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# Reworking the Mechanical Value of Heat: Instruments of Precision and Gestures of Accuracy in Early Victorian England

*Heinz Otto Sibum**

In this paper I address the questions of whether, and how, reworking historical experiments can contribute to the understanding of experimental practice in history. I concentrate on a particular experiment on the determination of the mechanical equivalent of heat performed by James Prescott Joule from Manchester. In his paper *On the Mechanical Equivalent of Heat* printed in the *Philosophical Transactions*[1] in 1850, Joule describes in detail the mechanical friction of fluids as the *direct method* for determining the mechanical equivalent of heat. After several earlier trials in evolving heat electrically he regarded the friction of water as the most simple and therefore convincing experiment to support his argument for the existence of such a constant relation between heat and work.[2] In that document Joule gives by far the most detailed description of the mechanical construction of the experimental set-ups and the design of the paddle-wheel for churning the water as well as minute accounts of how to perform the experiment properly. Tables of numbers are given to report the outcomes of his trials as accurate laboratory measurements, which should give evidence for the existence and the value of this constant of nature. But controversies about the existence of such a number and the reliability of the measurement techniques used to establish it lasted until the end of the nineteenth century. Joule's determination of the 'mechanical value of heat', his experiments on the friction of water in particular, still remained debatable until then. Historians of science have stressed in detail the meaning of this experimental trial for the development of thermodynamics and the

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[1]James Prescott Joule, 'On the Mechanical Equivalent of Heat', *Philosophical Transactions* (1850, Part I), read 21 June 1849. Reprinted *The Scientific Papers*, vol. 1 (London: Taylor and Francis, 1884), pp. 298–328.

[2]Methods for obtaining the mechanical equivalent of heat can be divided into direct and indirect methods. Joule's 'experiments on the friction of fluids' involve a *direct* method, i.e. mechanical energy is transformed into heat. Heat produced in water by an electric current is an *indirect* method.

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dynamical theory of heat in particular. This paper focuses on Joule's practice of measurement in its cultural context. The historical analysis includes work with replicas of Joule's experiment on the friction of water as a complementary resource to Joule's own renditions of his experimental practice as documented in his published papers, notebooks and correspondence. It is an attempt to study Joule's private place of knowledge production which led to his 1850 publication.

In the first part of this paper I will give a detailed report of my own experiences when reworking the paddle-wheel experiment with different replicas. The subsequent historical narrative opens dimensions of past practice which have not yet been considered. For example, I will show that Joule's exceptional experimental practice was based on the transformation of different, apparently unrelated traditions. It emerges that thermometrical skills which were rare in the early Victorian physics community were required in order to perform these trials. However, such skills were widely distributed in the brewing community to which Joule also belonged. The second section will introduce the reader to Manchester brewing culture and their changing practices. In a third section I will focus on contemporary sites of production in order to show that the new brewing practice represents a general change in the cultural habits of the time. Absolute standards were imposed in order to make local knowledge work elsewhere. Instruments of precision controlled skill and became representatives of accuracy. The fourth section describes Joule's laboratory life in which all his brewing craft skill came to bear. Characteristic forms of division of labour and knowledge will become visible. Over and above, Joule created his own standards of accuracy which made him a performer without audience. The final part deals with Joule's attempts to create his public space as a natural philosopher. Difficulties in communicating his local knowledge to the public will be described. His methods and choices of arguments given in his publication *On the Mechanical Equivalent of Heat* indicate a hybrid of craft consciousness and that of a gentleman specialist.[3] These attempts to communicate his knowledge highlight the importance of the reliability of measurements. The use of instruments of precision has to go along with the formation of accepted gestures of accuracy—an expert culture which had not yet been established.[4]

[3]For the meaning of craft and craft consciousness in that period see John Rule, 'The Property of Skill in the Period of Manufacture', in Patrick Joyce (ed.), *The Historical Meanings of Work* (Cambridge: Cambridge University Press, 1987), pp. 99–118. On 'gentlemen specialists', see Jack Morrell and Arnold Thackray, *Gentlemen of Science: Early Years of the British Association for the Advancement of Science* (Oxford: Clarendon Press, 1981). Joule's move from private to public spaces will be discussed in more detail in a forthcoming paper which focuses on the reception of his friction experiments and its importance for metrology and the development of energy physics in the second half of the nineteenth century.

[4]The expressions 'instruments of precision' and 'gestures of accuracy' reflect on a common use of the terms 'precision' and 'accuracy' in the period under analysis. For Joule and others, 'precision' refers to tools and their quality, whereas 'accuracy' refers to the quality of workmanship.

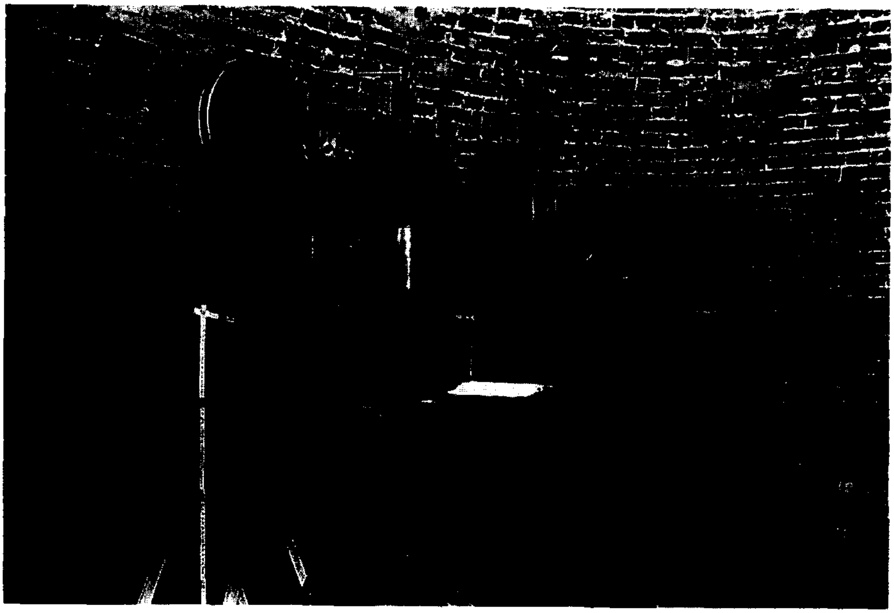

*Fig. 1. Preparations for performing Joule's paddle-wheel experiment in the Oldenburg powder tower. Picture: by permission of Norbert Gerdes, Oldenburg.*

## 'New Experiments on the Friction of Fluids' and its Troubles

Erstens kommt es anders, zweitens als man denkt.[5]

It is well known that doing an experiment is not only determined by material culture but also by the actors' abilities to interact properly with the objects and each other. A range of terms such as 'skill', 'tacit knowledge' or 'Geschick' are used to draw our attention to this crucial aspect of human practices. Historians of science use a variety of methodologies in order to study past practices. Playing the stranger, using actors' categories, and studying controversies are preferred methods to make their taken-for-granted practices explicit.[6] The example given here of reworking historical experiments is a complementary approach to the existing methods. This

[5]German adage.

[6]On historical studies of experimental practice, see Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton: Princeton University Press, 1985); David Gooding, Trevor Pinch and Simon Schaffer (eds), *The Uses of Experiment: Studies in the Natural Sciences* (Cambridge: Cambridge University Press, 1989); Peter Galison, *How Experiments End* (Chicago: University of Chicago Press, 1987); David Gooding, ' "In Nature's School": Faraday as an Experimentalist', in David Gooding and Frank A. J. L. James (eds), *Faraday Rediscovered: Essays on the Life and Work of Michael Faraday, 1791–1867* (Houndsmill: Macmillan Press, 1985). On anthropological and sociological approaches, see Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton: Princeton University Press, 1986); Bruno Latour, *Science in Action: How to Follow Scientists and Engineers Through Society* (Milton Keynes: Open University Press, 1987); Harry Collins, *Changing Order: Replication and Induction in Scientific Practice* (London: Sage, 1985).

anthropological method involves the design and building of replicas, the performance of experimental work with these replicas, and the historical, archival exploration of the world in which these historical experiments were developed. Each of these three strategies is designed to inform and improve the others. These actions may help us to reconstitute tacit dimensions of past practices that were either taken for granted, kept secret and therefore not written down, or became victims of substitution by formal or mechanical representation. This argument only stands if I can show that my own experiences in *doing* the experiment are relevant to the historical experimental practice. In order to be able to refer to my 'local knowledge'[7] I use the term *gestural knowledge*[8] for the complex of skills and forms of mastery developed in these real-time performances.

In the summer of 1990 we[9] began to replicate Joule's paddle-wheel experiment to determine the mechanical equivalent of heat. The design of the experimental set-up was based on the 1850 publication in the *Philosophical Transactions*. Here Joule gave a minute description of the apparatus, the experimental method and tables of experimental data in order to present his result as being obtained with 'exactness'. In rebuilding the first version of the experimental set-up we tried to follow carefully the instructions given by the texts. The thermometers used by Joule could not be rebuilt because of a lack of sufficient information and possibly the skill to do so.[10] Therefore the measurements were taken with two Beckmann thermometers which are highly sensitive and allow a reading of 1/100th of a degree Celsius. Such instruments of precision correspond with Joule's accounts of graduating his thermometers. We thought we could guarantee the 'uniformity of temperature' Joule mentioned by using an air-conditioned modern laboratory.

Joule's method of experimenting is as follows.

[7]On 'local knowledge', see Clifford Geertz, *Local Knowledge: Further Essays in Interpretive Anthropology* (New York: Basic Books, 1983).

[8]Historical studies ordinarily deal with literary sources and material relics. Rudolf zur Lippe stresses the importance of the productive power of gesture in history and suggested the term 'gestisch geschichtliches Wissen' as an analogy to the working knowledge of oral cultures. In my historical studies I pursued this concept further in order to be symmetrical with the non-literary traditions of past experimental practice. Therefore *gestural knowledge* is to be understood as knowledge united with the actor's performance of work, and it changes according to the specific kinds of performance, for example the manipulation of an instrument or the use of mathematical tools, and in ever new historical circumstances. For a further discussion of this historiographic approach, see the author's article 'Working Experiment: Bodies, Machines and Heat Values', in R. Staley (ed.), *The Physics of Empire* (Cambridge: Whipple Museum of the History of Science, 1994), pp. 29–56.

[9]During the first part of my studies I was assisted by Peter Heering, a Ph.D. student in the Research Group of Higher Education and History of Science at the Physics Department of the Carl von Ossietzky University, Oldenburg, Germany. All replicas were made there and I am very grateful to the Physics Department and the members of the project group in particular.

[10]Joule's thermometer doesn't exist anymore but I was able to reconstruct his design based on Joule's own records and Arthur Schuster, 'On the Thermometric Scale-value of the late Dr. Joule's Thermometers', *Philosophical Magazine* **5th series 39** (1895), pp. 477–501.

