



# Impact on Society of Fundamental Science





# Examples of Paradigm Shifting Technologies

**17<sup>th</sup> C:** Newton's Unification of terrestrial and celestial gravity → launching satellites, ....

**1870s:** Maxwell's Unification of electricity, magnetism and light → electrical power generation, industrial revolution....

**Early 20<sup>th</sup> C:** Atomic Physics, Quantum mechanics → semiconductor electronics, .....

**1905,1916:** Einsteins Special and General Theories of Relativity → GPS systems,.....

**1930s:** Dirac: Alignment of Quantum Mechanics with special relativity → PET and MRI imaging

**1964:** Bell's Theorem: foundation of quantum information science

**1970's:** proofs started emerging

**1970s:** Glashow Weinberg and Salam: unification of electromagnetic and weak interactions → ??

**1990s:** CERN WWW: sharing large data → scholarship, commerce, communication, (social media, AI,.....).....



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# Pathway of an Innovation: GPS

## Fundamental Science: Einstein Special and General Theories of Relativity

### 1905: Special Theory of Relativity

Einstein's paper titled "On the Electrodynamics of Moving Bodies"

Two key postulates (science):

- laws of physics are invariant in all inertial frames of reference
- The speed of light in vacuum is the same for all observers

Consequences: relativity of simultaneity, **time dilation**, length contraction, Lorentz transformation of velocities

### 1916: General Theory of Relativity

Geometric theory of gravitation

Three key postulates (science):

- Spacetime curvature (Wheeler → matter tells spacetime how to curve; spacetime tells matter how to move)
- Gravitation effects (curvature of spacetime is gravity)
- Principle of Equivalence

Consequences: gravitational waves, black holes, **time dilation**



# Pathway of an Innovation: GPS

Use 24 satellites to ensure at least 4 are always visible from any point on the Earth.

Satellites travel at  $\approx 14'000$  km/h at an altitude of  $\approx 20'000$ km from ground (orbital period of  $\approx 12$ hours).

## 1905: Special Theory of Relativity

**Time Dilation:** Clocks on satellites (travelling faster wrt to cars on Earth's surface) will be ticking slower (fall behind by  $\approx 7\mu\text{s/day}$  wrt terrestrial clocks)

