How Basic Science Drives Technological Progress
— And Vice Versa —

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February, 2017

BRIDGES
Dialogues Toward a Culture of Peace

Discoveries Can Be Intentional or Accidental

Some technological advances, such as X-Rays and Penicillin, arose from research that was unplanned and not directed toward any specific goal. These discoveries were unexpected and stumbled upon by accident.

Others, like Streptomycin and Nuclear Weapons, resulted from carefully planned and specifically targeted research.

The History of Science proves both methods to be essential...

... a fact that must be borne in mind by aspiring scientists and by governmental, academic and industrial agencies seeking to foster scientific and technological progress.

Immanuel Kant Versus The Princes of Serendip

Some scientists focus on well-defined goals: first they lay careful plans, then they look. They follow the so-called scientific method. I call this the Kantian approach to discovery.

Others have more fun: They look & listen to Nature with open minds, and sometimes discover amazing things. I call this the Serendipitous approach, like Columbus's 'discovery' of America but unlike Magellan's successful plan to circumnavigate the globe.

The two approaches often mix. Many Kantial efforts yield surprisimg discoveries. TNT was synthesized in 1863 and used as a yellow dye for 28 years until its value as an explosive was recognized. THALIDOMIDE, originally a sedative in the 1950s, led to a medical disaster. Much later it was found effective for treating cancer and leprosy!

Pure Science Versus Applied Science

Basic Research can proceed either by **K**antian (intentional) or **S**erendipitous (accidental) means, but there is a second dichotomy. Basic Research can be either **P**ure and curiousity-driven or **A**pplied and dedicated to societal, commercial or military needs. Several Nobel Prizewinning examples:

- **PK:** (2012) The Higgs Boson CERN
- (2015) Gravitational Radiation LIGO
- **PS:** (1932) Positrons Great Britain
- (1985) Fullerenes or Buckyballs USA
- **AK:** (1993) Blue LEDs Japan
- (1981) Artemisinin China
- **AS:** (2004) Graphene Great Britain
- (1981) Giant Magnetic Resistance France & Germany

Careless Chemists with Eyes Wide Open

These discoveries were both **A**pplied & **S**erendipitous. Their discoverers followed Pasteur: Chance favors only the prepared mind and Terence: You must by skill make good of what has fallen by chance.

DYES

- 1704: Prussian Blue
- 1846: Mauve
- 1859: Magenta
- 1863: Trinitrotoluene
- 1897: Synthetic Indigo
- 1928: Monestral Blue

SWEETS

- 1879: Saccharin
- 1937: Cyclamate
- 1965: Aspartane
- 1967: Acesulfane
- 1976: Sucralose
- 1988: Tagatose

Beyond the Rainbow — The Electromagnetic Spectrum

1704	**(K)**	Isaac Newton	The Visible Octave
1800	**(S)**	William Herschel	Infrared Radiation
1801	**(K)**	Johann Ritter	Ultraviolet Radiation
1888	**(K)**	Heinrich Hertz	Radio Waves
1894	**(S)**	Wilhelm Rontgen	X-Rays
1964	**(S)**	Penzias & Wilson	Cosmic Microwaves

W͡e are creatures of electromagnetism in all we see, feel, hear, smell, taste or do. For its theory we are indebted to serendipitous discoveries by Galvani that led Volta to the electric battery; by Oersted of the magnetic effects of electric currents; and by Faraday of the electric effects of moving magnets.

The Masters of Electromagnetism

- Ampère
- Biot
- Coulomb
- Faraday
- Franklin
- Gauss
- Gilbert
- Jansky
- Henry
- Hertz
- Maxwell
- Oersted
- Ohm
- Tesla
- Volta
- Weber

They established a keystone of modern physics — Electrodynamics — which set the stage for the Second Industrial Revolution: Electric Lights, Motors, Elevators, Air Conditioning, Telegraph, Radio, TV &c. None became wealthy from their dedicated efforts, although each of them was immortalized with his own eponymous unit.

Playboys of the Quantum World (1920s)

- Bohr
- Born
- Curie
- De Broglie
- Dirac
- Einstein
- Heisenberg
- Jordan
- Klein
- Kramers
- Pauli
- Schroedinger

These dreamers, among others, were the creators of Quantum Mechanics, another keystone of modern physics. They had loads of fun puzzling out and arguing about their mysterious new theory of atoms (and everything else!) but...

They had no patents, made no start-ups, signed no non-disclosure agreements and developed no marketable product. Yet today quantum mechanics underlies at least one third of the global economy!

