Creativity and innovation in science and technology

February – March 2012

What we need to understand

- The difference between science and technology; between creativity and innovation
- The drivers of innovation
- The barriers to innovation
- Why innovation is essentially a human activity
- How innovation is a cumulative process
- The unpredictability of the innovation process

Asking the right questions

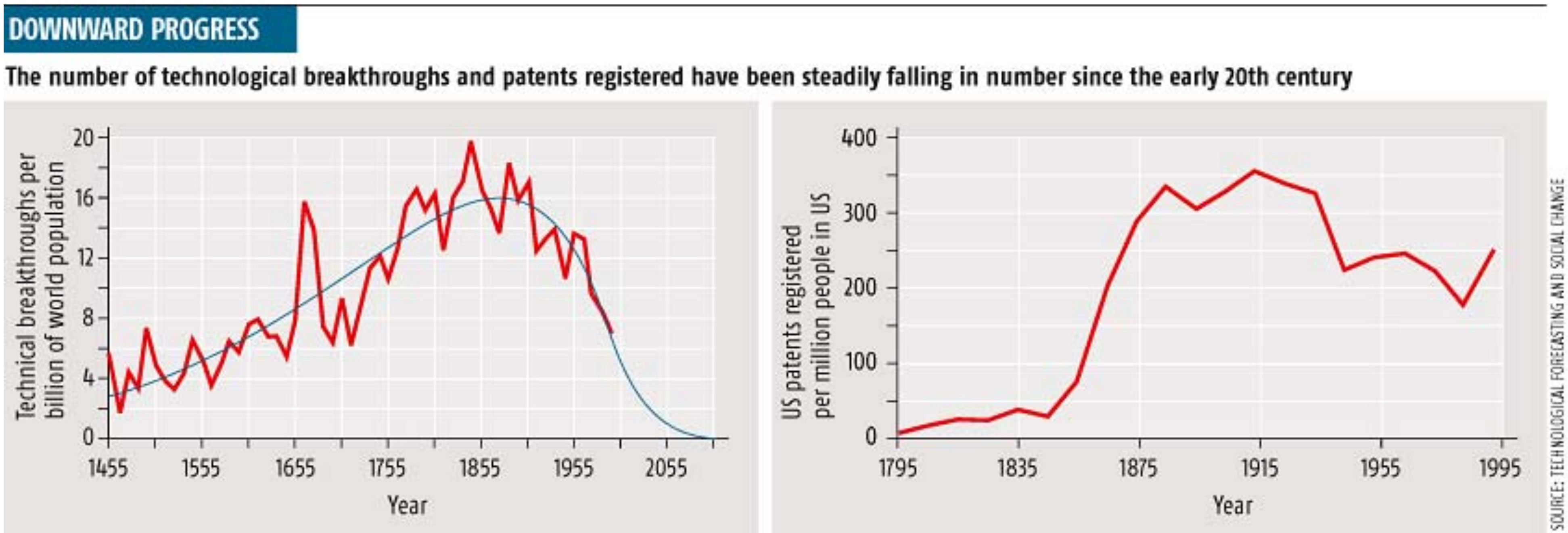
- A metric for innovation: Are patents a good measure?
- Can they be applied to all types of innovation?
- Does new science always lead to new technology?
- What does it take for new science to be turned into new technology?

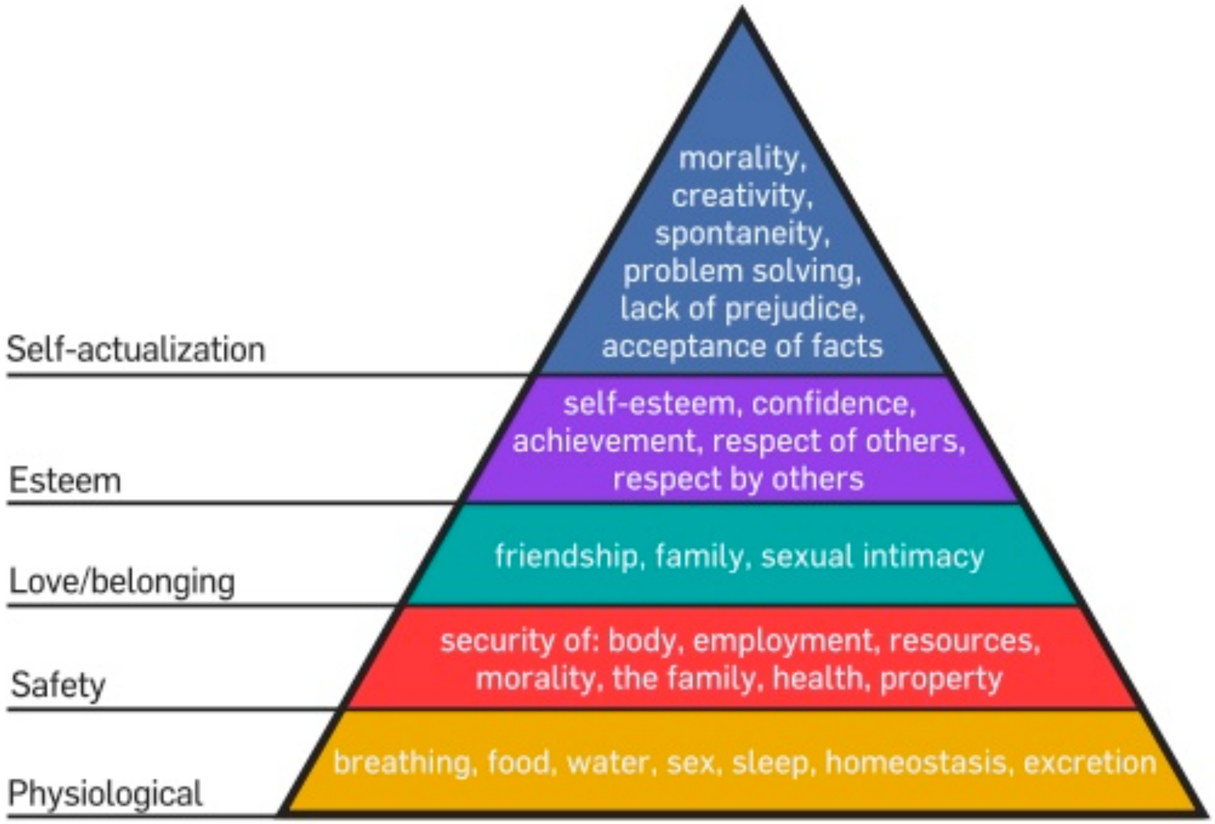
- Are there any new technologies which are not new science?
- And vice-versa?
- Is the gap between new science and new technology significant?
- Are we more innovative alone or in a group?
- Do economic factors play a role in the development of new technology? What about new science?

- Did innovation really stall during some periods in history? (The Dark Ages?)
- Do new mathematical and scientific models constitute innovation?
- Number of patents vs Number of scientific publications.
  - Does this tell us anything?
- Is there a link between the scale of social structures and the scale of innovation?

- Are we reaching the limit of
  - Human creativity (the brain)?
  - Economic means?
  - Energy sources?
  - The 'exploitable gap' between human requirements and technological solutions ?

  (*Do we really need all these gadgets?*)
  - Is there really a limit?





Abraham Maslow's 'hierarchy of needs'.
Which part of this can technology satisfy?

Scientific vs Technological innovation

- As the domain of validity of a theory becomes larger, the theory becomes more difficult to falsify.
- i.e. It becomes more difficult to formulate meaningful new theories.
- Is innovation necessarily a breakthrough? (Scientific revolutions vs The daily grind)

THE TOOLS OF PHYSICS (and all other sciences)

REDUCTION to component parts (break the system down into simpler systems)

ABSTRACTION/APPROXIMATION: use ideal components (study the ideal case first)

UNIFICATION: one rule has many applications (so our predictions are valid FOR ALL SUCH SYSTEMS)

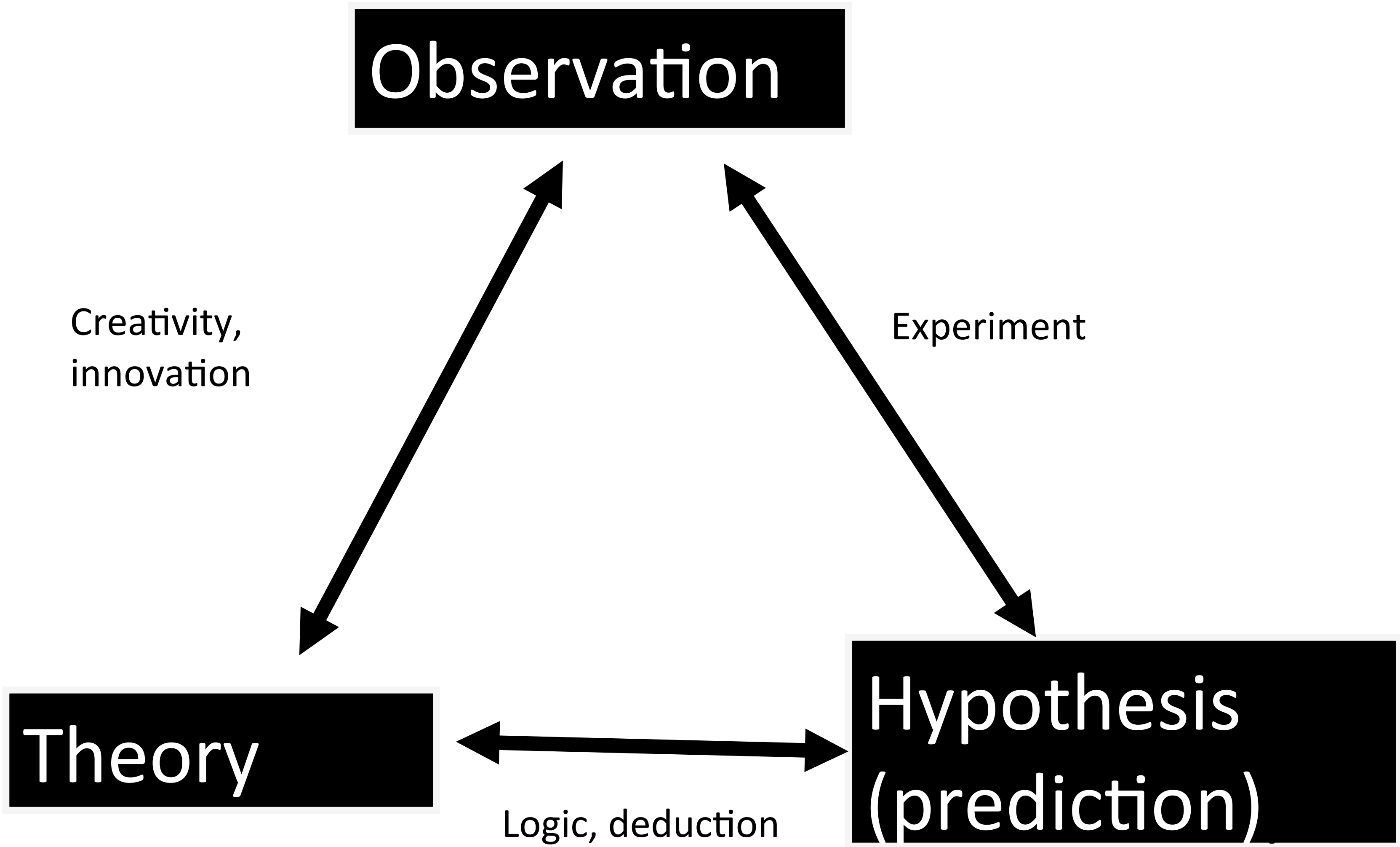
METHOD: examine facts and formulate rules

EXPERIMENTS

GATHER INFORMATION ABOUT THE OBSERVABLE SYSTEM

THEORIES

CLASSIFY THE FACTS AND PROVIDE RULES THAT NATURE APPEARS TO FOLLOW

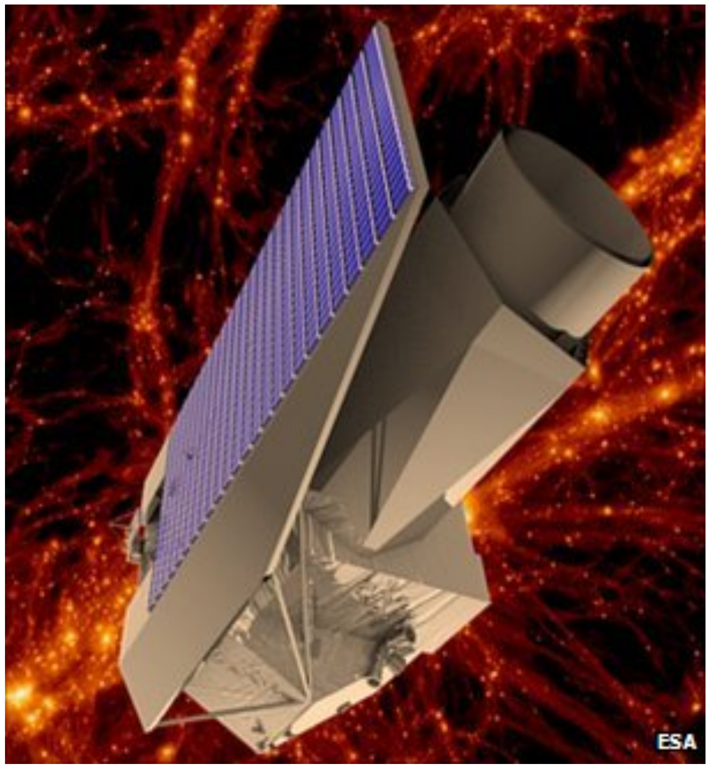

Observation
Creativity, innovation
Experiment
Theory
Hypothesis (prediction)
Logic, deduction

