

# Atomic clocks

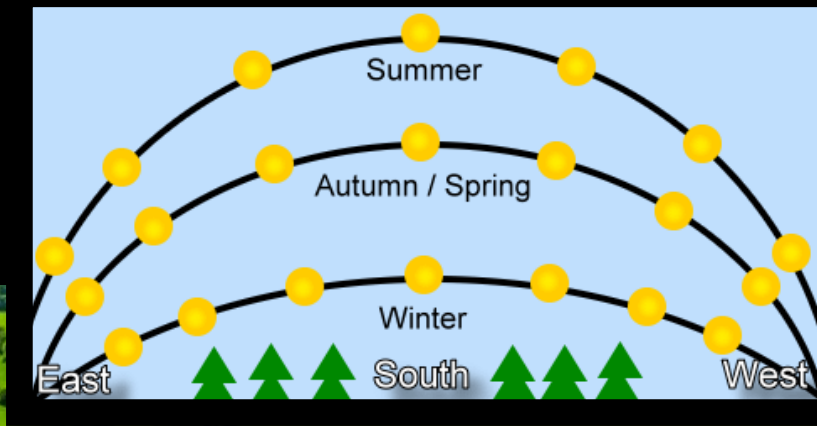
small, cold, precise, and accurate

**Paul Griffin**

University of Strathclyde

<https://eqop.phys.strath.ac.uk/>

# 4,000 BC



## Mechanism

Solar position

## Why

Crops (?)

## Precision

Month

3,000 BC



Mechanism

Sun dial

Water tower

Why

Prayer

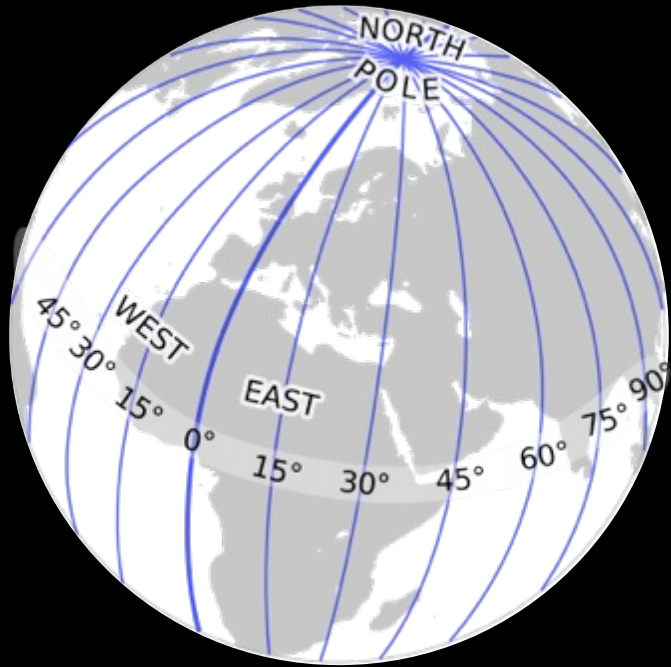
Prayer at night

Precision

Days/hours

Hours

# 17th century



Mechanism

Pendulum

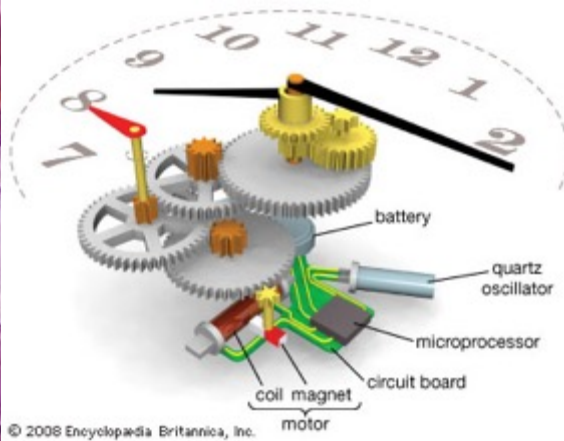
Why

Navigation

Precision

Seconds

# 20th century



Mechanism

Why

Precision

Quartz

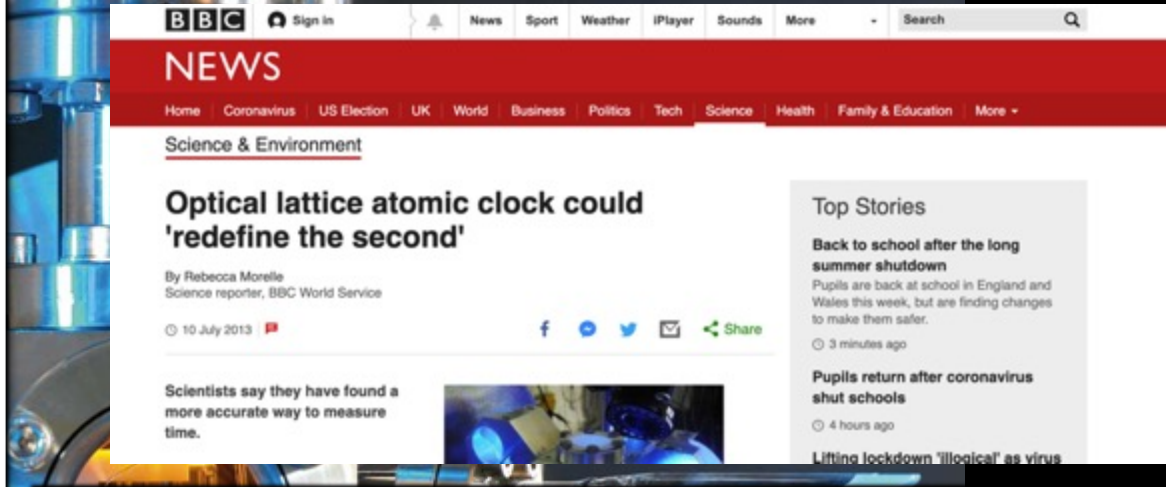
Information

$\leq 1$  ms

20<sup>th</sup>

171.  
Posted by  
**happyman**

I don't understand the purpose of all this complicated stuff. Why can't everybody just use what nature has given us, and wake up when the sun rises and sleep when the sun sets. That is what I do and life is so much simpler that way.



4.  
Posted by  
**Mac Man**

Don't understand this obsession with time? It's not as if our perception of time is even real time, i.e. Cats and Dogs have seven years to our one

40.  
Posted by  
**Worldweary1**

This is just a 'jolly' for the scientists involved. If they want to spend their time pursuing of childish nonsense they should fund themselves.

Posted by  
**U14820520**

Please BBC, give us something a bit more engaging on which to comment.

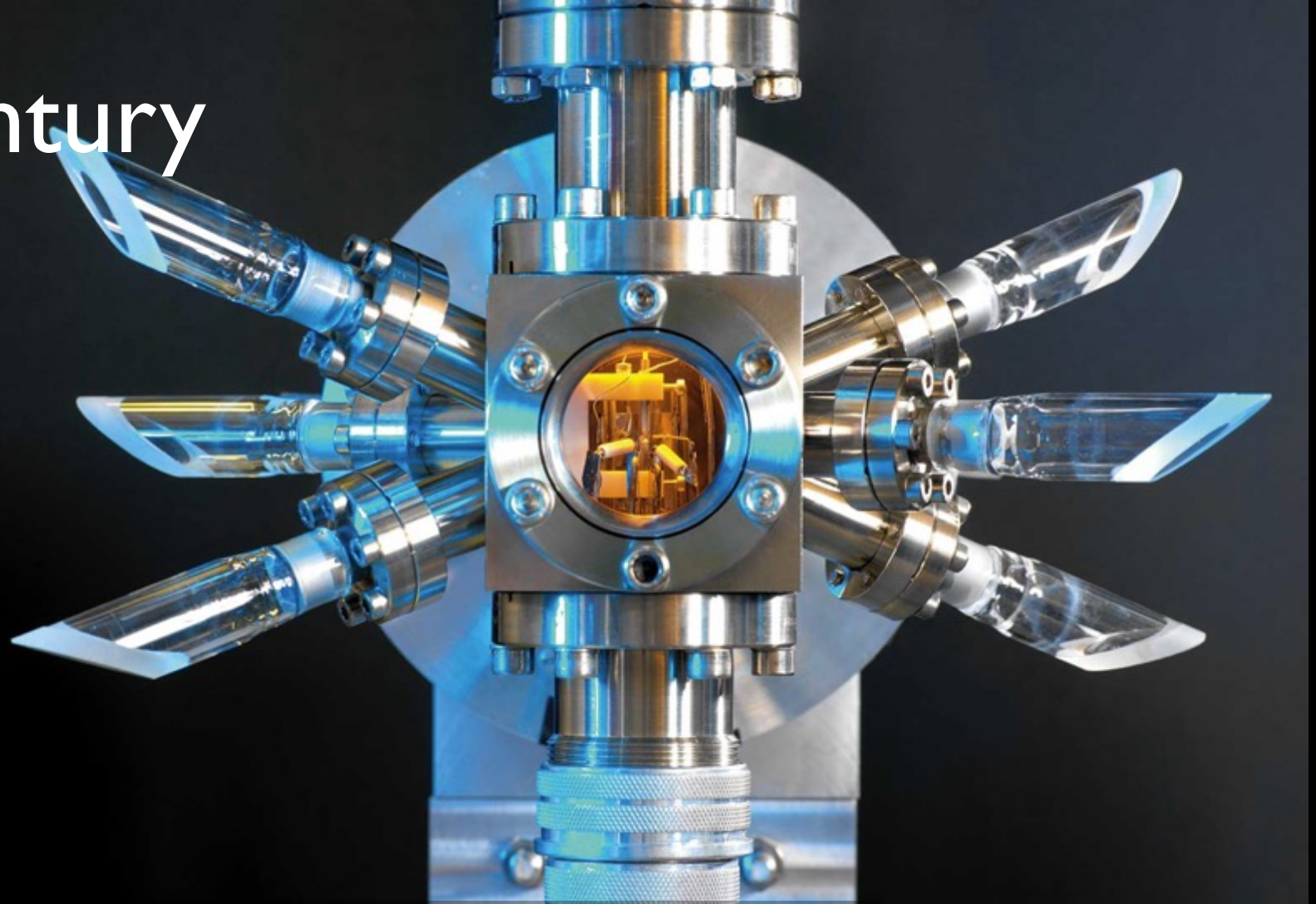
This is a story of interest to a very narrow band of scientists and nerds.

