SCHOOL OF PHYSICS

FINAL YEAR PROJECT REPORT

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Declaration and Acknowledgements

Most of the work for this project was conducted independently by the group, with little outside help – within our group we split work up fairly and in a manner that played towards individual strengths. This report is a continuation of our literature reviews of November 2012, with much of our prior research being revisited.

Notable exceptions to this were: Tom Kennedy in the lab who was very helpful in sourcing a lot of project materials and was always available to discuss the merits of particular methods; Richard Exley and Adrian Crimp in the UoB Physics Mechanical Workshop very kindly made the plywood cuts for our box and Sam Wright, a fellow 3rd year physicist who generously took our instrument home with him to use with his hamster, Mitchell. Finally, there's all the staff at Bristol zoo who helped us along the way – specifically Dr. Christoph Schwitzer for his guidance on lemur habits and previous projects; Dr. Sue Dow for administrative issues and Sarah Hall and Simon Robinson from the keepers team, who met us every day so we could collect data and change batteries.

Abstract

The aim of this project was to obtain a non-intrusive and indirect measurement of the basal metabolic rate of the Grey mouse lemur (*Microcebus murinus*) using a custom built open system calorimetry respirometer. No value of basal metabolic rate for a lemur was obtained, however, investigation with a Djungarian hamster (*Phodopus sungorus*) yielded a basal metabolic rate of 22.4±2.8 kcal day^{-1}. This is close to the expected energy expenditure of this species and is evidence that the calorimetry respirometer produced is a viable method of measuring metabolic rate. The research was undertaken with a view to applying the calorimetry respirometer to other species of mammals and birds. The theoretical size limitations of the device were considered and several other species identified as potential candidates for investigation.

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1 Introduction

Working in conjunction with Bristol Zoological Gardens (BZG), the aim of this project was to build an instrument capable of measuring the basic energy expenditure of the grey mouse lemur (*Microcebus murinus*), a small nocturnal primate indigenous to Madagascar. BZG is heavily involved in the conservation of endangered species of lemur and the development of breeding programs, which are designed to create a self-sustaining captive population for study and possible future reintroduction projects. The knowledge gained from metabolic research at the university will allow zookeepers a much greater insight into the physiology and nutritional needs of the animals they house and, in turn, will also inform the conservation measures of lemurs in the wild.

The measurement device that that was commissioned was to be used both in the zoo and in the wild and so must be able to withstand the extremes in temperature and humidity expected in Madagascar. The device was to be portable and cost-effective but, most importantly, nonintrusive. The protection of wildlife is of paramount importance to BZG, which is why work was carried out in accordance with the zoo's mission statement:

> "*Bristol Zoo Gardens maintains and defends biodiversity through breeding endangered species, conserving threatened species and habitats, and promoting a wider understanding of the natural world.*"

2 Detailed Background

2.1 Basal Metabolic Rate

In theory, a metabolic rate can be calculated from a balance sheet of energy gain and loss, as detailed in formula 1[1]:

$$\textit{rate of energy intake} - \textit{rate of energy expenditure} = \textit{metabolic rate} \tag{1}$$

The *basal* metabolic rate (BMR) of an animal is the energy it requires just to maintain vital organs; it is the minimum cost of living[2]. The BMR of an animal is defined as the energy expenditure of a non-growing individual per unit time when at complete rest in a post absorptive state, which means that its digestive system is not active. The animal must be under no physiological or physical stress, as this can significantly raise its metabolism. The animal must also be in a thermoneutral zone, which is defined as a temperature range at which an animal's heat production is equal to heat loss to its surroundings[3].

There are many alternative metabolic indices, such as the field metabolic rate (FMR), which is the cost of free existence in the wild, and includes other energy penalties such as locomotion, thermoregulation, reproduction and tissue growth. Although FMR gives a more accurate picture of real world energy consumption, BMR is a widely used and important parameter as it allows for comparison across species and higher taxa[4].

2.2 Motivation and the Importance of BMR

Animals housed in European zoos are frequently overfed which can lead to obesity and its associated health problems, such as diabetes and coronary heart disease. The problem of overfeeding is particularly pronounced in lemurs due to their low BMR, which is often overlooked by gamekeepers[5]. Obesity in mammals can cause infertility or miscarriage[6] and this is a major concern in the conservation of endangered species; reduced reproductive efficiency due to overfeeding would be counterproductive to the vital conservation work carried out at zoos. Nutrition plans in zoos are to a large extent based on trial and error. Gamekeepers have no accurate method of knowing an animal's daily energy expenditure and it can take a period of time before the negative impact of overfeeding becomes apparent. Using a calorimeter avoids this lag time and provides a live value of BMR. It is also a useful tool for zoologists as drug dosages can be administered based on an animal's metabolic rate[7]. Dr. Schwitzer, Head of Research at BZG, has also expressed interest in using the device to conduct research into daily torpor, which is the regular period of decreased physiological activity (and thus metabolic rate), which lemurs undergo in order to conserve energy.

There is no product like this on the market. There are invasive (and expensive) methods of calorimetry available, but even if BZG was prepared to use these, they contravene Home Office regulations. This is an exciting project: if successful in creating a non-invasive measurement device, it will be the first of its kind.

2.3 History

The earliest and simplest measurement device was developed by Antoine Lavoisier and Pierre de Laplace and was built in the 1780s. It consisted of a well-insulated chamber surrounded by densely packed ice. The apparatus was completely sealed save for a modest air pipe, which allowed the occupant to breath. The animal was placed inside the chamber and heat (and therefore energy) lost by the subject was calculated from the mass of the collected water and the latent heat of melting ice[3]. In principle this method was simple, though in practice it was cumbersome and expensive[8].

Historically the BMR of an animal has been estimated using formulae based on allometric laws – that is to say, laws which relate the geometry of a creature to its physiology. The earliest equations proposing BMR as a function of body mass were devised by Max Rubner in 1883, who concluded that BMR scaled with mass to the power of two thirds. Rubner's derivation was underpinned by the theory that BMR is proportional to heat output, and thus surface area[9]. He made numerous assumptions, including that an animal is spherical, and his work fell under experimental scrutiny. Half a century later, in 1932, Max Kleiber empirically showed "*a closer relation of basal metabolism to the three quarter power of body weight than to the geometric surface of [an] animal*" – a relation that came to be known as Kleiber's law:

$$BMR = \alpha M^{\frac{3}{4}} \tag{2}$$

Kleiber found α, the constant of proportionality, to be an average of 70kcal $kg^{-\frac{3}{4}}$ day^{-1} for mammals[10]. This exponent was the most commonly accepted value of the scaling factor for the majority on the 20th century, but the validity of the Kleiber exponent has recently been under further scrutiny. The intercept and exponent are of course both approximations, with $\frac{3}{4}$ chosen as much for convenience as for accuracy, and have been shown to be (sometimes significantly) different depending on species[4]; The evidence varies so much that some experts have rejected both exponents[11]. Whether data supports a power of $\frac{2}{3}$ or $\frac{3}{4}$, there is certainly no unilateral agreement on the relation, and markedly less agreement on the explanations behind the relations. For this reason it is necessary to experimentally measure, rather than estimate, an individual's metabolic rate.

2.4 Methods of Measurement

2.4.1 Direct Calorimetry

Methods of measurement can broadly be split into two groups: direct and indirect calorimetry. Direct calorimetry involves measuring the total amount of heat produced by an animal and equating this to its energy usage. The method relies on Hess's law, which states that the total energy released in the breakdown of a fuel to a given set of end products is always the same, irrespective of the intermediate steps or pathways used. The corollary of this is that, when no physical activity is being carried out and no new molecules are being synthesized, the total chemical energy released by an animal in performing its metabolic functions ultimately appears as heat[1]. The earliest measurement via direct calorimetry was that of Lavoisier and Laplace discussed in section 2.3. The main problem with direct calorimetry is that it is invasive, as the animal does not enter and leave the chamber under its own free will; this necessitates capturing the animal, which will artificially raise its BMR due to the physiological stress of handling. Studies have shown that metabolism of some mammals is elevated by up to 65% for two hours after human contact, and measurements taken during this relaxation period will not be true indicators of BMR[12]. This necessitates the use of the indirect calorimetry discussed next.

2.4.2 Indirect Calorimetry

Indirect calorimetry is widely regarded as the gold standard method for measuring BMR[13]. It depends on the measurement of some parameter related to energy expenditure other than heat production.

Among the techniques of indirect calorimetry respirometry is one, by which measurements of the rate of oxygen consumption or the rate of carbon dioxide production are related to energy expenditure. In the process of aerobic respiration Animals inhale oxygen from the air in order to oxidize organic compounds, which in turn releases the chemical energy stored in the bonds[1][9].

$$\begin{aligned} C_6H_{12} + 6O_2 &\rightarrow 6CO_2 + 6H_2O \\ \Delta G^\circ &= -686 kcal.\, mol^{-1} \end{aligned} \tag{3}$$

The total amount of energy released in the oxidation of 1mol of glucose (shown above) is 686kcal, (Gibb's free energy). In cellular respiration, 420kcal is released as heat and the remaining 266kcal is transferred as chemical energy to the molecule ATP, to be used for other physiological functions[14].

Much of the difference in oxygen necessary to metabolise the three predominant food groups is counteracted by differing releases of energy from their oxidation. This means that the calorific value per litre of oxygen consumed only varies by around 10% between them: being 5 kcal l^{-1}, 4.8 kcal l^{-1} and 4.5 kcal l^{-1} for carbohydrates, fats and proteins respectively[15]. Schmidt-Nielsen states that it is "*customary to use an average value of 4.8kcal l^{-1} O2 as a measure of metabolic rate. The largest error resulting from the use of this mean figure would be 6%*" [15]. In practice, a balanced diet is likely to mean this error is smaller than the maximum and perhaps insignificant in the face of larger experimental uncertainties. Using the average value stated by Schmidt-Nielsen we arrive at the following equation describing the relationship between BMR (in kcal s^{-1}) and oxygen consumption:

$$BMR = \frac{\delta(VO_2)}{\delta t} \times 4.8 \quad (4)$$

The amount of energy released per litre of carbon dioxide produced varies more greatly than that of oxygen consumed. For instance, the difference between the conversion rates across three predominant food groups causes a maximum discrepancy of 34%[9] contrasted with 6% for oxygen consumption. This makes oxygen consumption a far more suitable method for measuring BMR.

Two specific types of respirometry exist: In closed system respirometry the animal is confined to a sealed chamber which is maintained at a constant pressure. A steady controlled supply of oxygen is entered into the system which is an indication of the oxygen consumption of the animal [16]. In contrast, in open system respirometry, gas is able to flow in and out of the chamber. The difference between inflow and outflow is a measure of oxygen consumption.

In their traditional forms both open and closed system respirometry offer the same disadvantages as associated with direct calorimetry, that is, to enclose an animal in an unfamiliar environment, which is likely to increase stress and remove the animal from basal conditions[12].

As a variation to the closed system respirometry technique, for small animals using nesting boxes, such as the Grey Mouse Lemur, the system can be built around a nesting box similar to that which the animal would normally use. Thus, the animal should enter of its own volition. Not only is this in keeping with the BZG research policy, but it also allows for a more accurate measurement of BMR by ensuring that the animal is under minimal stress and therefore is as close as possible to basal conditions.

2.5 Previous Work at the University of Bristol

This project is a continuation of similar work carried out by three previous groups at the University of Bristol. Most recently, progressions were made in 2011, by G. Cohen and J. Humphries[17][18]. The aim of their project was to develop an instrument capable of measuring the BMR of the Grey Mouse Lemur in the zoo and in their natural habitat of Western Madagascar. 2011 was the first year it was proposed that the device should be taken to Madagascar for use in the field; hence, notable developments were to be made in portability and durability.

Following the trend from previous work, an open system respirometry chamber was developed, which aims to mimic the nesting box used by Grey Mouse Lemurs at BZG. The instrument comprises of two boxes, the first of which houses all circuitry, a data storage device and an Amicus18 board with an inbuild PIC microcontroller, which is programmed to manage the functions of the instrument. Connected to this is the lemur nesting box. On both the inside and the outside of the nesting box is an EC410 electrochemical oxygen sensor. The sensors are used in combination to measure the oxygen consumption of animals within the box.

Cohen and Humphries experienced several issues, throughout building the instrument and testing it at BZG, which ultimately resulted in a lack of data: throughout the two days of testing the lemurs only entered the nesting box for short periods of time, after being encouraged by placing food within the box. Most likely, the lemurs never became familiar or comfortable enough with the device, owing to the lack of time for which it was inside their enclosure. Moreover, the nesting box built by Cohen and Humphries is a poorly-considered replica of those which are used by lemurs at the zoo; this may have been a factor in lemurs' reluctance to use the box.

Cohen and Humphries were unable to implement a portable storage device due to difficulties in programing the Ammicus18 board. The solution was to use an LCD screen connected to the instrument which outputted oxygen concentrations. This method required constant observation, thus rendering the instrument impractical for use in the field, something which Cohen expressed strongly in his report: "*Collecting data was extremely hard, this is because it is difficult to maintain focus on a screen so small for hours.*" [17]

A single light gate system was implemented to determine if the nesting box was occupied. Readings were taken for one hour after the light gate was triggered. This technique neglects to consider whether a lemur is entering or leaving the box, meaning data collection opportunities are lost, or conversely data is collected needlessly[17].

3 Experimental Design

3.1 Device Design

The instrument was designed with the project aims in mind, the overarching themes being those of durability, portability, accuracy and animal comfort/welfare. Within each of these areas, simplicity and cost efficacy were also considered in order to be able to make the device easy and cheap to reproduce or fix.

The basic idea for the design, which differs from previous works, was to have the box containing the electronics and instrumentation attached but completely separable from the nesting box – this was achieved by tightly bolting the two parts together. This would allow the instrument to be removed and then attached to another nest box so that a different species can be researched. Furthermore, for remote field work it would be possible take just the instrument and then attach a nest box in-situ, thus saving weight and space, which may be restricted when travelling. The design of the nest and instrumentation box is shown below in figure 3.1.

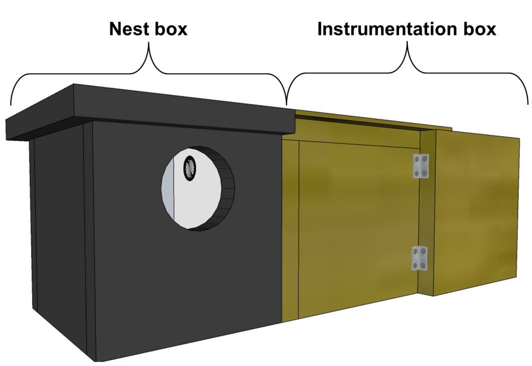


Figure 1: Basic design of the nest-instrumentation box.

