarded as an official responsibility of the professor in this old University!

Second, the Report stressed the establishment of the laboratory and the collection of equipment as much as the foundation of the Professorship. A good portion of the Report was devoted to explaining the necessity for a laboratory, instruments, apparatus, lecture rooms, and to estimating their cost. Without them, it stressed, the foundation of the professorship itself "would be incomplete."¹¹⁾ It was "obvious" that they were necessary to give "personal instruction to students in the laboratory."¹²⁾ The Report indicated that a sum of £6,300 would be required of which £5,000 would be allocated for a new laboratory building, and £1,300 for apparatus, cases and furnitures. Compared with the annual budget of £660 for the new posts (£500 for the Professor, £100 for the Demonstrator, and £60 for the lecture room Attendant), this was quite a large sum of money which could not be easily raised.

A question immediately arises. Why did the Syndicate propose this seemingly unrealistic scheme, though it was aware that raising such a large amount of money posed almost insurmountable difficulties and that the recommendation therefore might block the foundation of the Professorship itself? Moreover, it was obvious that the Syndicate did not have any clear ideas for the implementation of the financial plan. A plausible answer to the question is that the Syndicate appreciated the nature of experimental physics: the new subjects could not be taught effectively with a blackboard and chalk, or with simple demonstrations by a professor. William Thomson's laboratory in Glasgow and the German universities were proof that the well-equipped laboratory was necessary not only for effective teaching but also for successful research. Even Cambridge's sister university, Oxford, had shown an ambition to become a home for physical science, by constructing "a new laboratory" and offering "schol-

8) *Ibid.*, p. 94.

9) *Ibid.*, p. 94.

10) *Ibid.*, p. 96.

11) *Ibid.*, p. 94.

12) *Ibid.*, p. 94.

arships and exhibitions and studentships for the encouragement of natural and physical sciences in school.”¹³⁾ Thus, in the late 1860’s, people both inside and outside of the University were suggesting that Cambridge was falling behind other universities in the field of experimental physics. The article, “Stranger’s Impressions of Cambridge,” which was written by Professor Humphry, a member of the Syndicate, well expressed this feeling :¹⁴⁾

I had lately the pleasure of accompanying two eminent Professors, highly intelligent thoughtful men, one a German the other an Englishman, over the University and Colleges.

The German, after contemplating some of the newly erected College buildings, said, “If the money which has been expended in the many grand buildings I have seen, or half of it, had been well bestowed in promoting scientific education, how very different would now be the position of Cambridge and England with regard to science.…… If I were rich man I would come to Cambridge and build a laboratory. You do want working laboratories very much. Yet there are plenty of rich here, why are not more laboratories built for your University? I cannot think.” I need scarcely say that I had no good reason to offer. …… I would only add, that there is scarcely another University in Europe so hardly off in this respect. For instance, Oxford, Dublin, Edinburgh, and Glasgow has each a laboratory of Experimental Physics with apparatus and a teacher or teachers of eminence, and is ready to train and supply men to meet the quickly growing demand for this kind of instruction in the various schools of the United Kingdom.

The English Professor observed, “If the fund at the disposal of your Colleges were made the most educationally, neither London, Manchester, Edinburgh, Glasgow, Dublin or any other place in the kingdom, could pretend to compare with you. As it is, and unless great change is made here, these other places show good promise of beating you, at least as regards scientific education.”…… A similar feeling is, we know, growing in the University even among those most closely associated with Colleges, who feel most strongly the clog of College individuality upon their efforts to carry out combined plans for University improvement.

As the above comment suggests, the pressure and demand for change first came from the outside, and they were very serious ones. It was not just a problem of Cambridge’s standing in a given field. The issue was one declining institutional and regional competence, and national pride, for all of which Cambridge felt responsible. Therefore, even the conservative dons could not turn their eyes from this demand for change. Moreover, unlike the University reform movement of the 1840s and 1850s, the demands for change did not provoke the conservatives’ resistance because there seemed not very relevant to their immediate concern : the College system. Trying to exploit this favorable climate, the Syndicate might expect that Colleges would support financially the establishment of the Laboratory. This soon proved to be just a dream!

The third point to be noted in the Report is its recommendation that the Professorship and the Laboratory be simultaneously established. This was a revolutionary step both in British science and in the history of physical laboratories. The stress on simultaneity indicated that the future Laboratory would not be a private possession of the Professor, because the Professor

13) D. A. Winstanley, *Later Victorian Cambridge* (Cambridge:Cambridge Univ. Pr., 1974),p. 198. “Chapter V. Educational Reform(1860—1880)”provides a good background.

14) *CUR*, (Oct. 19, 1870), p. 26.

was not its promoter. Both of them were being advanced at the initiative of the University. Moreover, as a property of the University, the Laboratory would automatically receive the University's official recognition. Remember that William Thomson's laboratory had not been officially recognized by the University of Glasgow for sixteen years!¹⁵⁾ As a public place in the University, the Laboratory would be used to hold practical examinations as well as to teach, and sometimes to carry out research. Members of the University had the right to use the Laboratory with the permission of the Professor. In fact, when the Laboratory opened, Professor Maxwell, its first Director, issued the following notice: "The Cavendish Laboratory will be open daily from 10 A.M. to 6 P.M, under the superintendence of the Professor and the Demonstrator of Experimental Physics, for the use of any Member of the University who may desire to acquire a knowledge of experimental methods, or to take part in physical researches."¹⁶⁾ The open door policy helped attract a wider range of men, and, as a result, strengthened the position of both the Professor and the Laboratory within the University. By concentrating research and instruction of the most fashionable subjects in the Laboratory, the Professor was to become a powerful figure in the University.

The realization of this visionary scheme, however, depended heavily on the success of financing it. A syndicate was appointed on 13 May 1869, "to consider the means of raising the necessary funds for establishing a Professor and Demonstrator of Experimental Physics, and for providing buildings and apparatus required for that department of Science, and further to consider other wants of the University, and the sources from which those wants may be supplied." Its initial strategy to raise the necessary funds was revealed when they asked several Colleges "whether they would be willing to make contributions from their corporate funds." This approach was unsuccessful.¹⁷⁾ The rich Colleges were reluctant to share their resources for the University purpose. The syndicate then proposed 1) to raise the Capitation Tax for the income of the Professor and that of the Demonstrator until "the income of the Chest shall have been adequately increased by means of Contributions from the Colleges," 2) to use the income of the two University Building Funds for the construction of the Laboratory and the income of the Government Stock belonging to the Chest for the purchase of the apparatus, cases and furnitures.¹⁸⁾ These were quite reasonable proposals. However, raising tax was, as usual, unpopular and levying a tax on even non-residents seemed unfair to many members of the University. The use of the several University Funds was also problematic. As revealed in the discussion of the report¹⁹⁾ the financial problems it raised were so complicated and divisive that the foundation of the Professorship would probably have to

15) Romualdas Sviedrys, "The Rise of Physical Science at Victorian Cambridge," *HSPS* 2(1970), p.138. For more details about Thomson's laboratory, see David Murray, *Memories of the Old College of Glasgow: Some Chapters in its History of the University* (Glasgow: Jackson, Wylie and Co., 1927), pp. 131-140, and S. P. Thompson, *The Life of William Thomson* (London, 1910), vol. 1. Chapter VII.

16) *CUR*, (Jan. 25, 1876), p. 221.

17) *CUR*, (Oct. 19, 1870), p. 19.

18) *Ibid.*, p. 20.

19) *CUR*, (Oct. 26, 1870), pp. 49-51.

be delayed for a few years. The future of the whole plan became uncertain.

Then, all of a sudden, came a startling announcement. Before any further discussions had taken place on the Syndicate's plan, after the Long Vacation, the Vice-Chancellor published "the following munificent offer of his Grace the Duke of Devonshire, the Chancellor of the University"²⁰⁾ :

HOLKER HALL, GRANGE,
LANCASHIRE.

MY DEAR VICE-CHANCELLOR.

I have the honour to address you for the purpose of making an offer to the University, which, if you see no objection, I shall be much obliged to you to submit in such manner as you may think fit for the consideration of the Council and the University.

I find in the Report date Feb. 29[27 is right], 1869, of the Physical Science Syndicate, recommending the establishment of a Professor and Demonstrator of Experimental Physics, that the buildings and apparatus required for this department of Science are estimated to cost £6,300.

I am desirous to assist the University in carrying this recommendation into effect, and shall accordingly be prepared to provide the funds required for the building and apparatus, as soon as the University shall have in other respects completed its arrangements for teaching Experimental Physics, and shall have approved the plan of the building.

I remain,
My Dear Mr Vice-Chancellor
Your very faithfully
DEVONSHIRE.

After this generous offer from the Chancellor, the Colleges became more cooperative and indicated their readiness to provide the remuneration of the Professor and the Demonstrator. On 26 November 1870, the foundation of the Professorship of Experimental Physics was formally proposed in the Senate. The proposal was approved on 9 February 1871.

Before closing this section, it is worthwhile to consider briefly the life of the Chancellor, in order to understand his motivation for giving Cambridge the funds to build the much needed laboratory.²¹⁾

William Cavendish, Seventh Duke of Devonshire, was born on 27 April 1808. His great-grandfather was a first cousin of Henry Cavendish, the celebrated natural philosopher of the 18th century, and his great-grandmother was the direct descendent of Richard Boyle, who was brother to Robert Boyle. He was thus related to two of the most distinguished British scientists.

He was educated at Eton and at Trinity College, Cambridge. His career at the University was exceptionally brilliant. In 1829 he graduated as Second Wrangler, Eighth in the First Class of the Classical Tripos, and First Smith's Prizeman. It was said that Charles Babbage,

20) *CUR*, (Oct. 19, 1870), p. 13.

21) *Dictionary of National Biography Supplement* 22, (London), pp. 400–401, and "Obituary Notice," *Proc. Roy. Soc.*, 51(1892), pp. xxxviii–xli. See also J. G. Crowther, *The Cavendish Laboratory 1874–1974* (New York : Science History Publications, 1974), pp. 18–22.

the Lucasian Professor and one of his mathematical examiners at that time, was surprised by his high scores and that he gave Cavendish's papers to a second examiner to have checked them again.²²⁾

In politics, Cavendish was a Whig, following the family tradition. He served in the House of Commons, representing first Cambridge, then Malton in Yorkshire, and thereafter Derbyshire, and supported the government's proposal for parliamentary reform. In 1834, he succeeded his grandfather as Second Earl of Burlington. In the Upper House he was said to speak very rarely. He was a keen observer of the course of events but never participated in the debates. In 1858, he succeeded his cousin and became the Seventh Duke of Devonshire.

After his move to the House of Lords, Devonshire devoted himself to the scientific and industrial concerns of the country. He showed himself to be an enlightened, liberal landowner, and an able manager, who always thought of his tenants' interests and did not raise rent. He was one of the founders of the Royal Agricultural Society in 1839, and was its President in 1860. For fifty years he was a breeder of shorthorns, and his Holker had a wide reputation. He contributed to the foundation of the Agricultural College at Cirencester, and persuaded Cambridge University to take steps for promoting the study of scientific agriculture.

Besides being an agricultural reformer, the Duke was also one of the most successful English industrialists of the 19th century. His most important industrial venture was the mining of the rich deposits of high grade haematite iron ore on his estate in Furness. He there established one of the largest Bessemer plants in Europe, and the ore and products were transported by railway to Barrow, a port the Duke and his partners had built. When the Iron and Steel Institute was founded in 1868, he was elected its first President. His nickname was "The Iron Duke."²³⁾

Although not very active in politics, the Duke had been very committed to the extension of education. He was the Chancellor of the University of London from 1834 to 1856, and on the death of Prince Consort, in 1861, he was elected Chancellor of the University of Cambridge. He held this position until his death. He was at one time President of the Owens College, Manchester, and a generous benefactor both of Owens College and of Yorkshire College of Science. After the foundation of Victoria University in 1880, the former Owens College, he became its first Chancellor. He fully appreciated the importance of science in relation to industrial progress, and he was president of the Royal Commission on Technical and Scientific Instruction which helped awaken the public's attention to this subject.