Atomic transition

precision

in age of universe

# 20<sup>th</sup> & 21<sup>st</sup> century



**Mechanism**

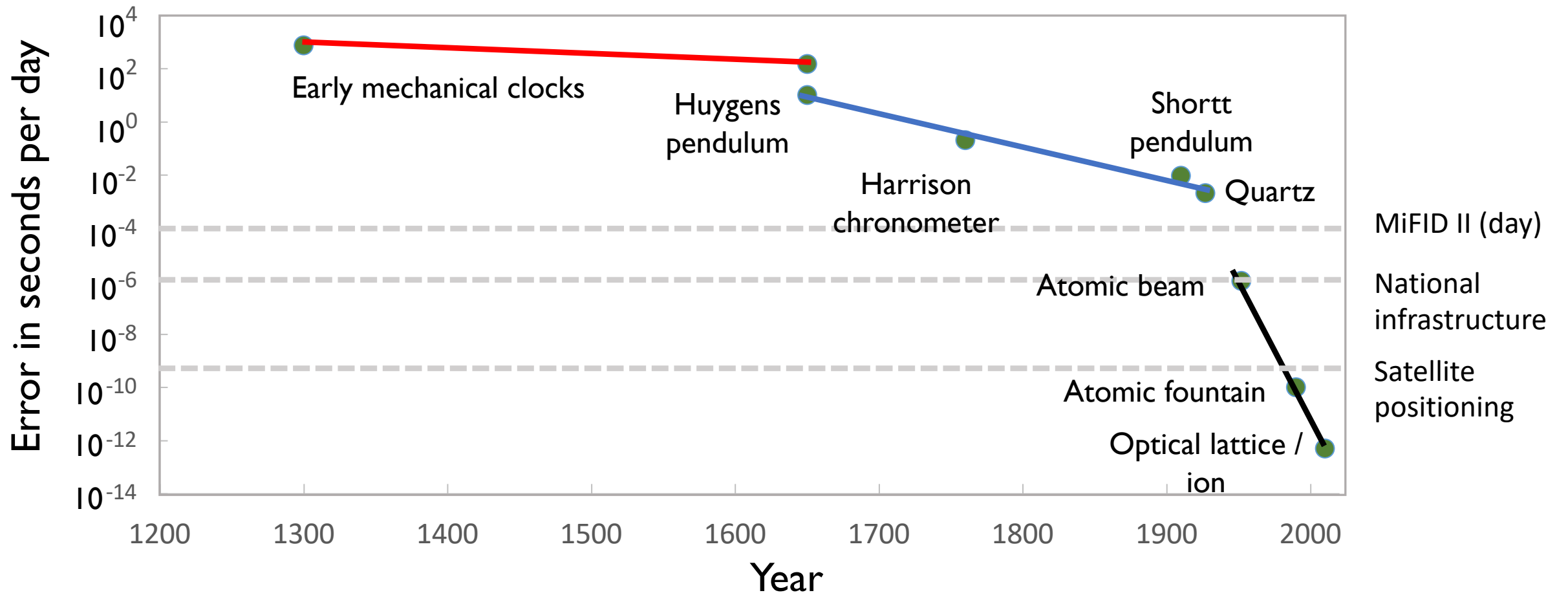
Atomic transitions

**Why**  
GPS

Telecoms  
Financial markets

**Precision**

$\leq 1$  s in age of universe

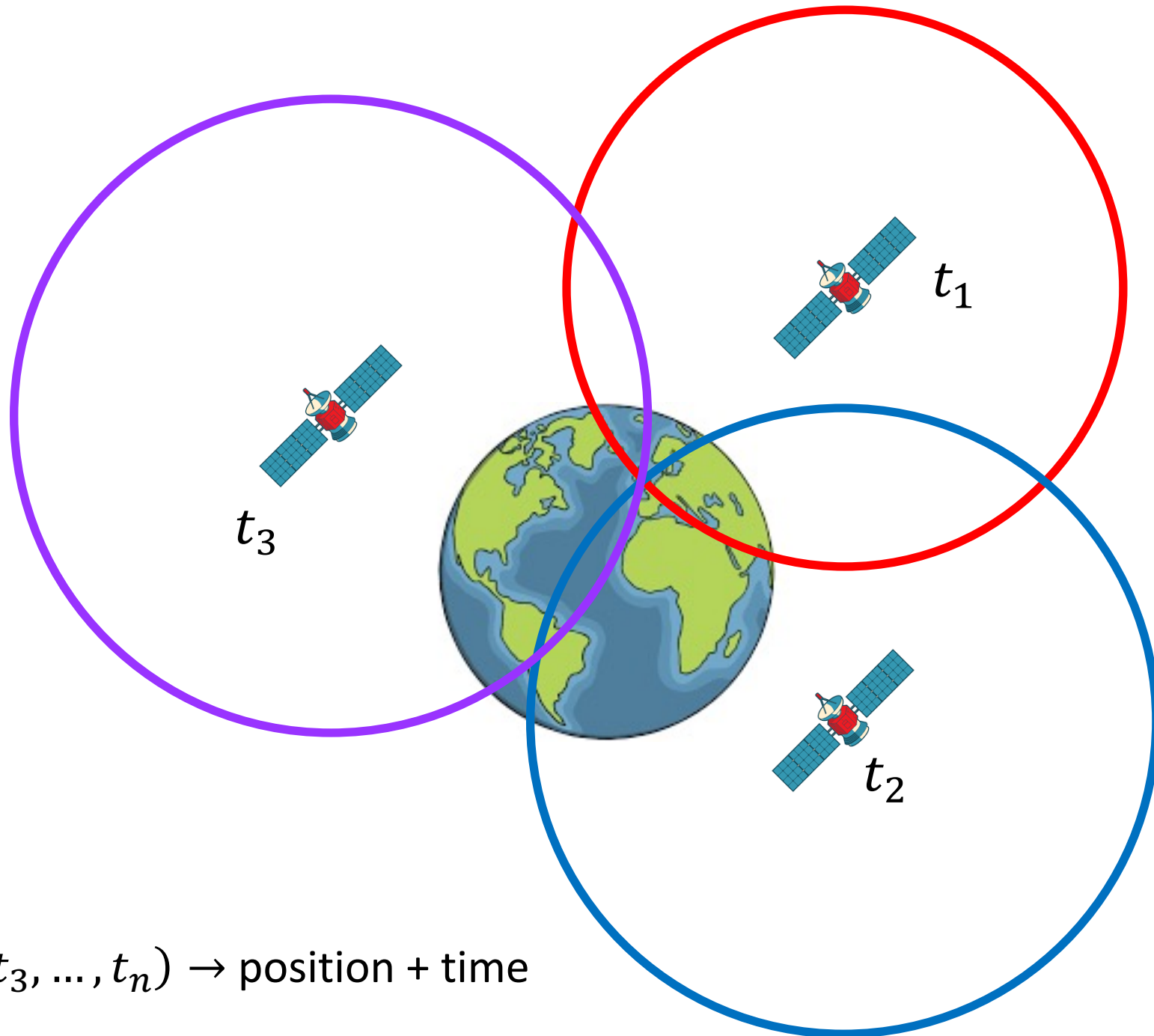






Any  
questions?

# GPS



$f(t_1, t_2, t_3, \dots, t_n) \rightarrow \text{position} + \text{time}$

# Global Positioning System (GPS)



I'm here, and the time is 10:30:23.458767



I'm here, and the time is 10:30:23.458767



For the system to work, clocks must be accurate to tiny fractions of a second!

# GNSS

- Multiple satellites
- Each with synchronised atomic clocks
- Find location by triangulation



GPS

GLONASS

GALILEO

BEIDOU

IRNSS

QZSS

Rb, Cs

Cs

H, Rb

Rb

Rb

Rb

Worldwide  
~24 satellites

Regional  
~5 satellites



Rb	6.8 GHz
Cs	9.2 GHz
H	1.4 GHz

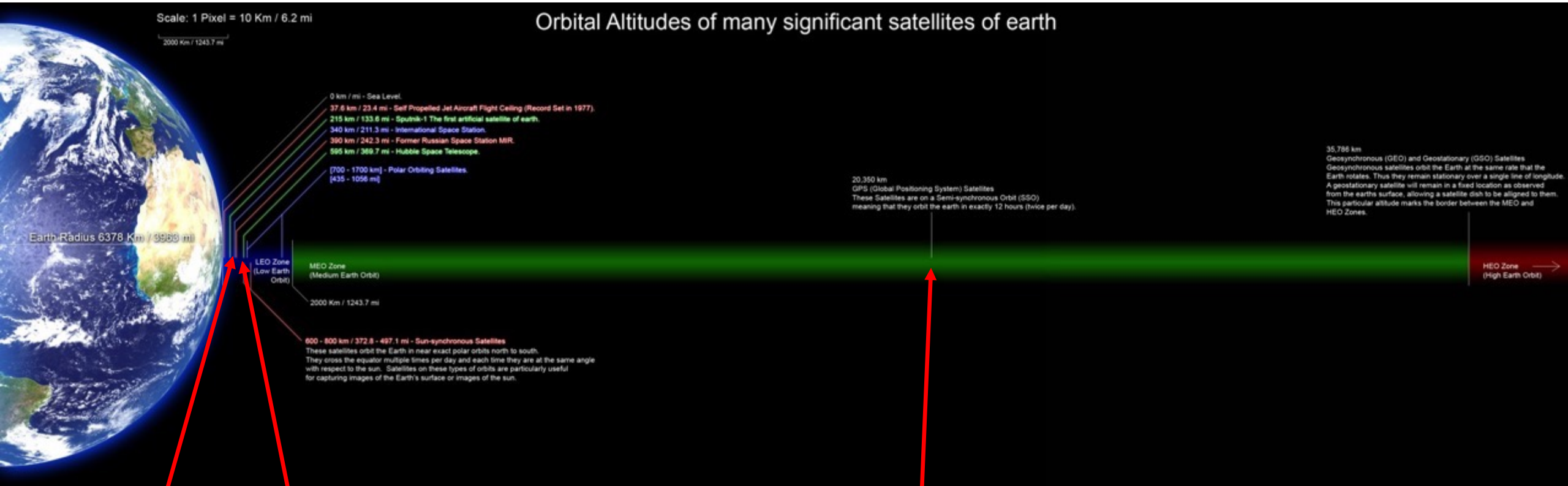
# GPS

## Directly impacts

- Transportation
  - Aviation, Marine, Road
- Logistics / Shipping
- Safety services
- Financial services
- Military
- Agriculture
- Communication networks
- Surveying
- Recreational
- Social (geo-tagging of photos)
- Atmospheric weather



# Problems with GPS



Space station

Hubble telescope

GPS


# Problems with GPS



**N.J. man fined \$32K for illegal GPS device that disrupted Newark airport system**

Published: Aug. 08, 2013, 8:28 p.m.



 politics Audio Live TV

**Russia jammed GPS during major NATO military exercise with US troops**

By [Ryan Browne](#), CNN

Updated 1648 GMT (0048 HKT) November 14, 2018



2018

**Iran controls US Dron spoofing**

By [Geospatial World](#) - 12/16/2011 2 Minutes Re

2011

2013

# Problems with GPS

**FINANCIAL TIMES**

UK COMPANIES TECH MARKETS CLIMATE OPINION WORK & CAREERS LIFE & ARTS HTSI

Opinion **Satellites**

## We are dangerously reliant on GPS to tell the time

Recent outages in satellite systems have confirmed the importance of data from atomic clocks as an invisible utility

ANJANA AHUJA [+ Add to myFT](#)



Financial Times, 25 October 2022

## Bloomberg UK

• Live Now Markets Economics Industries **Technology** Politics Wealth Pursuits

Technology | Hyperdrive

## Dallas Air Traffic Rerouted as FAA Probes Faulty GPS Signals

- Pilots, controllers using older technology to navigate
- 'Very unusual' air navigation glitch, says flight-track expert

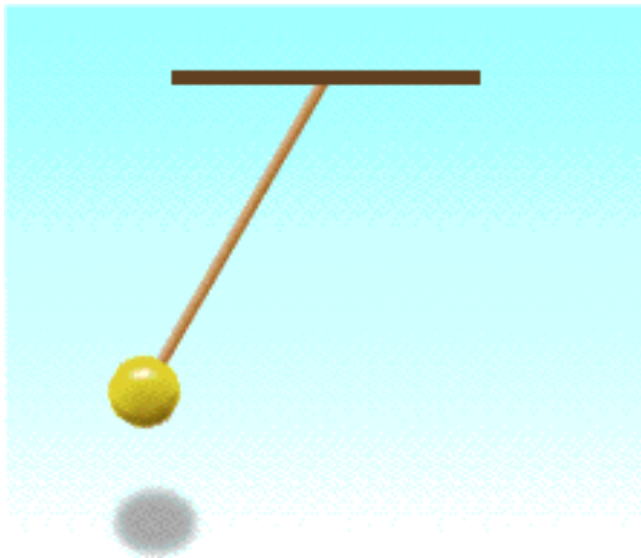
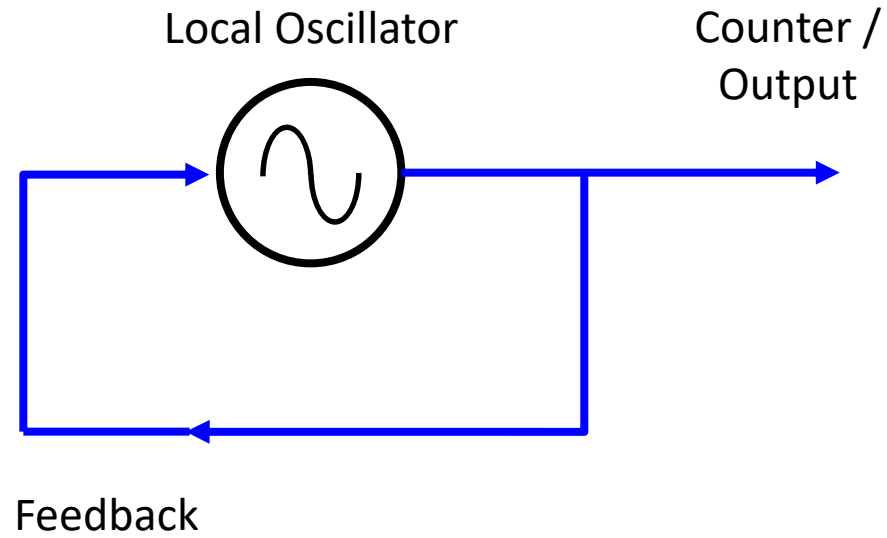
By [Alan Levin](#) and [Mary Schlangen](#)

