A CENTURY OF CANADIAN PHYSICS - MUCH TO CELEBRATE -

by Erich Vogt

There is much to be proud of in the past century of Canadian physics. In spite of almost continuous neglect of research funding by Canadian governments, some wonderful physics emerged from Canadian physicists working both in Canada and abroad. Perhaps the success of individual Canadian physicists is the result of a long tradition of excellent undergraduate physics training in Canada combined with the fact that Canada's geography evokes a strong response for the natural sciences. We shall discuss how the century of physics evolved in Canada in terms of the development of physics worldwide.

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HOW PHYSICS EVOLVED IN THE WORLD

Just before the end of the last century the main issues in physics appeared to be settled. Two centuries earlier Newton had created classical mechanics, which seemed to describe the motions of all objects on the earth or in the sky. Three decades before 1900 Maxwell had accomplished a remarkable synthesis of all phenomena pertaining to electricity, magnetism and light. Many of the important issues pertaining to gases and liquids were addressed by the new thermodynamics. A few issues remained; for example, about the atomistic nature of matter. Such issues were few enough that Lord Kelvin - clearly afflicted by an end-of-century malaise which also exists as the current century is turning - was led to surmise that all the principal problems of physics had been solved.

But Nature has a sense of humour, and so the present century began with a remarkable set of physics discoveries which launched an equally remarkable expansion of science as a whole. We begin by describing these discoveries and this expansion and then discuss the role that Canada played and how it responded to the new opportunities for physics and science.

The first three of these discoveries, about X-rays and radioactivity and the existence of the electron, came just before the turn of the century, almost as Lord Kelvin was uttering his unfortunate pronouncement. Roentgen's discovery, in 1895, of the penetrating radiation from a Crookes tube sparked great immediate interest worldwide, and many applications. Becquerel's discovery, in 1898, of radio-activity - the spontaneous radiation from the uranium salts whose fluorescence he was studying - did not spark quite such a strong immediate reaction from the world science community but had greater long range implications for physics. The Curies and Rutherford immediately explored the nature of radioactivity and its wide occurrence among the elements. Thomson's discovery of the electron, in 1897, was a cornerstone for the understanding of the atom, the development of quantum mechanics and a great deal of the whole edifice of modern physics.

Then, in 1900, Max Planck was led to postulate that thermal radiation was quantized with atoms radiating photons only at discrete energies. He knew at once that his conjecture, if true, would be world-shaking. Soon after, in 1905, which was undoubtedly the most miraculous year of discovery for any individual scientist, Einstein pushed the quantum idea further with his work on the photoelectric effect (for which he won the Nobel prize), published his Special Theory of Relativity and also his treatment of Brownian motion.

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But Nature was not yet finished with its sequence of discoveries to launch 20th century science. An understanding of the atom was needed to fully develop the quantum ideas.

It was in 1911 that Rutherford discovered the true nature of the atom as a "planetary" system with almost all of its mass concentrated in a very small, central, positively-charged nucleus surrounded by electrons. In a very simple experiment, alpha particles were aimed at a gold foil and the scattering of the alpha particles was observed. Geiger and Rutherford found that some of the alpha particles bounced right back. Using the Scattering Law for alpha particles which Rutherford derived very elegantly from his knowledge of the Kepler laws of planetary motion (he was a very good theorist in spite of his healthy disdain for theoretical physicists) a very good fit to Geiger's data was obtained. Thus Rutherford proved that the planetary model was valid for the atom and he was even able to find an upper limit for the size of the nucleus. Bohr was at Manchester with Rutherford at the time and very soon produced the Bohr atom in which the electrons surround the nucleus in discrete orbits. The atomic spectra corresponded to the emission of photons when electrons in excited orbits make transitions to lower orbits. Although initially he got it slightly wrong, Bohr's concept was momentous. Very rapidly Bohr's atom and the atomic spectra became the test bed for the proper development of quantum mechanics.

Quantum mechanics burst into prominence in 1925-26, largely through the work of Heisenberg, Schroedinger, Born, and Dirac. The concept of quantized spin was required for the understanding of atomic spectra. The strange concepts of quantum mechanics (discreteness rather than continuity, intrinsic uncertainty, probabilistic interpretations, etc.) and the requisite strange mathematics constituted a revolution in thinking about the physical world. Like all revolutions, this one ended with dogma: the Copenhagen Interpretation, accompanying the framework of quantum mechanics, has been an astonishingly successful description of the subatomic world. It is amusing that, in spite of all of the effort devoted to quantum mechanics, it is only now, after 70 years, that some of the dogma is being removed. We may eventually be able to teach our students about the systematics of quantum mechanics without the baggage of unphysical concepts such as wave function collapse. The convergence of theory to Nature's truth is asymptotic.

When, very early in the century, it became possible to liquify helium and to attain very low temperatures, some startling phenomena were observed, such as the discovery, in 1911, of superconductivity by Kamerlingh Onnes in Holland. Its understanding was a long time challenge for the new quantum mechanics.

Einstein's General Relativity, in 1920, reinterpreted gravity as space curvature. This discovery, quickly verified, is of huge consequence for physics. It underlies a great deal of modern cosmology. The reconciliation of gravity with quantum mechanics eluded Einstein and remains a major open problem today.

Just as Rutherford's 1911 experiment at Manchester created the study of the atom, the discovery of the neutron, in 1932, by Chadwick, in Rutherford's Cavendish Laboratory in Cambridge, created nuclear physics. Only a few years later fission was discovered and, during WWII, nuclear physicists lost their innocence with the creation of atomic weapons.

