Time & Time Measurement

OPCUG & PATACS

October 21, 2023

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Disclaimers

- Your speaker is a physics dilettante
- Simplification of necessity leads to some inaccuracies—i.e., not the complete picture
- Physics without mathematics is like spaghetti without sauce

Outline

- Definition of time
- Some ancient clocks
- Disaster at sea—the longitude problem
- Examples of historical timepieces
- Atomic clocks

Outline (cont.)

- So, you want to buy a watch?
- Definition of a second
- The speed of light
- Global Navigation Satellite Systems (GNSS)
- Time dilation
- Suggested reading

“What is time?
If one asks me, I know,

but if I wish to explain it to
him who asks, I do not know”

“Τι είναι ώρα?
Αν με ρωτήσει κάποιος, ξέρω.

αλλά αν θέλω να εξηγήσω
αυτό που ρωτάει, δεν το ξέρω”

Augustine of Hippo
354-430 AD

← Active hypertext links

Definition of Time

- “Of, relating to, or showing the passage of time” from Dictionary.com
- “The thing that is measured as seconds, minutes, hours, days, years, etc.” from *The Britannica Dictionary*

Definition of Time (cont.)

- “The continued sequence of existence and events that occurs in an apparently irreversible succession from the past, through the present, into the future” from *Wikipedia*

So, What is Time?

- *The concept of time is challengingly complex:*
  - ✓ Time is relative not absolute
  - ✓ Time is influenced by speed
  - ✓ Time is influenced by gravity
- This impacts our daily lives

Stay tuned for details…

Time Requires Change

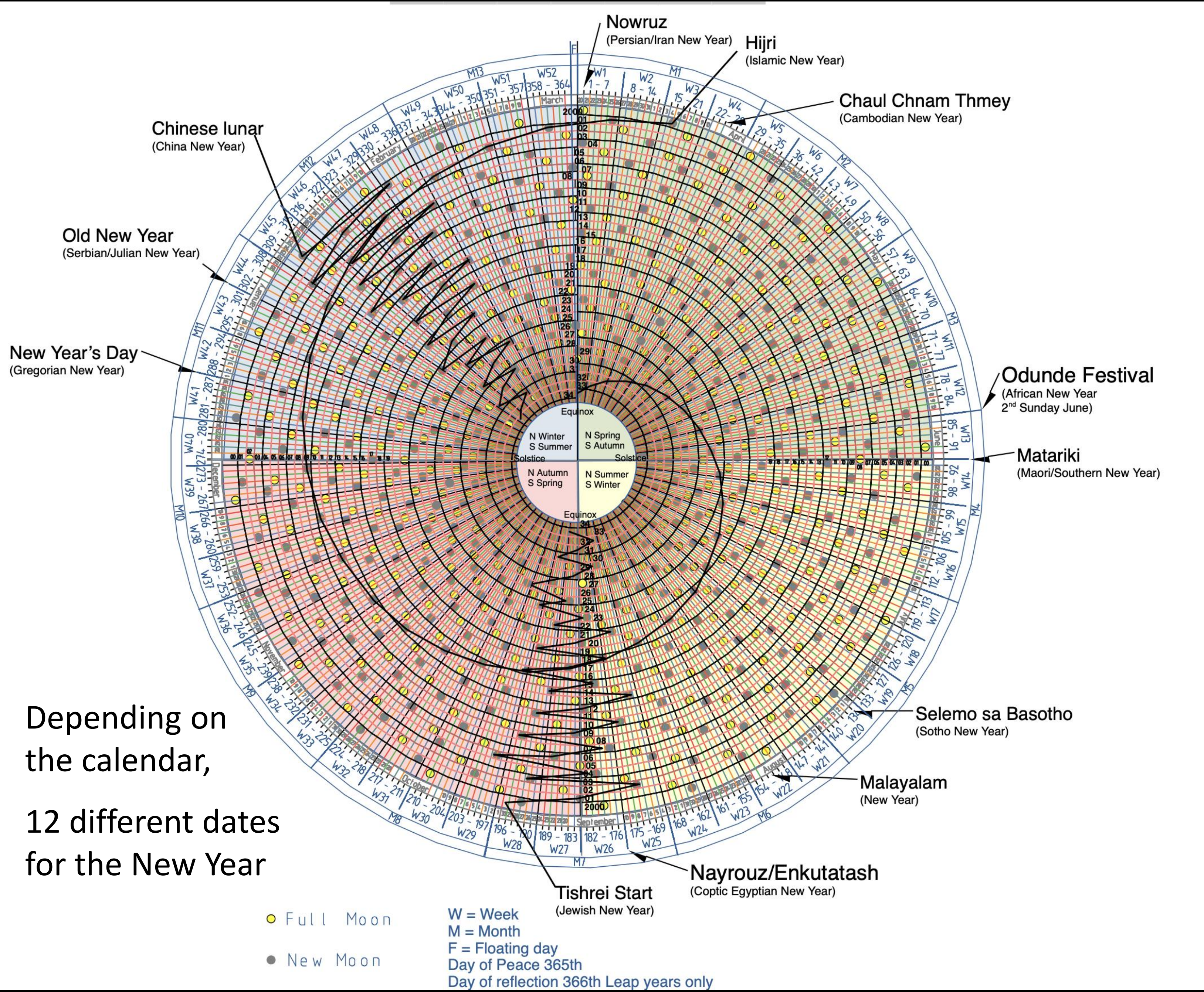
- Days, months, seasons, years, lifetimes, etc.
- Speed (miles/hour)
- Stars’ moving in the sky
- The moon circling the earth
- The earth circling the sun
- Tick-tock, tick-tock, tick-tock

Calendars

- Civil Calendars
  - ✓ Gregorian—accepted worldwide, the *de facto* standard
  - ✓ Chinese
  - ✓ Iranian (Persian)
- Religious
  - ✓ Eastern/Orthodox calendar—Julian calendar
  - ✓ Islamic (Hijri) calendar—a lunar calendar*
  - ✓ Hebrew/Jewish calendar—a lunar/solar calendar*
  - ✓ Buddhist calendar
  - ✓ 6 Hindu calendars

* Also a civil calendar

The Universal Calendar



Depending on the calendar,

12 different dates for the New Year

The Gregorian Calendar*

- A year is the time taken by the earth to make one revolution around the sun
  - ✓365 days a year—not exactly
  - ✓365.25 days a year—not exactly
  - ✓Average number of days in a year 365.2425
  - ✓97 out of 400 years are leap years, not 100

* Also applies to the Julian calendar

Meteorological Seasons

- Four seasons of three months each:
  - ✓ Spring: March 1 to May 31
  - ✓ Summer: June 1 to August 31
  - ✓ Fall: September 1 to November 30
  - ✓ Winter: December 1 to February 28/29

/aboutseasons.html

Astronomical Seasons

- Spring
  - ✓ Begins on the **spring equinox**, March 20^{th} *
- Summer
  - ✓ Begins on the **summer solstice**, June 21^{st} *
- Fall
  - ✓ Begins on the **fall equinox**, September 23^{rd} *
- Winter
  - ✓ Begins on the **winter solstice**, December 21^{st} *

* For 2023. The date varies from year to year

Equinoxes and Solstices

- Equinoxes—day and night are equally long
- Solstices—shortest and longest days of the year

Newgrange

Northeast Ireland

3200 BC

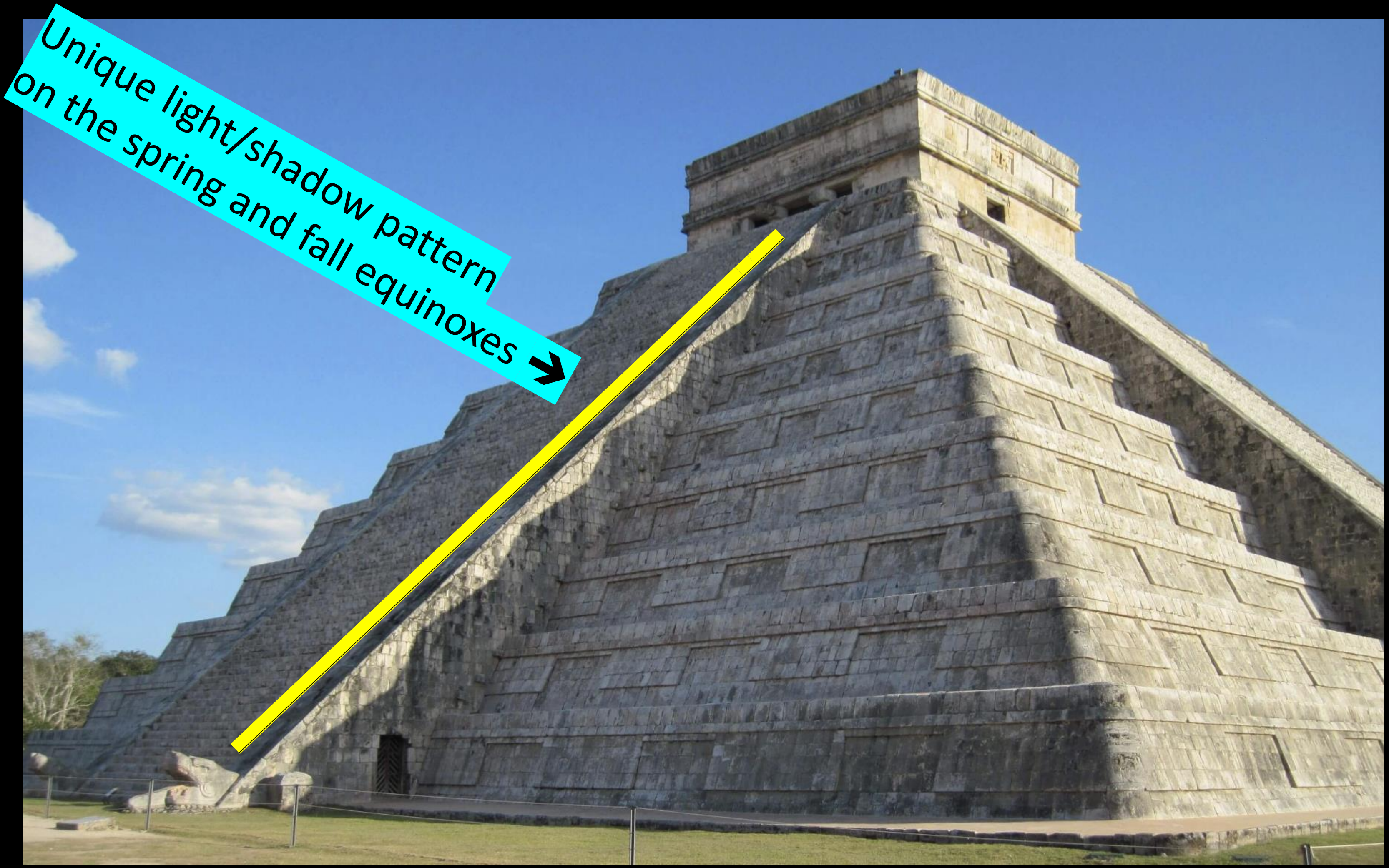
Sunrise on the Winter Solstice

Stonehenge (3000-2500 BC)

Modern day Druids celebrating the summer solstice

On the summer solstice, when the sun rises, the first rays shine into the heart of Stonehenge

Pyramid of Kukulkán at Chichén Itzá*



* Yucatan, Mexico

Built between 8th and 12th centuries AD

The Months

- January—31 days
- February—28 or 29 days
- March—31 days
- April—30 days
- May—31 days
- June—30 days
- July—31 days
- August—31 days
- September—30 days
- October—31 days
- November—30 days
- December—31 days

Time Related Questions

- What time is it?
- How fast are we going? $S = \frac{\partial D}{\partial T}$
- How can we find out where we are?
- What is the length of an American foot?