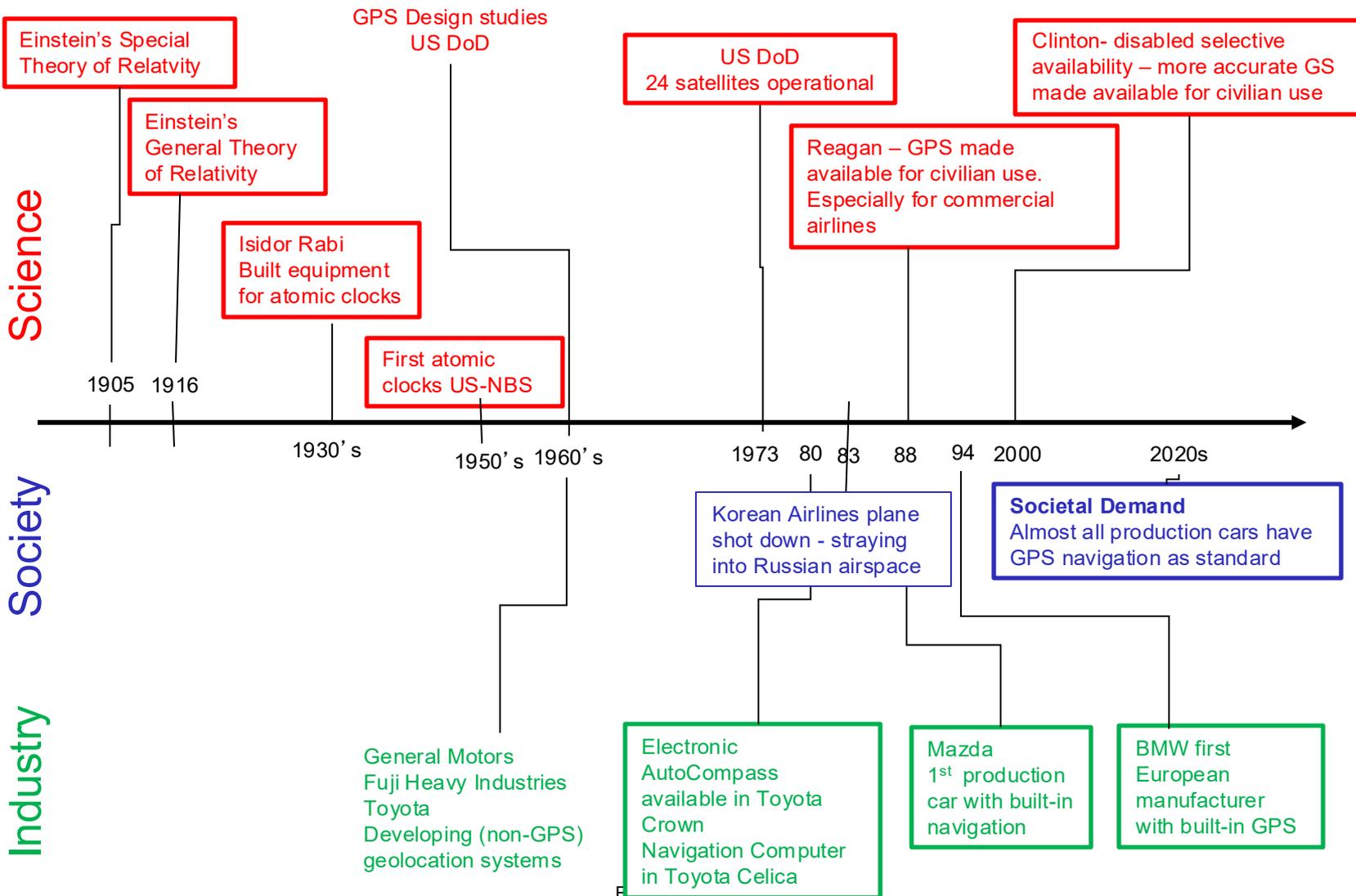
## 1916: General Theory of Relativity

**Time Dilation:** Clocks on satellites (in lower gravitational field) will be ticking faster (gain  $\approx 45\mu\text{s/day}$  wrt terrestrial clocks)

i.e. clocks on satellites tick faster than identical clocks on the ground by  $\approx 38$   $\mu\text{s/day}$ . Errors accumulate so by end of each day one would be off by a  $\sim 10$  km. Clocks on satellites need to be slightly slowed down.



# Global Positioning System in Cars





# Pathway of an Innovation: PET

## Fundamental Science: Dirac's Equation (marriage of QM and SR)

$$\left( \beta mc^2 + \sum_{k=1}^3 \alpha_k p_k c \right) \psi(\mathbf{x}, t) = i\hbar \frac{\partial \psi(\mathbf{x}, t)}{\partial t}$$

**1928:** Dirac's description of electrons consistent with Einstein's special theory of relativity and quantum mechanics

Predicted existence of anti-particles (**e.g positron - basis of PET**) and explained spin (**basis of MRI**)

**1932:** Operation of first cyclotron, the anti-electron (positron) discovered

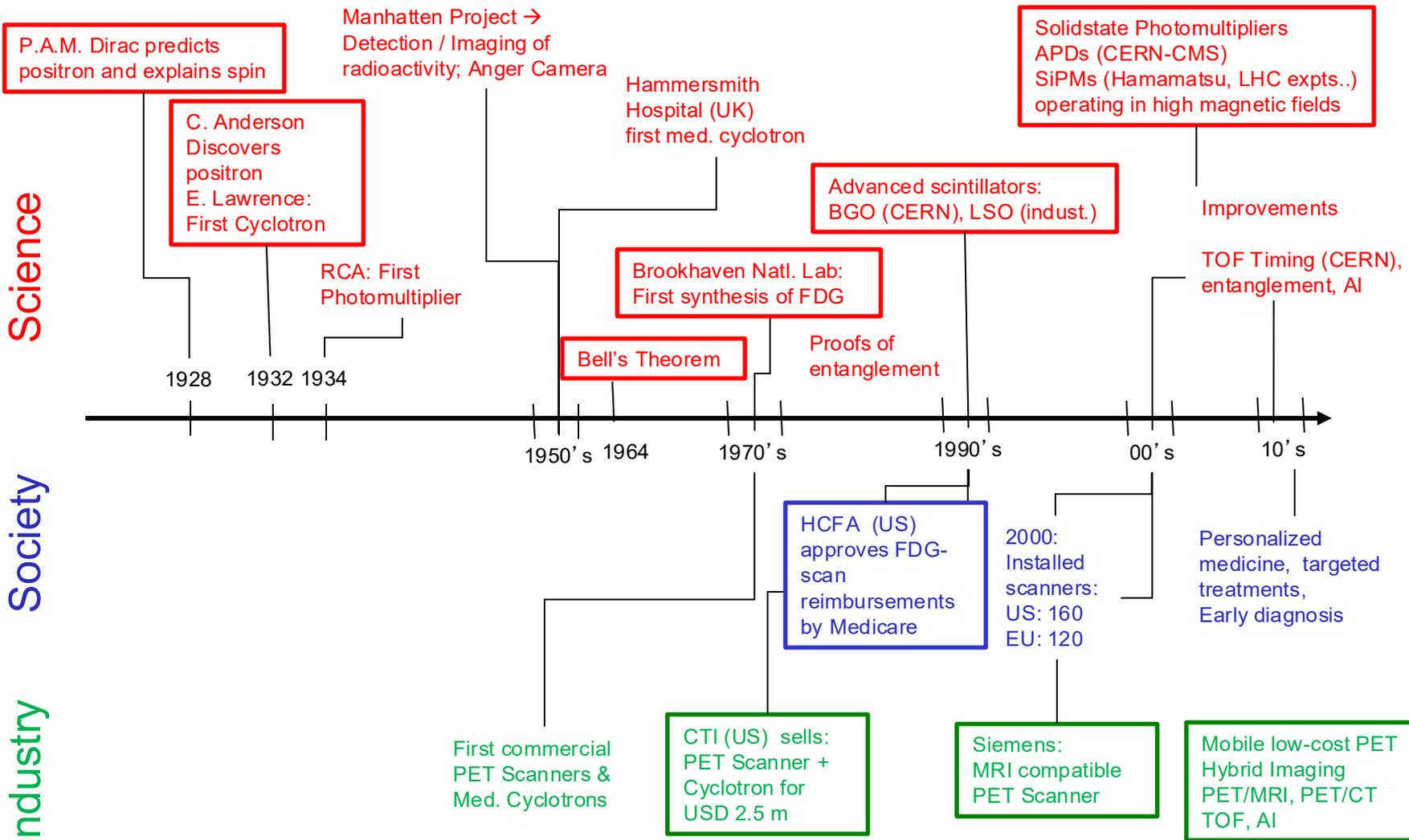
Radionuclides (e.g. fluorine-18 (half-life ~110min) used in PET scanning are produced by cyclotrons in hospitals

