Max Born
A Celebration
10. December 2004  Max Born Institut
On December 10 and 11, 2004, the Max Born Institute in Berlin celebrated the 50th anniversary of the awarding of the Nobel Prize to Max Born, whose name our institute is honored to bear. The ceremony comprised a scientific colloquium and a reception on December 10, and lectures on his life and science and an exhibition for the general public on the next day. Incidentally, December 11 also marked the 122nd anniversary of Max Born’s birthday.

The vestibule of the Max-Born-Saal, our main lecture hall, will from now on be graced by a plaque, modelled after a well-known pencil drawing by Max Born’s daughter, Gritli Born, and unveiled on this occasion. We express our gratitude to Professor G.V.R. Born, his eldest son, for permission to use the drawing as a template.

The life and the work of Max Born was commemorated in a two-day exhibition organized by Dr. h.c. Jost Lemmerich, whom we thank profoundly for his remarkable work in designing and assembling the exhibits. We note that they were later also displayed during the Annual Meeting of the German Physical Society in Berlin in the spring of 2005. During our ceremony, the exhibition attracted considerable attention, most notably by the students of the Max Born Gymnasium in Berlin who were excited to learn about the life of Max Born and to meet his son Gustav in person, an event that was apparently much enjoyed by both parties.

The Max Born institute was proud to welcome more than 200 guests from all over Germany to this ceremony. In the present volume, we present the three main lectures delivered on December 10 to our guests and to the staff of the institute. We were privileged to hear Professor G.V.R. Born, FRS, speak about “Max Born: a filial memoir”, encompassing reminiscences of his father’s life and on his own mounting concern — being an eminent scientist himself, albeit in a completely different field — about the effects of science on the future of mankind.

Professor Paul B. Corkum, FRS, Ottawa, Canada, gave a vivid account of the currently emerging field of attosecond physics, which allows scientists to image and observe atomic phenomena on the time-scale of the electronic motion in molecules and atoms. In many aspects, this work rests on Max Born’s revolutionary achievements during the early decades of the past century, where science first developed the concepts that govern the motion of particles on atomic scales. Professor Knut Urban, President of the German Physical Society DPG, gave an insightful summary of the volume and scope of Max Born’s work in physics. The ceremony was completed by a brief address by the Rector of the University of Wroclaw, Max Born’s birthplace. This address is also contained in the present booklet.

The Max Born Institute takes this opportunity to express its sincere gratitude to the speakers, to the organizer of the exhibition, and to our guests. Above all, however, the Institute is proud to honor and keep alive the memory of one of the most outstanding physicists and humanists of his time.
Wolfgang Sandner, Managing Director of MBI, during his welcome address

MBI Directors Thomas Elsaesser and Ingolf V. Hertel discussing with Gustav Born

Gustav Born, after unveiling the memorial plaque at the entrance to the Max Born Lecture Hall. The plaque was modeled after a pencil drawing by Max Born’s daughter Gritli. The original is in the possession of the Born family, with a copy given to the MBI on the occasion of the Institute’s inauguration ceremony in 1994. Jost Lemmerich is standing to the right of Gustav Born

Gustav Born with students from the Max Born Gymnasium, Berlin Pankow, and Director Helga Schulz-Lewicka
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Max Born with Princess Margareta.

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The King of Sweden applauding.

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The King with Hedi Born.
Fig. 1
Max Born (ca 1960).

Fig. 2
Max Born: pencil drawing by his daughter Gritli Born.
I would like to thank the Managing Director of the Max-Born-Institute for Nonlinear Optics, Professor Wolfgang Sandner, and his colleagues for inviting me to address this distinguished meeting in celebration of the award of the Nobel Prize for Physics to my father Max Born fifty years ago today, on the 10th December 1954. Tomorrow, the 11th December, is the anniversary of his birth in 1882; he died on the 5th January 1970. So this occasion evokes many memories of my remarkable father [1, 2].

One memory is of course of the Nobel Prize occasion. My parents went alone to Stockholm and came back with good stories and evocative pictures [3, 4, 5, 6]. Those occasions bring together strange bedfellows. The Nobel Prize for Literature that year went to Ernest Hemingway who, in character, did not turn up for the Award. I have just read about him in the biography of Martha Gellhorn, the remarkable war correspondent who was his second wife (Moorehead, 2003) [7]. Two more different characters than Hemingway and Max Born could hardly be imagined: Hemingway brutal and arrogant; my father gentle and modest (not to mention their opposite attitudes to women).

The Nobel Prize came at the end of the first year in the little house in Bad Pyrmont where my parents had retired in 1953 [8]. It was just at the right time to reinforce his main retirement occupation, which was to educate thinking people in Germany and elsewhere in the social, economic and political consequences of science [9]. He was, of course, principally concerned with the implications of nuclear physics for war and peace but also with other, what he called pathological features of our scientific age such as rocketry and space travel. With like-minded friends, notably Otto Hahn in Germany [10] and Einstein, Bertrand Russell and others, Max Born began to challenge public opinion with the revolutionary
implications of scientific discoveries. My father was a founding member of the Pugwash movement, and remained indefatigable in promoting his views through lectures, broadcasts and newspaper articles, and in conversation with people at all levels from his postman to Government ministers. The clarity and sincerity of his urgings made a profound and lasting impression on many people throughout the world, particularly on the younger generation. His published speeches and writings, e.g. My Life and My Views, remain well worth reading for insights and conclusions so well reasoned that they seem self-evident. It says much for the regeneration of Germany as a liberal democracy that, although his public utterances were often opposed to official policy and despite remaining a British citizen, there was never any question about his freedom to say what he liked. On the contrary, the German Government bestowed on him its highest distinction, the Grosse Verdienstkreuz, the German equivalent of the British Order of Merit.

At this point I feel bound to declare my credentials: I am a medical biologist, neither a physicist nor a mathematician, and therefore unable to pay any kind of informed tribute to my father’s massive contributions to science, most conspicuously to the foundations of quantum mechanics for which he was awarded the Nobel Prize, and of solid state physics which, in the opinions of Sir Neville Mott, where themselves of Nobel Prize calibre. His insights and originality were matched by the clarity in the exposition of his own ideas as well as those of other physicists. Max’s account in Physikalische Zeitschrift of the theory of relativity, published in 1916 soon after it first appea-
red, elicited an admiring acknowledgment from Einstein. Max then wrote the first book on the subject entitled Einstein’s Theory of Relativity [11]. This was published in 1921 and did much to spread knowledge and understanding of the relativity revolution around the world. The book also influenced Sir Karl Popper, who adopted Max’s powerful explanatory model, and used it whenever he discussed scientific progress (see Krieger, 1996).

Another immense pedagogic achievement is the Principles of Optics by Max Born and Emil Wolf [12]. This large tome, which must be a Bible in this Institute, was written after the War as a follow up to his earlier textbook Optik: Ein Lehrbuch der Elektromagnetischen Lichttheorie, published by Springer in Berlin in 1933: an unfortunate timing because it coincided with our forced emigration; I understand that it is soon to be republished. The Principles is still going strong: under Emil Wolf and with several specialist contributors, it continues in use around the World as “the most adult exposition of theoretical optics ever produced”. A comment of my father’s tells us about his attitude to work: “I wrote a successful textbook on optics and many years afterwards another. This shows that in order to write a learned volume one need not specialise in the subject but only grasp the essentials and do some hard work”. What hard work! Altogether Max wrote twenty-six books and about three hundred and fifty papers. (Just for comparison, in my long working life, albeit as a biological experimenter not a theoretical physicist, I managed to produce about three hundred papers including some book chapters, but no book. Perhaps I was put...
Fig. 16
Letter from Max to Gustav Born dated 21st August 1945 (shortly after the atom bombing of Hiroshima and Nagasaki).
Fig. 15
Max and Hedi Born in Bad Pyrmont (in the late 1950’s).

Figs. 17, 18
Letter from Max to Gustav Born dated 28th July 1939, to his birthday: “In spite of your youth, you are my best friend and comrade.”
off by my Oxford Professor Howard Florey [13] who said to us: “don’t waste your time writing books – keep doing experiments”). Max continued: “I never liked being a specialist and have always remained a dilettante, even in what were considered my own subjects.” His comment certainly enlarged the notion of dilettantism!

But perhaps the most amazing element in my father’s productivity, which will become much more widely known with the publication of Nancy Greenspan’s biography of Max Born next spring, is his almost unimaginably vast correspondence, made even more astonishing for my children, the e-mail generation, by being written by hand. It is hard to describe let alone comprehend the extent of his correspondence. Most of the letters, all in his small, crystal-clear handwriting, have been collected in two places: the Prussian State Archive in Berlin has about eight thousand of them including the correspondences with Erwin Schrödinger and with Albert Einstein. Many more thousand are in the Born Family Archive in Edinburgh University, which holds not only letters to and from other important scientists and public figures but also the enormous correspondence with family. The correspondence is a monument not only to my father’s responsiveness to developments in science and to his perspicacity about political and social issues, but also touching testimony of his devotion to family, friends and colleagues [14]. My mother was equally prolific as a letter writer and, consonant with her very different interests, her correspondence embraced eminent cultural contemporaries including André Gide, Romain Rolland, Albert Schweitzer and Freud’s disciple Lou Andreas Salomé, an intimate friend in Göttingen. Both parents often wrote letters together [15], making them particularly interesting because of their different views of the same people and events.