Huh?

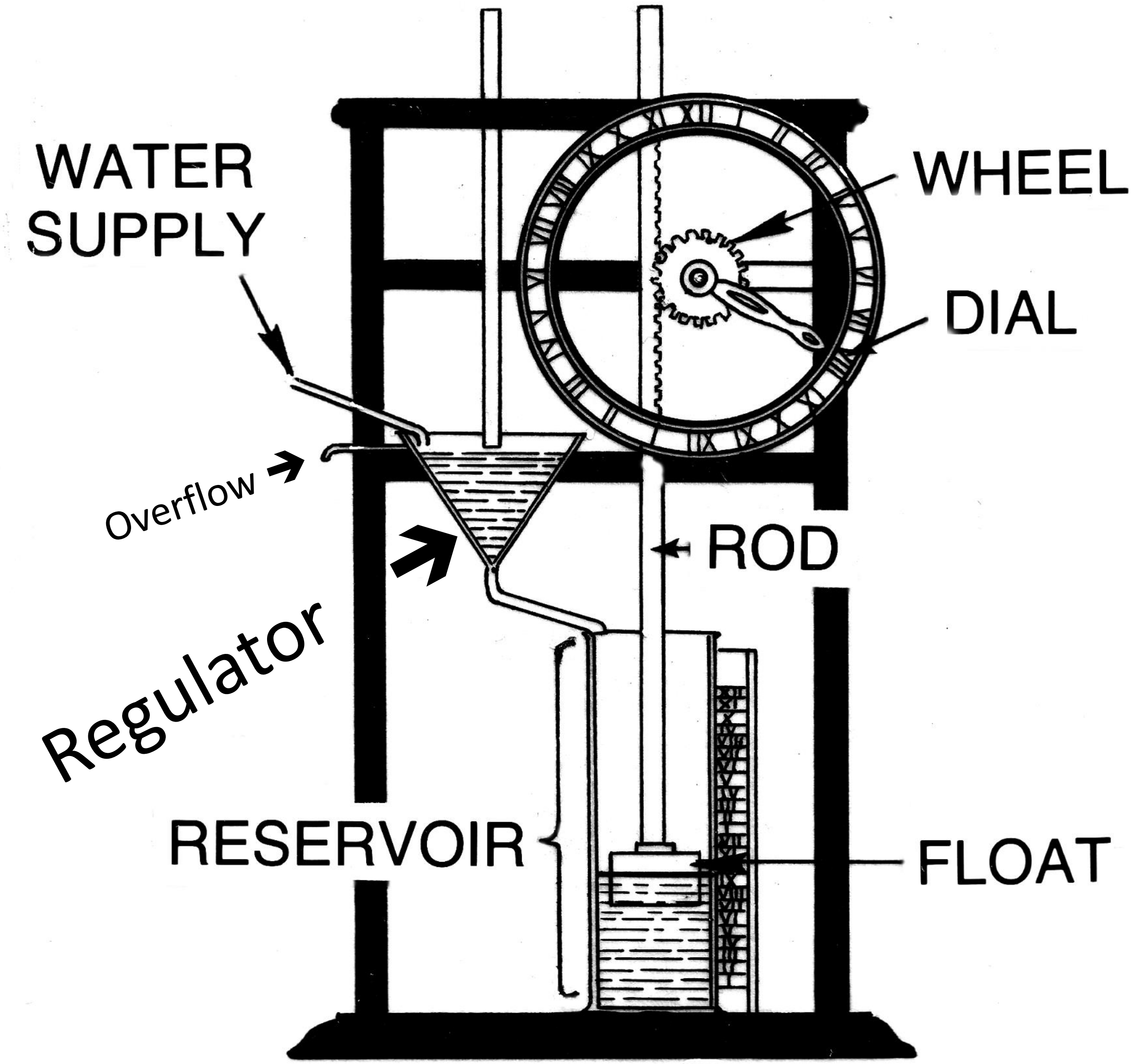
Yes, a foot is related to time

Sundial

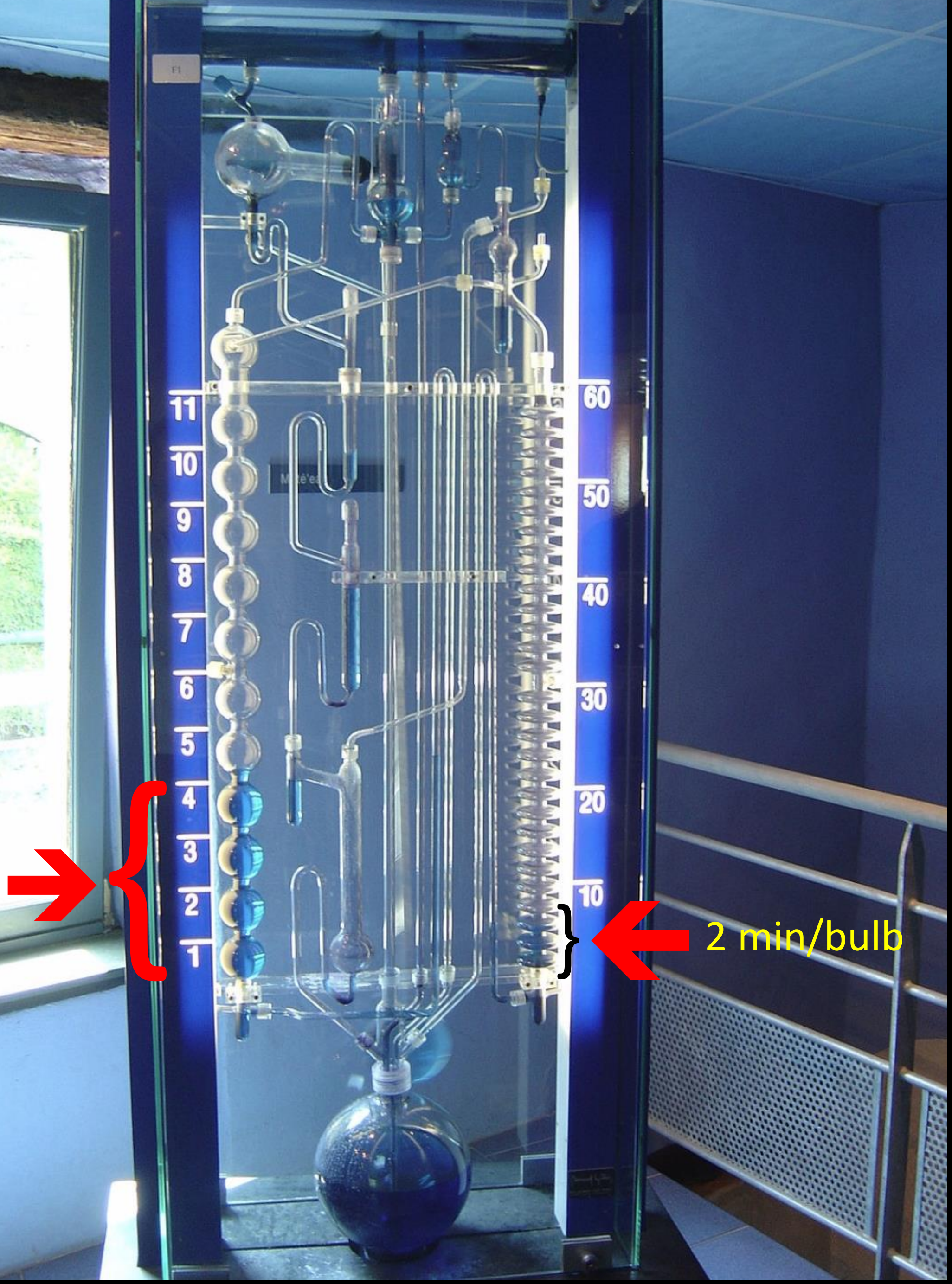
Earliest known: ~1500 BC in Egypt

Egyptian Karnak Clepsydra (Water Clock)