18 October 2022 at 17:54 BST Updated on 18 October 2022 at 20:40 BST

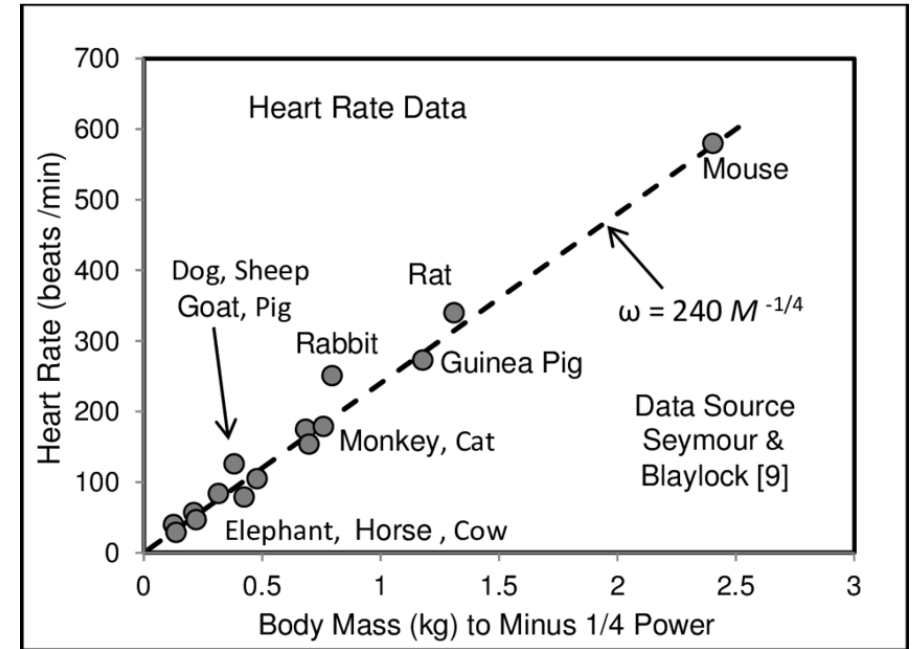
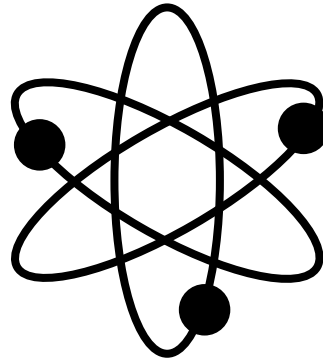




# Precision measurement – clock



# Big & small – slow and fast



# Atoms



Periodic Table of the Elements

1 IA 11A <b>H</b> Hydrogen 1.008	2 IIA 2A <b>He</b> Helium 4.003																	13 IIIA 3A <b>B</b> Boron 10.811	14 IVA 4A <b>C</b> Carbon 12.011	15 VA 5A <b>N</b> Nitrogen 14.007	16 VIA 6A <b>O</b> Oxygen 15.999	17 VIIA 7A <b>F</b> Fluorine 18.998	18 VIIIA 8A <b>Ne</b> Neon 20.180
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012																	5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.007	8 <b>O</b> Oxygen 15.999	9 <b>F</b> Fluorine 18.998	10 <b>Ne</b> Neon 20.180
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 1B	12 IIB 2B	13 <b>Al</b> Aluminum 26.982	14 <b>Si</b> Silicon 28.086	15 <b>P</b> Phosphorus 30.974	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948						
19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.942	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.933	27 <b>Co</b> Cobalt 58.933	28 <b>Ni</b> Nickel 58.693	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.732	32 <b>Ge</b> Germanium 72.61	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.09	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 84.80						
37 <b>Rb</b> Rubidium 84.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.906	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.906	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium 98.907	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.904	54 <b>Xe</b> Xenon 131.29						
55 <b>Cs</b> Cesium 132.905	56 <b>Ba</b> Barium 137.327	57-71 Lanthanide Series	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.948	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.980	84 <b>Po</b> Polonium [208.982]	85 <b>At</b> Astatine 209.987	86 <b>Rn</b> Radon 222.018						
87 <b>Fr</b> Francium 223.020	88 <b>Ra</b> Radium 226.025	89-103 Actinide Series	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>F1</b> Flerovium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium [298]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown						
Lanthanide Series			57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.966	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.930	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967						
Actinide Series			89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium 244.064	95 <b>Am</b> Americium 243.061	96 <b>Cm</b> Curium 247.070	97 <b>Bk</b> Berkelium 247.070	98 <b>Cf</b> Californium 251.080	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.095	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.101	103 <b>Lr</b> Lawrencium [262]						

Alkali Metal	Alkaline Earth	Transition Metal	Semimetal	Nonmetal	Basic Metal	Halogen	Noble Gas	Lanthanide	Actinide
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TREATISE  
ON  
NATURAL PHILOSOPHY

UNIV. OF  
CALIFORNIA  
BY  
LORD KELVIN, LL.D., D.C.L., F.R.S.

CAMBRIDGE:  
AT THE UNIVERSITY PRESS.  
1912

1879

223.]

DYNAMICAL LAWS AND PRINCIPLES.

227

lute than is the "absolute unit" now generally adopted, which is founded on the *mean solar second*. But this depends essentially on one particular piece of matter, and is therefore liable to all the accidents, etc. which affect so-called National Standards however carefully they may be preserved, as well as to the almost insuperable practical difficulties which are experienced when we attempt to make exact copies of them. Still, in the present state of science, we are really confined to such approximations. The recent discoveries due to the Kinetic theory of

Maxwell's  
two sugges-  
tions for  
Absolute  
Unit of  
Time.

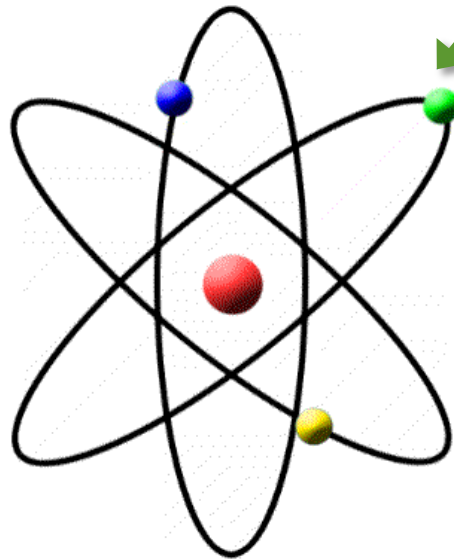
perty. The time of vibration of a sodium particle corresponding to any one of its modes of vibration, is known to be absolutely independent of its position in the universe, and it will probably remain the same so long as the particle itself exists. The wave-

length for that particular ray, *i.e.* the space through which light is propagated *in vacuo* during the time of one complete vibration of this period, gives a perfectly invariable unit of length; and it is possible that at some not very distant day the mass of such a sodium particle may be employed as a natural standard for the remaining fundamental unit. This, the latest improvement made upon our original suggestion of a *Perennial*

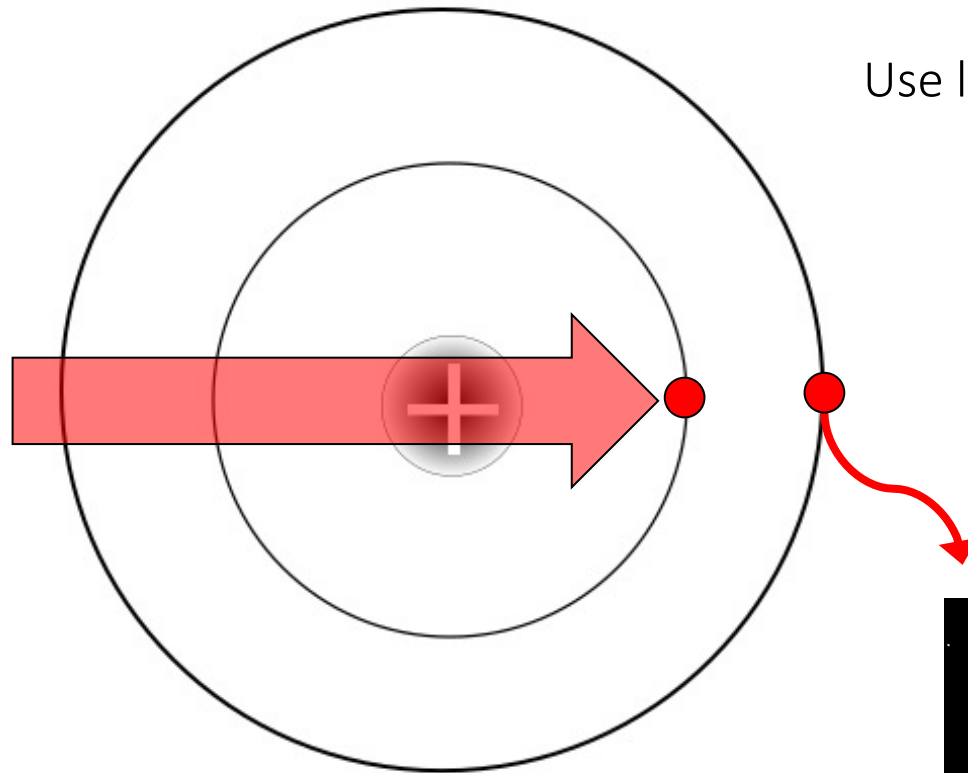


University of  
Strathclyde  
Science

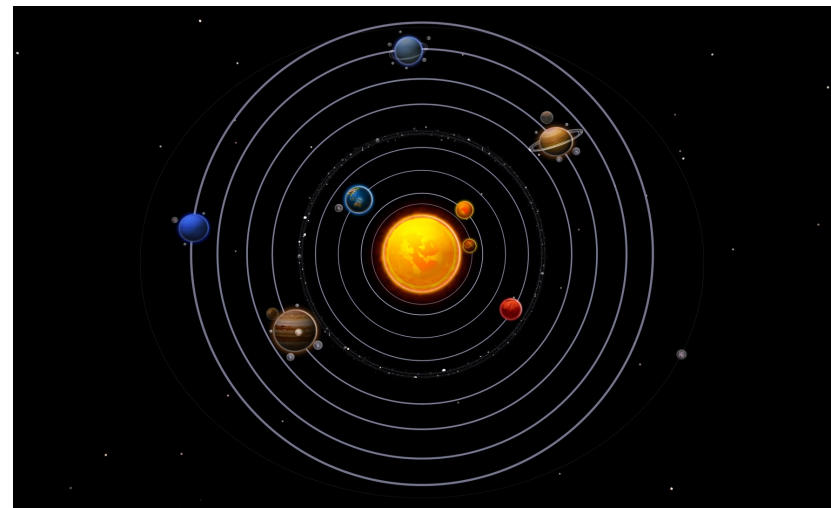
Clock = Oscillator + Counter



# Making an atom oscillate

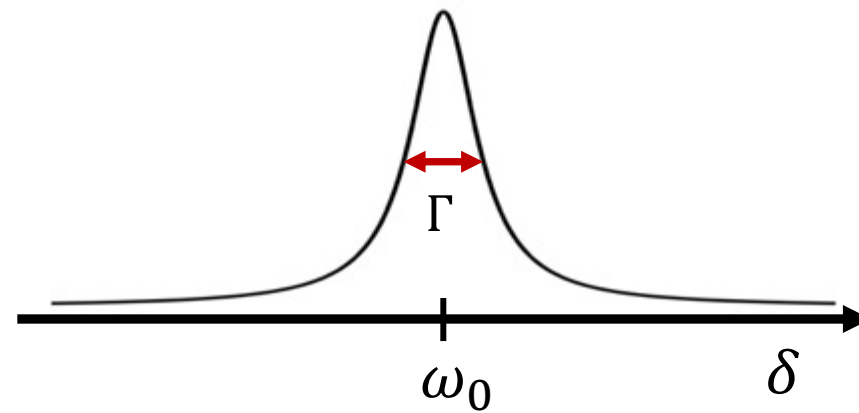
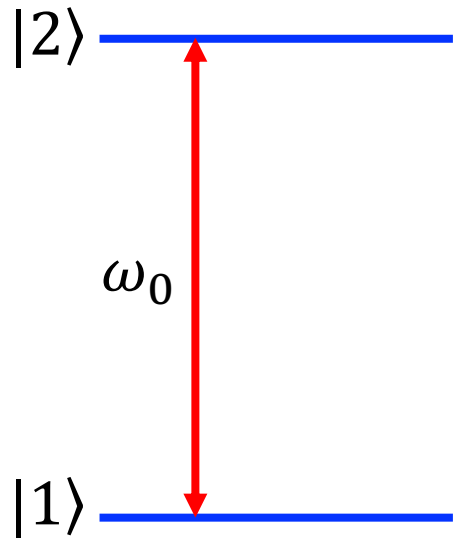