For the instrument to be capable of measuring BMR it needed a pair of oxygen sensors – one measuring O_2 concentration outside the nesting box and one inside – and a small computing unit. Additionally, light gates at the nest box entrance provided presence detection and built in scales allow extensions of research to allometric scaling laws, which rely on knowing an animal's mass [9].

3.1.1 Nesting Box

The design of the nesting box was based very closely on one BZG uses with their lemurs, with all dimensions being as close as possible to the box that was already in use – this was to maximise the familiarity of a new box to the lemurs. Some instruments necessitated slightly different measurements, which are mentioned in sections 3.1.6 and 3.1.7. Each change was approved by Dr Schwitzer, who was capable of judging what, if any, impact the difference would make on the lemur's welfare and likelihood to use the next box.

The material used was plywood (the same material as the zoo's box); specifically it was water and boil proof (WBP) plywood, which is resilient to water – a necessity should it be taken to the tropical climes Madagascar. Finally, the whole box was painted black to match that of the zoo.

3.1.2 Instrumentation Box

As with the nest box, the box containing the electronics was also constructed of WBP plywood. It was designed to have the capacity to fit all the essential electronics plus a power supply, the size was made as compact as possible to ensure portability. The interior was then to have wooden dividers to keep components separate and prevent damage from excessive movement of parts within the box. Much of the design of the instrument box centred on it being made waterproof for use in the field, which is discussed in section 3.1.9.

3.1.3 The Arduino

The project aims lend themselves to a small, cheap microcontroller unit that can take inputs from several different sensors, perform calculations and logic and is able to store data. After research, it appeared that the product that best fitted these characteristics was an Arduino UNO, which has 20 I/O pins (digital and analogue), costs under £20 and has a wide variety of attachments that can be used for various functions including data storage.

The microcontroller chip on the Arduino UNO is an ATmega328, which has a flash memory of 32kb and, with its 20MHz operating frequency, can achieve nearly 20MIPS (million instructions per second) [19]. 32kb of memory was deemed to be appropriate to contain all of the project code, assuming it was efficient, while 20MIPS was definitely in excess of the speed needed to run this project.

3.1.4 Data Storage

Arduino electronics are designed so that they can be used with a wide variety of add-ons (called shields) produced both by Arduino and also by third party manufacturers. Among these there is the Arduino Ethernet Shield, which primarily allows the controller to communicate via an Ethernet cable; however, it is the secondary function of this shield, its SD card interface, that made it attractive for this project.

The Ethernet Shield has a micro-SD port built in to it, which allows data to be passed from the Arduino onto a micro-SD card, which is a high-density storage medium. As mentioned in section 2.5, in previous years, remote storage has been an issue but by using the shield[17], what would otherwise be a hardware *and* software problem became a matter of just software: i.e. programming the Arduino to write to the SD card.

3.1.5 Oxygen Sensors

Previous iterations of this project have used the EC410 analogue electrochemical oxygen sensor but have consistently had problems with calibration. This particular sensor also needs an accompanying amplifying circuit, further complicating matters. The problems with the EC410 galvanised a search for a better sensor, which was found in the form of a LuminOx Oxygen Sensor, which is cheaper, has better resolution, a longer expected lifetime and contains no hazardous materials. These advantages were in addition to the LuminOx sensor's digital communication abilities and pre-calibration by the manufacturer[20]. Additionally, the sensor has the ability to measure atmospheric pressure and temperature, which is an advantage to calculate the diffusion constant of air were to maximum precision.

LuminOx works on a completely different principle to most other oxygen sensors: being based on the principle of fluorescence quenching by oxygen. While the exact technology behind the sensor is proprietary, a high level view of the process is as follows[21]:

1. An LED is pulsed into a fluorescent material, which excites it.
2. The excited matrix fluoresces at a different wavelength to the LED, with the intensity of fluorescence detected with an optical sensor.
3. If, instead of returning to a non-excited state by emitting a photon, an excited molecule encounters an oxygen molecule its energy can be transferred non-radiatively to the oxygen thus preventing (quenching) fluorescence.
4. The amount the material fluoresces is inversely proportional to the probability of an excited molecule encountering an O2 molecule. This is directly proportional to the concentration of oxygen in the fluorescent complex, which is itself directly proportional to (and in dynamic equilibrium with) the concentration of oxygen in the atmosphere.

Two LuminOx sensors were used in OSCaR – one was fed from the instrument box into the nest box to measure interior oxygen concentration while the other was placed through the floor of the instrument box to measure exterior concentration for comparison.

3.1.6 Light Gates

Grey mouse lemurs, especially the females, tend to nest in groups; this means that there could be several animals in one nest box at a time. Consequently, a way of counting the number of lemurs in the box was necessary so a BMR for each animal could be calculated; this had the additional advantage of being able to tell when the nest box was unoccupied, thus meaning that recordings would only be taken when an animal was present and also allowing a power saving mode to be entered in the meantime.

In this project, a pair of light gates were set into false panels at the front of the nest box entrance but were placed with at different depths within the entrance hole (these panels necessitated increasing the depth of the nest box entrance hole). This allowed the direction in which the animal moved through the hole to be ascertained depending on what order the two gates were triggered; intermediate stages, such as if an animal entered the entrance hole but turned back could also be discerned, further reducing any errors in animal count.

Each light gate was made up of an infrared LED directly opposite a Schmitt Trigger, which is an optical sensor that reads a binary state depending on the flux of the infrared light falling on it – a high voltage at high flux and vice versa; this means any blocking, even slight, of the LED by an animal sets off the trigger. The gates were positioned in a cross shape to prevent any 'blind spots' in the entrance that the animals could inadvertently slip through and said cross was orientated such that no sensor or LED was positioned directly at the bottom of the entrance where it could easily become blocked by debris.

3.1.7 Scales

Finding a set of commercial scales that was small enough to fit into the base of the nest box and then integrating them in with the Arduino electronics was deemed to be unnecessarily complex, instead it was decided to extract essential parts from commercially available scales and assemble a new set - though this still necessitated an increase in the height of the nest box to comfortably accomodate the mechanism.

The specific part needed was a load cell, which can be found in most kitchen scales. A load cell is essentially a Wheatstone bridge made up of strain gauges, which are fixed to a flexible metal bar; two strain gauges are fixed to the top of the bar and two to the bottom. When it is fixed at one end and a load is applied at the other, the bar bends slightly – this changes the resistance of the strain gauges depending on their position and creates a voltage across the Wheatstone bridge that varies linearly with load applied.

The voltage that occurred across the bridge was on the order of microvolts, which is too small for the Arduino to directly resolve. Consequently the signal needed to be amplified by a custom circuit: this consisted of an INA125P amplifier through which the output voltage of the Wheatstone bridge was run. The amplifying circuit – which is shown in the full circuit diagram in appendix I – then outputted a single voltage to Arduino with reference to ground. The gain of the amplifier could be adjusted depending on the gain resistance applied across it: a 10Ω resistor was added in this case, giving a gain of approximately 6000 and amplifying the voltage into the range of volts.

This output then needed to be calibrated to correspond to a mass placed on the scales, which is explained in section 3.4.1.

3.1.8 Power Source

The Arduino computer requires a power source of between 6V and 15V, which it then regulates down to 5V to run its own systems and also power any attached sensors. Initially this was provided by two 9V PP9 batteries, which have a high energy density (5000mAh each) but are only single use, making powering the device for long periods of time expensive. This meant that the majority of experimentation was carried out using 6V lead-acid batteries, which have a slightly lower energy density but are easily rechargeable – the major disadvantage of these batteries was that a capacity of only 4000mAh could fit into the battery compartment of OSCaR, which was designed with PP9s in mind. Also, while lead-acid batteries are technically suitable for air travel, complications can easily arise – refer to appendix V for more details.

3.1.9 Waterproofing

In order to be used in the field, the delicate electronics had to be waterproofed to prevent failure. The main challenge in this case was keeping everything sealed, while still running electronics between the two separable parts of the equipment. This was achieved by attaching rubber washers around any opening in the instrumentation box – these would then form a good seal when the instrumentation and nest boxes were bolted tightly together. The nest box oxygen sensor was also contained within a small piece of pipe protruding from the side of the instrumentation box to add further protection.

The design of the instrument box itself was planned so as to give minimal skywards facing joins, where water may seep through. To add further waterproofing to the joins they were sealed on the inside of the box with silicone sealant. This is also how the light gate LEDs and sensors were secured and waterproofed. The door to the box had rubber seals attached and was fastened with compression clips to give a secure seal.

The wood of the instrumentation box also needed protection from the long term effects of rain, such as warping, delamination and boils, which could affect the structural integrity and water-tightness of the container. This was achieved by coating the wooden panels of the box with epoxy resin, giving a plastic-like finish to the wood that was both tough and waterproof.

3.1.10 Animal Proofing

Several animal proofing measures were taken in building the instrument - for the safety of the animals and the longevity of the equipment. These were as follows:

- The oxygen sensors were covered in wire mesh to prevent animals being able to come into contact with them.
- The instrument box had clips attached to its door to prevent access to electronics.
- All light gate wiring was built into false panels at the front of the nest box.
- All wiring related to scales was run through the false floor of the nest box.
- As previously mentioned, all circuitry was well waterproofed to prevent electrical dangers to animals.

3.2 Code

The Arduino was coded in a language very similar to C. The code comprises of a set of switch functions, able to determine the direction of movement through the LED gate setup for the first animal to enter. After an animal is detected, a loop is entered in which oxygen percentage and temperature readings are taken every 10 seconds. An important feature of the code is that the loop is comprised of tens of thousands of tiny time delays, rather than one large one per reading interval, which allows for the constant monitoring of the LED gate system, so the system will always be able to detect an animal leaving, or a second entering. In these events the system averages all the data, calculates the BMR in kcal day^{-1}, and prints all the relevant data to the storage device. If the animal is the last to leave, the scales' zero-value intercept is recalibrated to take into account any nesting material added to the nest box and the device is returned to its original, more inactive state. A copy of the annotated code can be found in appendix II.

3.3 Calculating BMR

3.3.1 Fick's Law

Fick's first law is as follows[22]:

$$J = -D\frac{\partial c}{\partial x} \tag{5}$$

where J is the flux in units of mol m^{-2}s^{-1}, D is the diffusion coefficient in units of m^{-2}s^{-1} and $\frac{\partial c}{\partial x}$ is the concentration gradient in units of mol m^{-2}. This equation describes the steady state flow of a substance in one dimension. Steady state implies that for any quantity of the system in question, the partial derivative with respect to time is zero.

If it assumed that the flow of oxygen, associated with a lemur inside the calorimetry chamber, has reached steady state, i.e. the concentration at any point from just outside to well within the nesting box is unchanging in time, then equation 5 can be used to estimate the flow of oxygen into the nesting box.

By assuming that the oxygen concentration varies linearly across the entrance to the nesting box, $\frac{\partial c}{\partial x}$ is given by the formula:

$$\frac{\partial c}{\partial x} = \frac{C_2 - C_1}{X} \tag{6}$$

Where C_1 and C_2 are the oxygen concentrations in moles m^{-3} outside and inside of the nesting box respectively and X is the length of the nesting box entrance in metres.

3.3.2 Diffusion Coefficient

Experimental data shows that the diffusion coefficient, as an approximation, varies linearly with temperature from $(17.9\pm0.895) \times 10^{-6}$m^{2}s^{-1} at 0°C to $(22.7\pm1.135) \times 10^{-6}$m^{2}s^{-1} at 40 °C[23], giving the following relationship between D and T:

$$D = 1.2 \times 10^{-7} \times T - 1.488 \times 10^{-6} \tag{7}$$

Where T is in degrees Kelvin. There is an error associated with the two values in 7, however these are insignificant in comparison to the values themselves. The diffusion coefficient also has a dependence on pressure; however, over the altitude range at which this device will be used, the pressure dependence can be neglected.

3.3.3 Derivation of Final Equation

As outlined in section 2.4.2, an estimation for the BMR can be made via equation 4. This forms the basis of the calculation used in this project. Assuming the system has reached steady state, the amount of oxygen consumed per second in 4 is given by:

$$O_2\ consumption = JA \tag{8}$$

Where J is the flux in mol m^{-3}s^{-1} and A is the area of the entrance to the nesting box in m^2. The flux is calculated using Fick's law as described in section 3.3.1. A few subtleties in the formula for J arise due to unit conversions: $\frac{\partial c}{\partial x}$ should be in units of mol m^{-2}, however oxygen concentration provided by the LuminOx sensor is as a percentage, hence, the following adaption of Fick's law is used:

$$J = \left(\frac{C_2 - C_1}{100X} \right) \frac{P}{RT} D \tag{9}$$

Where C_1 and C_2 are oxygen concentrations, in parts per hundred, outside and inside of the nesting box respectively, P is the pressure in Pa, R is the gas constant in JK^{-1}mol^{-1} and T is the temperature in K. The factor of 100 in the denominator converts the oxygen concentrations to fractions and the quantity is the number of moles per m^3 of air from the ideal gas law. By substituting for J into equation 6, the oxygen consumption in mol s^{-1} can be found.

In order to use the newly found oxygen consumption in equation 4, it must first be converted into units of litre per second, this is performed as follows:

$$\begin{aligned} O_2\ Consumption\ (l\ s^{-1}) &= 1000 \frac{RT}{P} \\ &\times\ O_2\ Cons.\ (mol\ s^{-1}) \quad (10) \\ &= 10 \left(\frac{C_2 - C_1}{X} \right) AD \end{aligned}$$

The quantity $\frac{RT}{P}$ converts moles into m^3 and 1000 is the conversion factor for m^3 into litres.

Substitution of oxygen consumption into equation 4 gives the final equation for BMR as used in this project:

$$BMR\ (kcal\ s^{-1}) = 48 \left(\frac{C_2 - C_1}{X} \right) AD \tag{11}$$

3.4 Calibration and Design Testing

3.4.1 Scale Calibration

Once the scales were installed in the base of the nest box, they needed calibrating against a set of test masses. This was done by connecting the scales and accompanying amplifying circuit to the Arduino and creating a graph of voltage against mass, from which an equation linking the two could be found. This graph is shown in figure 2 below:

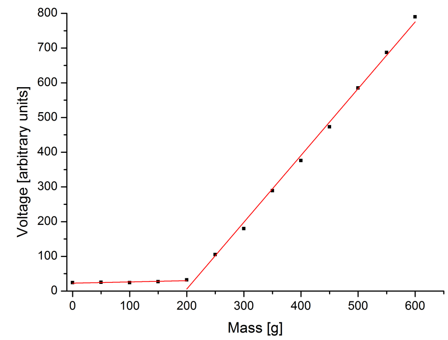


Figure 2: Initial calibration graph for the load cell, showing the measured voltage for a given mass. Voltage on the Arduino is measured in arbitrary increments of 205V^{-1}.