Roman Water Clock



Modern Water Clock
by Bernard Gitton



Time Displayed: 4:06

Salisbury Cathedral Clock ~1386

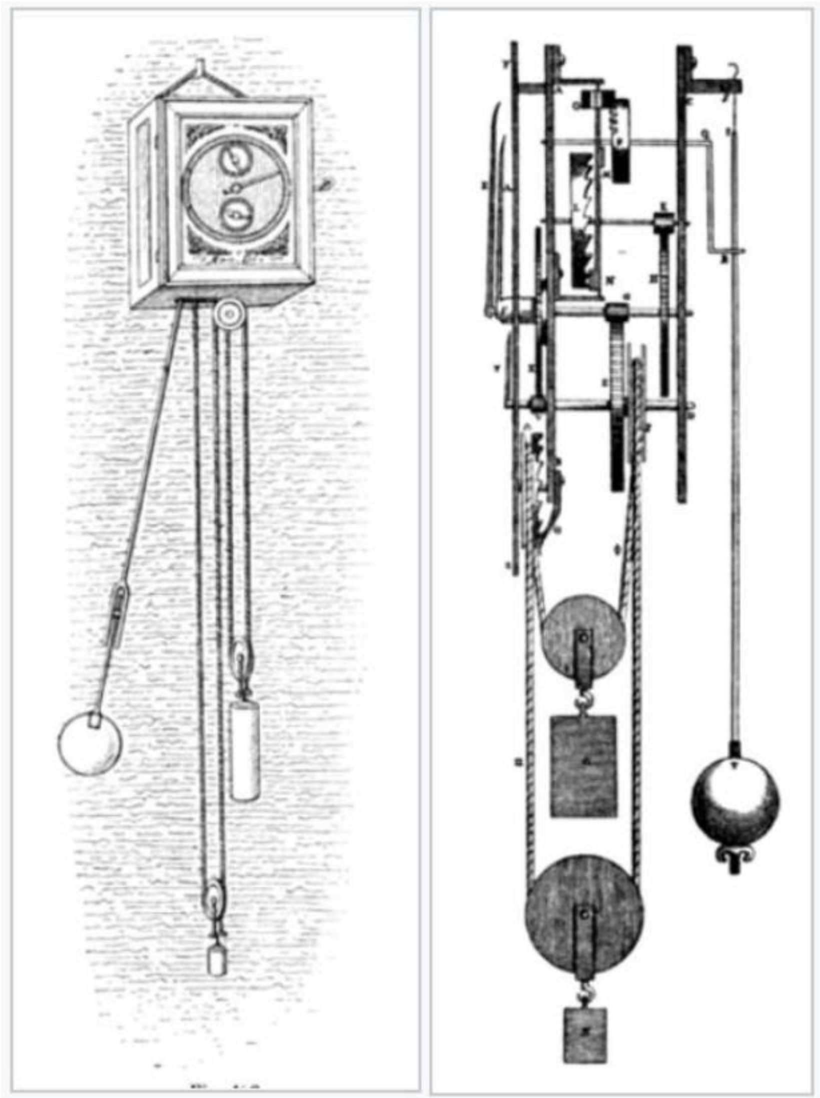
- “Oldest” working mechanical clock
- Time announced by a Bell—no dial

City Hall
Clock Tower
Passau, Bavaria

14th Century

"First" Spring Driven Mechanical Clock ~1430

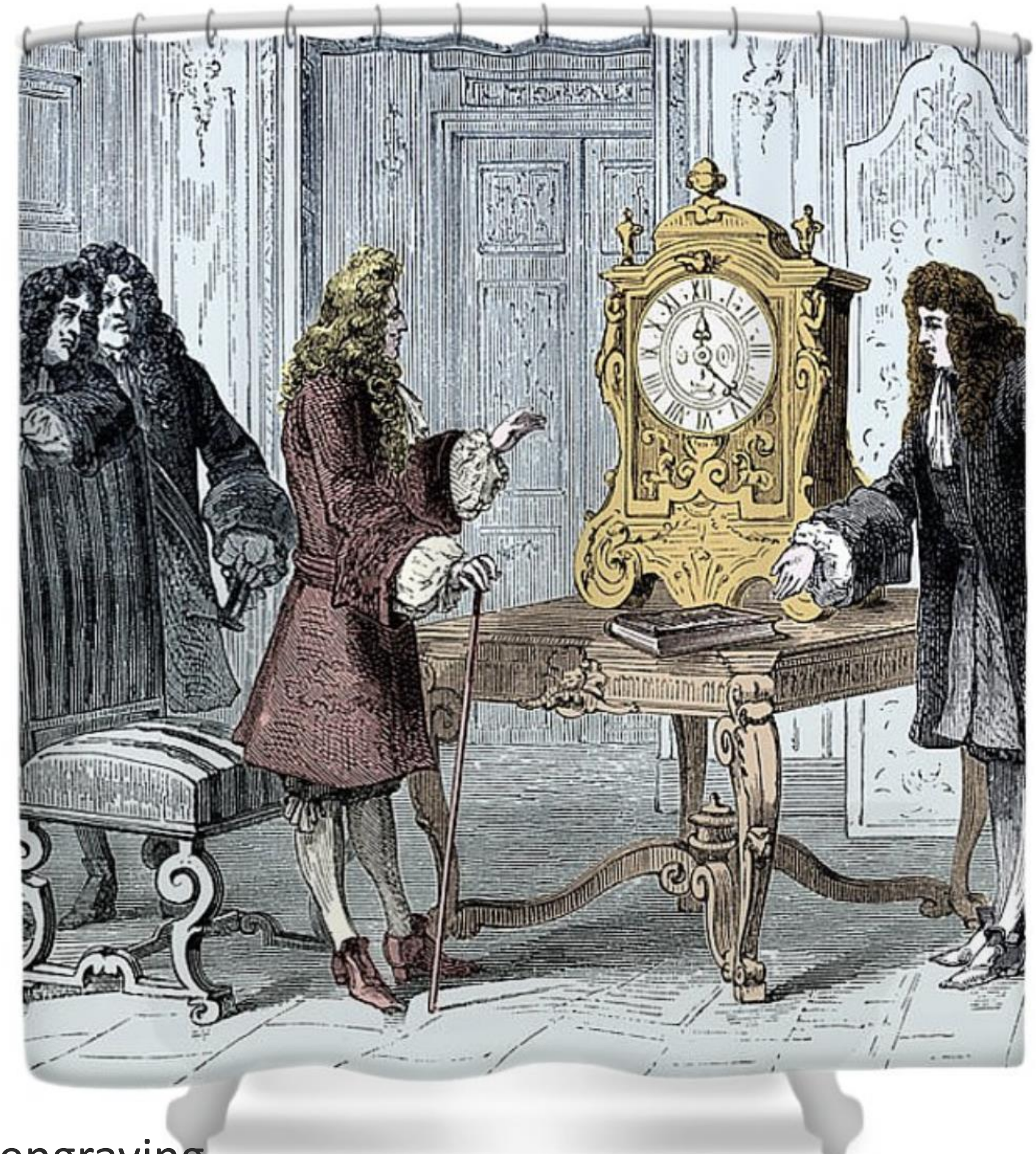
Given to Philip the Good
Duke of Burgundy



