Do we live in

The “Golden Age” of Science?

How did Science Arise?

The Exponential Growth of Science

A ‘Post-Discovery’ World?

How did Science Arise?

Prehistoric Times

- 5-10 million years ago - speciation from chimpanzees
- 2.5 million years ago - first tools
- 1.5 million years ago - first use of fire
- 200 thousand years ago - Homo sapiens first appeared
- 50 thousand years ago - exodus out of Africa
- 10 thousand year ago - agriculture $\rightarrow$ villages, towns, civilizations

(hunter-gatherers over almost all of this period, struggling for mere survival $\rightarrow$ no chance of developing anything remotely like modern science)

The Early Civilizations

- Major civilizations arose ~ 3000 - 500 BC: Mesopotamia, Egypt, the Indus River Valley, the Yellow River, Mesoamerica and South America.
- Developments in mathematics, astronomy, engineering and other fields

- **But none of these civilizations produced natural philosophy (the basis of modern science). Why?**
  - Poor peasants, villagers, workers would have had no opportunity
  - Learned individuals would have been enmeshed by the state
  - well-established religions and myths "explained the world"

Gods Everywhere!

Egyptian gods

Amun (king of the gods), Atum (the creator god), Geb (god of the Earth), Hapy (god of the flood), Hathor (goddess of love and joy), Isis (protective goddess) Ma'at (goddess of truth and justice), Nut (sky goddess), Osiris (god of the dead), Ra (the Sun god), Sekhmet (goddess of war), Seth (god of chaos), Shu (god of the air), Sobek (a Nile god), Tefnut (goddess of moisture), Thoth (god of writing)

Mesopotamian gods

Adad (god of storms), Ashur (god of the wind), Anu (god of heaven, father of the gods), Ereshkigal (goddess of the underworld), Ishtar (goddess of fertility and love), Nabu (god of wisdom and writing), Nanshe (goddess of justice), Nergal (god of war and plagues), Ninhursag (Earth and mother goddess), Ninlil (goddess of the air), Shamash (god of the Sun), Sin (god of the Moon)

Rigvedic gods

Indra (warlord, thunder and storm), Varuna (upholder of cosmic order), Soma (god of the plants), Yama (guardian of the dead), Surya (god of the Sun), Vayu (god of the wind), Dyaus (father of heaven), Aditi (goddess of eternity), Maruts (storm spirits), Apsaras (mistresses of gods), Rudra (archer of god), Aranyani (goddess of the forest), Usha (goddess of dawn), Prithvi (goddess of the Earth)

Greek gods

Aphrodite (goddess of beauty and love), Apollo (god of music, arts knowledge, manly beauty), Ares (god of war and violence), Athena (goddess of intelligence, skill and wisdom), Dionysus (god of wine and festivals), Hades (king of the underworld and the dead), Hera (queen of the gods), Hermes (god of travel, trade and writing), Poseidon (god of the sea, floods, droughts and earthquakes), Zeus (king of the gods)

The First Fundamental Step - The "Greek Miracle"

<u>Huge innovation</u>:

The world is to be explained by rational thought in terms of natural laws
(instead of religions, gods and myths)

Why Greece?

- Individual decentralized city-states
- Citizens were relatively free
- Religions were fragmented; no overall priestly caste to impose dogma
- Debate was customary, novel ideas could flourish.

Thales of Miletus (c. 625-545 BC) had this crucial insight:

- Worldly-wise and a polymath
- Wealthy background, well educated and traveled
- Involved in business and politics as well as astronomy, mathematics, metaphysics.

Aristotle: The most influential Greek philosopher on science

His View of the World:

- The Earth is a sphere at the centre of the universe
- The heavenly bodies are attached to a series of concentric spheres, rotating around the Earth
- The universe is a vast bounded sphere; no beginning or end in time
- Five elements: earth, water, air, fire, quintessence
- Bodies move towards their natural places, without force
- “violent (unnatural) motion” is caused by a force
- Four types of cause: material, formal, efficient, and final
- Heavy bodies fall faster than lighter bodies
- No sharp boundary between living and non-living things
- There is a continuum from plants and animals to man
- The heart is the seat of intelligence; there may be an independent soul

In Transit

- The Greek philosophical activity gradually faded away
  - perhaps because it was thought that the "Greek Miracle" was the pinnacle of civilization, which could never be surpassed –or that it could not actually be *used* for anything?
- The Roman and Byzantine empires were not interested
- Rise of Islam in the 7th century led to a massive 'translation movement', from Greek to Arabic, whence an impressive 'Islamic Golden Period' of science
- Islamic science declined after peaking around 1000 AD
  - Islamic religious forces became less tolerant
  - madrassas restricted their curricula to the Koran
  - the Arab world suffered from the Mongols