> The temperature of the frictional apparatus having been ascertained and the weights wound up with the assistance of the stand h, the roller [f] was refixed to the axis. The precise height of the weights above the ground having then been determined by means of the graduated slips of wood k,k, the roller was set at liberty and allowed to revolve until the weights reached the flagged floor of the laboratory, after accomplishing a fall of 63 inches. The roller was removed to the stand, the weights wound up again, and the friction renewed. After this has been repeated twenty times, the experiment was concluded with another observation of the temperature of the apparatus. The mean temperature of the laboratory was determined by observations made at the commencement, middle, and termination of each experiment. Previously to, or immediately after, each of the experiments, I made trials of the effect of radiation and conduction of heat to or from the atmosphere in depressing or raising the temperature of the frictional apparatus. In these trials the position of the apparatus, the quantity of water contained by it, the time occupied, the method of observing the thermometers, the position of the experimenter, in short everything, with the exception of the apparatus being at rest, was the same as in the experiments in which the effect of friction was observed.[11]

Our first attempts to repeat the trial in this version already gave us interesting insights into the process of making a scientific fact. Initially it seemed evident to us that the experiment should be performed by two persons, one to wind up the weights and the other to read the temperature. When we entered the room in order to read the temperature the thermometers responded immediately to our body radiation and we found that a constant temperature was recorded after one hour. In order to maintain this uniform temperature we had to prevent witnesses from entering the laboratory during the trials. Moreover, the high sensitivity of the thermometers demanded that we learn to use them properly. The act of reading the thermometer requires a certain technique which includes the right timing for taking measurements. The radiation effect between the actor and the instrument was very difficult to master. Long experience in using the particular thermometer was needed. We helped ourselves first by creating rules such as: wait two minutes then read off, and continue reading every minute; then take the mean temperature.

Joule's paper informs us that winding up the mass of 26 kg twenty times over a distance of 1.40 m should be done in 35 min. We failed completely, simply on physical grounds. We had to share the job because of a lack of strength. Even then, it took us one hour and twenty minutes to perform successfully. This activity made the stirrer move and increased the temperature in the water by 0.5 degrees Fahrenheit. It also caused an increase of one degree Fahrenheit in the room due to our sweating. In order to avoid these troublesome body radiations we decided to reduce the weights and to perform the experiments individually.

These first runs also showed that the paddle-wheel we had built moved totally differently from Joule's description. The velocity of the falling masses varied markedly from his account. Obviously our design of the paddle-wheel differed in a crucial way from the original one, despite our efforts to build a good copy. For our

[11] *Op. cit.*, note 1, pp. 305–306.

individual trials, we used 7 kg on each side because this corresponds with the published velocity of 2.42 in/s for the masses. Our results lay between 500 and 1500 ftlb/BTU. A further interesting question was raised here: does a different design of the paddle-wheel have any fundamental influence on the result? We could not give a satisfactory answer at this stage, because of the temperature fluctuations and the inaccuracy of our temperature readings. The use of a magnifying glass fastened on the thermometer allowed a precision of 0.001 degrees Celsius. So, at the end of the first attempt at historical replication the 'mean equivalent of twenty experiments (where the falling masses had a weight of about 5 kg each)' gave a value for the mechanical equivalent of heat of 705 ftlb/BTU with a standard deviation of 9.2%.[12]

This approach had to be complemented with historical information. The Museum of Science and Industry in Manchester is in possession of some relics of Joule's early paddle-wheel experiment from the year 1845. The different set-up and the measuring devices were of interest to us. A 'travelling microscope' at the Museum was designed by John Benjamin Dancer in order to graduate Joule's sensitive thermometers. Joule's notebooks are kept at the University of Manchester Institute of Science and Technology. The entries are very meagre with respect to the relevant experiment. The records of the relevant experimental runs are real-time recordings of numbers. There is no literary trace of Joule's thermometrical skills, nor does he give information about the machinery, possible problems in performance, or his likely assistants. But his notebook does contain many detailed calculations on the specific heats of the metals used. Also, he intensively recorded the calibration of his own thermometer scale against thermometers of contemporary researchers. Unfortunately, his thermometers were destroyed during a fire at the Philosophical Society at the beginning of the twentieth century. But through further archival research I gained quite a good understanding of the instrument and its calibration device (see Fig. 4, below).

The London Science Museum gave permission to take measurements of the existing paddle-wheel which it owns and which is reported to be the original. This gave me a basis for a new replica.[13] I used all possible information about the objects and modes of producing them, to come as close as possible to the design and material culture as primary resources and existing crafts skills allowed. Besides the usual primary sources like correspondence, instruments, notebooks, this second replica became a complementary resource. On 1 March 1992, I started a new series of experiments with this replica in a different space. Joule's working space was 'a spacious cellar, which had the advantage of possessing a uniformity of temperature

[12]I am very grateful to Peter Heering whose independent experimentation with this first version led to these results and allowed useful comparisons. For his report see Peter Heering, 'On J. P. Joule's Determination of the Mechanical Equivalent of Heat', *The History and Philosophy of Science in Science Education*, Kingston Conference Proceedings, vol. 1 (1992), pp. 502–504.

[13]I am very grateful to the Curator Neil Brown from the London Science Museum, who allowed me to take the measures from the original paddle-wheel. For the replica, see Fig. 5 below.

far superior to that of any other laboratory'. My previous experiences in doing the experiment alerted me to the significance of the spacious cellar: the immense heat radiation during the trials could be partly compensated through a spacious room at a lower temperature level. Therefore, I performed the experiment in an old powder tower in Oldenburg which was used as a store room for meat during the eighteenth century. It was spacious and the material construction allowed me to expect that its temperature conditions would give further information about Joule's workplace (Fig. 1). My research showed that the phrase 'uniformity of temperature' in the powder tower could be taken to mean fluctuations of about 0.5 degrees Celsius. I measured these effects during a time of changing weather from sunshine to stormy rain. But even during apparently constant weather conditions, the fluctuation over 70 min (the duration of one complete experimental run) amounted to 0.5 degrees Celsius.

Acclimatization after entering the room was necessary as well. Joule did not mention this as a problem at all. Even when he was asked by G. G. Stokes in 1853 he answered 'I have thought a great deal on the subject of your queries, and in the first place I do not think that for experiments on heat it is absolutely essential to have a uniform temperature although it would be desirable to obviate sudden or uncontrolled changes'.[14] This reply indicates that his understanding of uniformity obviously allowed such fluctuations. This was not because he was not aware of them but because he was convinced that he was able to control them by a certain technique of measuring temperatures.

Difficulties also arose through placing the thermometers in the room: temperature differences occurred through movements of the measuring devices. Practising with the thermometers in the room over weeks had already improved my abilities as I accustomed myself to the room and its conditions. From written material I could not get any further information about Joule's particular method for measuring the temperatures. His technique remained unknown to us. In order to replicate Joule's experimental practice it was crucial to know more. The sketch of Joule's thermometer reconstructed on the basis of primary sources and his notebook entries allowed me to state that in practice he actually read off a tenth part of a millimetre division on the scale.[15] His construction of the thermometer made it unnecessary to read off 1/20th of a division. It is reasonable to state that his famous remark 'constant practice enabled me to read off with the naked eye 1/20th of a division' was intended to demonstrate in public the reliability of his measurement.

Knowledge about the temperature difference between water and air turned out to be crucial. Joule did not state anything specific about it. His tables indicate a difference of 0.5–2 degrees Fahrenheit on one side or the other. If the water is slightly warmer

[14]Joule to Stokes, 12 November 1853 (Add MSS 7656 J 19, Cambridge University Library).

[15]All his relevant notebook entries show two kinds of numbers: the measured results are given to one decimal place; numbers calculated by means of 'interpolation' and conversion have two or three decimals. Joule 'Notebook' (1 June 1847), 2 (1843–1858), p. 162, UMIST, Manchester.

than the air, one would expect a loss of temperature over time, but this did not always happen. If the temperature of the water is much warmer or much colder than the air it is impossible to perform the experiment. Performing under the right temperature conditions needed a lot of experience.

Ending the experiment also needs a lot of experience. The correct timing and the appropriate habit of taking the temperature measurements is absolutely crucial. Presumably, a run should cease when the final, stable, temperature has been reached. The Beckmann thermometer indicated a stable temperature within 6 min after putting them into the water. We can assume a similar behaviour for Joule's thermometer. Joule had a reasonable expectation of the equilibrium value for the terminal temperature and managed his thermometry through keeping the thermometer indication near to the expected value. This reduced the time of taking the measure. But nevertheless the termination of experiment was problematic. Do these 4–6 min already count as radiation time? How can you calculate this uncertainty? This draws our attention to the reliability of his accounts on the radiation effect in general. Consider Joule's 6 l copper vessel filled with water. Using his data, could a temperature difference of 2.09 degrees Fahrenheit between air and water cause the total increase of temperature of 0.106 degrees within 35 min?

The spacious room obviously reduced the heat radiation effect of the human body. A total increase in the room after the experiment could not be measured. His notebook entries however gave increases between 0.1 and 0.16 degrees Fahrenheit. The final 'uniformity of temperature' was achieved through the method of means. In order to minimize the heat radiation from the experimenter's body that reached the vessel during the trials, the wooden shield was absolutely necessary. It would reflect the radiation into the room.

The design of the paddle-wheel, which we adopted, differed greatly from the one Joule sketched in the 1850 paper. Ours gives a velocity of 2.59 in/s, which is very close to Joule's written account of 2.42 in/s. Experiments with our first replica showed that we could not repeat the mechanical sequence as given in the text. The version of the paddle-wheel displayed in the Science Museum allowed us to do so. Therefore it seems evident that Joule had used this type of construction. We have to explain why Joule did not give the appropriate design in publication. It is especially interesting because our experiences with different forms of paddle-wheels gave different values for the mechanical equivalent of heat.[16]

The most troublesome mechanical problem was the weakness of the strings. The string that still connects the wooden roller of the paddle-wheel axle and the pulleys was made of a very thin baste fibre. We do not know what string Joule might have used for lifting the weights—probably a very thin one, because this would have reduced friction. In my experiments even strong fishing line (60 kg) didn't stand the

[16]For the different designs of the paddle-wheel compare the sketch in Joule's publication and Fig. 5. I will focus on this problem in the forthcoming second part of this study.

test. A lot of repair work had to be done. Mechanical problems, such as the changing friction of the roller axles, the changing centre of gravity of the wooden pulleys caused by the working mode of wood, the rigidity of the strings, the friction of the steel axle on the brass wheel, the determination of the actual distance of equable motion, and weighing the masses, are all sources of possible errors. In all these particular aspects Joule's notebook showed minute determinations. In order to calculate the effect of friction due to the pulleys and the rigidity of the strings he took measures over several days. He connected the two pulleys with twine passing round a roller of equal diameter to that employed in the experiments. Under these circumstances, the weight required to be added to one of the leaden weights in order to maintain them in equable motion could be found.[17] Out of the varying results due to changing working conditions of the apparatus he took the mean weight, which became the representative number Joule used for publication. The 'method of means' he used as the appropriate method to balance out the remaining irregularities. He continued taking this measure over years in order to achieve 'greater accuracy'. His knowledge about the material culture of his experiment is probably best described through his notes on the thermometer in which he followed and reported the rise of the zero point over 40 years.

The thin construction of the vessel compared with the weights was at the limits of its stability. Slight irregularities of the pulleys could produce a swinging of the unstable axle which could completely destroy the apparatus. I had to maintain absolutely smooth revolving pulleys in order to guarantee a secure drive for the delicate paddle-wheel. The handle on top of the axle was much too short to wind up the weights. The handle of the model at the Science Museum could not be the one which he or anyone else used during the experiment. In that shape it could have been used only as a demonstration device.

