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UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Science and observation: measuring for knowledge

Professor Andy Buffler

Inaugural Lecture
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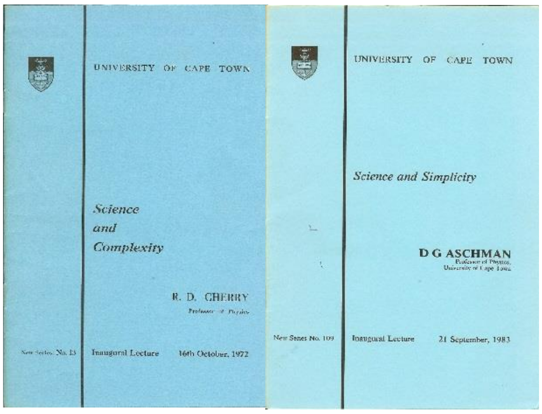
The gentleman in the photograph is Professor RW James, who came to UCT in 1937 to take up the position of the Chair of Physics and Head of Department. James' early life was interesting to say the least, highlighted by being a member of Sir Ernest Shackleton's ill-fated expedition to be the first to traverse the continent of Antarctic on foot. In those times it was usual to include scientists amongst the more motley seafarers, and it was James' plan to make the first set of comprehensive measurements of the Earth's magnetic field in the southern polar regions. Shackleton's vessel the *Endurance* left Southampton harbour 100 years ago, nearly to the day. Shortly after heading south from South Georgia Island, the *Endurance* encountered heavy pack ice, which beset and eventually crushed the ship, leaving the 28 man crew, pack dogs and equipment drifting on the ice shelf.

After 14 months on the ice, it became necessary to set sail north, in their three lifeboats, for Elephant Island, a tiny outcrop in the South Atlantic loved only by the resident elephant seals. James' skill in reading the heavens was critical to getting the castaways safely to Elephant Island, since the chronometers they had could no longer be trusted. James was able to get an accurate time from careful observations of lunar occultations, and using a Nautical Almanac, was able to determine their longitude while afloat.

Leaving most of the party on Elephant Island, Shackleton with 5 others, made his historic trip of 800 miles in a tiny life boat, the *James Caird*, back to the whaling station on South Georgia Island, returning four and a half months later to rescue all the remaining men from Elephant Island, including James.

A remarkable tale in the life of a remarkable man. RW James provides a thread through this evening's lecture.

Robin Cherry was appointed as a lecturer in the Department of Physics in 1956. Cherry had been lectured by James as a student and built a laboratory at UCT where he measured low levels of radioactivity in marine creatures. After being promoted to Professor, he entitled his inaugural lecture in 1972, *Science and Complexity*. George Ellis would have been pleased.



Not to be outdone by Robin Cherry, David Aschman, was lectured by Cherry during his undergraduate years at UCT, entitled his inaugural lecture in 1983 *Science and Simplicity*. Complexity and simplicity, can they both be correct?

Yes, indeed, and the key I believe lies with the notions of observation and measurement.

The art and act of measurement defines the very heart of the enterprise of Science. Apart from the extreme anti-realists that live among us, most of us would agree that we live in a real world of tangible experiences. It is the world of interactions, of experiment, of natural phenomena. The universe in which we exist is firstly very large (the cosmologists in the audience make a living out of this fact), and also infinitely complex (one point to Cherry).

It is thus necessary for scientists to make choices, to filter nature in order to reveal its secrets, to idealise the infinitely complex phenomena of our universe. The act of scientific observation thus becomes an approximation of reality, a simplification of complexity, an ordering to scale. The nature of this scale has itself become a serious pursuit of humankind and science.

American physicist and Nobel Prize winner in physics, Richard Feynman said of experiment:

"Now I'm going to discuss how we would look for a new law. In general, we look for a new law by the following process. First, we guess it, then we compute the consequences of the guess, to see what, if this is right, if this law we guess is right, to see what it would imply and then we compare the computation results to nature or we say compare to experiment or experience, compare it directly with observations to see if it works. If it disagrees with experiment, it's ***wrong****. In that simple statement is the key to science. It doesn't make any difference how beautiful your guess is, it doesn't matter how smart you are who made the guess, or what his name is… If it disagrees with experiment, it's wrong. That's all there is to it."*

String theorists take note.