You can imagine the wonder and gratitude with which I look back on the many hundreds of letters I received from my father during the periods I was away from home. For almost three
years I was a Medical Officer in the British Army on War service in the Far East. Throughout that time my father wrote to me at least once a week, my mother almost as often. I kept all the letters, and he kept all of mine (as he did with my sisters) [16]. Re-reading them now, more than half a century later, brings up a mix of powerful emotions. As an expression of love and care for his family and myself these letters cannot be surpassed. Although fully aware of my lack of knowledge of his own science, my father did his best to let me follow his thinking and to share the pleasures and disappointments of his scientific preoccupations, for example with his theory of liquids and about what he called reciprocity on which he worked in Edinburgh in the 1940s and '50s. For me the most touching letters is from 1937 [17, 18], when for my sixteenth birthday he wrote that despite my youth I was his best friend and comrade. That he meant it is shown by the openness and intimacy of his letters - and of our conversations – right up to the time of his death in 1970. That such a great man who happened to be my father gave me his total trust has, as you might expect, had a profound influence in my life.

What comes across from the letters is his strong sense of moral responsibility. This had been implanted during his childhood in Breslau by his father Gustav [19], Professor of Anatomy at the University, who up to his early death in 1900 at the age of fifty did original and important research in experimental embryology. (Most importantly, he discovered the function of the corpus luteum: Fraenkel,1901.) [20] Max wrote about his father: “I am certain that his deepest conviction was that the most fundamental rules of ethics can just as well or even better be derived from the study of nature, including man, than from religious tradition. For he believed that these rules during the course of evolution culminating in human civilisation have become intrinsic parts of our soul …” – a persuasive Darwinian argument for the evolutionary origin of conscience! “He imbued in me a deep respect for the right of every living creature to enjoy its span in the light of the sun” (Born, Brandt and Born, 1950). Nancy Greenspan records that one
summer grandfather Gustav returned from the Tyrol with a rare Alpine salamander for Max. He explained to his son the animal’s need for special care and feeding, and for a couple of weeks Max carefully followed his instructions. One night, however, he forgot. The next morning he found the salamander dead. His father did not scold him but rather used the event to illustrate the meaning of life and death. Max wrote later: “From that moment I suddenly knew what it meant to make another creature suffer and die.”

Moral responsibility so imbued, together with the high ethical standards of his Quaker wife, guided Max in every sphere, personal, public and political. This was recognised not only by those who knew him personally but through his speeches and writings all over the World.

After our forced emigration from Germany in 1933, we lived for three years in Cambridge [21] and then went to Edinburgh where Max followed Sir Charles Darwin in the Tait Chair of Natural Philosophy, in reality mathematical physics [22]. My parents foresaw the Hitler war coming. In 1938, during my last year at school, my father advised me to study medicine because as a doctor I would not have to kill people in the War. (He added that I was less likely to be killed myself.) I followed his advice, became a doctor then a medical research worker like my grandfather, and never regretted it [23]. Well informed by colleagues, Max was aware before the War of the possibility of an atomic bomb. But despite the threat that Hitler’s Germany might produce such a horror, apparently more than likely under the direction of his former assistant Werner Heisenberg [24], Max kept his distance. In 1943 Niels Bohr who was half Jewish left Denmark secretly for Sweden from where he was flown in a Royal Air Force Mosquito bomber to England. Bohr stayed under an assumed name in London’s Buckingham Gate, quite close to the Palace when my father asked me to deliver a message to him. I clearly remember that meeting of sixty years ago. Bohr was on his way to Los Alamos to take part in the bomb’s deve-
lopment, and I have no doubt that my father’s message was to the effect that he would not participate. I also recall a review in The Listener, at that time the house journal of the BBC, of Robert Jungk’s book Brighter than a Thousand Suns which gave the first coherent account of the development and dropping of the atomic bombs. The claws of my memory have kept a firm grip on the following sentence. “Of all the brilliant men that parade through these pages only one, Max Born, refused from the start to have anything to do with the devilish invention”. I am particularly proud of him for that!

With this in mind, great interest attaches to Max Born’s relationship with Robert Oppenheimer [25], who joined Max’s Institute in Göttingen in 1926 and during the War became Director of the Manhattan Project which produced the first atomic bombs. Göttingen was an exciting and exhilarating environment for Oppenheimer and the other brilliant young men working with Max Born, because their first papers on quantum mechanics were just appearing. In November 1926 Oppenheimer wrote to his friend Francis Ferguson: “The science [in Göttingen] is much better than at Cambridge, and on the whole probably the best to be found”. In his contribution to a Festschrift for Oppenheimer’s sixtieth birthday Max refers to the Born-Oppenheimer approximation, their most important work together, and makes complimentary comments; Max clearly recalled their collaboration as entirely enjoyable. That is interesting, because it sheds light on my father’s ability to empty his memory of unpleasantnesses. An anecdote from Oppenheimer’s Göttingen period shows him as a somewhat conceited young man, whose brashness caused trouble in the famous weekly seminars on the atom by dominating the discussion to the detriment of the other young participants, Heisenberg, Fermi, Teller, Weisskopf, Maria Göppert [26] – not people lightly ignored. After a while they complained, in writing. Max put their letter on his desk in such a way that Oppenheimer could not fail to see it when he came to talk about his thesis. The ruse worked and the interruption ceased. However, thinking that Oppenheimer
Fig. 27
Albert Einstein: photograph with German dedication reading: “Max und Hedi Born mit besten Grüßen.”

Fig. 28
Max and Hedi Born in Lindau in the 1960’s.

Fig. 29
Title page of the published correspondence between Max and Hedi Born and Albert Einstein (published in 1971; republished in the Einstein Year 2005).
Fig. 30
Gustav Born as Patron of the Max Born Gymnasium in Germering – Munich with the Headmistress Barbara Loos at a festive occasion (in June 2000).

Fig. 32
Gustav Born as Patron of the Max-Born-Gymnasium in Backnang, near Stuttgart, with the headmaster Günter Ost on the left of the photograph and the former headmaster Ingolf Eichberg on the right, with a group of students and their teacher Barbara Wangler.

Fig. 33
Backnang Gymnasium students with their teachers on a visit to Professor Gustav Born’s laboratories in the William Harvey Research Institute in London (in the 1990’s).

Fig. 31
Gustav Born’s commendation of the fund raising activities for the Germering School.
might have been seriously offended, my father blamed this episode for the lack of invitations to the United States after the War – actually most unlikely because Oppenheimer, as is well known, lost his authority and influence during the McCarthy period when his communist youth made him an object of suspicion. Max Born’s professional and personal relationships with friends and colleagues have been described in his own writings and in memoirs and biographies by others, notably those about Albert Einstein [27].

The enormous influence of Einstein on science and on world history is common knowledge. His influence on those who knew him personally was also very great. This is borne out by the correspondence between Einstein and my parents Max and Hedi Born [28]. These letters together with my father’s wide-ranging commentaries were first published in Germany in 1969. Brilliantly translated by my late sister Irene Newton-John, they were published in English in 1971 by Macmillan (Born, 1971) [29]. The book will be reissued in early 2005 – the Einstein Year – with an introductory note by myself and an updating preface by Diana Buchwald and Kip Thorne of Caltech. So this unique record will be available to new generations.

The letters are touching testimony to a close friendship from their time together in Berlin during the First World War until Einstein’s death in 1955. The tone is set by the first surviving communication, still in my possession: a handwritten postcard from Einstein dated 1916, the year after publication of the general theory of relativity, in response to a laudatory article by Max Born (1916). Einstein writes of his happiness at being completely understood “by one of the best of my colleagues”. Einstein had been so taken by an earlier letter from Hedi that it may have induced him to keep the letters from both parents thereafter. That they should have preserved Einstein’s letters is not really surprising.

From my early years I remember how often Einstein came up in family conversations. When the Nazis took power in 1933 and my father was ousted from his Göttingen Chair Einstein was already abroad; he urged my parents to leave Germany immediately, and thus helped to save our family. Einstein went to America where he stayed for the rest of his life. My father took his family to Britain. They never met again, but the friendship remained intact.

The friendship survived conflicting attitudes towards post-war-Germany. My parents returned to Germany in 1953 to help with the country’s democratic rehabilitation. In this purpose they were greatly aided by my father’s Nobel Prize a year later. Their return was understandably condem-
ned by other refugees including Einstein. As it turned out my parents were fully justified in this
difficult decision. Their achievements have been enduringly effective. Deeply impressed myself,
I have tried in small ways to continue their work, inter alia by working for the two large and
excellent secondary schools in Munich and near Stuttgart named after Max Born [30-33].