The crucial gestures involved in this experiment were *reading temperatures* and *doing the work*. Both techniques require the highest degree of attention. The worker had to take care of the symmetrical winding of the left and right strings. He had to disconnect the winder from the axle and control the behaviour of the axle and the pulleys. No disturbance in the machinery should occur otherwise the paddle-wheel as well as the thermometers could be destroyed. Perfect mastery of this part of the performance was reached when no swinging of the system occurred. The fragile design of the vessel and axle avoided a major source of error: heat produced through the constant rubbing against the bushings of the axle brace mount. But it made necessary an artistic mechanical performance. The reader had to take measures very quickly before, during and after the run. Keeping the temperature near to the expected point of increase during the runs, the specific working condition due to bad light, the

[17]James P. Joule, 'New Experiments on the Friction of Fluids', in 'Notebook' 2, Spring 1848, p. 175, UMIST, Manchester.

very fine graduation of the temperature scale, and the temperature fluctuations demanded the complete attention of this experimenter.

In ten experiments, I achieved a value for the equivalent of heat of 746.89 ftlbs/BTU. Joule got a value of 772.692 ftlbs. The modern value is 776.1 ftlbs/BTU. In the manner of a modern physicist I judged my own runs in terms of the variation of my measurements from the mean. This calculated standard deviation amounted to 2.1%, which is an excellent result by the standards of today.

My accomplishment of accuracy draws our attention towards our modern understanding of precision measurement. From a physicist's point of view it is reasonable to ask why repeating a historical experiment gave a result which is precise but not in conformity with the published value. A physicist would tend to argue that it was my fault or that Joule was inaccurate. From an anthropological point of view the result could also indicate that instruments of precision and their proper use are fundamentally connected with each other. My results show the lack of sufficient enculturation in order to accustom myself to the techniques involved in Joule's trial. But they gave me a sense for Joule's meanings for 'exactness', 'accurate thermometrical researches', 'to obtain that relation with still greater accuracy'. Moreover the result shows that precise measurements do not necessarily have to be in conformity with the culturally accepted value. The nearness of many results to each other—which to physicists indicates a high degree of precision—does not necessarily imply that the accepted value has been reached. In modern physics this nonconformity with the accepted value indicates a low degree of accuracy. I was precise without being accurate. This draws our attention to the reliability of precision measurement in general. It raises the question of the way cultures come to agree about accurate practices of measurement. Can we identify different forms of accurate measurements in Joule's time? Has our understanding of accuracy changed during time? How do cultures achieve a 'true' value? On what technologies do we tacitly rely when we use or produce numbers? What is it necessary to be able to do in order to measure temperatures, for example, as Joule did? How could anyone else acquire such obviously rare skills?

My answers to these questions will be historical. The proposed method will show the intimate link between the production of instruments of precision and the formation of a collective of accurate experimenters in the nineteenth century. In the remainder of this paper I will concentrate on Joule's practice of measurement in its context until the year 1850. It is a study of Joule's private place of knowledge production which led to his publication *On the Mechanical Equivalent of Heat* and the value of 772.692 ftlbs based on my own experiences in reworking the historical experiment. First of all, characteristic gestures of my own experimentation led me to look for historical spaces where such techniques could have been imitated and developed. The thermometrical skills and the modes of arranging the experimental sequences show close links to the historical actors' mundane practices of which there is no obvious literary trace. Fundamental techniques to achieve Joule's form of accuracy, which

Lord Kelvin later praised as magical, had their origins in the brewers' form of life.[18] In the next section I will describe Manchester brewing culture as a *gestural collective*[19] focusing on the relevant techniques and their major changes.

## Manchester's Changing Brewing Standards

> Formerly the lower classes who were, and still are, the principal consumers of beer, thought it a mark of effeminate refinement to require a glass to drink their beer from; and however thick the fluid, it flowed from the pewter pot, with inexpressible zest down their callous throats, and all was well: but not so in the present day! Nothing less than a clean glass filled with ale of sparkling brilliancy will suffice for the lowest of the low... Formerly the brewer was required to furnish beer to the public at the age of one, two, and three years... But such beer will not now be commonly drunk, and the brewer is required to brew all the year through, and to furnish it to the public at the end of few days after brewing, perfectly mild, full, and transparent. Now to do this in hot weather, is certainly no easy task to the uninitiated.[20]

Historical studies on the science of heat have usually stressed engineers' achievements in developing steam engines.[21] But in the 1840s, the main repository of a rare and unevenly distributed 'practical knowledge' of heat measurement was the brewery. 'Either partially or totally, the malt will be set, / If with water too hot or too cold it is wet'. Fortunately, some literary traces, like this adage, touch on this 'imitative knowledge': a form of knowledge 'personally communicated by some instructor, or is the fruits of the imitation of others, resulting from the close and attentive observation of their practical operations'.[22] George Adolphus Wigney, a middle-class brewer from Brighton and author of a first dictionary of brewing, presented a detailed account of the difficulties of transcribing this traditional 'practical or imitative knowledge' of brewing into textual representations. He translated his own experiences as a brewer as well as the historical collection of oral communications, such adages (proverbs), into *his* language of chemistry. But he himself wants us to regard this knowledge as hypothetical, because of the specific and subtle nature of

[18]Neither Joule's own writings nor the historians' accounts are explicit about this dimension of his experimental practice. Philip Mirowski does refer to the link between Joule's work and brewing. However, as a historian of the interaction of economics with physical models, he draws our attention away from 'meticulous descriptions of experiments' towards accounting. Indeed, Mirowski uses brewing to explain how Joule was allegedly able to produce a value of the mechanical equivalent despite his experiments. I am concerned to show how brewing practices allowed him to perform the experiment. Philip Mirowski, *More Heat than Light: Economics as Social Physics: Physics as Nature's Economics* (Cambridge: Cambridge University Press, 1990), pp. 128–129.

[19]I am using the term *gestural collective* in order to locate historical spaces of gestural knowledge. See also the term 'community of skills' which my colleagues Rob Iliffe and Michael Berlin use in order to point at places of skill. Michael Berlin and Rob Iliffe, 'The Places of Skill in Early Modern London', unpublished paper presented at the Achievement meeting, Oxford, June 1992.

[20]G. A. Wigney, *An Elementary Dictionary, or Cyclopaedia for the Use of Malsters, Brewers, Destillers, Rectifiers, Vinegar Manufacturers and Others* (Brighton, 1838), p. 97.

[21]See T. S. Kuhn, *The Essential Tension* (Chicago: University of Chicago Press, 1977), p. 77.

[22]*Op. cit.*, note 20, p. 137.

THE ART OF

**BREWING AND FERMENTING,**

*IN THE SUMMER,*

AND ALL OTHER SEASONS, TO THE GREATEST ADVANTAGE,

AND THE

**Making of Malt,**

EXHIBITED IN

ESSAYS, AND DECIMAL TABLES,

*ACCURATELY CALCULATED,*

THE RESULT OF UPWARDS OF FORTY YEARS' EXPERIENCE;

ALSO

A DESCRIPTION OF THE AUTHOR'S NEWLY-INVENTED

**THERMOMETER,**

By the Application of which extreme Precision and considerable Saving will be effected;

AND

*A COPPER-PLATE ENGRAVING*

OF AN

**Economical Plan**

FOR

THE ERECTION OF A BREWHOUSE,

INCLUDING HIS

*Newly-invented Copper with moveable Pan:*

LIKEWISE

A COMPARATIVE STATEMENT OF THE MALT LIQUOR BREWED IN LONDON

*In the Years 1739 and 1835,*

WITH THE NAMES OF THE BREWERS.

By JOHN LEVESQUE,

FORMERLY OF THE ANCHOR BREWHOUSE, OLD STREET, ST. LUKE'S.

SECOND EDITION.

**LONDON,**

Printed by PEART & Co. 143, St. John's Street Road, and

PUBLISHED BY THOMAS HURST, 65, ST. PAUL'S CHURCH YARD;

And Sold by Grant and Son, Edinburgh; Cary and Co. Dublin; and all Booksellers.

1836

*Fig. 2.* The Art of Brewing and Fermenting…, *by John Levesque. Picture: by permission of the Syndics of University Cambridge Library.*

the subject: 'If then the animal faculties of man are not competent to penetrate into the arcanum of nature, and view the formation of atoms ... why therefore should the mind, untutored by the senses, strive to furnish fiction as a substitute for truth?'[23]

In this oral culture, most practices, such as malting, were traditional processes.

> It is an imitative system of labour, in which three of the five animal senses are engaged, seeing, feeling and smelling; and in which the mental faculties have usually but little participation. An experienced practical malster can tell when his corn is in good order, when it needs turning or raking, more warmth, more air, or more water; an acceleration or retardation of the process, and when it is fit to go to the kiln and the various operations thereon, by the intuitive indication of one or all of these senses; but if you ask him to state the mode by which he judges, he is quite unable to express the means by any clear and definite language, because the mind has no participation in the determination, and as his experience is incommunicable in words, so it is in practice, for he cannot impart to another by any mental instruction, the discernment of the animal faculties, which he has himself acquired by long continued observation.[24]

In order to be symmetrical with the predominantly oral culture of brewing and their practices, I will call their forms of 'imitative knowledge' *gestural knowledge.*

The proverb quoted above clearly indicates that, for the determination of the appropriate mashing heats, personal experience was necessary in order to produce an invariable product. The correct temperature did not only depend upon the varying quantity and quality of the malt, and the changing temperature of the atmosphere according to a particular season, but also on the situation of and amount of radiation from the mash-tun. Therefore only long experience and a certain 'habit of taking his mashing heats' allowed a successful control of the brewing process. Brewers and malsters were bearers of this gestural knowledge. Mashing heats were often secrets of local brewers and depended on their particular scales and modes of production. The malster's skill made him one of the most important and respected 'agents'.[25] The production and the selling of ale or porter with a standard colour and flavour completely depended on the mastery of specific heats in the process of mashing and fermentation. Therefore 'heat was the principal agent' in the whole brewing process and the malster and the brewer its masters. For large breweries, Wigney proposed the employment of their own malsters with an extremely high salary in order to get control over this most critical component of the whole production process.[26] Even in

[23]*Ibid.*, pp. 193–194.

[24]*Ibid.*, p. 224. For an excellent study on incommunicable knowledge, see Christopher Lawrence, 'Incommunicable Knowledge: Science, Technology and the Clinical Art in Britain 1850–1914', *Journal of Contemporary History* **20** (1985), 503–520.

[25]The term 'agency' was used in brewing terminology as 'performance by a substitute, an acting medium between cause and effect' (*op. cit.*, note 20, p. 43). Malsters were agents as well as heat or air.

[26]For brewers at that time the process of malting was regarded as the economical window in brewing, i.e. due to the yearly changes in quality and quantity of malt brewers took their opportunity of buying the malt from different producers in order to keep their brewing costs at a constant level. But in order to guarantee a *standard taste* all the year round Wigney's proposal represents the main issue the new scientific brewer had to deal with. I am very grateful to Peter Mathias, who discussed this issue with me.

periodically occurring situations when 'first houses were out of order', i.e. leading breweries made foul or bad beer, which could go on for weeks, it was never regarded as the fault of the malting or brewing agent. It might have been a change in the atmosphere, a change of yeast or the quality of water. Brewers relied completely on such representatives of oral cultures and their gestural knowledge. They were the unquestionable standards in the production process.