PET cameras today use APDs (and Si PMs) and heavy scintillating crystals - now being combined with MRI scanners.

The scientific basis for all medical imaging (functional & physiological) is steeped in nuclear/particle physics



# Positron Emission Tomography





# PET and MRI

CT, MRI etc. scanners good at showing anatomical detail

PET makes metabolic activity visible

- determine how patients respond to drugs/therapy

- distinguish early Alzheimer's from other types of dementia?

## Costs

PET (+CT 2020) ~ 2.5 M\$ + 0.2M\$/yr

Cyclotron ~ 2.0 M&

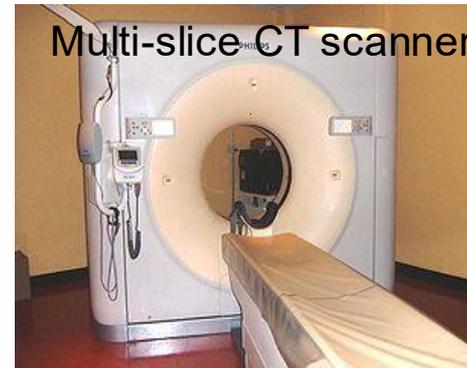
Infrastructure ~1.5 M&

Cost/Pet scan (2020) ~1' 500\$

NB: 1 cyclotron can service many PET scanners

**Developments:** reduce costs of PET scanners – new technology (e.g. heavy scintillating crystals coupled to compact low bias photodevices that can work in strong magnetic fields, precision timing, entanglement, AI....

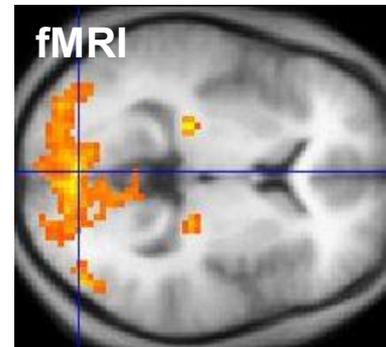
– aim to reduce cost/complexity/dose to patient,.....



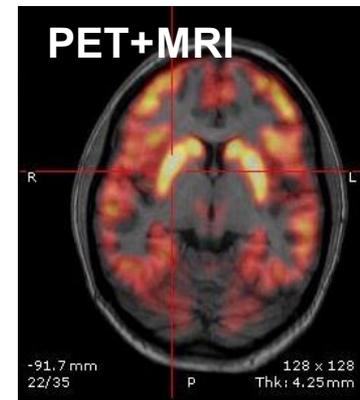
Multi-slice CT scanner



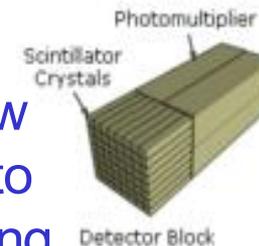
CT



fMRI



PET+MRI



Detector Block



Detector Rings



# Summary

Progress in fundamental science allows us to get a deeper understanding of how Nature works, through great scientific discoveries.

Over the centuries this understanding has very much altered the way we live – giving us a better life – providing us with paradigm shifting technologies.