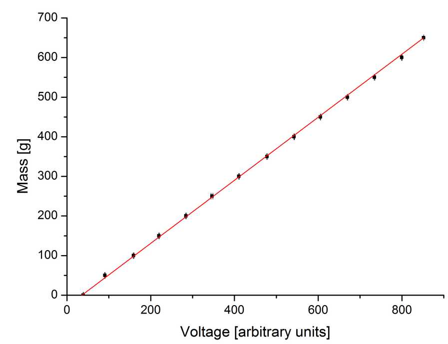


Figure 3: Calibration graph for the load cell, showing mass vs. voltage - the gradient of the line of best fit is 0.785±0.011 and the intercept is -24.51±0.35. Error bars are present but too small to be seen.

It can be seen in figure 2 that there is a prominent kink in the data set of mass versus voltage – the voltage goes up very slowly, staying almost constant until about 200g at which point the gradient becomes much steeper. The reason for this is hard to consider but suggests there are two flexing regimes in the scale mechanism. This is probably due to the wood and plastic support underneath the load cell, which may flex before the load cell does. This discontinuity in the graph gradient complicated matters and reduced the resolution of the scales at low masses; it was therefore decided to load the scales with enough weight to reach the point at which the gradient steepens. This was achieved by attaching approximately 200g in mass to the underside of the weighing platform. With this extra mass attached, the calibration was carried out again, giving figure 3. The equation of the line of best fit of figure 3 ($mass = 0.785V - 24.51$) was then used in the Arduino code to convert the measured voltage to a mass of the animal.

As well as the kink in the calibration graph, another interesting property of the scale system was that the values it gave fluctuated, not randomly, but in the fashion of a damped harmonic oscillator – an example of this is shown in figure 4:

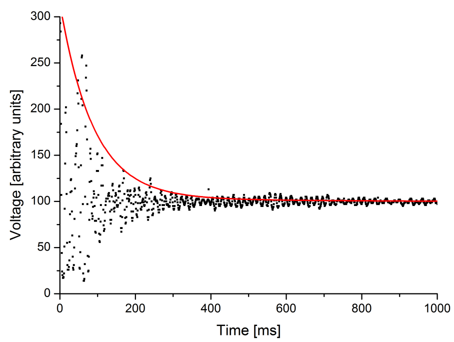


Figure 4: The oscillation of the load cell voltage reading with time after the addition of a 50g weight, showing the exponential decay in oscillation amplitude. The time constant in this case is approximately 100ms but is likely to be proportional to the applied mass, as is the case with harmonic oscillators.

This is a well-known artefact of load cells, known as 'ringing'[24], which is due to the physical vibration of the metal bar that makes up the cell. With harmonic oscillation the equilibrium point of the fluctuations is the true value for the given mass; so averaging over a significant period of time smooths out the variation and gives an accurate value, which was done in the section of code responsible for measuring mass.

3.4.2 Testing Waterproofing

As a crude measure of the durability of the control box, a small qualitative experiment was carried out – a sample piece of wood was coated in epoxy resin (as the equipment box was to be) and submerged in a beaker of warm water along with a control piece that had no resin on it. The reasoning was that being submerged constantly in water for long periods of time would accelerate any weathering that may occur in the field, particularly in warm, wet Madagascar, and thus show us the efficacy of the epoxy resin in protecting the wood and therefore the electronic equipment from the elements. The expected result was that the control piece would swell and warp much faster than the coated piece.

After several days submerged it was realised that this was not true weathering, as generally the wood will be only periodically wetted followed by dry periods – which may in fact put greater stresses on the wood and cause it to deform more. Therefore the experiment was changed to recreate such conditions; the wood was left to soak during the working day (approximately 8 hours) and then taken out to dry overnight. This gave a rough ratio of dry time to wet time of 2:1.

Once the control box was built, the overall design was also tested for weatherproofing. This test consisted of a prolonged submersion (approximately 30 minutes) of the box in a tank of water, followed by measuring how much water had managed to seep in.

3.4.3 Power Source Testing

To get an idea of how long a particular battery would run the device for, its power consumption was measured. This was a simple measure of the current being drawn from the battery using a multimeter. This current was then easy to change into a time – this is because battery capacity is measured in milliamp-hours (mAh) and the current drawn is on the order of milliamps, therefore:

$$Battery\ Life = \frac{Battery\ Capacity}{Current\ Drawn} \qquad (12)$$

This knowledge was important for knowing how often battery packs needed changing in order to maximise data-collection time.

4 Experimental Method

4.1 Testing with a Domestic Hamster

To test the system with a live subject, a domesticated Djungarian hamster (*Phodopus sungorus*) was used. The reason for using a domesticated hamster is that they are handleable, and much faster to accept changes to their smaller enclosures, while being of a similar size to a mouse lemur. The device was placed into the hamster's cage, with all other distractions and sleeping compartments were removed. The OSCaR was then powered on and left for a period of 48 hours, taking readings every ten seconds after detection of animal entry. The hamster was then left to freely enter and exit the device at will, so that the animal was not under stress when measurements were taken.

4.2 Bristol Zoological Gardens

The OSCaR was left in the Lemur enclosure in Twilight world at BZG for 4 weeks, as a stand-alone system where batteries were changed, and data collected, every 48 hours when PP9 batteries were used, and every 24 hours when the rechargeable lead acid batteries were used.

4.3 Size Limitations

The technique conceived through this on-going project has the potential to be implemented on numerous species besides the Grey Mouse Lemur. As an extension to the design of the OSCaR, the scope of the technique was examined with respect to size of the animal.

To model the respiratory rate of an animal, the oxidation of paraffin wax by combustion was used. This reaction both consumes oxygen at a given rate, as well as exuding heat, much the same as a warm blooded mammal of the type under investigation. Using this model it is possible to test the theory and equipment without using live animals in the laboratory.

Firstly, an effective BMR was calculated for a single 10g paraffin wax burner - that is, the value obtained from equation 11 from a single paraffin wax burner inside the OSCaR. This is so that a comparison between a particular animal and a certain number of paraffin wax burners can be made. Three 10g paraffin wax burners were measured and an average value was used.

To simulate animals with different sizes, cardboard boxes of varying volume (V), entrance hole area (A), and entrance hole length (L) were used in replacement of the OSCaR nesting box. Varying numbers of paraffin wax burners (N) were placed inside the boxes, to simulate animals of varying respiratory rates.

For 14 different combinations of box dimensions and number of burners, 5 plots of oxygen concentration vs. time were made. The plots were studied to assess the feasibility of using the technique on animals with similar oxygen consumption and similar nest box dimensions. The dimensions of the boxes and the number of paraffin wax burners used in each box are shown in appendix VII.

5 Results

5.1 Waterproofing Tests

5.1.1 Weathering Test

Figure 5: The epoxy treated wood shows little sign of degradation, while the non-treated control piece has become discoloured and has had pieces fall off around the edge upon handling after the experiment, suggesting fragility.

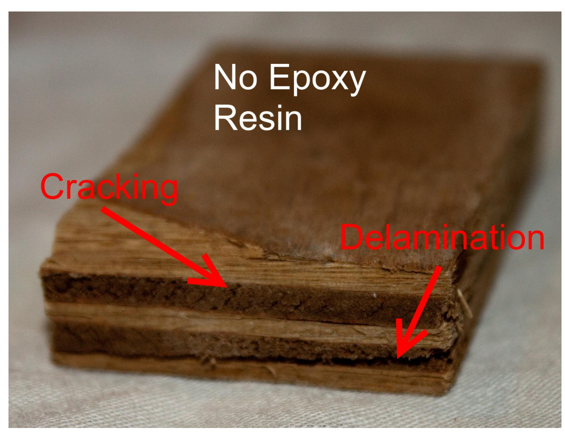


Figure 6: It is clear that cracks have appeared parallel to the grain lines in the original pieces of wood that make up the laminations. It should also be noted that delamination of the layers in beginning to occur.

The accelerated weathering of the differently treated wood types yielded significantly different results after 2 weeks of wet-dry cycling. Figure 5 shows a side-by-side comparison of the two pieces. Other issues become apparent with the control sample when viewed along the laminations, as seen in figure 6.

Comparatively, neither of the effects in figure 6 can be seen in the wood that was coated with epoxy resin, shown in figure 7:

Figure 7: The epoxy coating appears to have kept water out of the wood, leaving it in a better condition after weathering.

5.1.2 Dunk Tests

The dunk test of the control box was carried out twice. The first test yielded approximately 6mm of water in the bottom of the box after 30 minutes, which equates to approximately 135ml and a flow rate of 0.075ml s^{-1}.

It was thought that this leakage was most likely coming in through the corner seals of the door, which were subsequently improved and the box re-tested. This test yielded less than 1mm of water after 30 minutes.

5.2 Battery Life Testing

Using a multimeter to measure the current from the power source to the Arduino suggests that the whole system draws between 270 and 300mAh – the higher the voltage of the battery, the higher the current. This is most likely due to the power loss from the regulation of voltage to 5V, which increases with voltage above 5V.

Taking a conservative estimate, this current yields a battery lifetime of 3.3 hours per 1000mAh – therefore a 10000mAh pair of PP9 batteries would last approximately 33 hours while the 4000mAh lead-acid batteries used would give about 13 hours of operation.

The measured current draw tallies very well with the theoretical estimation obtained by adding up the specified power consumption of all the system components, which came to 298.5mA. A full table of these results is shown in appendix VI.

5.3 Hamster BMR Investigation

The hamster test subject used the device readily and became comfortable in the device for the duration of the test period, entering and exiting the device at will, and crucially spending a reasonable amount of time in the device.

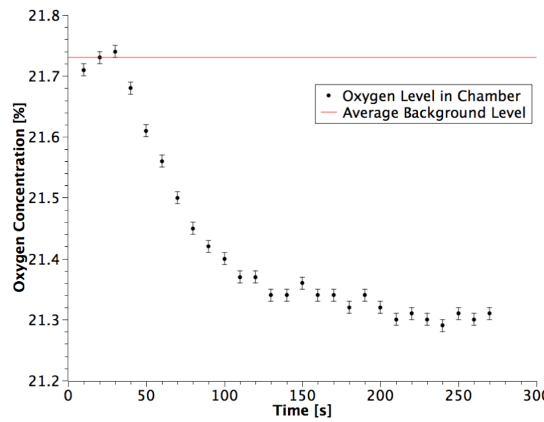


Figure 8: Oxygen level vs. time for hamster. Error bars from sensor resolution.

The variation of oxygen in the device from the respiration of the hamster is as expected. The drop to steady state can be seen in figure 8, occurring after only about 190 seconds. BMR calculations that were made after this 190 seconds using the methods shown in sections 3.2 and 3.3.3, and gave the BMR of this hamster to be 22.4±2.8 kcal day^{-1}.

5.4 Results from Bristol Zoological Gardens

Originally the device directly replaced the nesting box already in the enclosure, secured to a section of tree branch. Unfortunately the branch itself was unable to safely support the weight of the device, leading to the immediate removal of the device from the branch after two days for the safety of the animals. The device was then placed on supports on a shelf at the back of the enclosure where the lemurs are fed. In the period of these four weeks, the mouse lemurs in the enclosure were only logged as in the box by the system for a total of around 6 minutes. Most records of the animals entering the OSCaR were visits of under 20 seconds each and most occured in the first two days, while it was still secured to the branch. As a result of this, there was insufficient data for calculation of BMR for the grey mouse lemur.

5.5 Size Limitations

5.5.1 Paraffin Wax Burner - Effective BMR

The effective BMR of a single 10g paraffin wax burner was found to be 13±1.5 kcal day^{-1}. The error was calculated using the standard error in the mean.

5.5.2 Oxygen Concentrations in Varying Box Dimensions and Varying Oxygen Consumption

Figures 9-14 show examples of the plots made for certain box-burner combinations. T1 represents the time at which the animal enters the box and T2 represents the time at which steady state is reached. The steady state waiting period (T) is given by T2-T1. For each box-burner combination, T is averaged over the 5 plots. The full results are displayed in appendix VII.

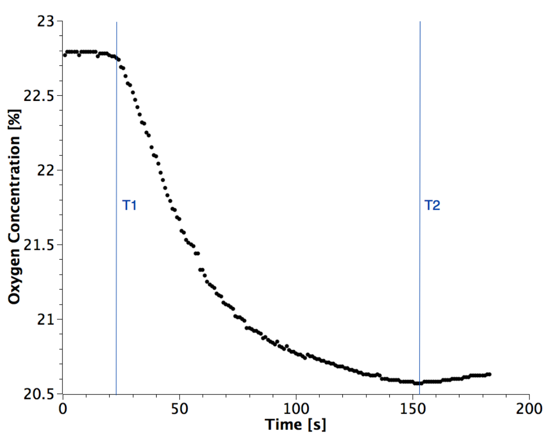


Figure 9: Plot of oxygen concentration vs. time for box 6 (dimensions: V = 0.00670m^3; A=0.001963m^2; L=0.04m and N=3), which gives T = 131s.

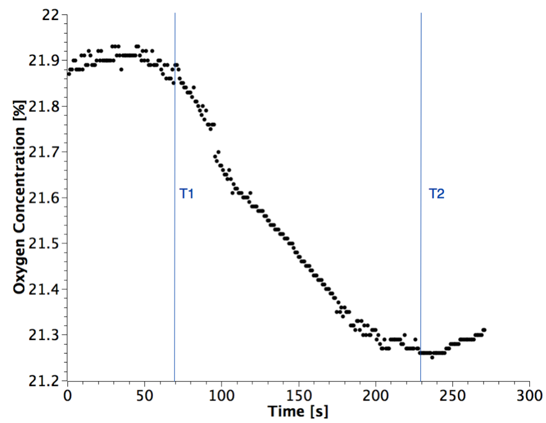


Figure 10: Plot of oxygen concentration vs. time for box 8 (dimensions: V = 0.0353m^3; A=0.001963m^2; L=0.04m and N=3), which gives T = 210s.

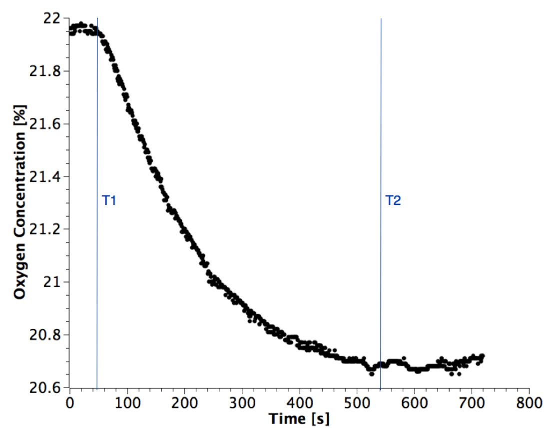


Figure 11: Plot of oxygen concentration vs. time for box 9 (dimensions: V = 0.0734m^3; A=0.001963m^2; L=0.017m and N=3), which gives T = 496s.