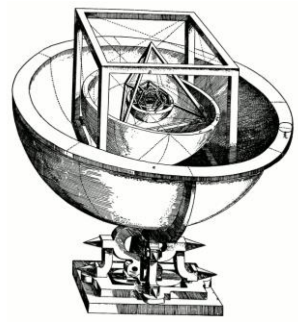
Measurement is what allows the complex to become simple. Observation leads to order, to pattern, to relationship, to law. But this was not always the case.

On the attraction of matter

Quaestiones quaedam philosophicae (*Certain philosophical questions*) is the name given to a set of notes that Isaac Newton kept for himself during his early years as a student in Cambridge, around 1661. They concerned questions in the natural philosophy of the day that interested him. He opened the first notebook with the slogan "Amicus Plato, Amicus Aristoteles, sed magis amica veritas." Plato is my friend, Aristotle is my friend, but truth is a better friend.

Newton was pointing to a view of natural philosophy related to the two giants of Greek thought, Plato and Aristotle, who had dominated humankind's thinking for centuries. Plato had no interest in science but this did not stop him from hypothesising about the processes of earthly and heavenly phenomena. Newton's other friend Aristotle was not much better. Speculation on the nature of things, supported by a priori reasoning and not by observation, was promoted to the status of dogma.

It took the dawning of the Renaissance to produce the conditions in which the observation and experiment was viewed as more important than the declared doctrine of the state and church. The motion of the heavenly bodies in relation to the Sun and the Earth was a very hot topic. Nicolaus Copernicus was the first to propose that the planets went around the sun and not the earth, in perfectly harmonious circles. Galileo Galilei got himself into a lot of trouble supporting and extending these notions, but recognised the value of trustworthy astronomical data, and thus spent a lot of effort both developing better telescopes and using them.



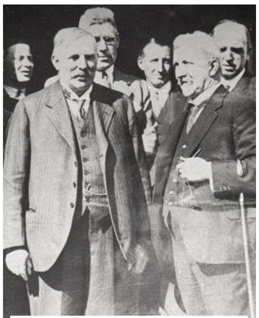
Around the same time, the Danish astronomer, Tycho Brahe, seen here without his artificial nose, meticulously observed and recorded the positions of the planets with great care, over decades. Johannes Kepler the great German scientist, hated Tycho but loved his data. Kepler needed Tycho's observations to prove his theory of the universe which featured the five Platonic geometric solids. Kepler analysed the motion of the planets around the sun by the method of trial and error. Eventually he had to reject his circular orbit theory since Tycho's measurements of the positions of Mars disagreed with his theory by only one twelfth of a degree, and could not be reconciled with his model. It was the precision of Tycho's measurements that lead to Kepler declaring that the planets did not move in circles at all, but in ellipses.

Isaac Newton was then able to show that Kepler's laws were consistent with a theory of gravity in which the force on a planet points in the direction of the sun, and that the force varied as the inverse square of the distance. Newton's great insight was to generalise this law and realise that not only the planets obey this law, but in fact every object in the universe attracts every other object according to this law. The same force that causes the apple to fall to the Earth is causing the Earth to fall around the Sun. The force of gravity is universal.

Gravity is the most important force on a cosmic scale, although it is a very weak. The force between two electric charges is stronger than gravity, but electrical charges can be either positive or negative and so can cancel out, and the electrical force between two electrically neutral bodies is nearly zero. The strong and weak nuclear force are both stronger than gravity but only operate over very small distances. Gravity determines the structure of the universe. Einstein had to modify the formulation of the law of gravity a little to link with his theory of general relativity, but these modifications were small, and have been checked experimentally. Today there is much work being directed towards a theory of quantum gravity, a formulation of gravity applicable to matter on the subatomic scale. This was a topic which troubled Einstein to his death, and most physicists believe that we will still need this for a consistent understanding of the very early universe.

There are physicists in the audience who can tell you more about this than I can. High energy physics, for example what happens at CERN, recreates the conditions of the early universe, and is aimed at answering questions such as "Why is the universe in the form it is?" Cosmology deals with the other end of the universe's career (as a universe). What is the large scale structure of the universe? How will the universe evolve? The SKA project hopes to contribute answers to some of these questions. The physics of the big questions such as "where did we come from and where are we going?" requires both big data and big thinking, and UCT is very much in it, with an impressive collection of physicists in Physics, Applied Mathematics and Astronomy. Big data is coming to UCT in bigger ways.