Use light to control electronic state



# Atomic transitions

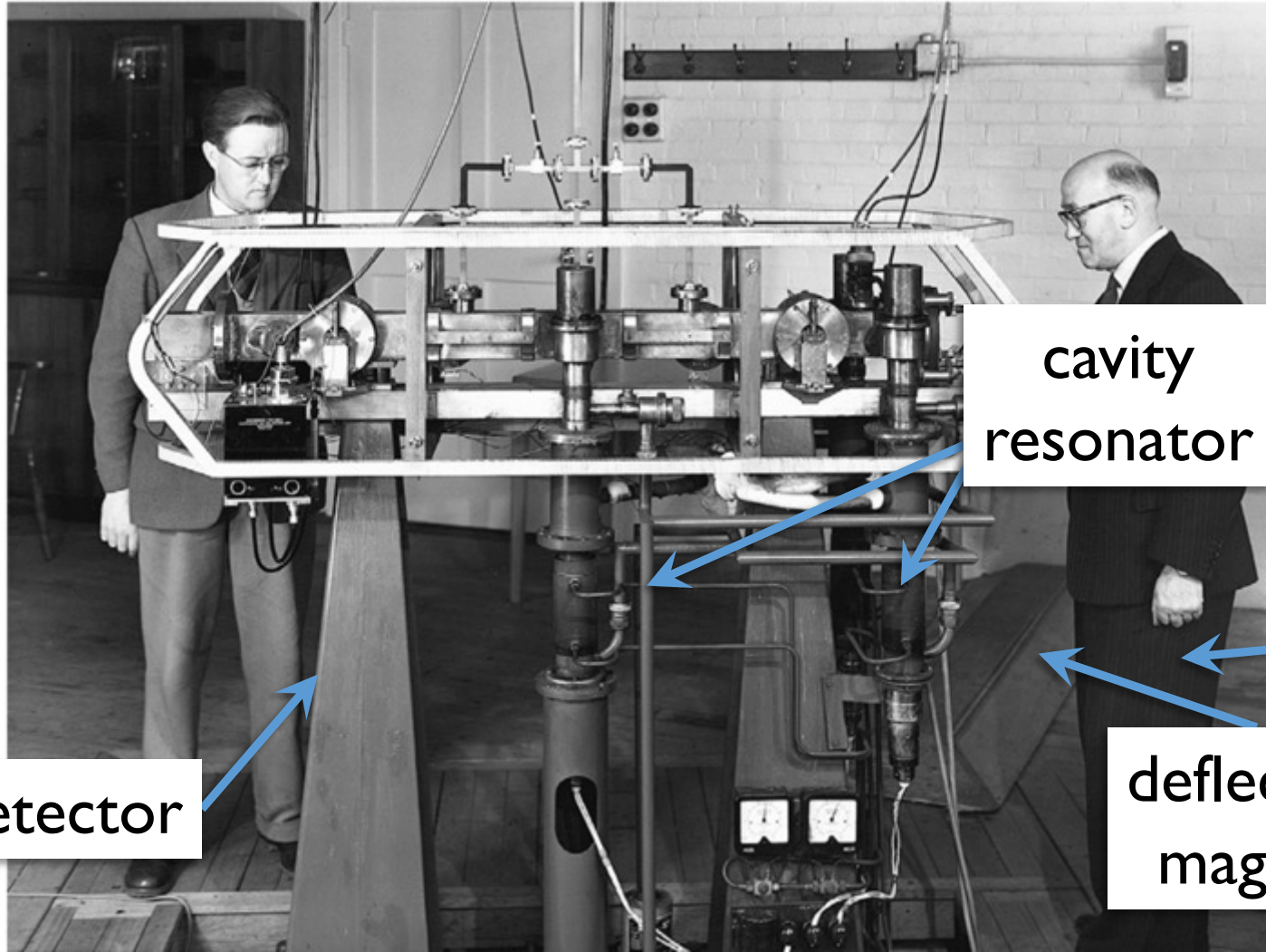
$$\Delta E \Delta t \sim \hbar$$



*Heisenberg*

# Precision measurement – clock

Local Oscillator



$$\omega_0 = \frac{E_2 - E_1}{\hbar}$$

cavity  
resonator

oven

detector

deflecting  
magnet

Essen and Parry  
*Philos. Trans. R. Soc.*  
*London* **250** 45 (1957)