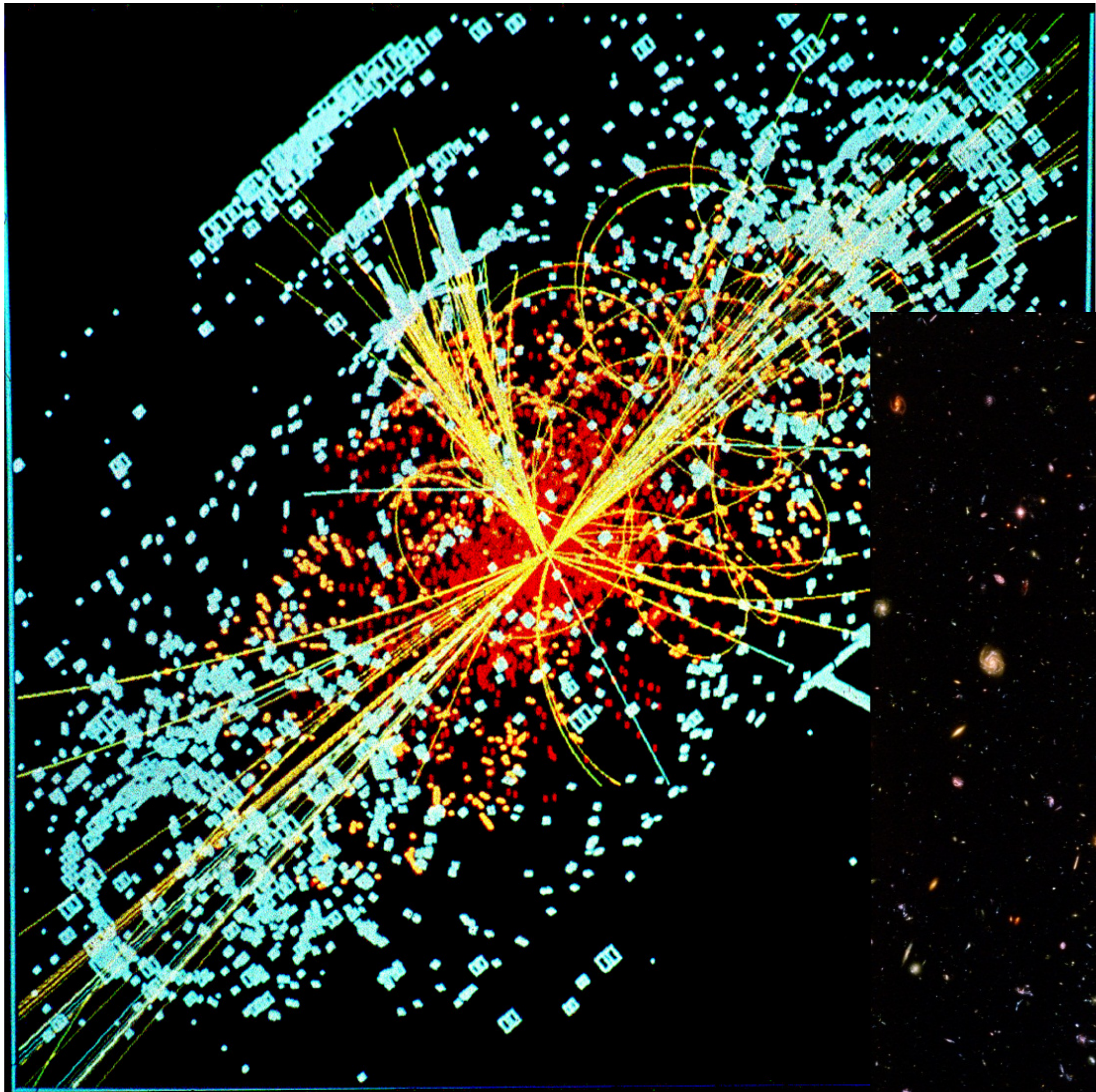
Natural science at different SCALES

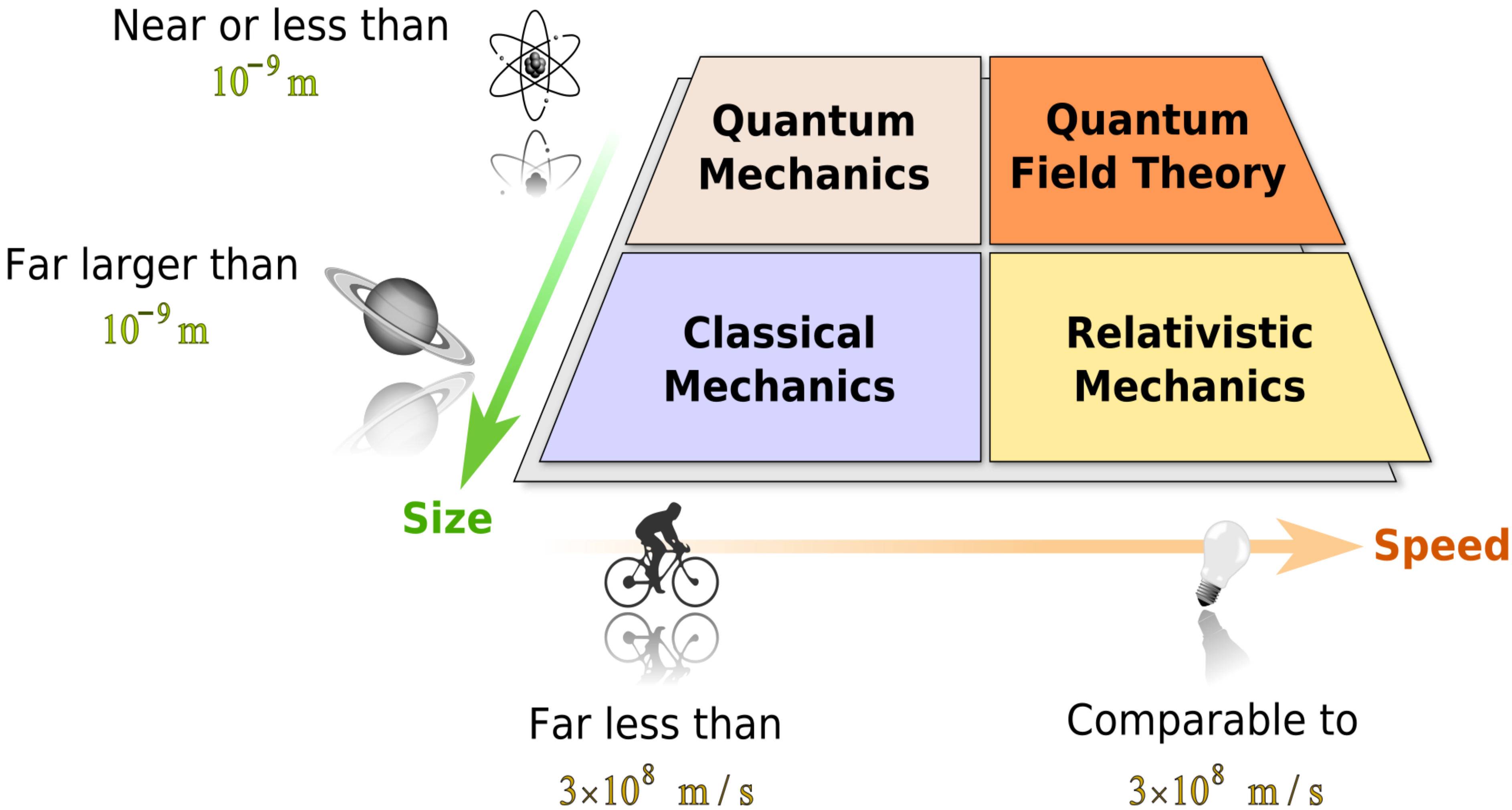
Only the simplest systems can be studied at such a basic level. Different scientific disciplines are all about systems on DIFFERENT SCALES.

Physics: Smallest and largest scales (quantum and atomic level; size of the known universe)

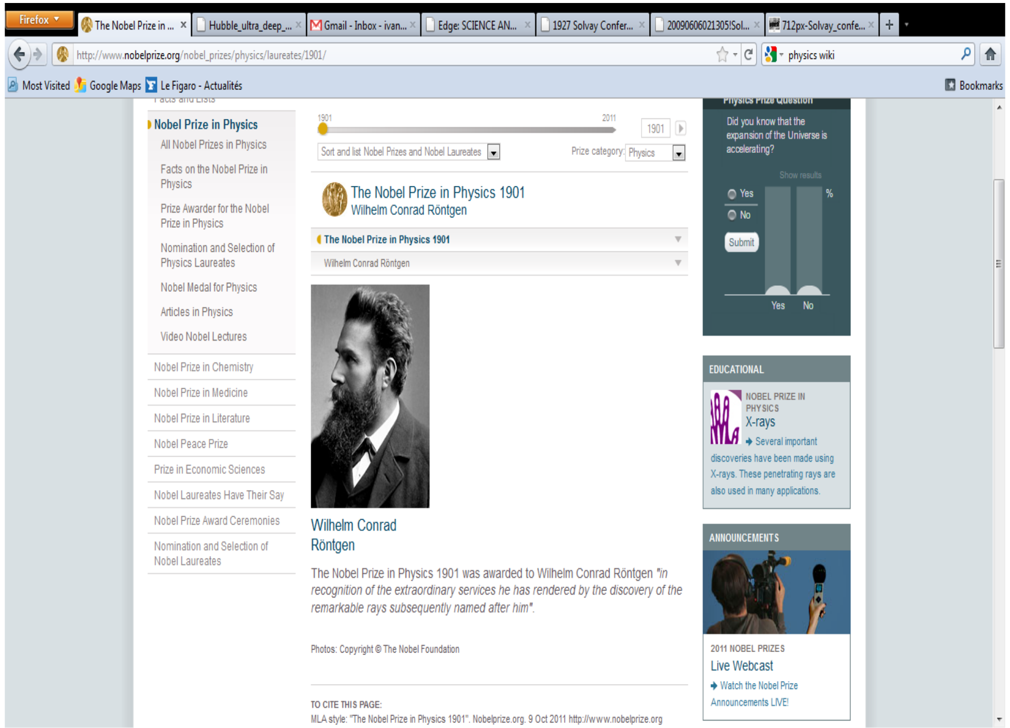
Chemistry, biology, other sciences: Everything in between (large number of molecules – chemistry; large number of chemical processes – biology…)

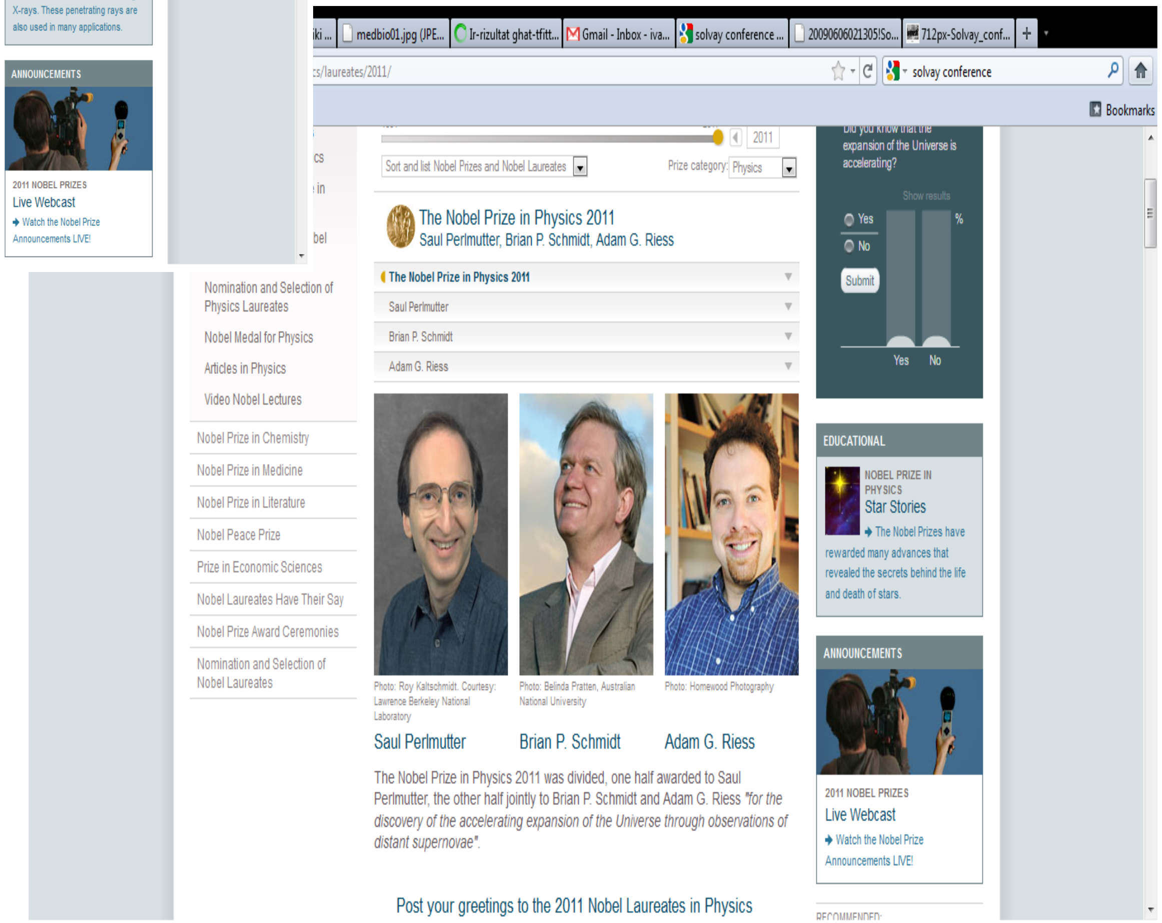


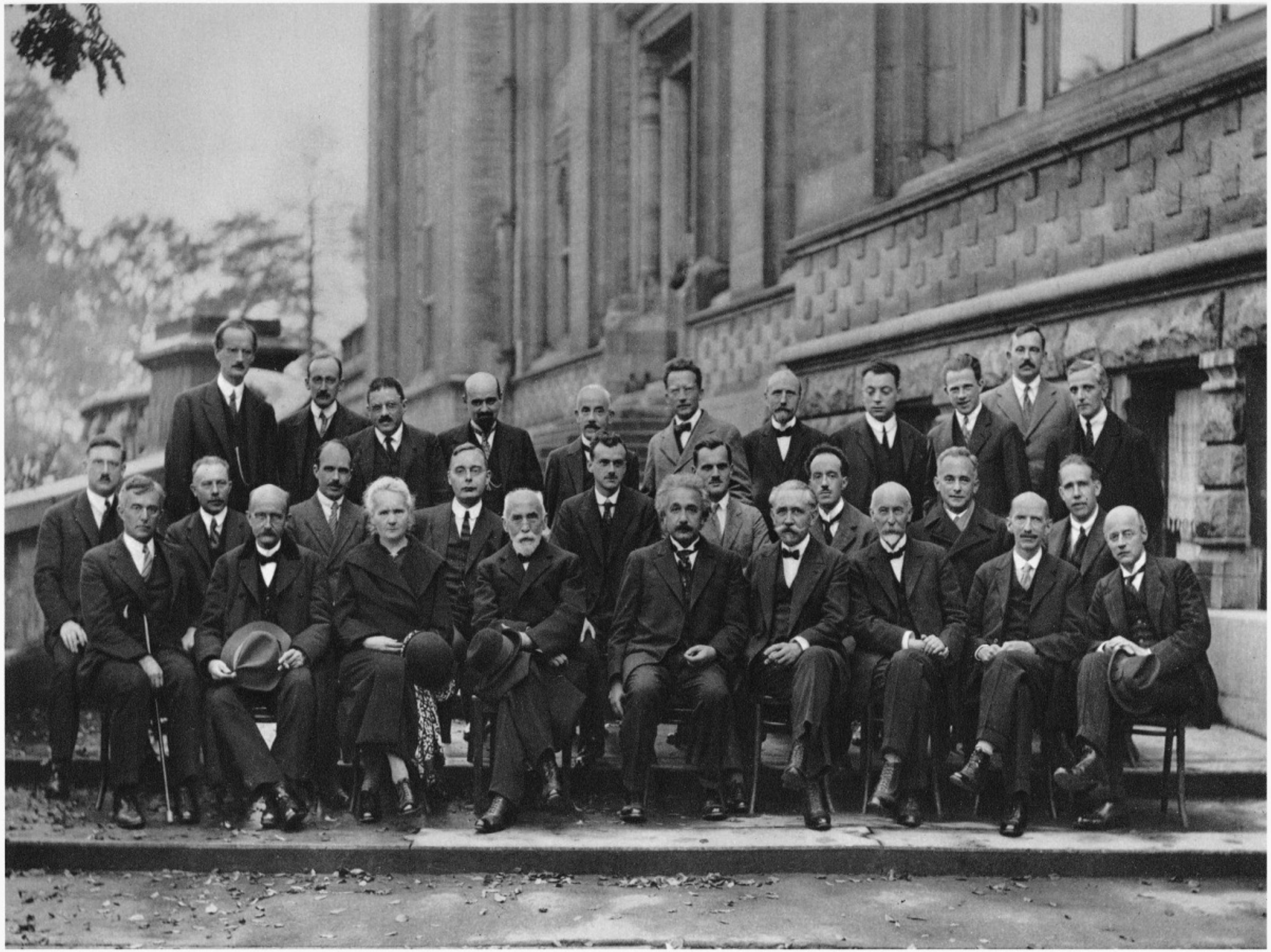




Near or less than
10^{-9} m
Far larger than
10^{-9} m
Quantum Mechanics
Quantum Field Theory
Classical Mechanics
Relativistic Mechanics
Size
Speed
Far less than
3×10^{8} m / s
Comparable to
3×10^{8} m / s

Nobel Prizes then and now



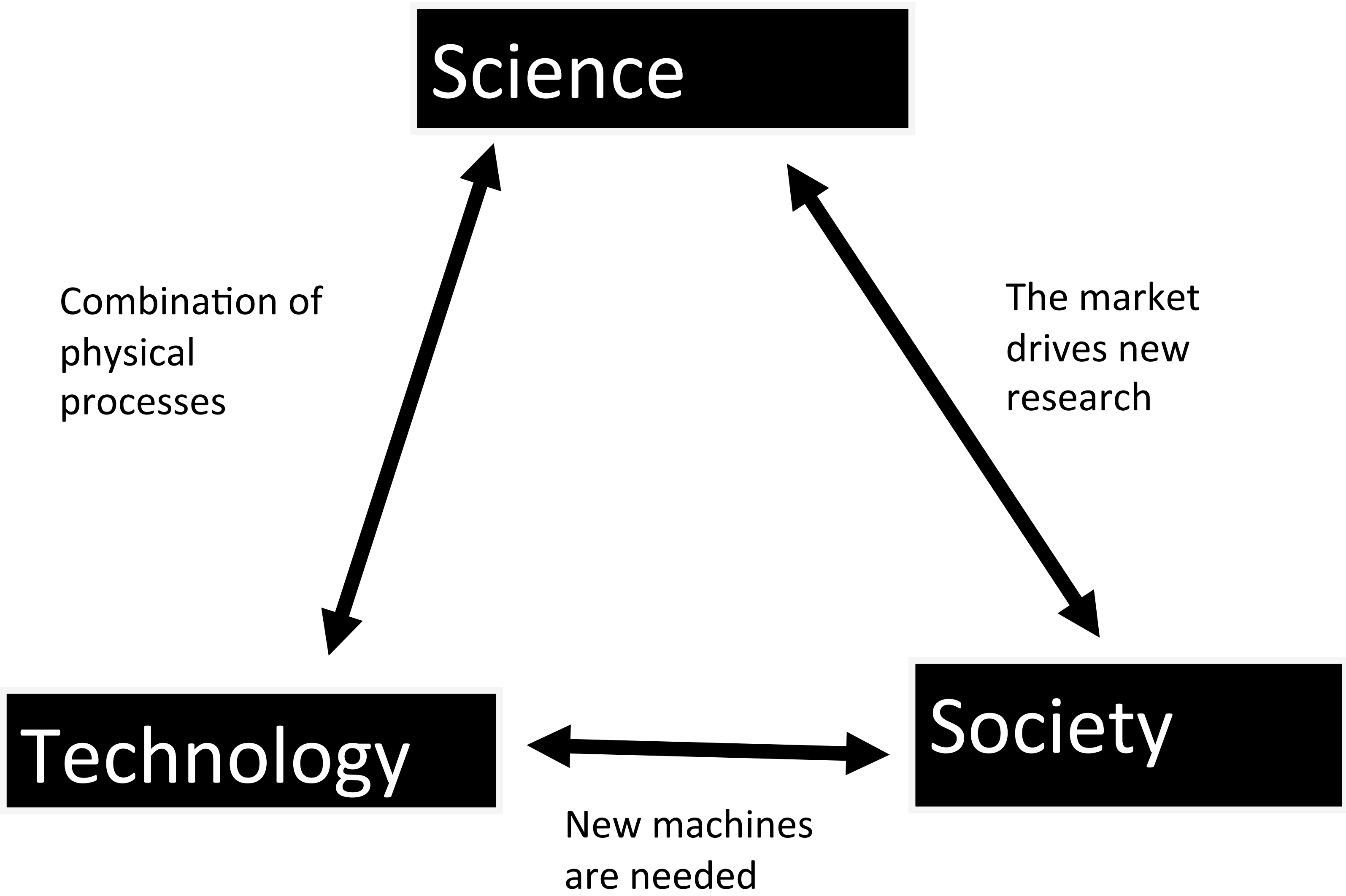




A. PICCARD E. HENRIOT P. EHRENFEST Ed. HERZEN Th. DE DONDER E. SCHRÖDINGER E. VERSCHAFFELT W. PAULI W. HEISENBERG R.H. FOWLER L. BRILLOUIN
P. DEBYE M. KNUDSEN W.L. BRAGG H.A. KRAMERS P.A.M. DIRAC A.H. COMPTON L. de BROGLIE M. BORN N. BOHR
I. LANGMUIR M. PLANCK Mme CURIE H.A. LORENTZ A. EINSTEIN P. LANGEVIN Ch.E. GUYE C.T.R. WILSON O W. RICHARDSON