VIRTUES OF BASIC SCIENCE FOR MEDICINE

DISCOVERY

- 1894 X-Rays
- 1932 Positrons
- 1950 Nuclear Magnetism
- 1912 Radioactive Isotopes
- 1934 Cyclotron
- 1957 Lasers
- 1986 Polymerase Chn Rctn
- 1928 Penicillin (by Chance!)
- 1953 DNA Structure

APPLICATION

- CAT Scanners
- PET Scanners
- MRI Scanners
- Brachytherapy
- Particle Beam Therapy
- Microsurgery
- Forensic Medicine
- Disease Control
- Gene Therapy

Each of these discoveries earned a Nobel Prize!

BASIC SCIENCE & INFORMATION TECHNOLOGY

- 1888 Radio Waves
- 1947 Holography
- 1947 Transistors
- 1951 Integrated Circuits
- 1966 Optical Fibers
- 1976 PK Cryptography
- 1988 Giant Magnetoresistance
- 1986 High T Superconductors
- 1989 World-Wide-Web
- 2012 Quantum Manipulation

- Wireless Transmission
- Secure Credit Cards
- 1st Computer Revolution
- 2nd Computer Revolution
- Rapid Data Transmission
- Secure Data Transmission
- Multi-Gigabyte Disks
- MRI Scanners
- The Information Age
- Quantum Computers (?)

All but three of these discoveries earned Nobel Prizes!

MORE FRUITS OF BASIC SCIENCE

- 1839 Photovoltaic Effect
- 1905 Photoelectric Effect
- 1912 X-Ray Diffraction
- 1916 General Relativity
- 1923 Matter Waves
- 1938 Nuclear Fission
- 1949 Carbon Dating
- 1969 Charge Coupled Device
- 1985 Bucky-Balls (Fullerenes)
- 2004 Graphene

- Solar Panels
- Charge Coupled Device
- DNA Structure
- Global Positioning
- Electron Microscope
- Nuclear Power
- Climate Research
- Digital Cameras
- Photodynamic Therapy
- ?

All but two of these discoveries earned Nobel Prizes! (Einstein's prize was for something other than general relativity.)

FROM DISCOVERY TO DEVICE

GMR Effect to Gigabyte Hard Drives:	3 years
CCD to Digital Camera:	6 years
Transistor to Transistor Radio:	7 years
Matter Waves to Electron Microscope:	10 years
Radio Waves to Wireless Telegraphy:	11 years
Fission to Nuclear Power:	19 years
General Relativity to Global Positioning:	78 years
Photovoltaics to Solar Panels:	115 years

The latency period has various causes:

Necessity (e.g., solar panels);

War (e.g., nuclear power);

Missing Technology (e.g., GPS needs satellites and microelectronics .)

ISOTOPES — From the Pure to the Practical

Atoms come as isotopes with almost identical chemistry, but different masses. Radioactive Isotopes were found by Soddy (1912), Stable Isotopes by Thompson (1913). Neutron discovery (1932) enabled nuclei to be characterized by two integers: **Z** is the number of protons in an atomic nucleus; **A** is the number of both protons and neutrons. Hydrogen has three isotopes. All have $Z = 1$. Ordinary hydrogen has $A = 1$, Deuterium (1932) is a stable isotope with $A = 2$, while Tritium (1934) is an unstable isotope with $A = 3$.

Soon afterward isotopes became very useful! Nuclear fission (1938) led scientists to realize that the isotope U-235 could be used to make bombs, or to provide a clean and novel source of energy. In 1948, Libby invented radioactive carbon-14 dating, which, among much else, would show the Shroud of Turin to be fake and Vikings to have preceded Columbus to America.

Some Practical Uses of Isotopes

- Astrophysics
- Medical Therapy
- PET Scanners
- Isotope Geology
- Gemology
- Sterilization
- Luggage Scans
- Flaw Detection
- Art Preservation
- Reactors
- Chronology
- Space Science
- Anthropology
- Biologic Tracers
- Diagnostics
- Nuclear Forensics
- Petrology
- Insect control
- Agriculture
- Leak Detection
- Smoke Detection
- Health Science
- Mutagenesis
- Runway Lighting
- Nuclear Science
- Engine Testing
- Paleontology

And, as an example of pure science — isotopic analyses of ancient rocks established Earth's age at 4.54 ± 0.04 Gy. Meanwhile, astrophysicists found the age of the Universe to be 12.82 ± 0.06 Gy. What incredible precision!

30,000 PARTICLE ACCELERATORS?!