# What is 1 second?

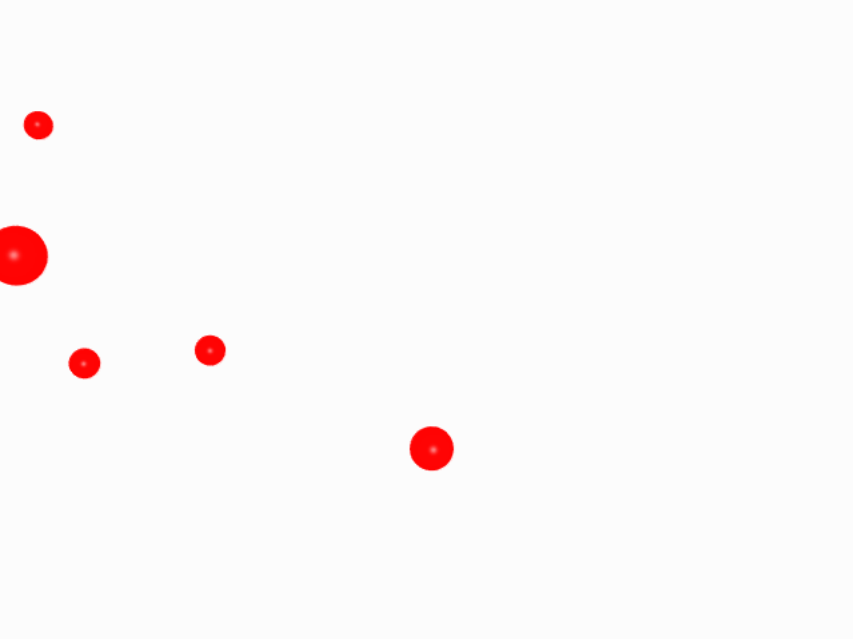


1/60th of a minute

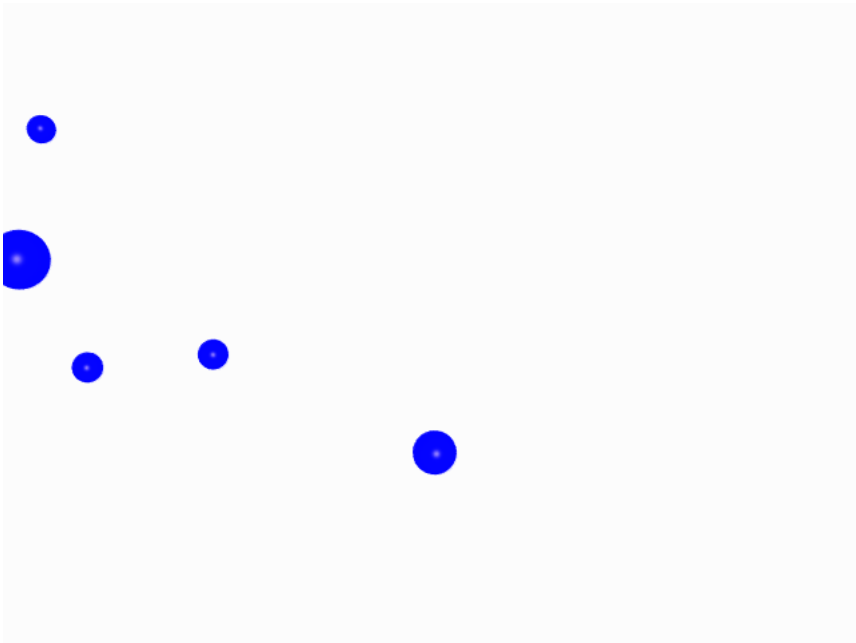


The duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

# Atoms move too fast to see



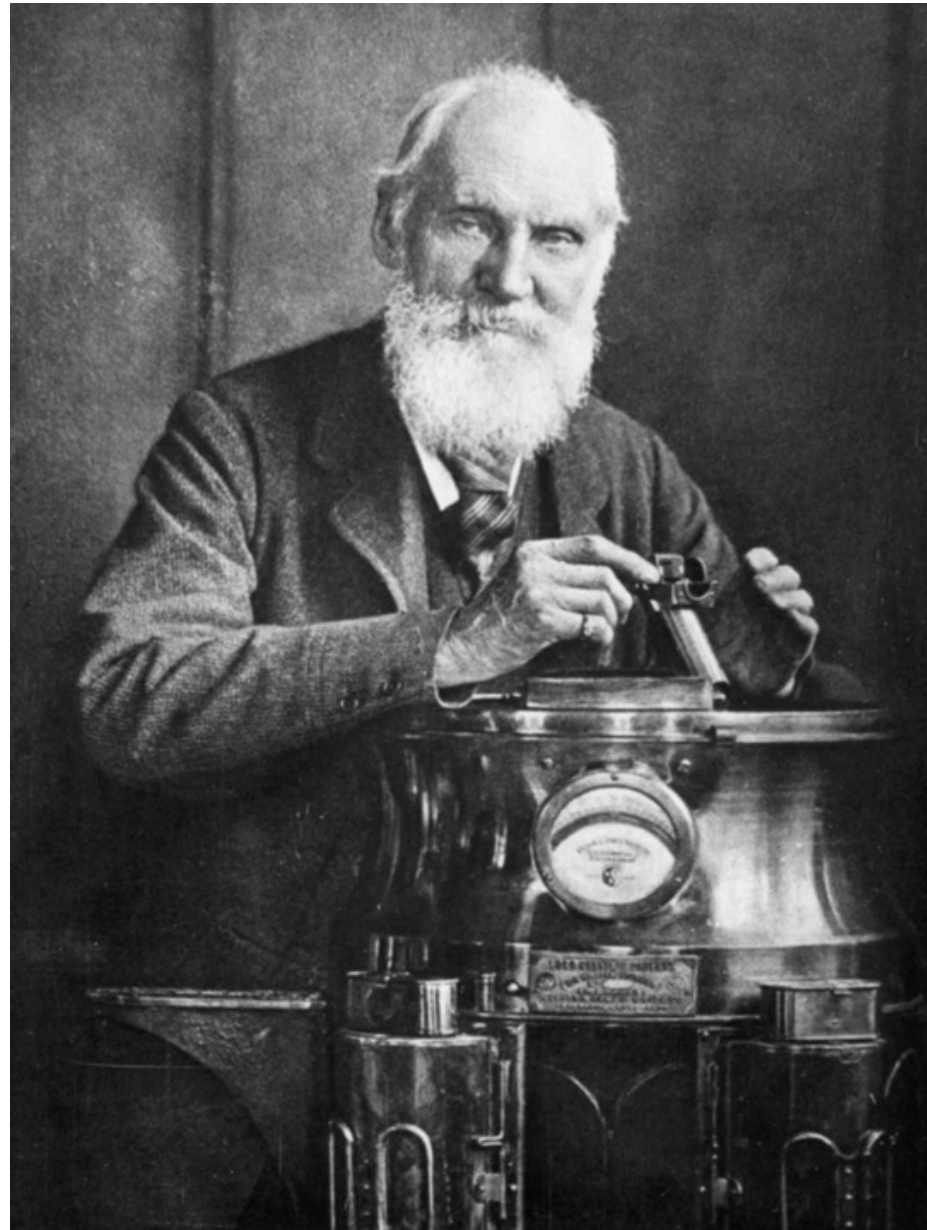
Room temperature atoms



Cold atoms



# Kelvin & temperature



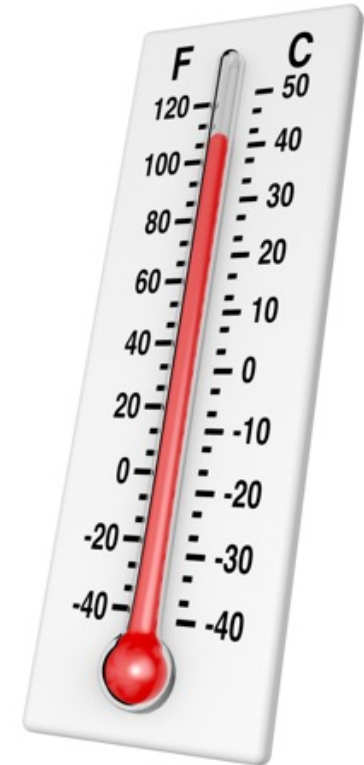
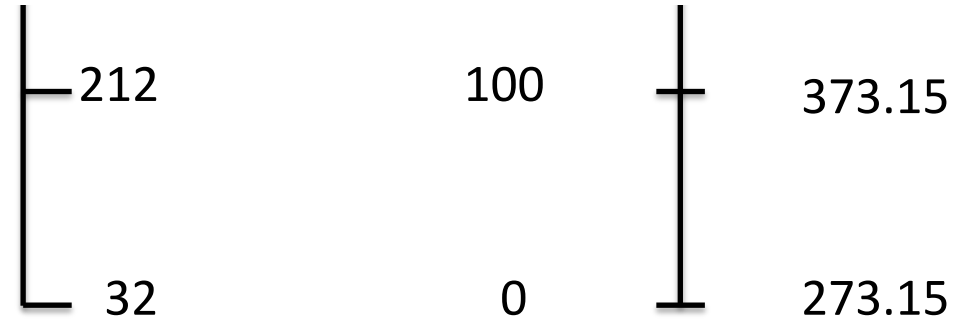
# What about temperature?



Fahrenheit

Celcius / Centigrade

Kelvin



Absolute  
Zero

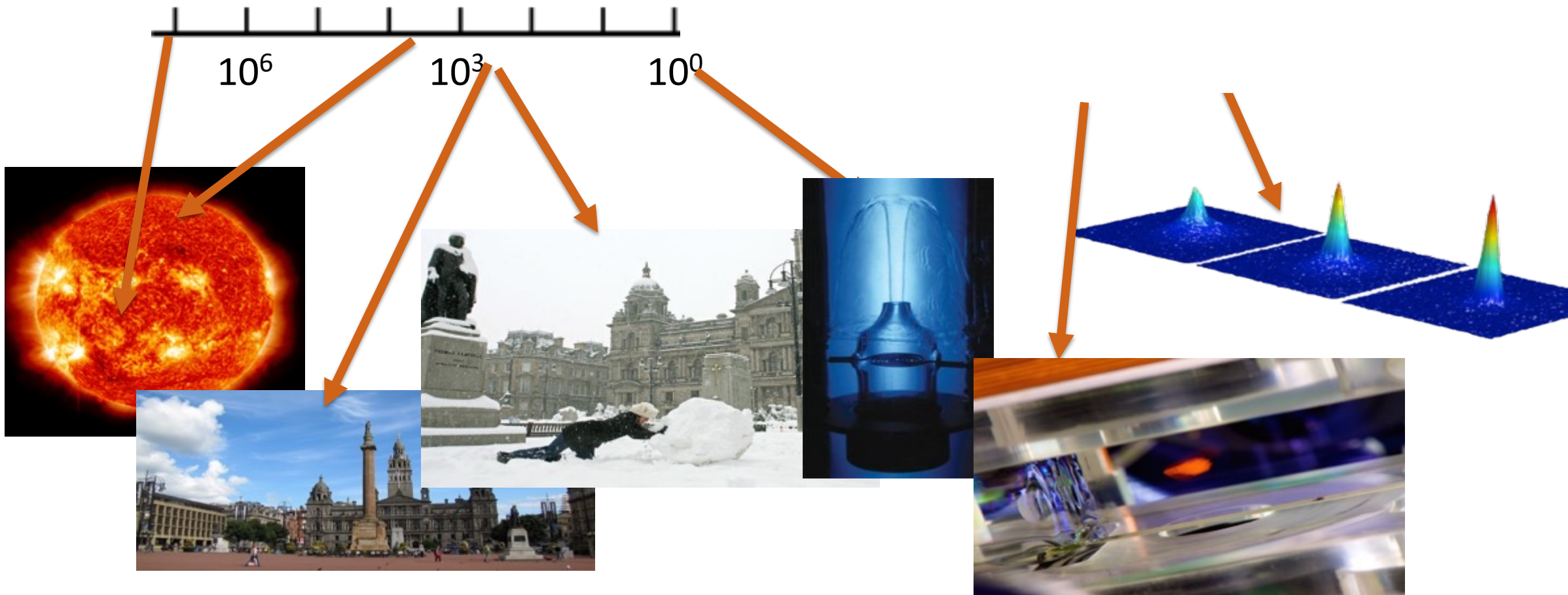
-459

-273.15

0

# Temperature

## Temperature in Kelvin





The image is a composite. The top half shows a bright comet with a long, glowing tail streaking across a dark, star-filled night sky. Below the sky is a silhouette of a mountain range. The bottom half is a diagram showing a central yellow sun labeled 'The Sun'. A white curved line represents a comet's orbit around the sun. Several small white dots are placed along this orbit, and from each dot, a blue beam of light radiates outwards, representing the radiation pressure exerted by the sun on the comet.

## Kepler (17<sup>th</sup> century):

comet's tails are caused by  
pressure of light

## Maxwell (19<sup>th</sup> century):

Pressure is due to  
electromagnetic fields





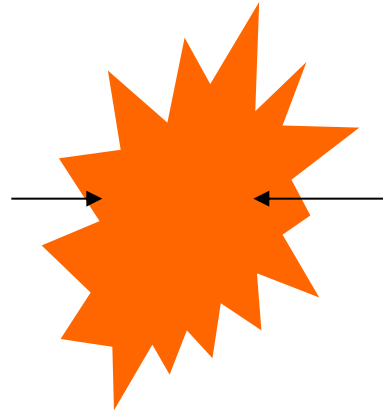




# Cooling by momentum exchange



150 g  
10 m/s



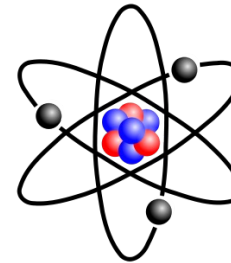
$$\vec{p}_{truck2} = \vec{p}_{truck1} + \vec{p}_{ball}$$



3 tons  
50 km/h



780 nm



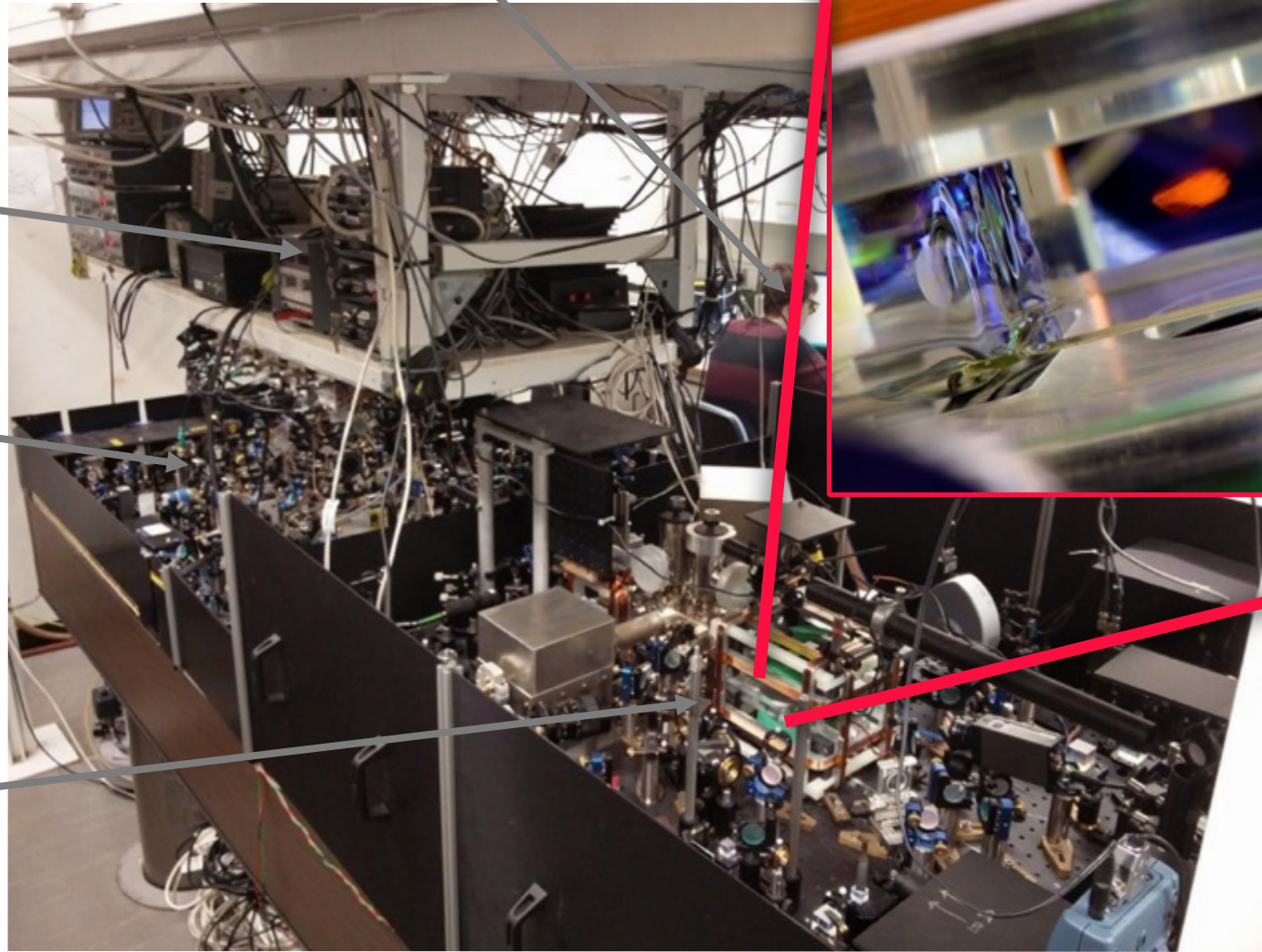
87  $m_u$   
170 m/s

People

Electronics

Lasers

Vacuum





**I'M GOING TO  
SHINE LASERS ON ATOMS!**



**TO HEAT THEM UP, RIGHT?**



imgflip.com



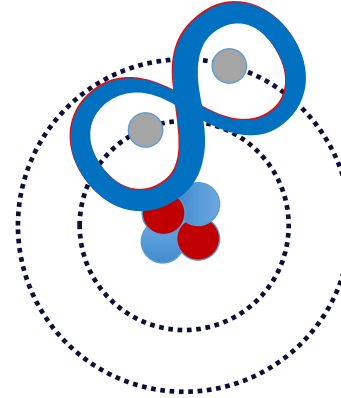
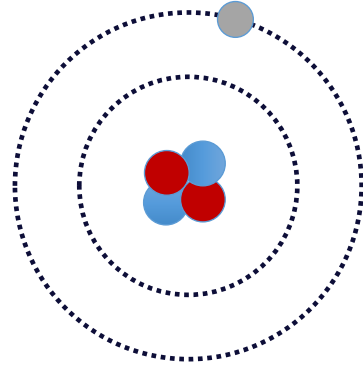
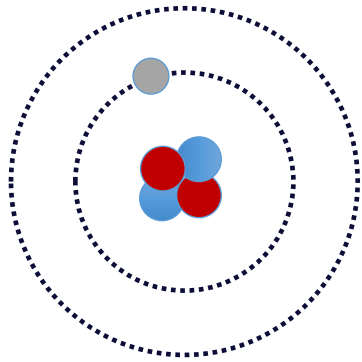
**TO HEAT THEM UP, RIGHT?**





**Any  
questions?**

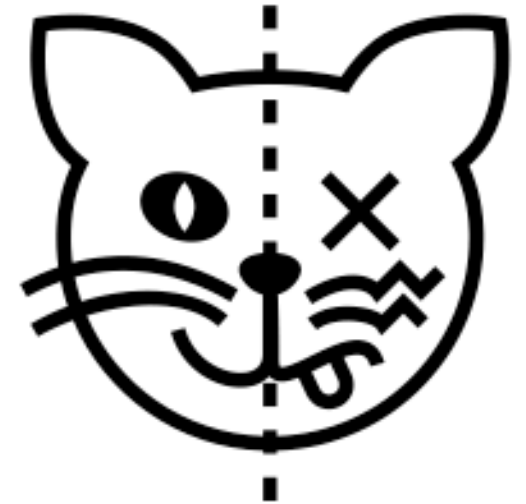
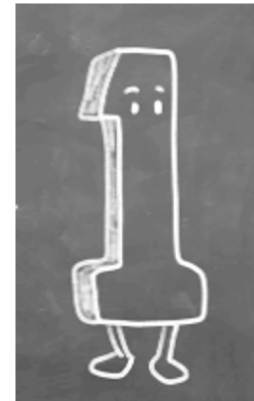
# Uses of atoms?