The process of brewing and the economy of the market were the conflicting poles of brewing. Furthermore, the vast scale of the government excise system established in the eighteenth century, in which accurate values of liquid were measured by widely distributed hydrometers, put brewers into a nationwide state-controlled system of metrology.[27] In the 1820s William Cobbett reported that the 'lowering of the wages of labour, compared with the prices of provision, by means of the paper money, the enormous tax upon the barley when made into malt, and the increased tax upon hops' had 'quite changed the customs of the English people as to their drink'. Drinking beer had become a public, as opposed to a domestic, culture. Labourers and tradesmen 'now spent their evenings at the public-house amidst tobacco smoke and empty noise'.[28] This decline of the home brewing and the changing taste of the public led to the wealth of breweries in the first decades of the century and it effected changes in their modes of production. New changes in supply and demand in the 1830s had direct influences on the practice of brewing too (see Fig. 2). Brewers became more interested in a chemical understanding of the principles and agencies in 'nature's vast laboratory'. More details about the nature of heat and the fermentation process in order to get 'exact control' would bring an economic advantage.[29] Through a scientific practice of brewing it was hoped to achieve communicable knowledge about exact temperatures, quantities and timings of brewing sequences and habits of buying and selling.

'Scientifically' minded, careful quantitative studies of the subtle process of heat conversion in germination, fermentation and mashing were envisaged as one major strategy of 'the new system' in brewing. G. A. Wigney coined this term in order to outline the 'science of brewing' as opposed to brewing as craftsmanship. Practical advice show clearly how these economic interests, caused by a 'never excusing public', moulded the practice of brewing. Wigney's cyclopaedia written in 1838 was a voluminous attempt to accustom the uneducated brewer to the virtues of science. For him, 'a brewery may appropriately be termed a brewing chemical laboratory;

[27]Even the names of beers like 'sixty shillings' and 'eighty shillings' remind us of this control system.

[28]William Cobbett, *Cottage Economy* (London, 1822), p. 12, p. 21.

[29]Joule's brewery was producing ale and porter. It was probably the most secure way to make profit. The two most important problems in order to improve brewing in the 1830s were described by William Black: 'In no treatise on brewing which I have seen have I been able to find any distinct or specific rules for taking the proper temperatures of mashing liquors; nor have I ever found, what may be called the most important though least understood operation in the process of brewing, vz. fermentation, treated or explained in such a manner, as to be any guide to a brewer'. William Black, *A Practical Treatise on Brewing and on Storing Beer: Deduced from Forty Years Experience* (London: Smith, Elder and Co., 1835), A2.

requiring to be fitted upon the best chemical and mechanical principles, so as to enable the brewer to furnish the best product at the least possible cost'.[30]

Large breweries like William Joule & Son provided spaces where different forms of life such as the old brewing culture with their particular local practices and the engineers' world of steam-engine technology interacted. The nature and economy of heat was their common concern, the gestural knowledge of the former hardly understood by the latter. Benjamin Joule's brewery provided the necessary capital which allowed their sons to participate in a form of life which G. A. Wigney portrayed as follows:

> The next period they [the brewers' sons] are found at school, as the sons of fortune, to whom education is not necessary, as the means of procuring bread, but merely to adorn and fit them to pass with eclat, through the ranks of polished society.... To take the mashing heats and weigh the worts, is quite sufficient for him! All the rest can be performed by the well organised menials. His father did well by it, and what can he need more?[31]

Wigney also concluded that this portrait was not appropriate for all brewing families; but we know that everyday life in the Joule family was organized by six live-in servants. The Joule brothers' private tutelage by the chemist Dalton perfectly represented brewers' interests at that time. But James's brother devoted his life to music, and James was also in the position to decide either to improve the business or to become a gentleman of science. He decided to do both. In the autumn of 1843 Benjamin Joule built his son James his own laboratory at their new residence in Oak Field, Whalley Range. Beforehand he had experimented in one of the spare rooms at Broom Hill. During the years 1834–1854 James attended his father's brewing business 'pretty constantly from nine to six'.[32] His experiments he performed before breakfast or in the evening. For twenty years his engagement with these two apparently unrelated spaces formed his life and work.[33]

As Peter Mathias has shown, the use of thermometers in the brewing community was in the late eighteenth century already regarded by 'men of reflection' as one of the major achievements in the exploitation of raw materials.[34] But only in connection with the hydrometer did it lead to the idea of standard heats which allowed the

[30] *Op. cit.*, note 20, p. 89.

[31] *Ibid.*, pp. 68 ff.

[32] J. P. Joule, 'Autobiographical Note', in J. R. Ashworth, 'A List of Apparatus now in Manchester which belonged to Dr. J. P. Joule, F.R.S., with Remarks on his MSS., Letters, and Autobiography', *Manchester Memoirs* **75** (1930–31), 105–117, on p. 113.

[33] Historical studies of Joule differ on this aspect. The question whether Joule was involved in the brewing business is treated differently. Cardwell's comment brilliantly summarizes the involved issue. 'Young Joule was a businessman. He was later to record that once his tutelage was over he used to attend at the brewery every day, from nine in the morning to six in the evening. This, by Manchester standards, was a far from excessive burden and Osborne Reynolds was later to assert that Joule had little connection with the business. But, while he carried out some of his researches at the brewery (he acknowledged as much in various papers), his correspondence indicates clearly that he was actively engaged in running the business until it was finally sold' (D. S. L. Cardwell, *James Joule: A Biography* (Manchester: Manchester University Press, 1989), p. 3).

[34] Peter Mathias, *The Brewing Industry in England 1700–1830* (Cambridge: Cambridge University Press, 1959), pp. 63 ff.

brewers, the distillers and the Government excise system in particular a more precise measurement of the specific gravity of liquids. 'The one showing the heat, and the other ascertaining the *strength*, or *gravity*, of the extract obtained at that heat. Here, and here only, we lay hold of the clue that leads with certainty to the establishing of *standard heats*'.[35]

In many other operations absolute measures were regarded as a disadvantage. For example, during the process of malting, excise officers had to control various stages of operation in order to prevent defrauding. But from the brewers' point of view it was 'much to be regretted' that the legislative period too often interfered with the malster's judgment.[36] From the excise officers perspective, using absolute measures was the only way to levy duties. In 1842 they set up their own laboratory in order to protect the revenue through establishing standards against which brewers' and distillers' work was calibrated.[37] Although these commercial interests existed on both sides, heat processes still remained difficult to calculate. A perfect mashing heat was variable to an extent of thirty degrees during the period of a year's practice. Hence Wigney concluded:

> If there was an invariable right standard heat, either for water or return wort, as well as a perfect heat, at which the best solution of malt extract, and the obtainment of the largest quantity could be effected; the discovery of it would be of the highest importance to brewers; and once made, and communicated to the public, its invariable adoption, would ensure to the fortunate possessor, the most profitable results, as relates to the process of extraction. But that which does not exist, cannot be discovered. Yet there is a perfect mashing heat, but it is a variable one, and may be said to be fugitive, the same heat scarcely ever being advantageously applicable to two successive brewings from the same malt.[38]

But as a result of the new economic situation of producing beer all the year round, thermometers and decimal tables became the brewers' indispensable practical and

[35] R. Shannon, *A Practical Treatise on Brewing, Destilling and Rectifying* (London, 1805), p. 57. On the role of the hydrometer at that time see William Speer, 'On the Hydrometer', *Philosophical Magazine* **14** (1802), 151–162 and 229–237.

[36] The malster's object is to obtain as much saccharine matter as possible, with the smallest loss of substance, by converting the starch of the barley into sugar. Malting consists of four processes: steeping, couching, flooring, and kiln-drying. In order to make correct charges the excise officers gauged the utensils and gave certain standard times ('legislative periods') for some operations. For a detailed description, see *Encyclopaedia Brittanica*, ninth edn, vol. 4 (Edinburgh: Adam and Charles Black, 1876), pp. 264–275; *op. cit.*, note 20, p. 4.

[37] 'The need for such a laboratory arose from a desire to protect the revenue, and not from any perception that an official body was needed to protect in any way the population or the environment in which we live. This role came later'. P. W. Hammond and Harold Egan, *Weighed in the Balance: A History of the Laboratory of the Government Chemist* (London: HMSO, 1992), p. 1; see also p. 51.

[38] *Op. cit.*, note 20, p. 32.

theoretical technologies.[39] The London brewer John Levesque clearly spelled out the advantage:

> No brewer can reasonably expect favourable results from his practice, without intimate knowledge of the heats requisite for the different stages of the process; and as ultimate success depends on the utmost accuracy in that important department, the author has invented a Thermometer (referred to in this work) on such unerring principles in the application, as to insure precision and prevent the possibility of error,—that great desideratum in the Art of Brewing. The Author concludes, that the more his Tables and newly-invented Thermometer is studied, the more they will be referred to and adopted, as the standard of calculation, &c. of the materials of brewing.[40]

Wigney, like Levesque, was one of the protagonists of this 'new system' of brewing. In his *Theoretical and Practical Treatise* he taught the reader to distinguish between the old and the new system:

> *The Old System.* The first mashing heat taken by guess; and by many to the same degree all the year through, regardless of seasons and circumstances, and by none with accuracy. *The New System.* The first mashing heat taken by rule, subject to arithmetical calculation, upon the data of the weight and heat of the malt, and the quantity of the malt, and the quantity of liquor mashed with, with tables to refer to, to save the practitioner the trouble of calculating for every brewing.[41]

In order to demonstrate the advantages Wigney presented typical brewing problems and discussed their ways of solving them in the old and new style:

> Example—A Brewer is required to mash 20 quarters of malt, weighing 40 lbs, and at a temperature of 50 degrees, with 40 barrels of water, weighing 360 lbs per barrel, and it is required that the heat of such malt, and water when mixed, should be at 144 degrees. Query! What should be the heat of the 40 barrels of water?[42]

The old rule of solving it was objected to because of its imperfection in representing the brewing process sufficiently. 'The loss of heat during the mashing' was not taken into account, nor was 'the increase in active heat arising from the conversion of latent into active heat'. But despite his efforts in highlighting the improvements of the new system he finally admitted:

> But it should be observed that all these objections, and others in addition, may, with as much and more propriety, be made to any fixed and arbitrary standard of heat, which is adopted upon any other principle, and it does not follow, that because we cannot attain perfection,

[39]For the use of technologies see Shapin and Schaffer, *op. cit.*, note 6; and Andrew Warwick, 'Cambridge Mathematics and Cavendish Physics: Cunningham, Campbell and Einstein's Theory of Relativity, 1905–1911; Part 1: The Uses of Theory', *Studies in History and Philosophy of Science* **23** (1992), 625–656.

[40]John Levesque, *The Art of Brewing and Fermenting in the Summer, and all Other Seasons, to the Greatest Advantage, and the Making of Malt, Exhibited in Essays, and Decimal Tables, Accurately Calculated, the Result of Upwards of Forty Years' Experience; also a Description of the Author's Newly-Invented Thermometer, By the Application of which Extreme Precision and Considerable Saving will be Effected*, 2nd edn (London: Thomas Hurst, 1836), preface.

[41]G. A. Wigney, *Theoretical and Practical Treatise of Brewing* (Brighton, 1835), p. 252.

[42]*Ibid.*, p. 102.