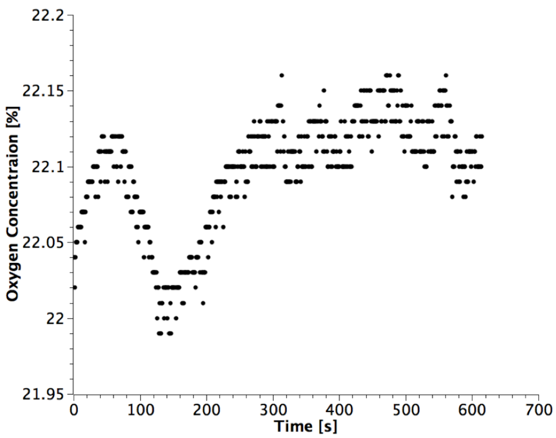


Figure 12: Plot of oxygen concentration vs. time for box 11 (dimensions: V = 0.0734m^3; A=0.0177m^2; L=0.017m and N=3), which gives T = N/A.

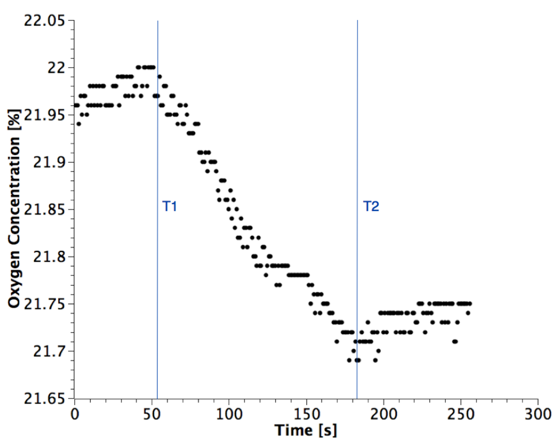


Figure 13: Plot of oxygen concentration vs. time for box 12 (dimensions: V = 0.0734m^3; A=0.0177m^2; L=0.017m and N=7), which gives T = 128s.

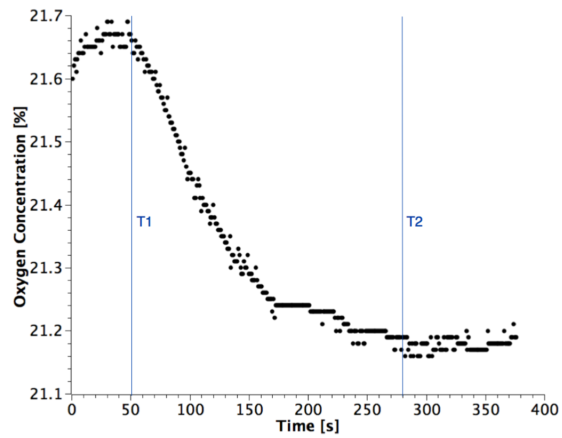


Figure 14: Plot of oxygen concentration vs time for box 14 (dimensions: V = 0.0734m^3; A=0.0177m^2; L=0.15m and N=7), which gives T = 230s.

6 Discussion

6.1 Field Suitability

6.1.1 Weatherproofing

Keeping the electronics safe against the elements appears to have been a success in lab tests. The technique of preserving wood with epoxy makes a significant difference to the rate at which it deteriorates and the general waterproofing of the whole control box was achieved too. The first dunk test suggested there was still a little work to do but after improvements to the door seals, the small amount of leakage in the second dunk test (0.01ml s^{-1}) suggests the control box is well sealed. It is also worth noting that these tests subjected the equipment to conditions far more severe than would be expected in the field; under normal precipitation it is very unlikely that any leakage at all would occur.

6.1.2 Power Supply

The longest lasting power supply available was a pair of 9V PP9s, which could power the system for around 33 hours – this was good, but fell far short of the 72+ hour lifetime that was hoped for. This was for a variety of reasons, the first being the power consumption of the Ethernet shield, which can be seen in appendix VI as being more than all of the other components combined. There are alternatives available though: at the time of purchasing the Arduino and Ethernet shield, there was a relative ignorance of the device's capabilities and the abundance of additional components – this meant the decision to purchase the

Ethernet shield was rushed as it was an Arduino produced add-on with the necessary functions.

Were it known that there were other shields available from third party manufacturers that were solely SD card interfaces without the energy wasting Ethernet chip, one of these would have been chosen – furthermore, just after purchase, Arduino released a new version of their wireless shield with an SD interface; this too would have been perfect as this particular shield did not come with a wireless chip and antenna as standard (it had to be purchased separately) so was essentially a bare-bones SD card reader/writer – a device like this could approximately halve power draw to 150mAh. A separate advantage of one of the third party options is that they use normal sized SD cards, which are much cheaper than their micro-SD counterparts.

The other reason for short battery life was that at the time of finalising cuts for the instrumentation box, a combination of a lower expected power usage and unrealistic expectations about battery technology (in terms of energy density) led to too little space being allocated for batteries. If the control box were made approximately 50mm longer, it would give space for a 15Ah lead-acid battery, which, when combined with power saving measures outlined above could give a running time of 100 hours (approximately 4 days).

6.1.3 Solar Panel Investigation

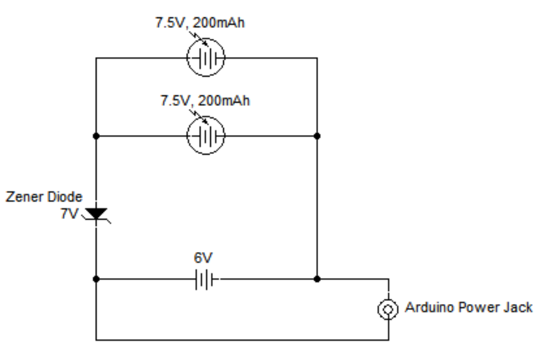


Figure 15: An example circuit for solar charging the instrument batteries. The Zener diode prevents the batteries discharging over the cells at night and also helps prevent overcharging by allowing charge flow to reverse if the battery voltage becomes too high.

The estimated battery life, even with a larger battery and lower power consumption, was still not ideal, so it was decided to carry out an investigation as to practicalities and cost efficacy of adding solar cells to the instrument that could charge the battery when it was sunny. A typical circuit for this is shown in figure 15.

Such a set up could be created for around £60 (using Solarex 7.5V Solar Cells from RS Components) and would greatly extend the running time of the system. A small simulation was run using climate data from the west of Madagascar (a typical field location for the box) to calculate how long the device could last with a 15Ah battery and 300mA of solar cells. Depending on the time of year, this could extend battery life to be between 8 and 41 days, with 21 days (3 weeks) being the average, which should be adequate for most field studies. It is also likely that these estimates are conservative, as they were made using just sunshine hours, not considering the fact that solar cells will still generate some power even when it is cloudy.

6.2 Hamster BMR Investigation

The result of the measured BMR can be directly compared to a previous more in depth investigation of the BMR of the Djungarian hamster using flow through gas respirometry. The result from this method gave a BMR of 17.28 kcal day^{-1}[25]. This result is slightly lower than the observed result in the OSCaR of 22.4±2.8 kcal day^{-1}. However this is expected as the hamster subject was not in the device long enough to be truly at rest, and had not been isolated from food to neglect effects of digestion. These factors would have caused the actual metabolic rate of the hamster to have been raised from its BMR, which is represented in the results recorded.

The error value of ±2.8 kcal day^{-1} was calculated by combining the errors associated with each variable in equation 11. As mentioned in section 2.4.2, the error associated with using a value of 4.8 kcal l^{-1} is ±6%. The error in oxygen concentrations and temperature are assumed to be the resolution of the LuminOx oxygen sensor, ±0.01% and ±2 degrees respectively. The errors in the radius of the entrance hole and the entrance hole length are ±0.05mm. The error in the diffusion coefficient was calculated using regression analysis of the straight line given by equation 7.

The hamster test also proved the capability of the animal detection system with live animals, which worked flawlessly, but raised issues of power capability as potential data was forfeited due to the device loosing power earlier than expected in the 48 hour testing period.

6.3 Zoological Gardens

The main issue with recording data with the mouse lemurs in the zoo enclosure was neophobia. Animals in captivity are known to be more neophobic than wild animals, and this neophobia has been recorded in previous attempts to measure the BMR of these lemurs, although this device was left for a much longer time period than in these attempts[17][18]. The lemurs were much more inquisitive about the box whilst it was in the position that they are accustomed to using a standard nest box. However, after the original position became unsafe for the animals, and the device was moved to the feeding shelf, a part of the enclosure where they were not used to using a nesting box, they became far more reluctant to even investigate the device for brief periods of time. The keepers were asked to occasionally place food inside the box to entice the lemurs in, but it is clear from the collected data that the animals would simply retrieve this food and immediately exit the box.

Even after four weeks of the box being present, the lemurs were not noticeably using the box any more than when it was moved, and would have unfortunately needed significantly more time to become accustomed to the box in its position on the shelf than was available.

6.4 Size Limitations

6.4.1 Paraffin Wax Burner - Effective BMR

The effective BMR of a 10g paraffin wax burner does not represent the number of calories that are combusted by the burner, rather it suggests what the BMR of an animal, with the same rate of oxygen consumption, would be, as calculated by the OSCaR.

If Kleiber's law, as described in section 2.3, is assumed to be accurate, then using equation 2, we find that the effective BMR of the 10g paraffin wax burner (13 ± 1.5 kcal day^{-1}) is approximately equal to the BMR that would be calculated for an animal of mass 0.12kg. The mass of the Grey Mouse Lemur ranges from 58-67g[26]. This suggests that two mouse lemurs can well be modelled by a single paraffin wax burner.

6.4.2 Oxygen Concentrations in Varying Box Dimensions with Varying Oxygen Consumption

To use the technique developed in this project, the system must satisfy certain conditions. Firstly, it is required that the system reaches steady state before any measurements of oxygen concentrations can be used in the calculation of BMR. Therefore, it is necessary that T is relatively small in comparison to the time for which the nest box is occupied. By analysis of the table in appendix VII, it is seen that T is decreased by decreasing N, decreasing V, decreasing L and increasing A. While the time taken to reach steady state is an important factor in considering whether this technique may be applied to a certain species, within the range of these tests T remains within a practical value, so long as the species in question typically occupies their nesting box for periods longer than 10 minutes. T may become too large, however, for animals that use large nest boxes with small entrance holes or for very large animals.

Much more significant, is the consequence of background noise. The difference between oxygen concentrations inside and outside the box must be large with respect to the level of fluctuations. Ultimately, the technique developed through this project will become unsuitable for species where the level of BMR is low and the volume of the nesting box is comparatively large, as is modelled by box 11. Figure 12 shows that for this type of system, fluctuations in the oxygen concentrations are too great to establish steady state. Box 12 has the same dimensions as box 11 however, it contains 4 more burners. It can be seen from figure 13 that steady state is established in box 12 and the fluctuations are relatively small in comparison to the difference between oxygen concentrations inside and outside of the box. Box 12 contains 7 burners; this is representative of an animal with a BMR of approximately 91 kcal day^{-1}. This corresponds to a mass of 1.4kg, using equation 2. It is therefore concluded that, to use the technique developed in this project, 1.4kg is an approximate lower bound for the mass of an animal inside a box of volume approximately 0.1m^3. Animals of lower mass may be considered by lowering V, as demonstrated by the lower levels of noise observed in figure 9 compared with figure 10. Alternatively, animals of lower mass may be considered by lowering A, demonstrated by the lower levels of noise observed in figure 11 compared with figure 12, or by increasing L demonstrated by the lower levels of noise observed in figure 14 compared with figure 13.

6.5 Further Work

From the results of the investigation in section 6.1.3, it is clear to see that further research into solar powering the OSCaR would be a very useful extension.

In order to leave the OSCaR inside the lemur enclosure without attendance and for extended periods of time, it may prove useful to investigate powering the device from the mains. This can simply be achieved with a cheap, commercially available adapter, which plugs directly into the Arduino.

The investigation into size limitations suggests that the technique conceived through this project is applicable to many other species. It is proposed that further exploration into using this technique with other specific animals is a fitting extension to the project. It would be practical for use with small mammals of similar size to the Grey mouse lemur such as the Kangaroo rat and the Kowari. The technique may also be appropriate for use on many different species of birds, in particular the Inca Tern, the Lilacine Amazon parrot and the Red-Vented Cockatoo. The study also suggests that the technique may be practical for use with significantly larger mammals and birds, specifically the Red panda and the African Penguin.

6.6 Market Research

6.6.1 Motivation

The motivation behind building the calorimeter was as an *industrial* project, which prompted consideration of the commercial viability of the OSCaR. Once a working device was created a market research survey was conducted to find out whether the calorimeter would be a viable method of measuring BMR for researchers and gamekeepers at other zoological establishments across the UK. Other potential uses of the OSCaR were investigated to gain a better understanding of how useful the calorimeter may be in a wider context, in terms of animal husbandry and conservation.

Dr. Schwitzer outlined three distinct groups of specialists who may be interested in a calorimeter, the first of which being other zoological gestablishments. He advised, however, that there may not get a huge response from his colleagues; most zoos are conservative organizations and tend not to be overly receptive to new ideas. Dr. Schwitzer explained that a new product is often first showcased, following a paper being published, at an international zoology conference, but it can take over a decade and require endorsement from a respected member of the scientific community, such as him, before it will be integrated into zoos on any significant scale. In addition, BZG is a rare organisation in that they have very strong connections to both the University of Bristol and the University of the West of England and is particularly research led. Most zoos are not specifically interested in optimising the nutrition of the animals they house; unlike in livestock husbandry, there is no cost or quality benefit to tailoring nutrition plans as animals are primarily there for decoration. Nonetheless, there is a distinct group of zoos that specialize in nutrition and/or research that would be worth contacting.

Dr. Schwitzer also suggested targeting American universities; Zoos in the US tend to outsource nutrition plans to universities who have specialised animal nutrition departments. He noted that broadly speaking, European zoos feed animals a fresh diet that includes a wide variety of fruit and vegetables, whilst animals in American zoos are mainly fed in the form of pellets. It would be interesting to compare the BMR of captive lemurs raised on very different diets.

Finally, he suggested that feed manufacturers may have a use for the product. There are many nutrition problems that are specific to lemurs, such as obesity and iron storage disease, which are potentially fatal. Lemurs should not be fed the same diet as other primates and require a nutrition plan high in fibre, low in iron and with readily available carbohydrate. As a nutrition and lemur specialist, other zoos frequently ask Dr. Schwitzer what they should feed their captive lemurs and he imagines there would be a large market for a lemur-specific range of feed. He highlighted Mazuri, supplier to BZG, as a company who do not currently have a lemur-specific pellet available. They may be interested in using a calorimeter to develop a new range of feed.

6.6.2 Survey

Primarily this investigation involved an online survey sent to various establishments who we identified as potential users of such a device. The survey also aimed to find out if these establishments already had devices for measuring BMR, whether using open or closed calorimetry, and any issues they had with the device they had, and the expected cost of such a device. A subsequent set of questions included details questioning what the device may be used for and what species each establishment would have specific interest in.