The large sum he donated to Cambridge for the establishment of the Laboratory, which would be named after him, should therefore be considered the result of his continuous interest in scientific education rather than his wanton to create "a factory..... a manufactory for discoveries" as J. G. Crowther thought.²⁴⁾ Above all, the Duke was a member of the English nobility who had a strong sense of social responsibility. As such he was different from

22) Crowther, *The Cavendish Laboratory*, p. 19-20.

23) *Ibid.*, p. 21.

24) *Ibid.*, p. 31.

most bourgeois—industrialists who were primarily interested in the returns of their investments. Moreover, as an outstanding graduate of Cambridge and as its Chancellor, he was well aware of its traditions and its present difficulties. As was stressed in the Report of 1869, the purpose of the foundation of the Professorship and the establishment of the Laboratory was purely academic. There was little room for industry in this old University.

II. Election of James Clerk Maxwell as the first Professor of Experimental Physics

Meanwhile, the question arose who would be the first Professor. Since the chair was to be a very prestigious and powerful one, a prominent figure should be appointed. Hence, the most famous British physicist at that time, William Thomson, was approached first. In 1869 there was an unsuccessful approach by the Master of Trinity to induce him to come to Cambridge, with an offer of a Praelectorship in Science. The attempt failed because of Lady Thomson's illness.²⁵⁾ When the foundation of the Professorship of Experimental Physics was officially proposed in November 1870, H. W. Cookson, master of Peterhouse, asked Thomson to accept the proposed chair. Thomson's reply was as follows:²⁶⁾

Glasgow College, Dec.1, 1870

My Dear Cookson—I thank you very much for your letter of the 29th Nov. Every decision that I make in such a matter is equally painful to me. In other circumstances the comparative mildness of the climate and the congeniality of Cambridge society would have decided me without hesitation to accept. But now I feel that there is nothing for me in life but to make the most of what time remains for doing everything I can do in scientific work. The great advantages I have here with the new College, the apparatus and the assistance provided, the convenience of Glasgow for getting mechanical work done, give me means of action which I could not have in any other place. It would be impossible for me to feel as free from anxiety regarding the duties of any new position, and especially one of so great importance and responsibility as the proposed professorship in Cambridge, as I feel here after 24 years' habit, and without that freedom from anxiety I could do nothing in scientific work. But above all I have an invincible repugnance, in the circumstances in which I am left, to the ideas of beginning a new life at all, and especially one which would have been so full interest—Believe me, yours very truly.

William Thomson

In fact, Thomson was too much involved in the economic, social, and scientific life of Glasgow to consider a move to Cambridge.²⁷⁾

Hermann Helmholtz in Berlin was approached next. Thomson wrote in January of 1871 to Helmholtz to explain the offer.²⁸⁾ In his letter Thomson indicated that he had been asked by Stokes and Cookson to inquire of Helmholtz whether he could be induced to accept the Professorship. Thomson expected that Helmholtz would also be offered a fellowship in St. Peter's College, or a praelector-fellowship in Trinity College, either of which would increase his in-

25) Thompson, *Life of W. Thomson*, vol. I, pp. 558–562.

26) *Ibid.*, p. 563.

27) Crosbie W. Smith & M. Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge Univ. Pr., 1989).

28) Thompson, *Life of W. Thomson*, Vol I, pp. 554–566.

come as Professor considerably. Even though he was prepared for a reply from Helmholtz that he was "absolute for Berlin," Thomson urged him to consider the invitation because his acceptance would be "a great gratification and advantage to English scientific men," and he himself "would consider the difference of distance from Glasgow to Cambridge and Berlin a great gain." Helmholtz, understandably, was not able to leave Berlin, where he was just appointed to the prestigious chair of physics that Gustav Magnus had filled.

When it became certain that neither Thomson nor Helmholtz would accept the Professorship, Maxwell was pressed to be a candidate. Since 1865, when he resigned the chair of Natural Philosophy at King's College, London, Maxwell had stayed at his estate, Glenlair. There he devoted himself to write up the results of his investigations in heat, electricity and magnetism : *Theory of Heat* appeared in 1870, and *A Treatise on Electricity and Magnetism* was published in 1873. So, it was uncertain whether Maxwell would abandon his comfortable life in Glenlair and come to Cambridge. Stokes,²⁹⁾ John Willian Strutt(third Lord Rayleigh), Rev. E. W. Blore(Vice-master of Trinity), and others wrote him in order to persuade him :

Feb. 13th 1871

My Dear Maxwell.

Our Professorship of Experimental Physics is now founded & though the salary is not magnificent (£500 a year) yet there is a general wish in the University that this branch of Science should be supported in a way creditable to the University. The Duke of Devonshire has undertaken the expense of the building & apparatus, & it remains for us that we should find the Professor. Many residents of influence are desirous that you should occupy the post hoping that in your hand this University would hold a leading place in this department. It has, I believe, been ascertain that Sir W. Thomson would not accept the Professorship. I mention this in case you should wish to avoid the possibility of coming into the field against him. Should you be willing to stand as I hope. I & many others will exert our influence to secure your election.

Believe me.

Your very truly
E.W.Blore.³⁰⁾

Cambridge, 14th February 1871

Dear maxwell,
.....

When I came here last Friday I found every one talking about the new professorship, and hoping that you would come. Thomson, it seems, has definitely declined..... There is no one here in the least fit for the post. What is wanted by most who know anything about it is not so much a lecturer as a mathematician who has actual experience in experimenting, and who might direct the energies of the younger Fellows and bachelors[of arts] into a proper channel. There must be many who would be willing to work under a competent man, and who, while learning themselves, would materially assist him. There would I am told be every disposition on the part of authorities to help the new Professor. I hope you may be induced

29) Stokes sent two letters, on Feb.16 & 18, to urge Maxwell to stand. See CUL MS, Add. 7655/II, 40, 42.

30) CUL MS, Add. 7655/II, 38A.

to come ; if not, I don't know who it is to be. Do not trouble to answer me about this, as I believe others have written to you about it.

Yours very truly,
Jonh W. Strutt³¹⁾

However, Maxwell, who indeed was “a mathematician who has actual experience in experimenting,” hesitated to stand and replied to Blore:³²⁾

Glenlair, Dalbeattie, 15th February 1871

MY DEAR BLORE—Though I feel much interest in the proposed Chair of Experimental Physics, I had no intention of applying for it when I got your letter, and I have none now, unless I come to see that I can do some good by it.

... I am sorry Sir W. Thomson has declined to stand. He has had practical experience in teaching experimental work, and his experimental corps have turned out very good work. I have no experience of this kind, and I have seen very little of the somewhat similar arrangements of a class of real practical chemistry. The class of Physical Investigations, which might be undertaken with the help of men of Cambridge education, and which would be creditable to the University, demand, in general, a considerable amount of dull labour which may or may not be attractive to the pupils.

A few days later he changed his mind and decided to stand, “on the understanding that he might retire at the end of a year, if he wished to do so”³³⁾ On 24 February, Maxwell's candidacy was formally announced by Blore, and there were no other candidates. On 8 March, he was elected to the Professorship of Experimental Physics without opposition.

The story of the election has some interesting aspects. First, the entire electoral procedure was very informal. The search for the candidates, in all cases, had occurred before the official notice of February 14th, and the period between it and the election was rather short. Moreover, there was only one candidate, and he was voted upon without one testimonial! All these indicate that the election was just a formal process and the choice was predetermined, as Blore's letter had suggested. It was not the usual situation. For example, William Thomson had collected some thirty testimonials through his father's efforts in order to compete with other four candidates for the vacant chair of Natural Philosophy at Glasgow.³⁴⁾ When Maxwell applied to the vacant post at the University of Edinburgh, he competed with many other candidates, and the chair went to his best friend, P. G. Tait. Maxwell did succeed in becoming the Professor of Natural Philosophy at King's College, but only after defeating four other candidates. In Cambridge, there were usually many contestants for the vacant chairs, and it was unusual to have only one candidate. In 1875, there

31) Robert John Strutt(Fourth Rayleigh), *The Life of John William Strutt, Third Baron Rayleigh* (London : Edward Arnold, 1924), pp. 48–49.

32) CUL MS, Add. 7655/II, 39.

33) Lewis Campbell & William Garnett, *The Life of James Clerk Maxwell* (London, 1882), p. 348.

34) Thompson, *Life of W. Thomson*, vol. 1, pp. 161 – 189.

were three candidates applying for the Jacksonian Professorship of Natural Experimental Philosophy,³⁵⁾ and, in that same year, another three candidates competed for the newly founded Professorship of Mechanism and Engineering.³⁶⁾

Another interesting point to note is that Maxwell was third on the list of candidates. While both Thomson and Helmholtz were already praised as great scientists, Maxwell was not. This corroborates the widely held opinion that he had not been highly appreciated by the public during his life. He was never a popular scientist, like Faraday or William Thomson. His name was unfamiliar even to the Cambridge students. Horace Lamb, a student during the first few years of Maxwell's Professorship, remembered that when Maxwell was appointed, "he was little more than a name to many of us, except that on one or two occasions he had responsible for some highly original questions set in the Mathematical Tripos."³⁷⁾ Though he became better known after the publication of his *Treatise* in 1873, it was only after his death that he became one of the "greats."

Maxwell's scientific style was also somewhat different from that of the other two "possible candidates," particularly from that of Thomson. Though he designed and performed experiments, and showed interest in technology—for example, the telephone and the governor³⁸⁾—he was never an engineer. He was the most mathematically and theoretically oriented physicist of his generation, and his fame depended almost wholly on mathematical and theoretical investigations. On the other hand, Thomson achieved his fame from the success in the operation of the trans-Atlantic cable in the 1860's, which eventually led to his knighthood.³⁹⁾ His interest in various fields of applied science and technology contributed not only to his reputation but was also responsible for his considerable wealth. As David B. Wilson argued, Thomson "had virtually an entire career as an engineer, as well as one as a physicist."⁴⁰⁾ While his papers on theoretical physics had influenced many generations of physicists throughout the world, most of his students in Glasgow laboratory became engineers, and "none was a physicist, either experimental or mathematical, of the first rank."⁴¹⁾ In short, Maxwell's interest was much more academic than Thomson's, and the tradition of the Cavendish Laboratory would be very different from that of Glasgow by virtue of Maxwell's acceptance of the chair.

35) *CUR*, (Mar. 23, 1875), p. 274 & 281.

36) *CUR*, (Nov. 2, 1875), p. 76. For more detailed story, see T. J. N. Hilken, *Engineering at Cambridge, 1783–1965* (Cambridge: Cambridge Univ. Pr., 1967), p. 63.

37) J. J. Thomson & Others, *James Clerk Maxwell: A Commemoration Volume, 1873–1879* (Cambridge: Cambridge Univ. Pr., 1931), p. 143.

38) See "Telephone (Rede Lecture)" in J. C. Maxwell, *The Scientific Papers of James Clerk Maxwell*, edited by W. D. Niven, 2 vols. new edition (New York: Dover, 1952), vol. 2, pp. 742–755. For governor, see pp. 105–120.

39) See Thompson, *Life of W. Thomson*, Chapter VIII, XI, and Smith & Wise, *Energy and Empire*, Chapter 19.

40) David B. Wilson, *Kelvin and Stokes: A Comparative Study in Victorian Physics* (Bristol: Adams Hilger, 1987), pp. 12–13.

41) *Ibid.*, p. 67.