> that we should not approach as near to it as we can, consistent with the convenience of common practice, based on careful and industrious principles. And to judge fairly of the merits and value of a system, we should weigh the products against the cost, the labour and the inconvenience of carrying into effect.[43]

He explained the given 'standard heats'[44] in his tables as representing common brewing practice, because they were results of years of experience. But it was no more than the closest 'approximation to a good practice' the brewing economy of that time would allow. But regardless of this fundamental issue Wigney had already been industrious to provide instructions for the proper use of these decimal tables in connection with the thermometer:

> Explanation relative to the use of the Tables—The weight of a bushel of the malt about to be brewed being ascertained, take the Thermometer out of the malt just before mashing, and note its temperature. Let us suppose that the weight of the malt is 40 lbs per bushel, and its heat 50 degrees, and you intend to mash with 2 barrels of water per quarter, then refer to the first column of the third Table, and find 50° then in a line therewith, and in the third column, under the head of two barrels, you will find 185 3/4 degrees, which should be the heat of the mashing water.[45]

This major change from the old to the new system in the practice of brewing stigmatized old traditions:

> If the brewer tells his pupil, that in order that he may know whether or not he has taken a first mashing heat correct, that he must apply a thermometer to the steam of wort, as it runs from the mash tun into the under back, when about half the expected quantity to come off is down; and if he finds the temperature at any point between 144 and 150 degrees, he may take it for granted that it was so; and if on the contrary he finds it above or below, that then he may conclude that it was incorrect, and to an amount proportionate to the extent of the difference in heat, between which it should and does come down; will not the pupil, if he is accustomed to think, naturally enquire, if such is the effect, what is the cause? And if to-day, one particular heat is right, why should not the same be tomorrow? And if the instructor cannot tell the instructed, what do we think of his knowledge of his business? And if the instructed should say, is it not possible to find out beforehand, what is the right mashing heat upon every occasion, and avoid the consequences of error; as well as to know by the result, whether or not the right heat has been taken, which is no consolation to know if it should happen to be wrong? And if the instructor, who is not accustomed to think, reflect, deduce, and discover, replies, it is impossible, for the person who taught me, was a good brewer and he never knew the means...?[46]

The introduction of standard heats created the idea of error and deviation in that industry, at the expense of the prestige of humans, whose skills had mastered each particular situation by judging the actual heat conditions. Thermometers made it

[43] *Ibid.*, p. 103.
[44] 'Standard heats' are only one type of standard measures. Other standards were 'The weight of yeast to pitch the tun with, in the ratio of its density' or 'Weights of hops, which had to be added in relation to the increase of warmth in weather', etc.
[45] *Op. cit.*, note 41, p. 105.
[46] *Op. cit.*, note 20, p. 16.

possible to produce numbers which helped to replace these craft skills—the gestural knowledge—by absolute standards. The new demand for the brewers' products made tables of decimals and thermometers the trustworthy companions of the scientific brewer. Thermometers with a sensitivity of tenths of a degree became the required standards. Their constant use gave evidence for the 'advantageous points' for each mashing condition, but simultaneously declared the particular as deviation.

Wigney's book documents this conflict between individuals as bearers of gestural knowledge which was regarded as incommunicable and the scientific brewer. He tried to unify these two sites of knowledge by inventing the terms 'theoretical' and 'practical' chemist.

> Both malsters and brewers are practical chemists, in the proper acceptation of the term; yet what do they (generally) know of chemistry? So little indeed, that it would be no trifling task to convince them, that the process of either malting and brewing is chemical... The man who devotes his time and attention to the study of chemistry, merely as a scientific pursuit, may for the sake of distinction be called a theoretical chemist: and the person, who performs chemical operations as a matter of business, may be termed a practical chemist... Thus the theoretical chemist while sitting in his study, discovers and develops the arcanum of the process; while the practical chemist (the malster) fulfils all the mechanical conditions of the operation, without a knowledge of the theory.[47]

Wigney cleverly turned their common practice of learning by imitation into an argument for the study of science, especially chemistry. Brewers and malsters were now represented as 'mere automata' and as 'children', both mechanical and juvenile:

> As the malster is, so is the brewer taught; or rather he learns a series of practical operations, the whole of which are (perhaps to him) a mass of mysteries, as relates to the causes which produce certain effects, and effects which produce certain causes: he is but a child, that assists to work the complicated and extensive machinery of the factory, instead of being as the conscious inventor, who comprehends and commands the movement of the whole, with ease, order and regularity. He is a mere automaton, without knowledge, judgment, or skill, as relates to his profession or manufacture, if unacquainted with the theoretical department of chemistry.[48]

The new brewer should understand that his business was a complex mixture between theoretical and practical tasks, and 'mere theorists, as well as mere practitioners, [would be] ...ever grasping at a shadow and losing the substance'. Only science could save the traditional brewer from remaining an 'automaton exemplar', 'a blind and unconscious agent in the performance of a chemical work, a stranger to the wonderful transitions which he had assisted to affect, and without a comprehension of the cause'.[49]

[47] *Ibid.*, pp. 59–61.
[48] *Ibid.*, pp. 63–64.
[49] *Ibid.*, p. 64.

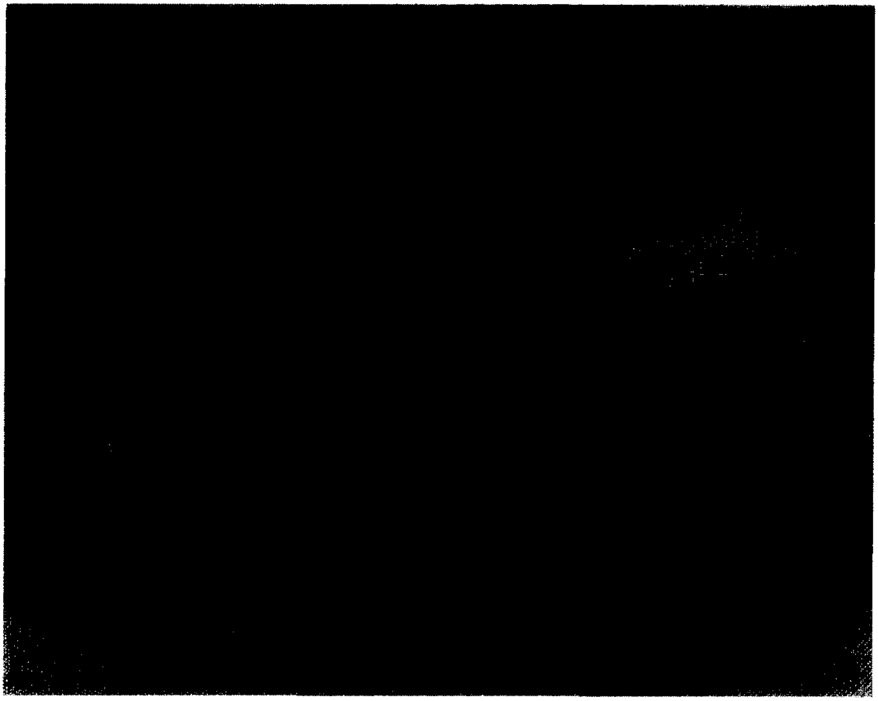

*Fig. 3. Model made by Henry Maudslay about 1805 in order to be able to produce copies of his new micrometer, which he called the 'Lord Chancellor'. Used exemplars of this 'companion of the bench' hardly exist any more because they have been worked to death. Picture: by permission of The Science Museum/Science and Society Picture Library.*

## Mass Production and Accurate 'Companions of the Bench'

> If we go on as some mechanics are doing, we shall soon be boiling our eggs with a chronometer.[50]

The new system of brewing was only one indicator for a fundamental cultural change in British society in the first half of the nineteenth century. Especially in industrial cities like Manchester, rapid mechanization of the manufacturing industry produced the vision of a 'self-acting' society. Self-acting machine tools driven by steam engines revealed the new metropolitan habit of replacing self-moving forces in nature through the scientific study of self-acting powers in culture. Economic reasoning about the costs of exploiting natural forces became an important task for engineers and natural philosophers. Mass production and its need for exact measurement, standards and control skill, increased rapidly. This changing economic situation and the 'Machinery question'[51] affected the habits of the actors in everyday life as well as in the sciences.

[50]Henry Maudslay in Samuel Smiles (ed.), *James Nasmyth, Engineer: An Autobiography* (London, 1885), p. 146 n.1.

[51]Maxine Berg, *The Machinery Question and the Making of Political Economy 1815–1848* (Cambridge: Cambridge University Press, 1980). Iwan Morus, 'Correlation and Control: William Robert Grove and the Construction of a New Philosophy of Scientific Reform', *Studies in History and Philosophy of Science* **22** (1991), 589–621.

The transference of bodily techniques to machines went along with the devaluation of the body and of gestural knowledge.

> Machinery is rapidly supplanting human labour, and rendering mere muscular force a *worthless drug*. That natural machine, the human body, is depreciated in the market. But if the *body* has lost its value, the *mind* must get into business without delay. The intelligence of man must be *brought to the mint* and *coined* and set in instant circulation.[52]

For engineers self-acting tools involved a successful replacement of 'irregularity and carelessness of the workman'. Or as James Nasmyth put it: 'The machines never got drunk; their hands never shook from excess; they were never absent from work; they did not strike for wages; they were unfailing in accuracy and regularity, while producing the most delicate or ponderous portions of mechanical structures'.[53] The bold marketing of self-acting machine tools helped to create the image of unreliable humans and their failing senses. The want of uniformity was made obvious after the opening of the Liverpool–Manchester railway line in 1831. The 'uniformity of screws' became especially important for the needs of railway constructors. Before Henry Maudslay introduced his screw-cutting machine, every bolt and nut was unique in itself. This economic interest went along with a programme of producing instruments of precision and disciplined human beings. Maudslay, for example, constructed and propagated his 'Companion of the Bench', which every craftsman should use to control his own accuracy of work (Fig. 3).

> So much depended upon the manner in which the ordinary measuring instruments were handled and applied that they sometimes failed to give the required verdict as to accuracy. In order, therefore, to get rid of all difficulties in this respect, he designed and constructed a very compact and handy instrument which he always had on his bench beside his vice... In consequence of the absolute truth of the verdicts of the instrument, he considered it as a Court of Final Appeal, and humorously called it 'The Lord Chancellor'.[54]

In order to guarantee the making of standard products, companions of the bench were introduced in several sites of production. Even composers began to calibrate musical performances against an absolute time measure by means of the metronome.[55] The use of these companions changed the performance of work and contributed to the formation of new kinds of gestural knowledge. But although the use of thermometers was still discussed controversially within the brewing culture, experts of the new system of brewing neither took care to pass on the old brewers knowledge of how to use hand and elbow as a temperature measuring device nor translated it into a text.

[52]James Martineau, cited in W. Hawkes Smith, 'On the Tendency & Prospects of Mechanics Institutions', *The Analyst* **2** (1835), 336.

[53]Smiles, *op. cit.*, note 50, p. 193.

[54]*Ibid.*, p. 145.

[55]A classical example of a companion of the bench is the metronome with its absolute time measure, developed in Germany during the late eighteenth and early nineteenth century. As a result of the composer's changing economic situation, compositions became commodities which involved standardization. This led to the invention of the conductor and the metronome which serves as the mediator between composer, conductor and the orchestra. For further details see the author's article 'Working Experiments', *op. cit.*, note 8; Peter Schleuning, *Das 18. Jahrhundert: Der Bürger erhebt sich*, Geschichte der Musik in Deutschland, Band I (Reinbek bei Hamburg, 1989), pp. 459–474.

With regard to the economic and social context of manufacture and the devaluation of bodily work in particular, the possession of this instrument already made the new brewer a 'man of reflection' and indicated his affiliation to a gentlemanly form of life.