6.6.3 Results

An encouraging 25% of establishments invited to partake in the survey responded. Zoological institutions with research departments were specifically targeted, of which 100% of the replies indicated that they would have use for such a device for various purposes for a range of species. The majority of species indications were for small nesting mammals and birds. Interestingly, two institutions expressed direct interest in measuring the metabolic rates of large cats (in dens) with such a technique.

None of the zoological institutions that responded already had a device capable of measuring the BMR of an animal, and many indicated that tight budgets may prevent the purchase of such a device. Most institutions expected such a device to cost thousands of pounds, but all indicated they would not buy such a device at this expected cost.

Only one academic institution responded and gave limited information about the closed system calorimeters they currently had in use. They also indicated that they would still be interested in an open system device.

While it is excellent that 100% of the replies indicated a use for the device, it is important to consider a bias where representatives of institutions not immediately interested in the idea as outlined in the letter sent to them may have not been willing to spare time from their busy schedules to fill in the survey at all, whereas representatives interested have taken the time to express this interest. The full set of questions and all responses have been included in the appendix VIII.

6.6.4 Conclusion

From the responses to this survey it can be assumed that their is an interest and a market for an open system metabolic calorimeter both in zoological and academic establishments. Cost would be the main issue, but this device is much cheaper to produce than most respondents would expect to pay, indicating that this device could be a viable option for many establishments, and therefore could be a marketable device.

7 Conclusion

The project was successful in creating a device capable of providing a non-intrusive and indirect measurement of the BMR of the Grey mouse lemur using an open system calorimetry respirometer. Unfortunately no value of BMR for a lemur was obtained, as the lemurs did not use the nest box for periods of time long enough to retrieve useful data. Investigation into the BMR of the Djungarian hamster yielded a result of 22.4 ± 2.8 kcal day^{-1}, which is close to the expected value for this species, and was evidence that the device is a viable method of measuring BMR.

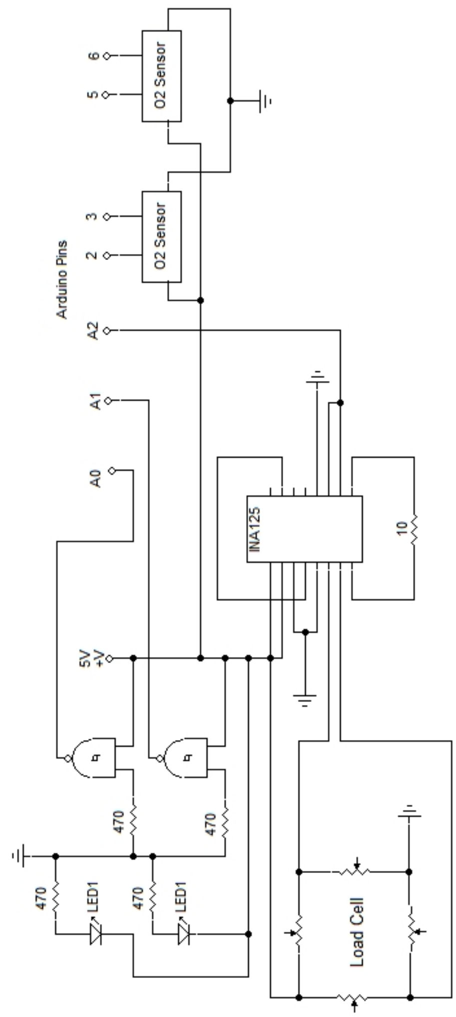
The project achieved the objectives outlined by BZG, which were that the calorimeter should be portable, inexpensive, able to withstand the extremes of temperature and humidity expected in Madagascar and, most importantly, be non-intrusive.

The theoretical size limitations of the device were considered and several other species were identified as potential candidates to which this method of open system calorimetry respirometry could be applied.

Appendices

Appendix I - Circuit Diagram

Circuit diagram showing the electronic layout of components that make the instrument.



Appendix II - Complete Arduino Code

```
#include <Arduino.h>
#include <SD.h>
#include <SoftwareSerial.h>

#define rxPininside 2
#define txPininside 3
#define rxPinoutside 5
#define txPinoutside 6

SoftwareSerial mySerialin(rxPininside, txPininside);
SoftwareSerial mySerialout(rxPinoutside, txPinoutside);

// The two values below MUST be individualised for a nest box
```

```
const double Area = 0.002206; //Area of entrance in metres squared
const double Length =0.036; //entrance length in metres

const double interval=10; //time interval between readings


long t;
int sensor0 = A0;
int sensor1 = A1;
int lemnum = 0,numnow=0, initial = 1, state = 1, i = 0;
int array[2];
const int chipSelect = 4;//chipSelect pin needed for interface with SD card
File dataFile;

double mass, masssum;
double interceptOffset=0;

double BMR,BMRsum,BMRnow,BMRday,D,avtemp;

double Percentage(),Temp();
double percentin,percentout,tempin,tempout;
int h,j,k,E,Run;
char c[8], c2[6], d[8], d2[6];

void setup() {
   Serial.begin(9600);
   pinMode(10, OUTPUT);
   Serial.println("Initializing SD card...");
   if (!SD.begin(chipSelect))
  {
      Serial.println("card failed, or not present");
      return;
  }
  Serial.println("card initialized");


  dataFile = SD.open("data.txt", FILE_WRITE);
  if (dataFile)
      {dataFile.println("Setup");
       Serial.println("Setup");
       dataFile.close(); }
       //if the file doesn't open, pop up an error
       else
       { Serial.println("error opening file.txt"); }
}


void loop() {

//start animal detection
t=0; k=0; BMRsum=0;

if (analogRead(sensor0)<600)//mouse lemur in entrance
  {
```

```
    array[0] = 1;
  }
else if (analogRead(sensor0)>=600)//no mouse lemur in entrance
  {
    array[0] = 0;
  }
if (analogRead(sensor1)<600) //mouse lemur in entrance
  {
    array[1] = 1;
  }
else if (analogRead(sensor1)>=600)//no mouse lemur in entrance
  {
    array[1] = 0;
  }

switch (state){
  case 1:
  if ((array[0] == 1) && (array[1] == 0))
  {
   state = 2;
  }
  else if ((array[0] == 0) && (array[1] == 1))
  {
   state = 5;
  }
  break;
  case 2:
  if ((array[0] == 0) && (array[1] == 0))
  {
   state = 1;
  }
  else if ((array[0] == 1) && (array[1] == 1))
  {
   state = 3;
  }
  break;
  case 3:
  if ((array[0] == 1) && (array[1] == 0))
  {
   state = 2;
  }
  else if ((array[0] == 0) && (array[1] == 1))
  {
   state = 4;
  }
  break;
  case 4:
  if ((array[0] == 1) && (array[1] == 1))
  {
   state = 3;
  }
  else if ((array[0] == 0) && (array[1] == 0))
  {
   lemnum+= 1;
```

```
    state = 1;
   }
   break;
   case 5:
   if ((array[0] == 0) && (array[1] == 0))
   {
    state = 1;
   }
   else if ((array[0] == 1) && (array[1] == 1))
   {
    state = 6;
   }
   break;
   case 6:
   if ((array[0] == 0) && (array[1] == 1))
   {
    state = 5;
   }
   else if ((array[0] == 1) && (array[1] == 0))
   {
    state = 7;
   }
   break;
   case 7:
   if ((array[0] == 1) && (array[1] == 1))
   {
    state = 6;
   }
   else if ((array[0] == 0) && (array[1] ==0))
   {
    lemnum-=1;
    state = 1;
   }
   break;
}
//end animal detection

numnow=lemnum;

while(lemnum == initial) // while animal present take data
{
   t+=1;
   //Serial.println(t);
   delay(1); //slows the time loop slightly (1 microsecond)
   if((t!=0)&& (t%6500==0)&&(t<13000)) //ignores values taken below equilibration time
   {
    Percentage();

    Serial.print("%O2 inside=");Serial.print(percentin);Serial.print(" %\t\t");
    Serial.print("%O2 outside="); Serial.print(percentout);Serial.println(" %");

    dataFile = SD.open("data.txt", FILE_WRITE);
    if (dataFile)
    {dataFile.print(percentin);
```

```
    dataFile.print("\t");
    dataFile.println(percentout);
    dataFile.close(); }
    //if the file doesn't open, pop up an error
    else
    { Serial.println("error opening file.txt"); }
}
else if((t>13000)&&(t%6500==0)) //main data reading sequence.
{
  Percentage();
  Temp();

  Serial.print("%O2 inside=");Serial.print(percentin);Serial.print(" %\t\t");
  Serial.print("%O2 outside="); Serial.print(percentout);Serial.println(" %");

  dataFile = SD.open("data.txt", FILE_WRITE);
  if (dataFile)
  {dataFile.print(percentin);
   dataFile.print("\t");
   dataFile.println(percentout);
   dataFile.close(); }
   //if the file doesn't open, pop up an error
  else
  { Serial.println("error opening file.txt"); }

  avtemp=((tempin+tempout)/2)+273.15;//convert to Kelvin
  D=(0.12*(avtemp)-14.878)*pow(10,-6);
  BMRnow=((percentout-percentin)/Length)*D*48.57*interval*Area;

  if((BMRnow >= 0)&&(percentin>5))
  {
   BMRsum+=BMRnow;
   Serial.println(BMRsum,10);

   masssum+=massFinder(interceptOffset);
   k+=1;
  }
  else if((percentin>5)&&(percentout>5))
  {
   masssum+=massFinder(interceptOffset);
   k+=1;
  }
  if(t==26000)
  {
   t=19500;
  }
}

//start monitor animal detection in this loop
if (analogRead(sensor0)<600) //mouse lemur in entrance
{
 array[0] = 1;
}
else if (analogRead(sensor0)>=600)//no mouse lemur in entrance
```

```
{
 array[0] = 0;
}
if (analogRead(sensor1)<600) //mouse lemur in entrance
{
 array[1] = 1;
}
else if (analogRead(sensor1)>=600)//no mouse lemur in entrance
{
 array[1] = 0;
}

switch (state){
  case 1:
  if ((array[0] == 1) && (array[1] == 0))
  {
   state = 2;
  }
  else if ((array[0] == 0) && (array[1] == 1))
  {
   state = 5;
  }
  break;
  case 2:
  if ((array[0] == 0) && (array[1] == 0))
  {
   state = 1;
  }
  else if ((array[0] == 1) && (array[1] == 1))
  {
   state = 3;
  }
  break;
  case 3:
  if ((array[0] == 1) && (array[1] == 0))
  {
   state = 2;
  }
  else if ((array[0] == 0) && (array[1] == 1))
  {
   state = 4;
  }
  break;
  case 4:
  if ((array[0] == 1) && (array[1] == 1))
  {
   state = 3;
  }
  else if ((array[0] == 0) && (array[1] == 0))
  {
   lemnum += 1;
   state = 1;
  }
  break;
```

```
  case 5:
  if ((array[0] == 0) && (array[1] == 0))
  {
   state = 1;
  }
  else if ((array[0] == 1) && (array[1] == 1))
  {
   state = 6;
  }
  break;
  case 6:
  if ((array[0] == 0) && (array[1] == 1))
  {
   state = 5;
  }
  else if ((array[0] == 1) && (array[1] == 0))
  {
   state = 7;
  }
  break;
  case 7:
  if ((array[0] == 1) && (array[1] == 1))
  {
   state = 6;
  }
  else if ((array[0] == 0) && (array[1] ==0))
  {
   lemnum -= 1;
   state = 1;
  }
  break;}
}
//end animal detection monitoring in this loop

if(lemnum != 0)
{
  initial = lemnum;
  Serial.println("lemnumchange");
  dataFile = SD.open("data.txt", FILE_WRITE);

  if (dataFile)
  {dataFile.print("lemnum change \t");
   dataFile.println(lemnum);
   dataFile.close(); }
   //if the file doesn't open, pop up an error
  else
  { Serial.println("error opening file.txt"); }


  Serial.println(lemnum);
}

if(lemnum==0)
{
```

```
    interceptOffset=analogRead(A2);    //variable to recalibrate the scale to zero when no
                                                                          //lemurs are presen
  }

  E=0;
  if(lemnum>=15) // counter error, happens when the line of sight
  // between LED and detector is on a slight angle
  {
    E=1;
    lemnum=0;
  }
  if(lemnum<0) // counter error, happens when the line of sight
  // between LED and detector is on a slight angle
  {
    E=2;
    lemnum=0;
  }
  if((t != 0) && (k!=0)) //calculates and prints BMR after last animal leaves
  {
    dataFile = SD.open("data.txt", FILE_WRITE);
    //if the file is available write to it
    if (dataFile)
    {
     Run+=1;
     BMR=(BMRsum/k)/numnow;
     BMRday=(86400/interval)*BMR;

     //print all data collected to SD
     Serial.print(Run); dataFile.print(Run);
     Serial.print("  Number of animals:  "); Serial.print(numnow);
     dataFile.print("  Number of animals:  "); dataFile.print(numnow);
     Serial.print(" BMR="); dataFile.print("\tBMR=");
     Serial.print(BMRday,10); dataFile.print(BMRday,10);
     Serial.print("\t with  " ); dataFile.print("\t with  " );
     Serial.print(k); dataFile.print(k);
     Serial.print(" readings taken"); dataFile.print("  readings taken");
     mass=(masssum/k)/numnow;
     Serial.print("\tmass="); Serial.print(mass);
     dataFile.print("\tmass="); dataFile.print(mass);
     Temp();
     Serial.print("\tT="); Serial.print(tempout);
     dataFile.print("\tT="); dataFile.print(tempout);

     if(E==0)
     {Serial.println();dataFile.println();}
     else if(E==1)
     {Serial.println("\tError 1: Animal counter error");
     dataFile.println("\tError 1: Animal counter error");}
     else if(E==2)
     {Serial.println("\tError 2: Negative animal count");
      dataFile.println("\tError 2: Negative animal count");}

     dataFile.close();
```

```
    numnow=lemnum;
    }
    //if the file doesn't open, pop up an error
    else
    {
     Serial.println("error opening lemur.txt");
    }
    }

}


double Percentage() //Here begins the list of functions for various data capture
{
  h=0; j=0;
  mySerialin.begin(9600);
  mySerialin.write("%\r\n");
  delay(13);

  while (mySerialin.available() > 0) {
   c[h]=mySerialin.read();
   h+=1;
  }

  mySerialout.begin(9600);
  mySerialout.write("%\r\n");
  delay(13);

  while (mySerialout.available() > 0) {
  d[j]=mySerialout.read();
  j+=1;
  }
  c2[0]=c[2];  d2[0]=d[2];  //cuts the letter off the data returned by the
  c2[1]=c[3];  d2[1]=d[3];  //sensor so it can be converted to a double
  c2[2]=c[4];  d2[2]=d[4];
  c2[3]=c[5];  d2[3]=d[5];
  c2[4]=c[6];  d2[4]=d[6];
  c2[5]=c[7];  d2[5]=d[7];

  percentin = atof(c2); //conversion from string to double
  percentout = atof(d2);
  return(percentin,percentout);
}

double Temp()
{
h=0; j=0;
mySerialin.begin(9600);
mySerialin.write("T\r\n");
delay(7);

while (mySerialin.available() > 0) {
   c[h]=mySerialin.read();
   h+=1;
```

```
  }

mySerialout.begin(9600);
mySerialout.write("T\r\n");
delay(7);

while (mySerialout.available() > 0) {
   d[j]=mySerialout.read();
   j+=1;
  }

c2[0]=c[2];   d2[0]=d[2];
c2[1]=c[3];   d2[1]=d[3];
c2[2]=c[4];   d2[2]=d[4];
c2[3]=c[5];   d2[3]=d[5];
c2[4]=c[6];   d2[4]=d[6];
c2[5]=c[7];   d2[5]=d[7];

tempin = atof(c2);
tempout = atof(d2);
return(tempin,tempout);
}

int massFinder(double offset)
{
int mass=0;
double loadCellValueAverage=0;
loadCellValueAverage=analogRead(A2);
for(int count=0; count<200; count++)
{
  int loadCellValue = analogRead(A2);
  loadCellValueAverage= 0.95*loadCellValueAverage + 0.05*loadCellValue;
  delay(1);
}

const double gradient=0.7852;
double intercept=24.513+offset;//adds the offset to the intercept to account for any
                                                         //nesting material, or similar,
mass=(loadCellValueAverage*gradient)-intercept;
if (mass<10) //simple clause to set any very low measured masses to zero:
                         //this line won't usually be used in normal function as mass
                           is only taken when lemurs (mass>10g) are in the box
{
  mass=0;
}
return(mass);
}
```

Appendix III - Financial Report

Group industrial projects are allocated £100 budget per person, making a total budget of £400. The budget is generally used for travel expenses but in this case the industrial partner was based in Bristol and the project itself needed to purchase many items not found in the lab; therefore the budget was lent less to travel and more to procurement, with a small amount spent on refreshments for meetings and presentations.