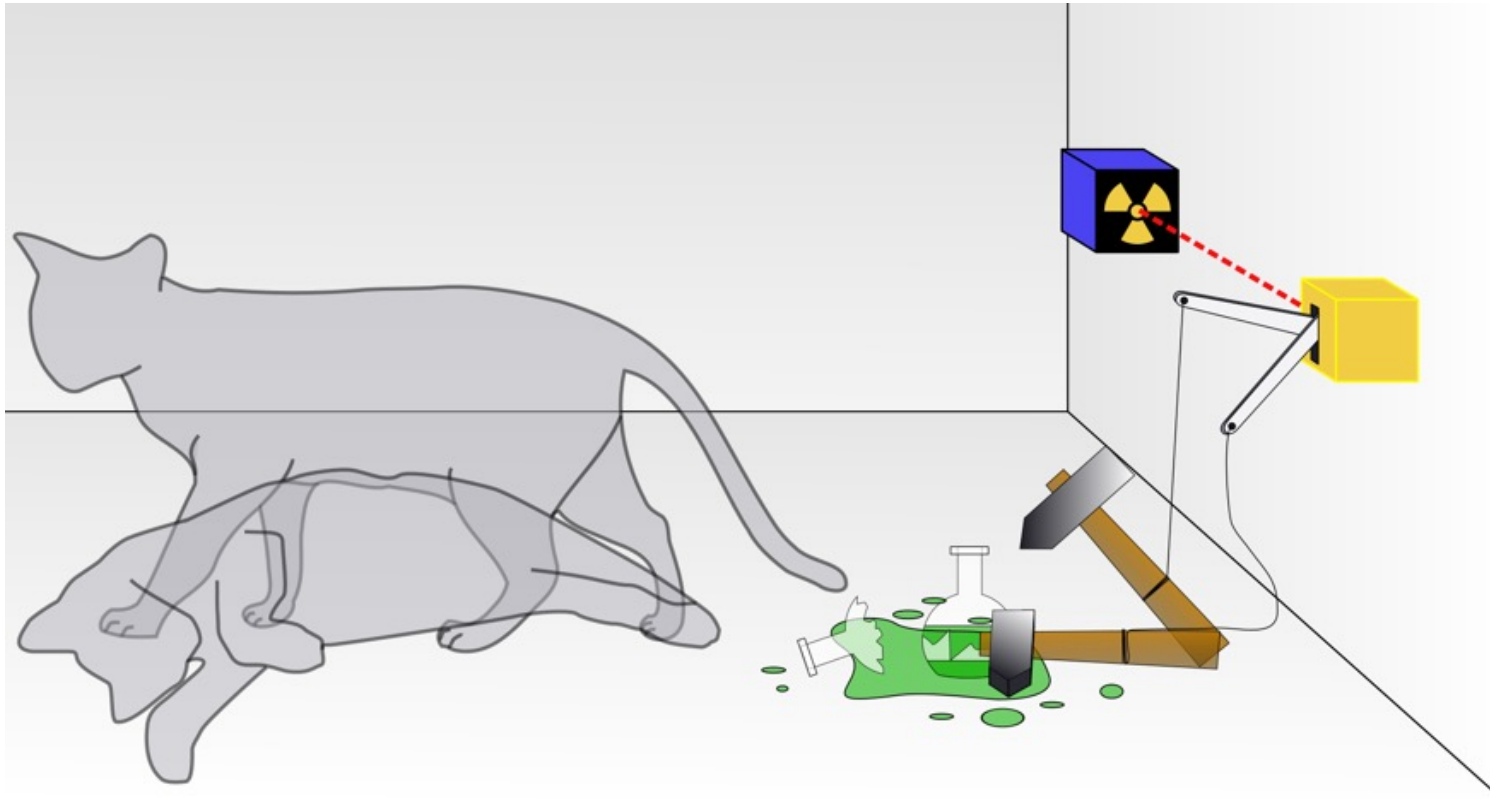
1



0

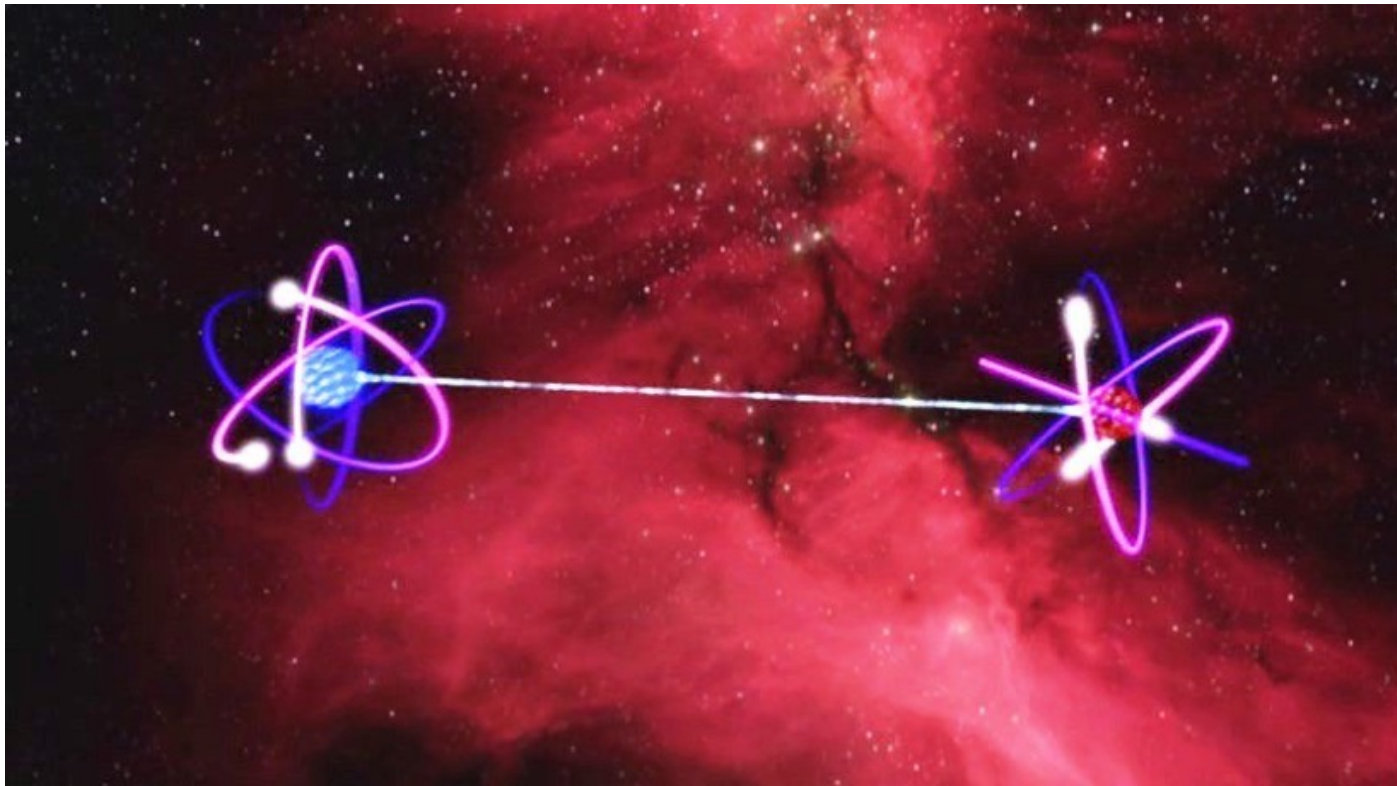


# Superposition



Schrödinger's Cat

# Entanglement



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## EINSTEIN ATTACKS QUANTUM THEORY

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Scientist and Two Colleagues  
Find It Is Not 'Complete'  
Even Though 'Correct.'

---

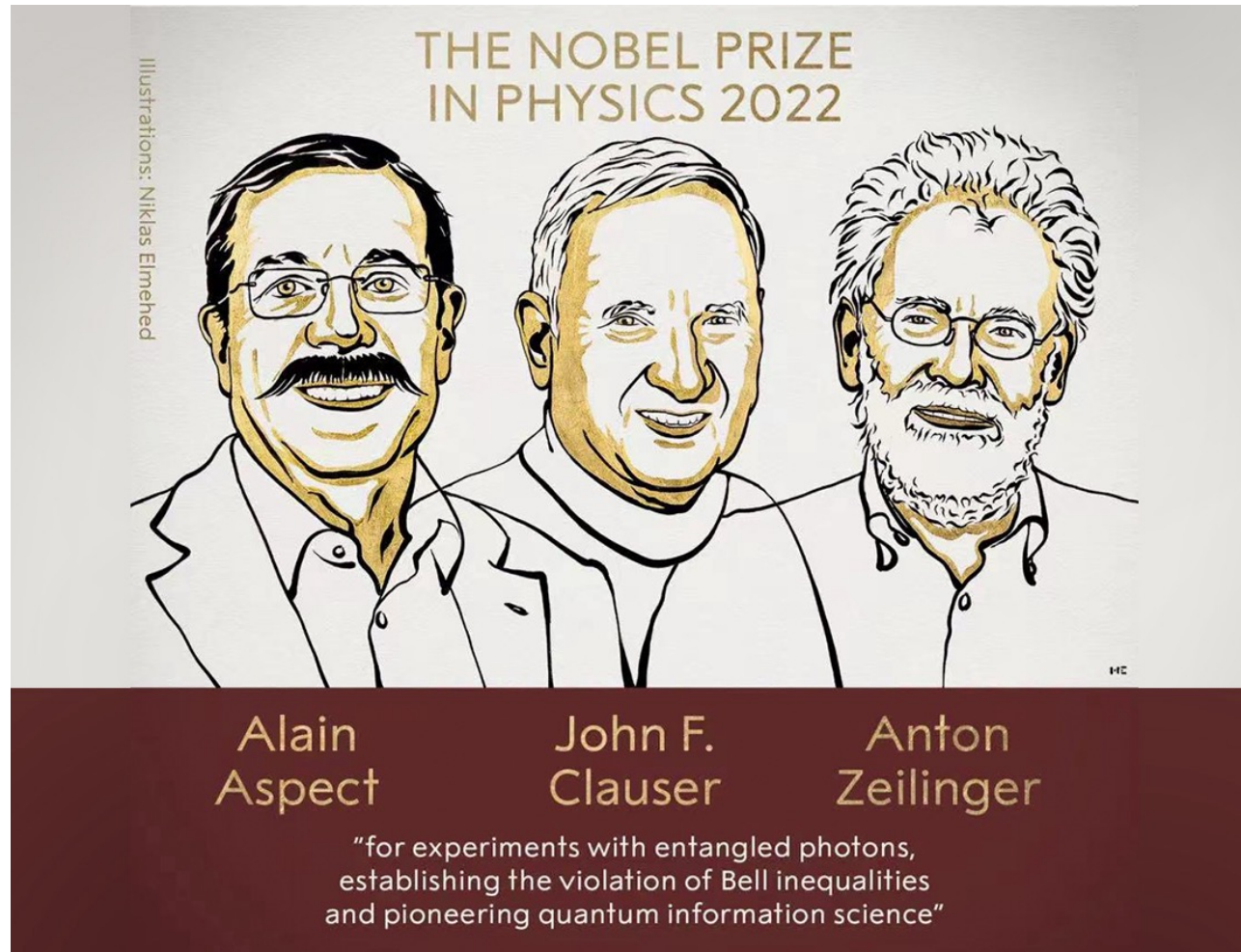
SEE FULLER ONE POSSIBLE

---

Believe a Whole Description of  
'the Physical Reality' Can Be  
Provided Eventually.