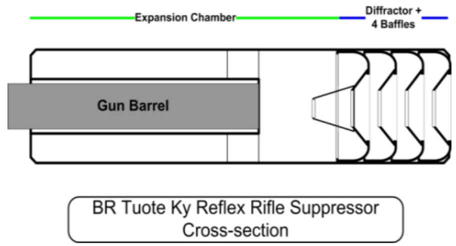
Absents : Sir W.H. BRAGG, H. DESLANDRES et E. VAN AUBEL

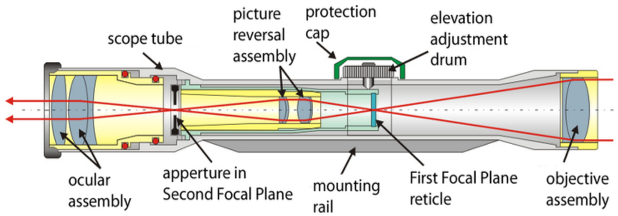
The second trinity

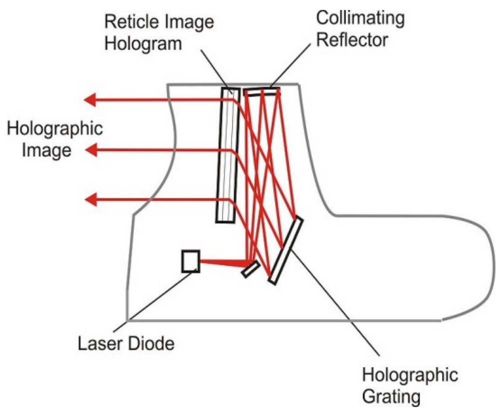


Innovation: from the medieval *gonne* to a modern assault rifle

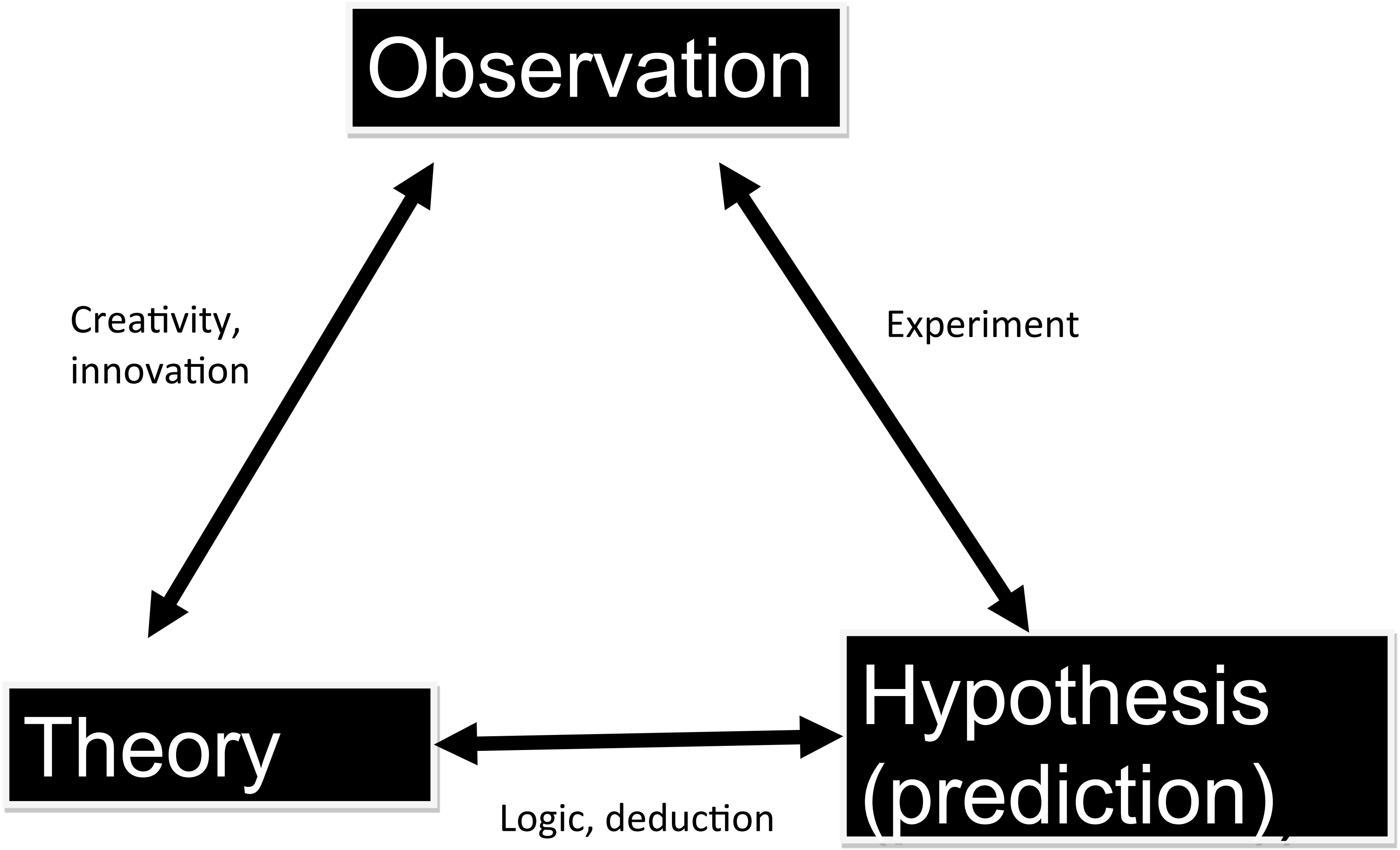
How much of this is new science?



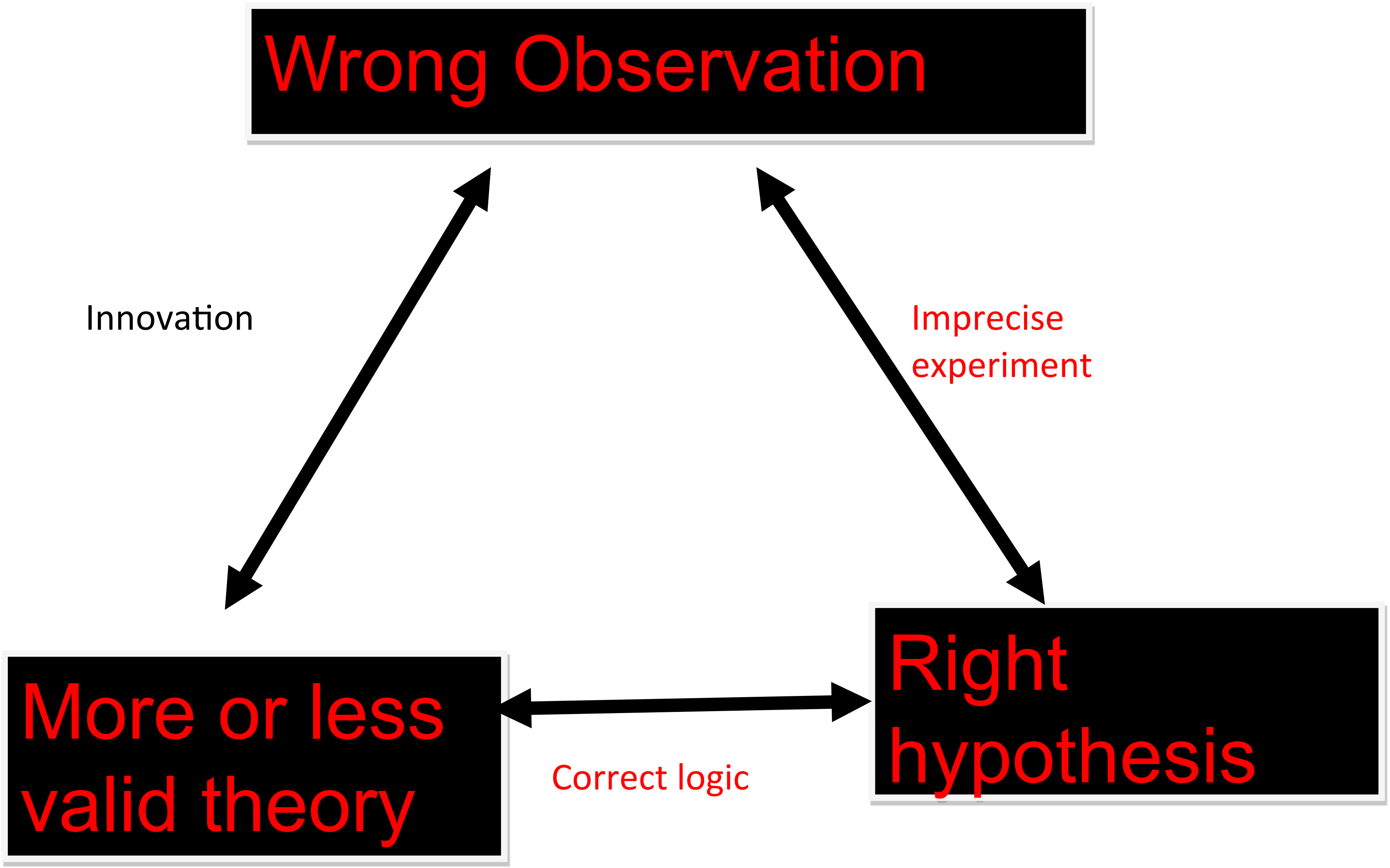




`Popper's perfect trinity'

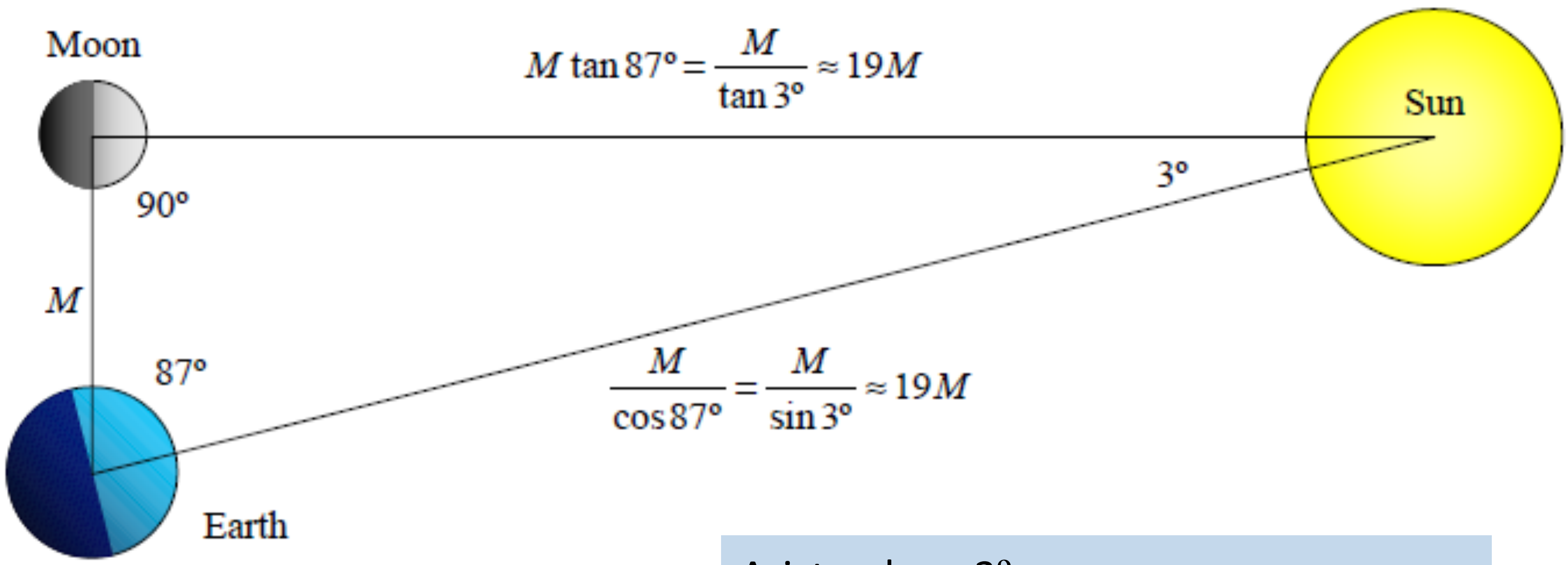


In reality


Wrong Observation
Innovation
Imprecise experiment
More or less valid theory
Correct logic
Right hypothesis

Case study: Do planets in the Solar System orbit the Sun?

- Aristarchos of Samos: 310 BC – 230 BC
- First heliocentric model
- Arrived at the right conclusion using the wrong data

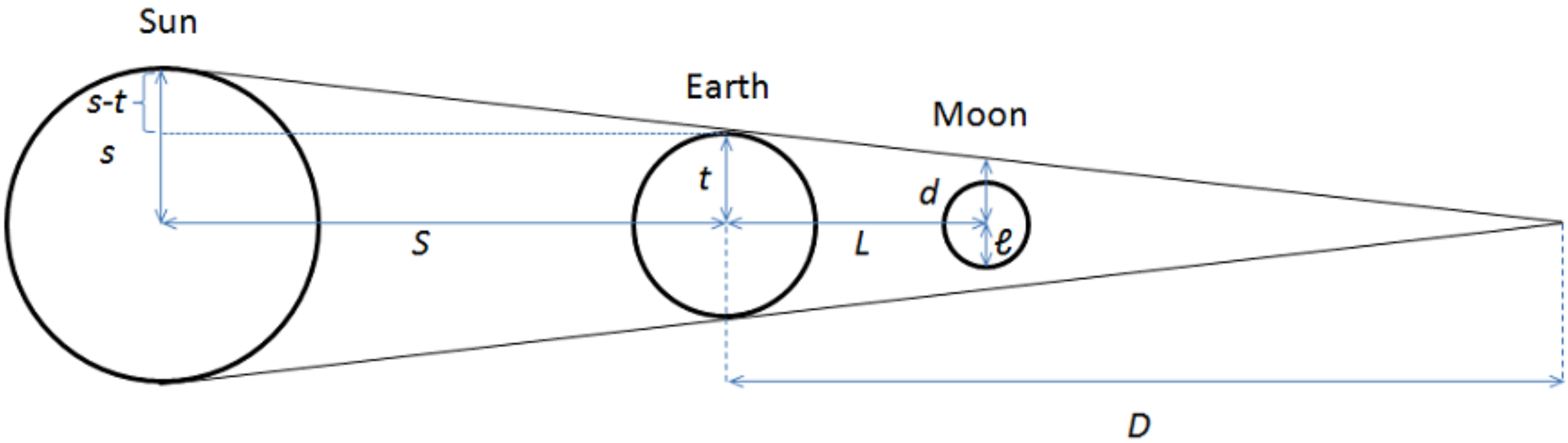


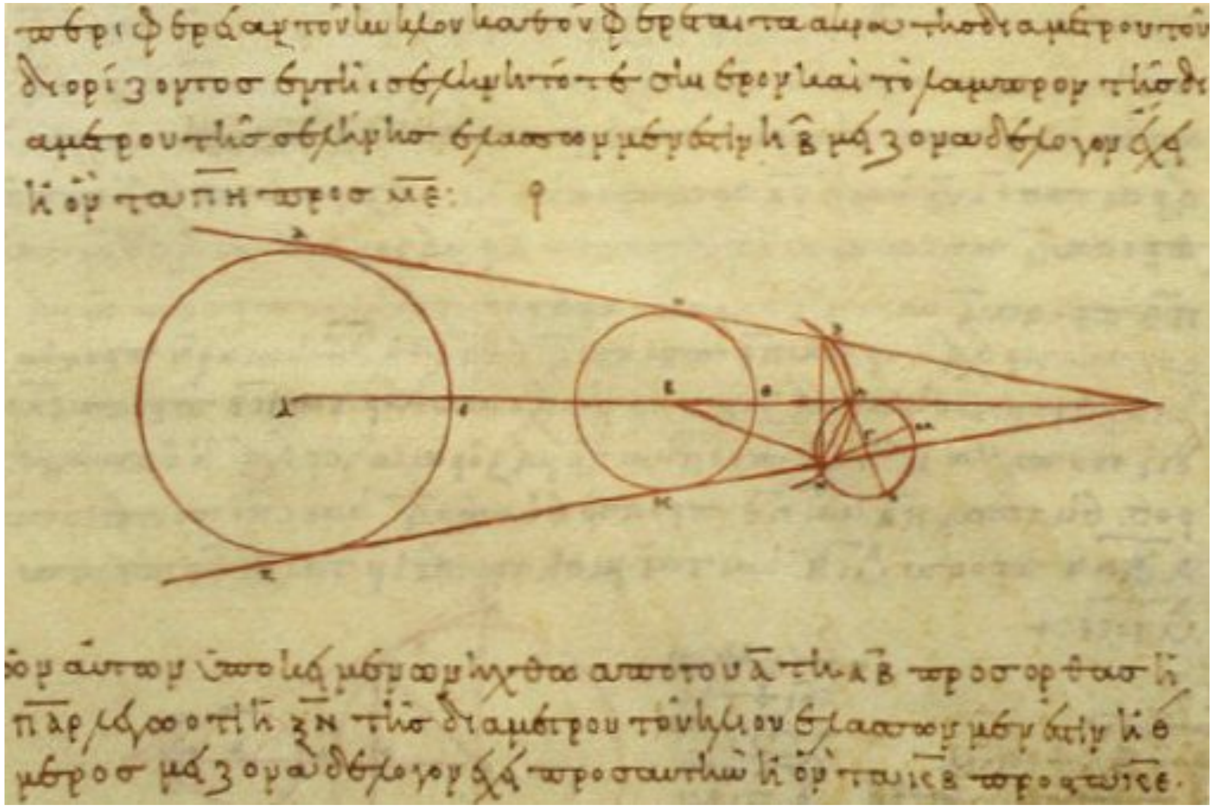
Aristarchos: 3°

Actual angle: 0.53°

$$18 < \frac{S}{L} < 20.$$

i.e. distance between the Sun and the Earth is between 18 and 20 times the distance from the Earth to the Moon