A full income/expenditure table is shown on the following page, with the total expenditure being £274.59. This includes purchases of multipack items, often where only a fraction of the pack was used and also of items that were later found not to be needed for the project. For those reasons total expenditure is not a true reflection of the cost of building one OSCaR, instead simply taking the cost of necessary parts (not including tools and power source, which is subject to user choice) the cost of one instrument comes to £144.35. A full list of equipment is given in Appendix XI along with their supplier of origin.

INCOME

Item	Price per Unit	Number of Units	Total
GIP Initial Budget			£400.00
Total income			**£400.00**

EXPENDITURE

Item	Price per Unit	Number of Units	Total
Equipment Costs			
Arduino Uno	£18.04	1	£18.04
Arduino Ethernet Shield	£25.42	1	£25.42
Infrared T-1¾ LED 880nm	£0.91	4	£3.64
Luminox Oxygen Sensor	£28.44	3	£85.32
Salter Black Kitchen Scales	£9.99	1	£9.99
Instrumentation amplifier, INA125P	£4.39	1	£4.39
Structural Hardwood Plywood WBP	£28.28	1	£28.28
Epoxy Coating Resin 500g Pack	2p /gram	500g	£10.00
Eveready PP9 Zinc Carbon 9V battery	£3.90	7	£27.30
Wilkinson Paint Brushes 5pk	£2.00	1	£2.00
Wilkinson Paint Container	£1.00	1	£1.00
Sainsbury's Basics Vineger	£0.22	1	£0.22
Brass Plated Hinges	£3.97	1	£3.97
Spray Paint - Matt Black	£5.18	1	£5.18
Copper Tube Crimp Lugs - 6mm^2	£1.98	1	£1.98
PVC coupler 20mm Black	£0.11	2	£0.22
PEX Insert 22mm	£0.17	2	£0.34
Weatherstrip P profile - brown	£6.48	1	£6.48
UltraFire 18650 Rechargeable Battery	£2.30	4	£9.20
Battery Holder for 18650 Battery	£1.00	2	£2.00
DC power cable mount plug 2.1mm	£0.50	10	£4.95
PCB mount DC power socket 2.1mm	£0.55	10	£5.49
Press studs for PP9 cell (pair)	£0.91	5	£4.57
SD5620 OptoSchmitt Detector	£3.32	2	£6.64
Spring loaded mini steel toggle latch	£2.99	2	£5.98
Wilko Everyday Value Lantern Battery 6V	£1.99	1	£1.99
Total Equipment Costs			**£274.59**
Incidental Costs			
Terry's Milk Chocolate Orange	£2.75	1	£2.75
Sainsbury's Biscuit Variety Pack	£1.00	1	£1.00
Sainsbury's Semi Skimmed Milk, 1 pint	£0.49	2	£0.98
Total Incidental Costs			**£4.73**
Total Expenditure			**£279.32**
Budget Remaining			**£120.68**

Appendix IV - Parts List with Suppliers

A list of components used to build the instrument.

Product	Price per Unit	Supplier
Arduino Uno	£18.04	RS Components
Arduino Ethernet Shield	£25.42	RS Components
Infrared T-1¾ LED 880nm	£0.91	RS Components
Luminox Oxygen Sensor	£28.44	SST Sensing
Salter Black Kitchen Scales	£9.99	Tesco.com
Instrumentation amplifier, INA125P	£4.39	RS Components
Structural Hardwood Plywood WBP	£28.28	Travis Perkins
Epoxy Coating Resin 500g Pack	2p /gram	EasyComposites.com
Eveready PP9 Zinc Carbon 9V battery	£3.90	RS Components/Wilkinson
Brass Plated Hinges	£0.40	Tool Station
Spray Paint - Matt Black	£5.18	Tool Station
PEX Insert 22mm	£0.17	Tool Station
Weatherstrip P profile - brown	£6.48	Tool Station
DC power cable mount plug 2.1mm	£0.50	RS Components
PCB mount DC power socket 2.1mm	£0.55	RS Components
Press studs for PP9 cell (pair)	£0.91	RS Components
SD5620 OptoSchmitt Detector	£3.32	RS Components
Spring loaded mini steel toggle latch	£2.99	RS Components
Transcend 4Gb Micro SD card with reader	£5.00	Maplin

Appendix V - Travelling With Lead-acid Batteries

Most modern lead acid batteries are suitable for air travel but this does not necessarily mean they will be cleared to go on-board. The important specifications to look for in the datasheets for the battery (which can be found on the manufacturer's website) are that:

- It is sealed or non-spillable
- It has gas recombination technology
- It has a power capacity of less than 100Wh (equivalent to 16600mAh for a 6V battery or 8300mAh for 12V).

If attempting to take batteries while air travelling, the battery should be taken in hand baggage, its terminals should be insulated (e.g. by taping them) and the battery data sheet should be carried with it along with a print out of the air-carrier's restrictions to demonstrate it is an allowable item. It may also be advisable to contact the carrier regarding this before flying.

Unfortunately, it is at the discretion of security as to what goes through the checkpoints and they have the power to confiscate anything they deem to be dangerous or potentially alarming to other passengers; so these precautions do not guarantee being able to travel with the battery. A safer idea is to send a battery ahead to its destination with a courier such as FedEx or UPS.

A further note: Lithium Ion batteries of the necessary capacity to run the device are not permissible in any form on-board aircraft due to current regulations.

Appendix VI - Table of Component Power Consumption

Table of power consumption of components that make up the OSCaR.

Component	Quantity	Current Per Component (mA)	Curent Drawn (mA)
Arduino	1	50	50
Ethernet Shield	1	150	150
Oxygen Sensor	2	10	20
Load Cell	1	14	14
INA125 Amplifier	1	0.5	0.5
OptoShmitt Trigger	2	12	24
IR LEDs	2	20	40
		Total	298.5

Appendix VII - Tables of Steady State Waiting Times

Results of equilibrium time for each box-burner combination, with details of dimensions of the boxes and the number of 10g paraffin wax burners used in each box. All errors calculated using standard error in mean.

	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6	Box 7
$V(m^3)$	0.00670 ±0.00003	0.00670 ±0.00003	0.00670 ±0.00003	0.00670 ±0.00003	0.00670 ±0.00003	0.00670 ±0.00003	0.0353 ±0.0002
$A(m^2)$	0.001963 ±0.00008	0.001963 ±0.00008	0.001963 ±0.00008	0.001963 ±0.00008	0.001963 ±0.00008	0.001963 ±0.00008	0.001963 ±0.00008
L(m)	0.017 ±0.0005	0.017 ±0.0005	0.04 ±0.0005	0.04 ±0.0005	0.017 ±0.0005	0.04 ±0.0005	0.017 ±0.0005
N	1	2	1	2	3	3	3
T(s)	162 ± 12	197 ± 17	226 ± 20	252 ± 10	109 ± 9	121 ± 5	221 ± 20

	Box 8	Box 9	Box 10	Box 11	Box 12	Box 13	Box 14
$V(m^3)$	0.0353 ±0.0002	0.0734 ±0.0002	0.0734 ±0.0002	0.0734 ±0.0002	0.0734 ±0.0002	0.0734 ±0.0002	0.0734 ±0.0002
$A(m^2)$	0.001963 ±0.00008	0.001963 ±0.00008	0.001963 ±0.00008	0.0177 ±0.0002	0.0177 ±0.0002	0.0177 ±0.0002	0.0177 ±0.0002
L(m)	0.04 ±0.0005	0.017 ±0.0005	0.04 ±0.0005	0.017 ±0.0005	0.017 ±0.0005	0.15 ±0.0005	0.15 ±0.0005
N	3	3	3	3	7	3	7
T(s)	228 ± 22	555 ± 47	601 ± 43	N/A	127 ± 30	248 ± 51	261 ± 23

Appendix VIII - Zoo Survey Responses

Below is the full set of responses to market surveys

Name	Establishment	Job Title	Willing to be contacted ?	Expected cost	Realistic purchase price for use in your establishment?	Similar device?	Would your establishment have use for such a device?	Device use	Species of interest	Comments
Christoph Schwitzer	Bristol Zoo Gardens	Head of Research	Yes	£1050-£5000	1000	No	Yes, both of the above	Nutrition plans, Drug dosage, General research, Reducing obesity	"Lemurs of all shapes and sizes African Penguins"	
	DWCT		Yes	£1050-£5000	It's not just the cost of the piece of kit to consider.	No	Unsure	Nutrition plans, Drug dosage, General research, Reducing obesity	"Without knowing the structure and design of the "Without knowing the structure and design of the piece of equipment it is hard to know. In principle it would be useful for many species. In practical terms we would have to ensure there would no adverse impact on animal welfare."	This sounds like it could be useful - particularly within the context of allometric scaling. There are welfare and practical considerations plus the disruption to the staff (with allied salary costs) and animal routines. It would be best to start modestly, perhaps within the context of a project and with a very fine focus, and then determine any benefits accrued and look at a broader "cost:benefit" analysis.
Josia Razafindramanana	Malagasy Primate Working Group	Project coordinator	Yes	less than £100	50	No	Yes, in the field	Nutrition plans, General research	Ring-tailed lemurs, crowned sifaka, mongoose lemurs, decken's sifaka	I have used activity sensors for lemurs. The device was attached to the radiocollar. Are you thinking of having similar things, easy to attach and to control? Really appreciate your work.

Name	Establishment	Job Title	Willing to be contacted ?	Expected cost	Realistic purchase price for use in your establishment?	Similar device?	Would your establishment have use for such a device?	Device use	Species of interest	Comments
Amy Plowman	Paignton Zoo	Director of Conservation , Research and Advocacy	Yes	£500-£1000	Up to £100 (at the moment)	No	Yes, in the enclosures	Nutrition plans, Reducing obesity	"Pygmy slow loris and other small primates Many bird species Tenrecs Dormice Armadillo Echidna"	"Looks like a very useful system, could it be developed for bigger spaces eg large cat sleeping dens? At the moment we are on very tight budgets so my answer to the last question is very low. I would hope in another year or two it could be higher!"
Adam Cook	Dartmoor Zoological Park	Head of Conservation & Research	No	£150-£500	£150	No	Yes, both of the above	Nutrition plans, General research	Many - Primarily small primates and pssibly large mammals such as our tigers if possible.	
Zak Showell	Twycross Zoo		Yes	£500-£1000	Dependant on needs	No	Yes, in the enclosures	Nutrition plans, Drug dosage, General research, Reducing obesity	Any nest box using species of interest	
Lorna Hughes	RZSS Edinburgh Zoo	Animal Team Leader	No	less than £100	?	No	Unsure	General research	Small primate and bird species	At present we have no requirement for this piece of equipment other than for general interest.

Appendix IX - User Manual

The following pages contain a user manual written to accompany the OSCaR, which helps to fulfil one of the initital aims of having an easy to use metabolic chamber.

Open System Calorimetry Respirometer (OSCaR) User Guide

Version 1.3

Hello!

We understand that electronic instrumentation can be intimidating at times, especially when there is no documentation to accompany it. This is why we have created this guide to accompany the instrumentation box for measuring the BMR of animals; including information on adapting the equipment for different animals and building duplicate apparatus from scratch as well as the more basic day to day functions.

We hope that this guide helps you with any enquiries you may have regarding the equipment and therefore furthers any health or conservation goals you may have regarding the observed animal.

Sarah Buxton
Charlie Hannigan
Fergus Kidd
Nick Pestell
Designers and creators, OSCaR BMR Instrumentation Box

Table of Contents

1 Introduction

The OSCaR has been designed to measure the Basal Metabolic Rate of an animal (or animals) in a non-invasive manner and return the data to the user in the simplest possible way.

Even with its simple design, there are still some pitfalls to be wary of and information that needs to be provided in order to facilitate any duplication of or changes to be made to the equipment.

A short description of the reasoning and science behind the device is provided in section 1.1 below but is not necessary knowledge for the operation of the instrument box and can be skipped with no loss to the reader.

Later sections will cover:
- Setting up the equipment to take readings
- Retrieving and interpreting data
- Adaptation of the OSCaR to new nest boxes
- Common issues and their resolution

1.1 Background

OSCaR effectively turns an animal's nest box into an open system respirometry chamber. It works by measuring the oxygen concentrations inside and outside a nest box while an animal is present, which allows the oxygen consumed to be calculated. Due to an approximately constant amount of oxygen consumed per unit energy, knowing oxygen consumed allows for BMR to be calculated. OSCaR leaves no fiddling around with complex data sets or further calculation – it simply gives the animal's BMR, no fuss.

The device also incorporates light gates in the nest box entrance that act as advanced presence detectors. These allow not only the presence of an animal in a nest box to be discerned but also the number of animals in the box at any one time – a real advantage when animals nest in pairs or groups. Furthermore, a scale is also incorporated seamlessly into the base of the nesting box, allowing masses of single or multiple nesting animals to be measured – this can be important for telling animals in a population apart and also for trying to ascertain allometric scaling laws for the BMR of a species. Advanced logic allows animals to bring food or nesting material into their nest without this affecting any weight measurements. Naturally, along with the BMR of the animal(s) in a nesting box, the number of animals and their mass is also given.