# Entanglement



# Uses of Quantum physics?

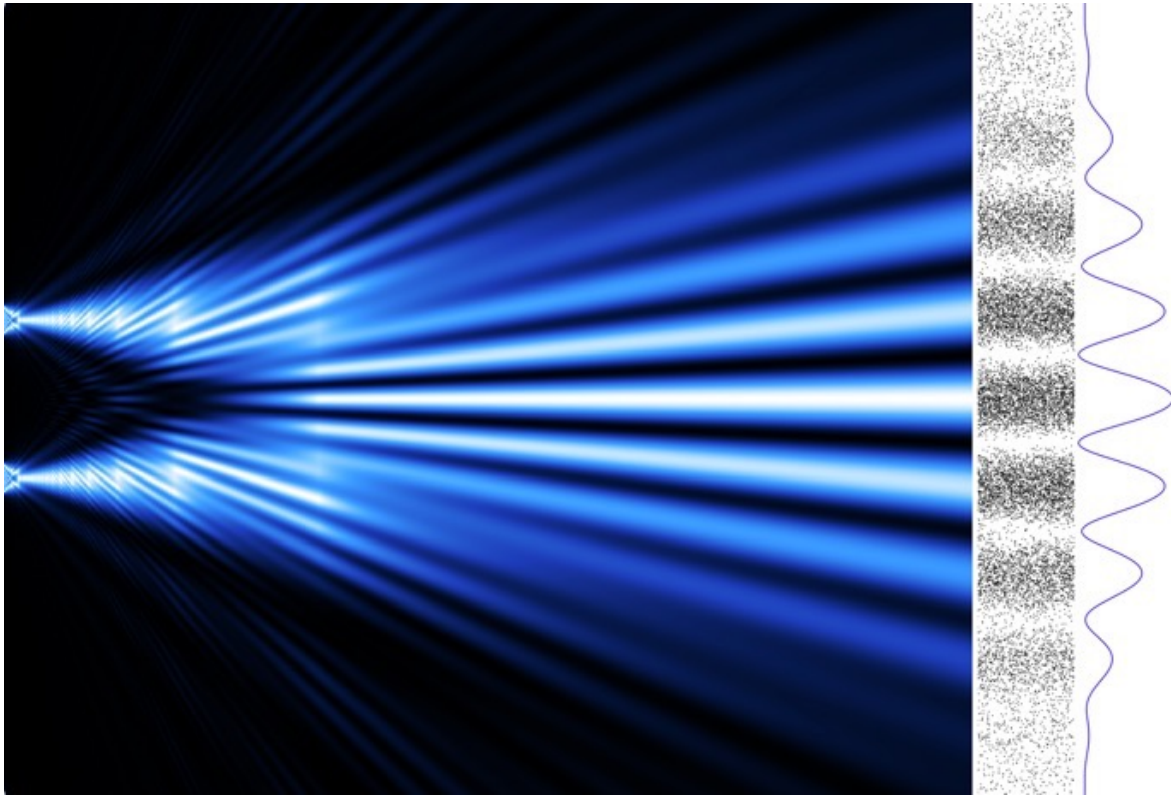
Semiconductors



Lasers

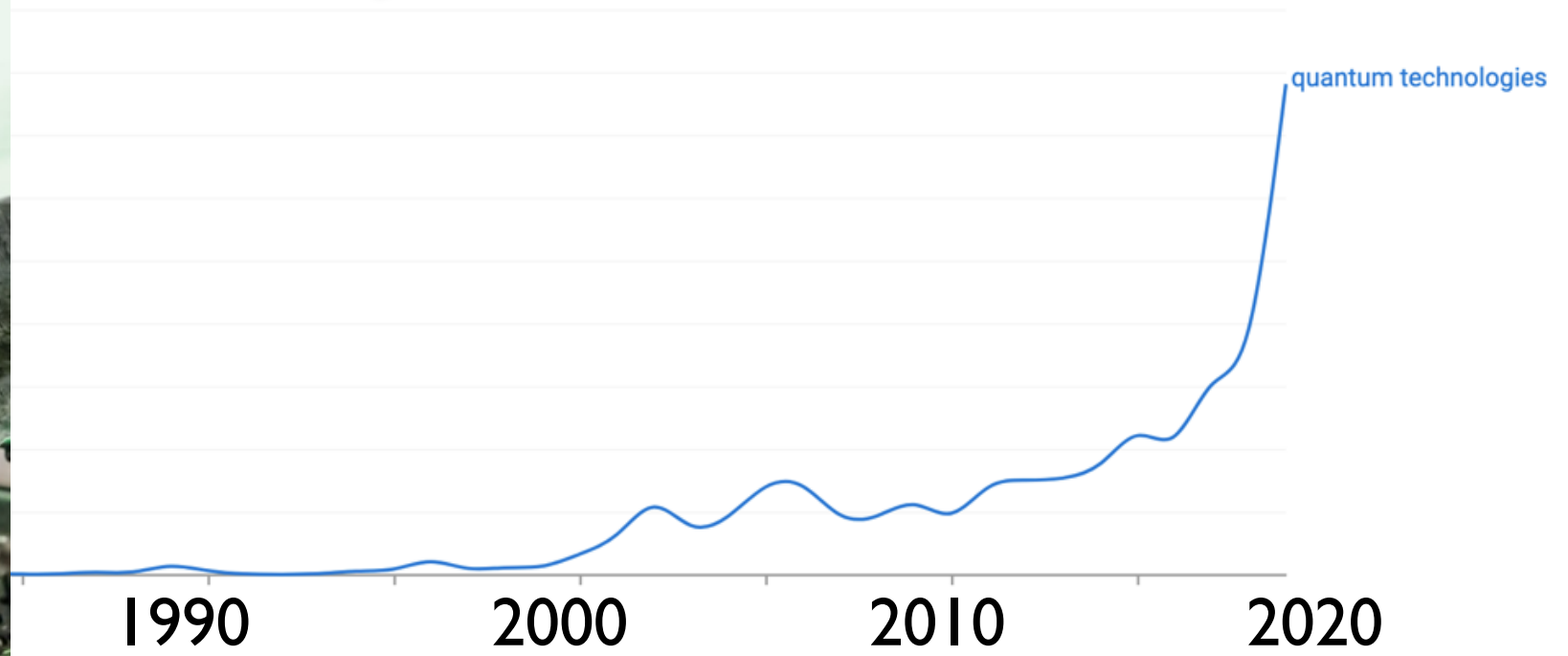
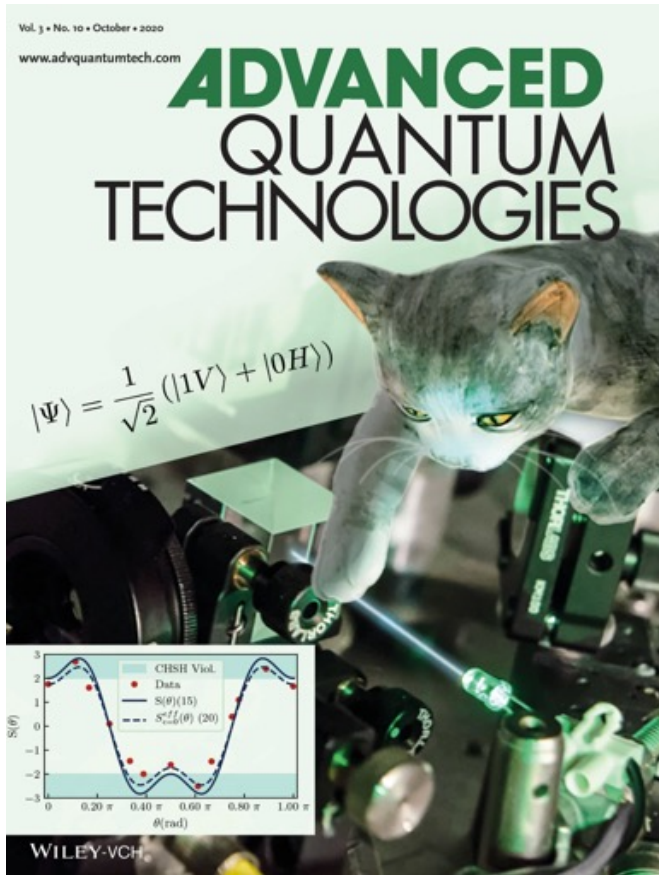


# Atom Interferometry



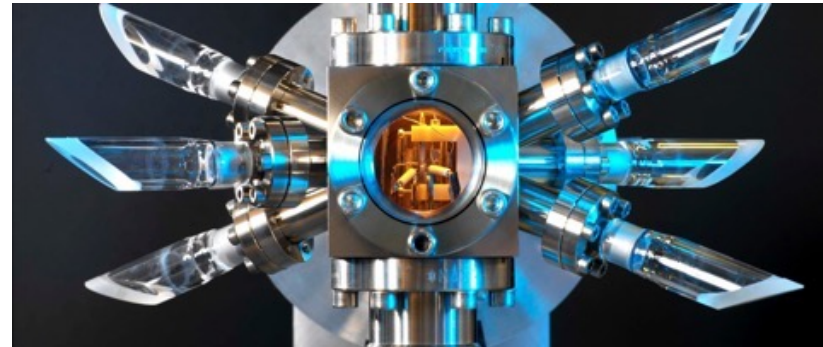
# Quantum technologies

Quantum technologies exploit quantum physics

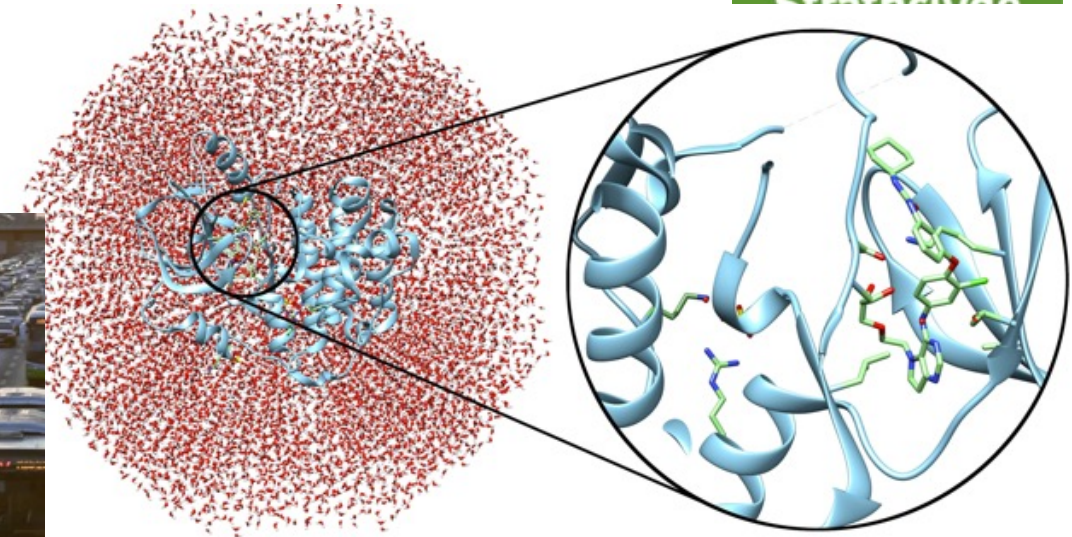


# Applications

- Better clocks
- Better magnetic sensors
- Better navigation
- Secure communications
- Quantum enhanced imaging
- Quantum computers