III. Inaugural Lecture : the Guideline

In October 1871, Maxwell delivered his Inaugural Lecture. The Lecture was delivered in “an out of the way lecture room,” not in the Senate House as expected. There had been only one announcement of it, and only “a score or so of students” attended.⁴²⁾ In his lecture Maxwell described the role he intended the future “Devonshire Physical Laboratory” to play in the scientific life of Cambridge.⁴³⁾ After stating his optimistic assessment of the future of science, he outlined his views of experimental physics, and then presented his guidelines for the Laboratory.

Let me say a few words on these two classes of experiments—Experiments of Illustration and Experiments of Research. The aim of an experiment of illustration is to throw light upon some scientific idea so that the student may be enabled to grasp it. The circumstances of the experiment are so arranged that the phenomenon which we wish to observe or to exhibit is brought into prominence, instead of being obscured and entangled among other phenomena, as it is when it occurs in the ordinary course of nature.

.....

In an experiment of research, on the other hand, this is not the principal aim. It is true that an experiment, in which the principal aim is to see what happens in the certain conditions, may be regarded as an experiment of research by those who are not yet familiar with the result, but in experimental researches, strictly so called, the ultimate object is to measure something which we have already seen—to obtain numerical estimate of some magnitude.

Experiments of this class—those in which measurement of some kind is involved, are the proper work of a Physical laboratory. [all italics are mine] In every experiment we have first to make our senses familiar with the phenomenon, but we must not stop here we must find out which of its features are capable of measurement, and what measurements are required in order to make a complete specification of the phenomenon. We must then make these measurements, and deduce from them the result which we require to find.⁴⁴⁾

Maxwell here clearly expressed his opinion that his Laboratory would not be used solely as a teaching laboratory for “Experiments of Illustration,” but would be principally a serious research center, something the University lacked. Though the principal purpose of the Laboratory and that of the Professorship were to provide Cambridge undergraduates with laboratory training, the Laboratory also would be a research center. Maxwell was aware of the tension that existed between the two groups which emphasized either research or teaching. The balance between the two aims, which had been the focus of lively discussions among the Cambridge dons,⁴⁵⁾ would be determined by the Director. Maxwell, in a letter to Mrs.

42) *A Commemoration*, p. 143.

43) Maxwell, *Scientific Papers*, vol. 2, pp. 241–255.

44) *Ibid.*, pp. 242–243.

45) J. J. Thomson & Others, *A History of Cavendish Laboratory 1871–1910* (London : Longmans, Green, & Co., 1910), p. 14.

Maxwell just after his appointment, noted this tension and revealed a plan to solve it : ⁴⁶⁾

20th March 1871

.....

There are two parties about the professorship. One wants popular lectures, and the other cares more for experimental work. I think there should be a graduation—popular lectures and rough experiments for the masses ; real experiments for real students ; and laborious experiments for first rate men like Trotter and Stuart and Strutt.

What kinds of “real experiments” and “laborious experiments” did Maxwell have in mind? It was natural to assume that, as an experimental laboratory, the main work of the future Cavendish Laboratory would consist of measurements. Maxwell accepted this, but his emphasis was in a different direction.

This characteristic of modern experiments—that they consist principally of measurements—is so prominent, that the opinion seems to have got abroad, that in a few years all the great physical constants will have been approximately estimated, and that the only occupation which will then left to men of science will be to carry on these measurements to another place of decimals.

If this is really the state of things to which we are approaching, our Laboratory may perhaps become celebrated as a place of conscientious labour and consummate skill, but it will be out of place in the University, and ought rather to be classed with the other great workshops of our country, where equal ability is directed to useful ends.

.....

...But the history of science shew that even during that phase of her progress in which she devotes herself to improving the accuracy of the numerical measurement of quantities with which she has long been familiar, she is preparing the materials for the subjugation of new regions, which would have remained unknown if she had been contented with the rough methods of her early pioneers. I might bring forward instances gathered from every branch of science, shewing how the labour of careful measurement has been rewarded by the discovery of new fields of research, and by the development of new scientific ideas. But the history of the science of terrestrial magnetism affords us a sufficient example of what may be done by Experiments in Concert, such as we hope someday to perform in our Laboratory.⁴⁷⁾

The point was that Maxwell did not consider measurements as the ultimate goal. Rather precision measurement would be a vehicle to opening new domains of inquire: “The increase in the accuracy and completeness of magnetic observations which was obtained by the new method, opened up fields of research which were hardly suspected to exist by those whose observations of the magnetic needle had been conducted in a more primitive manner.”⁴⁸⁾ Thus, it was not the proper work of the future Laboratory to carry the experiments “to another place of decimals” exclusively. The “real” and “laborious” experiments Maxwell had in mind were much more complicated and ambitious ones : they not only would carry out measurements but would also employ some theoretical studies. The key word here was to be

46) Campbell & Garnett, *Life of Maxwell*, p. 381.

47) Maxwell, *Scientific Papers*, vol.2, p. 244.

48) *Ibid.*, P. 245.

“method,” by which Maxwell understood the new ways of posing questions to nature that he intended to in the Laboratory.

There is no more powerful method for introducing knowledge into the mind than that of presenting it in as many different ways as we can. It is therefore natural to expect that the knowledge of physical science obtained by *the combined use of mathematical analysis and experimental research* will be of a more solid, available, and enduring kind than that possessed by the mere mathematician or experimenter.⁴⁹⁾

.....

We might even imagine a course of experimental study the arrangement of which should be founded on a classification of methods, and not on that of the objects of investigation. A combination of the two plans seems to me better than either, and while we take every opportunity of studying methods, we shall take care not to dissociate the method from the scientific research to which it is applied, and to which it owes its value.

We shall therefore *arrange our lectures according to the classification of the principal natural phenomena*, such as heat, electricity, magnetism and so on.

In the laboratory, on the other hand, the place of the different instruments will be determined by a classification according to methods, such as weighing and measuring, observations of time, optical and electrical methods of observation, and so on.⁵⁰⁾

Maxwell's view of experimental physics and his vision of the Laboratory were certainly far beyond the expectation of the two parties. He firmly believed that, only through the successful marriage of mathematical and experimental science, could the flourishing of experimental physics in the University be achieved. “The combined use of mathematical analysis and experimental research” was not a new slogan : it had long been the ideal of scientists since Bacon. However, it had only recently begun to be realized. What was new in Maxwell's lecture was his aim to “institutionalize” this ideal in the University where only mathematical one had been recognized officially.

By mid-century the harmonization of mathematics and experimental sciences was rapidly being advanced by several German-speaking physicists under the new title of “theoretical physics.” Recently Christa Jungnickel and Russell McCormmach have thoroughly recounted these developments in their impressive study, *Intellectual Mastery of Nature : Theoretical Physics from Ohm to Einstein*.⁵¹⁾ On the one hand, theoretical physics was different from mathematical physics, the latter of which aimed to “abstract” the natural phenomena. Theoretical physicists were concerned with experimental and real data, and often did experiments with their own hands, as Gauss, Weber, Helmholtz, and later Hertz showed. On the other hand, it was distinct from experimental physics whose aim was to collect data or to measure “another place of decimals.” Most theoretical physicists, unlike experimenters, were quite competent in mathematics, and they would “consult or even col-

49) *Ibid.*, p. 247.

50) *Ibid.*, p. 249.

51) Christa Jungnickel & Russell McCormmach, *Intellectual Mastery of Nature : Theoretical Physics from Ohm to Einstein*. 2 vols. (Chicago : Univ. of Chicago Pr., 1986).

52) *Ibid.*, vol. 1, p. 185.

laborate with a mathematician.”⁵²⁾ The real strength of German theoretical physics, however, came from its successful institutionalization in the universities.

In Britain, there were some leading physicists, for example, Herschel, Thomson, Stokes, Maxwell, and Rayleigh, who could be called as “theoretical physicists.” But their scientific styles had not greatly influenced British education. Cambridge University, the nursery of many British physicists or “natural philosophers”, had been the fortress of mathematical physics ever since the foundation of the Mathematical Tripos in the mid-18th century. There students could safely neglect experiments in order to get higher score in the examination. Maxwell, as the Director of the Laboratory and the Professor of Experimental Physics (the only physics professorship), had the opportunity to change the map by introducing a German style curriculum, i.e., by establishing a close link among lectures, laboratory training, and research. Only through this new method of inquiry, could the Laboratory breed the competent researchers who would be able to carry out the “real” and “laborious” experiments like their German counterparts. And only through it, could Maxwell’s ultimate dream be realized.

*Our principal work, however, in the Laboratory must be to acquaint ourselves with all kinds of scientific methods, to compare them, and to estimate their value. It will, I think, be a result worthy of our University, and more likely to be accomplished here than in any private laboratory, if, by the free and full discussion of the relative value of different scientific procedures, we succeed in forming a school of scientific criticism, and in assisting the development of the doctrine of method.*⁵³⁾

Maxwell’s goal was quite novel. Rather than merely directing a teaching laboratory or forming a research school of his own, he aimed to found “a school of criticism” which would foster “all kinds of scientific methods.” Maxwell’s emphasis on, “criticism,” and “method” foreshadowed the characteristics of the Laboratory to be : it would not be one man’s school and it would allow and endure any “criticism.” As Maxwell had intended, during the last quarter of the century, the Cavendish Laboratory would evolve, slowly but steadily, into a true “school of scientific criticism,” embracing many different scientific methods and various experimental subjects.

IV. Cambridge Physics Education during the 1870’s

The success of Maxwell’s ambitious plan for “a school of scientific criticism” depended largely on whether his lectures and the Laboratory could attract a sufficient number of able students. Since the Laboratory was, first of all, a part of the University educational system, let me put Cambridge physics education next.

The first priority of shaping this “school” was thus to find the right men in the University. Those targeted were, naturally, the candidates and the graduates of the MT and the NST. However, it was not an easy task to enroll Cambridge students in professorial lectures, since

53) Maxwell, *Scientific Papers*, vol. 2, p. 250.

the Colleges had taken the teaching responsibility into their own hands with the unique system of tutoring. In fact, tutoring, tutors' lectures, and private lessons were the usual means for preparing for both Triposes. Unless professorial lectures were given on subjects directly related to the examinations, students were advised, by their tutors, not to attend them. In mathematics, professorial lectures were considered reserved for the few highly talented candidates or for those who had already passed the examinations. Even the competition among the tutors was intense. J. J. Thomson remembered that he had been lucky because his tutor was "a classic, and I found this an advantage, for he let me choose the mathematical lectures I attended, whereas if he had been a mathematician he would have made me go to his own lectures."⁵⁴⁾ He therefore could attend professorial lectures given by C. Cayley, J. C. Adams and Stokes. In Cayley's lectures, he was the only undergraduate attending along with two Masters, one of whom, J. W. L. Glashier, was his teacher.⁵⁵⁾ This situation was more clearly revealed in the MT whose candidates had long been trained by several legendary coaches(private tutors) like William Hopkins and Routh.⁵⁶⁾ Even popular lectures by Stokes on optics and hydrodynamics(both were the subjects of the MT) attracted on the average 18 students a year during the 1870's⁵⁷⁾ Meanwhile, in the NST, the situation was a little better since professorial lectures were the main sources of instructions. For example, "the numbers of most of the more important University classes [of natural sciences] are from 20 to 30. In Elementary Biology the number is larger. In Chemistry it is nearly a hundred."⁵⁸⁾

The number of students attending Maxwell's lectures was very dissapointing. According to a memo in the back of one of his notebook,⁵⁹⁾ 19 students registered to study heat, when he first delivered his regular lectures in the Michaelmas Term(autumn) of 1871. In the Lent Term(winter) of 1872, 26 students enrolled, and in the Easter Term(spring) of 1872, 10. In the Michaelmas Term of 1872, when he lectured on the same subject, only 8 students attended his class. No further information is available about the number of students enrolled in his lectures, but it is certain that it remained very small. J. A. Fleming, who came to Cambridge in 1877 "with the object of benefitting by his[Maxwell's] lectures and laboratory teaching," was surprised to find "a teacher who was everywhere regarded as the great living authority on his subjects lecturing to a class of two or there students in place of the 100 or more attentive listeners he would have had in any Scottish or German universities.····· In the last year of his life the only two attendants at his lectures were an American gentleman,

54) Joseph John Thomson, *Recollections and Reflections* (New York : MacMillan Co., 1937), p. 34.