RW James and UCT



Ernest Rutherford with Jock Beattie *et al.* at UCT in 1929

During the closing decades of the nineteenth century, the work of JJ Thomson, and others, had conclusively show the electron to be a constituents of all atoms. Around the same time Max Planck proposed the notion of light as a photon, a particle having no mass and a quantum of energy directly related to its frequency. Ernest Rutherford was then able to show experimentally that the atom should not be regarded as a ball of positive charge in which electrons are embedded, raison-like, as Thomson purported, but rather akin to a solar system. All the heavy positively-charged protons (and also neutrons) are very tightly collected into a nucleus, and the much lighter electrons inhabit the vast empty space around the nucleus.

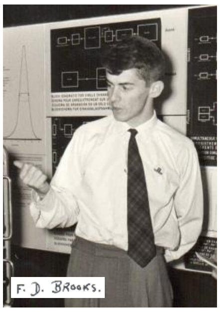
After the war James joined the academic staff at Manchester University where he established himself as a leading authority on X-ray crystallography, under the leadership of William Lawrence Bragg, son of William Henry Bragg.

The father and son team quite famously developed a method (now known as "Bragg's Law") to determine the positions of the atoms within a crystal from the way in which an X-ray beam is diffracted by the crystal lattice. For this work they were jointly awarded the Nobel Prize in Physics in 1915, at which time Lawrence Bragg was still only 25 years old. R.W. James had met young Bragg at the Cavendish Laboratory at Cambridge where they studied together and were in fact lectured by JJ Thomson on the properties of matter and electricity.

When RW James came to UCT in 1937 it had a growing reputation as an excellent teaching university, providing a sound education for students with talent to find opportunities for postgraduate study overseas. James was determined to change this, and with the help of vice chancellor TB Davie, and others, set about growing UCT as a research-intensive university.

The 1920s through 1950s were a golden age for the New Physics. It was a time when the modern theoretical pillars of modern physics were being thrashed out: quantum mechanics and special relativity. At the same time new technologies were being developed such as the machines that could accelerate protons, and others that could detect radiation and measure the properties of particles. In 1932 James Chadwick confirmed the existence of the neutron through a very cunning measurement, easily replicated in our teaching lab today. At UCT RW James employed the new technology of the X-ray spectrometer in both teaching and research. Two of UCT's Nobel Prize winners, Aaron Klug (1982 in Chemistry) and Allan Cormack (1979 in Physiology or Medicine) learnt their crystallography from James. Klug wrote of James:

"I had by then decided that I wanted to do research in physics and I went to the University of Cape Town which was then offering scholarships which enabled one to do an M.Sc. degree, in return for demonstrating in laboratory classes. (Present postgraduates take note). The University lay in a beautiful site on the slopes of Table Mountain, which one climbed at week-ends. I was lucky to find as Professor there, R.W. James, the X-ray crystallographer, who had brought to Cape Town the traditions of the Bragg school at Manchester."



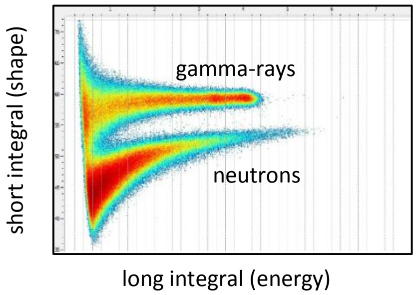
After the death of RW James in 1964, UCT Physics made two significant appointments. Willie Frahn was appointed to the Chair of Theoretical Physics, which set the foundation for the very powerful theory group we have today in the department, and Frank Brooks was appointed Professor of Nuclear Physics.

Brooks built up the research and teaching of nuclear physics in the Cape region, and grew his international reputation as a pioneer in the detection and application of neutrons, which became a theme in my own research life.

Measuring neutrons and gamma-rays

I brought a demonstration with me this evening. I brought a radiation source: a combination of americium-241 and beryllium-9 which produces a both fast neutrons and gamma-rays. I also brought a radiation detector, a liquid scintillator, chemically engineered from a recipe of hydrocarbons. When a neutron enters the detector it may collide with a hydrogen or carbon nucleus in the liquid, with the consequence of knocking out a proton. This proton recoils and slows down by interacting with the electrons in the material via the electrostatic (or Coulomb) force. Many millions of these interactions occur as the proton slows down, resulting in a shower of ionized electrons in its wake. When these electrons return to their unexcited state, they release photons which are typically in the visible or ultraviolet region of the spectrum. These photons together form a scintillation, which may be processed by a photomultiplier, which converts the light it collects into an electrical signal. The height of this electrical pulse (in volts) is proportional to the light collected, and in turn proportional to the energy of the recoiling proton. Gamma-rays entering the detector interact directly with the electrons in the material which also produce a scintillation as they slow down after an interaction.