Through the discoveries just outlined, physics dominated fundamental science for the first half of the past century. Nuclear physics became, at mid-century, the leading field of physics. But then quantum mechanics and the experience during WWII of large teams of physicists creating radar, the Manhattan Project, etc., led to a very impressive worldwide expansion of science. Entirely new fields of science emerged - such as cosmology, microbiology, materials science and microelectronics, particle physics, etc. - which challenged and even displaced nuclear physics from its place on centre stage. Almost all physicists active in Canada today are personally familiar only with this expansionary era in the second half of the century.

For several decades following WWII, nuclear physics remained a prime vehicle for exploring the laws of quantum mechanics as they applied to subatomic systems. Almost every university in the Western world acquired a small accelerator. The detailed properties of thousands of nuclear energy levels were explored and elegant models emerged for nuclear spectroscopy, the study of the oscillation, vibration, and rotation of systems of neutrons and protons. In recent decades the focus on nuclear spectroscopy declined somewhat and the interests of nuclear physics turned to the use of higher energy accelerators for the elucidation of strong interaction physics (including the possible impact of the quark substructure of the nucleons), Big Bang physics, fundamental symmetries, nuclear astrophysics, and exploration of the farthest reaches of the nuclear landscape. This landscape includes the ridge of stable isotopes but continues to the unstable isotopes whose neutron and proton numbers place them far from the ridge. One can proceed to superheavy elements beyond uranium or to the regions of ligther isotopes far from the stable ridge. These regions extend up to the neutron or proton drip lines at which nucleons can no longer be held. The physics in these exotic regions is very different from that of the stable nuclei and is a new challenge for the field.

Perhaps future generations will consider the biggest achievement of the past century of science the fact that with modern cosmology we have been able to articulate the history of the universe in which we live from its earliest moments to the present. This cosmology owes its creation to quantum mechanics, to General Relativity, and to nuclear physics. We can observe remnants of the initial Big Bang and now, both in particle physics and in space astronomy, we can trace the history of the universe back to a million-billionth of a second after the Big Bang. We also understand the various processes of stellar collapse including the final explosive stage in which a white dwarf, a neutron star, or a black hole is generated. The very lightest isotopes of all of the elements were generated in the initial Big Bang and the isotopes of all of the heavier elements in the various stages of a star's evolution. The final collapse of a star involves all of the thousands of isotopes of the entire nuclear landscape. It remains a challenge for current nuclear astrophysics to understand, experimentally and theoretically, all of the reactions involved.

Particle physics emerged from nuclear physics after WWII, through the development of higher energy accelerators and also through theoretical tools to describe the fundamental building blocks and forces of Nature. The experimental tools of nuclear physics were accelerators with beams of protons, electrons, etc. with energies below about 100 MeV, commensurate with the energies of nuclear states. The tools also included ever more sophisticated (and sometimes larger) detectors to measure the reaction products. Since 1930, accelerator energies have leapt by an order of magnitude every six years, starting with Lawrence's cyclotron, in 1930, whose energy was below 1 MeV. Accelerators to create pions emerged soon after the war. Very rapidly one found hundreds of new particles, especially mesons (related to the pion) and baryons (related to the nucleon). What to make of this zoo? It is not surprising that the scientific method, applied to this data, soon led to the discovery of the building blocks (quarks) for these strongly-interacting "elementary" particles. Evidence for the existence of quarks first came in 1967, at Stanford University, from the deep-inelastic scattering of very high energy electrons from protons. A Canadian, Richard Taylor, was one of the Nobel Laureates in physics, in 1990, for this work at Stanford University. Six quarks were soon joined by six leptons (weakly interacting particles such as the electron and its neutrino) to complete the new understanding of Nature's basic building blocks.

In the postwar decades a unified description of the fundamental forces of nature began to emerge. First, in the late 1940's, quantum electrodynamics (QED) was liberated from the infinities which had plagued it. This renormalization of QED, by Feynman, Schwinger, Tomonaga, and Dyson was possible because of the local gauge symmetry of Maxwell's electromagnetism according to which the theory had a "gauge" freely adjustable at every position. QED was the first quantum field theory with local gauge symmetry. It became a template for the quantum field theories for other interactions, especially for the weak interaction. In a unified description of electromagnetism and the weak interaction through a local gauge theory (the electroweak theory), neutral currents emerged and the quantum of electromagnetism, the massless photon, was joined by three very massive vector bosons, the positive and negative W and the neutral Z. The quadruplet of bosons (the vector bosons and the photon) were the quanta of the electroweak field. In parallel a local quantum field theory, quantum chromodynamics (QCD), with gluons as the exchange particles, emerged for the strong interaction. Further, candidate theories for the unification of the electroweak theory with QCD (Grand Unification Theories) emerged. In all cases the local gauge symmetry was essential for renormalization and, as a side effect, gave very interesting new properties to the vacuum. Ideas about the inclusion of gravity in a unified description of all of the fundamental forces have come forward, and there are hopes of reconciling gravity with quantum mechanics. However, the realization of these hopes, through superstring theory, may still be decades away.

The so-called Standard Model of quarks, leptons and partially unified forces achieved its greatest confirmation with the discovery, at CERN, in 1982, of the gauge bosons of the electroweak theory. The large team which made this discovery was led by Carlo Rubbia of Italy; Alan Astbury, now director of TRIUMF, was the deputy leader. Since then the goal of particle physics has been to try to find what lies beyond the Standard Model. Where is the Higgs particle, the quantum of the fields which give mass to the basic building blocks? Why does the Standard Model have so many dozens of parameters? Is there some Supersymmetry or do we live in a world of Superstrings? Will the new supercollider at CERN, scheduled to begin operation in 2005, provide answers? As the century closed the Standard Model remained remarkably resilient. Perhaps Nature is poised again to surprise us at the beginning of this next century.