Christiaan Huygens patented first pendulum clock June 16, 1657

Huygens presents a pendulum clock to Louis XIV*

Shower curtain ➔



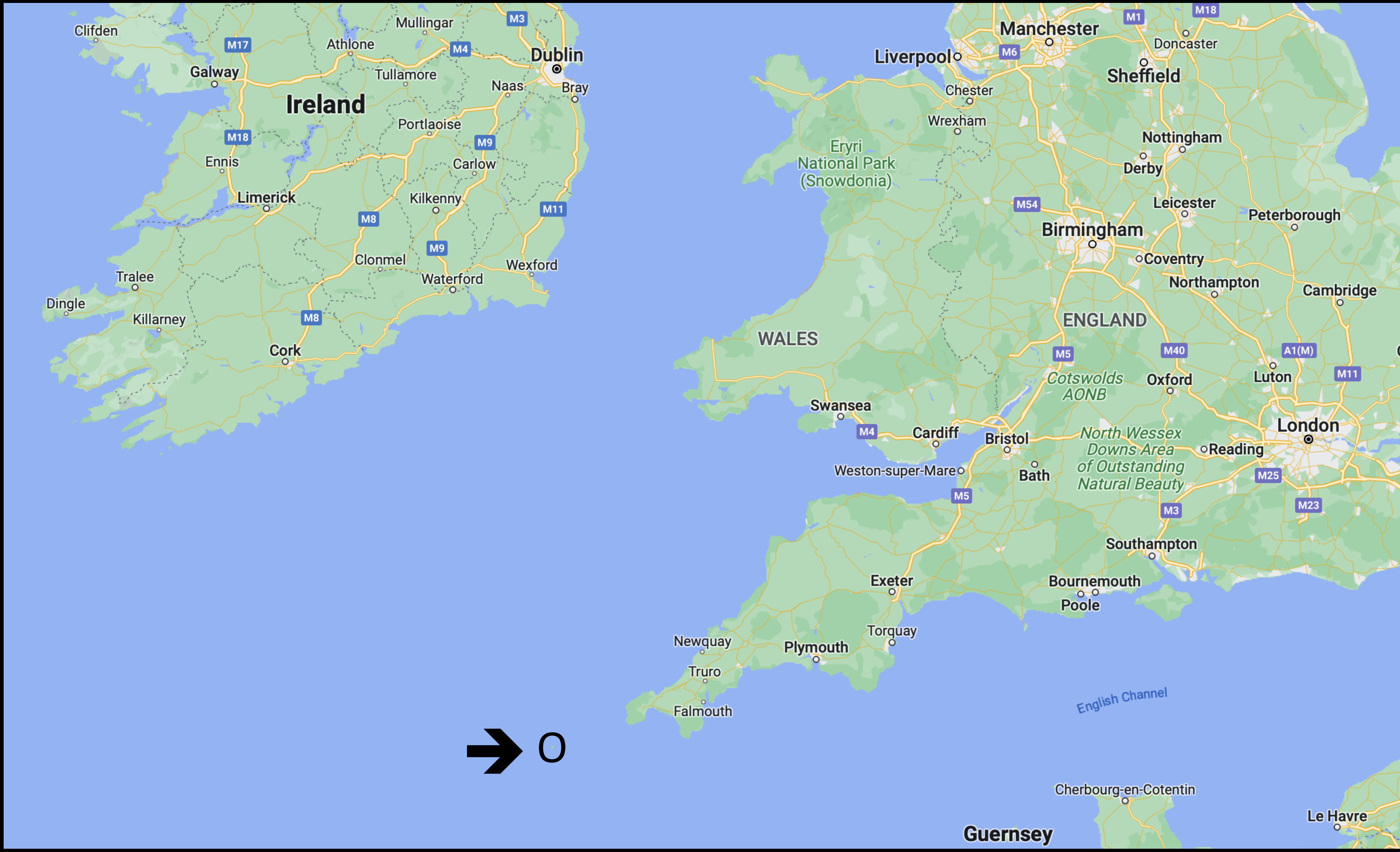
* After a 1659 engraving

Grandfather (Pendulum) Clocks

Popular 1940s-50s Electric Clock

More accurate than quartz clocks over a period of months

Isles of Scilly, England



Isles of Scilly, England

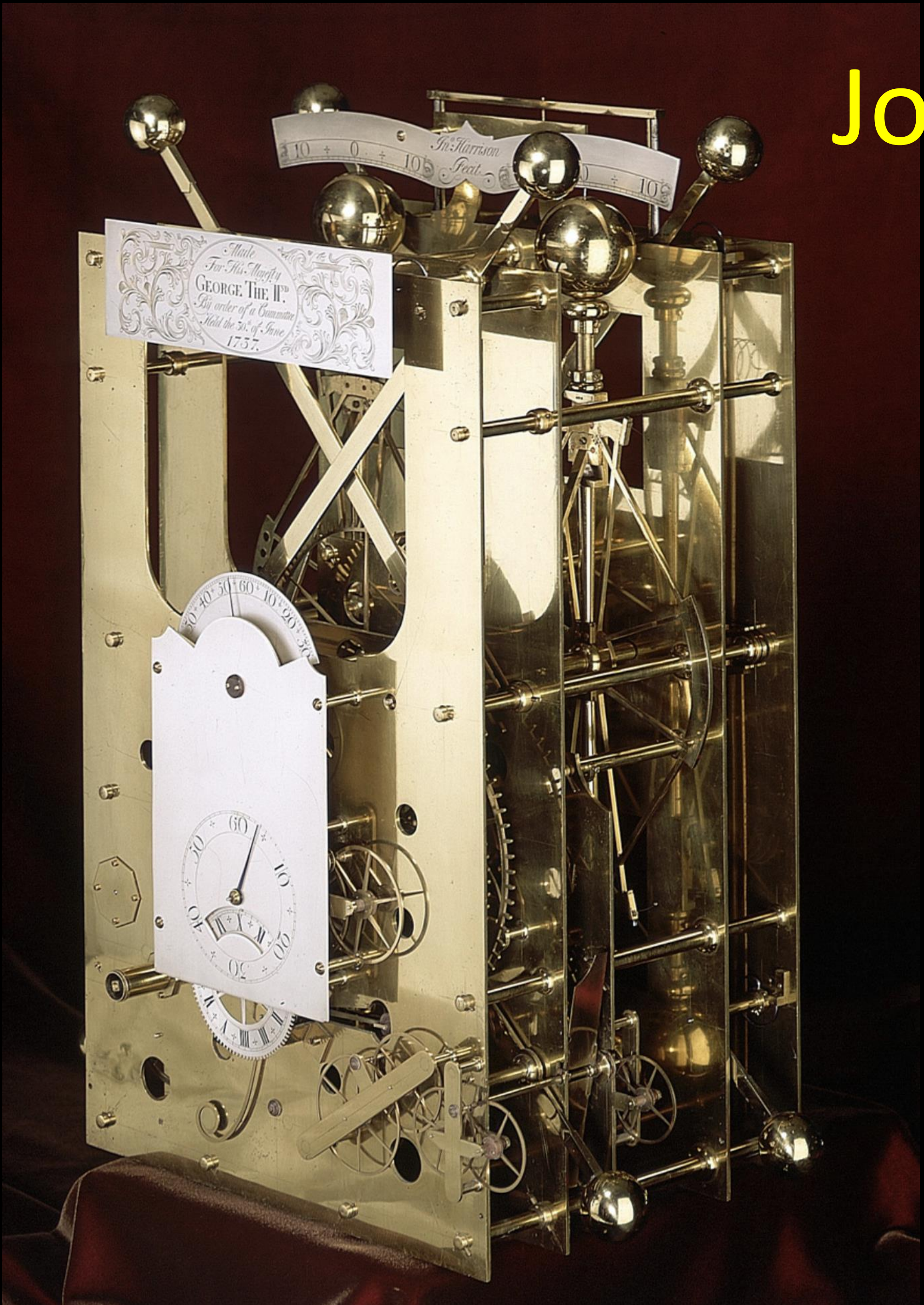
Disaster at Sea

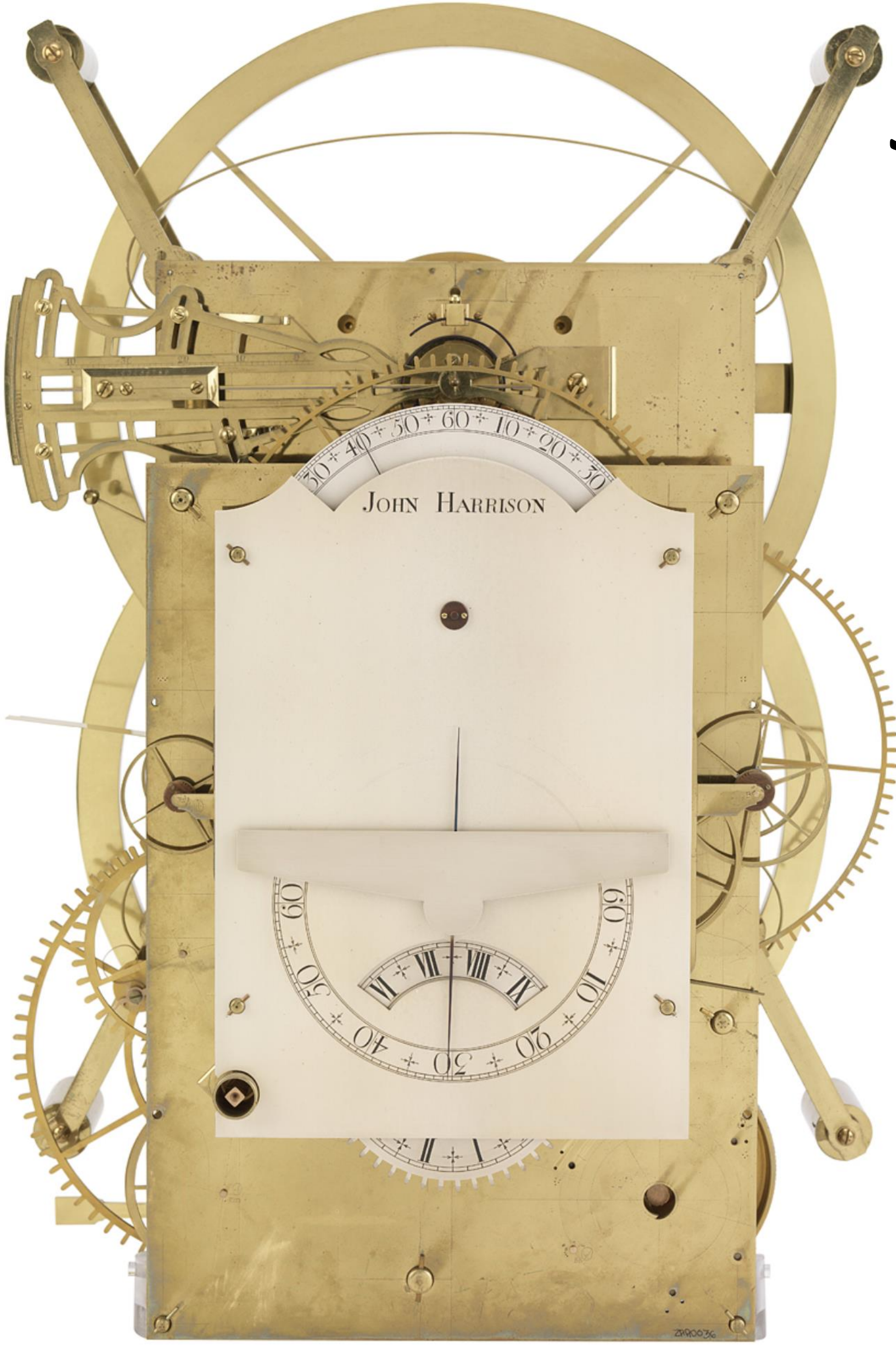
- October 22, 1707
  - ✓ Four Royal Navy ships ran into the Isles of Scilly and sunk
  - ✓ 1,400 to 2,000 lives were lost
  - ✓ Cause—bad weather and they didn't know where they were, **specifically their longitude**
- 1714—British Parliament passed the Longitude Act
  - ✓ For finding a good method to determine longitude at sea
  - ✓ Reward: £20,000 ($4.37 million in 2023 dollars)

John Harrison 1693-1776

John Harrison's H1 1735

John Harrison’s H2
1737-1739





John Harrison's H3
1757

John Harrison's H4 Marine Chronometer 1759

Accuracy –0.11 s/day

Voyage to Jamaica in 1762 corrected position was off by 1 mile

5.2" x 4.9" x 1.1"
3.2 lbs.


Harrison's H3 Clock
H4 Marine Chronometer

A Harrison Clock

~1722

Clock made of wood (oak and lignum vitae) <u>and</u> <u>still</u> <u>running</u>!