In certain scintillation detectors, such as the one I brought with me this evening, we can do more: the shape of the pulse can be used to determine the type of particle that is interacting. With a little digital pulse processing and analysis we can easily deal with the pulses as they are produced. We integrate the pulse over both a short and long time. The short integral gives information about the radiation type: neutron or gamma-ray. The long integral is proportional to the energy of the recoiling particle in the detector.



A two dimensional representation of these parameters produces two distinct ridges; one associated with neutrons and the other with gamma-rays, demonstrating the technique of "pulse shape discrimination." Angus Comrie in the audience this evening is well into his PhD project which will result in the system you see before you being compacted down to a size that will allow it to run on your mobile phone. New scintillator materials and compact silicon-based photomultipliers makes this possible nowadays. One of the applications we are targeting is for the detector to be used in space and at high altitude.

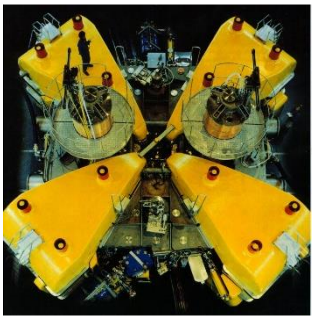
Neutrons for applications

At this stage we need to step back from this lecture room and take a cosmic perspective. Cosmic rays originate from the supernovae of stars, but also from normal stellar processes. Most of the cosmic rays that hit the Earth originate from our Sun, and are typically, but not exclusively, protons. The energies of these cosmic ray protons may reach 10^{20} eV, more than a million times the energy of protons accelerated in the Large Hadron Collider at CERN. Consider that, particle physicists in the audience. The units of electron volts are useful in atomic and nuclear physics, since one electron volt is equivalent to the energy that an electron gains after accelerating across a potential difference of one volt. It is equivalent to 3.8×10^{-20} calories (for those of you who think in these terms). The beam of the Large Hadron Collider at CERN provides 7 TeV per proton or 21×10^{26} eV for the whole beam (which in turn is equal to 8×10^{7} calories, equivalent to eating a 10 elephants - the ultimate Banting diet).

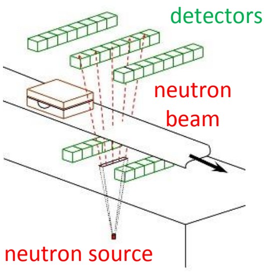
The Earth's magnetic field protects us from most of the cosmic rays from our Sun (evidenced by the aurorae seen at both poles), but some will interact with the Earth's atmosphere. Many different types of secondary particles are produced, including neutrons. In fact, neutrons make up about 45% of the secondary radiation produced by cosmic rays, with an energy spectrum that features both a low energy component and a strong peak at 100 MeV. It is becoming increasing important to measure and monitor these neutrons, since increasing lengths of time are being spent by astronauts in space, for example.

Astronauts and frequent fliers receive a higher radiation dose from neutrons than radiation workers at nuclear power plants. The effect of cosmic ray radiation on electronics is also a hot topic of research.

In order to develop instrumentation for this measurements in these conditions, a well characterized neutron beam is required, for experiments under laboratory conditions. On our doorstep down the N2 is iThemba LABS national laboratory where there is a cyclotron which can accelerate protons up to 200 MeV. The radiation beams are used for nuclear physics research, particle radiotherapy and the production of radioisotopes. Our neutron beam facility at iThemba LABS can produce beams of neutrons which are nearly monoenergetic, and in recent years we have developed this capability to a point where the facility is soon to be recognised as a unique international metrology standard for neutron beams.



Let me put this is context. All measurement, and I mean all measurement, is linked to a number of primary and secondary standards which are internationally regulated. In South Africa, the National Metrology Institute takes care of things for us, governed by the Measurement Act of 2006. So when you weigh out ingredients for dinner, you do so under the protection of this Act, and the scale you use can be traced all the way back to the international prototype kilogram which sits at the *Bureau International des Poids et Mesures* in Paris. All other fundamental units, such as the metre and second, are also well defined and regulated. Think of our neutron beam in the same way as the standard kilogram.