The basic concepts of materials science began to emerge after the birth of quantum mechanics in the 1920's. For a quantum description of solids one needed phonons, the quanta of vibration of the atoms in their lattice, and also the dynamics of electrons moving in bands in the periodic lattice. The events which brought condensed matter physics into prominence occurred in the 1950's, first with the experimental discovery of the properties of semiconductors which led to transistor devices, and secondly with the theoretical understanding of superconductivity in terms of electron-phonon interactions. The transistor was discovered by Bardeen, Brattain and Shockley at Bell Telephone Laboratories and the superconductor theory by Bardeen, Cooper and Schrieffer at the University of Illinois. The burst of activity which soon followed made condensed matter the largest subfield or constituency of physics. A Canadian physicist, Walter Kohn, received the Nobel prize for chemistry in 1998 for his work in understanding the electronic structure of materials. Many elegant ideas emerged in condensed matter physics which had impact on all of physics. These ideas and discoveries pertained to superfluids, high-temperature superconductors, quantum Hall effect, etc. They are ample testimony to the fact that the human sense of wonder is excited not only by questions about the basic building blocks and forces but also by complexity in the wonderful systems of atoms and molecules which our world provides.

The field of microelectronics, which derived from condensed matter physics, is now all-pervasive in modern life. The way we communicate, the way we travel, the way we relax, and even the way in which we do physics is driven by microelectronics. Proper communication was so important for particle physics that physicists at CERN invented the World-Wide-Web. Although microelectronics can be regarded now as a large field of its own, it continues to count on physics, especially such new subfields as nanophysics - and possibly quantum computing - for ideas for its future development.

In the second half of the century many other fields of physics emerged, owing their impetus largely to quantum mechanics. The development of lasers in atomic physics and of much beautiful science associated with plasma physics are two examples. Arthur Schawlow, a Canadian physicist working at Stanford University, received the Nobel Prize in physics in 1981 for his contributions to laser spectroscopy. He had also been a co-inventor of the laser, along with Charles Townes, in 1958. A field in which Canada became very strong was geophysics. Professor Tuzo Wilson of the University of Toronto, a towering figure in the field, was the father of plate tectonics which is now crucial for the understanding of the earth's crust and the movement of the continents.

The very important advances in microbiology began, in the early 1950's with the discovery by two physicists, Crick and Watson, of the structure of DNA. By the end of the century this became a large and separate discipline, competing with the best of physics for centre stage in the world effort in science.

Physics has been on a roll. Will it continue? Judging from the open problems in cosmology, particle physics and the science of complex systems the challenges are as great as at any time in the past century. There is certainly no grounds for the end-of-century malaise evident in Lord Kelvin's pessimism a hundred years ago, and now echoed by John Horgan's new book, "The End of Science". Nature is whimsical and does not deal kindly with experts who make predictions. Challenges and opportunities abound.

CANADIAN PHYSICS IN A WORLD PERSPECTIVE

We describe what happened in Canada during the past century in terms of the development of physics worldwide, as discussed above. It is a story of strong individual accomplishments rather than Canada as a country vigorously seizing science opportunities. Similarly, with a few notable exceptions, Canadian governments of all parties have largely ignored science throughout the century. Their rhetoric has often included science but the performance of Canadian governments in supporting science initiatives, even ones of great potential benefit to the country, has been generally very weak compared to that of governments of other countries with whom Canada is competing economically. Why?

Canada is a vast and beautiful country with abundant natural resources and blessed, throughout the century, by the ideas and energy of immigrants. It has achieved a living standard and social services envied worldwide, using its natural resources and its influx of immigrants. Therefore Canada has not had to aggressively harness its brainpower for economic advancement in the way that Japan, Britain or even the United States have done. It has also attained an outstanding educational system so that every Canadian with a natural gift for physics can achieve excellent training in the subject. But our national culture does not nurture science. It is not that Canadians do not have national pride or do not value achievements by Canadians in science: they do. It is rather that collectively we never seem to have understood the value of science, especially fundamental science, as a driver of our economy. Other countries have understood and have reaped the benefits of physics research much more than Canada. Many of our best scientists have found opportunities abroad, and continue to do so.

Much of the often discussed Canadian brain drain is natural. Physics is a universal subject and those driven to make a career of it can cast their net widely. Canada is a relatively small country compared to the United States. Even if the playing field were completely even - which it isn't - a large number of Canadian physicists should be expected to drift to the United States. Similarly a large fraction of physicists raised in California (a pool of scientists comparable to that of Canada) end up in careers out of that state. Considering the unevenness of the playing field it is then a minor miracle that a substantial fraction of our scientists stayed in Canada. Their number has been augmented by a substantial influx of scientists into Canada from abroad, especially from Europe. But it is not an even slate. Probably almost every Canadian physicist throughout the century, whether working at home or abroad, has believed that Canada could have benefited even more from science. Our physics history is one of outstanding individual leaders and of world-class accomplishments. But it could have been even more. Here we celebrate what did happen.

Although many of the leaders of Canadian physics were born in Canada, Canadian physics, like Canada itself, benefited greatly from immigration. Among the outstanding individuals from abroad were Rutherford at McGill, Herzberg at Saskatchewan and NRC, Rasetti at Laval, Lewis at Chalk River, Pringle at Manitoba, D.KC. MacDonald at NRC, etc. Many of them are featured in the articles or brief vignettes of this issue. Canada welcomed and accommodated some of the world's best.

The history of Canadian physics appears to have no important milestones before the century began. There were a few universities in Ontario, Quebec and the Maritimes, and only a handful of physics professors. In most of the smaller universities there were one or two teachers for science as a whole. McGill University and the University of Toronto had physicists on their staff teaching physics. The universities were often innovative. For example, the first woman to obtain a science degree from a university in the British Empire was Grace Annie Lockhart who graduated from Mount Allison University in 1875. (Her grandson, Professor Kenneth Dawson, had a distinguished physics career at the University of Alberta and at TRIUMF).