55) *Ibid.*, p. 47.

56) William Hopkins is known to have trained 175 Wranglers including 17 First Wranglers, and William Thomson, Stokes, Maxwell, Strutt were once his students. E. J. Routh, who was the First Wrangler in 1854 when Maxwell was the Second, coached J. J. Thomson and others since 1870s.

57) Wilson, *Kelvin and Stokes*, p. 48.

58) *CUR*, (Mar. 17, 1876), p. 353. In the Syndicate Report of 1876 on "the requirement of the University in different departments of study," the Board of Mathematical Studies asked no additional Teachers, while the Board of Natural Science Studies asked for 7 additional teachers among whom at least one was for physics. see *ibid.*, pp. 299–358.

59) CUL MS, Add 7655/Vn., 2.

Mr. Middleton, who was a resident at St. John's, and myself."⁶⁰⁾

The chief reason for the poor attendance was that his lectures were not connected in an essential manner with preparation for the Triposes. Judging from Fleming's notebooks on electricity and thermodynamics, they were also too difficult and too demanding for most students.⁶¹⁾ For those who wanted to study experimental physics for Triposes, more practical ways existed: tutor's lectures, and, after the Lent Term of 1877, the Elementary Experimental Lectures by the Demonstrator of Experimental Physics.

The Elementary Experimental Lectures were organized by Maxwell and given by his Demonstrator, William Garnett, who had been the Fourth Wrangler in 1873 and had "impressed Maxwell[the Additional Examiner of that year] by the knowledge of physics displayed in his papers."⁶²⁾ These elementary courses were designed so as to provide the student with the basic knowledge of the subjects and to expose him to the practical experiments, which were required for the physics examination in the NST and the previous examination all medical students should take. The course covered mechanical physics, heat, electricity, magnetism, and light, and "no previous knowledge of Mathematics beyond Arithmetic" was required.⁶³⁾ The lectures were so successful that they "soon became popular and formed some of the largest Science classes in the University."⁶⁴⁾ However, the students in these classes did not plan to become physicists. These lectures were of little help in recruiting future physicists, most of whom still came from the MT.

In a word, the lack of concrete and systematic programs for physics education was a real weakness of Cambridge. There was no distinct curriculum for those who wanted to "major" in physics. Physics was included in both the MT and the NST, but it was never treated as an independent division. The MT, which had produced several eminent physicists since its introduction, was an imperfect way to breed physicists. It was anyway a *written mathematical* examination. Even after 1873 when heat, electricity and magnetism were added to the list, most of the questions in it were highly mathematical ones.⁶⁵⁾ In the first three days, candidates would tackle Euclid, elementary algebra, elementary part of conic sections, elementary part of statics and dynamics, some parts of Newton's *Principia*, and elementary

60) *A Commemoration*, pp. 117—118.

61) CUL MS, Add. 8082(Thermodynamics), 8083(Electricity). The latter contains the following subjects: "fundamental experiments, Electromotive force, on insulator and insulating stands, Gauss' method of charging electrometer so as to avoid vibration, Cavendish's proof of the law of inverse squares, Maxwell's theory of the foregoing experiment, Coefficients of induction and capacity, Maxwell's method of measuring specific induction capacity, Boltzman specific induction capacity of gases, specific induction capacity—how to measure, electrical induction, expression for energy of field, current distribution in network of conductors, Wheatstone's bridge, thermoelectricity, and potential." Mathematics used in the notebook was certainly beyond the level of the NST, even though Fleming was a candidate of the NST.

62) *History of Cavendish Laboratory*, p. 18.

63) *CUR*, (Dec. 12, 1876), p. 146.

64) *History of Cavendish Laboratory*, p. 35.

65) For the complete list of subjects, see David B. Wilson, "Experimentalists among Mathematicians: Physics in the Cambridge Natural Science Tripos, 1851—1900," *HSPS*, 12(1982), pp. 367—371.

parts of hydrostatics, optics and astronomy. During the next five days, the subjects would be more diverse and were arranged in five divisions that included algebra, trigonometry, differential equations, analytical geometry, differential and integral calculus, dynamics, optics, statics, theory of chances, Newton's *Principia*, Laplace's coefficients, hydrodynamics, sound, wave, theory of elastic solids, heat, electricity, and magnetism. According to David B. Wilson, the division that included heat, electricity and magnetism "constituted twelve per cent of the examination—small enough to be safely ignored by someone not interested, large enough to make a man low wrangler if he collected all the marks in the division."⁶⁶⁾ In fact, students had no time to study these new subjects deeply, and in 1874 the Board of Mathematical Studies reported that "the questions on Electrodynamics and Magnetism were hardly attempted by any of the candidates."⁶⁷⁾ Moreover, candidates were advised by tutors to sacrifice depth for quantity in order to obtain higher marks. This was against the intention of the examiners who in 1876 "regret[ed] to say that very few of the Candidates appear to confine their reading to two or three of the Divisions, as was anticipated when the present Regulations were drawn up, and in the words of the Additional Examiner[Lord Rayleigh], 'feel strongly that something ought to be done to prevent men getting up a quantity of bookwork without a proper study of the subject.'"⁶⁸⁾ Over the years, as the competition became more and more intense, "success seemed to depend upon fast writing : some able men left questions unanswered merely because they could not in the time allowed write fast enough to shew all their knowledge"⁶⁹⁾ The true intention of the reform to make students more familiar with contemporary experimental subject therefore could not be achieved as long as the MT was competitive written examination.

The importance of physics in the NST was increased considerably. When the NST was first introduced in 1851, physics was not a separate subject. It was a part of the first division, chemistry, and it was also taught in mineralogy, geology, and physiology. Since the NST did not require any higher mathematics, the level of physics in the NST was lower than that in the MT, and, in fact, the NST did not produce any physicists at first. However, some dramatic changes occurred during the 1870s. In 1871, the Board of Natural Science Studies recommended the following reforms, which were to take effect in 1873⁷⁰⁾ : 1) physics become a separate subject[not a separate division] ; 2) the NST, like the MT, be divided into two parts, with the first three days reserved for the elementary part, and the last three days for the more advanced part with two additional days for practical examinations ; 3) all candidates for Honours in the NST be required to show some knowledge of the elementary prin-

66) *Ibid.*, p. 339.

67) *CUR*, (May 5, 1874), p. 356.

68) *CUR*, (May 9, 1876), p. 451. Similar feeling was expressed by many others. In 1871, J. F. Moulton of Christ's College said, "One of the chief reasons given by men not reading a subject exhaustively is that there is a great chance of its being represented in the Tripos by but one or two questions, and that they cannot afford to risk spending so much time on it." : *CUR*, (Feb. 22, 1871), p. 202. See also *CUR*, (May 23, 1876), pp. 514—515.

69) *CUR*, (May 23, 1876), p. 515.

70) *CUR*, (Mar. 1, 1871), pp. 212—218.

ciples of chemistry and physics. The report was passed in the Senate with the last item left out.⁷¹⁾ Further changes occurred in 1876, when it was decided to divide the examination: the elementary part would be given in June, and the advanced part, together with the practical examination, in December.⁷²⁾ The aim of the plan was to give some serious students sufficient time to study few selected subjects deeply. The first examination given under this regulation proved that the principle worked too far. After analyzing the 1876 examination, the Board of the Natural Science Studies reported that some students had confined their efforts too narrowly to a single subject, so that "though they have shewn considerable knowledge of the details of their special subjects, they have not shewn sufficient acquaintance with the principles of the cognate and subsidiary subjects."⁷³⁾ The Board therefore recommended to regroup the subjects, and physics was grouped with chemistry and mineralogy.⁷⁴⁾

The changes that were instituted during the 1870's meant that the NST required more thorough knowledge of every branch of natural sciences, while the MT still aimed to foster the mathematical mind of gentlemen. The future of physics thus seemed brighter in the NST than that in the MT. Furthermore, the candidates for the NST were the chief beneficiaries of offerings of the Cavendish Laboratory which formally opened on 16 June 1874. The Laboratory became the site where the practical examinations of the NST were held. In the Lent Term of 1877, the Elementary Experimental Lectures were introduced. Starting with the Michaelmas Term of 1877, the NST students were advised to take Practical Physics under the supervision of the Professor or the Demonstrator.⁷⁵⁾ The Laboratory remained open during the Long Vacation, and candidates for the advanced part of the NST could prepare for their practical examination during the period.

However, despite all of these changes, the NST was still not considered the conduit for first rate physicists. Most of the talented students who came to Cambridge to study physics still took the MT. William Napier Shaw, who obtained a first class with distinction in physics in 1876, was the only physicist who took the NST before 1879, but he was also a Wrangler (sixteenth in the same year).⁷⁶⁾ A defect of the NST physics was the exclusion of advanced mathematics, and the lack of tradition—a very crucial factor at the University. While the MT required the knowledge of a good deal of mathematics even from the elementary parts, the questions in the first part of the NST physics were limited to definitions, principles, laws, simple applications and experiments.⁷⁷⁾ Candidates for the NST would therefore spend a

71) Winstanley, *Later Victorian Cambridge*, p. 199.

72) *CUR*, (Mar. 14, 1876), p. 291. See also the Report of Natural Science Studies in *CUR*, (Jun. 9, 1874), pp.440—442. The second part of the examination opened only to "those who are declared to have so acquitted themselves as to deserve a B. A. degree, and no others."

73) *CUR*, (Mar.6, 1877), p.270.

74) *CUR*, (May.29, 1877), pp.472—474.

75) According to H. F. Newall, "the first organized course of practical experiments in physics was given in Michaelmas Term of 1879" (*History of Cavendish Laboratory*, p. 109). But it is still unclear "when" the class actually began.

76) For the list of Honours, see *The Historical Register of the University of Cambridge* (Cambridge, 1917).

77) *CUR*, (Jun. 15, 1875), p. 491 & (Mar. 14, 1876), p. 290.

great deal of time memorizing these definitions and laws rather than solving problems. This regrettable “divorce between Mathematics and Experimental Work.”⁷⁸⁾ which was so detrimental to a sound physics education, was often pointed out and regretted by many Cambridge men. But no acceptable solution seemed possible, as long as the two Triposes were the main vehicles for training future physicists at Cambridge.

The lack of a systematic program for physics at Cambridge is also illustrated by the fact that several sets of overlapping lectures on the same subject were given in the same term. During the 1870’s Cambridge physics never suffered from a want of lectures on leading subjects. Cambridge might have been the leading university in Europe as far as the number of lectures in experimental physics was concerned. But most of these lectures were delivered by tutors, not by professors, and there was always the greater risk of discontinuity than of overlap. For example, in the Lent Term of 1877, lectures on electricity and electrodynamics were given by one Professor(Maxwell) and by three tutors. One year later, during the Lent Term of 1878, Maxwell again delivered his lectures on electricity, but no tutorial lectures were given on electricity and electrodynamics. Throughout the 1870s, only Coutts Trotter regularly delivered tutorial lectures on experimental physics, mainly for the candidates for the NST and medical students. As Table 1 shows, there were great fluctuations in the number of tutorial lectures as well as changes of lecturers, proof of the fact that Cambridge still lacked a stable program.

Nonetheless, the syndicates’s report on “the requirement of the University in different departments of study,” issued in 1877, did not reflect this defect.⁷⁹⁾ After simply comparing the lecture lists of Cambridge, Berlin, and Leipzig, the syndicate felt no deficiency and did not recommend any new professorship for physics. In fact, it suggested that Cambridge might be superior to, or at least equal to, its German counterparts in physics education. However, this was an untenable conclusion. It did not correctly assess the superior German educational system : its systematic link among lectures, laboratory training, and seminars, its successful institutionalization of research, theoretical physics and, most importantly, its establishment of graduate studies that were smoothly connected with the undergraduate curriculum thus extending the years of disciplinary studies. As a rule, German professors attracted students more easily and influenced their students’ study more than English professors.