In a book of essays entitled The Luxury of a Conscience, actually in German, my parents wro-
ted about their respective relationships with Einstein, my father mainly about their scientific dis-
cussions and my mother about Einstein the private person. Max’s article ends: “I know what it
means to have been his friend”; and Hedi’s: “Now his living voice is silent, but those who heard
it will hear it to the end of their days”.

The famous divergence between Einstein and Max Born in their basic scientific tenets in no way
diminished their mutual respect and affection. As Bertrand Russell comments, both were humble as well as brilliant, so that opposing convictions did not make them think less of the other.
The divergence was of course the unwillingness of Einstein to accept that which Max Born evi-
dently considered his most important contribution to science, namely the statistical interpreta-
tion of quantum mechanics (Born, 1955). Those words form the title of his Nobel Lecture given
this day fifty years ago, from which I should like to quote the first paragraph: “The published
work for which the honour of the Nobel Prize for the year 1954 has been accorded to me does
not contain the discovery of a new phenomenon of nature, but, rather, the foundations of a
new way of thinking about the phenomena of nature. This way of thinking has permeated
experimental and theoretical physics to such an extent that it seems scarcely possible to say
anything more about it that has not often been said already”. Max describes how he arrived at
the necessity to abandon classical physics and the naïve conception of reality, which is to think
of the particles of atomic physics as if they were exceedingly small grains of sand, with at each
instance a definite position and velocity. For an electron this is not the case: if one determines
the position with increasing accuracy the accuracy of determining the velocity becomes less,
and vice versa. Through investigations involving collision theory he reached the point of say-
ing: “One gets no answer to the question ‘what is the state after the collision?’ but only to the
question “how probable is a specific outcome of the collision?” He proposed that electron
waves were not continuous clouds of electricity, as Schrödinger interpreted them, but instead
represented the probability of finding a particle in a certain place after a collision. Born conclud-
ed that the motion of particles follows probability rules, but that the probability itself conforms
to causality. To quote Nancy Greenspans’s biography: “Causality had been the basis of the laws
of nature for centuries. Born’s statistical interpretation of Schrödinger’s wave function, an essential element of quantum mechanics, was causality’s death knell.”

Schrödinger [34] found Born’s interpretation of the wave function so unsettling that at one point he wished that he had never written his original article. What fostered dissent was not the mathematical formalism but the physical interpretation. To Schrödinger the wave function was real; in Born’s new theory it was probabilistic. Einstein too felt unable to accept this new and fundamental indeterminism. In December 1926 he wrote to Max: “Quantum mechanics is certainly imposing but an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of ‘the old one’. I, at any rate, am convinced that He is not playing at dice…” Max comments: “Einstein’s verdict on quantum mechanics came as a hard blow to me: he rejected it not for any definite reason, but rather by referring to an ‘inner voice’. This rejection... was based on a basic difference of philosophical attitude, which separated Einstein from the younger generation to which I felt that I belonged, although I was only a few years younger than Einstein”. When my father died at the age of eighty-seven I thought of him as still the youngest man I have ever known!

Max went on to explain: “I am emphatically for the retention of the particle idea... I was witnessing the fertility of the particle concept every day in Franck’s brilliant experiments on atomic and molecular collisions [35], and was convinced that particles could not simply be abolished” (Born, 1958). And in the Nobel Lecture he asked: “Can we still call something with which the concept of position and motion cannot be associated in the usual way a thing, a particle? And if not, what is the reality that our theory has been invented to describe? The answer to
his question is no longer physics but philosophy... Naturally it is necessary to redefine what is meant. For this purpose well-developed concepts are available which are familiar in mathematics under the name of invariants with respect to transformations. Every object that we perceive appears in innumerable aspects. The concept of the object is the invariant of all these aspects. From this point of view, the present universally used conceptual system, in which particles and waves occur at the same time, can be completely justified”. So Max Born thus introduced probability as the most basic concept in quantum mechanics. The probabilistic basis of quantum mechanics has been confirmed by innumerable experiments and is at the base of our marvellous electronic technologies.

When my parents retired to Bad Pyrmont in 1953 my father continued to work on the wider implications of what he had established in atomic physics. Einstein contributed to a Festschrift for Max's seventieth birthday. In reply, Max justified the statistical standpoint by showing that the claim of classical mechanics to be deterministic is not justified because it depends on the assumption that absolutely precise data have a physical meaning, and this he regarded as absurd. So he developed a statistical formulation of classical mechanics.

Biological scientists absorb, or should absorb, probabilistic thinking with their mother's milk, because statistics has been at the basis of modern biology since Mendel's genetical discoveries and Darwin's theory of evolution by natural selection. Molecular biology and molecular genetics have laid bare the underlying mechanisms. Point mutations are random events; mutagenic agents merely affect the overall frequencies of such events, not where and when the individual events occur. A good medical example is lung cancer. When taken to task about his smoking a
A colleague of mine growled: “Churchill smoked all his life and lived to ninety-six, and my little brother never smoked and died at three months”. But the connection between lung cancer and cigarette smoking had been firmly established in 1950 by Sir Richard Doll (Doll and Bradford Hill, 1950) [36, 37]. Fifty years later, understanding of carcinogenesis has increased enormously (Peto et al, 2000) [38, 39]; but there is no way of predicting the occurrence of lung cancer in any given individual, other than to say that smoking increases the chances by a measurable amount. Thus in analogy to the deterministic probability waves in physics, in biology causality is in overall command of individual probabilistic events.

Nevertheless the situations are of course quite different. Quantum physics deals with inferred particles of which it is in principle impossible to determine position and momentum simultaneously with equal accuracy. In biology we are dealing with identifiable molecular structures; and in principle the proposition remains open that even multiple causes of events might become individually determinable. In practice, the indeterminacy arises from the enormous complexity of interacting causative factors, which makes the contribution of each impossible to predict.

My friend and co-worker Professor Peter Richardson [40], a physicist as well as a physiologist, puts this as follows: “Indeterminism in physics has an analogy in biology. This is usually referred to as biological variability which is meant to include genetic variations. With increasing
Fig. 42
Micropipette for the iontophoretic application of ADP to the outside of a venule in the mesentery of an anaesthetized mouse.

Fig. 43
Growing white body produced by the iontophoretic application of ADP to a venule. The white body appears as a segment of a circle. Below is a diagram showing the measurements made for calculating the volume of the white body by the formula (figs 43-46 from Begent, N.A. and Born, G.V.R., (1970). Nature (Lond.), 227, 926-930).

Fig. 44
Increase in volume of a white body with time (o). On the right, the increase in volume is plotted semi-logarithmically against time, showing the line of best fit.

Fig. 45
Serial photomicrographs, at intervals of 1/16 s, of two white bodies passing along the same venule. The white body on the left moved at 625 µm/s and that on the right at 655 µm/s. Scales, 100 µm.
understanding of cell mechanics, particularly through knowledge of the membrane channels that transport ions, of other transmembrane structures that transmit information (receptor signalling) and of cytoskeletal components that link to these structures, we have come to recognise the enormity of the co-ordinated processes responsible for the state of a cell at any given instant. Thus, so much needs to be known about a cell at any moment to be able to predict changes in its state that at present we do not have methods which might provide the information without disturbing what the cell would do if we did not interrogate its current state” (Richardson, 2004).

Ion channels permit the selective exchange of sodium and potassium across cell membranes otherwise impermeable to these ions. The channels are complicated, selective structures with gates which are open and shut by chemical activators. Each gate is in one of two states, open or shut. Only the numbers of open and shut gates are statistically measurable, not the state of the individual gate. Another statistical phenomenon is the quantal release of the neurotransmitter acetyl choline from small vesicles inside nerve endings [41]. Quantal release is individually demonstrable but not predictable, and measurable only when occurring together in larg-
A graduate student, Nicola Begent, and I borrowed a method from neurophysiology to make thrombi grow in blood vessels. This was to apply a platelet-aggregating agent to the outside of a vessel by micro-iontophoresis [42-47]. Thrombi consisting entirely of platelets grew inside the vessel on its walls. The exponential growth rate depended in a complex but understandable way on the blood flow. Many thousand of platelets were involved, so that these were statistical measurements. Peter Richardson has now developed a computer model for following the movements of 50,000 individual platelets in such a model. This is an example of what can be done nowadays to get at individual cell behaviour in complex situations (Begent and Born, 1970; Richardson, 2004). Ultimately perhaps, biological methodology may come up against the very limits exposed by quantum mechanics.

The victory won by statistical thinking in science could bring incalculable benefits to far distant spheres, because to my mind by far the most important intellectual legacy of Max Born was
put by him as follows [48, 49]: “I believe that ideas such as absolute certitude, absolute exactness, final truth, etc. are figments of the imagination which should not be admissible in any field of science. On the other hand, any assertion of probability is either right or wrong from the standpoint of the theory on which it is based. This loosening of thinking (Lockerung des Denkens) seems to me to be the greatest blessing which modern science has given to us. For the belief in a single truth and in being the possessor thereof is the root cause of all evil in the world” (Born, 1978). This seems to me so true and important that the handwritten quotation stands framed on my desk. The idea of a loosening of thinking given to us by science provides a solid basis for rejecting dogmas in all their many different guises, which are without question the greatest danger to the future of human and indeed of all life on earth.