In western Canada the only university which began before the turn of the century was the University of Manitoba, founded in 1877. However, the first physics professor at this university was Professor Frank Allen, appointed in 1904. The university was located then on its Broadway campus, near the Manitoba Parliament buildings. The life of the campus was disrupted, occasionally, by the hanging of a prisoner in the gaol next door. In his fine history of this department Robin Connor (PiC, **50**, page 340, 1994) has described how physics in Winnipeg obtained an enormous boost when the British Association for the Advancement of Science held its meeting there in August, 1909. Among the 1468 participants were Sir J.J. Thomson, Ernest Rutherford, Lord Rayleigh, and Professors Helmholtz, W.K. Roentgen, A.E.H. Love and J.H. Poynting. It was a real intellectual feast for a frontier outpost. Winnipeg was then a city with a population approaching 100,000 but it was at the edge of the world. It was only a few decades since the Canadian Pacific Railroad had marched west into virgin territory from which the buffalo were just disappearing.

The appointment of Ernest Rutherford as a Professor at McGill University in 1898 (see John Robson's article on Rutherford in this issue) and the appointment, a few years later of John McLennan at the University of Toronto (see Craig Brown's article in this issue) can be regarded as the initiation of physics research in Canada. Rutherford was very young and energetic and at the height of his powers. Singlehandedly he brought world leadership to McGill in the hottest new physics subject at the time, radioactivity. He teamed with Frederic Soddy to elucidate the chemistry of the radioactive isotopes and he discovered at McGill many of the most important properties of radioactivity. As Robson describes in his article in this issue, Rutherford's decade in Canada and his subsequent nurturing of a whole generation of Canadian physicists had profound influence on Canada.

John McLennan was home grown but he also singlehandedly placed Toronto on the world map in physics research. Working in the early decades of this century, he began with a virtually unknown physics department and made it into one of the top few on the continent. He was strongly influenced and supported by Rutherford at McGill. McLennan ranged widely in research, including the exploration of atmospheric radioactivity, which he thought came from the earth rather than from cosmic rays originating in outer space. (He should have looked up rather than down!) Therefore he missed the boat. He eventually focussed on low temperature physics and was among the first in North America to liquify helium. He was very self assured - perhaps too self assured as people from Toronto have been known to be - and travelled to Europe frequently, boosting the University of Toronto and in search of ideas and physicists. As a result he wasn't always liked. Sir Rudolf Peierls told me how, in 1935, he had been in Lord Cherwell's office at Oxford when someone came in and informed Cherwell that McLennan had died. Without hesitation Cherwell replied: "He won't be worrying about low temperatures now." The physics department which McLennan created in Toronto has remained, throughout the century, as Canada's strongest. One of Canada's outstanding scientists, Harry Welsh, personally supervised about 65 Ph.D. students at the University of Toronto.

The only times when the Canadian government left its normal state of inertia to create substantial science enterprises was during the two world wars. In WWI the National Research Council (NRC) was created; in WWII the Chalk River Nuclear Laboratory was initiated. These two national laboratories had greater impact on Canada's physics during the past century than anything else. We dwell on them at some length here not only because of their glory but also because the recent decline of their physics is an exceptionally poignant story. The university scene in Canada is less melodramatic.

In this issue Paul Redhead describes, very impressively, the history of accomplishments of NRC. Created in 1916 as the Honorary Advisory Council for Scientific and Industrial Research it immediately funded science fellowships at Canadian universities and created a research inventory. In 1928, during the presidency of H.M. Tory, the NRC Laboratory was authorized and grew steadily to a total staff of several hundred by the time WWII began. During that war it played a central role in many fields: medicine, synthetic fuels, weapons, etc. NRC was fortunate to be led by two great presidents in succession, C.J. MacKenzie (1939-1952) and E.W.R. Steacie (1952-1962). Under their visionary leadership the staff of the NRC Laboratory grew to several thousand and embraced a large variety of programs in science and engineering. It was MacKenzie, an engineer, who established a stronger basis for fundamental science. Steacie raised the extramural funding of research grants to Canadian universities to roughly equal the NRC Laboratory funding. The extraordinary development of university research in physics and of graduate training after WWII, as described by Preston and Howard-Lock in this issue, was due to this inspired stewardship of grant funding by NRC.

NRC gave birth to a number of other agencies, important not only for physics research in Canada but for more general science. Atomic Energy of Canada Ltd. was spun off soon after the war. So was defence research to the Defence Research Board (DRB). The Medical Research Council (MRC) became a separate entity in 1966 and the Natural Sciences and Engineering Research Council (NSERC) in 1978. Also science policy for Canada, which had been part of NRC's mandate for almost five decades, became the function of the Science Secretariat and the Science Council in 1964.

What we need to celebrate most about NRC is not its growth in numbers or its progeny but the quality of its science during its prime years, the first few decades after the war. A beacon of excellence was needed by Canadian physics and NRC was it. C.J. MacKenzie sought outstanding scientists and found them in

Herzberg, D.K.C. MacDonald and many others. The NRC Laboratory became a place to which outstanding young scientists from around the world flocked. Many stayed. Perhaps, also, many Canadians who had gone abroad returned to Canada, despite the uneven playing field, because it was a country which nurtured the NRC, whose work was honoured around the globe. NRC matured into the soul of Canadian science.