- Western Europe in early medieval times - a cultural and economic backwater, with scattered agriculture, towns and tribes.
  - Population was mostly illiterate.
  - Unlikely place to inherit the mantle of high civilization from Greece!
- Translations from Greek and Arabic sources into Latin
- First universities: Bologna (1088), Paris (1150), Oxford (1167), Cambridge (1209), Padua (1222) - there were 80 by 1500.
- Clash of Aristotle with the Roman Catholic Church, reconciled by Thomas Aquinas.
- Medieval science: subjects included optics, acoustics, astronomy, statics, dynamics, momentum, and the scientific method.

The Second Fundamental Step:

The Scientific Revolution

- Nicolaus Copernicus (1473-1543) wondered whether the Ptolemaic model may be better if one considered the Sun, rather than the Earth, to be at the centre of the universe.
- His model automatically solved some of the puzzles, but was not much less complex or more accurate.
- Tycho Brahe (1546-1601) built a large observatory near Copenhagen and made two decades of observations of unprecedented accuracy.
- Johannes Kepler (1571-1630), a mathematician, inherited this extensive data set, and discovered his three laws of planetary motion (based on the Copernican model).

- Galileo Galilei (1564-1642) made famous experiments in physics, including those on gravity using balls rolling down a plane
- In 1609 he built a telescope and discovered the moons of Jupiter, the phases of Venus, craters on the Moon, spots on the Sun, countless stars comprising the Milky Way - strong evidence for the Copernican model.
- Famous dispute with the Roman Catholic Church; he was forced to renounce his belief in Copernicanism (“I abjure, curse and detest my errors”) and was sentenced to lifelong house arrest.
- (The Church finally apologized to Galileo 350 years later, in 1992)

- Isaac Newton (1642-1726), at Cambridge, worked on optics, mathematics, mechanics, gravity - and also on alchemy and the Bible.
- His early years (late 1660s) were productive, but his work matured over the next two decades, culminating in a Herculean effort in 1684-1686 to produce the greatest publication in the history of science, the *Principia*, which changed science forever:

- **The universe and its contents work according to fixed laws that make <u>accurate predictions</u> possible.**
- **Aristotle's qualitative and descriptive science was replaced by Newton's quantitative and prescriptive science**
- **And all based on the scientific method, verification by experimentation and observation.**

→ Modern science was born

Science from Then to Now:

329 years of science since publication of the *Principia*.

Three examples: The Very Large, The Very Small, The World of Life

The Very Large

Cassini, Huygens, Halley, Venus transits, Wright, Bradley, Bessel, Herschels, Olbers, Dreyer, Rosse, Wollaston, Huggins, Jansen, Lockyer, Hertzsprung, Russell, Leavitt, Einstein, Eddington, Shapley, Curtis, Slipher, Lemaitre, Hubble, Unsold, McCrea, Jansky, Zwicky, Gamow, Alpher, Herman, Hoyle, Bondi, Gold, Burbidges, Fowler, Schmidt, Penzias & Wilson, Bell, Hewish, Ryle, Rubin, Hulse & Taylor, Guth, Smoot et al., Mayor & Queloz, Perlmutter et al., Riess & Schmidt et al., Abbott et al.

→ The Big Bang universe, its evolution and contents

The Very Small

Boyle, Halley, Black, Priestly, Stahl, Cavendish, Lavoisier, Davy, Dalton, Brown, Berzelius, Gay-Lussac, Avogadro, Young, Loschmidt, Frankland, Couper, Newlands, de Chancourtois, Meyer, Mendeleev, Maxwell, Boltzmann, Crookes, Thomson, Planck, Einstein, Rutherford, Bohr, Millikan, Perrin, de Broglie, Schrodinger, Heisenberg, Dirac, Anderson, Chadwick, Pauli, Fermi, Tomonaga, Schwinger, Feynman, Gell-Mann, Zweig, Glashow, Weinberg, Salam, Rubbia, van der Meer, Higgs