2 Setup

The electronics and accompanying computer code have been designed to be as easy to set up as possible, though there are several steps needed to get everything up and running.

2.1 If the initial set up has been completed

If everything above has been completed but you disconnect the device from its power source or, equivalently, the batteries run out, then pressing the red reset button once power has been restored will start the device running again, with the results then showing multiple instances of a 'setup' – this is completely normal.

2.2 Adapting an animal nest box for the device

When looking to change the animal, and therefore nest box, that the device will be measuring, there are several factors to take into account. Attaching the instrumentation box means first altering the nest box it will be attached to – the OSCaR has several holes through which instruments protrude or instrument wiring runs and appropriate holes must also be made in the adapted nest box. One hole should be made for the internal oxygen sensor, which has a bore of 22mm, one at the bottom for the scale wiring and another for the light gate wiring. There should also be three small holes made for the bolts that attach OSCaR to the nest box. The approximate positions and sizes of these holes on a nest box are shown in figure 1 but accurate alignment should be carried out with the OSCaR in-situ. While the oxygen sensor can simply be slipped into the wall of the nest box the light gates and scales need to be fitted.

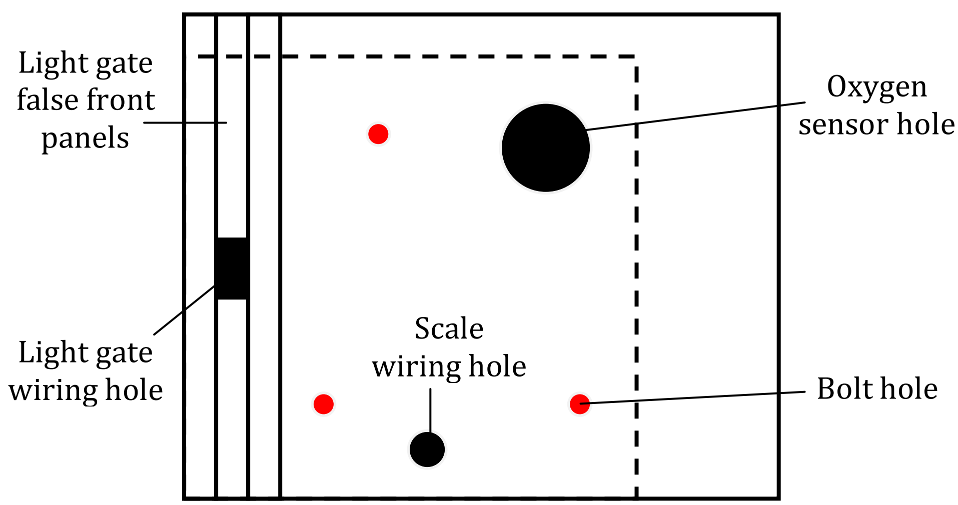


Figure 1: Diagram of hole positioning on an adapted nest box, which has three front panels housing the light gates – the nest box is denoted by the solid box while the OSCaR Device outline is shown as dashed. This shows how OSCaR can be attached to larger nest boxes than itself provided that it is aligned with the front-bottom corner of the nest box.

2.2.1 Measurement of the new box

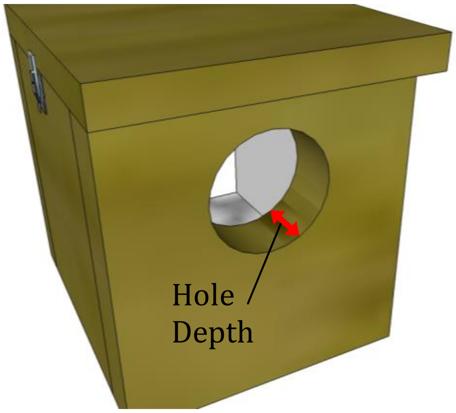


Figure 1: Demonstration of what is meant by hole depth.

Before fitting any hardware, let's deal with the software: firstly the area of the animal hole in the box and the depth of this hole must be measured. The measurement of the depth of the hole (shown in figure 1) can be carried out simply with a ruler. The trickier measurement is that of the area of the animal hole, for which the calculation changes depending on the shape: for a circular hole the diameter of the opening is measured and the following equation is then applied to find the area:

$$Area = \pi\left(\frac{D}{2}\right)^2$$

Where D is the diameter and π is a constant roughly equal to 3.142.

If the opening is square or rectangular then the area is simply equal to the length of the two sides multiplied together.

These two measurements must then be inputted into the code in the Arduino. The Arduino is accessed through a custom program which is downloadable from the Arduino website (http://arduino.cc/en/Main/Software) along with instructions on how to set it up for use. After installing the program, open a blank file and copy the code from Appendix I into it, inserting the variables that you measured previously in the relevant places, which are found near the top of the program:

```
const double Area = (e.g. 0.0022); //Area of entrance in m^2
const double Length = (e.g. 0.002); //entrance length in metres
```

The Arduino can then be plugged into the computer using a USB cable; at this point there is no need for an external power supply for the Arduino as it is powered through the computer. Once the Arduino is connected, the upload button (a circular button with an arrow pointing right) should be pressed to send the altered code to the device – if the program asks you to save the sketch before uploading, do so.

The Arduino can now be disconnected from your computer and connected to the outside power source, usually a battery.

2.2.2 Light Gates

When changing the OSCaR onto a new nest box the false panels that conceal the light gates in the entrance to the nest box need to be replaced with appropriately sized ones.

The steps for this are as follows:

1. Cut two panels identical to the existing entrance panel on the front of the nest box, including the entrance hole.
2. On one panel, mark out where the first set of light gates will lie across the box's entrance hole. They should be directly opposite to each other as they rely on line-of-sight.
3. On the front panel of the nest box do the same, ensuring that the position of these light gates is approximately 90° offset from those in step 2.

> Note: For this step it is important to be aware that the light gates in the nest box front panel are set into the outside while those in the separately cut panel will be set on the inside – i.e. you must think about the rotational geometry of the situation. These instructions may seem confusing at first but using the existing altered nest box should clarify what is said here.

4. Additionally, channels should be marked out on both panels where the light gate wiring will run. These channels should start at the markings made in previous steps and terminate in the same area near the edge that will be adjacent to the OSCaR control box, in the area where the light gate wiring hole in OSCaR is.
5. Use a chisel to form the channels and holes marked out previously, making them deep enough to contain the necessary LEDs, light sensors and wiring – in practice this means channels about 5mm deep.
6. In the third, un-chiselled panel, cut a small square out of the edge in line with the appropriate hole in OSCaR. This square should also line up with the ends of the wiring channels cut in step 5.
7. Now insert the LEDs and light sensors that make up the light gates into the channels – there should be one light sensor and one LED in each of the two panels and they should be placed opposite each other. The wiring should then be run down the channels, followed by the whole set-up being secured with silicone sealant. This helps keep everything in place, as well as waterproofing the electronics.
8. As the silicone dries it is important to make sure the light gates are finely aligned. Do this one panel at a time:
    a. First plug the Arduino into a computer using a USB cable.
    b. Power up the LED; this means connecting a 470Ω resistor to the black wire (ground) then connecting this to the pin marked GND on the Arduino. The red wire (positive) should be attached to the pin marked 5V on the Arduino.

c. Likewise, the light sensor also needs power. As in step b, the black wire of the light sensor should be connected to the second GND pin via a 470Ω resistor and as there is only one 5V pin on the Arduino, the red wire of the light sensor should be connected to digital pin 7. The white, signal wire should then be connected to analogue pin A0.
d. Now open the Arduino software and paste in the following code:

```
int lightSensor = 7;

void setup() {
  Serial.begin(9600);
  pinMode(led, OUTPUT)
}

void loop() {
  digitalWrite(lightSensor, HIGH);
  int sensorValue = analogRead(A0);
  Serial.println(sensorValue);
}
```

e. Upload the code to the Arduino and then open the serial monitor (Ctrl+Shift+M).
f. If the LED is properly aligned with the sensor then you will see a fairly constant list of high numbers (>1000) printed in the serial monitor – this should be double checked by blocking the LED with a finger and checking the listed numbers step to a much lower value (<750).
g. If the numbers are low or very variable initially then the LED and sensor aren't properly aligned – you should adjust their positions within the channel until you are happy they are aligned as in step f.
h. Repeat the above steps for the other light gate panel.

9. The panels can now be secured to the front of the nest box and the relevant wires inserted into the instrument box.
10. The light gates now need to be permanently wired in: inside the OSCaR control box, there is a circuit board with several screw pin terminals soldered on to it. There should be two free screw-pin terminals marked with a+ and a-, the red wires of the light gates should be attached to the + side of these terminals and the black wires to the - side. The two white signal wires of the light gate pair should be attached directly into analog pins A0 and A1.

2.2.3 Scales

As with the light gates, the scales cannot be taken straight from one nest box and inserted into another. The platform of the scale must fit snugly into the bottom of a nest box, so as to minimize detritus getting into the scale mechanism and make the box as 'normal' as possible for the animal.

The scale consists of a wooden platform screwed to a load cell, which is then combined with a plastic base and bolted to the bottom of the nest box. The steps for altering this set up for a new box are as follows:

1. Measure the internal dimensions of the bottom of the nest box and cut a piece of plywood to be one or two millimetres smaller in each dimension.
2. Unscrew the previous platform from the load cell and screw in the one that was cut in the previous step. The load cell should be approximately centred on the platform, and the wooden spacer between the platform and the cell should be used – this allows the load cell to flex freely, which is how weight is measured.
3. At the opposite end of the load cell to where the platform was attached there are two more holes, which will be used to attach the scales to the box. Measure where these two holes lie in relation to the base of the nest box and then drill appropriately sized holes in the base at these points.

> Note: steps 2 and 3 can be conducted in either order, depending on what you find easier.

4. Now secure the full apparatus into the nest box with the screws provided, ensuring you run the wires from the load cell though the appropriate hole.

> Warning: if the weighing platform is in contact with the sides of the nest box, this will cause poor measurements. In this case, the platform should be removed and sanded or planed down to ensure a good fit.

5. As with the light gates, the scales must be calibrated with the Arduino, this also requires the use of a spreadsheet program, such as Microsoft Excel. Due to the ubiquity of Excel, all instructions referring to spreadsheets will use Excel commands but most other spreadsheet programs are very similar. Calibration is as follows:
    a. First plug the Arduino into a computer using a USB cable.
    b. Inside the OSCaR control box there is a circuit board with several screw pin terminals soldered on to it. Connect the terminal marked +V to the 5V pin of the Arduino and the terminal marked –V to the ground (GND) pin.

c. Power the load cell, this means connecting the red wire of the load cell to the E+ screw pin on the circuit board and the black wire to the E- screw pin.
d. Connect the signal wires: attach the white wire from the load cell to the screw pin marked S+ and the green wire to the pin S-. Then connect the analog 2 pin on the Arduino to the screw pin on the board marked 'Signal'.
e. Now open the Arduino software and paste in the following code:

```
void setup() {
  Serial.begin(9600);
}

void loop() {
  int loadCellValue = analogRead(A2);
  float massVoltage = loadCellValue;
  Serial.println(massVoltage);
}
```

f. Upload the code to the Arduino and then open the serial monitor (Ctrl+Shift+M).
g. Calibrating the scale involves adding known masses to the scale and comparing with what the Arduino reads – this means having a set of masses or more likely a pre-calibrated set of scales (e.g. kitchen scales) that can be used to measure an object before it is placed in the nest box scale. If no masses are on hand, a great way to create a mass is with a lightweight vessel filled with varying amounts of water.
h. With no weight on the scales, the serial monitor should read relatively low values, but is unlikely to be zero. You should add a range of masses from 0 to around 500g on your scales and note down said mass and the corresponding serial monitor value in adjacent columns in the spreadsheet. Around 10 data points should suffice.
i. Now collate this data into a scatter graph. On Excel, this means selecting the two columns your data is stored in then going to the Insert tab → Scatter → Scatter with only markers.

Note: The known masses should be along the y-axis and the measured values along the x-axis – if this is not the case, delete the graph, switch the column order in the spreadsheet and then re-create the graph

j. Nest, right click on one of the data points on the chart and click 'Add Trendline' then check the box 'Display Equation on chart' and click close. This should give you a formula for the line of best fit in the form y=mx+c, where m is the gradient of the line and c is the y-axis intercept.

k. These two values now need to be inserted into the main code, so an accurate mass of the animals entering the nest box can be found. The full code for OSCaR can be found in appendix I at the back of this guide and in the final few lines is the code for the scales. Within this code there should be this couple of lines:

```
float gradient= m;
float intercept= c + offset;
```

Where m and c are actual numbers from previous calibrations. The values for the intercept, c, and the gradient, m, should be inserted in place of these previous values and the full code uploaded to the Arduino.

6. Calibration of the scales is complete and the OSCaR device is ready for use with a new animal.

3 Retrieving Data

The data generated by the electronics is stored on a standard 2GB micro SD card which is housed in a small metal adaptor slot on the Ethernet shield of the Arduino.

Make sure the device is powered OFF.

To remove the card, gently push the card into the Arduino – the card holder is spring loaded, and the card should decouple itself from the slot. Gently pull the card out from the slot.

The data on the card is stored in a standard plain text file (.txt) which can be read by any personal computer. To retrieve this file, named "DATA" the micro SD card must first be put into an adaptor that can fit into a personal computer. Examples include a micro SD card to standard SD card adaptor, which will fit into devices with SD card slots, or micro SD to USB adaptors, which fit all modern computers.

When the file is opened, the top line should read "Setup" indicating that the system has set up correctly and established connection to the SD card. If this is not shown, refer to section 5.

Under this should read the recorded data, if an animal has used the device for more than the allotted equilibration time. The data takes the form of:

```
X  Number of animals:  X  BMR=X.XXXXXXXXXX with  XX  readings
taken     mass=X.XX  T=XX.XX
```

Where X represents a digit. The first Number displayed is the number of the data set taken. Number of animals represents how many animals were in the box during the readings. The BMR is the average BMR per animal in the box per day, displayed in kCal day^{-1}. The number of readings taken is the number of useful, non-anomalous readings taken after the waiting period that contributed to the average BMR. The higher this number the more accurate the BMR reading. The mass is the mass per animal in the box, and is displayed in grams, and the temperature ‘T’ is displayed in degrees Celsius.

4 Troubleshooting

This section of the guide highlights common issues users may encounter and offer simple solutions. The device is able to self identify a limited number of issues, which present themselves as error codes within the saved data on the storage device. There are also a few other issues which can be easily diagnosed.

4.0 No Data

If the device has not read any data there could be a variety of problems. If the data file reads "Setup" and no additional information text, then the device has been powered and successfully initiated, but no animals have been present in the box.