Royal Observatory Greenwich

Burgess Clock B

1975 clock based on Harrison’s principles

In 2014 the clock lost 0.625 seconds in 100 days URL URL

Big Ben*

(1859) URL URL

Weight 5 tons

± 2 sec/week

* Renamed “Elizabeth Tower Clock” in 2012

Shortt Pendulum Clock

Most accurate pendulum clock invented ±1 sec/year

At NIST Museum in Gaithersburg

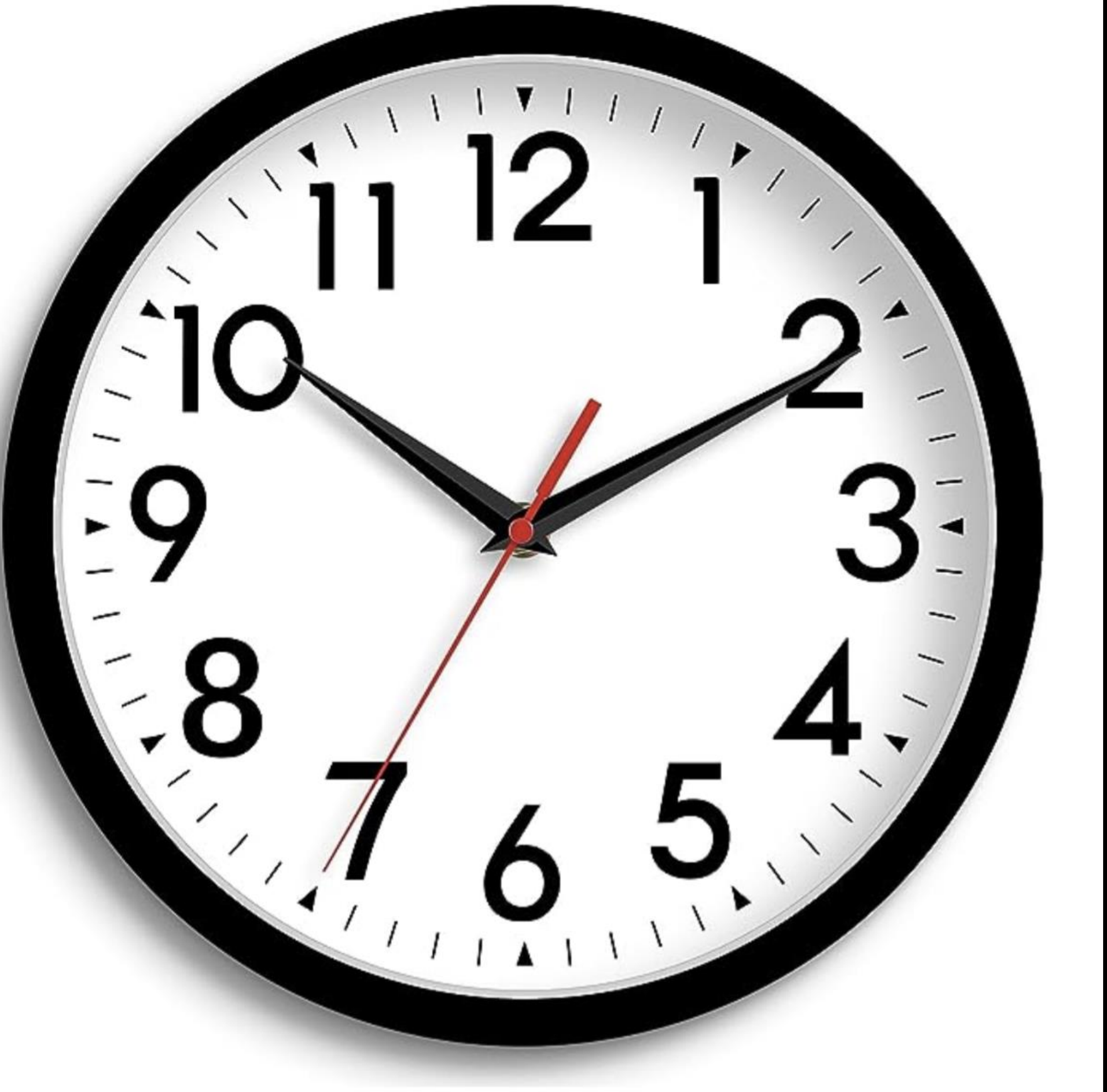
Ulysse Nardin Ship's Chronometer

Gimballed

Accuracy – 4/+6 s/day

Mechanical movement

Price: $2,350

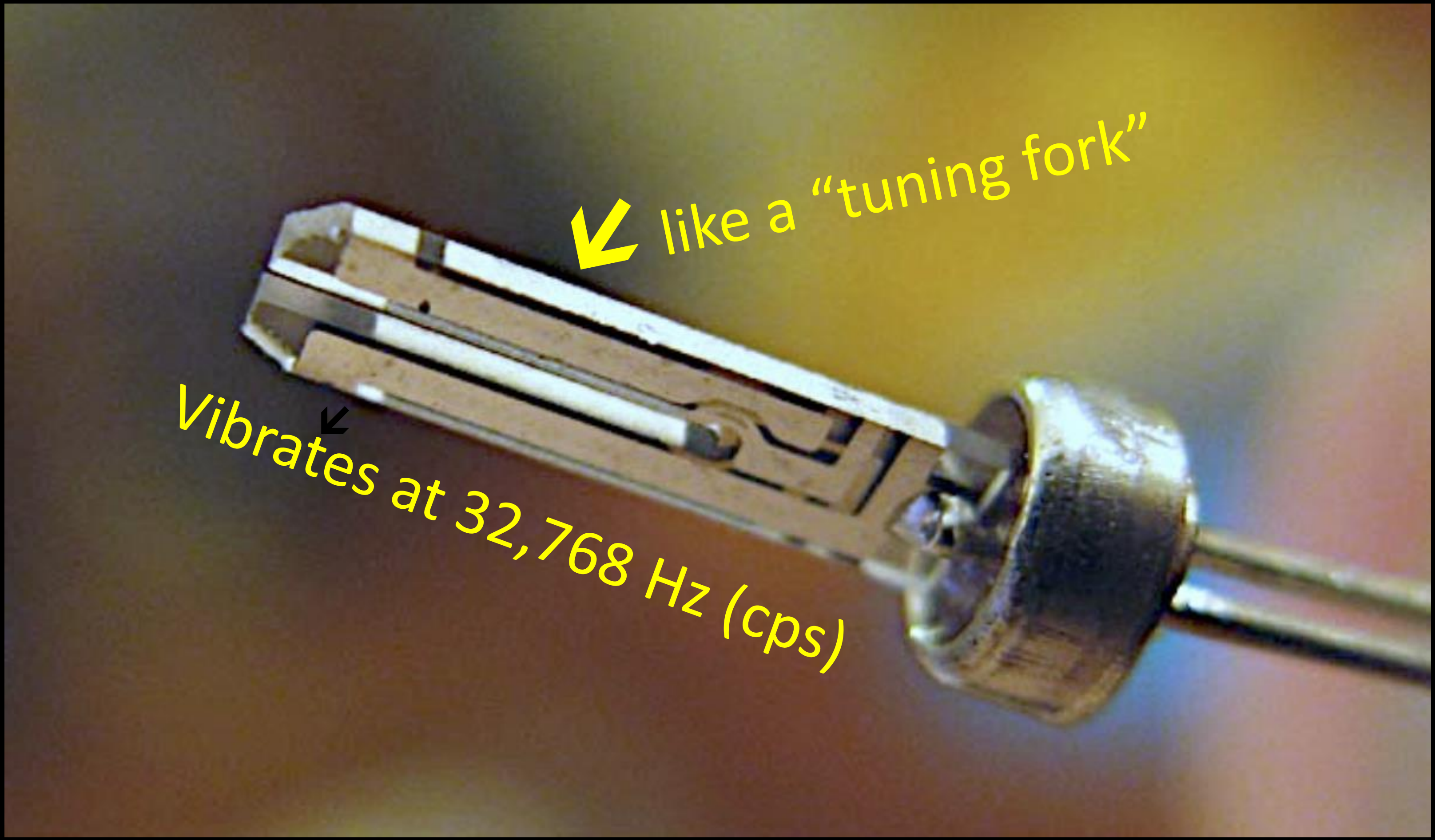


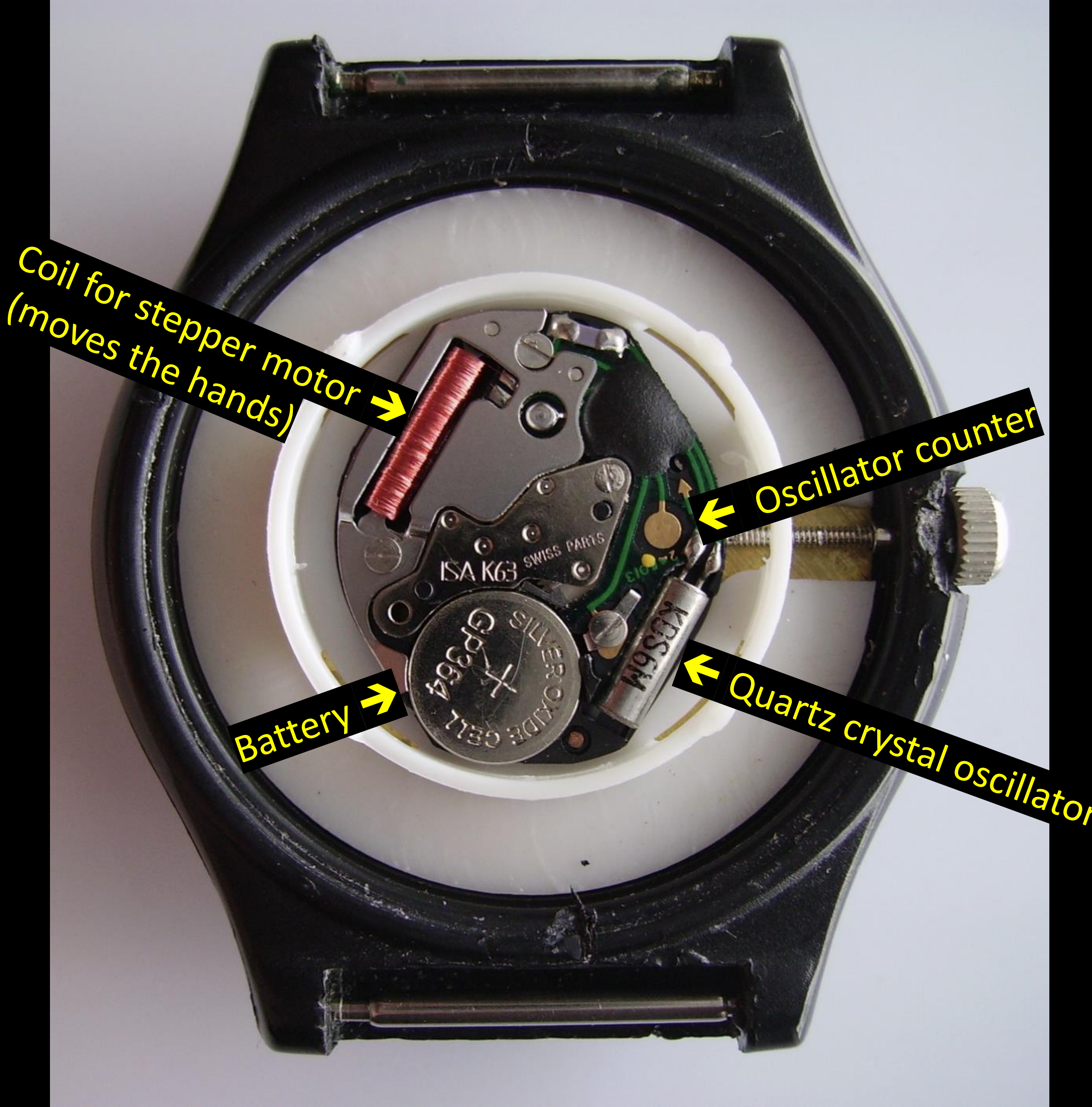
Modern Quartz Wall Clock

Battery Powered
Amazon: $10

$\pm$0.1 to 0.2 sec/day

Quartz (SiO_2) Crystal Resonators




Coil for stepper motor
(moves the hands)
Oscillator counter
Battery
Quartz crystal oscillator
ISA K63
SWISS PARTS
GP364
SILVER OXIDE CELL
KDS6M

Radio Clocks—**NOT** Atomic Clocks

+1 color/pattern

La Crosse Technology Atomic Analog Wall Clock, 10", Silver

4.6 ★ (4.8K+)