Great science is catching and there was an epidemic of good physics at NRC. Some of the best of it was assembled within the NRC Laboratory into the Herzberg Laboratory for Astrophysics. It is very sad for Canada that NRC did not continue to receive the visionary leadership which created its scientific momentum. Even in the areas of physics in which NRC was traditionally strong it could have remained a world centre for high quality physics. Looking at NRC from a distance it is not hard to envisage that it could have pioneered Bose-Einstein condensates or fourth-generation synchrotron radiation facilities for Canada or fast-laser physics or nascent efforts with thermonuclear fusion. Instead, beginning in about 1980, much of its best science withered, many of its best scientists fled or were invited to leave, the Herzberg Institute decamped, and the fusion program was cancelled even though it had many excellent scientists. Again, why? There were some well intentioned leaders and a lot of government neglect which changed conditions. However, in its science programs Canada seems to have been afflicted more than other western nations by the impact of government bureaucrats infected with a disease called "science policy" and who did not possess either the knowledge of science or the vision, and the feeling about the wonder of it all and of its impact on the economy. Governed by this malaise, the bureaucrats demanded that the large institutions be steered to achieve spin-offs directly relevant to the national economy. Sometimes the bureaucrats were aided and abetted by special advisory panels, established for this purpose, from a divided community of academic scientists. The realignment was a major obstacle for NRC's leaders and, for a while, they did not appear to be able to overcome it. Only recently have there been signs of positive change in NRC. But a significant fraction of what constituted NRC's (and Canada's) science glory has fled and it will not be easy to restore it. We should all wish NRC well for the next century.

There is a truism which Canada needs to relearn about science and the economy. If you want to be world class in the impact of science on the economy what you need is world-class ideas and world-class scientists provided with the right culture. For this purpose fundamental science is at least as good a vehicle as science more closely related to the desired spin-offs, in part because it often attracts better scientists. Governments in many countries resonate with this truism, as do their constituents, even when the bureaucracy develops contrary views. For example, even the most right-wing parties in countries like the United States advocate a strong central role of government in long-range research. By being directed to focus on the stimulation of Canadian industry, rather than keeping an important component of fundamental research and the top notch scientists who go with it, NRC was weakening its ability for that very mission. The NRC of Gerhard Herzberg and D.K.C. MacDonald was a great vehicle for fundamental research and for spin-offs. It would be wonderful for Canada if, in the new century, NRC were encouraged to sparkle like that again.

Canada had moments when visionary scientists interacted directly with senior elected politicians and initiated major science programs. The handshake of C.J. Mackenzie with C.D. Howe for the creation of Chalk River was one such moment; the interaction of George Laurence with his Minister, Jean-Luc Pépin, for the creation of TRIUMF was another. More recently the possible science programs have been carried by non-visionary bureaucrats fettered with unnecessary science policy concerns. In the crucial game of science, since 1980, the removal of much of NRC's fundamental science made the score: Bureaucrats 1, Canada 0.

The development of Canada's nuclear energy program and the physics research of the Chalk River Nuclear Laboratories (CRNL) are the subject of three articles in this issue. Phillip Wallace gives a vivid first hand account of the Montreal Laboratory during WWII, at which Canada's nuclear program was initiated. Jim Geiger and Tom Alexander give a history of nuclear physics at CRNL. Bill Buyers describes the personalities involved in the creation of Canada's neutron program.

Greatness was thrust upon Canada in nuclear physics. Ernest Rutherford, whose impact on Canada is described by John Robson in this issue, literally created nuclear physics. In the first decade of this century he was at McGill University and then, during several decades at the Cavendish Laboratory in Cambridge, England, he trained a number of Canadian scientists who were key to the development of Canada's program. Soon after fission was discovered, one of Rutherford's students, George Laurence, began work at the wartime NRC laboratories in Ottawa on building a reactor. The future program was shaped by a thrilling wartime story in which most of the world's supply of heavy water was spirited out of Norway, just before the Germans could get hold of it, and sent to Canada, via France and Britain. The dice were cast in the Quebec City meeting, in August 1943, of Churchill, Roosevelt and Mackenzie King, at which the Allies assigned to Canada the role of exploring heavy-water reactors. This was a part of the overall effort to exploit fission, of which the Manhattan project was the biggest component. As Wallace describes, French, British, American and Canadian physicists of the top rank then worked at a secret laboratory located at the University of Montreal. This was the cradle of CRNL. There was great concern about the state of the German fission program and significant suspicion about collaboration with the USSR: there were tensions about the connections of the initial French management of the Montreal laboratory with Frederic Joliot-Curie in France, a known Communist and possible informant for the USSR. In wartime secrecy, with a cast of international luminaries, CRNL was conceived and then created by the famous handshake of NRC's visionary president, C.J. Mackenzie with the great cabinet minister, C.D. Howe. Great Canadian physics followed.

The 70th birthday of W. Bennett Lewis at the home of Erich Vogt in Vancouver. In the photo from left to right are: Mrs. Barbara Vogt, W. Bennett Lewis, Gordon Shrum, Akito Arima (currently the science Minister of Japan), George Volkoff and Mrs. Olga Volkoff.

It was great to be a young Canadian physicist when CRNL began. Physics emerged from WWII as the queen of the sciences and nuclear physics was the dominant field. The CANDU reactor program was the lodestar and the NRX reactor, coming into operation, was the stepping stone. It led the world in neutron flux and, indeed, CRNL soon was among the strongest laboratories in the world in nuclear physics. There was a "Golden Era" of several decades after the war in which CRNL placed Canada on centre stage in the world science effort as at no other time.