All dogmas are essentially alike, whether in religion, politics, economics or any other field. The sameness resides in a tightening of thinking which does not permit the search for objective evidence and clings to ideas which are unprovable in any rational sense. Indeed, it seems to be their unprovability which makes dogmas appealing: no mental work is required, only belief. Believers defend their different faiths ferociously; in Britain Defender of the Faith is still inscribed on every coin but has happily become obsolete in our long-tolerant country. The most tenacious dogmas such as the doctrines of the great religions originated long before the seventeenth century when rationality and science began to become real influences in the historical process. Since then, dogmas have originated through ignorance or through perversions of hard-won factual knowledge. Take medicine: when at the end of the eighteenth century Samuel Hahnemann first dreamt up homeopathy, its nonsensical doctrines could be excused by ignorance of the law of mass action and of biological mechanisms at that time. Advocating homeopathy nowadays is disreputable and inexcusable. Or take capitalist economics with its dogma of unlimited growth: as William Keegan said in The Observer (21th November 2004): “there is something wrong with a world where all the leading economies are trying to achieve export-led growth. They cannot all succeed unless they start trading with Mars.” In politics there are,
or were, the dogmas of dialectical materialism. Communist regimes claimed these to be scientific in nature (Krieger, 1996). This claim was demolished by Max Born in his reply, unfortunately unpublished, to a letter from the communist physicist Leon Rosenfeld (Born, 1955).

Liberation of the human mind from religious dogma began with my mother’s ancestor Martin Luther [50] and some like-minded contemporaries. It was a prerequisite of the improvement in the human condition during the last five hundred years (Born, GVR, 2002). Like Denis Healey I am sure that the scientific revolution has created an irresistible demand for political freedom (Healey, 1989). Berlin can thank the electronic media which the Wall could not keep out [51] for causing its downfall and for re-unification.

The speed of scientific and technological advances makes it desperately clear that we are not discarding the doctrinal shackles of history fast enough! In order to survive we have to storm and sack – very quickly indeed – so many inherited mental prisons that, looking at and listening to what is going on in the world, it seems an impossible task (Born, 2004). One also has to contend with vested interests which ignore or falsify evidence, for example by the misleading economists whom Bjorn Lomborg recently assembled in Copenhagen (Vidal, 2004). The curse of gradualness – how imperceptibly your car’s fuel indicator creeps towards empty – is still hindering worldwide awareness of global warming which already causes glacier meltdown and hurricane build-up; climate change is happening too fast for the embattled and inadequate proposals for slowing it down (Crutzen and Steffen, 2003; King, 2004; Lawton, 2004) [52, 53]. From this perspective, all the violent conflicts which dominate the World’s attention – always somewhere, at present in Iraq and Darfur, however terrible for the people involved – are mere distractions.

It is a sad thought that the flowering of rationality with its fruits in the conquests of disease, discomfort and distance might still fail to win the battle against unshakeable dogmas. And it is
Fig. 52
The increasing rates of change in human activity since the beginning of the Industrial Revolution. Significant increases in the rates of change occur around the 1950s in each case and illustrate how the past 50 years have been a period of dramatic and unprecedented change in human history (from Crutzen, P. and Steffen, W., (2003). Climatic Change, 61, 251-257).
Fig. 53
an appalling thought that our children and grandchildren should remain endangered by conflicts fought with the latest quantum technologies between contemporary adherents of doctrines invented for small, totally different and long gone societies.

If Max Born’s exhortation to change our ways of thinking is not followed the outlook is bleak. In 1965 he wrote: “It seems that the attempt made by Nature on this earth to produce a thinking animal may have failed.” (Born, 1968). He goes on to give reasons for this pessimism. At that time the dominant reason was the increasing probability that a nuclear war might destroy all life on earth. Forty years on that possibility still exists, the more so as nuclear arsenals spread to smaller countries ruled by intolerant dogmatists such as Iran. But this threat has now been superseded by that of climate change, which is already endangering the lives of millions around the world.

Max Born has a great-granddaughter called Amalie [54, 55] who, just three years old, is such a delightful thinking animal that my friend Lorie Karnath and I are busy producing a book called “Answers for Amalie” to her memorable questions (a recent one: “I am growing bigger every day. How will I know when to stop?”). All children and grandchildren are as valuable as Amalie. We thinking animals have a duty to safeguard their future by promoting universal acceptance of Max Born’s loosening of thinking [56].

I am very grateful to Sheila Lawler and Jed Lawler for excellent assistance in preparing this lecture.

References


Crutzen, P. J. and Steffen, W., (2003). How long have we been in the anthropocene era?, Climatic Change, 61, 251-257.
The importance of a researcher’s contribution to science can be measured by two factors – whether it extends the scientific foundations laid by previous generations and how it enables future developments. Looking back over the 50 years since Max Born was awarded the Noble Prize, we can see that he and the other fathers of quantum mechanics made one of the greatest contributions to science in its history: They extended the classical mechanics of Newton into the world of electrons, nuclei, atoms and molecules. In so doing, they transformed physics, chemistry and biology. Some of their ideas, such as the ‘quantum leap’, have even entered the common language.

I never met Max Born. In fact, Canadian science hardly existed at the time of his most important contributions, and yet my connection to his legacy is not so far removed. I work in the National Research Council of Canada, which came into international prominence after World War II with the arrival of Gerhard Herzberg. Herzberg had been a postdoctoral fellow in Göttingen in 1928. During his stay there he was greatly influenced by both the science that James Franck and Max Born were studying and the atmosphere in which it was pursued. Herzberg was particularly impressed by the interplay between theory and experiment that Franck and Born encouraged. He staffed the group that he formed at NRC with both theoretical and experimental scientists. This mixture also characterizes my own group’s approach to femtosecond science today.

Herzberg and his team extended the new quantum mechanics to molecules. By comparing its predictions with the measurements that he and his group were performing, they revealed the architecture of many molecules. Today, scientists around the world are still building on the insights gained by Herzberg’s work on molecular structure and Max Born’s contributions to quantum mechanics.

I am very pleased that my office at NRC is next to the former office of Dr. Herzberg. It is now kept as a living “museum” used by guests at NRC. In Herzberg’s time these office walls displayed portraits of some of the great scientists who had influenced him. They are still there. There are 12 of them. Figure 1 shows a grouping of four portraits that includes James Franck.
and Max Born. Herzberg was a prolific letter writer. Not only did he write letters almost every night, but he also kept copies of everything he wrote. When he immigrated to Canada he even brought copies of letters he had written in Germany. In a wonderful biography \[1\] written about Herzberg’s life, Boris Stoicheff, his biographer, former student and co-worker, quotes from a letter written by Herzberg to Born or Franck (Stoicheff does not specify to whom it was addressed). In this letter, Herzberg thanks Born and Franck for their great help to him as follows: "Thank you for friendly guidance, not only in Physics but particularly in the proper attitude of a scientist to his work". I wonder to what he was referring?

I like to take students to Herzberg’s office to inspire them. I think that these great men become more real to the students when they stand in the office where Herzberg stood and look at the portraits as Herzberg would have seen them. I hope that they feel the weight of responsibility to make their own contribution to science. Through these links – the scientific approach assimilated in Goettingen, Herzberg's contributions to quantum mechanics and the inspiration found in Herzberg’s office – the line extends from Max Born to Ottawa, even though, to my knowledge, he never visited.

The line connecting Max Born to Ottawa is also intellectual. My research speciality is laser science. It combines both quantum mechanics and optics. Max Born made important contributions to both subjects.

My essay is included in this volume because the specific scientific advance that I will describe has even stronger connections with Max Born. Max Born showed scientists how to think about the wave function and what measurements were possible. My group uses his insight. We split an electron wave function into two parts. Then we use one part of the wave function to measure the other. In this way we image a molecule's electron, also building on the Herzberg legacy.

Let me start with our dream. In the late 19th century, Eadward Muybridge developed photographic techniques for measuring the fastest motion of his time – people moving, horses galloping or trotting. The technology enabled him to obtain striking images \[2\] of motion such as the one in Fig. 2. I think that it is a beautiful image. In four consecutive frames we can see the motion of a horse pulling a buggy. This was the forefront of ultrafast science in the 1870's.

**Extending Born’s legacy into the 21 century:**

**Inspired by movies of horses and waves:**

*Fig. 1*
A group of portraits from the walls of G. Herzberg’s office. From left to right: James Franck, Max Born, Paul Dirac and Max von Laue.

*Fig. 2*
Series of photos taken by Eadward Muybridge in the 1870’s. This was the scientific forefront of ultrafast measurement at the time these images were taken.
A related set of images occupied the front cover of the October 19th edition of Scientific American in 1878. *If we could make similar images of molecules as they undergo chemical reactions, then we could “watch” chemical processes as they unfold, just as Muyerbridge’s photos allowed him to watch the real motion of the horse.*

You, the reader, may say that Max Born would have objected. “Quantum Mechanics” he might say, “showed that it is impossible to obtain sharp images” and he would be correct. The image that we obtain is the image of a wave. However, anyone who visits a wave pool and or sits on a beach watching ocean waves break on the shore, knows that images of waves are also arresting.