500+ bought in past month

$22.49 List: ~~$37.95~~

✓prime One-Day

FREE delivery **Tomorrow, Sep 14**

More Buying Choices

$19.99 (16 used & new offers)

+1 color/pattern

SHARP Atomic Clock - Never Needs Setting! - Jumbo 3" Easy to Read Numbers - Indoor/Outdoor Temperature Display with Wireless Outdoor Sensor - Gloss Black

4.2 ★ (2.3K+)

800+ bought in past month

$32.99 List: ~~$59.99~~

✓prime One-Day

FREE delivery **Tomorrow, Sep 14**

Radio Signal
WWVB

Atomic or Nuclear Anything

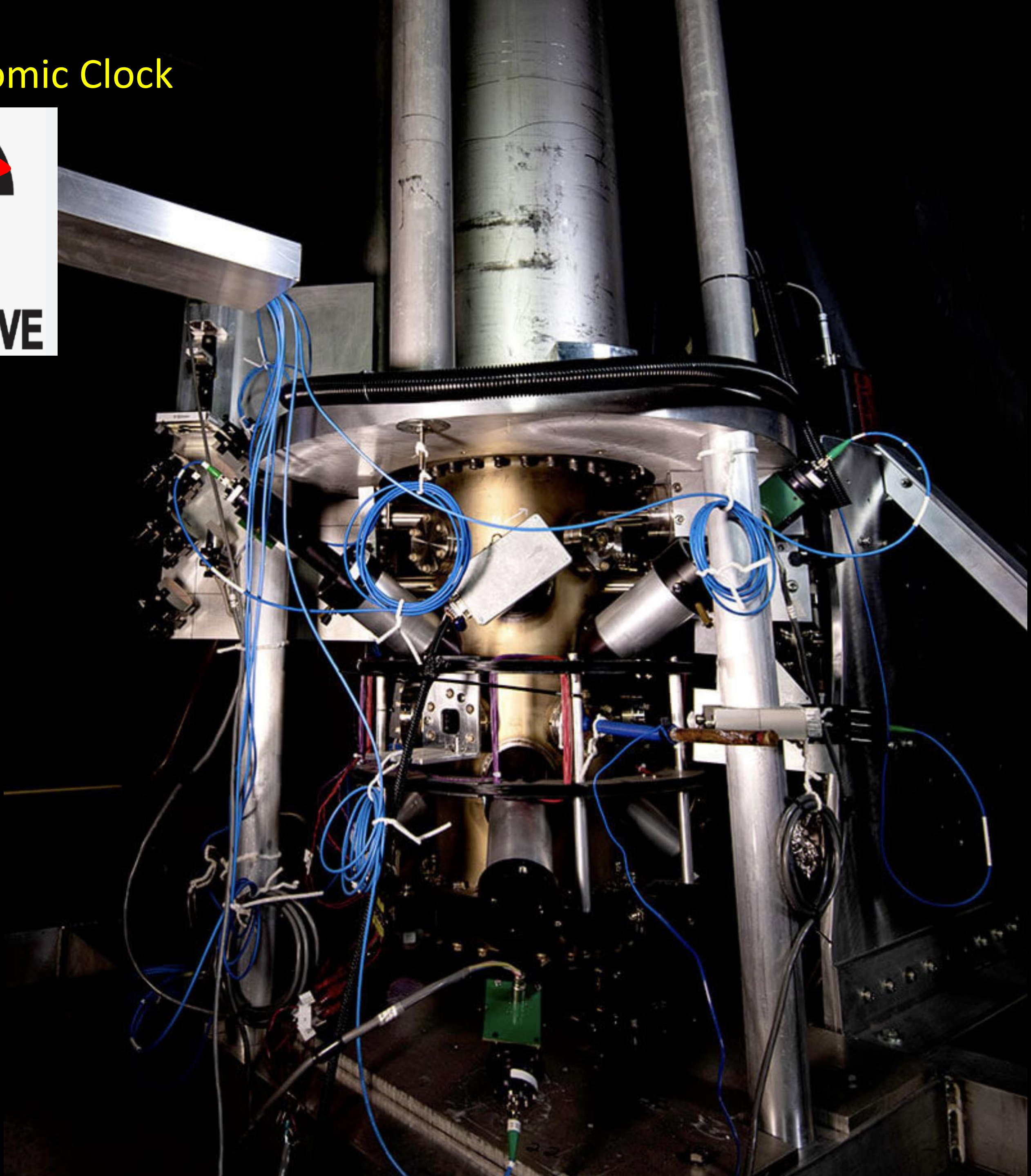
Image by WikiImages on Pixabay

MRI Machine (Medical Resonance Imaging)

NMR (Nuclear Magnetic Resonance) technology

Nuclear?

NIST-F2 Atomic Clock



History of Atomic Clocks

- 1949—first atomic clock
- 1952—first Cs clock (NBS-1)
- 1958—first commercial atomic clock, $202,000*
- 1968—NBS-4 Cs clock used into the 1990s
- 1975—NBS-6 Cs clock ±1 sec in 300,000 years

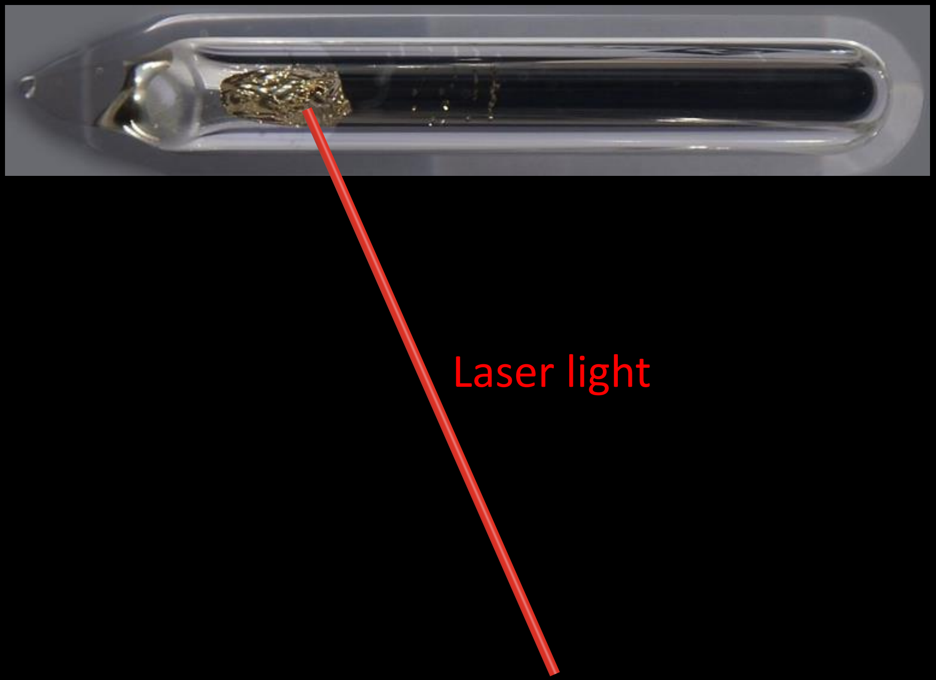
* 2023 dollars

NISTS' Fountain Cesium Clocks

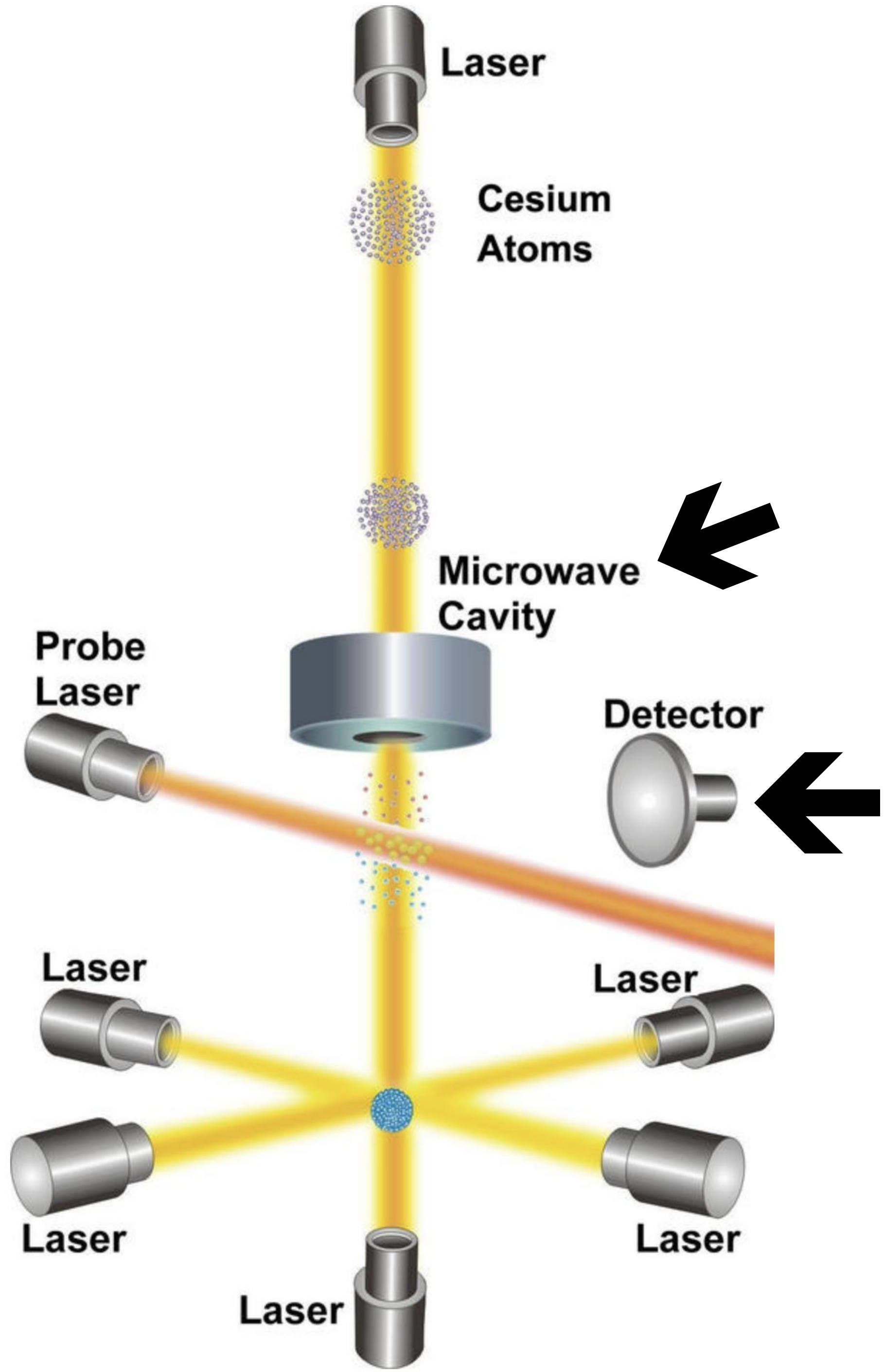
- NIST-F1 in service 1999 to 2013
  - ✓ ±1 sec in 20 million years
- NIST-F2 in service 2013 to present
  - ✓ ±1 sec in 300 million years
- NIST-F3 under development
- NIST-F4 under evaluation

How Do Atomic Clocks Work?