These cultural changes go along with fundamental shifts even in the manners of natural philosophy, another site of knowledge production. In the eighteenth century the credibility of experimental practices was very much based on face-to-face interactions. 'Natural philosophers had to pay attention to the means by which experiments tried in private space, backstage, could be made to transit to the public settings of polite culture'. Simon Schaffer has identified the emergence of trust in self-registering technology and the disembodied genius as a new cultural manner of the early nineteenth century.[56] In the period under analysis, the imposition of increases in the sensitivity of instruments of precision made necessary new gestures of accuracy. The use of new companions of the bench led to practices which even required their particular spaces and did not necessarily conform with the patterns of bodily behaviour customary to Joule's contemporary natural philosophers. In order to understand what was regarded as reliable experimental practice we have to look at the natural philosophers' attempts to define standards of accuracy and methods of calibration.

In a report to the British Association for the Advancement of Science, the natural philosopher J. D. Forbes was quite explicit about the predominant issue of how to get reliable data:

> Great numerical accuracy is always of extremely difficult attainment; and it is hoped that the good sense of observers will dismiss from Meteorology, as well as from some other branches of physical science in which it has prevailed, that superfluity of decimal places, which when they exceed to a great extent the compass of the instrument to verify, create rather a distrust in the observer than confidence in his observations. Even within very moderate limits it is clear that, where accuracy so entirely depends upon the extreme precision of instruments and attention to their condition, and upon perfect regularity and consistency of observation, there are few individuals who can furnish the numerical data now required for the advancement of science.[57]

For the supply of meteorological heat data he then suggested substituting the 'good sense of the observer' by 'the hands of merely mechanical observers, under the occasional superintendence of persons of greater acquirements'.[58] These disciplined hands he found in the army at Leith. Military officers executed the temperature readings of great extent during the years 1824 and 1825. Besides these hands of

[56]See Simon Schaffer, 'Self Evidence', *Critical Inquiry* (Winter 1992), pp. 327–362. On discipline formation in electrical research and the changing role of the experimenter's body, see H. O. Sibum, *Physik aus ihrer Geschichte verstehen: Entstehung und Entwicklung naturwissenschaftlicher Denk- und Arbeitsstile in der Elektrizitätsforschung des 18. Jahrhunderts* (Wiesbaden: Deutscher Universität Verlag, 1990), pp. 219–254.

[57]James D. Forbes, 'Report upon the Recent Progress and State of Meteorology', *BAAS Report* (1832), pp. 196–258, p. 199.

[58]*Ibid.*

mechanical observers, self-registering instruments were introduced as the appropriate replacements.[59]

In Cambridge University, Forbes's ally William Whewell worked on the development of another companion of the bench which allowed control over sites of knowledge production outside the natural philosopher's own place. In the chapter on 'Special Methods of Induction Applicable to Quantity' of his *Philosophy of the Inductive Sciences*, he introduced the 'method of curves' as the most efficient technology for calibrating individual practices against a geometrical standard.

> But the Method of Curves not only enables us to obtain laws of nature from *good* Observation, but also in a great degree, from Observations which are very imperfect... The regular curve which we thus obtain, thus freed from the casual errors of observation, is that in which we endeavour to discover the laws of change and succession. By this method, thus getting rid at once, in great measure, of errors of observation, we obtain data which *are more true than* the individual *facts themselves*. The philosopher's business is to compare his hypotheses with facts, as we have often said. But if we make the comparison with separate special facts, we are liable to be perplexed or misled, to an unknown amount, by errors of observation; which may cause the hypothetical and the observed result to agree, or to disagree, when otherwise they would not do so. If however, we thus take the *whole mass of the facts* and remove the errors of actual observation, by making the curve which expresses the supposed observations regular and smooth, we have the separate facts corrected by their general tendency. We are put in possession, as we have said, of something more true than any fact itself is.[60]

In accordance with the customs of these sites of production, different technologies became the trustworthy companions of skilled individuals. Simultaneously, their absolute measures became the guideline for the production process.[61] These were the places where particular human experiences became marked as deviation, where the 'companion of the bench' became the representative of 'absolute truth'. In order to further the advancement of science and society, human skill partly became standardized or was irretrievably lost. Instruments became the reification of accuracy and humans turned into instruments of precision developing new forms of gestural knowledge.

## Joule's Laboratory Life and its Values

> Art is long and life is short. [Joule]

In the 'new system' of brewing and in other sites of production, an array of 'companions of the bench' were to act as standards of competent performance. It involved the establishment of new hierarchies of mind and body. This general change

[59] John Phillips, 'Description of a New Self-Registering Maximum Thermometer', *BAAS Report* (1832), pp. 574–575, p. 574.

[60] William Whewell, *The Philosophy of the Inductive Sciences, Founded Upon Their History*, 2 vols (London: John W. Parker, 1840), vol. 2, pp. 206–207.

[61] For further examples of the practice of absolute measures and its troubles, see the Glaswegian Professor of Engineering Lewis Gordon on pyrometers and dynamometers. M. Norton Wise, 'Work and Waste: Political Economy and Natural Philosophy in Nineteenth Century Britain (III)', *History of Science* **28** (1990), 221–261.

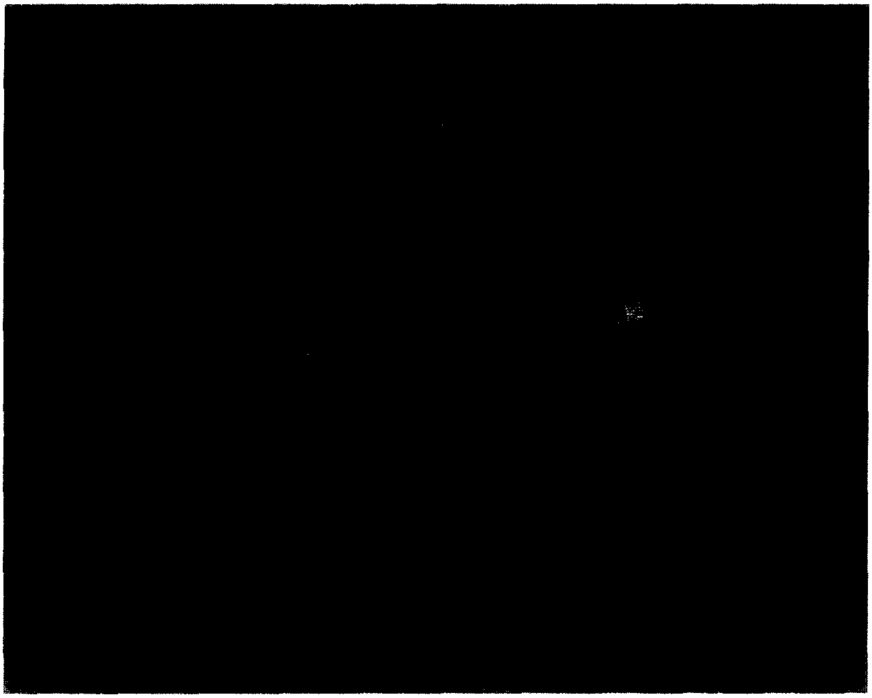

*Fig. 4. John Benjamin Dancer's travelling microscope built for the calibration and graduation of Joule's thermometer. Picture: by permission of the Museum of Science and Industry, Manchester.*

in cultural manners helps us to clarify the connections between Joule's work as brewer and his efforts to turn himself into a natural philosopher. Joule's autobiographical note as well as his notebook entries show that he performed more than the minimal tasks of a brewer: taking the mashing heats, weighing the worts and balancing the books. He also did experiments on the combustion of hay and corn, and on brewing procedures[62] as well as studies on the duty of electro-motors. With respect to the Manchester engineering background it is not surprising that he wanted to measure nature's agents such as heat and electricity, 'ever at work in her vast laboratory; commanding indestructible atoms to unite and disunite'.[63] His experience with

[62]Joule, 'Notebook', 2, pp. 181–185, pp. 222–223, 9 January 1846, 14 October and November to December 1847, October 1849, UMIST, Manchester.

[63]In his study on Joule's work, John Forrester has shown that his various attempts to identify primary forces in nature—heat, electricity and mechanical force—were favourites used in his various atomic theories. Latent heat and electricity were exactly the most important issues in brewing practice. See in Wigney the explanations of 'Electricity, Attraction without Magnetism' and 'Heat, the Sensation caused by Fire, Hot Weather &c' and 'Decomposition'. *Op. cit.*, note 20, pp. 121–122 and pp. 179–185. John Forrester, 'Chemistry and the Conservation of Energy: The Work of James Prescott Joule', *Studies in History and Philosophy of Science* **6** (1975), 273–313.

decomposing organic materials by mechanical and chemical means made it self-evident to reflect on friction as a source of heat rather than as an obstacle engineers had to overcome. In the brewers' form of life, even Joule's use of the conservation of living force shows a close analogy to the brewer's understanding of conversion processes as discussed in Wigney's dictionary.[64] Determining the 'mechanical value of heat' was his attempt to calibrate nature at work.[65] The duty of electro-motors as well as other moving forces were well worth knowing in order to estimate the costs a self-acting society had to match.[66]

During these twenty years of participation in the brewing world, Joule developed a particular gestural knowledge which came to bear in his new location as a natural philosopher. His development of the gestures of perceiving and measuring temperatures became a self-evident technique during his experiments on the mechanical equivalent of heat. They were steadily extended. In the notebooks his practice of reading temperatures was not mentioned at all. But we know from our replication that in order to avoid errors it is necessary to have extraordinary experience in the use of the thermometer and the working conditions. Both were available to Joule. He performed the experiment of 1850 in the cellar of the brewery, which appeared to be a more familiar place to him than his new laboratory. But the temperature fluctuations identified in a similar building indicated that he must have had long experience in taking the temperatures in order to avoid these disturbing effects. How he did it will, to a certain extent, remain unknown to us; but from the practice of brewing we already know that a successful performance of mashing was based on calculating and measuring the mashing heats to a tenth of a degree related to air temperature changes of one degree.

We can also conclude that his earlier experiments in determining the mechanical equivalent of heat were not as accurate as in the 1850 version. The constructions of the earlier technical set-ups prevented him from producing reliable results. It is obvious that he was absolutely convinced beforehand that such an equivalent existed. In the brewers' form of life, using equivalents was one operation within the practice of 'mensuration'. As a result of the different scales used for different kinds of goods, brewers and excise officers both had to be perfectly acquainted with decimal arithmetic. Tables of decimals in connection with the 'sliding-rule' were their

[64]See there the sections on 'Generate' and 'Germinate'. This issue requires further research but it seems that conversion processes and the role of human agency in them are the characteristic problem situations not only of Joule but also of researchers like Julius Robert Mayer and Justus von Liebig. *Op. cit.*, note 20, pp. 167–170.

[65]Joule used the term 'mechanical value of heat' in his paper 'On the Caloric Effects of Magneto-Electricity, and on the Mechanical Value of Heat' (1843), in Joule, *The Scientific Papers*, *op. cit.*, note 1, pp. 123ff.

[66]Historians of science usually connect the term 'duty' with an old engineers' concern of measuring the efficiency of an engine. In fact that meaning was very recent, compared with the meaning of 'payment to the public revenue levied upon the manufacture and sale of commodities'.