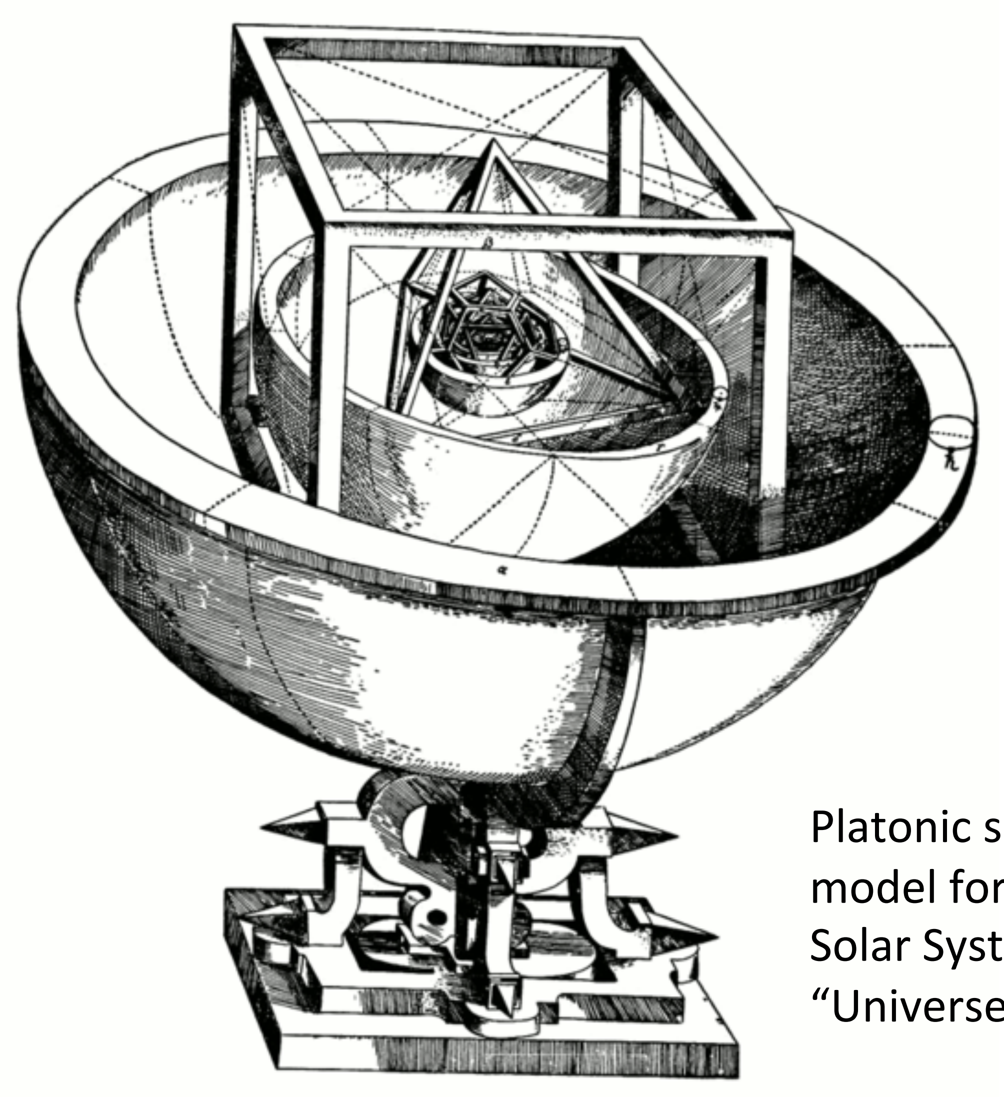

Sun
Earth
Moon
s-t
s
t
d
S
L
ℓ
D



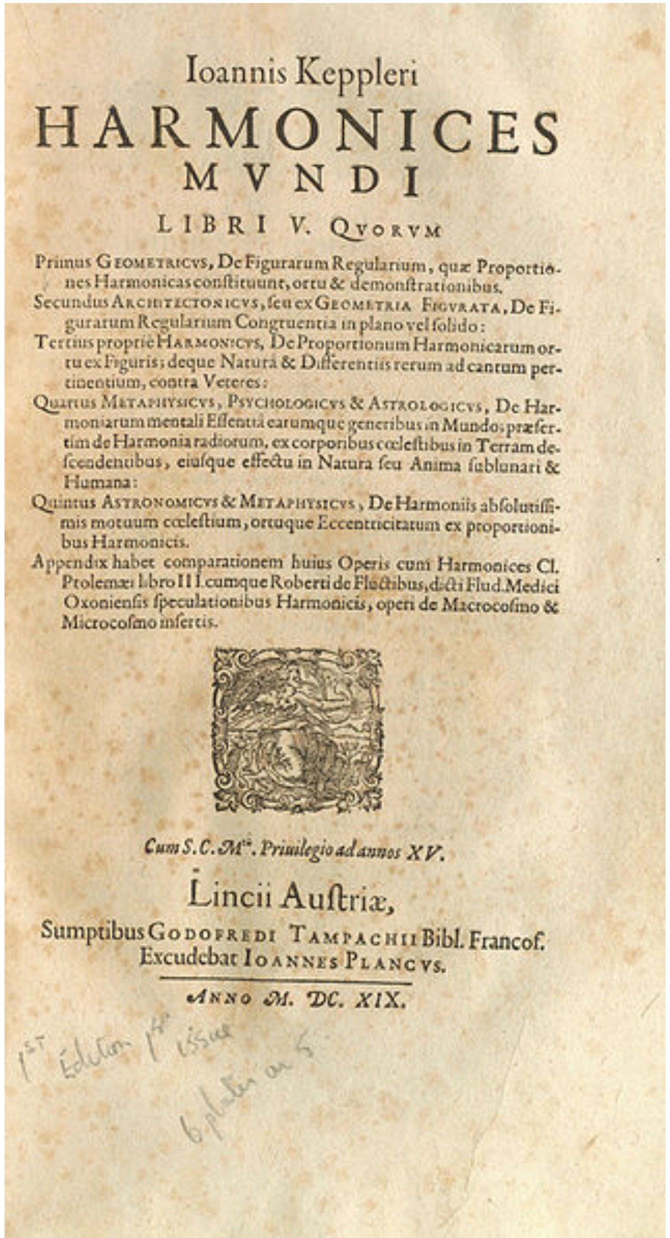
Case Study 2: Same calculation, 18 centuries years later

- Meanwhile:
  - invention of the telescope (new technology using new science)
  - Trigonometry (new logic)
  - Coordinate geometry (new logic)

Johannes Kepler (1571-1630)



Platonic solids as model for the Solar System (the "Universe")



Ioannis Keppleri

HARMONICES
MVNDI

LIBRI V. QVORVM

Primus GEOMETRICVS, De Figurarum Regularium, quæ Proportiones Harmonicas conſtituunt, ortu & demonſtrationibus.

Secundus ARCHITECTONICVS, ſeu ex GEOMETRIA FIGVRATA, De Figurarum Regularium Congruentia in plano vel ſolido:

Tertius propriè HARMONICVS, De Proportionum Harmonicarum ortu ex Figuris; deque Naturâ & Differentiis rerum ad cantum pertinentium, contra Veteres:

Quartus METAPHYSICVS, PSYCHOLOGICVS & ASTROLOGICVS, De Harmoniarum mentali Eſſentiâ earumque generibus in Mundo; præſertim de Harmonia radiorum, ex corporibus cœleſtibus in Terram deſcendentibus, eiuſque effectu in Natura ſeu Anima ſublunari & Humana:

Quintus ASTRONOMICVS & METAPHYSICVS, De Harmoniis abſolutiſſimis motuum cœleſtium, ortuque Eccentricitatum ex proportionibus Harmonicis.

Appendix habet comparationem huius Operis cum Harmonices Cl. Ptolemæi libro III. cumque Roberti de Fluctibus, dicti Flud. Medici Oxonienſis ſpeculationibus Harmonicis, operi de Macrocoſmo & Microcoſmo inſertis.

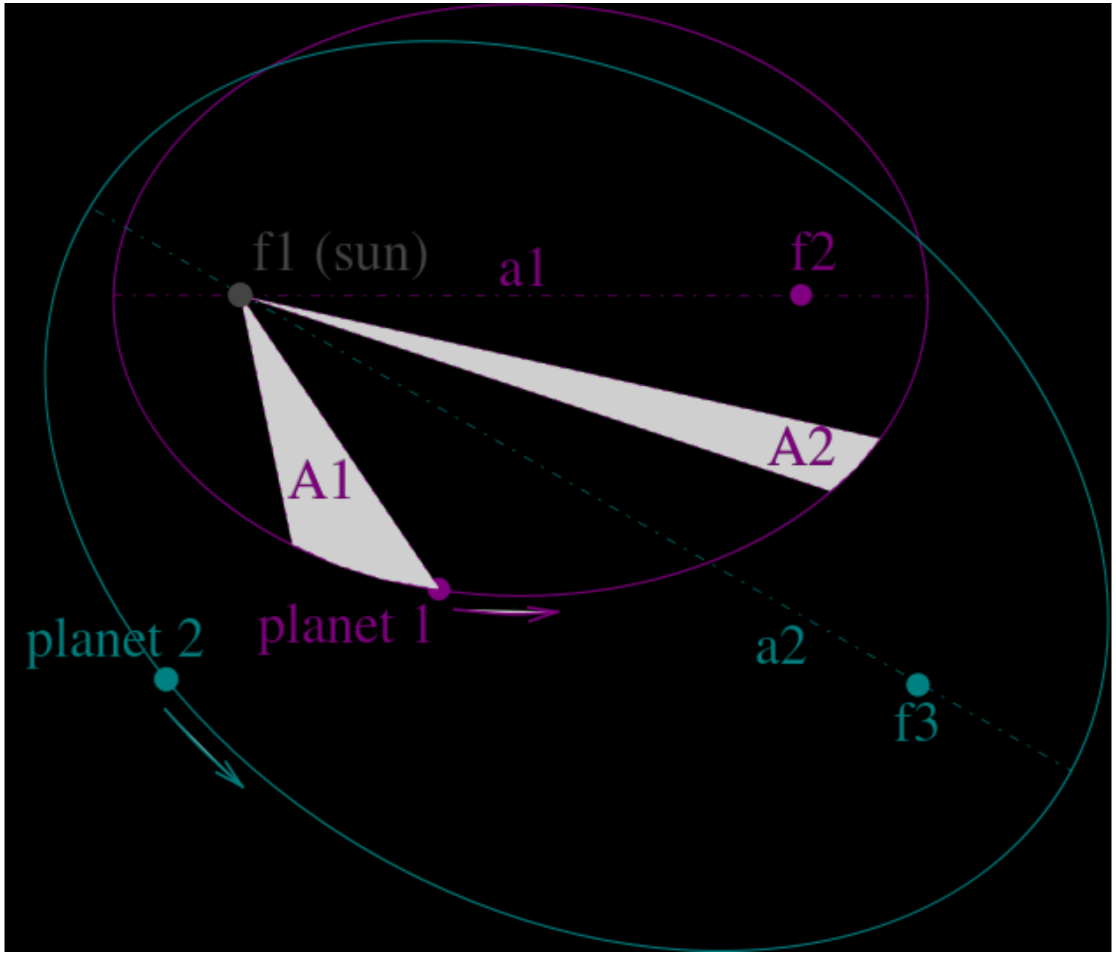
Cum S. C. Mtis. Priuilegio ad annos XV.

Lincii Auſtriæ,

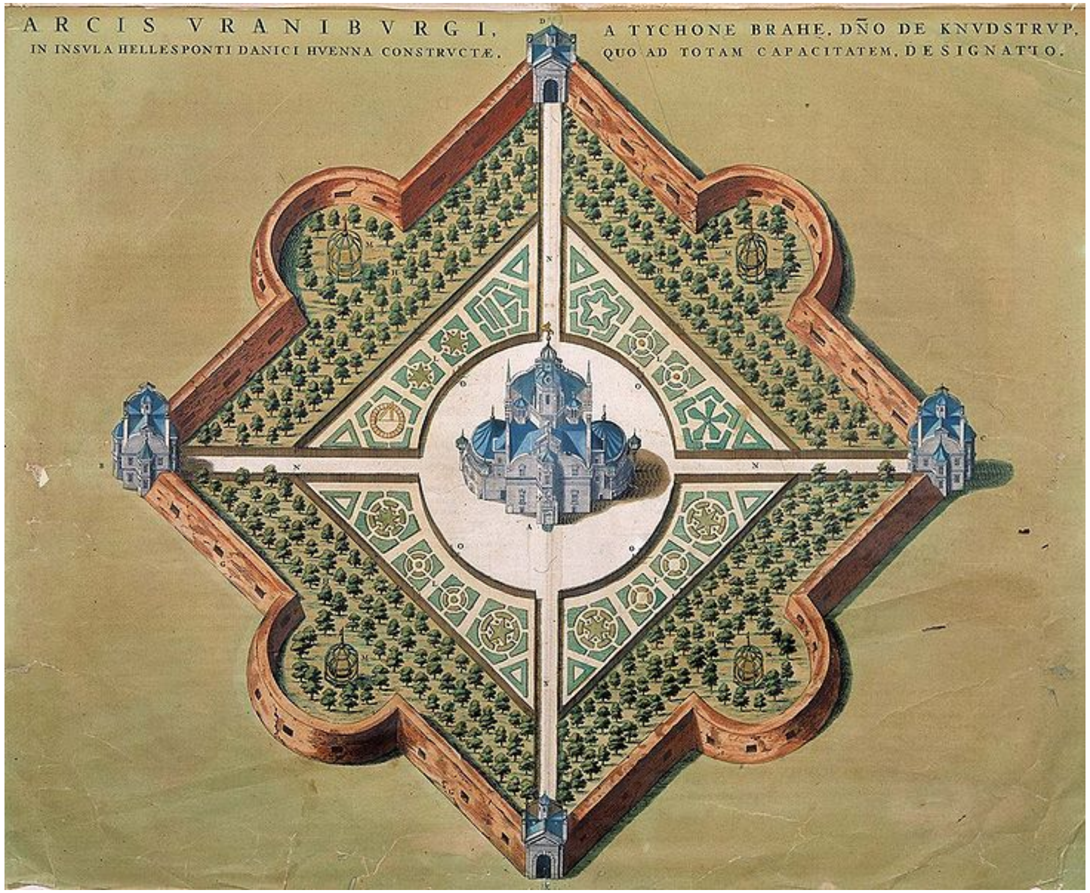
Sumptibus GODOFREDI TAMPACHII Bibl. Francof.
Excudebat IOANNES PLANCVS.

ANNO M. DC. XIX.