At Cambridge, the situation was worse. For there dons competed with professors in anything related to College life, and in particular in teaching. The so-called “Germanizing the University,” which aimed to increase greatly the number of professors and to place all the teaching into their hands, met with harsh opposition from the majority. Henry Sidgwick, who attacked this trend in a series of articles, “Academic Teachers,” suggested that Cambridge appoint more College lecturers or praelectors instead of University professors, and that a relaxed system of inter-collegiate lectures would be the proper remedy.⁸⁰⁾

78) Glazebrook, *Maxwell and Modern Physics*, p. 76.

79) *CUR*, (Dec. 12, 1877), p. 186.

80) *CUR*, (Feb. 22, 1871), pp. 204–205 ; (Mar. 1, 1871), p. 221 ; (Mar. 8, 1871), pp. 235–236.

〈Table 1〉 Lectures on Experimental Physics at Cambridge, 1876—1878.

1876—77	Michaelmas Term	* Heat and the Constitution of Bodies, by Prof. Maxwell. * Electricity, by Mr. C. Trotter. Trinity. * Electrostatics, by Mr. Niven. Trinity. * Magnetism, by Mr. Chrystal. Corpus Christi. * Thermoelectricity, by Mr. Pirie. Queen's
	Lent Term	* Electricity, by Prof. Maxwell. * Elementary Experimental Lectures on Heat and Light, by Demonstrator, W. Garnett. * Electricity (continued), by Mr. C. Trotter. Trinity. * Mechanical Theory of Heat, by Mr. Pirie. Queen's * Electrodynamics, by Mr. Chrystal. Corpus Christi. * Electrodynamics, by Mr. Niven. Trinity. * Physical Optics, by Mr. Appleton. Trinity.
	Easter Term	* Hydrodynamics and Physical Optics, by Prof. Stokes. * Electromagnetism, by Prof. Maxwell. * Elementary Experimental Lectures on Electricity and Magnetism, by Demonstrator Garnett. * Electricity (continued), by Mr. C. Trotter. Trinity. * Elementary Physics (Light & c.), by Mr. C. Trotter. Trinity * Electrodynamics and Electromagnetism, by Mr. Chrystal. Corpus Christi. * Hydrodynamics, Sound and Light, by Mr. Routh. Peterhouse. * Heat, by Mr. Dale. Trinity.
1877—78	Michaelmas Term	* Heat and the Constitution of Bodies, by Prof. Maxwell. * Elementary Experimental Lectures on Electro-Magnetism and Electrical Measurements, by Demonstrator Garnett. * Elementary Experimental Lectures on Mechanics, by Demonstrator Garnett. * Practical Physics, by Professor or Demonstrator of Experimental Physics. * Magnetism, by Mr. Chrystal. Corpus Christi.
	Lent Term	* Electricity, by Prof. Maxwell. * Elementary Experimental Lectures on Heat, by Demonstrator Garnett. * Practical Physics, by Professor or Demonstrator of Experimental Physics. * Sound and Light, by Mr. C. Trotter. Trinity.
	Easter Term	* Optics, by Prof. Stokes. * Electromagnetism, by Prof. Maxwell. * Elementary Experimental Lectures on Electricity and Magnetism, by Demonstrator Garnett. * Practical Physics, by Professor or Demonstrator of Experimental Physics. * Sound and Light, by Mr. C. Trotter. Trinity. * Electricity (Elementary), by Mr. Dickson. Peterhouse. * Heat, by Mr. Pirie. Queen's.

(The list is based on the lecture lists in the *Cambridge University Reporter*)

Given the unfavorable circumstances, Maxwell's plan to connect his lectures with laboratory training and research had difficulty in being realized. The failure to attract an adequate number of students in his classes was the indication of the problem at hand, a failure often magnified by his personality. As his original plan faded away, he concentrated on establishing a research tradition in the Laboratory rather than fighting to change the status quo. The contemplated changes, in fact, were not realized during Maxwell's tenure, but would be realized during the next decades under Rayleigh and J. J. Thomson.

V. Maxwell as the Director of the Cavendish Laboratory

Maxwell's first job as the Director of the Laboratory was to design and supervise the erection of the Laboratory building. He visited Thomson's laboratory at Glasgow and Clifton's at Oxford,⁸¹⁾ in order to see what features of their arrangements might be adopted. Coutts Trotter also visited a number of laboratories for the same purpose. W. M. Fawcett of Cambridge was appointed as architect and he meticulously carried out all Maxwell's suggestions. The work of arranging and furnishing the Laboratory took up a considerable amount of time, and, while this was going on, Maxwell lectured wherever he could.⁸²⁾ The building was only completed in June 1874, and on the 16th of that month the Chancellor formally presented his gift of the Cavendish Laboratory to the University.

The structure of the building attracted lots of interest among scientists, and nine days after its opening a detailed description of the Laboratory was published in *Nature*.⁸³⁾ On the ground floor, there were the magnetic room, the clock and pendulum room, the balance room, the room devoted to calorimetry and other heat experiments, the battery room, and the storage. On the first floor there was the large laboratory intended for the general use of students. The Professor's private room was connected with this room by two hatches, through which he could glance, from time to time, to see what was going on. A large apparatus room and a large lecture room with the preparation room were also in this floor. The second floor was devoted to the more advanced experiments. There were rooms for acoustics, calculating and drawing, radiant heat, optics, electricity, and photography. The entire building was so well-designed that when the air in the lecture room[on the first floor] was too damp for good electrical experiments, "an insulated wire connected with the prime conductor of the electrical machine[on the second floor] ... [would] supply electricity on the lecture table."⁸⁴⁾ Except for not having a library of its own, the Cavendish Laboratory became the model for

81) There is a blueprint of the Clarendon Laboratory(Oxford) in Maxwell's manuscripts. See CUL MS Add. 7655/Vj., 1.

82) In his letter from Glenlair, "Lectures begin 24th," he wrote on 19th October 1872, "Laboratory rising, I hear, but I have no place to erect my chair, but move about like the cuckoo, depositing my notions in the Chemical Lecture room 1st term, in the Botanical in Lent, and in Comparative Anatomy in Easter." (in Glazebrook, *Maxwell and Modern Physics*, p. 73)

83) Anonymous editorial. "The New Physical Laboratory of the University of Cambridge," *Nature*, 10 (1874), pp. 139–142.

84) *Ibid.*, p. 141.

many experimental laboratories built subsequently.

When work formally began in October 1874, Maxwell's direction of the Laboratory emerged to take shape. As he revealed in his Inaugural Lecture, his highest priority was to make the Laboratory a center of experimental researches in the University. This was also the first step towards establishing "school of scientific criticism." His first official action was to open the door of the Laboratory to every member of the University. Even though this had been the desire of the syndicate that had recommended the establishment of the Laboratory, this could not have been realized without Maxwell's characteristic unselfishness. The aim of his policy was to attract virtually anyone who wanted to do research. But, in addition, this step prevented any possible criticism that he monopolized the University's property, and made it difficult for those who were involved in physics teaching to be jealous.

Then, who would work in the Laboratory? After three years as Professor, Maxwell realized that the link among his lectures, laboratory training and research would not be cemented in the near future, and that his endeavor to do so would inevitably result in some friction between him and other physics teachers in the University. At the beginning of his tenure he also had the ambition to change the intellectual map of the University. In a letter to Rayleigh on 15 March 1871, just after his appointment, he wrote: "if we succeed too well, and corrupt the minds of youth till they observe vibrations and deflections and become Senior Optimes instead of Wranglers, we may bring the whole University and all parents about our ears."⁸⁵ However, it soon became clear that any talented students did not want to become Senior Optimes with experimental training but wanted rather to become Wranglers without it. The traditional system was too firmly entrenched to be able to change it in a few years. Even though he never attempted "to attract to the Laboratory, or to his own lectures, large classes of undergraduates,"⁸⁶ it was not because of his deliberated avoidance of them but because of Cambridge's traditional system and of his own character. The alternative was to seek students who already had passed the examinations and were therefore free to follow their interests. In fact, such students were the first to enter to the Laboratory. Furthermore, they were the right persons with whom to plant and nurture a research tradition in the University. Maxwell concentrated his efforts on training such students, safely leaving the burden of teaching elementary classes to Garnett.

Maxwell's way of training research students was quite unique. Instead of teaching skills or providing knowhow, he left students to find out what apparatus to use and how to use it.⁸⁷ Students were never discouraged from making their own decisions, and were allowed to choose their own experiments. Only when students asked him for suggestions for research subjects—in the case of G. Chrystal and Fleming—did he provide ideas. He was always en-

85) *A Commemoration*, pp. 112–113. Or see Strutt, *Life of Rayleigh*, pp. 49–50. Maxwell also said in the letter, "To wrench the mind from symbols and even from experiments on paper to concrete apparatus is very trying at first, though it is quite possible to get fascinated with a course of observation as soon as we have forgotten all about the scientific part of it."

86) *Ibid.*, p. 115.

87) Schuster provided the best descriptions in these days. See *History of Cavendish Laboratory*, pp. 14–39.

couraging, “even when he thought a student was on the wrong track.” He once told Arthur Schuster, “I never try to dissuade a man from trying an experiment. If he does not find what he wants, he may find out something else.”⁸⁸⁾ But this did not mean that he neglected his duty as Director. Rather “he took an active part in every research that was carried out in the Laboratory. He used to come round daily, enter the various rooms, and say a few words, discussing results or making suggestions.”⁸⁹⁾ What he strove for was to encourage students to think creatively : he was firmly committed to the notion that research should not be determined by the Director’s opinion or wish.

On the whole, Maxwell played role of a great “teacher” rather than that of a bureaucratic “director.” Since the research group was quite small, he was easily approached by his students, and “was always ready to listen.”⁹⁰⁾ He was a generous counselor whom the students could always contact whether he was at Cambridge or at Glenlair. And this was the case whether the students were at Cambridge or had finished their studies there. The letters between Maxwell and Chrystal, the latter who had left the Laboratory in 1877, are illustrative of the fact that Maxwell still acted as his advisor, answering questions regarding thermo-electric question,⁹¹⁾ providing “the best method of comparing capacities,”⁹²⁾ and suggesting the interesting research topic of “testing the resistance of batteries by the telephone.”⁹³⁾ An indication of the closeness of the ties between Maxwell and his research students can also be found in their memoirs, in which they unanimously praised his generosity. They all agreed that no authoritarian demeanor could be found in him and they were all impressed by his modesty.⁹⁴⁾ He certainly encouraged his very self confident and highly gifted students to work independently. Schuster, one in whom Maxwell’s influence was most clearly reflected, correctly summarized Maxwell’s impact on the students :⁹⁵⁾

It is not easy to define Maxwell’s position as a teacher. His influence on scientific thought was mainly exerted through his writings, and reached its full effect only after his death ; while the power which he exercised by personal contact was principally a moral one. Having originated new and fertile ideas in all branches of Physics, Maxwell might easily have found students eager to work out in detail some problem arising out of his theoretical investigations. This would have been the recognized method of a teacher anxious to found a ‘school’ ; but it was not Maxwell’s method. He considered it best both for the advance of science and for the training of the student’s mind, that everyone should follow his own path. His sympathy with all scientific inquiries, whether they touched points of fundamental importance or minor de-

88) *Ibid.*, pp. 38–39.

89) *Ibid.*, p. 31.

90) Glazebrook, *Maxwell and Modern Physics*, p. 78.

91) CUL MS, Add. 8375. 15:Maxwell to Chrystal, 1 January 1878.

92) CUL MS, Add. 8375, 18:Maxwell to Chrystal, 17 July 1878.