$\rightarrow$ Standard Model of Particle Physics - scales < 10^{-18} metres

The World of Life

Ray, Willughby, Linnaeus, de Buffon, Malthus, Couvier, Lamarck, Saint-Hillaire, Hutton, Lyell, Darwin, Wallace, Flemming, Weismann, Mendel, de Vries, Correns, von Tschermak, Spillman, Morgan, Miescher, Hertwig, Levene, Avery, Waddington, Chargaff, Crick, Watson, Wilkins, Franklin, Nirenberg, Khorana, Holley, Jacob, Monod, Arber, Nathans, Smith, Sanger

$\rightarrow$ The basis of life (Evolution, DNA and the genetic code)

The Exponential Growth of Science

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- 200 thousand years ago - Homo sapiens first appeared
- 50 thousand year ago - exodus from Africa
- 5-10 thousand years ago - first civilizations
- 2.6 thousand years ago - The Greek Miracle
- 330 years ago - The Scientific Revolution
- 115 years ago - radio technology

Looking back from the present, in units of ‘Rons’

(1 Ron = 75 years)

2 Rons ago (1866)

- no electricity, no telephones, no radio, no television, no movies, no cars, no airplanes, no satellites, no moon travel, no nuclear power, no internet.
- The atom was just speculation, the universe was unknown, the basis of life was unknown

3 Rons ago (1791)

- Fastest travel was by horse, transoceanic travel took months in wooden ships with sails (similar to thousands of years ago)

6 Rons ago (1566)

- The world was that described by Aristotle

90% of all the scientists who have ever lived are alive today.

- Exponential growth rate ~4% p.a. since mid-1700s, currently 6.6% p.a. in China (doubling times 18 and 11 yrs)
- Now ~ 8-9 million researchers in the world, publishing ~1.5-2 million refereed papers per year
- De Solla Price (1961, 1963) found growth rates of 5.6% p.a. (journals) and 4.7% p.a. (papers); he wondered whether they may have already started to saturate
- But the present rate is not flattening off:
  Recent studies show growth rate as high as 8-9% p.a. $\rightarrow$ global science output may be doubling in less than a decade!

Will this exponential growth continue?

The End of Physics in 1900?

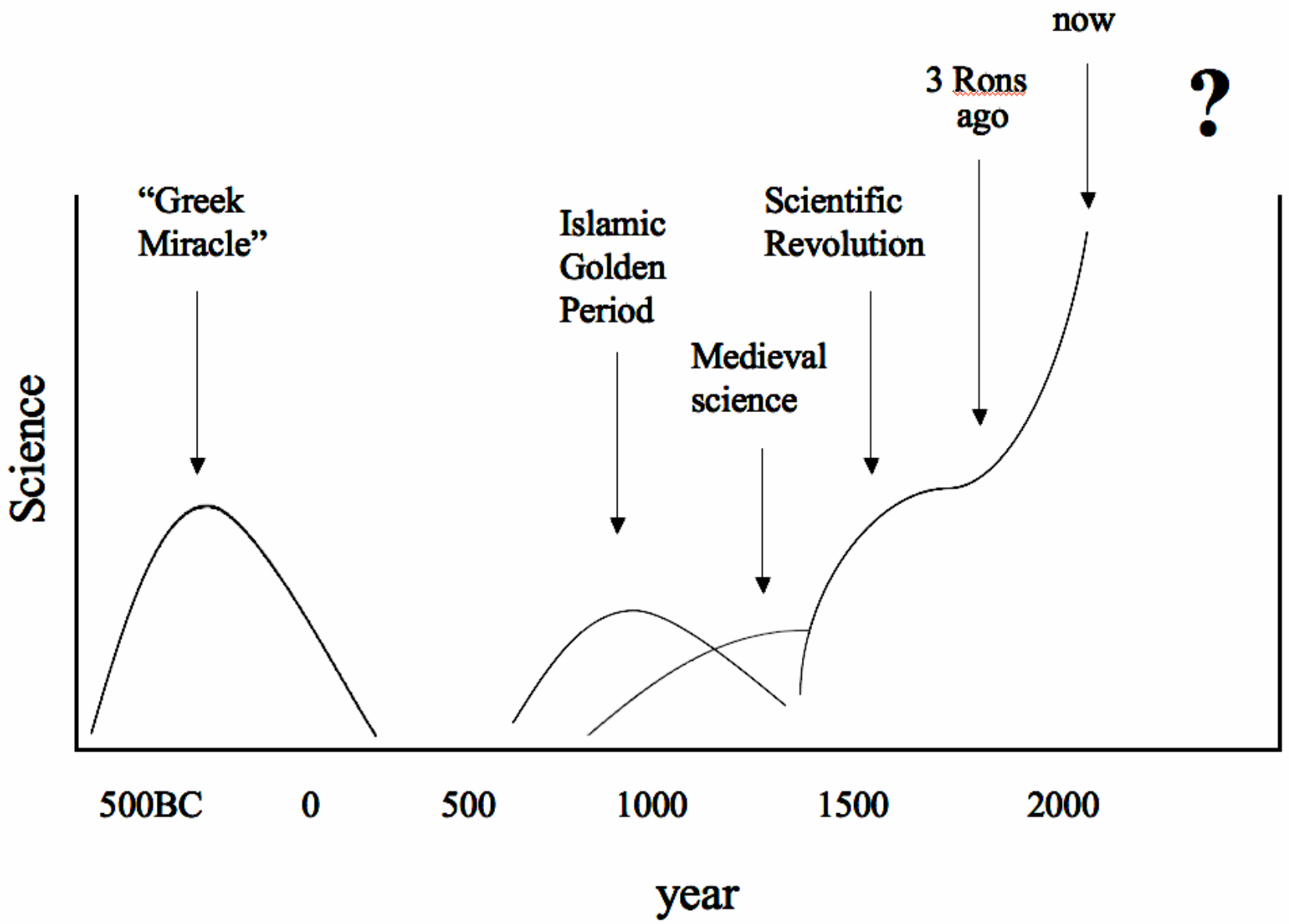
- 1894, Albert Michelson: “The more important fundamental laws and facts of physical science have all been discovered…Our future discoveries must be looked for in the sixth place of decimals”.