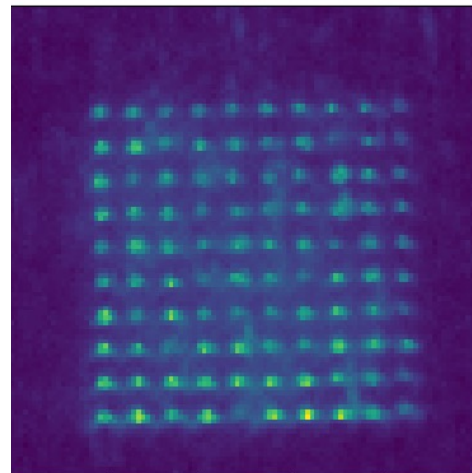
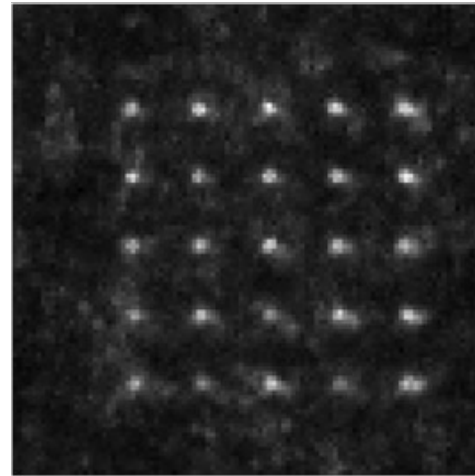
# Quantum computing



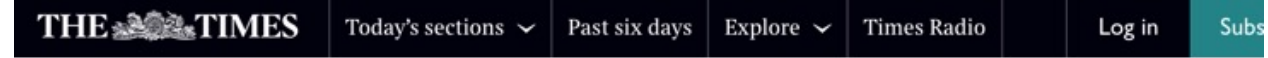
quantum computers are as different from today's digital computers as today's computers are from an abacus

*William Phillips, Nobel*

*Prize 1997*



*Jonathan Pritchard*



WORKING LIFE

# Quantum computing is on cusp of commercial breakthrough

James Hurley, Enterprise Editor

Monday September 07 2020, 12.01am, The Times

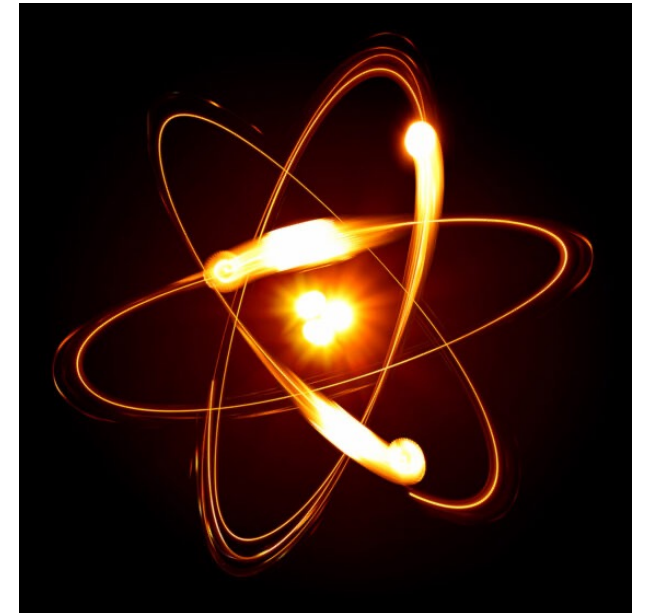
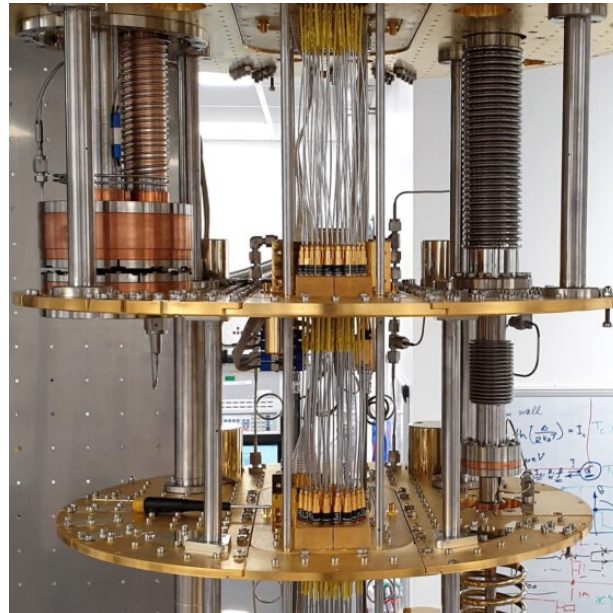
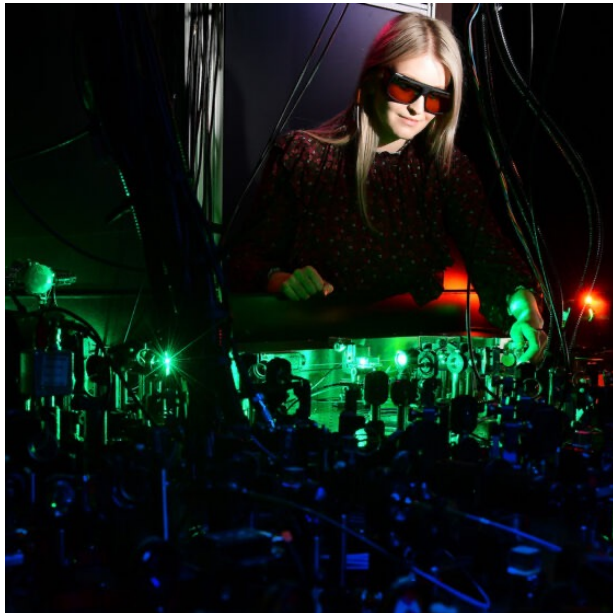


The thought experiment of Schrödinger's cat, and whether it can be dead and alive at the same time, is an analogy for the "superposition" inside a quantum computer

# Quantum computing



University of Strathclyde  
University of Edinburgh  
University of Glasgow





# Quantum sensing

## Navigation

Positioning with cm-resolution  
Driver-less cars



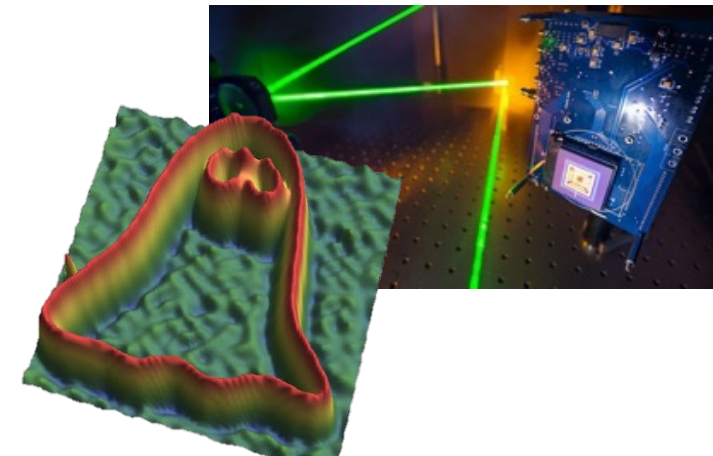
## Medical

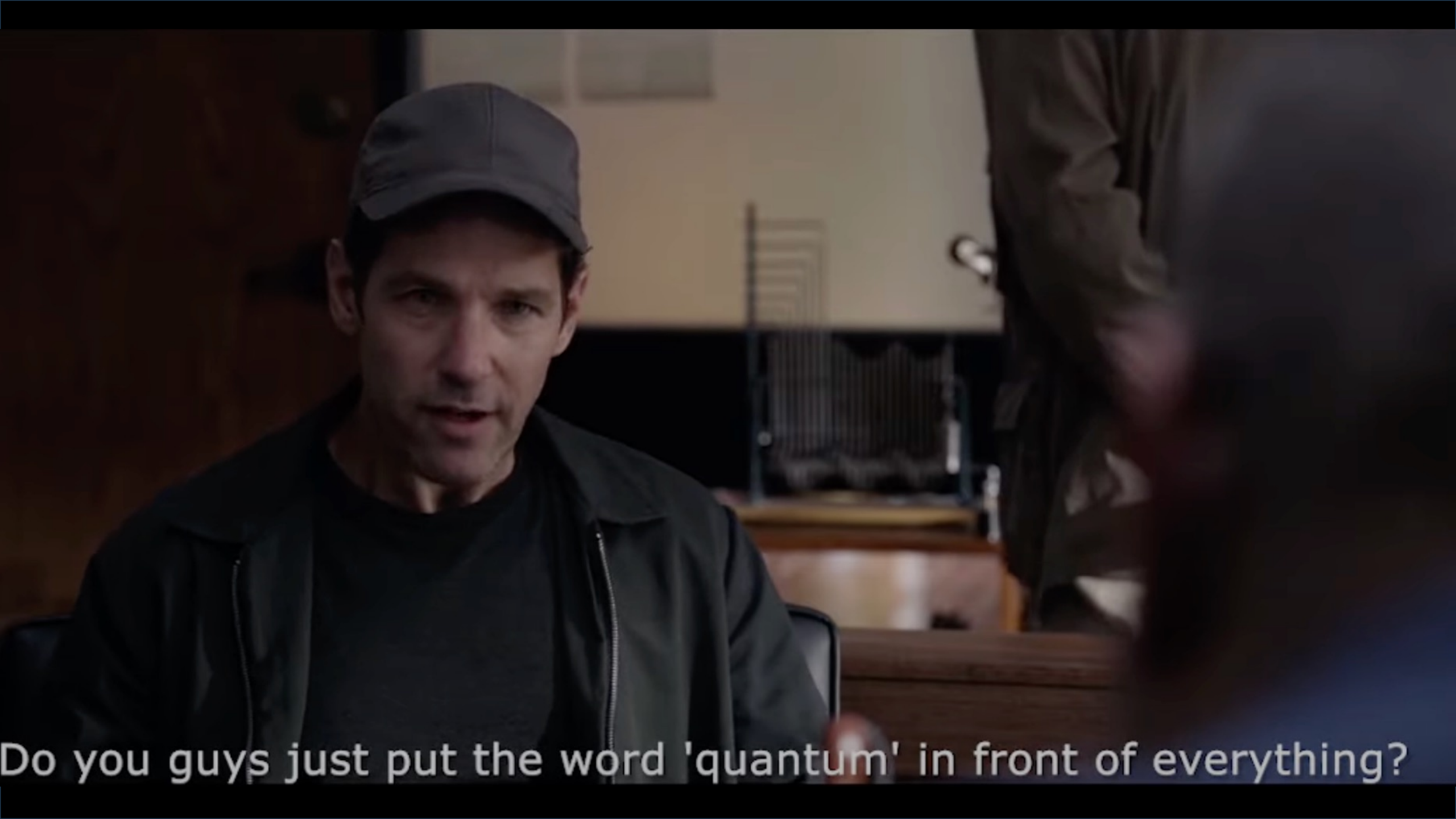
New brain scanners



## Imaging

Seeing through objects and around corners



A man wearing a grey cap and a dark jacket is sitting at a desk in an office. He is looking towards the camera with a serious expression. In the background, there is a typewriter on a desk and a person's legs in dark pants standing to the right. The lighting is somewhat dim, creating a professional and slightly somber atmosphere.

Do you guys just put the word 'quantum' in front of everything?

# Quantum products





## gMOT

A compact grating Magneto-Optical Trap chip for the generation of ultra-cold atoms.

### Features

#### Performance

- Trapping over 10 million  $^{87}\text{Rb}$  atoms
- Cooling below 40  $\mu\text{K}$



<https://www.kntnano.com/quantum/gmotgrating/>

# Jobs



river lane

OQC

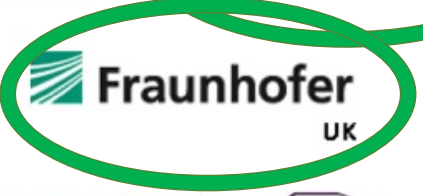


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TOSHIBA



THALES







Any  
questions?