One last thing before I begin to discuss how attosecond images can be recorded. Max Born wrote a very famous textbook on optics that is still used today [3]. He would have told you that we often use an interferometer to characterize light waves. Figure 3 is a sketch of an optical interferometer. Light entering from the bottom of the figure encounters a beam splitter (which is really a mirror that partially transmits light). Some of the light beam passes through the mirror, and some reflects from it. The part that reflects is directed back and overlaps the part that passed through. As the light beams intersect, the light waves interfere with each other. By measuring the interference pattern, we can determine everything about the light waves in each beam — their spatial pattern, their frequency, etc. It is as if we could see the individual waves in each light beam. I will now show you how to make an electron interferometer in a single molecule [4].

When setting out to make an electron interferometer that can image the molecule’s electron, you will immediately be confronted by three challenges: First, “how can we split the molecule’s electron?” I will show you that it can be done with an intense laser pulse. Second, “how can we make the electron return to interfere with itself?” I will also show you that this happens naturally when an intense laser pulse splits the electron. And finally, “how can we see the interference if it occurs?” That brings me back to the title of my talk “attosecond imaging.” I will show you that the attosecond optical pulses or trains of optical pulses are produced by this interference, and therefore measuring the attosecond pulses is equivalent to measuring the interference.

The ability to generate attosecond pulses is the culmination of 40 years of development of short-pulse laser science and technology. Lasers were achieved experimentally in 1960. In my opinion, the laser was one of the major developments of the second half of the 20th century. And just like quantum mechanics before it, laser science built on pre-existing science — in this case optics and quantum mechanics. Furthermore, just as quantum mechanics transformed the science that followed, lasers are now transforming experimental science.

Attosecond Pulses
Thanks to the laser, we have gained the ability to directly measure very short time intervals. We usually do this by using very short laser pulses. These pulses operate like strobe lights in a disco, but in the case of lasers, atoms and molecules inhabit the disco floor.

Figure 4 shows a time line of the duration of laser pulses. It shows that we have just passed an important milestone – we can now make optical pulses that have durations measured in attoseconds [5, 6]. The attosecond time scale is especially promising because it is the scale on which electrons move. An electron in a hydrogen atom completes its Bohr orbit in 150 attoseconds. Pulses shorter than this will allow us to "freeze electron motion" in hydrogen.

As I tell you about imaging electrons I will automatically also tell you about how attosecond pulses are generated and the science that underlies their generation. This area of science is rapidly gaining the name "attosecond science" because it grows out of "ultrashort pulse" science – (pre-attosecond science).

Splitting the electron

Light is actually a wave of force on a charged particle. We speak of this force as an electric field. It is a field (like a farmer’s field) because a wave, by its very nature, cannot be confined to a point, but must undulate over an extended region of space. Figure 5 is an image of a 5-femtosecond light pulse. This is the shortest pulse that can be produced using conventional laser technology. Although one axis of the graph represents time, you can also think of Fig. 5 as an image by simply multiplying time by the speed of light. Then 2.7 femtoseconds is equivalent to 0.8 microns (or 8/100,000 cm). The light’s field in Fig. 5 is confined to a few microns in space along its propagation direction.

Figure 6 depicts the potential that an atom’s electron would experience while immersed in the light wave. (Everything that I say about Figs. 6 and 7 would be much the same if the image were a molecule.) The electron is confined to an atom in much the same way that water is confined inside a glass. Of course, the “sides of the glass” are not physical in the electron’s case. Instead, the electrons are confined to the atom by the Coulomb attraction between the negative charge of the electron and the positive charge of the ion. The laser field tips the glass. You can see the lip through which the electron could escape.

Figure 7 is a one-dimensional cut through the atom in Fig. 6. By simplifying the figure, I have space to show the electron wave that is confined by the atom (technically, the atom’s wave-function). In Fig. 7, the wave covers only 1/2 oscillation and is labelled by the symbol $\Psi_g$. You might think of the electron bouncing back and forth in the glass or oscillating like the string of a violin. The image shows its blurred position.
Remember, light is also a wave – a wave of force on a charged particle. As a short laser light pulse passes an atom, it pushes back and forth on the electron. If it pushes hard enough, the electron might detach from the ion. Returning to the analogy of water in a glass, the laser pulse “tips” the glass, first left, then right. If it tips the glass far enough, some of the water might spill while some would remains in the glass. In the water example we split the water into two parts: the water that spills and the water that stays in the glass. In the atomic example, we split the electron. Some of the electron spills (tunnels) from the atom [7] and some of it remains behind.

This very easily solves the first problem – how to split the electron. The electrical field of an intense light pulse interacting with the electrical forces binding the electron to an atom forms a beam splitter. The electron is divided into two parts. One part remains bound to the atom (Ψ₉); the other part – called an electron wave packet – moves in response to the force of the light wave. Figure 7 shows the wave packet emanating from the atom.

If the light pulse that splits the electron contains more than half an oscillation, the fraction of the electron that remains bound to the positive ion can be “spilled” again and yet again, forming many wave packets. In other words, the same electron can be split many times.

Once the electron is split, the attraction of the negative electron to the positive ion rapidly decreases: Since the force that the light exerts on the electron does not depend on how close the electron is to the ion, the force exerted by the light wave controls the electron wave packet motion. At first the light pushes the wave packet away from the ion, but soon the light wave reverses direction and the force begins to push the electron back [8]. Parts of the wave packet return and pass over their first point of origin. In the figure, the motion of the electron is represented by the red arrow. The figure shows the wave packet sweeping over the ion. In Fig. 7 the wave packet is represented by the symbol Ψ₉.

Figure 8 reviews how we have met the first two challenges. Shown on the left is the optical interferometer, and on the right, the electron interferometer. We have made a beam splitter for an electron by ionizing the electron with an intense laser pulse. We have found a method to redirect the electron back to where it came from. There it must interfere with its former self just like any other wave interferes. This process is often termed a “re-collision.” The term “re-collision” emphasizes the particle-like nature of electrons, while the electron interfering with itself [9] emphasizes the wave-like nature of the electron.

The final challenge: How can we record the interference? To clarify the answer, I will first take an interlude to show how intense the re-collision electron can be. The re-collision probability is large enough to have a major effect. What I show might not come as a surprise. The electron
is driven so strongly by the light field and returns to the atoms so quickly after its birth that it can hardly miss! Still, in science, it is important to measure to make sure.

In quantum mechanics, the way measurements are made determines what we can learn about the object that we measure. We start with a hydrogen molecule. Although we do not know if the electron makes it through the beam-splitter (i.e., ionizes), the molecule itself can tell us – if we measure a hydrogen molecular ion, then we know that the molecule ionized. The molecule can tell us even more. Whenever the electron is removed from the hydrogen molecule, one of the two electrons binding hydrogen is removed. With that one electron gone, the bond weakens. The molecular ion stretches. That is, it starts to vibrate much like a vibrating quartz crystal in a watch, or the oscillation of a pendulum in a grandfather clock. In other words, removing the electron starts a clock ticking – starts a stopwatch [10].

If the removed electron re-collides with the ion, it can dislodge the one remaining electron. Should this occur, the vibration ceases – the watch stops ticking – and the molecule is transformed into two hydrogen ions in close proximity. We are interested in the delay between ionization and re-collision and the likelihood that re-collision will occur.

We determine the probability of re-collision by comparing the number of atomic hydrogen ions that are produced to the total number of ionization events.

Since we know that like charges repel and that the kinetic energy they gain depends on how close they were to each other when the second electron was dislodged, measuring the ion's kinetic energy reveals how far they were separated when the re-collision occurred (in other words, measuring the delay between ionization and re-collision).

Figure 9 shows a light wave on which we have superimposed the time and probability of the re-collision. For illustration purposes, the figure assumes that ionization occurred near the field maximum represented by the arrow. In the language of “collision physics,” we use the term “current density,” by which we mean the electrical current per unit area of an electron beam that would be needed to simulate the re-collision. The current density is closely related to the time dependent probability of an electron ion re-collision. The solid curve is from a simulation. The data points (not shown here, but available in [10]) are obtained by reading the molecular clock. The electron is most likely to return about 1.7 femtoseconds after it has left, and most of the probability of the electron re-colliding is confined to about 1 femtosecond (1000 attoseconds).
Not shown in Fig. 9 is that those electrons that re-collide early in the pulse (for example about 1 femtosecond after ionization) have low velocity (long wavelength). Those that re-collide near the peak of the pulse (about 1.7 femtoseconds) have high velocity (shorter wavelengths). Those that re-collide after the pulse peak (for example about 2.5 femtoseconds) have longer wavelengths again. It is this well-confined re-collision, combined with the energy sweep that accompanies it, that ultimately allows us to produce attosecond pulses.