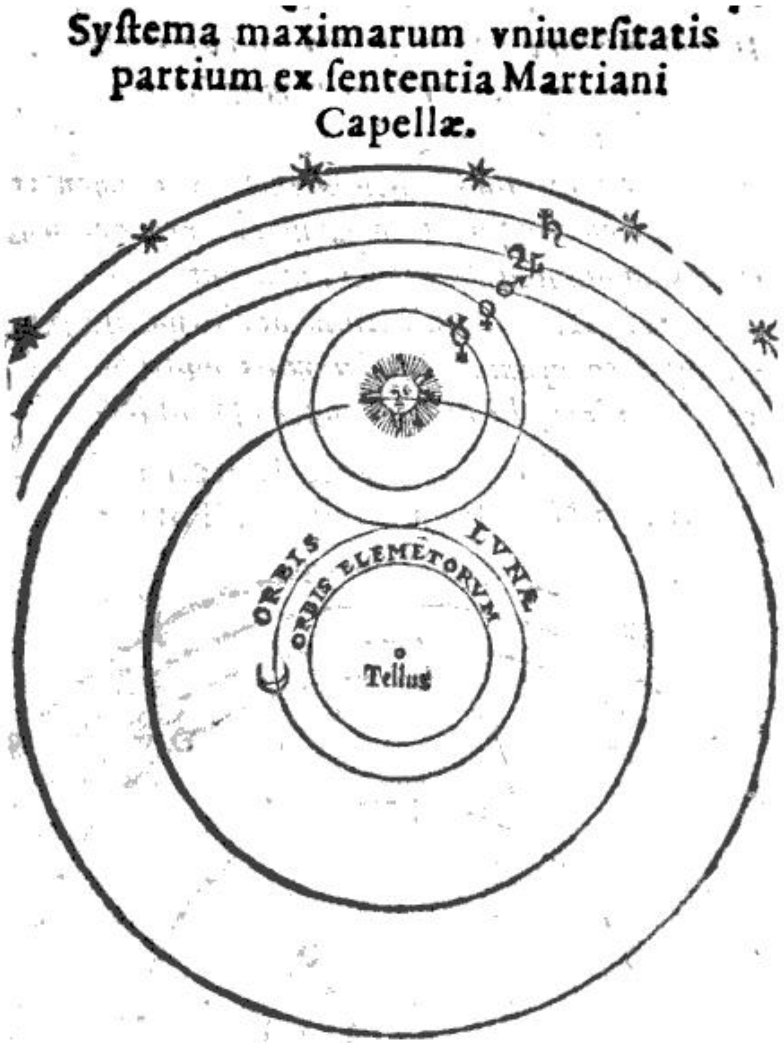
- Planetary orbits are ellipses
- Third law of planetary motion:
  - The square of the orbital period of a planet is directly proportional to the semi-major axis of the orbit.

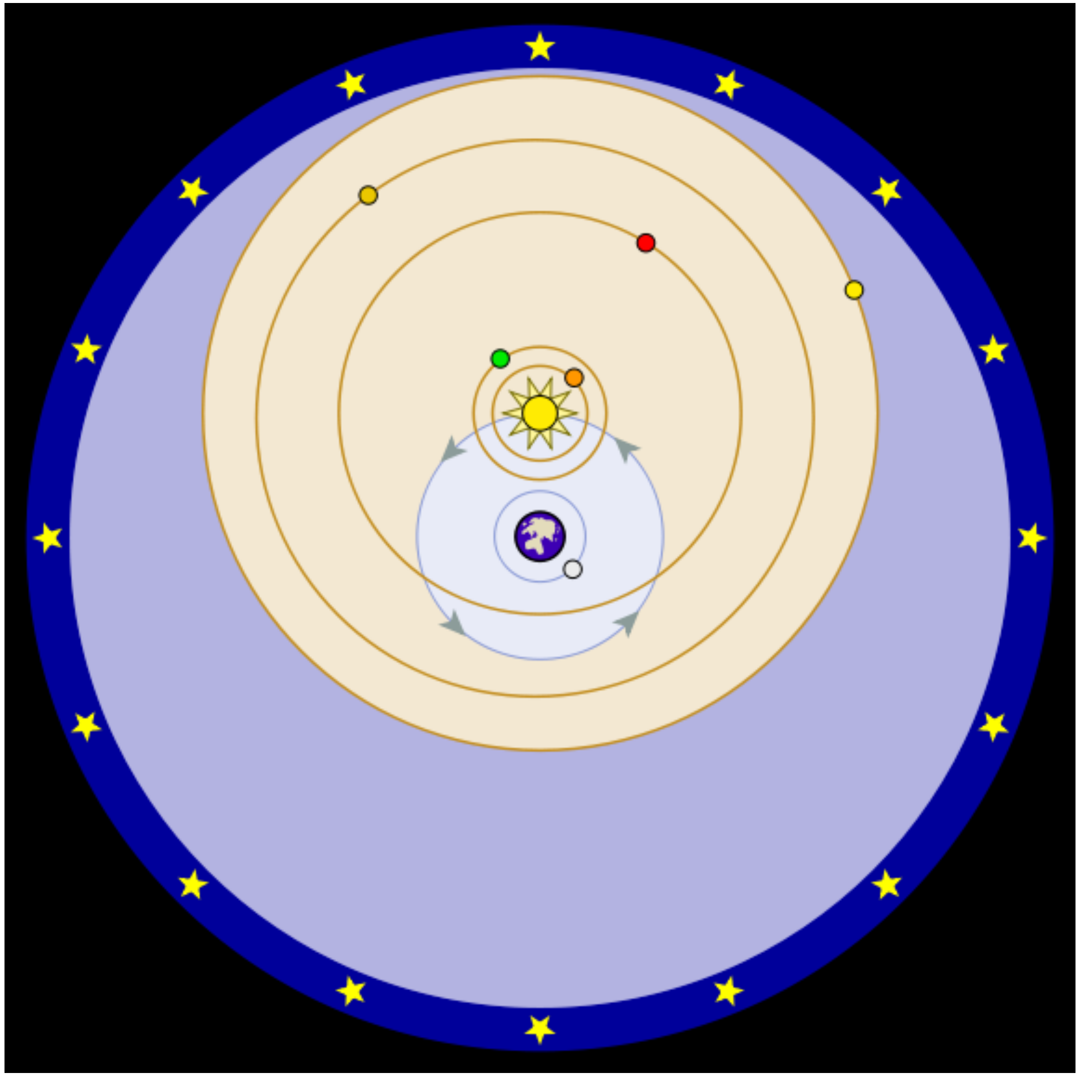


Tycho Brahe (1546-1601)



Tycho Brahe’s geoheliocentric model





	Solar parallax	Earth radii
Aristarchus (3rd cent. BCE)	40″	380-1,520 10,000
Hipparchus (2nd cent. BCE)	7′	490
Ptolemy (2nd cent.)	2′ 50″	1,210
Godefroy Wendelin (1635)	15″	14,000
Jeremiah Horrocks (1639)	15″	14,000
Christiaan Huygens (1659)	8.6″	24,000
Cassini & Richer (1672)	9½″	21,700
Jérôme Lalande (1771)	8.6″	24,000
Simon Newcomb (1895)	8.80″	23,440
Arthur Hinks (1909)	8.807″	23,420
H. Spencer Jones (1941)	8.790″	23,466
modern	8.794143″	23,455

$$A^3 = \frac{D^2}{GM_\odot k^2}$$

- Other examples of wrong data/logic/theory leading to right conclusions:
  - The cosmological constant (Einstein)

The Toaster Project

- www.thetoasterproject.org
- Is it possible for us to make the things that surround us?
- Jules Verne, *The Mysterious Island*

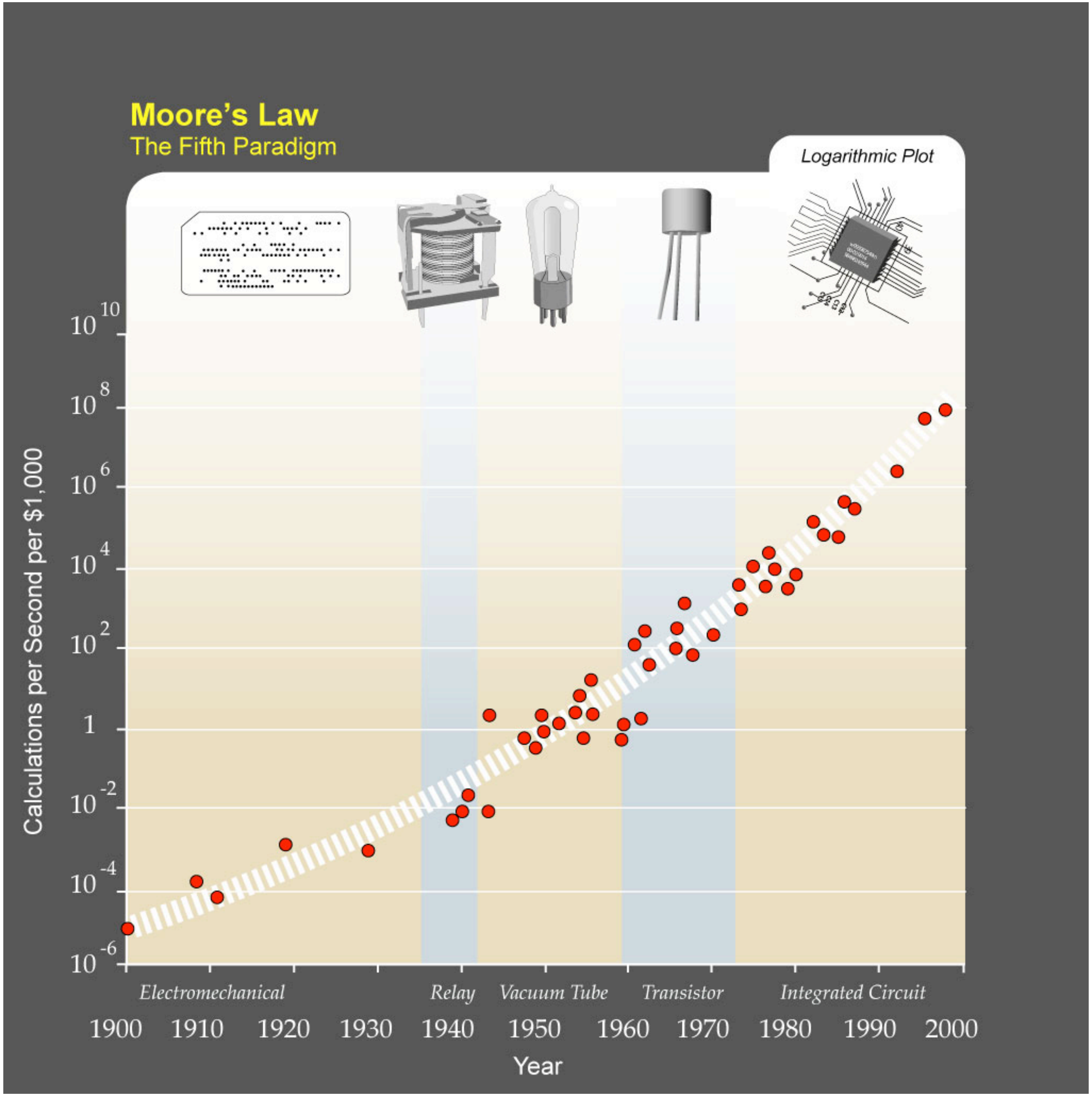
Limits to innovation

Physical (method)

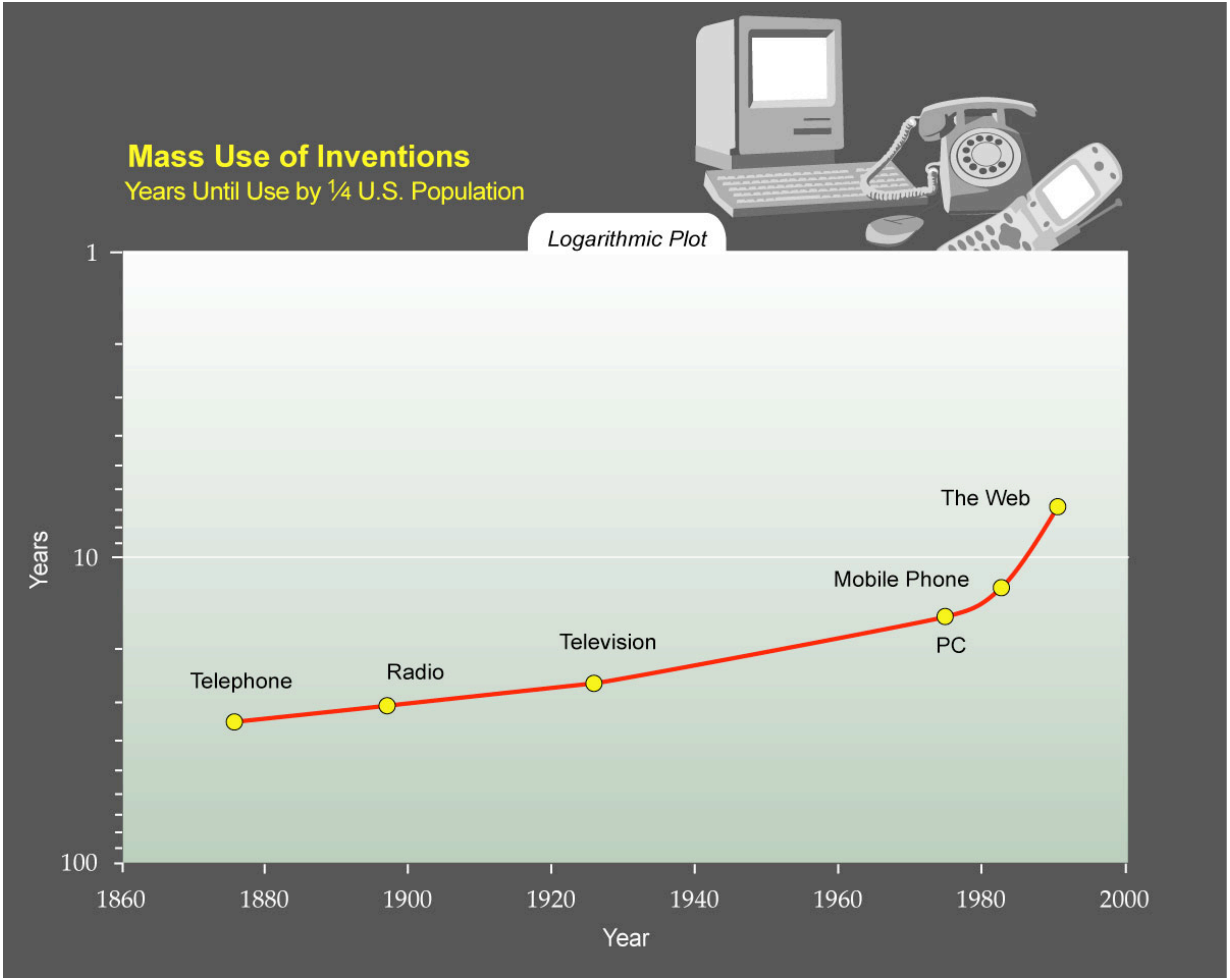
Economic (means)

Social (needs, capabilities)

Semantic (thought process)



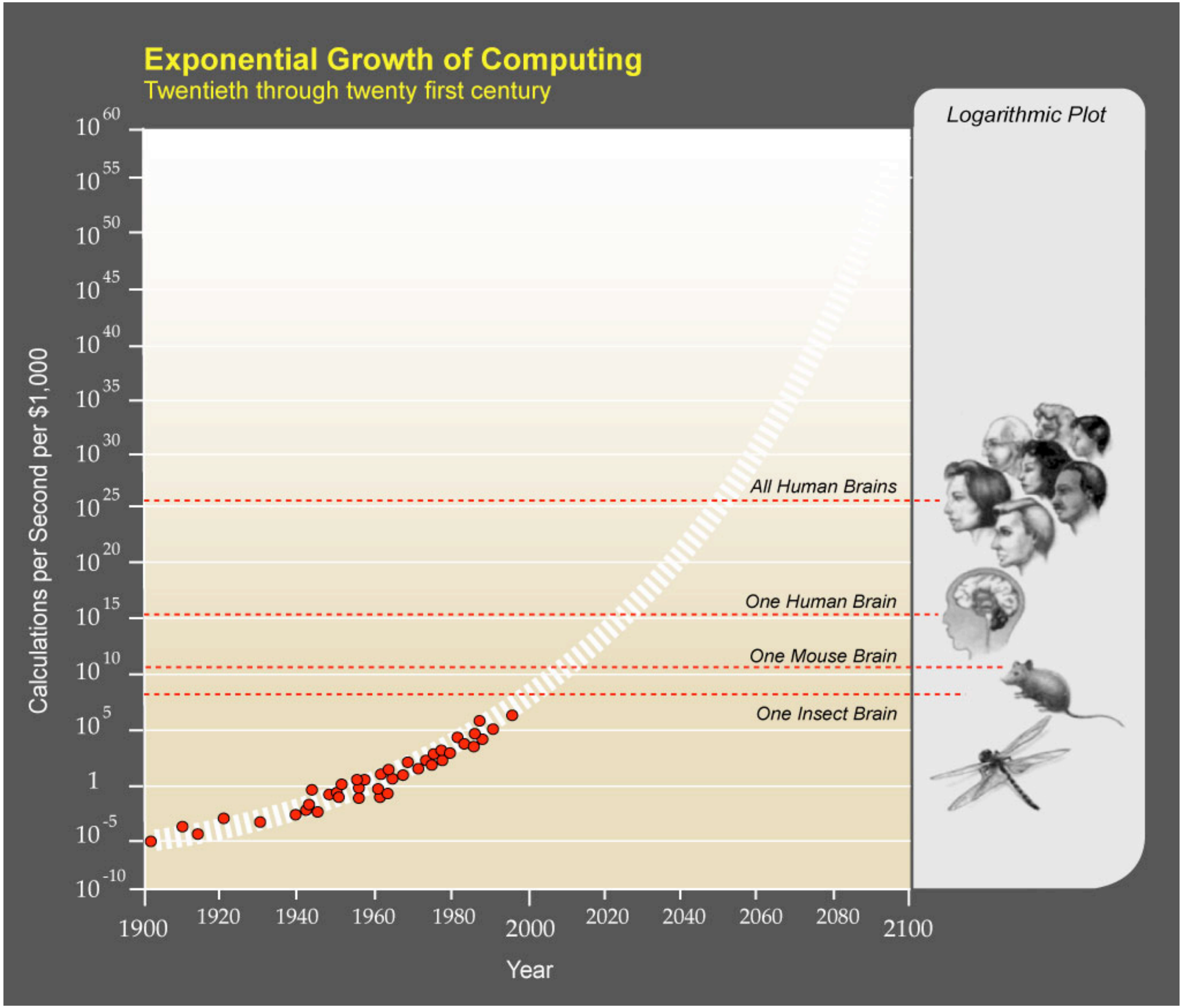
Moore's Law
The Fifth Paradigm
Logarithmic Plot
Calculations per Second per $1,000
10^10
10^8
10^6
10^4
10^2
1
10^-2
10^-4
10^-6
Electromechanical
Relay
Vacuum Tube
Transistor
Integrated Circuit
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year