93) CUL MS, Add. 8375. 19:Maxwell to Chrystal, 8 August 1878,

94) Maxwell’s modesty was well known at Cambridge. Coutt Trotter said, in his obituary, “[Maxwell] never uttered a hasty word even to his servants, but treated all like as brethren and equals. If mistakes were made or accidents occurred which caused him trouble, expense, or delay, he never complained, but tried to smooth the way for those who were to blame.” {from *Daily News*, (Nov. 8 1879)}.

95) *History of Cavendish Laboratory*, pp. 38–39.

tails, seemed inexhaustible ; It was the seriousness with which he discussed all ideas put before him by his students that, from the beginning, gave the Laboratory its atmosphere of pure and unselfish research.

Since Schuster had studied physics in both England and Germany (he received his Ph. D. under Kirhhoff at Heidelberg and did research under Weber at Gottingen and Helmholtz at Berlin) his comments carry special weight.⁹⁶⁾

The philosophy that guided Maxwell was a kind of *laissez-faire*. He wished to found "a school of criticism," not one that researched and supplemented his own theories. He therefore carefully separated his own researches from that of his students'. He carried out his researches by himself, and did so essentially without any direct assistance from students.⁹⁷⁾

It is very interesting to note that, during his tenure, Maxwell never attempted to prove experimentally the existence of the electromagnetic waves. This was "a matter of surprise" not only to Fleming alone,⁹⁸⁾ but also to many later readers of his works. His famous *Treatise* was published in 1873, and the Cavendish Laboratory opened in 1874. It would seem that it was the right time and that the Cavendish Laboratory was the right place to undertake such a project under the guidance of Maxwell, who now was the Director of the Laboratory. Nevertheless, this did not happen. The reason for this, I think, can be *partially* explained by his wish to foster *laissez-faire* policy in the Laboratory.

Some years ago, a different answer to this query was given by Thomas K. Simpson.⁹⁹⁾ In his article, "Maxwell and the Direct Experimental Test of His Electromagnetic Theory," Simpson suggested that Maxwell's main concern lay in "the nature of light and of light bearing medium," not in the electromagnetic phenomena.¹⁰⁰⁾ To support his argument, Simpson pointed out that the topic of electrical oscillations—the key to prove the theory experimentally—was not fully investigated by Maxwell but rather by William Thomson. Furthermore, in his investigation of electromagnetic radiation from an oscillation circuit, "the point at which Maxwell solves the basic equations to yield the wave equation—falls in Chapter 20 of Part 4, on the 'Electromagnetic Theory of Light', the interest of which is explicitly

96) For the life and work of A. Schuster, see A. Schuster, *The Progress of Physics during 33 Years* (1875–1908), reprint (New York : Arno, 1975), and *Biographical Fragments* (London : MacMillan, 1932), both of which contain many vivid descriptions of scientific figures at that time. For his laboratory in Manchester, see also *The Physical Laboratories of the University of Manchester : A Record of 25 Years' Work prepared in commemoration of the 25th anniversary of the election of Schuster to a Professorship in the Owens College by his old students and assistants* (Manchester : Manchester Univ. Pr., 1906), pp. 1–38.

97) However, Garnett had often assisted Maxwell's researches. See CUL MS, Add. 8375. 17 : Maxwell to Chrystal ; "He[Garnett] undertook at my request to compare the proofs of the last of Cavendish's published paper with the *Phil. Trans.* for 1771....."

98) *A Commemoration*, pp. 123.

99) Thomas K. Simpson, "Maxwell and the Direct Experimental Test of His Electromagnetic Theory," *Isis*, 57(1966), pp. 411–432.

100) *Ibid.*, p. 430.

with optics.”¹⁰¹⁾ Whether Simpson’s argument is correct or not, it misses an important element. Like many others, Simpson overlooked Maxwell’s life-long interest in experiments, which is easily corroborated in the *Treatise* as well as in his manuscripts. He never depreciated experiments and wanted to see their results. He often designed experiments, and, in the 1860’s when he was a professor at King’s College, he participated in the British Association’s project to standardize the unit of resistance.¹⁰²⁾ Therefore, whether the emphasis lay in optics or in electromagnetism, the possibility of testing the theory experimentally still existed, and Simpson’s argument seems weak.

Besides his *laissez-faire* policy, another plausible explanation, though still *partial* one, is the fact that Maxwell, as Professor of Experimental Physics at Cambridge, now felt public responsibility and had relatively less time to pursue his own scientific activities. The post was important in shaping the future of British physics, because, as Professor, Maxwell headed the “first” physics department at “Cambridge.” However imperfect Cambridge’s physics program was and however preferable programs at other institutions’ were, Cambridge still occupied the most prominent place in British physics. Maxwell, therefore, represented physics in public. In fact, since 1871, he had written several general articles, such like a series of articles for the *Encyclopaedia Britannica*, book reviews, biographical notes, and articles for the museum handbook.¹⁰³⁾ It is rememberable that Maxwell never wrote such general articles before 1871.

Another “public” work, on which Maxwell spent a great deal of time, was editing Henry Cavendish’s manuscripts, a task he began in 1874. In this role as historian of science, he “copied out[the manuscripts that he obtained from the Duke of Devonshire] with his own hand ; he saturated his mind with the scientific literature of Cavendish’s period, he repeated his experiments, being especially attracted by his device to use himself as a galvanometer to measure(Cavendish measured everything he came near) currents of electricity by the physiological effects they produced when they passed through him.”¹⁰⁴⁾ Maxwell perhaps considered it his public duty to celebrate this forgotten English hero. *An Account of the Electrical Re-*

101) *Ibid.*, p. 431. Simpson concluded his interesting paper with following comment : “In the *Treatise*, Maxwell’s interest is ultimately in optics:he develops a theory of the electromagnetic field as the medium for the propagation of light. He seems content to have other consequences remain implicit, and to leave to others the question of providing direct experimental verification of the electromagnetic theory.” (p. 432).

102) *BA Report*, 32(1862), pp. 125-163 ; 33(1863), pp. 111-176 ; 34(1864), pp. 345-367 ; 35(1865), pp. 308-313. Also, “On Method of Making a Direct Comparison of Electrostatic with Electromagnetic Force:with a Note on the Electromagnetic Theory of Light,” in Maxwell, *Scientific Papers*, vol. 2, pp. 125-143. See I. B. Hopley, “Maxwell’ work on Electrical Resistance. 1. The Determination of the Absolute Unit of Resistance ; 2. Proposals for the Re-determination of the B. A. Unit of 1863 ; 3. Improvement of Mance’s Method for the Measurement of Battery Resistance,” *Annals of Science*, 13 (1957), pp. 265-272;14(1985), pp. 197-210;15(1959), pp. 51-55,” And also Hopley, “Maxwell’s Determination of the Number of Electrostatic Units in One Electromagnetic Unit of Electricity” *Annals of Science*, 15(1959), pp. 91-108.

103) Maxwell, *Scientific Papers*, vol. 2.

104) *A Commemoration*, p. 22.

searches of the Honourable Henry Cavendish, F. R. S., between 1771 and 1781, which was published in 1879, contributed significantly to increasing Cavendish's reputation. It was truly "his chief literary work during the last seven years."¹⁰⁵⁾

In all senses, Maxwell sacrificed his scientific activities to this public service in his last years. During the 70's, Maxwell continued to do research on electromagnetism, statistical and molecular physics, and thermodynamics. However, he was certainly less productive than he had been in the 50's and 60's when he had more free time to work without interruption. Now as the Professor and the Director of the newly founded Laboratory, his researches were constantly interrupted by research students as well as by "public" responsibility. The Cambridge students, who came to the Laboratory for researches, were much more serious than those whom he had taught in London and Aberdeen. While he was fortunate to secure these talented students in the Laboratory, they were, nonetheless, a burden to him. Glazebrook's recollection indicates how seriously Maxwell took this assignment;¹⁰⁶⁾

When difficulties occurred Maxwell was always ready to listen. Often the answer did not come at once, but it always did come after a little time. I remember one day, when I was in a serious dilemma, I told him my long tale, and he said : -

"Well, Chrystal has been talking to me, and Garnett and Schuster have been asking questions, and all this has formed a good thick crust round my brain. What you have said will take some time to soak through, but we will see about it." In a few days he came back with - "I have been thinking over what you said the other day, and if you do so - and - so it will be all right."

The "public" roles, however, interrupted more seriously his researches than his duty of directing research students. For example, the project of editing Cavendish's manuscripts occupied such a considerable time and energy that, when Lewis Campbell, in 1877, asked Maxwell what was going on his own investigations, he answered, "I have given up so many things."¹⁰⁷⁾ It is noteworthy that just after he had finished this project he started to revise the *Treatise*.¹⁰⁸⁾ His failing health and his death the following year prevented him from completing the task. Only the first nine chapters were revised by him, and these nine clearly indicates "how extensive were the changes intended by professor Maxwell both in the substance and in the treatment of the subject."¹⁰⁹⁾ What would have happened if Maxwell had not spent

105) Campbell & Garnett, *Life of Maxwell*, p. 374 Besides *Treatise on Heat*(1870) and *Treatise on Electricity and Magnetism*(1874), Maxwell published an interesting monograph, *Matter and Motion*, in 1874. Another book, *Elementary Treatise on Electricity*, was on preparation but only published in 1881, edited by Garnett.

106) Glazebrook, *Maxwell and Modern Physics*, pp. 78-79.

107) Campbell & Garnett, *Life of Maxwell*, p. 376. Campbell remembered that Maxwell seemed very sad when he said so, "which till then I had never seen in his eyes."

108) In his letter to Chrystal on July 1878, he informed him : "I am preparing a new edition of Elec. & Mag. Have you any errata on improvements in Electorstatics? I am revising the Chapter on System of Conductors." See CUL. Add MS. 8375. 16:Maxwell to Chrystal, 9 July 1878.

109) Maxwell, *Treatise*, p. xiii. The remaining work was carried by W. D. Niven, with the assistance from Professor Charles Niven and J. J. Thomson. Except for the first nine chapters, second and third editions(the latter was edited in 1891, by J. J. Thomson) were essentially reprints of the first with some added footnotes and revised mathematics.

his valuable last few years to edit Cavendish's manuscripts? His professorial duties as the public figure certainly reduced his scientific productivity. The possibility of testing his theory experimentally during his life, therefore, seems to fall victim to these demands.

Perhaps the real importance of this affair lay in the fact that since Maxwell did not, or could not, try to test his theory in the Laboratory, the Laboratory lost the chance to become the preeminent center of electromagnetic researches. In Britain the leading "Maxwellians" were to be found outside Cambridge: J. H. Poynting in Birmingham, S. P. Thompson and Oliver Heaviside in London, G. F. FitzGerald in Dublin, and Oliver Lodge in Liverpool.¹¹⁰⁾ Except for Poynting who had carried out some research on the gravitational constance under Maxwell's direction, they had little connection with the Cavendish Laboratory, and had learned Maxwell's theory from his books. Recent studies by Bruce J. Hunter and Jed Z. Buchwald show that these Maxwellians were the ones who developed and propagated the theory.¹¹¹⁾ On the Continent, Helmholtz played an important role in its introduction. H. A. Lorentz and Heinrich Hertz were among the first to commit themselves to the theory and their careers were colselly tied to it. In Cambridge Maxwell's theory was studied and developed in two ditections. In several College rooms, researches in its theoretical and mathematical aspects had been carried out by W. D. Niven, Glazebrook, J. J. Thomson, and Joseph Larmor¹¹²⁾ ever since 1873. In the Cavendish Laboratory, there were some attempts to confirm the theory experimentally, by W. M. Hicks and J. E. H. Gordon in the 70's and by J. J. Thomson, L. R. Wilberforce, W. Cassie, and H. F. Newall in the 80's.¹¹³⁾ However, during the 70's and 80's all these Cambridge men, except J. J. Thomson, were less enthusiastic about the theory than the "Maxwellias" outside Cambridge, and their interest did not last long. Thomson was the exception: he was the only one at Cambridge who carried out research on the theory both theoretically and experimentally.