The "Golden Era" was an exciting mix of people and ideas. Propelling the program was W. Bennett Lewis who commandeered great science to bring CANDU to fruition. First Bernice Sargeant, and then Lloyd Elliott, gave great personal leadership to the physics research. John Robson gave the first accurate measurement of the lifetime of the neutron. Pontecorvo and Hincks measured the lifetime of the muon and studied the muon's rare decays. Hanna and Pontecorvo were the first to pursue solar neutrinos by the chlorine radiochemical technique and to search for neutrino mass from the beta decay of tritium. Kinsey and Bartholemew initiated high resolution neutron capture gamma-ray studies. Brockhouse and his colleagues began the Nobel-Prize winning work on the use of neutrons for the dynamics of condensed matter. Elliott and Bell used new scintillation counters for a wide ranging program of beta and gamma ray spectroscopy. Graham, Ewan and Geiger used a superb beta spectrometer for beta spectroscopy and later Ewan, Fowler and Tavendale developed Li-drifted Germanium detectors which revolutionized nuclear spectroscopy. Milton and Fraser carried out systematic measurements of neutron emission from fission fragments. These are just a few examples of the experiments which characterized CRNL during the "Golden Era". The supporting programs in theory, electronics and detector development were also outstanding. A strong characteristic of CRNL was the extraordinary intensity with which physics was pursued and the correspondingly strong personalities of the physicists involved.

,The most celebrated science in this "Golden Era" pertained to the Chalk River tandem in the late 1950's and beyond. Eric Paul, Einar Almqvist and others had pioneered work at CRNL with low-energy electrostatic accelerators but it was the world's first tandem accelerator at CRNL which established the importance of high quality beams for nuclear spectroscopy and led to hundreds of similar machines being built elsewhere. The initial leaders of this tandem work were Bromley, Gove and Litherland, who all subsequently had brilliant careers at other institutions, as well as Ferguson, Kuehner and Almqvist. They were followed by Haeusser and Hardy and many others who, through many decades, maintained the very high quality of nuclear physics at CRNL as decribed by Geiger and Alexander in this issue.

During the "Golden Era", while neutron physics was born at CRNL and nuclear physics flourished, Alistair Cameron became a leader in the new field of nuclear astrophysics. The field of nucleosynthesis and stellar evolution began in the late 1950's with the work at Cal. Tech. of Burbidge, Burbidge, Fowler and Hoyle (for which Fowler subsequently received the Nobel Prize). Cameron's work at CRNL was contemporaneous and of great importance for the field. After leaving Chalk River in the early 1960's Cameron remained one of the key leaders of the field.

Why, then, was the nuclear physics program at CRNL terminated three years ago and the Nobel-Prize winning neutron program handed off to NRC? Certainly fiscal pressures from the federal government existed and perhaps the culture at CRNL no longer commandeered fundamental science for CANDU as it had in Lewis' day. However almost all of the full blame must be assigned to the lack of vision at Atomic Energy of Canada Limited (AECL), which had forgotten the powerful role that fundamental science can play for its main mission of economic nuclear power. It was a failure of the system, of AECL management, and of its prestigious Advisory Councils. It was the same lack of visionary leadership which led to the reduction of fundamental physics at NRC (Game score: Bureaucrats 2, Canada 0).

The failure of leadership was the subject of an editorial by Fred Boyd in the Bulletin of the Canadian Nuclear Society (Vol.20,No.3, October, 1999). Entitled "Leadership" the editorial said: "From our (worm's eye?) view, an element that has been sadly lacking in our Canadian nuclear program over the past few years is leadership" .... "Each organization appears to be going its own way, concerned with only its particular interest and only for the immediate future"... He then quotes some questions posed by the AECB president, Agnes Bishop: "What about the research and development necessary not only for safety but to maintain the industry and move it forward? There are few young people in the nuclear program - where is the next generation of nuclear scientists, engineers and technicians to come from? What about the credibility of the nuclear industry in the eyes of the public?" In the special case of Chalk River there is a splendid new opportunity for AECL for redemption and to return to fundamental physics for the support of the reactor program. The proposed Canadian Neutron Facility may now be funded by the federal government. It is a very important research opportunity for Canada and, although it is now under the aegis of NRC, its physical location at Chalk River could be helpful to CRNL to make CANDU prosper.

CANDU must prosper. The world will need CANDU in the next century and Nature intends that nuclear power should thrive in Canada. We celebrate CANDU as Canada's greatest scientific and engineering accomplishment. For a world needing clean energy sources, CANDU is the ideal vehicle which does not induce global warming. Canada had the initiative for CANDU thrust upon it during WWII and now Nature has provided us with the uranium "potatoes" in our northland so that we have the world's best source of nuclear fuel. These "potatoes" are spectacularly-rich newly-discovered deposits of uranium a few hundred meters underground and shaped like a potato, with dimensions of about a hundred meters. For example, the McArthur River "potato" 620 km north of Saskatoon has 416 million pounds of uranium oxide at an average grade of 13%, with some core drillings averaging 35%. Nowhere else on our globe is there anything close to such richness. This is not only a miracle but also a signal that CANDU is our destiny.

The fate of our two large national laboratories makes it useful to ponder about them. Alone among the western nations, Canada terminates rather than redirects its national science programs. The termination of nuclear physics at AECL and of fusion research at IREQ in Quebec (Bureaucrats 3, Canada 0), as well as the great curtailment of fundamental science at NRC, are great blows to Canadian physics. There are very few examples of similar terminations abroad. For example, a few years ago when the LAMPF accelerator project was cancelled at Los Alamos National Laboratory, the large group of scientists involved were directed to other projects, mostly also in fundamental science. It takes much time to establish a world-class science laboratory which unthinking Canadian bureaucrats can terminate at once. The kind of options for NRC given above also could have been used for any redirection of CRNL and the fusion laboratory, although it must be said that, in the case of the fusion program, we in Canada had no other active laboratory and therefore the cancellation terminated our ability to remain literate in the field. Compared to all other competing western countries, Canada has very few national laboratories and very little "Big Science", and it is most frivolous in terminating what it has.