- 1900, Lord Kelvin: “There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.”

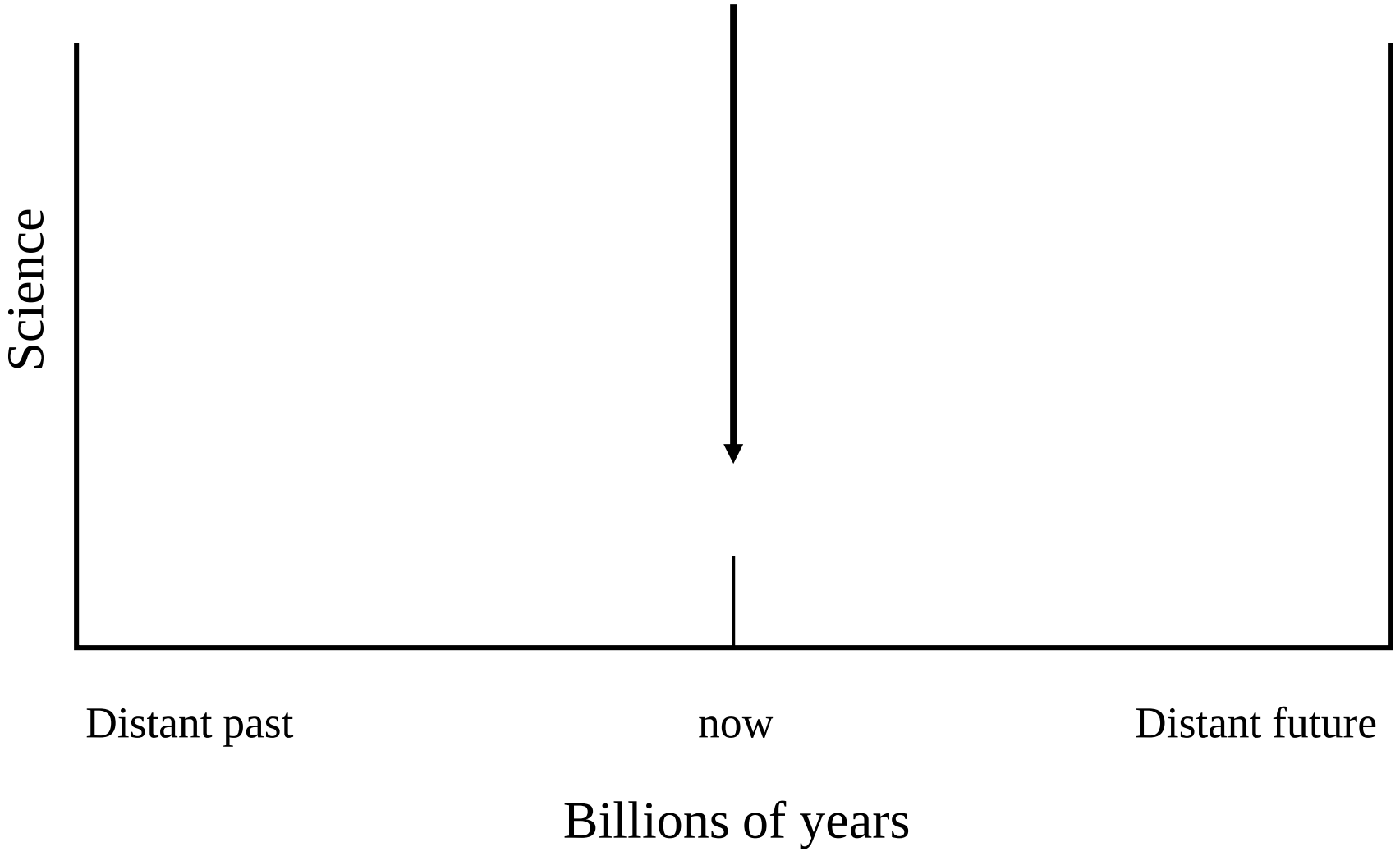
(but then - in 1900 and 1905 - Planck and Einstein’s famous papers that led to quantum mechanics, the universe of curved spacetime and the atomic bomb!)