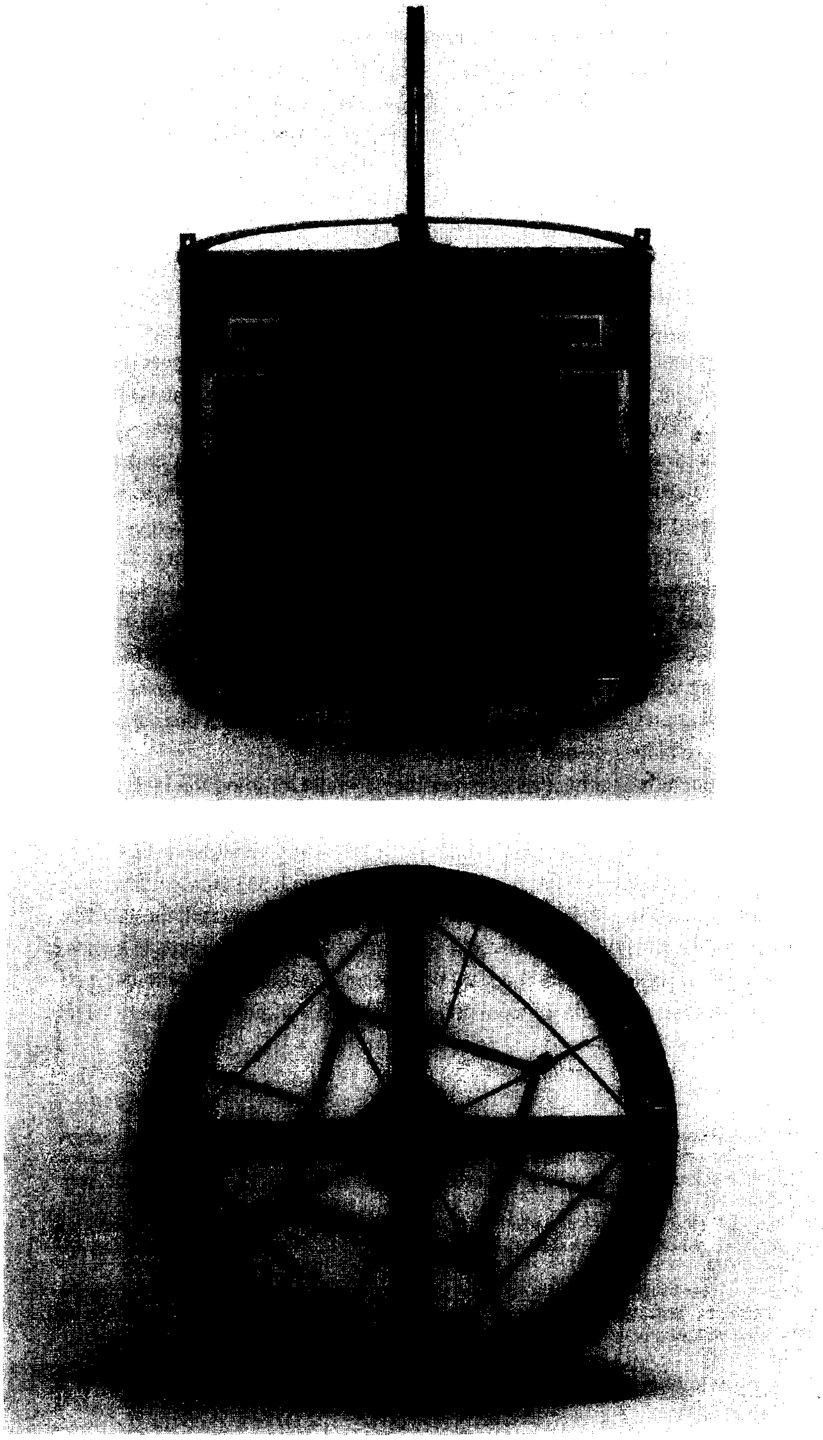

*Fig. 5. Second replica of Joule's paddle-wheel device based on the exemplar held in the Science Museum London. Built at the C.v.O. University, Oldenburg. Picture: by permission of the Research Group on Higher Education and History of Science, Carl von Ossietzky University, Oldenburg.*

trustworthy companions[67] in order to find numerical expressions which served as a measure of value for the other. This conversion of units and measures was a mundane practice for Joule as well. But the challenge for him was to achieve an *experimental practice* which would allow him to claim that heat has a mechanical equivalent.[68]

A further major advantage was his collaboration with instrument makers and workers. Our replication shows that an athlete would have been perfect to wind up the weights. An athlete's physical condition would prevent unnecessary temperature increases in the room during the trial, which had to be performed as fast as possible. Probably, an unknown brewing mate was hired by Joule to do the job. But not only did his bodily conditions have to be appropriate, the winding had to be done with particular care. Joule's final design of the vessel for the 1850 publication did not allow any mechanical irregularities during the trials. From my own experience I conclude that in order to measure the friction of water every other possible source of error had to be avoided. For example a stabilizer attached to the thin axle produced heat due to the friction of the axle which made it necessary to perform without it. In fact this made the mechanical sequence of the experiment an artistic performance.

Joule could improve his work of measurement only because John Benjamin Dancer built nearly all the equipment he needed to perform the experiments on the friction of fluids in order to determine a mechanical value of heat. Dancer was a Manchester instrument maker mainly known for his micro-photography.[69] His skill and the Manchester material culture were the crucial preconditions in order to become unbeatable in temperature measurements. One of the most important precision instruments, which Dancer himself called the 'travelling microscope', allowed the construction of an 'extreme sensible' thermometer. This companion of the bench consisted of a low power microscope, which could be moved horizontally by rotating a screw. The distance of travel could be determined from a graduated disc at the one end of the screw. But it also served as a means of rotating the screw. The pitch of the screw was 1/20 in and the circumference of the disc was divided into 200 equal parts, so that the instrument read to 1/4000 in. This precision instrument enabled Joule to build the most precise thermometers of his time.[70]

[67]As Peter Mathias tells us: 'In no case was a brewer's word to be taken for the gauge, or a brewer's table used to calculate it'. *Op. cit.*, note 34, p. 349.

[68]A standard for precise experimental work on determining equivalents was surely set by the newly founded Excise Laboratory when an 'equivalent weight of sugar to a quarter of malt in brewing' was determined by their officers and confirmed by law in 1847. Particularly in this field of metrology, the frame of reference for producing numbers was 'skill in experimenting', which was judged by professors of chemistry like Thomas Graham who made a considerable part of his income from being a consultant for the revenue. Cf. *op. cit.*, note 37, pp. 49ff., p. 319, n. 12.

[69]W. Browning, 'John Benjamin Dancer, F.R.A.S., 1812–1887', *Memoirs and Proceedings of the Manchester Literary and Philosophical Society* **107** (1964/65), 115–142; H. Milligan, 'New Light on J. B. Dancer', *ibid.* **15**, 80–88. In 1844 Dancer also built the paddle-wheel for the experiments which led to the 1850 publication. On micro-photography see Brian Bracegirdle and James B. McCormick, *The Microscopic Photographs of J. B. Dancer* (Chicago: Science Heritage Limited, 1993).

[70]For an illustration of the travelling microscope see Fig. 4.

The exceptional manner of graduation and calibration and its impact on Joule's work can be explained as follows. Firstly, the 'travelling microscope' was extremely helpful for proving the quality of the glass bore. Take a glass tube of narrow bore and introduce a one-inch column of mercury. Measure the distance between the two end points of the drop. Then move the drop so that one of its ends is at one of the previous points. Then take a second measurement of the drop's length. If the bore is of constant diameter, successive distances will also be constant. In each position the probable varying length of the column can be ascertained to the 1/4000th part of an inch. The bore of Joule's thermometer was 'conical, gradually diminishing in diameter. The mean cross-sections near the two ends of the tube differ by about 20%.'[71] This process of checking the bore over a certain length helped in selecting the best quality of glass tubes.

Secondly, the instrument allowed a precise graduation, 'The surface of the glass having then been covered with a thin film of bees-wax, the portions of tube previously measured were each divided into the same number of parts by a machine constructed for the purpose. The divisions were then etched by means of the vapour of fluoric acid'.[72] His instrument enabled him to determine these distances easily because it could distinguish 1/4000th part of an inch. On the basis of Joule's table of measures, differences of about 0.00635 mm were identifiable.

These technical achievements, due to Manchester material culture and instrument makers' skill, provided Joule with an extraordinary calibrating device. The method given above allowed him to 'calibrate the thermometer by the graduation itself'.[73] If the tube had a perfectly uniform bore it only would have been necessary to make a millimetre scale of equal parts between the freezing and boiling points. But usually no bore had these conditions. Joule therefore decided, in dividing the scale, to make allowance for the variations in the tube's capacity. The process described above, enabled him to identify the varying length of the mercury column. Afterwards, these different distances were each graduated into 50 divisions. The divisions of a thermometer built like thus did not represent degrees of the ordinary scales of temperature, but of an arbitrary value, differing for each instrument.

This method provided Joule with a unique measuring device which improved the sensitivity of its measurements immensely. His readings became the most direct and sensitive measures of temperature increases available. He achieved the necessary consciousness about his accuracy in using this new companion of the bench from his constant practice. In the old brewing culture he had experienced impressive role models. In this respect Joule continued in the manner of a malster whose individual skill in performance was the evidence of, and therefore the unquestioned guideline

[71] Arthur Schuster, 'On the Scale-Value of the late Dr. Joule's Thermometers', *Philosophical Magazine* **39** (1895), 477–501, p. 481.

[72] James P. Joule, 'On the Heat Disengaged in Chemical Combinations', *The Scientific Papers, op. cit.*, note 1, p. 214.

[73] Joule to Thomson, 25 May 1879, Add MSS 7342 J 291, Cambridge University Library.

for, his research and judgment. This interpretation fits the brewers' dictionary definition of 'accuracy' defined as 'exactness' or 'nicety of attention and performance'. Joule worked entirely in this craftsman manner. His skill in taking measures and performing the experiments could not be doubted even when the laboratory 'went out of order'. But simultaneously Joule had made his measurements their own standards because he created a system of values and assigned them to a particular thermometer which no one else possessed. His arbitrary scale allowed him to increase the sensitivity but made him the only person able to judge his accuracy.

Joule had created a space of innovation with its own values. He had become a performer without an audience: as our reconstruction has shown, nobody could have witnessed his experiment directly due to the disturbing effects of body radiation. Neither could Joule go out and demonstrate a successful trial. His newly developed instruments carried arbitrary values with them which nobody could control at that time. In order to compare his measurements with those of contemporary researchers he very often brought foreign thermometers into his laboratory either to calibrate them against his own or to use them for air temperature readings during his trials. These 'standards' were very well chosen. One thermometer was given to him by Professor Thomas Graham, an eminent chemist from University College London. In the 1840s he was also one of the main consultants for the Revenue, both to do chemical analysis and also to referee the work of the excise staff.[74] The second standard was given by Lyon Playfair, an industrial chemist and Professor of Chemistry at the Royal Institution in Manchester.

In the 1840s he improved his abilities in doing more sensitive measurements. It even prompted him to move out of his laboratory to perform his final trials in his brewing cellar, probably in order to minimize the heat losses and to get a uniform temperature. As the replication shows, this performance could not be repeated. Joule's skill and that of others made the brewing cellar a unique site. Metaphorically speaking the 'frozen vegetables'[75] stored inside would already have melted, even by opening the door of the cellar. Therefore Joule's experiments on the friction of fluids were problematic not only because they told against the caloric theory of heat. For Joule the problem became at that time more one of demonstrating the reliability of his work. This move from private to public now confronted him with culturally shared standards which he had to match.