We have already shown that when intense laser pulses ionize atoms or molecules, an electron interferometer is naturally formed. To use the interferometer to characterize the waves, we must find a way to “see” the interference.

Figure 10 (which is a three-dimensional version of Fig. 7) concentrates on the region where the re-collision electron and the initial wavefunction overlap. This is where the interference actually occurs. The wave in blue on the top left and right images represents the re-collision electron. It looks like a uniform wave passing over the initial wave function. The left and right images represent the wave at two closely spaced instants. In Fig. 10, the re-collision wave has advanced by 1/2 wavelength between the two images.

When waves interfere, we add the overlapping components of the wave – in this case, the re-collision wave packet and the bound-state wave function. (The same things happen in a swimming pool when the wave packets created by two divers meet.) The upper images contain this addition. The biggest peak on the sum wave moves from one side of the atom to the other between the two images. We highlight this in the colour coding.

Max Born taught us that the square of the image represents the probability of finding the electron in any region of space. The square of the wave function is shown on the middle image. The bottom images are two-dimensional projections of the 3-D images in the middle frames. They are included as an alternative (and perhaps easier) way to visualize the process.

The middle images or their 2-D projections show that interference between the bound and the re-collision electron transfers the charge from left to right. This rapid oscillating motion continues as long as the re-collision lasts. The faster the re-collision electron moves, the faster the oscillation.

An oscillating charge produces radiation at the frequency of the oscillation. Observing this light solves our third challenge – “how to read the interference pattern.” Scientists have known for some time that gases of ionizing atoms produce extreme ultraviolet light. Since 1993, it has been known that re-collision explained the physics that underlies this light source [9]. Thus,
our re-colliding electron has another important role besides orbital tomography—it produces short-wavelength coherent light.

The re-collision electron has another application as well that we have already highlighted. Re-collision electrons produce the shortest-duration light pulses (by a factor of ~20) that are currently produced [5, 6]. To make an isolated attosecond pulse, all we need is to shape the electric field [6] of the light pulse that is controlling the electron “beam-splitter” and the electron trajectory. For example, if we could produce a light pulse like that shown in Fig. 11, an ionizing electron would have only one option to re-collide—the electron would need to ionize near the first crest of the laser field and re-collide about 2/3 periods later. The blue arrow in the Fig. 11 represents the most likely electron path and the blue pulse on the bottom of the frame represents the resulting attosecond pulse.

While the pulse sketched in Fig. 11 is not a realistic pulse, the pulse shown in Fig. 5 is very similar and it is realistic. A pulse like that in Fig. 5 is used to produce single-attosecond pulses. The shortest pulse produced in this way is ~250 attoseconds [6].

Ionizing pulses that are longer than the one shown in Fig. 5 can split the wave function many times. In such cases, a series of attosecond pulses separated by 1/2 period of the driving laser field are produced [6]. Mathematics tells us that this is equivalent to an array of harmonics of the driving laser frequency. The harmonics are spaced by twice the photon energy of the fundamental beam, since they are produced twice per laser period. They are odd-numbered harmonics of the laser because the electron re-collides from opposite sides every 1/2 period.

Now we return to imaging, but with the knowledge that, if needed, our camera shutter can capture an image in a few hundred attoseconds.

When a patient goes to the hospital for a tomographic image—a “CAT scan”—a medical technician records a series of two-dimensional X-ray images taken with the X-rays passing at different angles through the patient’s body. These two-dimensional projections contain enough information to reconstruct a 3-D image of the body.

If we could align a molecule as if it were a patient, then multiple high-harmonic spectra, taken for different molecular alignments, would contain information about the electron in the same way that the multiple images in X-ray tomography tell us about a patient’s body. We could actually re-construct an image of the electron orbital from this spectrum. In the electron’s case, it would be an orbital image—the orbital from which the electron was split by tunnelling. So the critical question is, can we align a molecule like a patient is aligned in an
X-ray machine? The answer is yes! Here is how it is done. As we have already discussed, a low-frequency laser pulse moves the molecule's electrons in the same way that water moves as a glass is tipped. The electrons would move further if the glass walls (the Coulomb attraction between the electrons and ions) would allow it. (In other words, the electrons apply a force on the ions just as the ions apply a force on the electron.) The force includes a torque (twist) on the molecule [11, 12]. The molecule responds to the torque much as a pendulum responds to gravity: that is, the molecule rotates to minimize its potential energy. Like a pendulum, all small-angle molecules pass through a period of alignment. At this particular time, we have aligned the molecule in space much as we align a patient.

However, our "molecular patient" cannot remain still. Therefore, we must catch our image "on the fly." This is not as hard as it sounds for two reasons. First, our lasers have pulses that are short enough to "freeze" almost any motion. Second, quantum mechanics forces the molecule to pass through periods of alignment at regular and predictable intervals.

Figure 12 outlines the experiment [13]. We use one optical pulse (the pump or alignment pulse) to start the molecule rotating, and a second pulse (the probe or HHG pulse) to generate high-harmonic radiation when the molecule is transiently aligned. This harmonic spectrum is the information that we need to image the orbital. The illustration shows the two laser beams focussed into the molecular jet and the harmonic beam (in blue) being dispersed in a spectrograph. The lower image shows the harmonic spectrum obtained from nitrogen molecules that are aligned parallel to the electric field of the pulse that generates the harmonics.

In my lab, we use N2 molecules. A set of spectra obtained for 19 different projections of the highest occupied molecular orbital (a one-electron approximation of the multi-electron wave function). These spectra contain all of the information that we need for an image – with the exception of one detail – we need to know how bright the re-collision electron is at any given energy. We use an argon atom for this purpose. Argon has the same ionization potential as N2 and ionizes almost identically. Comparing the harmonic spectra from argon and N2, we calibrate the strength of the re-collision electron. Figure 13 shows 5 of the 19 calibrated spectra.

The calibrated spectra in Fig. 13 are the input needed to produce a tomographic image of an orbital. The lower frame in Fig. 14 shows the orbital for N2 that we obtain using the tomographic re-construction procedure. This image is compared with the "Highest Occupied Molecular Orbital" (HOMO) of N2 shown in the lower frame.
Figure 14 shows that we measured the relative phase of the electron orbital correctly and that we correctly found the position of the nodes of the wave function. However the orbital is too large at its extremes. The small errors that remain are probably due to the relatively low energy of our re-collision electron. Had we used a laser beam shifted further into the infrared, then our cut-off harmonics would have been higher and our spatial resolution better.

When a molecule’s atoms move during a chemical reaction, they carry their electrons with them. Our technology is fast enough to image this motion. This would fulfill the dream of truly imaging chemical reactions as they occur. As we extend the technology to more complex molecules and molecules undergoing dynamics, we will obtain images of chemistry reactions-in-progress that will as dramatic as Muybridge’s images of trotting horses taken more than 125 years ago.

But the technology promises more – it is capable of attosecond time resolution. Of course, for attosecond imaging to be worthwhile, there must be interesting things happening on this time scale to observe. Attoseconds are the time scale for electron motion. A classical electron completes a Bohr orbit in about 150 attoseconds. Although quantum mechanics says that the Bohr orbit is not observable, it does allow us to observe something comparable. As we have seen, quantum mechanics allows us to split an electron. If we split it so that it occupies two or more orbitals simultaneously, then the interference between these parts of the electron wave function look very much like an orbiting electron (i.e., like Bohr orbit motion). This classical-like motion is another example of a wave packet — a term I have already introduced to you when describing the motion of the electron that escapes the atom and then re-collides. I now show one way to measure this bound-state electron wave packet – with attosecond precision.

Figure 15 illustrates the idea [14]. This time we split the electron twice. First, we split it to make the bound-state wave packet. Such wave packets require population in two or more orbits. These interfere with each other just as our re-collision electron interferes with its parent orbital, with their interference corresponding to the attosecond motion that we wish to measure. (This first splitting can occur naturally during the process that we want to study, or we can stimulate its occurrence with resonant light.)

We then split the electron a second time. This time we use an intense light pulse just as we described in the earlier sections of the paper. Almost certainly it is the upper state that ionizes, since it is less strongly held by the ion. When the electron wave packet re-collides, it interferes with both bound parts of the previously split electron. Both contribute to the short wavelength light that is emitted. They “write” their joint signature on the light that the atom emits. Figure 16 is a plot of the theoretical prediction of the light intensity emitted by a single atom. On the horizontal axis is the photon energy in electron volts. The vertical axis is a measure of the
strength of the light emission. In a real experiment, many atoms would contribute in synchronism and so the light emission would be much more intense. The signal shown in this figure was calculated for the 6 fs pulse shown on the right. It has a central wavelength of 1.6 \( \mu \)m and an intensity of \( 10^{14} \) W/cm\(^2\). The figure plots the results for wave packets with periods of 390, 330 and 444 attoseconds.

Prominent on each figure are periodic modulations of the light emission. It is possible to show that the maxima appear when the two wave packets co-propagate. The minima appear when they counter-propagate. Therefore a single image measures the wave packet motion [14].