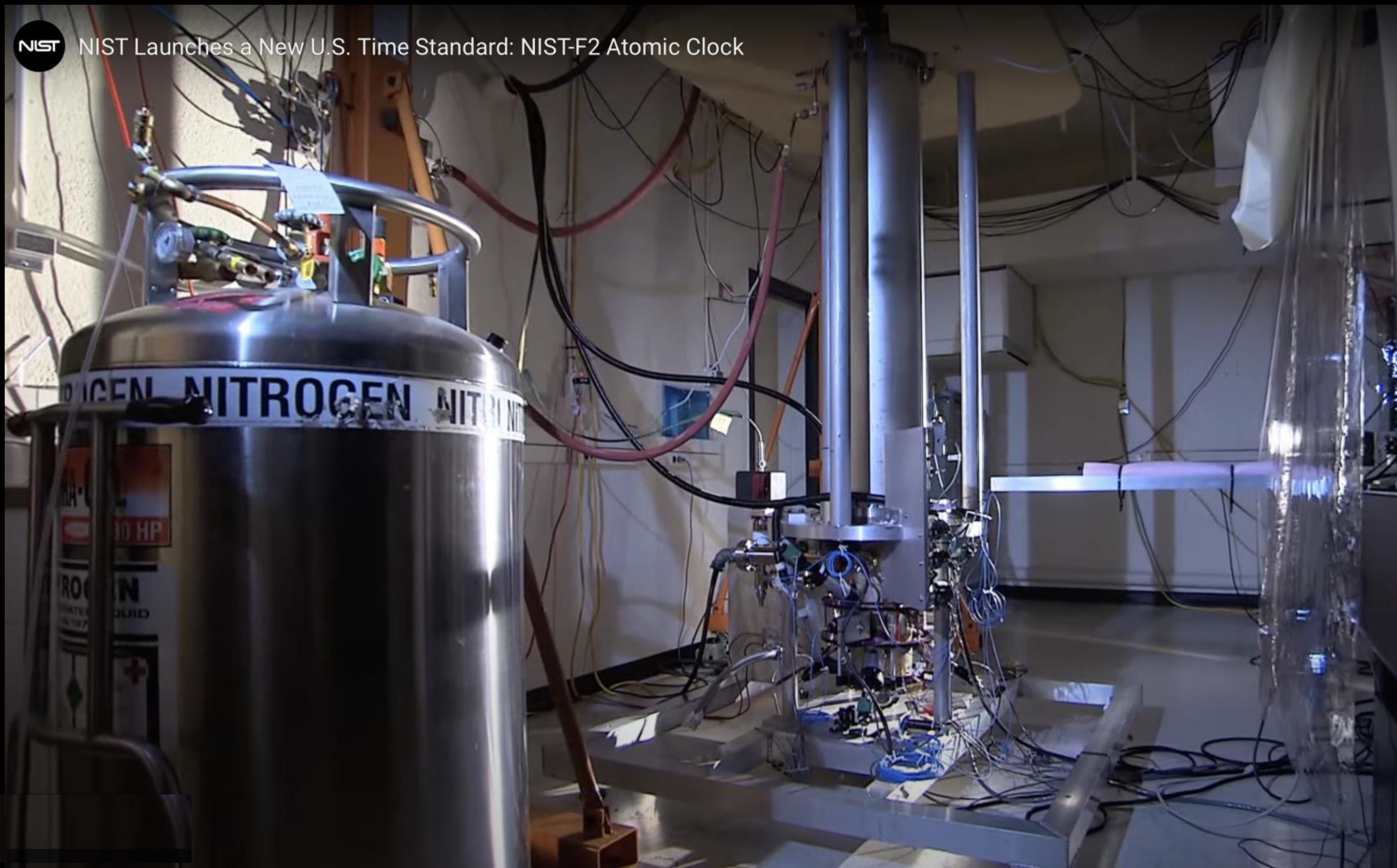
111 Hz
(or cps)



9,192,631,770 Hz
(or cps)


Laser
Cesium
Atoms
Microwave
Cavity
Probe
Laser
Detector
Laser
Laser
Laser
Laser
Laser