## Defending Tradition and Writing For Acceptance

> By the term science, we understand it to imply that species of knowledge, in the obtainment of which the mind is exclusively engaged, without the aid of the bodily organs, let the subject of acquirement be what it may; and that the purport of its use is to distinguish it from that

[74]See *op. cit.*, note 37, p. 53, pp. 319–320; Joule 'Notebook', 2, p. 162, UMIST, Manchester.

[75]Bruno Latour used the term 'frozen vegetable' to describe the problem that skill—as a character of a social setting—can hardly travel. It always changes. He used the term at the Bath conference on 'Rediscovering Skill'.

> peculiar knowledge which results from the combined exercise of the mental and physical powers.[76]

When Joule started to publish his experiences in experimenting on the nature of heat he wanted to present himself as a natural philosopher. The nature of his work on the mechanical value of heat, however, put him in an awkward position. He could only *report* about the actual performance in his laboratory because the sensitive measurements did not allow direct witnessing. These reports had to be written in such a way that the audience would understand and believe him. Therefore on their own they do not give an adequate account of Joule's work. The reconstitution of his private experimental form of life throws a different light on his persona and his publication *On the Mechanical Equivalent of Heat.*[77]

Changes in the design of the experimental set-up during the years 1843–1850 show that he responded to public criticism in order to demonstrate 'numerical accuracy'. At the Cambridge meeting of the British Association in June 1845 he presented a version of his experiment in which the copper vessel was not isolated. This set-up was publicly criticized. Two years later, at the Oxford meeting, he said that the earlier experiments 'though abundantly sufficient to establish the equivalency of heat to mechanical power, were not adapted to determine the equivalent with very great numerical accuracy, owing to the apparatus having been situated in the open air, and having been in consequence liable to great cooling or heating effects from the atmosphere'.[78] So Joule presented an improved version in which the copper vessel had been isolated. In his 1850 version, however, he again announced that he had set up the experiment without isolating the vessel. Instead he gave numerical calculations about these 'cooling and heating effects'. My own experiments, however, have shown that the 'radiation effect' was indeed difficult to measure. One major reason was my lack of experience in the correct timing of taking the measures. In 1875 the American physicist Henry Rowland commented on this problem in his diary in order to overcome this possible source of error: 'Having set the machine in operation, using water colder than the air, we note the thermometer and then wait until the temperature has risen the same distance above that of air. In this way all correction for radiation is avoided'.[79]

But Joule's consciousness of and probably his ability to control these atmospheric influences were based on long experience in constructing thermometers and

[76] *Op. cit.*, note 20, p. 307.

[77] This is also indicated by the divergent characterizations of Joule's experimental work. In the recent biography of Joule, Cardwell states: 'Joule was not a metrologist nor was his main interest in exact measurement. But Sarton [who mentioned this fifty years ago] was doing no more than repeating a view that was common at the time and had persisted in some quarters to the present day. In fact Joule was a highly original man of science and, undeniably, a bridge figure.' *Op. cit.*, note 33, p. viii.

[78] James P. Joule, 'On the Mechanical Equivalent of Heat, as Determined by Heat Evolved by the Friction of Fluids', *The Scientific Papers*, *op. cit.*, note 1, p. 278.

[79] Henry Rowland, 'European Trip Diary', Johns Hopkins University Library, MS.6, series 4, pp. 37–38. Cf. H. Rubens, 'Apparat zur Bestimmung des mechanischen Wärmeäquivalents', *Physikalische Zeitschrift* 7 (1906), 272–276.

developing a particular 'habit of taking measures'. Here the 'brewing chemical laboratory' was the most perfect place to accustom himself to it and to do the performance as well. But that embodied capability, that particular gestural knowledge, was incommunicable. Over and above that, he could not defend his experimental accuracy by appealing to brewers' craftsman skill. On the contrary it was more advantageous to distance himself from this particular gestural collective.

However, in order to convince the public Joule could also use his experimental privacy. His actual resources could remain secret. With the demonstration of the isolated version in Oxford he avoided a debate about his skill in keeping control over these 'radiation effects'. With respect to the participants it was more secure to argue with the isolated version. An influential and hostile listener, Sir John Herschel, was not given the chance to make his fundamental methodological attack. In a paper on the 'actinometer'[80] Herschel criticized every static measurement of heat radiation because it failed to take time into account. Joule's skill, his habit of taking measures, the constant use of these particularly sensitive thermometers and the speed of performing made him feel conscious of managing that problem. Therefore in private he continued experimentation in the old manner. He used a very thin copper vessel in order to minimize any isolating effect between water and air. He got his assistant to perform in 35 min and used the brewing cellar in order to reduce the radiation effect caused by the experimenters' bodies. He read off temperatures in the usual manner. As the reworking has shown, such a performance was only possible in that particular space. In order to make his local experimental work a transparent natural phenomenon and make himself the authority, Joule had to invent convincing demonstration devices which made his 'individual fact' universal. A quantitative measure of the 'radiation effect' demonstrated advanced control over such disturbing effects and gave his determination of the 'mechanical equivalent of heat' more 'numerical accuracy'.

But accurate measurement was not regarded by all as the major precondition for demonstrating a natural phenomenon. Michael Faraday, for example, worked very hard to make an experiment transparent so that the techniques and the equipment appeared to contribute nothing to the outcome.[81] This gentlemanly behaviour of an early nineteenth-century researcher represented one experimental form of life. William Sturgeon, a contemporary electrician, represented an opposing form of life. 'His decision to make public the details of his experimental apparatus was designed to support his claim that the world was an electrical machine and that only those skilled in the workings of machinery could understand such a world'.[82]

[80]'The instrument itself is nothing more than a very large cylindrical thermometer bulb with a scale greatly enlarged, so as to render the smallest possible increase of temperature distinctly measurable.' Sir John F. W. Herschel, 'Explanation of the Principle and Construction of the Actinometer', *BAAS Report* (1833), pp. 379–381, on p. 379f.

[81]Gooding, ' "In Nature's School" ', *op. cit.*, note 6, pp. 105ff.

[82]Iwan Rhys Morus, 'Different Experimental Lives: Michael Faraday and William Sturgeon', *History of Science* **30** (1992), 1–28, p. 23.

Joule's early writings indicate a form of life very close to Sturgeon's. But he also orientated himself to Faraday's method of distinguishing between the private and the public space of knowledge production. Joule's particular experimental result, however, made his mechanical equivalent of heat appear to be a *constant of nature*.[83] Therefore, in his 1850 publication he had effaced all the immense labour which had gone into the performance of his experiment. In the 1850 paper he distinguishes himself from any of the gestural collectives which had become objects of the disciplining programme described above. The unreliable unskilled working class represented by the unknown brewing mate was not mentioned at all. The instrument maker Dancer, as a representative of the skilled working class, was given the status of a valuable servant. Only Joule himself remained, but now as the disembodied observer of nature who displayed herself. He distanced himself from any kind of sensuous perception other than those gestures of accuracy which demonstrated remote control of the object of research: reading off temperature scales from the best instruments by means of a 'practised eye'. This would fit the assumed manners of the reader of the *Philosophical Transactions* and was precisely the kind of science that Wigney had in mind when he wrote his dictionary and the quotation set as an epigraph to this section. Moreover William Whewell, who coined the word 'scientist' at this time, did help to promote this ideal of scientific practice in which sight and hearing were privileged above the other senses. 'The other senses have not any peculiar prerogatives, at least none which bear on the formation of science'.[84]

Yet not only the labour, but even the machine which was needed to perform the experiment, was not explained sufficiently well nor given in a complete picture. The only parts of the machinery which were sketched were very cleverly chosen. The shape of the suspension of the pulleys was probably taken from a standard textbook illustration of George Atwood's machine. Such an image would take the reader into the academic world of Cambridge University mechanics where no friction existed:[85] it would diminish the reader's doubts as to whether this source of friction could become a major error. This particular design, connected with long tables of numbers, made Joule appear as a master of precision measurement and his number as a constant of nature.

Despite his efforts in writing for acceptance, Joule constantly defended brewing traditions. After all his 1850 publication became a hybrid of the different collectives

[83]This neologism was used by Charles Babbage for his encyclopaedic project started in the 1830s, of collecting facts which could be expressed by numbers. Joule's number, the mechanical equivalent of heat, was a perfect example of such a constant. But its existence was not a common opinion in the natural philosophical community. Charles Babbage, *Smithsonian Institution Annual Report* (1856), pp. 289–302. For constants see also Ian Hacking, *The Taming of Chance* (Cambridge: Cambridge University Press, 1990).

[84]*Op. cit.*, note 60, vol. 1., p. 280.

[85]It seems Joule could have learnt of Atwood's machine through the Manchester Literary and Philosophical Society. Peter Ewart, 'On the Measure of Moving Force', *Memoirs and Proceedings of the Manchester Literary and Philosophical Society* **2** (1813), 105–228.

he participated in. His uses of the terms 'accuracy' and 'exactness' were still signs of this private craftsman consciousness. He presented himself as a self-conscious, experienced experimentalist whose reliability was not allowed to be doubted because he was the only experienced bearer of this knowledge. He did not even discuss possible errors in his temperature readings. Only once, when he had increased the sensitivity of his thermometers, did he explain why he had given very doubtful numbers to three decimal places. 'The scale being arbitrary, the indications of the thermometer had to be reduced in every instance, a circumstance which accounts for my having given the temperatures in the tables to three places of decimals'.[86] In his final publication he presented the following specimen of his extraordinary abilities in order to present himself as an accurate experimentalist: 'And since constant practice enabled me to read off with the naked eye 1/20 of a division, it followed that 1/200 of a degree Fahr. was an appreciable temperature'.[87]

With this statement Joule linked together an extraordinarily sensitive instrument of precision with his individual gestures of accuracy. It was a self-evident brewing practice that an 'approximation to a good practice',[88] would determine the result. Only his skill, not a foreign 'companion of the bench' could be the ultimate guideline of his practice. Therefore, using arbitrary scales in order to achieve greater sensitivity and variations in his calculated results did not provide him with a problem; on the contrary, it exemplified his excellence of workmanship. Moreover, his initial circumspection about graphical methods give further evidence that he was convinced that a constant practice of taking measures was superior in achieving a true value than the procedure of drawing a curve in which the 'eye often spontaneously detects the law'.[89] Joule's self-presentation in public had its origins in the experimental form of life described above. His gestural knowledge in reading temperatures was systematically built up through an everyday practice. This knowledge came to bear not only as a measuring technique but also as self-consciousness about this practice. The use of decimal tables was the complementary practice which gave confidence in keeping control through calculations. When he decided to create his own experimental space with its own values all these experiences were applied. But just as his brewers' economic interests had demanded control over crafts skill, he now experienced himself as a craftsman controlled by the scholars of natural philosophy.

[86]James P. Joule, 'On the Changes of Temperature produced by the Rarefraction and Condensation of Air', *The Scientific Papers*, *op. cit.*, note 1, p. 175.

[87]James Prescott Joule, 'On the Mechanical Equivalent of Heat', *op. cit.*, note 1, p. 303.

[88]This interpretation of 'Approximation' is given in the cyclopedia and it represented at that time quality in workmanship. The quality wasn't measured by an absolute standard but given through the skill of the individual. *Op. cit.*, note 20, pp. 68–70.

[89]*Op. cit.*, note 60, vol. 2, p. 551.

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