Before concluding, I would like to generalize what I have said so far. We have concentrated on how the re-collision electron "sees" its former self by splitting and interfering with itself. But we do not know which path the electron took and when we observe the photon produced by this interference, we destroy any possibility of measuring it.

What would happen if we looked directly at the electron? The information that we could retrieve would be very different – but no less interesting. In that case we would know that the electron could not have interfered with itself, because we would know that the molecule either has, or has not ionized. Instead, the ionized electron re-collides with the ion it had left. During that re-collision, the electron can diffract [15, 16]: The diffraction pattern tells us where the atoms that make up the molecule were at the time of re-collision. Laser-induced electron diffraction gives complementary information to orbital tomography. We image the atoms of the molecule by diffraction and the electrons by tomography.

There have been many important science developments since the introduction of quantum mechanics. The laser, discovered about 40 years later, is an essential tool today. It allows us to reach into the quantum world with precision. We have used the fact that lasers control electric fields that are as strong as, or stronger than, the fields that bind electron to atoms. These strong fields can make an electron beam splitter and the delay arm in an electron interferometer. Laser science now allows electric fields to be controlled with sub-cycle precision – control that we can use to fabricate attosecond pulses and to take attosecond-molecular images.

So, just as quantum mechanics relied on the scientific developments that preceded it, attosecond science also relies on its preceding science. Future generations will judge how important attosecond science will be. I will be very happy if the 21st century science that I have described here has even a fraction of the impact on future directions of science that Max Born’s science has had. (Of course, I will not know.)
Many people from NRC’s femtosecond science group (and elsewhere) have contributed key ideas and experiments to the work that I have covered. While their specific contributions are mentioned in the references, references alone can never show the intellectual team work that underlies this research.
References

50 Jahre Nobelpreis Max Born
50th Anniversary of Max Born's Nobel Award
10. Dezember 2004
Max-Born-Institut Berlin
On the Fiftieth Anniversary of the Nobel Prize being Awarded to Max Born

Knut Urban
Forschungszentrum Jülich
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Ladies and Gentlemen,

On the occasion of this event commemorating the fiftieth anniversary of the Nobel Prize for Physics being awarded to Max Born, I would like to express warmest greetings to you from the German Physics Society.

We also send kind regards to the Directors of the Max Born Institute, Professors Sandner, Elsässer and Hertel, and their staff. With its work in the field of laser physics, nonlinear optics and short pulse spectroscopy, the Max Born Institute is an outstanding international institution and is a great credit to Max Born’s name.

When we today celebrate the anniversary of Max Born’s Nobel Prize, we commemorate a scientist who was, in particular, a model for his own generation and for the generation of his many distinguished students. His personality still illuminates our work today and even in future he will continue to be a reference point for young physicists with respect to the link between research, teaching and social responsibility.

Max Born had the great good fortune not only to be a witness to events but to be an active participant in one of the greatest scientific upheavals in the history of mankind. When he was appointed to the chair of the Second Physics Institute at the University of Göttingen in 1921, Born could already look back on an impressive scientific career. The stages in this career comprise the development of the quantum formulation of specific heat together with Theodor van Karman in Göttingen in 1912, at the same time as the work by Peter Debye in Zürich on the same topic, and the book "Dynamics of Crystal Lattices" in 1915. With this work and his many years of research in this field, Born became the father of crystal lattice theory.

In addition to Max Planck, he was associate professor of theoretical physics in Berlin and in 1919 was appointed to a chair of theoretical physics in Frankfurt. Otto Stern was then the first in Born’s undoubtedly unique series of outstanding assistants, who on the basis of their work in the immediate circle around their great teacher became Nobel laureates themselves. At this time, in 1920, Born also published his book "Einstein’s Theory of Relativity", a popular representation of both the special and the general theory of relativity, which he developed from the manuscripts of numerous popular science lectures on this topic for the public at large. A few weeks ago, I once again looked into this book that I bought as a student almost forty years ago. It is still very readable even today and, moreover, in addition to the scientific content also represents a model for the popular treatment of complex facts.
In 1921, Max Born was appointed to a chair in Göttingen as the successor to Peter Debye. Together with James Franck, whose appointment to a post at Göttingen he made a precondition for accepting his own chair, and Robert Wichard Pohl, Born then became the founder of the famous Göttingen School. At this time Born began to concern himself with the quantum physics of atoms. Basic inadequacies had become apparent in Bohr’s treatment of the atom model. The conformity of quantum physics at the time with classical physics, maintained via the correspondence principle, had led to quantum rules that could be used to describe the simple hydrogen atom, but which already failed in their treatment of problems of even slightly greater complexity, such as the scattering of light and the influence of static magnetic and electric fields.

The interest of Max Born and his colleagues in atomic physics was attracted by the lectures given by Niels Bohr in Göttingen in 1922. Initially, they sought a solution in Göttingen within the framework of many-body models oriented to classical physics. Born’s assistant, Werner Heisenberg, then succeeded in finding the solution during his famous trip to Heligoland in 1925. Heisenberg treated the spectral lines of the atom on the basis of a system of oscillators by replacing the classical amplitudes of the emitted radiation by quantum-theory amplitudes, which depend on two figures characterizing the transition from one state to another. He succeeded in transcribing Bohr’s quantum condition within the framework of the same assumptions and discovered that his formulation perfectly fulfilled the principle of the conservation of energy, which had been a problem for earlier treatments of semi-classical concepts.

Fulfilling Ritz’s combination principle required the rule of noncommutative multiplication. After Heisenberg’s return from Heligoland, Born recognized that the result intuitively discovered by Heisenberg was the formation of a product of matrices. Today we know Max Born’s formulation, \( i(pq - qp) = (h/2\pi) \), which is also inscribed on his gravestone in Göttingen, in the form of Heisenberg’s commutation relations between the components of the operator of the space coordinate and the component of momentum. Born thus became the father of the matrix formulation of quantum theory.

In the following years, Born devoted himself to the application of quantum mechanics to nonperiodic and time-dependent processes, especially of scattering theory. In 1933 he wrote his famous book on optics, which, when forced into exile in Edinburgh by the Nazis, he later revised with Emil Wolf and republished in 1959 as "The Principles of Optics". This book, which we still use as a reference in my institute even today, has since become a standard work of modern optics.
On 24 November 1954, Albert Einstein wrote to his friend Max Born: "I was very pleased to hear that you have been awarded the Nobel Prize – even though somewhat belatedly – for your contributions to the present quantum theory. After all, it was particularly your rigorous statistical interpretation of the description that decisively clarified our thinking. This seems to me to be quite clearly the case in spite of our inconclusive correspondence on this subject."

Born and Einstein had been close friends since 1913, that is to say roughly since Born’s time in Berlin, but – as indicated by Einstein’s allusion in this letter – they had never been able to agree upon a joint interpretation of quantum theory.

Born describes the origin of his idea of a statistical significance of the wave function, for which he was awarded the Nobel Prize, in his speech of acceptance and in his autobiography. I quote from the latter: "I was guided here by a remark of Einstein’s about the significance of the intensity of light (i.e. of an electromagnetic wave) from the aspect of the photon. This intensity must represent the number of photons, but the latter was, of course, to be regarded statistically as the mean of a certain photon distribution. Einstein had made some profound considerations of the statistical nature of this distribution ... I was very familiar with these considerations and they led me directly to the conjecture that the intensity of the de Broglie wave, i.e. the square of Schrödinger’s wave equation, had to be regarded as the probability density, as the probability of a particle being present in a volume unit”.

This is still the approach that we take in physics today. Born’s statistical interpretation was also the starting point for the Copenhagen interpretation of quantum mechanics, which has survived up to the present day in a variety of forms. Nevertheless, the interpretation of the wave function even today remains an unsolved physical and above all epistemological problem which we have carried over in our baggage from the physics of the twentieth century into our work in the twenty-first century. The collapse and Everitt interpretations are current versions of these attempts to synchronize our powers of imagination oriented to classical physics with the concepts of quantum theory.

Einstein was surprised that Born received the Nobel Prize so late. In his memoirs, Born himself wrote on the subject: “My statistical interpretation of the $\Psi$ function was merely the first step in our understanding of the relation between particles and waves in atomic physics. Even if the vast majority of physicists accepted this interpretation, there were always those for whom this was not the case including ... Planck, Einstein, de Broglie and Schrödinger, ... This may well be the explanation of why I only received the Nobel Prize for my work 28 years later".
Heisenberg, who had already received the Nobel Prize in 1933 – on his own – regretted this omission in a letter to Born: "I find the fact that I alone received the Nobel Prize for work that we did together in Göttingen – you, Jordan and me – very upsetting ..." He at least tries to make Born stand out from the group of scientists when he continues: "I also believe that all good physicists know how great your contribution ... to the construction of quantum physics was – and that cannot be changed by an incorrect assessment of the situation by outsiders."