Mass Use of Inventions
Years Until Use by ¼ U.S. Population
Logarithmic Plot
Years
1
10
100
Year
1860
1880
1900
1920
1940
1960
1980
2000
Telephone
Radio
Television
PC
Mobile Phone
The Web

Kurzweil's Law

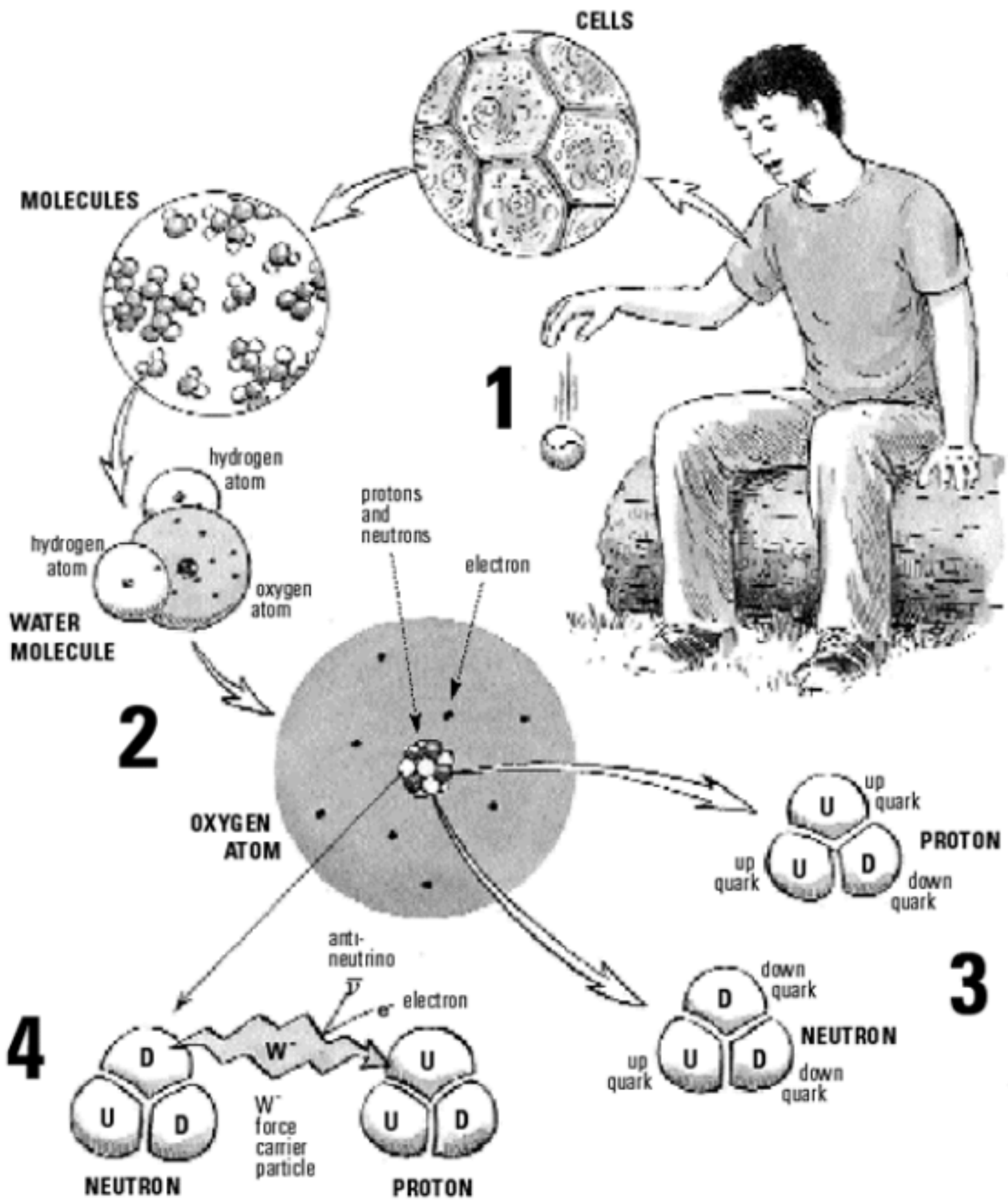
Will innovation be limited to computing power?



Energy use

- White's Law (Leslie White, 1943): other factors remaining constant, culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the instrumental means of putting the energy to work is increased.

- Kardashev scale (Nikolai Kardashev): The amount of usable energy that a civilisation has at its disposal (Type I - earth, Type II - star, Type III - galaxy)


CELLS
MOLECULES
1
hydrogen atom
hydrogen atom
oxygen atom
WATER MOLECULE
protons and neutrons
electron
2
OXYGEN ATOM
up quark
U
PROTON
up quark
U
D
down quark
3
down quark
D
NEUTRON
up quark
U
D
down quark
4
D
U
D
NEUTRON
W⁻
W⁻ force carrier particle
anti-neutrino
$\overline{\nu}$
e^- electron
U
U
D
PROTON

interuallum numerorum 2. minor autem 1 N. atque ideo maior 1 N. + 2. Oportet itaque 4 N. + 4. triplos esse ad 2. & adhuc superaddere 10. Ter igitur 2. adscitis vnitatibus 10. æquatur 4 N. + 4. & fit 1 N. 3. Erit ergo minor 3. maior 5. & satisfaciunt quæstioni.

ϛ° ἑνός. ὁ ἄρα μείζων ἔσται ϛ° ἑνὸς μ° β. δεήσει ἄρα ἀριθμοὺς δ μονάδας δ τριπλασίονας εἶναι μ° β. καὶ ἔτι ὑπερέχειν μ° ι. τρὶς ἄρα μονάδες β μετὰ μ° ι ἴσαι εἰσὶν ςς δ μονάσι δ. καὶ γίνεται ὁ ἀριθμὸς μ° γ. ἔσται ὁ μὲν ἐλάσσων μ° γ. ὁ δὲ μείζων μ° ε. καὶ ποιοῦσι τὸ πρόβλημα.

IN QVAESTIONEM VII.

CONDITIONIS appositæ eadem rattio est quæ & appositæ præcedenti quæstioni, nil enim aliud requirit quàm vt quadratus interualli numerorum sit minor interuallo quadratorum, & Canones iidem hic etiam locum habebunt, vt manifestum est.

QVÆSTIO VIII.

PROPOSITVM quadratum diuidere in duos quadratos. Imperatum sit vt 16. diuidatur in duos quadratos. Ponatur primus 1 Q. Oportet igitur 16 − 1 Q. æquales esse quadrato. Fingo quadratum à numeris quotquot libuerit, cum defectu tot vnitatum quod continet latus ipsius 16. esto à 2 N. − 4. ipse igitur quadratus erit 4 Q. + 16. − 16 N. hæc æquabuntur vnitatibus 16 − 1 Q. Communis adiiciatur vtrimque defectus, & à similibus auferantur similia, fient 5 Q. æquales 16 N. & fit 1 N. $\frac{16}{5}$ Erit igitur alter quadratorum $\frac{256}{25}$. alter verò $\frac{144}{25}$ & vtriusque summa est $\frac{400}{25}$ seu 16. & vterque quadratus est.

ΤΟΝ ἐπιταχθέντα τετράγωνον διελεῖν εἰς δύο τετραγώνους. ἐπιτετάχθω δὴ τὸν ιϛ διελεῖν εἰς δύο τετραγώνους. καὶ τετάχθω ὁ πρῶτος δυνάμεως μιᾶς. δεήσει ἄρα μονάδας ιϛ λείψει δυνάμεως μιᾶς ἴσας εἶναι τετραγώνῳ. πλάσσω τὸν τετράγωνον ἀπὸ ςς. ὅσων δή ποτε λείψει τοσούτων μ° ὅσων ἐστὶν ἡ τῶν ιϛ μ° πλευρά. ἔστω ςς β λείψει μ° δ. αὐτὸς ἄρα ὁ τετράγωνος ἔσται δυνάμεων δ μ° ιϛ λείψει ςς ιϛ. ταῦτα ἴσα μονάσι ιϛ λείψει δυνάμεως μιᾶς. κοινὴ προσκείσθω ἡ λεῖψις, καὶ ἀπὸ ὁμοίων ὅμοια. δυνάμεις ἄρα ε ἴσαι ἀριθμοῖς ιϛ. καὶ γίνεται ὁ ἀριθμὸς ιϛ πέμπτων. ἔσται ὁ μὲν σνϛ εἰκοστοπέμπτων. ὁ δὲ ρμδ εἰκοστοπέμπτων, καὶ οἱ δύο συντεθέντες ποιοῦσι υ εἰκοστόπεμπτα, ἤτοι μονάδας ιϛ. καὶ ἔστιν ἑκάτερος τετράγωνος.

OBSERVATIO DOMINI PETRI DE FERMAT.

CVbum autem in duos cubos, aut quadratoquadratum in duos quadratoquadratos & generaliter nullam in infinitum vltra quadratum potestatem in duos eiusdem nominis fas est diuidere cuius rei demonstrationem mirabilem sane detexi. Hanc marginis exiguitas non caperet.

QVÆSTIO IX.

RVRSVS oporteat quadratum 16 diuidere in duos quadratos. Ponatur rursus primi latus 1 N. alterius verò quotcunque numerorum cum defectu tot vnitatum, quot constat latus diuidendi. Esto itaque 2 N. − 4. erunt quadrati, hic quidem 1 Q. ille verò 4 Q. + 16. − 16 N. Cæterum volo vtrumque simul æquari vnitatibus 16. Igitur 5 Q. + 16. − 16 N. æquatur vnitatibus 16. & fit 1 N. $\frac{16}{5}$ erit

ΕΣΤΩ δὴ πάλιν τὸν ιϛ τετράγωνον διελεῖν εἰς δύο τετραγώνους. τετάχθω πάλιν ἡ τοῦ πρώτου πλευρὰ ϛ° ἑνός, ἡ δὲ τοῦ ἑτέρου ςς ὅσων δήποτε λείψει μ° ὅσων ἐστὶν ἡ τοῦ διαιρουμένου πλευρά. ἔστω δὴ ςς β λείψει μ° δ. ἔσονται οἱ τετράγωνοι ὃς μὲν δυνάμεως μιᾶς, ὃς δὲ δυνάμεων δ μ° ιϛ λείψει ςς ιϛ. βούλομαι τοὺς δύο λοιπὸν συντεθέντας ἴσους εἶναι μ° ιϛ. δυνάμεις ἄρα ε μ° ιϛ λείψει ςς ιϛ ἴσαι μ° ιϛ. καὶ γίνεται ὁ ἀριθμὸς ιϛ πέμπτων.

Cubum autem in duos cubos, aut quadratoquadratum in duos quadratoquadratos, et generaliter nullam in infinitum ultra quadratum potestatem in duos eiusdem nominis fas est dividere

The semantics of innovation: passing on the word

- Progress requires the sharing of information.
- We are swamped by data, a fraction of that is information, only a fraction of that is knowledge.
- Language is essential to civilisation.
- Before that, it was essential to have a urban centres. A sedentary society can develop in ways that a nomadic one cannot. (It cannot build libraries).

- Language must be used precisely if it is to be used in science.
- Example: mathematics before symbols were developed.
- Example: Arabic numerals. An easier mathematical language
- Example: Computer languages. Do we go to machine code or to high level human-like language?

Is there a semantic limit to innovation?

- Have we reached a plateau in language development with a common language for everyone?
- Can we invent new semantic dictionaries?
- Peer-review publications are the manuscripts of the modern age.
- BUT has self-publishing destroyed quality? No peer-review means quack science can flourish. But is this an obstacle to innovation?
- Can it create political pressure which is based on faulty science?

Scientific and technical publishing

- From manuscript to print. From self publishing to peer review.
- Learned societies:17th/18th century, coinciding with the ‘mathematisation’ of science. Served to codify scientific language.
  - Sodalitas Litterarum Vistulana (1488)
  - Académie Française (1635)
  - Royal Society of London (1660)
- Peer review only came about in the mid-20th century.
- Open access. Back to self-publishing. Does it damage the scientific process? Does it hinder progress?
  - e.g. Wikipedia, Arxiv.org

PHILOSOPHICAL TRANSACTIONS:

GIVING SOME

ACCOMPT

OF THE PRESENT

Undertakings, Studies, and Labours

OF THE

INGENIOUS

IN MANY

CONSIDERABLE PARTS

OF THE

WORLD.

Vol I.

For *Anno* 1665, and 1666.

In the *SAVOY*,

Printed by *T. N.* for *John Martyn* at the Bell, a little without *Temple-Bar*, and *James Allestry* in *Duck-Lane*, Printers to the *Royal Society*.

Peer review failure

Drummond Rennie, deputy editor of Journal of the American Medical Association is an organizer of the International Congress on Peer Review and Biomedical Publication:

There seems to be no study too fragmented, no hypothesis too trivial, no literature too biased or too egotistical, no design too warped, no methodology too bungled, no presentation of results too inaccurate, too obscure, and too contradictory, no analysis too self-serving, no argument too circular, no conclusions too trifling or too unjustified, and no grammar and syntax too offensive for a paper to end up in print.

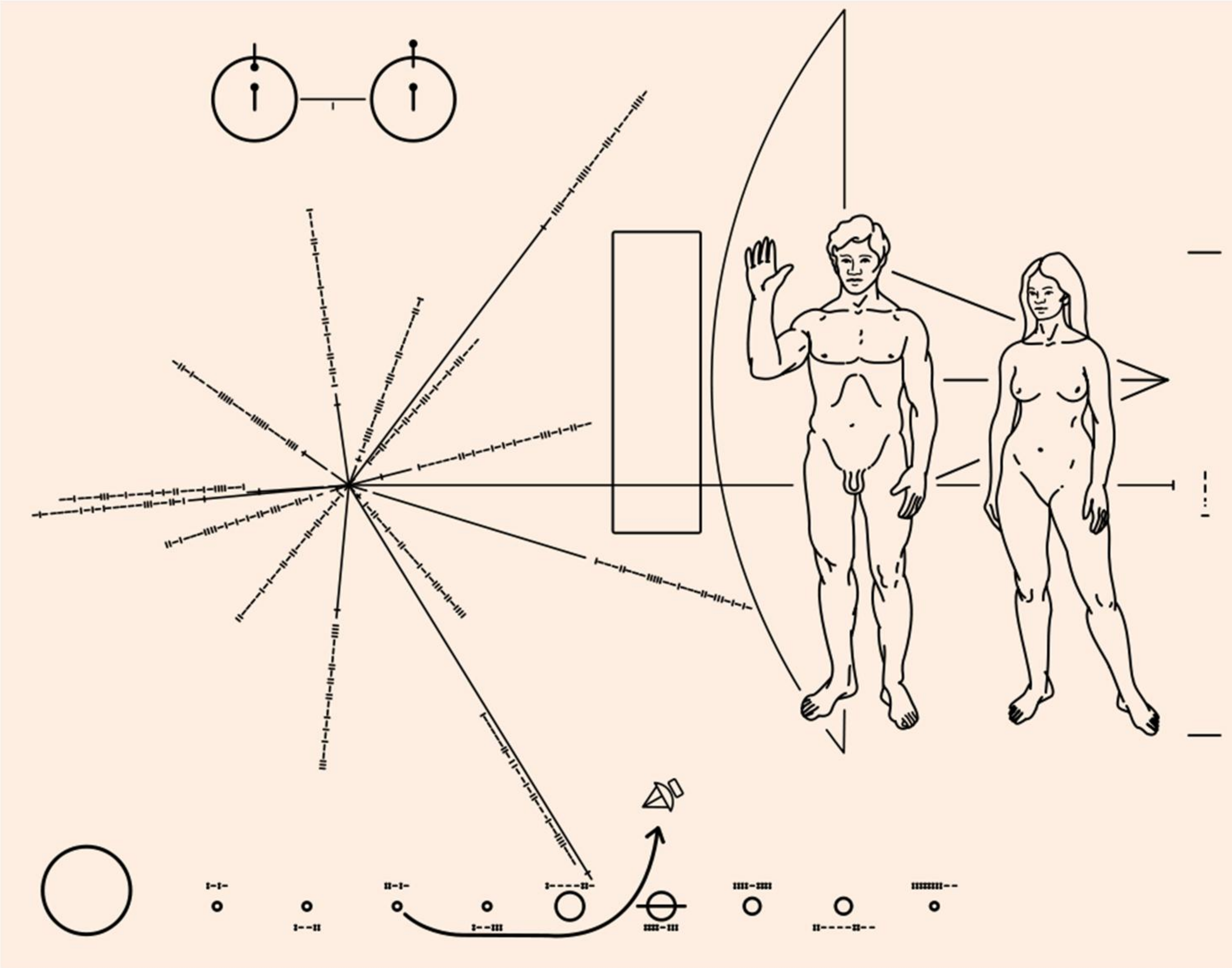
Richard Horton, editor of the British medical journal The Lancet:

The mistake, of course, is to have thought that peer review was any more than a crude means of discovering the acceptability—not the validity—of a new finding. Editors and scientists alike insist on the pivotal importance of peer review. We portray peer review to the public as a quasi-sacred process that helps to make science our most objective truth teller. But we know that the system of peer review is biased, unjust, unaccountable, incomplete, easily fixed, often insulting, usually ignorant, occasionally foolish, and frequently wrong.

http://en.wikipedia.org/wiki/Peer_review_failure

	Journals	Annual papers per journal	Total papers
ISI-indexed journals	**8466**	*111,7*	**945 900**
Other journals listed in Ulrich's as peer-reviewed, scientific and active	*15 284*	***26,2***	*400 400*
Total	**23 750**	*56,7*	*1 346 000*

Data for 2006 from
http://informationr.net/ir/14-1/paper391.html



Economics and innovation

- What do we **need**? (personal and social needs)

- How do we **achieve it**? (physical and technological means)

- How do we **pay** for it? (economic means)

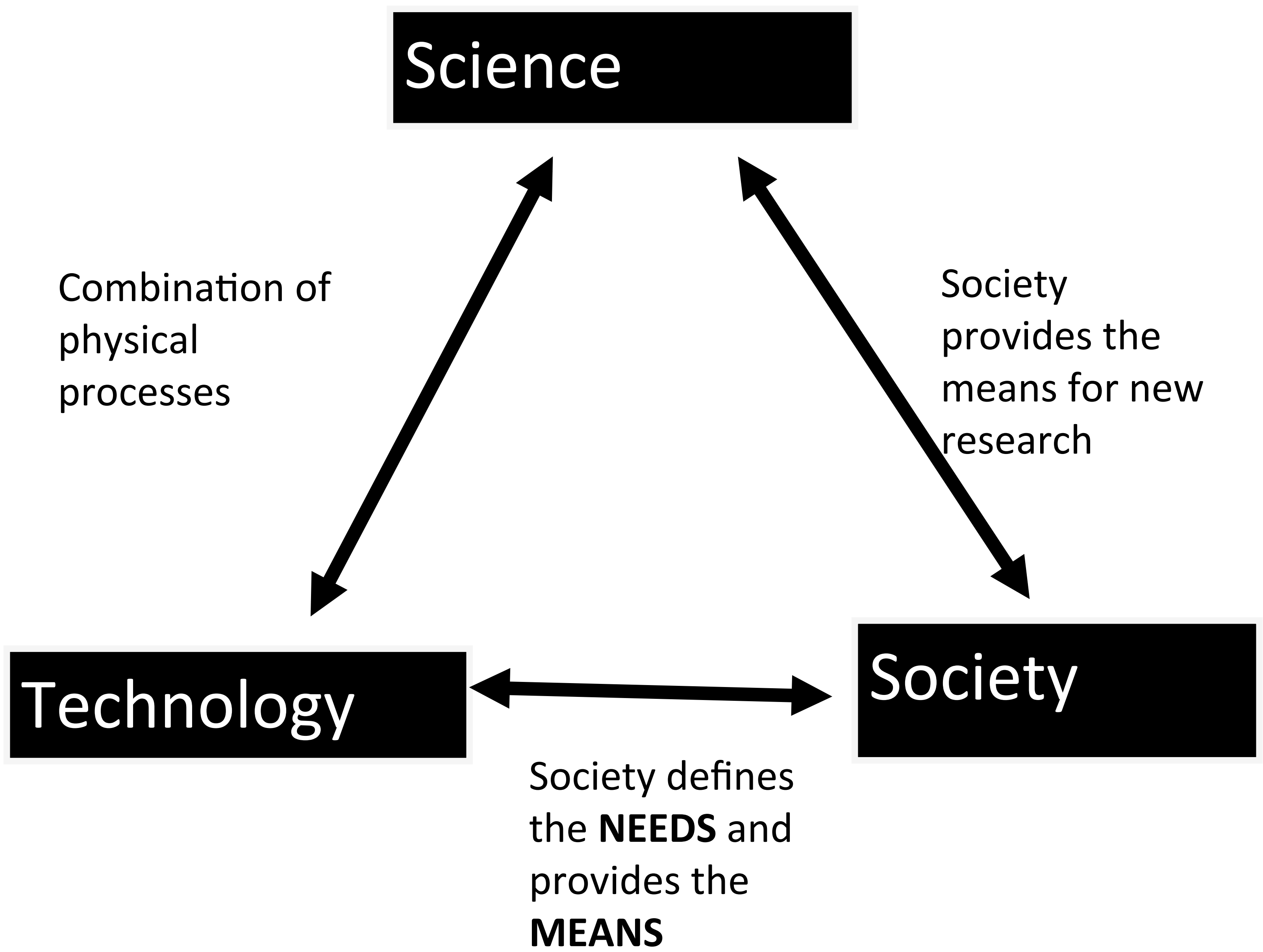
- **Needs** and **means** are closely linked to the size of social structures.

- Are we running out of money?

Money for science

- Is it possible to do science on a budget?

- Most everyday phenomena occur at low energies and human-sized scales. To observe new phenomena, we need to go to high or very low energies and very small or very large scales.
- We need new instruments. Which require appropriate economic means.
- **BUT** science is still cheap compared to other human activities (academics do not seek profit - yet)


Science
Combination of physical processes
Society provides the means for new research
Technology
Society
Society defines the NEEDS and provides the MEANS

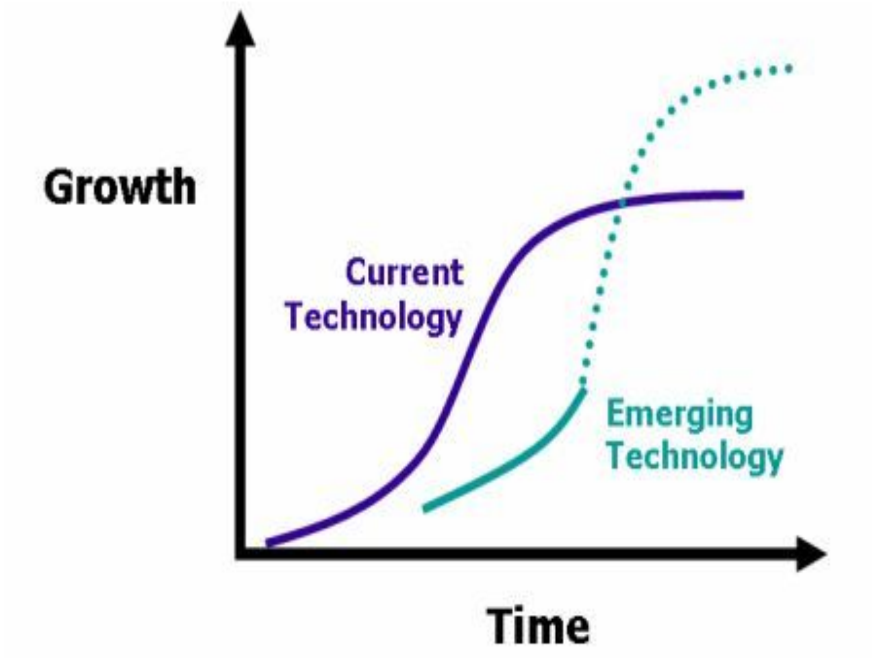
The economics of technological innovation

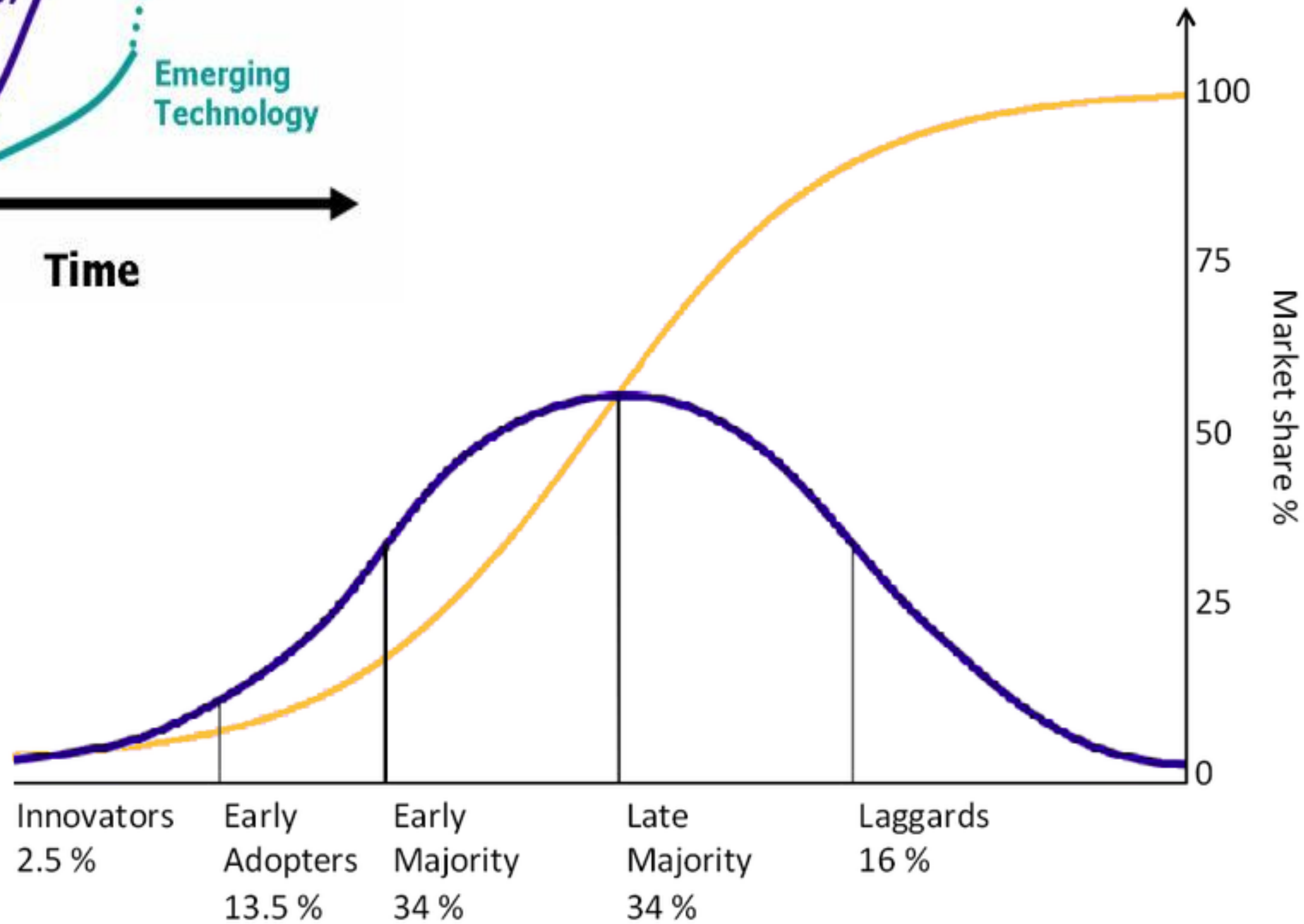
- What does it take to make a toaster?

- Can we still make the things around us ourselves? (industrialisation)

- When did the change occur?

- Does the reliance on an ever-larger system of existing technologies act as a brake on innovation?


Growth
Current Technology
Emerging Technology
Time


100
75
50
25
0
Market share %
Innovators 2.5 %
Early Adopters 13.5 %
Early Majority 34 %
Late Majority 34 %
Laggards 16 %

Can we establish a hierarchy of challenges to innovation?

Innovation = wealth.
Is this a modern viewpoint or has been there all along?

The deep future

The four kinds of futurists:

- **Consensus**

Who is breaking new ground? What do they have in common?

- **Extrapolation**

What will the picture be in the near future?

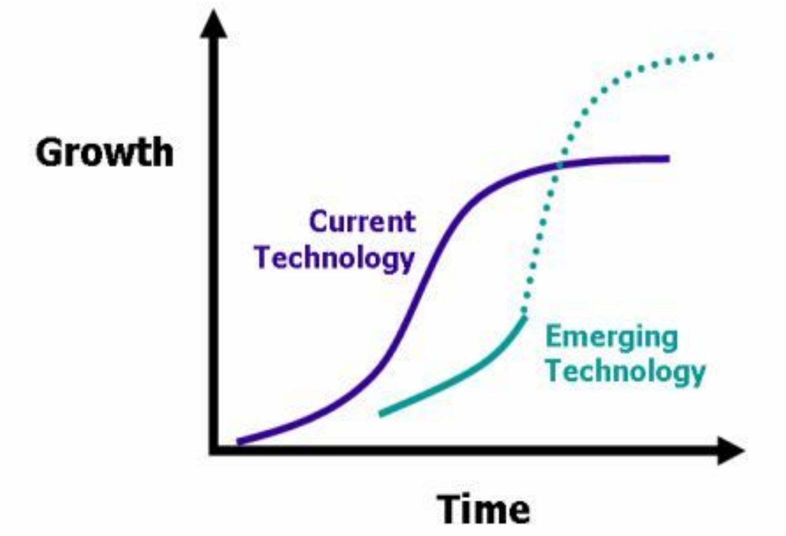
- **Historical analogy**

You can become the change you want to be.

- **Generating paths to futurity**

Imagining the unimaginable.