In recent times this has allowed us with confidence to be part of some interesting projects, such as calibrating the same radiation detectors that are presently on the Curiosity rover on Mars, or others which are presently flying on the International Space Station. A particular interest of mine is the consideration of new techniques for the detection of explosives in luggage, for example. Without very careful measurement of the radiation we use to interrogate the object, none of these applications would be possible.

Another recent application in my research life is positron emission particle tracking. Position emission tomography, PET, continues to have extremely useful clinical impact, particularly in cancer diagnosis and management, cardiology and neurology. PET is based on the simultaneously detection of the two gamma-rays released from a radioisotope which decays by position emission. A three dimensional image may be constructed from a collection of such events, measured at many angles, using the analytical methods of tomography (thanks to Allan Cormack). Radionuclides for PET are nowadays easily produced using particle accelerators, including the cyclotron at iThemba LABS.

Together with my partner in the venture, Indresan Govender, we established what is only the second operational PEPT lab in the world, sited at iThemba LABS. This relied on a donation from Imperial College London of a really special PET scanner, which features over 27 000 detector elements. Since PEPT is a non-invasive technique, it can be used to map flow fields in robust, industrial systems to the level of detail that is demanded for tests of both analytical and computational models of flow.

Therefore it is measurement which provides the underpinning not only of scientific advancement but the development of technologies for industry, particularly those which demand improved levels of efficiency, safety and security, all of which are prerequisites for both development and economic growth.

Physics for human development

Physics for development: the development of knowledge and applications which are relevant to the needs of South Africa, Africa, and beyond. Development is also about human capital development.

UCT has ambitious goals to continue to grow its excellence in teaching and research. We are all part of that and need to contribute with determination and institutional pride. The challenge that the university continues to face is around providing the right type of structures and curricula which maximises the chances of all students succeeding, no matter what their educational history. Every student admitted to UCT should have an excellent chance of graduating from UCT. If we can't get this right, with all our advantages, then we can't expect the South African higher education sector, broadly, to improve its efficiency.

However, it is clear, 20 years after the dawning of democracy in South Africa, that it remains a massive challenge for the Department of Basic Education to achieve significant improvement in the South African school system across the board. Of particular concern remains the state of mathematics and physical science teaching where there is now evidence that teachers' abilities to deliver the curriculum effectively is actually diminishing. Laboratory work and the teaching of experimentation in science has particularly suffered, as equipment is safely locked away in fear of theft or breakage, and teachers' confidence to lead laboratory work is reduced within the context of ever changing curricula. The fine arts are suffering similar fates.

Recent press reports on research into the preparedness of mathematics teachers comes as no surprise. Similar data are available for the teaching of Physical Science. Indeed, fewer and fewer schools are now offering Mathematics and Physical Science. Furthermore, performances of South African students on international benchmark tests, such as the Trends in International Mathematics and Science Study (TIMSS), have been famously dismal, with South Africa consistently ranking bottom of the list of the countries who elected to take part. South Africa subsequently withdrew from TIMSS.

The ability of the tertiary education sector to influence the practice in schools is limited, and it is clear that universities will continue to need to deal with the wide spectrum in the abilities of school leavers. The challenges identified in the higher education sector the 1980s remain with us today, but what has changed is both our experience and the tools we have developed to deal with these challenges. The Academic Development Programme at UCT has for over nearly three decades implemented structural and teaching interventions which are now largely integrated into faculty programmes. For example, last year the Faculty of Science moved away from placing students onto an extended degree programme at the start of the year, but puts more emphasis on students' abilities to cope early with their course load, delaying the constitution of the extended degree programme to the start of the 2nd term. The Faculty of Engineering and the Built Environment duplicated this scheme this year. There are many examples of the mainstreaming of academic development activities across the faculties, where performance, and not race, is used as the main criterion for placement. Recent thinking and debate around increasing the time for the first degree by one year has also pointed to the fact that universities need to take an increasing level of responsibility for working with the output from our schools, and not bemoaning it. It is my own firm view that extra time for the first degree across the sector is the only practical solution. UCT's main institutional goals of excellence in teaching and research are not orthogonal to these ideas.