As in other cases, the way the Nobel Committee reaches its decisions remains hidden from outsiders – and this is right and proper. At the time the decision on the Nobel Prize was taken, however, Heisenberg had undertaken other important work: the uncertainty principles originated in 1927, the work on ferromagnetism in 1928, and on nuclear physics and isospin in 1932. I believe that in retrospect we must also consider that the mid – twenties was an enormously productive time for scientific work thus making the decisions on the Nobel Prizes awarded in the mid – thirties very difficult. At that time there simply weren’t enough prizes to properly honour all the fundamental work that had been done.

In any case, Pauli was right when he wrote to Max Born: "I am certain that the statistical character of the natural laws – on which you insisted from the very beginning in spite of Schrödinger’s resistance – will determine the style of the laws for several centuries at least."

Born’s circle during his time in Frankfurt and Göttingen included, in addition to Stern, Heisenberg and Wolfgang Pauli as his assistants, also his PhD students Pasquale Jordan, Friedrich Hund, Max Delbrück, Maria Göppert – Mayer, Robert Oppenheimer and Victor Weisskopf, as well as John von Neumann, Edward Teller and Eugen Wigner as permanent guests; five of whom later became Nobel laureates. Max Born was an enthusiastic and charismatic researcher and an exemplary teacher, a reference point for his students in professional and human terms.

But Max Born was more than this, he was a role model due to his wide range of interests. At that time, and especially today when there are hyperfigures for every conceivable activity ranging from brilliant scientists and gifted engineers, through actors, stars of classical and modern music, writers and philosophers, up to sports stars, there is more than ever a need to encourage people to develop various aspects of their personalities.

A concern with the interesting aspects of the world does not mean breaking some extroverted record or another but in the first instance enriching one’s own, very personal experience of life. In his "My Life & My Views" Max Born writes: “I never wanted to be a specialist”, and he refers to the fact that in the original sense of the word a “dilettante” is a person who enjoys something, and he continues, “and I always remained a dilettante myself even in those fields that
I regarded as my own. I would have difficulty in adapting to the modern way of doing science with teams of specialists. The philosophical background of science has always interested me more than its special results.”

Max Born was also a role model with respect to yet another important aspect – a scientist’s responsibility to society. As a witness and also as a party involved in the – in the strictest sense of the word – enormous development of the sciences and technology he warned against the consequences. Particularly after his return from Edinburgh in 1953, in his lectures and writings Born took a stance against nuclear armament, which seemed almost inevitable at the height of the Cold War. Born is one of the most prominent authors of the Göttingen Manifesto of 12 April 1957 published by 18 German nuclear scientists protesting against acquiring atomic weapons for the German Armed Forces.

In his memoirs, Max Born concludes with a chapter that urges us all to think about our lives, and from which I take the following quotation: “I am haunted by the idea that this break in human civilization, caused by the discovery of the scientific method, may be irreparable. Although I love science I have the feeling that it is so completely opposed to historical development and tradition that it cannot be absorbed by our civilization. The political and military terror and the complete collapse of ethics which I witnessed in my life are not symptoms of a temporary social weakness but are rather the inevitable consequence of the rise of science – which in itself is one of the greatest intellectual achievements of mankind.”

These words are of great relevance today. It is important that we are aware what a minor role the nuclear threat plays in public opinion today – even after the threats by North Korea and Iran. After the end of the Cold War, the threats have shifted. Our attention is not focused so much on the possibility of the nuclear danger but on the reality of the cynicism of religiously motivated terrorists. Ultimately, however, the basis for this possible terror has not been reduced, but has, on the contrary, expanded. Today no one can definitively rule out the possibility of the fanatics of this world acquiring nuclear weapons and making use of them in a mad orgy of destruction.

And Born only referred to physical research and its fall, in the Biblical sense, expressed in the famous statement by Born’s student Oppenheimer with reference to the uranium and plutonium bombs dropped on Hiroshima and Nagasaki. Physics was the leading science of Max Born’s twentieth century. Much points to biology becoming the leading science of the twenty-first century. Once again, mankind feels called upon to imitate Prometheus. But we should remember that after Prometheus the gods sent us Pandora’s box. I believe that hardly anyone today would assume or even recognize the smallest sign that the process of learning which Max Born,
Carl-Friedrich von Weizsäcker, Karl Jaspers and many others had hoped for has actually taken place. Yes, Max Born’s fears are still as valid as they ever were. I shall use the words of Carl-Friedrich von Weizsäcker in his memorable speech on the 50th anniversary of the first nuclear weapons test in the Nevada desert, in which he coined the expression: “A straight path leads directly from Galileo to the atomic bomb.” Where will this road take us?

When we today commemorate the Nobel Prize awarded to Max Born fifty years ago, then we must include a consideration of all these aspects of his personality – the passionate scientist, the teacher and also his appeal to take on individual social responsibility in the humanistic sense.
Dr. h.c. Jost Lemmerich, organizer of the Max Born exhibition, giving explanations to Professor Dr. Klaus Lüders, Professor Dr. Jürgen Mlynek, and Professor Dr. Knut Urban
Address by the Rector of the University of Wrocław

Zdzisław Latajka,
University of Wrocław,
Wrocław, Poland
Prof. Wolfgang SANDER  
Director of the Max Born Institute  
for Nonlinear Optics  
and Short Pulse Spectroscopy  
Berlin

Dear Director,

I would like to express my approval for organizing symposium dedicated to the great mathematician and physician - Max Born. I have a great honour to congratulate you on this occasion.

Max Born, one of the authors of the quantum mechanics and the theory of the crystals is one of the University of Wroclaw scientists, who became the Nobel-Prize winners. This great scientist gained recognition around the world because of his appeal against using the atomic physics for the construction of the nuclear weapon.

Max Born is very well known to everyone from Wroclaw. He was born in our city, he grew up and studied in Wroclaw. There is the special plaque, founded in 2002, located on the building on the Wołości Square in Wroclaw, where Max Born lived. To pay homage to this great scientist the authorities of Wroclaw gave also Max Born name to the Square, where at the present time the building of the university physics is. There is also the special plaque in the main building of the University of Wroclaw, where among the Nobel-Prize winners connected with our University is Max Born name.

Dear Director! On behalf of the whole academic community of our University and myself, I would like to congratulate you one more time on this occasion. Please accept my warmest wishes of great celebration of 50 anniversary of awarding the Nobel Prize for Physics to Max Born and on His 122 Birthday.

Sincerely yours,

Prof. dr hab. Zdzisław Łatajka  
Rector of the University of Wroclaw

Wroclaw, December 3rd, 2004
Gustav Victor Rudolf Born was born in Göttingen in 1921 as the son of Max Born (Nobel laureate in Physics 1954). In 1933 the Born family was forced to leave Germany and settled in Britain. Gustav Born obtained his medical degree at Edinburgh University and his research doctorate in Oxford. During his long and distinguished academic career, Born has held chairs of pharmacology at the Royal College of Surgeons, at Cambridge University, and at King's College London. At present he is Research Professor at the William Harvey Research Institute in London. Born has made outstanding contributions to knowledge of the pathophysiology of the circulation, particularly of haemostasis, thrombosis and atherogenesis. His many honours include the Fellowship and the Royal Medal of the Royal Society and nine honorary doctorates. Göttingen University awarded him the Albrecht von Haller Medal. Married to the physician Faith Born, Gustav Born has five children and nine grandchildren.

Paul Corkum was born in Saint John, New Brunswick, Canada. He graduated from Lehigh University (USA) in 1972 with a Ph. D. in theoretical physics. In 1973 he joined the staff of the National Research Council of Canada. At NRC he concentrated first on laser technology and then on using intense laser pulses to study and control matter. Dr. Corkum is best known for introducing many of the concepts in strong field atomic and molecular science and then confirming them experimentally. Dr. Corkum is the program leader of the Atomic, Molecular and Optical Science Group at NRC. He is a member of the Royal Societies of London and of Canada. Among his awards are the Canadian Association of Physicists’ gold medal for lifetime achievement in Physics (1996), the Royal Society of Canada’s Tory award (2003), the Optical Society’s Charles Townes award (2005) and the IEEE’s Quantum electronics award (2005). He will receive the American Physical Society’s Arthur L Schawlow prize in 2006.

Knut Wolf Urban was born in Stuttgart in 1941. He studied physics at the Technical University of Stuttgart where he also got his doctor degree in natural sciences. Stations of his research career were the Max-Planck-Institute for Metals Research in Stuttgart and the Section de Recherche de Metallurgie Physique in Saclay, France. In 1984 he became a Professor in Materials Science at the University of Erlangen. Since 1987 he holds a Chair for Experimental Physics at RWTH Aachen University. In the same year he founded the Institute for Microstructure Research at the Research Centre Jülich. Urban’s research interests range from applied superconductivity and complex metallic alloys to oxides. In 2003 he founded the Ernst Ruska Centre as Germany’s first user centre in ultra high resolution electron microscopy employing aberration-corrected electron optics, a field which Urban and his colleagues have pioneered since 1991. Urban held a number of honorary posts in German science. He was Physics Chairman of the renowned Gesellschaft Deutscher Naturforscher und Ärzte. Currently he is President of the German Physical Society.