Predictions of the future


Growth
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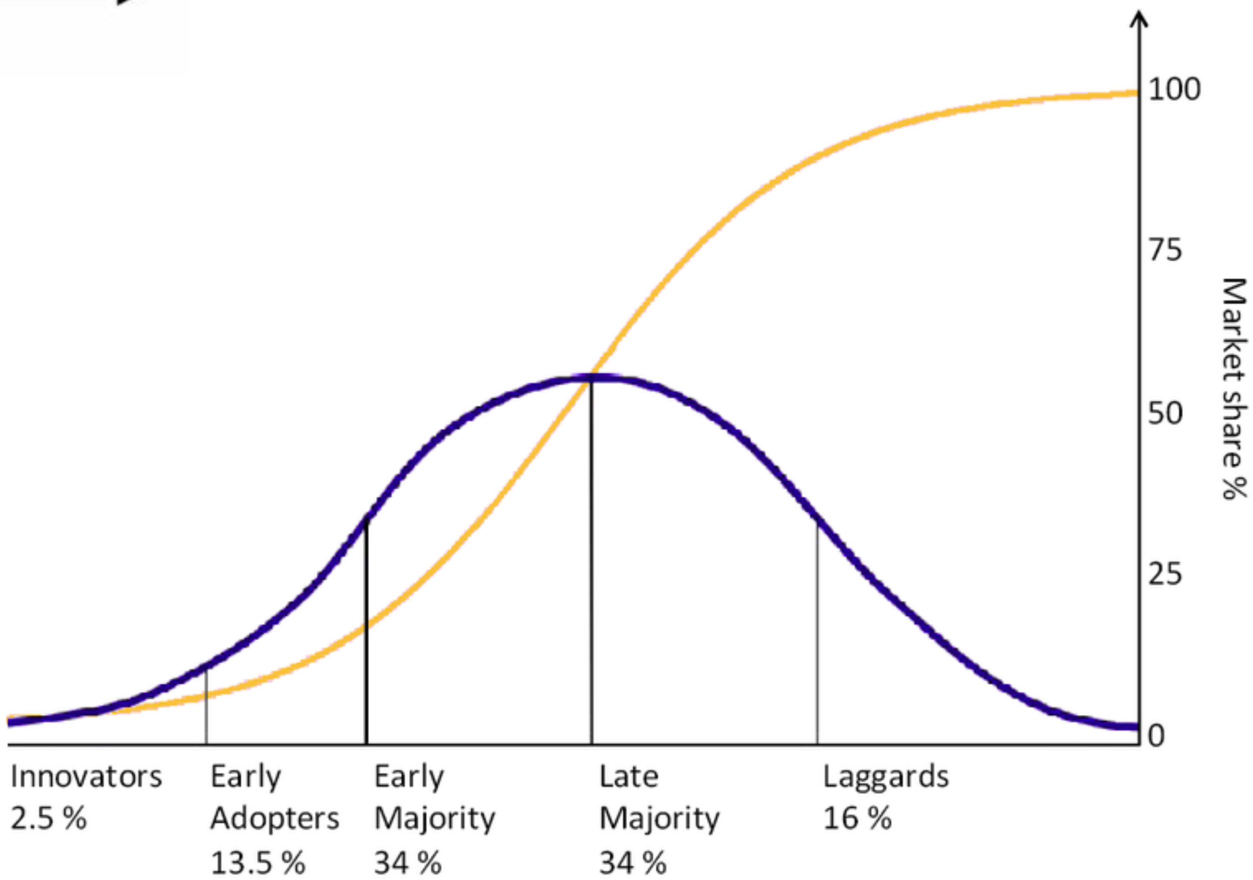
100
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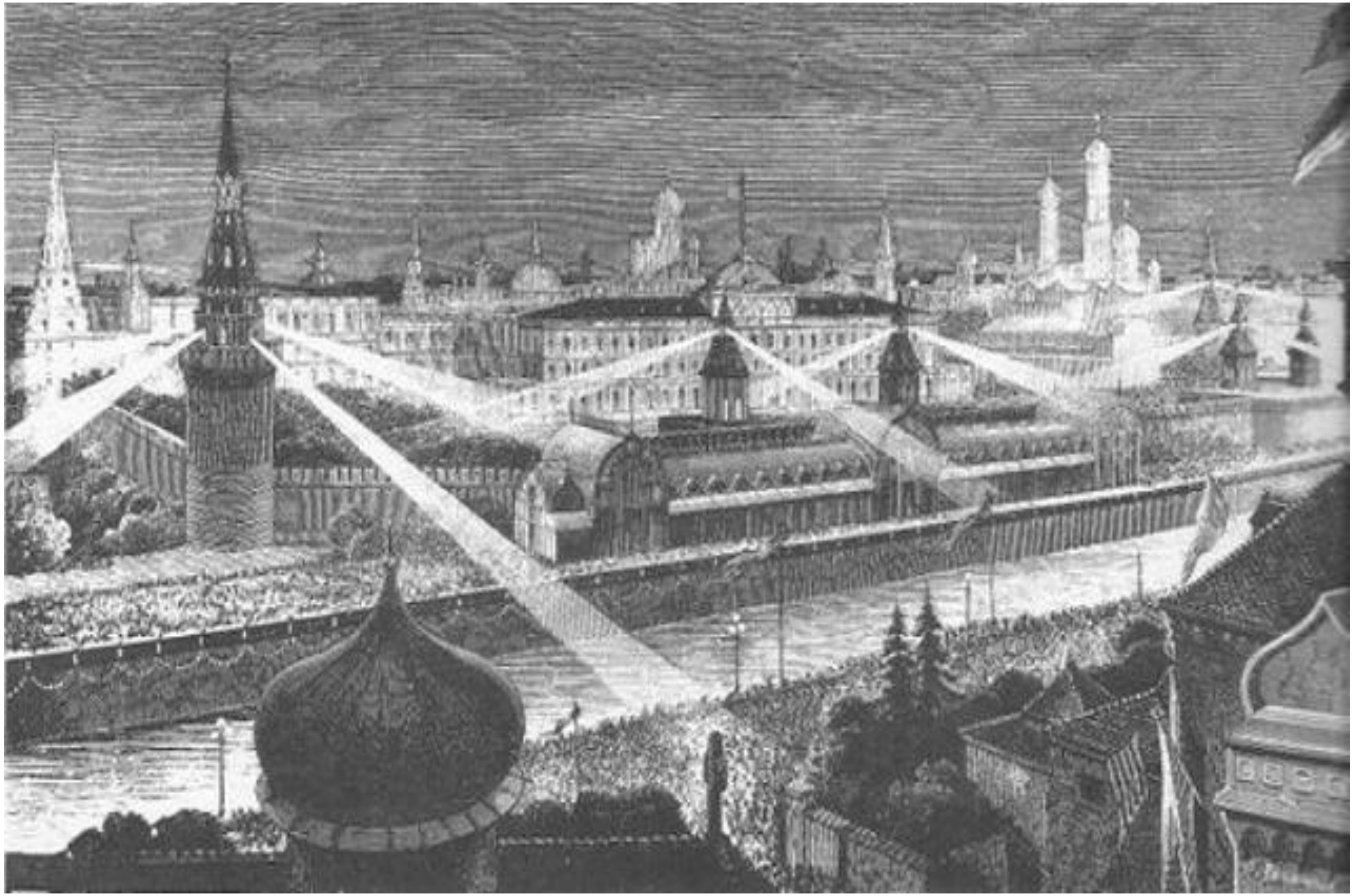
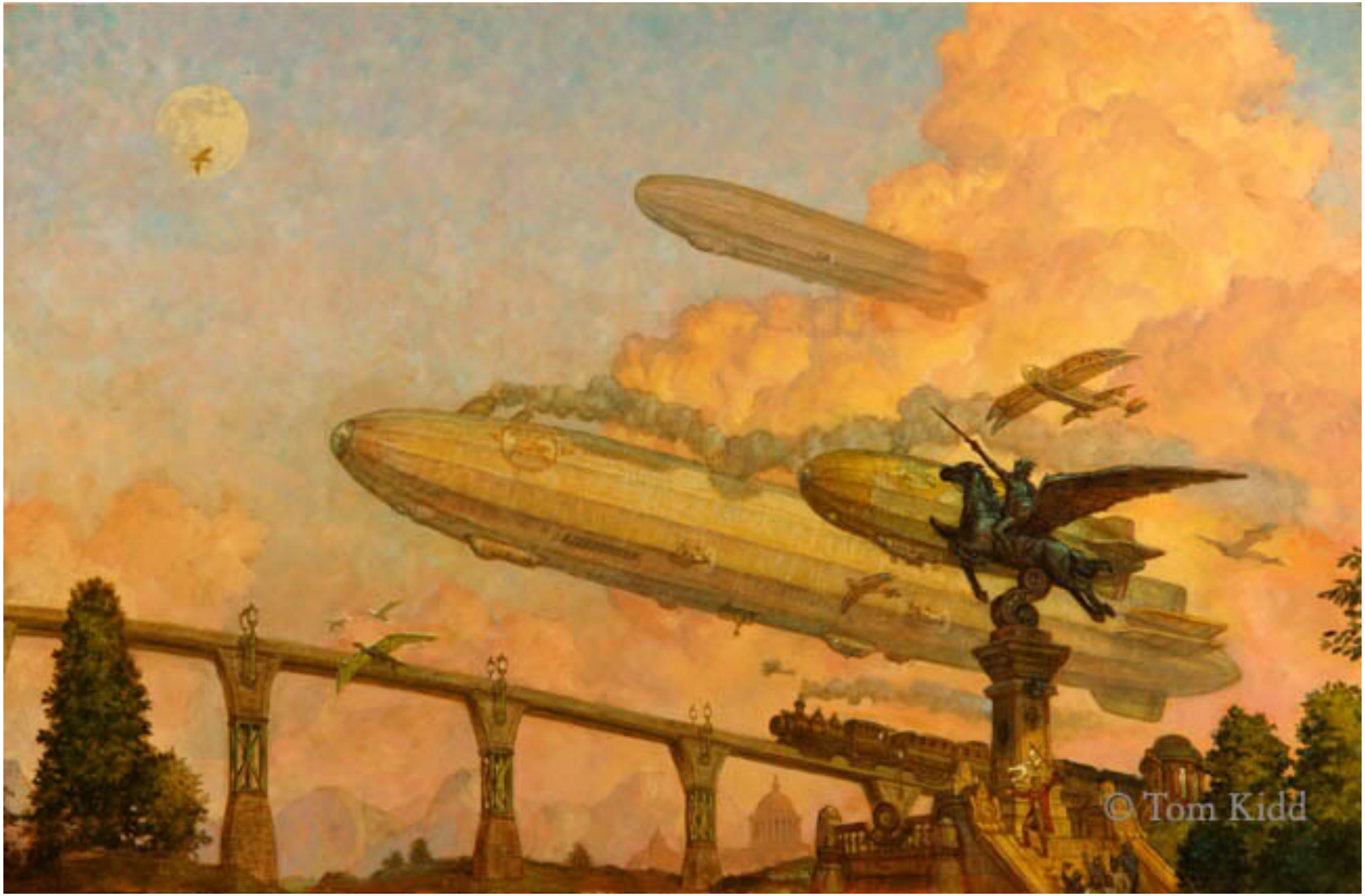
Forecasting future science and technology trends



1890

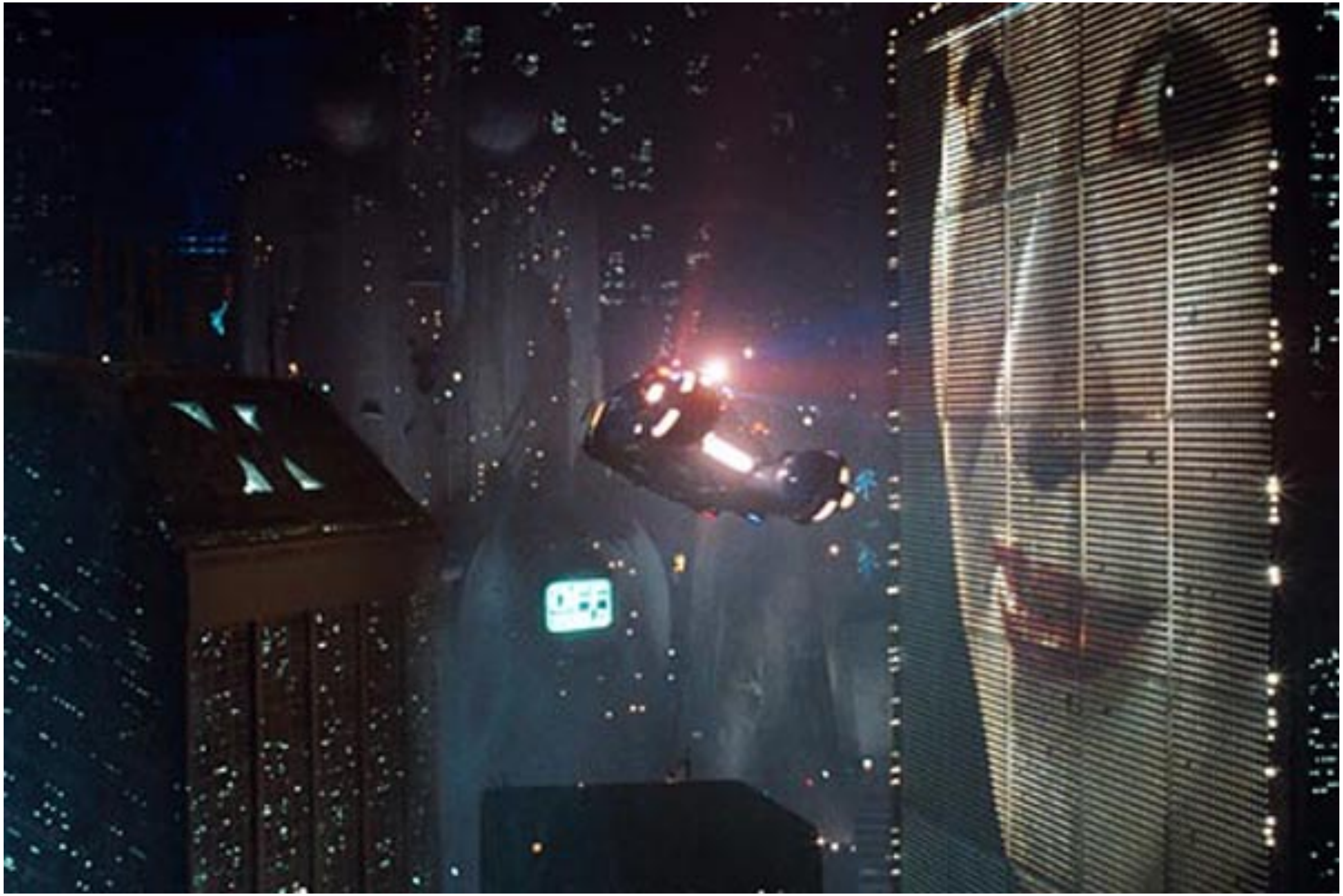


1900

1922 predicting 1972

1950s

1970s prediction



1980s

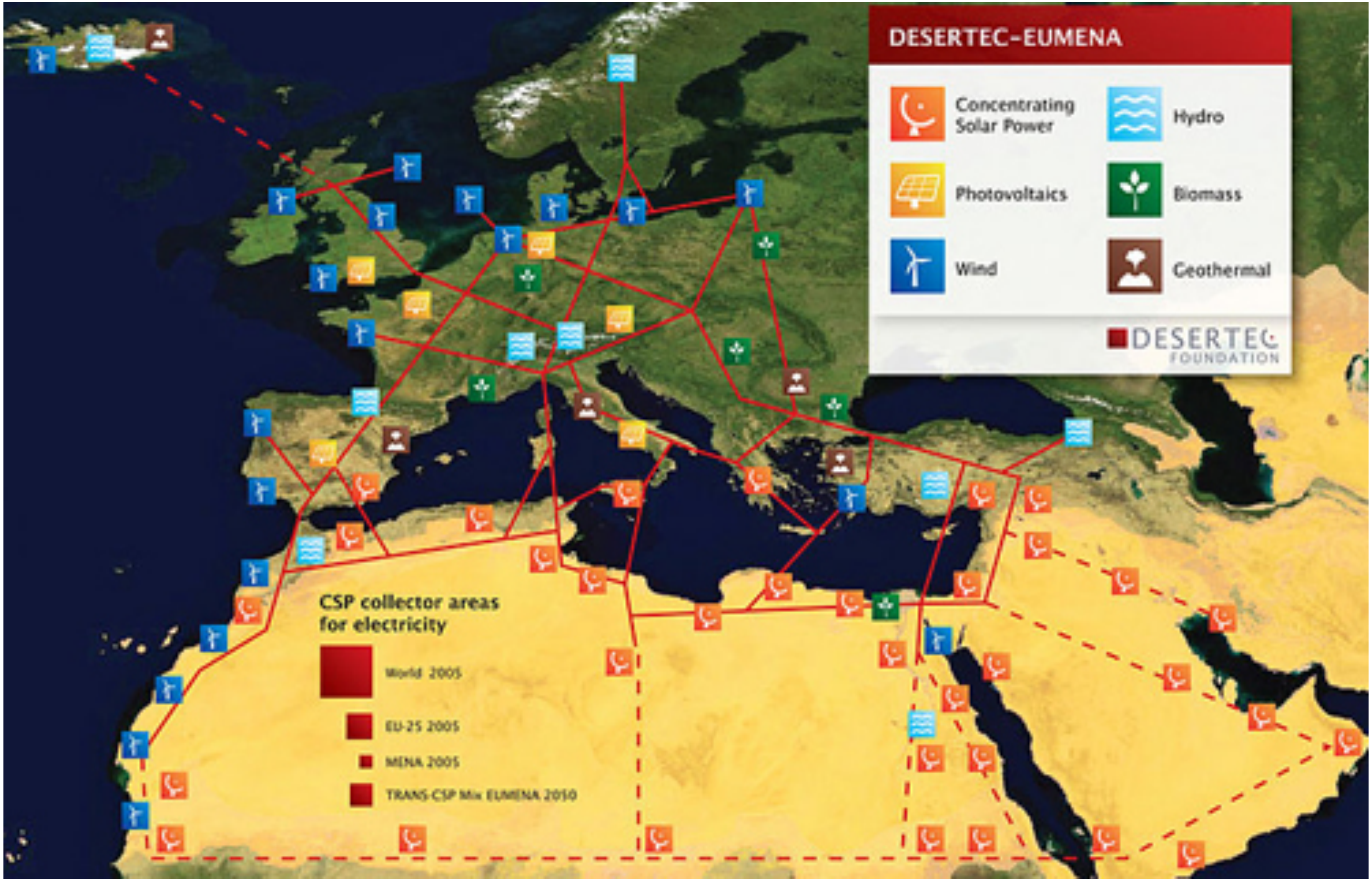
Do androids dream of electric sheep?

Common elements of futurology

- The future is a projection of the present
- **A preoccupation with emerging technologies and systems**
  - Steam power, locomotives and socially-conscious white empires in the 1850s
  - Airships and global travel in 1900
  - Electricity and radio in the 1920s
  - Personal vehicles, nuclear power and prosperity in the 1950s
  - Powered flight and space exploration in the 1970s
  - Computers, artificial intelligence, the power of corporations, hegemonic government in the 1980s
  - The 2000s? (uncertainty; the ecosystem; natural resources; social interaction; human consciousness)
- The future as we would like it to be, rather than the future as it is likely to be?
- Did optimism turn to pessimism? When? Why?

What energy sources will we use?

- Most global power output is hydrocarbon-driven. Nuclear fission a tiny fraction.
- First power-producing fusion reactor c. 2030
- Will it go the way of fission? (Different process = different political fallout BUT technology harder to master)
- Renewable energy:
  - Solar energy striking the Earth in a 40-minute period is equal to annual global energy consumption
  - This is still two billionths of the Sun's energy output
  - Solartec project requires political and economic cooperation
  - Still requires natural resources: metals; rare earth elements



DESERTEC-EUMENA
Concentrating Solar Power
Hydro
Photovoltaics
Biomass
Wind
Geothermal
DESERTEC FOUNDATION
CSP collector areas for electricity
World 2005
EU-25 2005
MENA 2005
TRANS-CSP Mix EUMENA 2050

Where will we explore?

- Closest star 4.3 light years away. Impossible to reach with current spaceflight technology (chemical rockets would take 115,000 years) .
- Likely to be still confined to our Solar System
- Revisit the Moon? Visit Mars? To what purpose?
- What drives exploration?
- There is nothing inevitable about space travel. ("There are enough problems down here on earth."

What will scientists be doing?

- Data collection and storage becoming easier. Science increasingly dependent on computing power.
- The frontiers of science lie at very small and large scales, and very high and low energies.
  - Large scales: Theories of gravity, cosmology
  - Small scales: Particle and quantum physics
  - Biochemistry, nanotechnology
- Computing power and **statistical science** increasingly important
  - 1st step: Given the data, the model and the parameters, what are the parameter values?
  - 2nd step: Given the data and the model, what are the parameters?
  - 3rd step: Given the data, what is the model?
  - e.g. protein folding; drug design; solid-state physics; meteorology; cosmology

Future technology trends

- Computers increasingly present in all technologies BUT Moore's Law reaching limit. Possible solution: Exploit quantum properties of matter at very small scales.
- New technologies beyond the integrated circuit
- Coding increasingly important in technological innovation
- Materials engineered at the nanoscale
- Increasing importance of the **user experience**
- Limitation: no new energy sources BUT increasing efficiency
- At what price? Better technology for a select few or cheaper technology for everyone?
- A world of technology haves and have-nots?