As the century closes, we can celebrate the wonderful science which we have enjoyed from our national laboratories and look forward with optimism at those which still continue. We have the continuation of TRIUMF in Vancouver, the full exploitation of the Sudbury Neutrino Observatory (Bureaucrats 3, Canada 1), the beginning of a synchrotron radiation facility in Saskatoon (although this was preceded by the cancellation of the very active linac laboratory in Saskatoon and therefore the score was: Bureaucrats 4, Canada 2) and also the prospect of a major new neutron research facility at Chalk River. They all contribute to our hope for the future.

University physics research emerged and flourished after WWII as described in this issue by Mel Preston and Helen Howard-Lock. There had been strong graduate schools in Europe and the United States since the beginning of the century, and almost all Canadian physicists received their graduate degrees abroad. With the help of the NRC graduate support programs, a few dozen Ph.D. degrees in physics had been awarded in Canada during the first half of the century. Then the flow erupted. In the second half of the century more than a thousand Canadians - and many foreign students - received Ph.D. degrees in physics at Canadian universities. Correspondingly, physics research at Canadian universities flourished, first through grants from NRC but, in the last quarter of the century, from a special agency - The National Science and Engineering Research Council (NSERC) established for this purpose. NSERC has given vital support through innovative programs but has consistently been starved for funds.

In Quebec there had been virtually no francophone physicists until a refugee from Italy, Franco Rasetti, came to Laval University during WWII. There had been a strong tradition of classical colleges, preparing students for the law or for medicine. Any francophone seeking to enter a science career needed first to graduate from one of the classical colleges and almost no one overcame that hurdle. Rasetti had been one of Fermi's principal colleagues at Rome. The impact of his stay at Laval is described in the article in this issue by Le Tourneux. Simultaneously, physics research and graduate training began at the University of Montreal and subsequently at many other Quebec post-secondary institutions. Within very few decades a disproportionate number of Canada's best physicists emerged from Quebec. The so-called "Quiet Revolution" which swept Quebec four decades ago clearly carried with it deep intellectual components from which this momentum for physics arose.

Postwar university physics research first developed strongly in experimental nuclear physics and in theoretical physics, with the continuation of some longer-standing programs in atomic and molecular spectroscopy and in low temperature physics. The focus on nuclear physics was not surprising considering the worldwide development of physics and Canada's strength at Chalk River. The first major nuclear physics accelerator at a Canadian university was the McGill cyclotron (see the vignette on J.S. Foster in this issue). The second was the Saskatoon linear accelerator (see the article in this issue by Preston and Howard-Lock). When the Chalk River tandem led to a worldwide network of low energy accelerators for nuclear spectroscopy many Canadian universities followed. They were in no special order and probably an incomplete list: McMaster, Manitoba, Laval, Montreal, Queens, Ottawa, Toronto, Alberta, and British Columbia. They were supported initially by grants from the Atomic Energy Control Board (AECB) and later by NSERC. Most of these university accelerators have been decommissioned or adapted to uses other than nuclear spectroscopy. As the worldwide interest in subatomic physics changed to higher energies and larger machines for nuclear physics, and to very large centers for particle physics, the Canadian program followed.

There was some vision evident at the AECB, led by George Laurence, when a large, multi-university project, TRIUMF, was funded in 1968. This project was a natural one for Canada. John Warren had trained a large group of excellent nuclear physicists at UBC who needed a challenge. They were joined by physicists and chemists from the University of Alberta and from two new universities, Simon Fraser and Victoria. Reg Richardson, who had come from B.C. to work with Ernest Lawrence at Berkeley, had just proposed a very innovative cyclotron, a negative-ion, sector-focused machine to produce protons at the 500 MeV. Such a facility with its continuous, high-intensity beams at medium energy was then sought, worldwide, for the new directions of nuclear physics. TRIUMF has now worked for several decades as a very successful meson factory and has also developed major opportunities for condensed matter research with muons as well as for medical applications. The vision which created TRIUMF was no longer evident in the Canadian government when the proposed KAON Factory was turned down in 1994 (Bureaucrats 5, Canada 2). However, TRIUMF remains strong and enters the new century with world-leading new facilities for radioactive beam research.

At this moment the eyes of the world are on the Sudbury Neutrino Observatory (SNO) which was funded a decade ago and is now in its initial year of operation. There is a great deal of new interest in neutrinos, pertaining to the questions of whether or not they have mass (with the consequence that the different neutrino species oscillate among each other) and about the flux of neutrinos from the central core of our sun (the solar neutrino problem). A number of large neutrino observatories have been built among which SNO is very special. Its detector uses Canada's large reserve of heavy water for CANDU - a gift which makes SNO possible only in Canada. With SNO's heavy-water detector deep underground in a Sudbury mine, one measures deuterium dissociation by neutrinos as well as neutrino scattering from the electrons of deuterium. Consequently this unique observatory can distinguish the species of neutrinos, their direction, and the flux of each species. It promises to be a major new tool for resolving the long-standing solar neutrino problem. SNO is an imaginative idea and involves scientists from across Canada. We celebrate its promise.

Canada continues to struggle for a role in particle physics. In the absence of KAON we have no home-based accelerator laboratory, but there are reasonably strong user groups at many universities who continue to be welcomed at large, particle physics facilities abroad, especially at CERN in Geneva, Switzerland, where the large proton-proton collider (LHC) is scheduled for completion in 2005. It will search for the field quanta (Higgs particles) which may tell us how the quarks and leptons acquire mass, for evidence of supersymmetric particles and for any possible surprises at the energy frontier. Other involvements include the B-Factory at SLAC, just beginning operation, and also the electron-proton collider (HERA) in Hamburg, Germany. In each case significant contributions are made by Canada to the detectors and/or to the accelerators. Although the university groups involved are strong and NSERC has continued to nobly support these groups with its meagre total funds, Canada's expenditures on subatomic physics remain at a very low level, per capita, compared to those of other G7 nations.