In conclusion, the research tradition, the *laissez-faire* policy, and the public figure nature of the Professorship were successfully rooted in the Cavendish Laboratory during Maxwell's tenure, while sacrificing the chance to become the center of electromagnetic research. They became parts of "the Cavendish traditions." "Tradition" is the key word by which to understand British society, culture, and history. Once a "tradition" is established, particularly at a place like Cambridge, it is very difficult to break it. Cambridge was once the stronghold of several "traditions": a new approach cannot be easily rooted where old "traditions" already

110) See Bruce J. Hunter, "Practice vs. Theory: The British Electrical Debate, 1881–1891," *Isis*, 74 (1983), pp. 341–355, and his Ph. D. thesis, *The Maxwellians* (Baltimore: Johns Hopkins Univ., 1984).

111) Jed Z. Buchwald, *From Maxwell to Microphysics* (Chicago: Univ. of Chicago Pr., 1985). It is somewhat too technical, but helpful to glimpse at the main trend of the late 19th c. electromagnetism.

112) Larmor was at once appointed as professor of natural philosophy in Queen's College, Galway, just after taking Tripos in 1880. He returned to Cambridge in 1885 to become a University Lecturer in mathematics. Since then he had emerged the main figure of the study of electromagnetism in the University. He became the Lucasian Professor after Stokes, and took charge of teaching electromagnetism from 1905.

113) *History of Cavendish Laboratory*, pp. 19–20, & 132–135.

114) A. Schuster, "Lord Rayleigh," *Nature*, 110 Supplement(1926), p. 48.

exist, but once it succeeds it too becomes a "tradition." In physics, mathematical "tradition" had a long history of some two hundred years. The Cavendish Laboratory too was not free of its influence. For example, the *laissez-faire* policy got so well rooted that when Rayleigh, the second Professor after Maxwell, asked the research students to participate in his project of the determination of h , only Schuster volunteered for it immediately.¹¹⁴⁾

VI. Researchers and Researches

Who were the research students in the Cavendish Laboratory during the 1870's? This is a difficult question to answer because there were no official records that registered them, and the Cavendish Laboratory was open to every member of the University. I let the "researchers" identify themselves. There are memoirs written by students who worked in the Laboratory at the time that describe other workers vividly. Another valuable source is the "list of those who have carried out researches at the Cavendish Laboratory" that can be found in *A History of the Cavendish Laboratory, 1871-1910* published to celebrate J. J. Thomson's 25 years of tenure of the Cavendish Professorship. Though the list is not complete, it is nonetheless the most useful one. I have used it to define "researchers," with some modifications whenever further evidence was found.

As was the case with Maxwell's lectures, the number of research students in the Laboratory was very limited, never exceeding 10 per year. Though the Laboratory was open to undergraduates, they were often discouraged by their tutors who described the Laboratory as a place "intended for research work of graduates, and ...[had] yet no accommodation for young students."¹¹⁵⁾ But, when H. F. Newall, a courageous undergraduate, applied to Garnett, he was welcomed by the Demonstrator, who "took much trouble in finding simple apparatus for [Newall] to work with."¹¹⁶⁾ The future Professor of Astrophysics then spent 5 years in the Laboratory.¹¹⁷⁾ The only other undergraduates who worked in the Laboratory were A. P. Trotter and Fleming. However, Fleming already had received a Bachelor of Science in 1870 from the University of London, and had taught science at Rossall School and at Cheltenham College.¹¹⁸⁾ When in 1877 he went to Cambridge with the specific purpose to study and do research under Maxwell, he was already a 32-year-old scholar. Furthermore, he received the degree of Doctor of Science from the University of London in 1879, one year before he took the NST!

Since there was little hope in attracting undergraduates who were busy preparing for their examinations, the Laboratory began to be filled with those who had passed the examinations. Table 2 indicates that most of the research students entered the Laboratory "after" they had received their B.A. degrees, or at least had passed the examinations.

115) *History of Cavendish Laboratory*, p. 104.

116) *Ibid.*, p. 104.

117) Newall, however, did not mention his undergraduate period in the Laboratory, and reported only 1885-90 as his research period in the list.

118) *Dictionary of National Biography*, (1941-1950), pp. 258-260.

〈Table 2〉 Research Students in the Cavendish Labortory(1874-1879)

Name	at C.L.	Cambridge Years	MT/NST	Fellows
* W. M. Hicks	1873-4	M.1869, A.B.1873, A.M.1876	7th Wr.(73)	Joh.
W. Garnett	1874-80	M.1869, A.B.1873, A.M.1876	5th Wr.(73)	Joh.
* W. D. Niven	1875(78?)	M.1862, A.B.1866, A.M.1869	3ed Wr.(66)	Trin.
\$\$ G. Chrystal	1875-7	M.1871, A.B.1875, A.M.1878	2nd Wr.(75)	C. C.
J. E. H. Gordon	1875-8	E.1872, A.B.1875	Junior Optimes 12th(75)	
S. A. Saunder	1875-6	M.1871, A.B.1875, A.M.1878	14th Wr.(75)	
A. W. Clayden	1876-8	M.1873, A.B.1877, A.M.1880	NST Second Class(76)	
* A Schuster	1876-81			
A. P. Trotter	1876-9	M.1876, A.B.1880	NST Second Class(79)	
* J. A. Fleming	1877-82	M.1877, A.B.1881, A.M.1884	NST First Class(80) **	Joh.
\$ D. MacAlister	1877-8	M.1873, A.B.1877, A.M.1880	1st Wr.(77)	Joh.
A.W.Sunderland	1877-?	M.1872, A.B.1876, A.M.1879	7th Wr.(76)	
* R. T. Glazebrook	1878(76?)-97	M.1872, A.B.1876, A.M.1879	5th Wr.(76)	Trin.
* J. H. Poynting	1878-80(76?)	M.1872, A.B.1876, A.M.1879	3rd Wr.(76)	Trin.
W. N. Shaw	1879(76?)-99	M.1872, A.B.1876, A.M.1879	16th Wr.& NST First Class (76)	Em.
C. T. Heyoock	(1876 ?)	M.1877, A.B.1881, A.M.1884		King's
A. L. Pirie	(1876 ?)	M.1872, A.B.1876, A.M.1881		

* F. R. S. \$ 1st Smith's Prize. \$\$ 2nd Smith's Prize. ** Distinguished in Physics

M : entered Michaelmas Term. E : entered Easter Term

1. This table is based on "A List of those who have carried out researches at the Cavendish Laboratory." in *A History of the cavendish Laboratory, 1871-1910*, p.324-334 with some modification if necessary. The years in the parentheses were the years which they seemed to have spent in the Laboratory but did not claim as the research period by themselves in the above data. Informations about individuals were also collected from *The Book of Matriculations and Degrees, 1851-1900*(Combridge, 1901).

2. Day(Emm.), Hewitt(Christs), Pigeon(Christs), Burnett(Downing), Middleton(N. C.), Whitham(Cauis), Taylos(N. C.), Vickers(St. Johns) [with Schuster, Shaw, Sunderland, Glazebrook, Niven, and Trotter] were reported as "Gentlemen at Practical Work, Lent Term 1878" by Maxwell, but were unable to be identified. (CUL, Add. 7655/Vj. 5)

It is noteworthy that Cambridge University had neither formal graduate programs nor the supporting systems for them. By the nineteenth century, residence requirement for the M.A. had virtually disappeared, and at Cambridge and Oxford it was awarded to the graduates with three or four years' standing.¹¹⁹⁾ Graduates could remain at Cambridge in order to study further, to prepare for contests such as the Sminth's Prize, or to write the dissertations for College Fellowships. However, as more and more students came from the "lower" class,

119) For a brief introduction, see E. Rudd & R. Simpson, *The High Education : A Study of Graduate Education in Britain* (London : Routledge & Kegan, 1975), pp. 6-15.

the problem of how to support them financially became more serious. Without scholarships or lectureships, these students could not spend time on research but had to leave Cambridge for their living. Scholarships for the graduates were few in number, and teaching opportunities, on which most graduates depended, were generally given first to the elected Fellows. All of this meant that only highly talented and highly motivated graduates could or would remain after graduation, with the hope of being elected as Fellows. In fact, College Fellowships were the only way to remain in the University after graduation, and Table 2 suggests that election to a Fellowship was either the motive or what allowed for many researchers to come to the Laboratory.

The Cavendish Laboratory, then, played the role of a graduate school : it was filled with highly talented and motivated graduates. The first group of research students was a very select one. As Table 2 indicates, 10 out of the total of 15 were the Wranglers (with 8 out of these 10 having placed within the first 10th), 2 were Smith's Prize men, 2 obtained first class in the NST with distinction in physics, 9 were Fellows of Colleges, and 6 eventually became F.R.S. More surprising is the fact that they came to the Laboratory on their own will; neither outside pressure nor academic requirements propelled them there.

It was either Maxwell or the Cavendish Laboratory that had attracted them, though the priority between these varied according to individual. Schuster, Fleming, Poynting and Shaw came because of Maxwell : Schuster, the only non-Cambridge man in the Laboratory, was attracted by Maxwell himself ; Fleming entered St. John's College with a very specific aim ; Poynting returned to Cambridge, resigning the demonstratorship at Owens College, to study under Maxwell ; Shaw was recalled from Berlin at Maxwell's request. However, most of the other students came to the Laboratory because it provided rooms and apparatus as well as a great teacher. For them, the Cavendish Laboratory was truly a "graduate school" : Hicks, Chrystal, Gordon, Saunderson, Clayden, and MacAlister entered the Laboratory the same year they received the B.A. degrees ; Clayden entered it after the NST but before receiving the B.A. ; Sunderland and Glazebrook entered it after one or two years respectively. The case of Niven and Garnett was different from the others : the former was not only a tutor but also was an examiner for the MT since 1875, and the latter was the Demonstrator.

In a word, the Laboratory succeeded in institutionalizing graduate studies in the University. However, it must be remembered that neither Maxwell's nor the Laboratory has been regarded as a place for graduates research is that graduates occupied and then dominated the place first. Furthermore, since they were distinguished by their high ranks in the MT or the NST, their presence in the Laboratory was enough to discourage ordinary undergraduates from coming there for their researches.

The Cavendish Laboratory, as a graduate school, had to face many problems. There were no regulations to control the graduate students. Only Maxwell and Garnett were available to direct them. Maxwell did not provide them with any solid experimental training programs. This was a very serious defect, because the students desperately needed such guidance. As Table 2 shows, they were principally mathematicians with little experience in experiments. For example, Glazebrook went to the Laboratory to find a dissertation topic for his Trinity

Fellowship. He was to regret this belated visit because Maxwell took the occasion to explain to him the principle of Wheatstone's Bridge : this 5th Wrangler did not answered Rayleigh's question to "explain the Wheatston's Bridge method of measuring resistance" a few weeks ago.¹²⁰⁾ His experience was common to most of the research students. Although they were talented and though Maxwell's *laisser-faire* policy had great merits, nonetheless they needed some basic training. This Maxwell failed to provide systematically. Lastly, Maxwell could not provide any financial aid to the research students. Without financial support, students left the Laboratory when they found jobs, leaving their projects unfinished. For the most part, their relatively short stay in the Laboratory was the result of the lack of financial support.