As part of a large research programme focussed on laboratory teaching in Physics, we have surveyed incoming Science students at UCT on their experiences of laboratory work at school. We have consistently found that only around half report that they undertook hands-on science activities themselves at their school, one quarter report that only the teacher used the apparatus (in demonstration mode) and one quarter report that they had no experience at all with experimental work at all. And these are UCT students.

Furthermore there is now clear and unambiguous evidence for views that our incoming students have about the nature of experimentation and measurement in science. We have completed comprehensive surveys and interviews over a long time base. Without going into too much detail here, more than half of our students have a view of the enterprise of science that can be characterised as pragmatic revelation: the truth is out there. Nature will reveal itself to us. Experimentation is thus about uncovering, rather than exploring. This philosophy has also driven the development of the teaching of experimentation over decades.

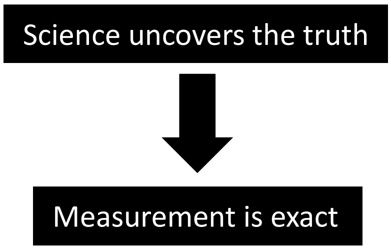
Towards a philosophy of measurement in the science teaching laboratory

Experimental work at school, and perhaps surprisingly at university at the introductory level at least, remains largely in the form of a cookbook. Students follow recipes which lead to results which are already known, *a priori*. There is clearly an argument which can be constructed for this approach. For example, dealing with large numbers of students with diverse backgrounds and experiences, the instructor's confidence or lack thereof to deal with unexpected results, the educational goal of teaching laboratory skills where aiming for a known outcome may be desired; and perhaps the desire to display a natural phenomenon or process, the demonstration of a law.

It was noted at the July 1905 convention of the U.S. Department of Science Instructors, "*In the laboratory the student is introduced at once to the difficult subject of measurement, required to make immediate use of such unfamiliar instruments as the diagonal scales, the vernier calliper, and the balance sensitive to a centigram; to report his results in terms of the metric system, to discuss errors, sources of error, percentages of error, averages and probabilities; to deduce laws, many of which he knew before, from data that cannot be made to prove anything …*"

These are not new issues.

One of the main consequence of this approach is a cementing of a view in the minds of school learners and university students that nature is entirely predictable and deterministic, and unexpected results should be regarded as wrong, a consequence of faulty apparatus or student error. Students believe that measurement within the scientific context is an exact activity, and in principle will yield a point-like result. From a technical measurement point of view, it is in principle possible to reduce the measurement uncertainty to zero.

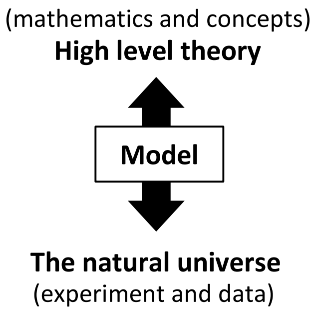


We have found this to be an extremely robust view, and even after the first year in university science, many students prevail with this epistemology, even though they are able to apply rigorous techniques of data analysis and uncertainty estimates. This is not an entirely local problem. We have tested students in Australia, the United States, England, France, Germany and Greece, with similar outcomes. The science education research literature is now well populated with articles dealing with the importance of measurement in science education, many of them pointing to our early work in the area. The difference, however, within the context of university-level science education in South Africa, is the wide diversity in the experiences of students who are admitted. Therefore some care is needed if effective education in the science laboratory is to take place.

I suggest a few ideas.

Foremost is an overt and sustained development in our university science curricula of a philosophy of science which forefronts the role of observation in science. The creation of new knowledge in science makes use of mathematical rules and technical tools. It is the relationship between the world of high level theory and data from observation that lies at the very heart of the enterprise of science. I thus believe that our students need to be exposed early on to this relationship in ways which are least not completely inconsistent. This points to the need for some form of philosophical framework to be developed within our science students for them to make sense of the different components of their educational experience.

There is a strong link between young people's views of the nature of science and their ability to develop the tools of science. For example, in the most naïve sense, a belief in science as an activity to uncover the truths of nature results in approaches to learning science with are aligned with memorizing facts and picking formulae to solve numerical problems. At university-level we have found that students will continue this formula-driven approaches to learning science. Laboratory work is seen as an activity to prove what is already known. Of course there is a spectrum of views. Even my colleagues have a wide range of philosophical views about their own practice.