4.0.1 No Setup

If the data file does not read "setup" on the first line then the device has had no power, or been unable to establish a connection to the micro SD card. First put the micro SD card in the device and power it on, making sure the Arduino LEDs are visibly on. Wait around 30 seconds before turning it off again. Remove the micro SD card and open the data file. If the device still does not read "Setup" on the top line, the micro SD card or the Arduino shield may be faulty.
If it does now read "Setup" then the device was either incorrectly powered, or the micro SD card was not inserted into the Ethernet shield properly

4.0.2 Multiple Setups

The card should read "Setup" each time the device is powered on. If the data reads "Setup" multiple times, or more times than the device has been powered on and off without the data being deleted from the micro SD card then there may be a faulty connection in the power circuit which is causing the device to be powered down.

- Check all connections in the power circuit are strongly connected and able to carry current
- Check that the black power connector is fully inserted into the main Arduino board

4.1 Error 1: Animal Counter Error

Error one is an animal counter error. It occurs when there is a faulty line of sight between a sensor and LED, or a faulty electrical connection on either of these. The error presents itself in the data, as “Error 1: Animal counter error” when the device prints its final data. When the error occurs, the animal count is reset to 0.

- Check the line of sight of the LED and sensor on the entrance to the nest box
- Check all connections are complete
- Check senor voltage levels both next to and away from the LED
- Replace any faulty parts

4.2 Error 2: Negative Animal Count

Error two is a negative count error. It occurs when the system identifies a negative number of animals in the box. It is common for this error to present itself after error 1, as the animal count is reset, whilst animals are still in the box. This error also resets the animal count, allowing it to correct itself when all remaining animals have left. The error presents itself in the data, as “Error 2: Negative Animal Count” when the device prints its final data.

- Discard Data with this Error

4.3 Error 3 and Error 4: Oxygen sensor not working

Errors 3 and 4 alert the user that one or both of the oxygen sensors are not functioning correctly. The error presents itself amongst the data as "Error 3: Inside Oxygen sensor not working" and "Error 4: Outside Oxygen sensor not working". The error may occasionally present itself at random in the data, which should be ignored. The error is only valid if presented multiple times in a row.

- Check connections to relevant sensor
- If problems continue, replace relevant sensor

5 Appendices

The User Manual does contain appendices but they are duplicates of those already found within the project report appendices.

Appendix X - Meeting Minutes

The following pages contain minutes from group meetings, which were compiled by the group secretary (Fergus Kidd) as part of the Industrial Project.

Meeting:	Initial Meeting
Date:	6/11/2012
Location:	H.H. Wills Physics Laboratory
Chairperson:	Nicholas Pestell
Secretary:	Fergus Kidd
In Attendance:	Professor. Peter Barham, Project Supervisor Charles Hannigan, Treasurer Sarah Buxton, Communications Officer

1. Project Brief

Professor Barham proposed that although the project brief was not certain yet, it would be about metabolism, in the form of an electronics and programming exercise, and that the group should investigate microprocessing and sensor types, as well as becoming familiar with a suitable programming language.

Action: Group

2. Required Skills

Professor Barham suggested that the group assign internal roles, and acquire the relevant skills to fulfilling the given role. Roles include, chairperson, treasurer, secretary, and communications officer. He also suggested researching some level of zoology and biology to become familiar with the basics that will be required to investigate metabolic rates.

Action: Group

2. Zoo Contact

Professor Barham proposed that Dr. Christoph Schwitzer, head of research at Bristol Zoo Gardens be contacted for a meeting about possible project briefs.

Action: Sarah Buxton

Meeting:	Project Brief
Date:	12/11/2012
Location:	Bristol Zoo Gardens
Chairperson:	Nicholas Pestell
Secretary:	Fergus Kidd
In Attendance:	Dr. Christoph Schwitzer, Head of Research BZG Prof. Peter Barham, Group Supervisor Sarah Buxton, Group Contact Charles Hannigan, Treasurer
Apologies:	N/A

1. Project Brief

Dr. Schwitzer proposed that the brief of the project be the design and production of a device to measure the basal metabolic rate of the Grey mouse lemur. The device should be free standing, log data, and withstand environmental conditions for use in the field in Madagascar. The device may be tested using the Grey mouse lemurs at BZG.
Prof. Barham added that the project could be extended to adapt the instrumentation for different types of animals, and calculate the theoretical limit to the size of animal suitable for experimentation with the method.

Action: Members acknowledged.

2. Accessing Past Apparatus

Prof. Barham proposed that Tom Kennedy be contacted in order to obtain and examine equipment used by previous students with similar brief.

Action: Sarah Buxton

3. Access to Zoo Resources

Dr. Schwitzer proposed access to zoo with research passes, and use of zoo literature.

Action: Deferred until required

4. Zoo Project Proposal

Dr. Schwitzer requested completion of a BZG project proposal form.

Action: Sarah Buxton

Meeting:	Access to Zoo and Resources
Date:	12/01/2013
Location:	Bristol Zoo Gardens
Chairperson:	Nicholas Pestell
Secretary:	Fergus Kidd
In Attendance:	Dr .Sue Dow, Research Officer Bristol Zoo Gardens Sarah Buxton, Communications Officer Charles Hannigan, Treasurer
Apologies:	N/A

1. Research Passes

Dr. Sue Dow organised for project members to be provided with research passes to gain access to the zoo at any time.

Action: Members to collect research passes from BZG membership office

2. Accessing Keepers

Dr. Sue Dow proposed that she be point of contact for all zoo keepers, should members require any information or action from keeping staff.

Action: Sarah Buxton

3. Zoo Familiarisation

Dr. Sue Dow proposed a brief tour of Bristol Zoo Gardens, specifically twilight world, to familiarise project members with layout of the zoo, and the location of the test animals discussed in the meeting of 12/11/2012.

Action: Members receive tour

4. Next Meeting

Deferred until further notice.

Meeting:	Diffusion laws
Date:	20/02/2013
Location:	Centre for Nanoscience and Quantum Information
Chairperson:	Charles Hannigan
Secretary:	Fergus Kidd
In Attendance:	Prof. Heinrich Hoerber, Professor of Nano-biophysics and supervisor of previous Bristol zoo projects Sarah Buxton, Communications Officer
Apologies:	Nicholas Pestell

1. Diffusion Laws

Sarah Buxton proposed discussion of gaseous diffusion models in application to experimental corrections of BMR, and the use and application of Fick's laws.

Action: Prof. Hoerber suggested Fick's first law, although not strictly physically representative of the actual system, would be enough to make initial estimations of the oxygen diffusion. He also suggested researching the speed of diffusion of oxygen in air.

2. Calibration of oxygen sensors

Fergus Kidd proposed discussion of previously used methods for calibration of oxygen sensors, as used by Guy Cohen in the 2011 project report of measuring the BMR of the Grey mouse lemur.

Action: Prof. Hoerber suggested contact with Prof. Rob Richardson and Dr. Adrian Barnes as their equipment was used.

3. Next Meeting

Action: Sarah Buxton arrange meetings with Prof. Rob Richardson and Dr. Adrian Barnes if necessary after initial contact.

Meeting:	Interim Presentation
Date:	22/02/2013
Location:	H.H. Wills Physics Laboratory
Chairperson:	Nicholas Pestell
Secretary:	Fergus Kidd
In Attendance:	Professor. Ashraf Alam, Professor of Physics and Project Assessor Dr. Christoph Schwitzer, Head of Research BZG Sarah Buxton, Communications Officer
Apologies:	N/A

1. Presentation

The group gave the interim presentation of progress made on the project to date to Prof. Alam and Dr. Schwitzer. The relevance of work to the given brief was shown, and practical demonstrations of working light gate detection, oxygen and temperature sensing, as well as the load cell for mass measurement were given. Detailed box designs were also shown, as well as a timetable for the future work. This document addresses two specific issues that require relevant action that arose in the question section at the end of the presentation.

2. Availability of Power Supply

Dr. Schwitzer expressed concern that the type of battery (9V PP9) used in the demonstration of equipment would not be readily available in Madagascar, and that international air travel with batteries would not be a suitable alternative.

Action: Group. Replace PP9 battery with a series of smaller PP3 batteries which Dr. Schwitzer suggested are readily available in madagascar. Research more into the use of solar panelling.

3. Extended Applications of the Device

Dr. Schwitzer asked about the possibility of using the device with mains power in the zoo to monitor BMR changes with varying temperature over a period of a year.

Action: Group. Research mains power adaptation to the system. Add a temperature reading on the output data saved to the SD card.

4. Next Meeting

A preliminary window of dates for the final project presentation was given for the week beginning the 13th of May. Meeting with Dr. Schwitzer to place equipment in enclosures at BZG to be arranged at a convenient time.

Action: Sarah Buxton

Meeting:	Extension Problems
Date:	28/02/2013
Location:	H.H. Wills Physics Laboratory
Chairperson:	Nicholas Pestell
Secretary:	Fergus Kidd
In Attendance:	Professor. Peter Barham, Project Supervisor Charles Hannigan, Treasurer Sarah Buxton, Communications Officer

1. Project Brief

Professor Barham proposed that although the project brief was not certain yet, it would be about metabolism, in the form of an electronics and programming exercise, and that the group should investigate microprocessing and sensor types, as well as becoming familiar with a suitable programming language.

Action: Group

2. Required Skills

Professor Barham suggested that the group assign internal roles, and acquire the relevant skills to fulfilling the given role. Roles include, chairperson, treasurer, secretary, and communications officer. He also suggested researching some level of zoology and biology to become familiar with the basics that will be required to investigate metabolic rates.

Action: Group

2. Zoo Contact

Professor Barham proposed that Dr. Christoph Schwitzer, head of research at Bristol Zoo Gardens be contacted for a meeting about possible project briefs.

Action: Sarah Buxton

Appendix XI - Certification of Ownership

Project Report presented as part of, and in accordance with, the requirements for the Final Degree of BSc at the University of Bristol, Faculty of Science.

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Authors	S. L. Buxton, C. S. Hanngian, F. E. Kidd and, N. J. Pestell
Title	Non-intrusive measurement of Basal Metabolic Rate using an Open System Calorimetry Respirometer (OSCaR)
Date of Submission	09/05/2013

Signed: Sarah Buxton, Charles Hannigan, Fergus Kidd, Nicholas Pestell

Full names: Sarah Buxton, Charles Hannigan, Fergus Kidd, Nicholas Pestell

Date: 09/05/2013

References

[1] D. Randell, W. Burggren & K. French, K, 'Animal Physiology – Mechanics and Adaptions', 4th Edition, W.H. Freeman and Company, pp 666-667, 661, 674, 668, 79-81, 669h

[2] A.J. Hulbert and P. L. Else, 'Basal Metabolic Rate: History, Composition, Regulation and Usefulness', Physiological and Biochemical Zoology 77(6):869-876 (2003)

[3] M. Gordon, 'Animal Physiology – Principles and Adaptations', Macmillan Publishing Co., pp 55, 47-48, 51, 53

[4] I. D. Hume, 'Marsupial Metabolics', Cambridge University Press, pp. 2-17 (1999)

[5] S. Goodchild and C. Schwitzer, 'The Problems of Obesity in Captive Lemurs', International Zoo News Vol. 55, No. 6, pp. 353-357 (2008)

[6] E. Knobil, and J. D. Neill, 'Physiology of Reproduction', Gulf Professional Publishing, Ch. 47, pp. 2555-2563 (2006)

[7] S. Wolfensohn and M. Lloyd, 'Handbook of Laboratory Animal Management and Welfare', John Wiley & Sons, Chapter 15 pp.330-333 (2012)

[8] S.C. Rastogi, 'Essentials of Animal Physiology', New Age International, p122 (1977)

[9] C. R. White and R. S. Seymour, 'Allometric Scaling of Mammalian Metabolism', Journal of Experimental Biology, 208, 1611-1619 (2005)

[10] M. Kleiber, 'Body Size and Metabolic Rate', Physiological Reviews, 27, 511-541 (1932)

[11] F. Bokma, 'Evidence Against Universal Metabolic Allometry', Functional Ecology, Volume 18, Issue 2, pages 184–187 (2004)

[12] J. R. Speakman, R. M. McDevitt and K. R. Cole, 'Measurement of Basal Metabolic Rates: Don't Lose Sight of Reality in the Quest for Comparability', Physiological Zoology, Vol. 66, No. 6, pp. 1045-1049 (2003)

[13] R.C. Hill, 'Challenges in Measuring Energy Expenditure in Companion Animals: A Clinicians Perspective', *The Journal of Nutrition* (2006)

[14] D. Randell, W. Burggren & K. French, *Animal Physiology – Mechanics and Adaptions*, fourth edition, W.H. Freeman and Company, p.674 (1997)

[15] K. Schmidt-Neilson, *Animal Physiology: Adaptation and Environment*, Cambridge University Press (1997)

[16] P.J. Moors, 'A Closed-circuit respirometer for measuring the average daily metabolic rate of small animals', Copenhagen, *Oikos* 28:304-308 (1977)

[17] G. Cohen, 'An investigation into the basal metabolic rates of Grey mouse lemurs through non-invasive automatic measurement of Oxygen concentrations', Bristol, Department of Physics, University of Bristol (2011)

[18] J. Humphreys, 2011, 'A Portable Device for Measurement of Basal Rate of Metabolism', University of Bristol

[19] Arduino, Arduino Uno [Online]. Available: http://arduino.cc/en/Main/ArduinoBoardUno, accessed 01/05/2013

[20] SST Sensing, 'LuminOx Preliminary Datasheet', SST Sensing Ltd (2011)

[21] P. L, K. P, G. H, S. L & J. C. R, 'Optical fiber fluorescence sensor system for measuring oxygen levels in gas involves the use of a fiber-optic fluorescence oxygen sensor containing a ruthenium complex for quenching the fluorescence by singlet oxygen atoms', *United States patent application* (2001)

[22] H. Tyrrell, *The Origin and Present Status of Fick's Diffusion Law Journal of Chemical Education*, 41:397–400 (1964)

[23] M. Denny, *Air and Water: The Biology And Physics of Life's Media*, Precenton University Press (1993)

[24] B. Roebuck, M. Brooks, & M.G. Gee, 'Load cell ringing in high rate compression tests', *Advances in Experimental Mechanics*, 1-2, 205-209 (2004)

[25] R. Pannorfi, B.M. Zee, I. Vatnick, N. Berner & S.M. Hiebert, 'Dietary Lipid Saturation Influences Environmental Temperature Preference but Not Resting Metabolic Rate in the Djungarian Hamster (Phodopus sungorus)', *Physiological and Biochemical Zoology*, 85, 405-414 (2012)

[26] R. Mittermeier, E.E. Louis Jr., M. Richardson, C.Schwitzer et al, *Lemurs of Madagascar,* Third edition, Conservation International, p.116-117 (2010)