Responding to world-wide opportunities, condensed matter physics gradually became a strong component of the research profile of most Canadian universities. At a few universities, such as Waterloo and Simon Fraser, it dominated the interests of the department. In Canada it lacked the stimulus of very active industrial research laboratories working in this field. We had no equivalent of Bell Telephone Laboratories or IBM, etc., which contributed so greatly to condensed matter physics in the U.S.A. It has been a wonder that Canada, which was able to negotiate agreements with the U.S.A. for automobile production and defence production, never even attempted to do so for the research laboratories of large multinationals, an agreement which was arguably even more vital for its national interests. Our so-called science policy appears to have been sterile rhetoric. For the new microelectronics laboratories the scene is different and they have significant impact on Canadian industrial research in general and the employment of physicists in particular. Recently Nortel has emerged in Canada as a truly global telecommunications company which has impacted on the research on silicon devices in Canadian universities. There is now a significant community of users at Canadian universities for the synchrotron radiation facilities and for the proposed new neutron facility and, if both materialize, then condensed matter physics will remain strong.

There are many other Canadian achievements to celebrate. The wide spectrum of such achievements is illustrated with the work of the winners of the CAP prizes listed in the article in this issue, by F.M. Ford, on the "Evolution of CAP/ACP Activities". A few examples of achievements worth special mention are, in no particular order:

1. The creation of the Canadian Institute of Theoretical Institute of Astronomy (CITA) at the University of Toronto. This

institute has been a world leader in its field for several decades.

2. The establishment of the Canadian Institute of Advanced Research (CIAR), with Fraser Mustard as its first head. This institute has been very effective at funnelling private sector funds to some of Canada's finest physics research.

3. The pioneering work of Harold Johns in radiation therapy and the development of the company Nordion, a world leader in isotope production.

4. The strength of Canadian research in Geophysics and Oceanography, for which Tuzo Wilson pioneered continental drift and Robert Stewart and others did outstanding work on the air-sea interaction.

5. The development of great strength in atomic physics at the University of Windsor, York University, Laval University and several others.

6. The role Canada played in the Pugwash conferences which played a prominent role in nuclear disarmament and in the reprochment between East and West in the hottest years of the Cold War. Pugwash was founded by the Canadian-born industrialist, Cyrus Eaton, and is named after his home town, Pugwash, Nova Scotia, where the movement's first meetings were held. Major figures in Pugwash included Sir Josef Rotblatt (recent Nobel Peace Prize winner) and Sir Rudolph Peierls, who influenced many Canadian physicists.

7. Theoretical physics has been at considerable strength for much of the century but, recently, is more outstanding than ever.

8. The birth of the Canadian Association of Physicists (CAP) after WWII and its interesting subsequent history and evolution of activities as described by Donald Betts and Francine Ford in this issue. The strong individuals who led Canadian physics are given not only by the vignettes of prominent physicists sprinkled throughout this issue but also by the lists of CAP presidents and prize winners which appear as Tables in the article by F.M. Ford in this issue.

The lack of an even playing field has continued to be a factor in luring many of our best physicists abroad, especially to the United States. They include Nobel Laureates, such as Kohn, Schawlow and Taylor, and many other prominent scientists. For example, D. Allan Bromley became Presidential Science Advisor in Washington during the recent Bush administration (1990-94). He is also regarded as the father of heavy-ion physics and has more honorary degrees (>40) than, probably, any other Canadian scientist. He would have been among the Canadian icons for whom we have vignettes in this issue if he were not so very alive and well.

In summary, during the past century there have been many exceptionally fine achievements in Canadian physics. The very best occurred in our two large national laboratories which recently have been jolted by major perturbations, but which may now have opportunities to again play an important role for physics and for Canada. We should celebrate and remember what was achieved.

Whither Canadian physics in the next century or Millenium? The challenges for physics are as great as they have ever been. The conditions for physics in Canada are basically sound for us to respond to the challenges and, therefore, for Canadian physics to prosper. The wonder remains. It is foolish to forecast where it will lead us, but some of the challenges can be envisaged. Some young Canadian may help to discover how gravity fits into a unified description of Nature's fundamental forces. Others may help us to learn more about the structure of the early universe and its dynamics. A new interpretation of quantum mechanics, supplanting the Copenhagen Interpretation, may take hold. Large steps in our understanding of complexity seem to lie just ahead. There is much scope for Nature to continue to surprise and amuse us. Therefore many young Canadians will continue to be stimulated and will want to respond.

For our national response to the new physics opportunities, it is important that the high quality of Canadian physics undergraduate education continues at our universities. The possibility of good graduate training in almost any field of physics can now be found at our universities. We have abundant natural resources and a high quality of living which allow us - nay, they should compel us - to employ more science for the economic benefit of the nation. We are poised for greatness.

There are some indications that a balanced physics program in Canada can be hoped for with strength in all three sectors: universities, government and industry. In the recent past we have developed strong university programs, supported by NSERC, which, however, remain underfunded. The corresponding development, for balance, of industrial research and of national laboratories has been lagging. In microelectronics the industrial component is improving. The two large national laboratories, NRC and CRNL, have opportunities for evolving toward their strong former position in the national program of physics research. With less focus on the national debt and more on our international competitiveness, the federal government has the opportunity now to provide more leadership in science. By celebrating what has been best in our past we may help to direct our future to even finer physics. Canada deserves it.