All these defects are illustrated in Table 3. In it I tabulate the number of research papers published from 1874 to 1879. It is readily seen that Maxwell, the Director, was the only productive researcher in the Laboratory. Schuster, the second most prolific researcher, had earned a German Ph.D. before coming to Cambridge. The others, the true Cambridge graduates, were not so productive as the first two because they needed time to learn how to carry out experiments. One interesting person on the list is Garnett, the Demonstrator. He was the only person in the Laboratory who did not need to worry about finances because he was

〈Table 3〉 Number of articles published during the period 1874-79

Name	Number of articles	
	Individual work	Co-work
J. C. Maxwell	40	
A. Schuster	8	
J. E. H. Gordon	2	
G. Chrystal	2	1/2 (2+1/2)
S. A. Saunder	1	1/2 (1+1/2)
W. D. Niven	1	
R. T. Glazebrook	1	
D. MacAlister	1	
A. W. Clayden		1/2
C. T. Heycock		1/2
Total 10	58	

Table 3 is based on "A List of memoirs containing an account of work done in the Cavendish Laboratory" in *A History of Cavendish Laboratory 1871-1919*, p. 281-323. Some modifications are applied.

120) *A Commemoration*, p. 133. Glazebrook, however, reported that he entered the Laboratory in 1878, not 1876. He might begin to work from 1876 on and off.

handsomely paid by the University. In fact, he was in an ideal position to produce many research papers. His successors actually did so. But he was too busy to do his own research without interruption. His job was "to lecture to the more elementary students, and render mechanical assistance to the Laboratory students and to those engaged in their own researches." As he himself remembered, "I was occupied a good deal in devising experiments for lecture illustration and making suitable apparatus... I never embarked on a continuous research of my own."¹²¹⁾ Later, the burden of the Demonstrator was halved when Rayleigh created another Demonstratorship. The two Demonstrators would become the chief researchers in the Laboratory.

Though the number of research papers was not that impressive, their contents were. As a whole, the students' researches often reflected their high talents and presaged the promising future. Of course, the results were not always successful. Let me survey briefly the works.

Understandably, in these early days, the most popular subjects were electricity and magnetism. Two unsuccessful attempts were made to prove Maxwell's electromagnetic theory of light. W. M. Hicks, the first research student who was "fired with the desire of measuring experimentally the velocity of propagation of electromagnetic waves," designed "a piece of apparatus." It consisted of two coils and a light magnetic needle that would detect the electromagnetic disturbance if the current were suddenly started or stopped.¹²²⁾ J. E. H. Gordon, the second research student, carried out a series of experiments to determine Verdet's constant, which is the ratio between the amount of rotation of plane polarized light and the intensity of the magnetic field.¹²³⁾ The result, if correct, is important because it is "the number in optical measure which is equivalent to unity in electromagnetic measure," and, therefore, "quantities expressed in electromagnetic measure can be expressed in optical measure by multiplying them by this number."¹²⁴⁾ The first result was read on 17 June 1875 in the Royal Society,¹²⁵⁾ and the second one, with a serious modification, was published two years later. However, both of them were not so satisfactory as anticipated.

The transfer of a number of British Association(B.A.) resistance coils from the Kew Observatory to the Laboratory was not only valuable addition to the still-poor-stock of apparatus but also provided the equipment for several research topics. Under the guidance of

121) *History of Cavendish Laboratory*, p. 35.

122) *Ibid.*, p. 19.

123) J. E. H. Gordon, "On the Determination of Verdet's Constants in Absolute Units," *Philosophical Transactions*, 167(1877), p.2. Maxwell summarised Verdet's results that "...the angular rotation is numerically equal to the amount by which the magnetic potential increases, from the point at which the ray enters the medium to that at which it leaves it, multiplied by a coefficient, which, for diamagnetic media, is generally positive." [Maxwell, *Treatise*, vol.2, p. 453(article 808)].

124) J. E. H. Gordon, *ibid.*, p.33. The dimension of Verdet's constant(w) is $[w]=[M]^{-1/2}[L]^{-1/2}[T]$.

125) J. E. H. Gordon, "On the Determination of Verdet's Constant in Absolute Units," *Proc. Roy. Soc.*, 23 (1874-5), pp. 504-6. Schuster remembered that, through this paper, Gordon became the first student to present the result of the research carried out in the Laboratory. However, it had some mistakes and was later withdrawn by the author. The modified version is the above paper (124).

Maxwell, the experiment to measure the B.A. units at frequent intervals was initiated, and Maxwell even planned the redetermination of the units. Its first result was Chrystal and Saunder's report in 1876, in which they carefully measured "the difference between the resistances of the several coils at some standard temperature, and also the coefficients of variation of resistance with temperature in the neighborhood of the standard temperature."¹²⁶⁾ Saunder also worked on the new form of Leclanche's cell and illustrated "how the electromotive force of this cell varies when it works for a considerable time through circuits of various resistances."¹²⁷⁾

Around 1875–76, Chrystal launched a series of experiments to test Ohm's law. The project was originally conceived by a B.A. committee consisting of Maxwell, Schuster, and J. D. Everett, but all the experiments were carried out by Chrystal in the Cavendish Laboratory. Under the supervision of Maxwell, Chrystal devised three different kinds of experiments and virtually confirmed the law,¹²⁸⁾ saying that "if a conductor of iron, platinum, or German silver of one square centimetre in section has a resistance of one ohm for infinitely small currents, its resistance when acted on by an electromotive force of one volt(provided its temperature is kept the same)is not altered by so much as $1/10^{12}$ part."¹²⁹⁾ Another paper on the deflection of a galvanometer was a by-product of testing Ohm's law where he showed the influence of induced magnetism of the galvanometer that caused "an apparent departure from Ohm's law."¹³⁰⁾ After Chrystal left Cambridge, the project was subsequently continued by Glazebrook and Fleming. The latter designed a very convenient bridge, "Fleming's banjo," for quick comparisons of resistances.

Electricity and magnetism represented however roughly half of the research subjects in these days, and other areas also flourished in the Laboratory. Niven worked on "the Calculation of the Trajectories of Shot," which aimed at simple solution of trajectories and at re-

126) G. Chrystal & S. A. Saunder, "Results of a Comparison of the British Association Units of Electrical Resistance," *BA Report*, 46(1876), pp. 13. They suggested two alterations in the construction of standard coils.

127) S. A. Saunder, "On the Variations of the Electromotive Force of a New Form of Leclanch's Cell," *Nature*, 12(1875), p. 564.

128) Report of the Committee, consisting of Professor Clerk Maxwell, Professor J. D. Everett, and Dr. A. Schuster, "For Testing Experimentally Ohm's Law," *BA Report*, 46(1876), pp. 36–63. The first experiment adopted a bridge which consisted of five resistance coils, but it had the defect that "it is impossible to pass a current of great intensity through a conductor without heating it so rapidly that there is no time to make an observation before its resistance has been considerably increased by the rise of temperature." To remedy this, the second experiment employed the method in which the resistances were compared by strong and weak currents. Since currents passed so fast alternatively in a second that "the temperature of the wire could not sensibly alter during the interval between one current and the next," In fact, Ohm's law was confirmed by this second method. The third experiment employed the induction coil and its peculiar results led Chrystal to this next paper (130).

129) *Ibid.*, p. 38.

130) G. Chrystal, "On Bi- and Unilateral Galvanometer Deflection," *Phil. Mag.* 5th ser., 2(1876), p. 402.

duction of the amount of calculation by employing three different methods.¹³¹⁾ A. W. Clayden and C. T. Heycock's experiment on the spectrum of indium, in which they found sixteen lines "instead of the three lines expected," was first initiated in a course of chemical lectures on spectrum analysis. Then, they moved to the Laboratory and spent a summer there to produce a new table.¹³²⁾ Glazebrook worked on the measurement of the velocity of normal propagation of plane waves in a biaxial crystal, an experiment that had been suggested by Stokes in 1862. The result virtually confirmed Fresnel's theory of double refraction experimentally, leaving "the phenomena of dispersion to explain the variation from it."¹³³⁾ Sunderland worked on the anomalous dispersion in fuchsin to determine the refractive indices as close to the absorption band as possible, but the work was never finished.¹³⁴⁾ MacAlister, working with Maxwell's improved version of the set of the sphere and hemispheres, experimented on the law of the inverse square, the famous subject of Henry Cavendish.¹³⁵⁾ Poynting's research on the gravitational constant and Shaw's meteorological experiments were also initiated during Maxwell's period but were finished only after his death.

Schuster was very exceptional figure, compared with the other researchers. He produced as many research papers as all the other "Cambridge men" did (see Table 3). Initially he was induced by Maxwell because of his interest in Ohm's law, but, as soon as he arrived at Cambridge, he changed his topic into spectroscopy and became one of its pioneers in Britain. The papers on the presence of oxygen in the sun in 1877¹³⁶⁾ and on the spectra of metalloids in 1878 were two products of his researches in the Laboratory.¹³⁷⁾ He was also one of the first to start research on the conductivity and discharge of electricity through gases.¹³⁸⁾

As a whole, this "catholicity" of research subjects—from the Cavendish's old experiment on electrical charge to spectroscopic ones—characterized this period. This was partly due to the fact that research students often came to the Laboratory "for a definite purpose of working out either an idea of their own or one which had been suggested to them."¹³⁹⁾ There was also such student like Glazebrook who had come to the Laboratory for their Fellowship dissertations. However, most of the credit for its wider range should be given to Maxwell and his *laissez-faire* policy. By imposing no specific directions and by encouraging students' creative minds, he freed the Laboratory from becoming a place carrying the Director's re-

131) W. D. Niven, "On the Calculation of the Trajectories of Shot," *Proc. Roy. Soc.*, 26(1876), pp. 268–287.

132) A. W. Clayden & C. T. Heycock, "The Spectra of Indium," *Phil. Mag. 5th ser.*, 2(1876), p. 387–389.

133) R. T. Glazebrook, "An Experimental Investigation into the Velocities of Normal Propagation of Plane Waves in a Biaxial Crystal, with a Comparison of the Results with Theory," *Proc. Roy. Soc.*, 27(1878), pp. 496–502.

134) *History of Cavendish Laboratory*, p. 28.

135) *Ibid.*, p. 33.

136) A. Schuster, "On the Presence of Oxygen in the Sun," *Nature*, 17(1870–8), pp. 148–9.

137) A. Schuster, "On the Spectra of Metalloids. Spectrum of Oxygen," *Proc. Roy. Soc.*, 27(1878), pp. 383–8.

138) A. Schuster, "On the Passage of Electricity through Gases," *Proceedings of the Cambridge Philosophical Society*, 3(1876–80), pp. 5–61.

139) *History of Cavendish Laboratory*, p. 29.

search interests.

The above survey of the researches carried out in the Laboratory also reveals that the students were, in general, very ambitious. Even though they had little experience and even though there was little chance of producing successful results, they nonetheless aimed high. But, their ambitious efforts were often blocked or slowed down by their lack of training of experiment : Hicks and Gordon failed ; Clayden, Heycock, Saunder must satisfied with simpler experiments ; Chrystal should carried out other's (B.A. committee's) experiments before his own in order to get experience ; Glazebrook's experiment required about two years to produce results. However, once they had gained experience, their productivity rose rapidly. Glazebrook, for example, produced more than 10 research papers during 1880–1884.

That students did not work together was another characteristic of this period. They often borrowed apparatus from one another but did not collaborate often. As Table 3 shows, there were only 2 collaborative works between students(Chrystal–Saunder & Clayden–Heycock) among a total 58 papers. During Rayleigh's tenure, there were 7 co–authored works, including 2 by three workers.

As a graduate school, the Cavendish Laboratory definitely needed some organization to train and guide these talented but inexperienced students. But Maxwell failed to create them. In fact, there existed no mechanism to connect the students together : a student was related to the Laboratory or to other students only through Maxwell. They were all Maxwell's students, but they were not a community and only one–to–one relationship between the Director and individual student existed. As a whole, Maxwell was a man of ideas but not of organization. While research tradition was successfully rooted and his idea of “school of criticism” was implanted in the Laboratory, it was still far from bearing fruits. In 1879 the Cavendish Laboratory was a place for doing researches in the University, but it was not yet either a research community or a “school.”