The End of Science Today?

- Physics: Quantum mechanics and the Standard Model explain all the experiments from the world's accelerators and provide an accurate physical foundation underpinning chemistry, electronics, materials science, astrophysics, and much of cosmology. The physics of everyday life is largely understood.
- Astronomy and Cosmology: the properties and evolution of our universe are known, and the mechanisms of stellar evolution are understood.
- The World of Life: the basis of all life is understood (DNA and the genetic code), and the entire human genome has been sequenced. The nature and cause of evolution are known.


now
3 Rons ago
?
"Greek Miracle"
Islamic Golden Period
Medieval science
Scientific Revolution
Science
500BC
0
500
1000
1500
2000
year

The “Golden Age of Science”?



A ‘Post-Discovery’ World?

- Will the current exponential rate of growth flatten off and then decline sometime in the future?
  - Will people at that time - hundreds, thousands or millions of years from now - look back wistfully at a past **‘golden age of science’**, the peak in the rate of discovery?
  - A future time when almost all of the most important things that can be discovered have been discovered?

- Or will the current pace of science continue forever, without end?
  - Perhaps dealing increasingly with subjects of less and less importance?
  - Will we find layers of more and more fundamental science?
  - Is there some reality all around us that we’re not yet even aware of - are we like the early Greeks before they thought of the laws of nature?
  - There are limits (e.g. when everyone in the world is a scientist)
  - In any case, science will probably never be totally complete.

Or - will we finally give up, and ask our galactic neighbours (who are billions of years more advanced) for the answers to our remaining questions?

Meanwhile, there's lots to do:

- **Astronomy:**

  Dark Matter, Dark Energy, Reionization, Gravitational waves, Cosmological Parameters, Inflation, the Multiverse, Extra-Solar Planets, Extraterrestrial Life ….

- **Physics:**

  Physics beyond the Standard Model, Dark Matter, Dark Energy, Supersymmetry, Extra Dimensions, String theory, Matter-Antimatter Asymmetry, Quantum Entanglement, Fundamental Physics, Theory of Everything ….

- **Life Sciences:**

  Epigenetics, Epigenotype, Consciousness, Fundamentals of Biological Systems, Artificial Life, Origin of Life ….

… and the great unexpected new discoveries of this century

Can Science ever be Complete?

- There will always be measurement uncertainty
- The vast number of particles in the universe - this has dealt with by understanding the governing principles - but there remains the problem of induction
- The complexity of living systems - evolution never stops, life is ever-changing
- We can't see beyond our 'light cone"
- We can't see inside the 'event horizon' of a black hole
- In a multiverse we could not see the other universes, and our laws of physics would just be due to local random 'weather'
- There may be tiny variations in the laws of physics in space and time
- Particle accelerators and telescopes may become impossibly expensive
- The uncertainty principle limits our knowledge of the subatomic world
- We can never *prove* the validity of a theory (Popper)
- We can never be sure that our models of the subatomic world are unique
- Any infinities in space or time would render our scientific knowledge incomplete
- We could never be sure that a 'Theory of Everything' encompasses everything that exists. Even if it did, while science would then be complete, we could never prove it.
- Gödel's theorems may limit any attempts at completeness in a set of axioms from which all knowledge could in principle be deduced

$\rightarrow$ Perhaps the best we can expect is just *a working knowledge* of everything we can *detect*.