In 1930 the first tiny cyclotron yielded protons of modest energy. Today's 5-mile wide LHC studies Higgs Bosons with protons a hundred million times more energetic. About 30,000 particle accelerators operate today, the vast majority doing useful things:

- Medical Therapy, Research and Diagnosis
- Isotope Synthesis & Ion Implantation
- Computer Chip Manufacture & Bomb Detection
- Atomic, Nuclear, Molecular and Fusion Research
- Trace Element Detection and Measurement
- Corrosion & Erosion Studies, Metallurgy
- Radiation Processing & Microlithography
- Detecting & Measuring Semiconductor Contaminants
- Accelerator Mass Spectroscopy, And potentially:
- Ultra-Safe Nuclear Power Reactors
- Large Scale Magnetic Energy Storage

SYNCHROTRON LIGHT SOURCES

Synchrotron radiation, once a severe problem at electron accelerators, is now a multi-billion dollar enterprise. Synchrotron light is used throughout science, medicine, engineering and industry. About 80 of these large, expensive and sophisticated light sources are deployed in over 20 countries, most recently in JORDAN. Even more powerful "Free Electron Lasers," such as those in Hamburg and Stanford, represent their fourth generation. At least 5 Chemistry Nobel Prizes were awarded for work done at light sources: in 1997, 2003, 2006, 2009 and 2012. Applications of light sources include:

- Neuro-Chemistry, Nanoscience and Pharmacology
- Cancer Therapy, Molecular Biology and Material Science
- Imaging Crystals, Ribosomes, Proteins and Viruses
- Analyses of Strains, Cracks and Corrosion
- Paleoentomology, Biochemistry & Archaeology...

NUMBER THEORY: Another Useless Discipline?

'There is one science whose very remoteness from ordinary human actuvities should keep it gentle and clean'... G.H. Hardy 1840

Tell that to the NSA! Number theory has become essential to modern cryptography, an immensely practical discipline:

- Military (and industrial) encryption and decryption,
- Electronic money for gaming and financial services,
- Telephonic encryption, Online signature authorization,
- Network and email security, Speech synthesis,
- Ensuring data integrity and preservation, cyberwar,
- Security trading, Concert Hall acoustics, cybersecurity,
- Computational Biology, Online Payments, ATMs, bitcoin,
- Error correcting codes & Secure data transmission for:
- Finance, Industry, Military, Governments & Individuals.

Technology Drives Progress in Basic Science As Well!

- Steam engines were invented long before they could be understood, thus challenging physicists to develop the science of thermodynamics.
- The 19th century inventions of spark coils (by Ruhmkorff), photography (by Daguerre) and mercury air pumps (by Geissler) made many turn-of-the-century discoveries possible: radio waves, X-rays, radioactivity, the electron, atomic number, cathode ray tubes....
- The antenna used by Penzias and Wilson to discover the cosmic microwave background was built by ATT for early satellite communication.
- Mysterious gamma-ray bursts were first detected by US Air Force satellites looking for illicit Soviet nuclear tests.
- Supercomputers enable otherwise impossible calculations in both pure and applied science, e.g., the four color theorem.

Synthetic Elements & Nuclear Fission — A Story

- (1925) Ida Noddack et al. claim to find *Masurium* (43) and *Rhenium* (75), but 43 is neither accepted nor confirmed.
- (1934) Fermi bombards Uranium with neutrons, claiming *Ausonium* (93) and *Hesperium* (94). Ida Noddack doubts his claim, suggests fission instead, but...
- (1937) Synthetic Technetium (43) found by Segré. Noddack's prior claim still disputed.
- Fermi wins Nobel Prize for his discoveries of transuranic elements. Fission discovered, thereby refuting Fermi's claims.
- (1940) Neptunium (93) and Plutonium (94) synthesized.
- (1944-45) Americium (95) and Curium (96) synthesized; Promethium (61) found among fission products of Uranium.
- (1949-50) Berkelium (97) and Californium (98) symthesized.

The Story Continues: To Z=118 and Beyond !

Today, all chemical elements from Z=1 to Z=118 are observed, studied and named. Some synthetic elements turned out to be surprisingly useful:

- Technetium as a remarkable corrosion inhibitor.
- Plutonium as nuclear fuel and to make weapons.
- Americium is used in household smoke detectors.
- Curium is used as a power source for spacecraft
- Californium is used for oil & gas exploration.

The game continues, even though heavier elements tend to be very short lived. The last four have half-lives measured in milliseconds. Elements beyond Californium are unlikely to have any practical applications. Nonetheless, several countries (Germany, Russia, Japan and USA) struggle to produce elements beyond Z=118 in pursuit of a conjectured 'island of stability.' I wish them well.

APOLOGIA

Basic Scientific Research has enabled most of the technological and medical marvels of modern life. But that is not at all what motivates most of those who pursue the disciplines of cosmology and particle physics.

Rather, as heirs to Nature's splendors, we find it our duty to try — as best we can — to understand the nature of All Things Great and Small: from the Birth, Evolution and Fate of the Universe, to the tiniest Building Blocks of Matter and the Rules they Obey

— THANK YOU —