Richard Feynman suggested somewhat ungraciously, "*Philosophy of science is about as useful to scientists as ornithology is to birds*."

Notwithstanding this view, we indeed be introducing science students early on to philosophical tools to make sense of science as an enterprise. Personally I would advocate a framework in which the scientific model is viewed to mediate between high level theory and the results from observation in the real world. Linked to this is a need for the different science disciplines (Physics, Chemistry, Biological Sciences, …) to communicate a consistent view of the role of experiment and observation to students.

The role of measurement uncertainty, an aspect of laboratory work often hated by students (and instructors), should developed as a natural aspect of measurement. We have shown that the so-called ISO-GUM approach offers tremendous pedagogical advantage, since the uncertainty in measurement is associated with the quality knowledge gained as a consequence of the measurement.

We should present students with laboratory tasks for which the outcome is unknown. These tasks should be cast within contexts which are authentic, aligned with real science. This not only adds motivation to the experiment, but can be linked to a philosophical framework. Laboratory work should include aspects of problem solving which can only be achieved by including data from direct observation from experiment. Parents with young kids take note: do experiments with your kids that lead to unexpected results, and then don't look too confused yourself.

In Physics we are recognising the advantages of including undergraduate students in the department's research activities. Whether we like it or not, we are living in an increasing digital age, in which the amount of data is increasing without bound. Big science means big data. Lots of it. Therefore extracting useful information from measured data increasingly means the need for tools of data visualization. We thus need to develop skills of data visualization in our science laboratory teaching, and this is best achieved within an authentic research environment.

Finally, the departments should celebrate the research laboratories that we have on campus. Undergraduates must see postgraduates working in laboratories, taking measurements with modern equipment. This is how we might generate context and meaning in our undergraduate teaching programmes.

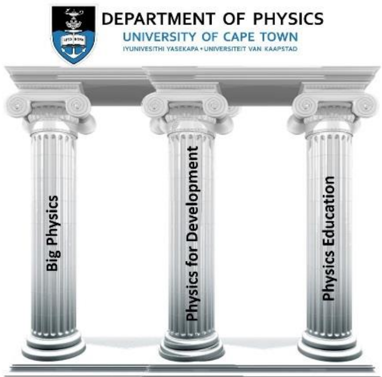
These ideas are neither complicated nor profound. Within an environment where diversity is to be celebrated, our teaching laboratory curricula need to provide students with the structure to locate their different educational experiences. This requires value to be placed on the role of measurement and observation in science.

Epilogue

Physics stands at the forefront of the fundamental sciences. The big questions in science all rely on the advancement of Physics: the physiology of consciousness and reasoning in the human brain, the coding of the genome, the structure of the universe, the nature of matter, climate change, new materials, the production of new sources of usable energy. There are almost no areas of human advancement where physics is not making a contribution.

I have made the case that observation lies at the very heart of what science is about. In the modern age, the rate at which data are generated is driving new ways of looking for pattern and simplicity in the data. UCT is very conscious of the need to be involved in Big Science and Big Data. My colleagues in physics who work at CERN will tell you that data from the detectors are recorded at a rate of over 1 TB per second. The first phase of SKA will easily surpass this. The largest scientific data centre in the world will therefore need to be built in South Africa and UCT should lead this.

Big Science is related to Big Development. The positioning of UCT as the premier university on the African continent, with growing international reputation, places us at the gateway into Africa. Physics drives technological development which in turn drives social development. Applied physics research at UCT locates itself within this institutional goal.



Both of these pillars, Big Physics and Physics for Development, lose meaning without the third pillar, Physics Education. UCT needs to produce graduates of the highest quality who can tackle big challenges which have relevance to Africa. The development of South Africa requires this, and UCT should never be ashamed of striving for excellence. I have argued further that excellence in science education requires training our students in understanding the nature of measurement and the quality of data. We have room to improve here. Our graduates must not only be able to reason from data, but be able to build models based on observational evidence. This requires excellent laboratory curricula.

In the foyer of the RW James building is a cabinet with a few memorabilia associated with RW James. Included in the collection is an X-ray spectrometer on which both of UCT's science-related Nobel Prize winners, Aaron Klug and Allan Cormack, learnt their art of scientific measurement. In the audience this evening lies the potential to follow these great scientists.

Endnotes

Introduction: Professor Anton le Roex, Dean of Science
Vote of thanks: Emeritus Professor David Aschman, Department of Physics