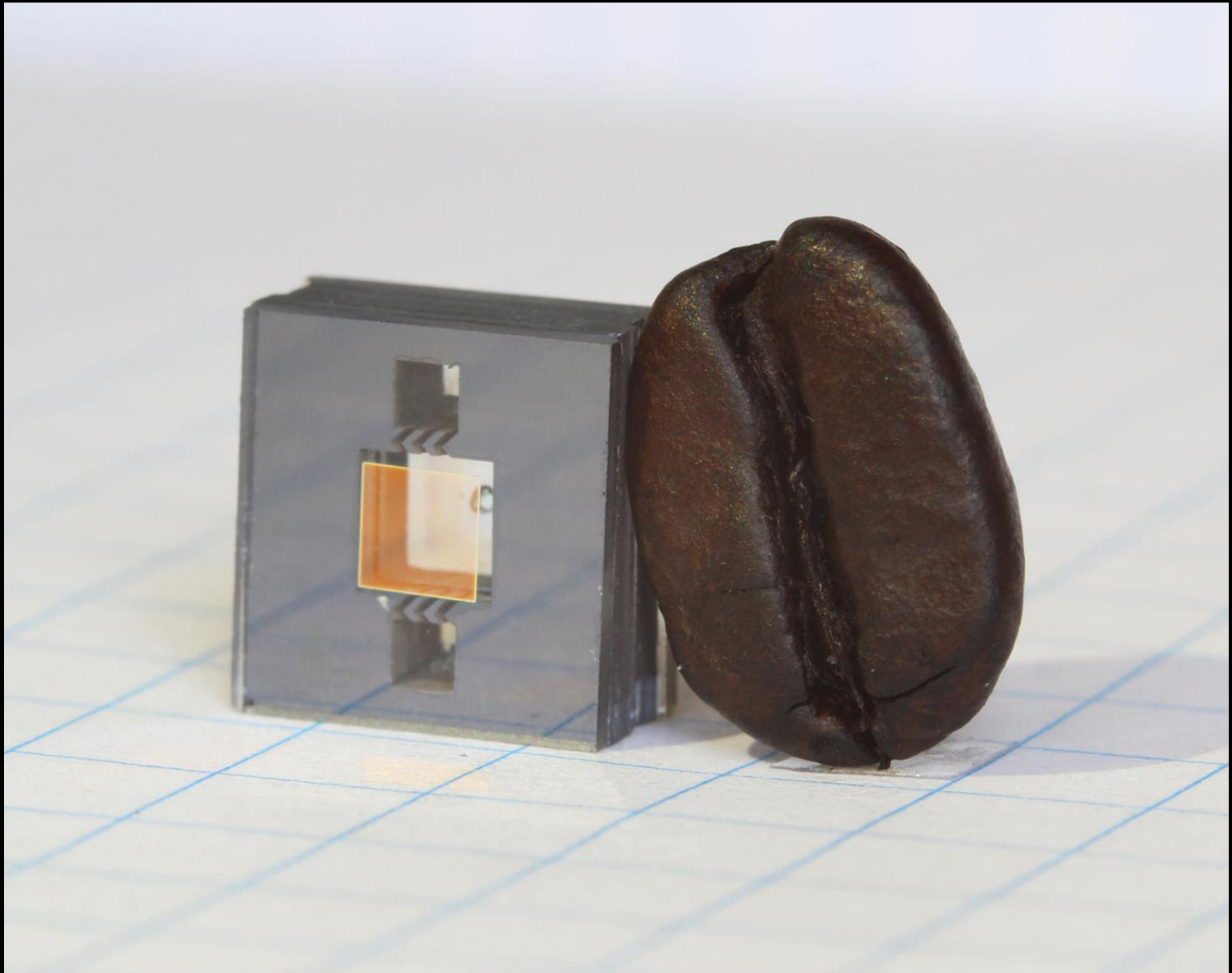
The NIST-F2 Cesium Atomic Clock*



* AKA NIST-F2 Cesium <u>Fountain</u> Atomic Clock

NIST's Miniature Atomic Clock

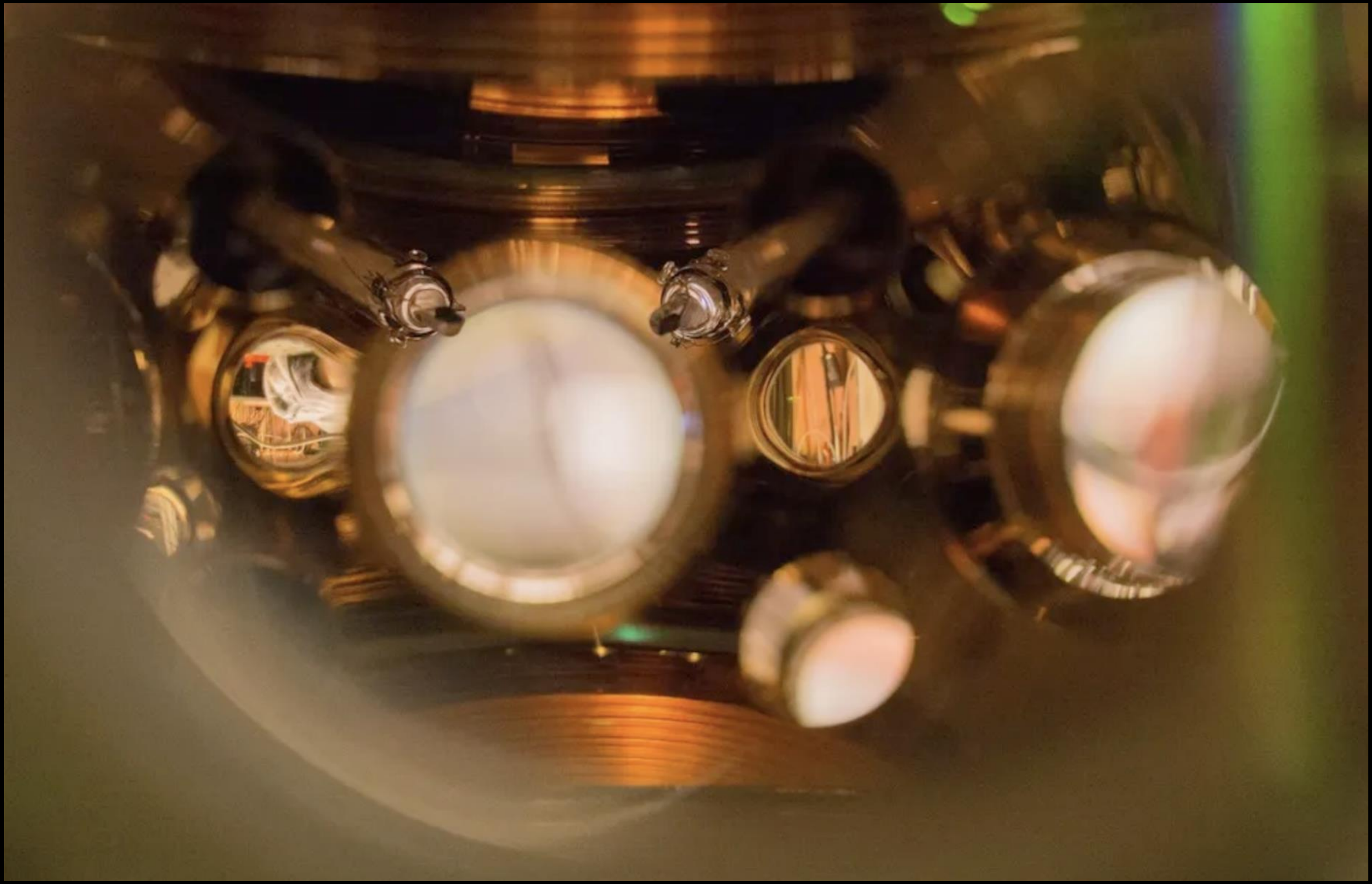
(next to a coffee bean)



NIST-F2—A Very Accurate Clock

±1 second in 300 million years

JILA Strontium Atomic Clock*



* JILA = Joint Institute of the University of Colorado and NIST

For detailed information see URL URL

JILA Sr Atomic Clock—An Extremely Accurate Clock

±1 second in 15 billion years

Cs Atomic Clocks for Sale

- Axtal
- Brandywine Communications
- Microchip Technology, Inc

Cs Atomic Wristwatch

~$6,000

Typical Accuracy of Clocks

Time Keeper	Accuracy	Tick-Tock

UTC—Coordinated Universal Time

- Used worldwide for civil time (including the US)
- Time established via the synchronization of 400 atomic clocks
- UTC is, in effect, the replacement for GMT
- For more information see

So, you want to buy a watch?

How Thick Is Your Wallet?

Richard Mille Wristwatch

1.75 mm thick (or 0.0689”)

Price $1.88 million*

* Must be a Ferrari car owner to qualify for purchase

Rolex Daytona

Accuracy ±2 s/day

$75,000

A Used Rolex Daytona

Sold at auction $17.8 million
Belonged to Paul Newman

Now for Us Cheapskates!

My Everyday Watch

- Purchased 2008
- Price $15 to $18
- Quartz movement
- Accuracy?
  - ✓ <u>Minus</u> 6 seconds/year*

* Minus 0.0164 seconds/day

Why Not Decimal Time?

- 10 hours/day
- 100 minutes/hour
- 100 seconds/minute
- Promoted in France in 1792 during the French Revolution

French decimal clock from the time of the French Revolution

The large dial shows the ten hours of the decimal day In Arabic numerals

The small dial shows the two 12-hour periods of the standard 24-hour-day in Roman numerals

Flopped like an opera aria at a rock concert

What is a Second?

- 1 Mississippi
- 2 Mississippi
- 3 Mississippi
- 4 Mississippi
- 5 Mississippi
- 6 Mississippi

What is a Second? (cont.)

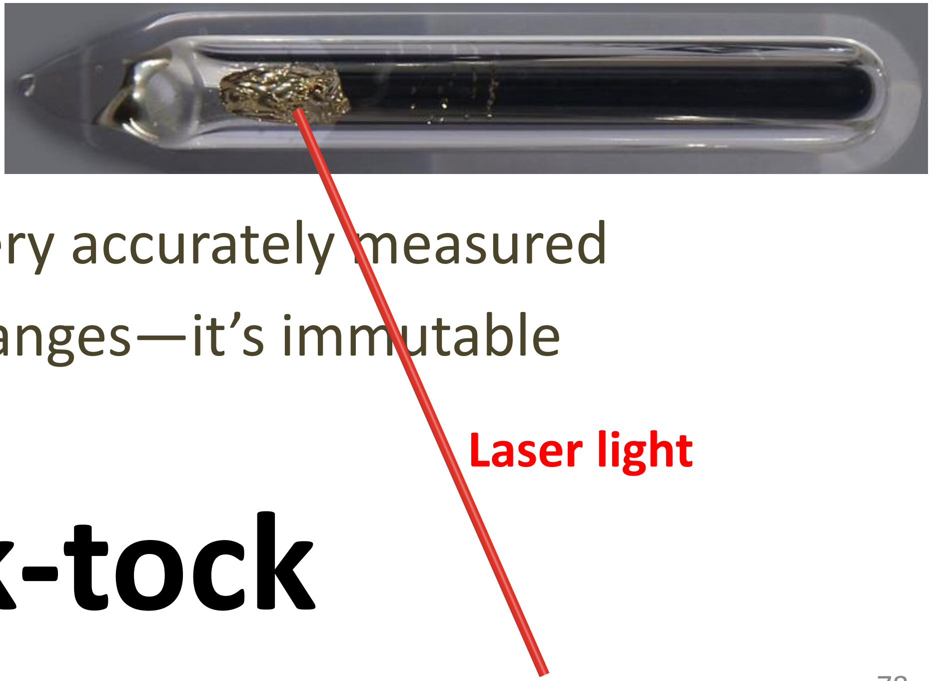
- The SI definition of time (International System of Units, the modern metric system) is…
- The second is equal to the duration of 9,192,631,770 periods of radiation corresponding to the transition between hyperfine levels of the unperturbed ground state of the ^{133}Cs atom

Huh?

- For more information see URL URL URL

What is a Second? (cont.)

- Zapped with a laser, the single electron in a cesium atom’s outermost shell will cycle back and forth between two states—known as a hyperfine transition



  - ✓ This transition can be very accurately measured
  - ✓ This transition never changes—it’s immutable

tick-tock tick-tock

Speed of Light

- 299,792,458 m/s (~300,000,000 m/s)
- 299,792.458 km/s (~300,000 km/s)
- 186,282.397 mi/s (~186,000 mi/s)

That's fast!

Patience, this is relevant

History: Speed of Light Measurements

In km/second

<1638	Galileo, covered lanterns	inconclusive[118][119][120]:1252[Note 15]	
<1667	Accademia del Cimento, covered lanterns	inconclusive[120]:1253[121]	
1675	Rømer and Huygens, moons of Jupiter	220 000[94][122]	−27% error
1729	James Bradley, aberration of light	301 000[104]	+0.40% error
1849	Hippolyte Fizeau, toothed wheel	315 000[104]	+5.1% error
1862	Léon Foucault, rotating mirror	298 000 ±500[104]	−0.60% error
1907	Rosa and Dorsey, EM constants	299 710 ±30[108][109]	−280 ppm error
1926	Albert A. Michelson, rotating mirror	299 796 ±4[123]	+12 ppm error
1950	Essen and Gordon-Smith, cavity resonator	299 792.5 ±3.0[111]	+0.14 ppm error
1958	K.D. Froome, radio interferometry	299 792.50 ±0.10[115]	+0.14 ppm error
1972	Evenson *et al.*, laser interferometry	299 792.4562 ±0.0011[117]	−0.006 ppm error
1983	17th CGPM, definition of the metre	299 792.458 (exact)[92]	exact, as defined

From Wikipedia

CGPM = Conférence générale des poids et mesures

Speed of Light in Translucent Substances

- The speed of light in a vacuum is ~300,000 km/s

Water: ~225,000 km/s

Glass: ~200,000 km/s

Diamond: ~125,000 km/s

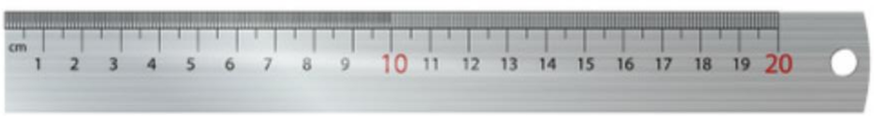
When the light exits a translucent substance its speed returns to ~300,000 km/s

For Perfectionists

- Speed of light in a vacuum: 299,792,458 m/s
- Speed of light in the atmosphere: 299,702,547 m/s
- In the atmosphere light moves 1.0003 times slower (i.e., 299,792,458 ÷ 1.0003 = 299,702,547)

Kitchen Physics

Determining the Speed of Light



Kitchen Physics (cont.)
Determining the Speed of Light

- Information needed:
  - ✓ 2.54 cm = 1 inch
  - ✓ Frequency of the microwave oven, typically 2450 MHz (2450 MHz = 2450×10^6 Hz or <u>2,450,000,000 Hz</u>)
- The formula $c = \lambda f$ where…
  - ✓ c = the speed of light (m/s) (p.s. c = ~300,000,000)
  - ✓ λ = wavelength (m) [which you measure]
  - ✓ f = frequency (Hz)

For details see URL URL URL URL URL

And now, a minor distraction…

Length of a Meter

- The meter is defined in terms of the **second** and the **speed of light**
- Effective 1983, the meter is the length of the path travelled by light in a vacuum during a time interval of $\frac{1}{299\,792\,458}$ of a second

299,792,458 m/s $\frac{1}{299\,792\,458}$ s/m

The American Foot

- Metric Act of U.S. Congress 1866
  - ✓ legally protected use of the metric system in commerce from lawsuit
  - ✓ provide an official conversion table for U.S. customary units
- Since 1893 the American foot has been defined as $1200/3937^{th}$ of a meter, i.e., 1 ft ≈ 0.30480061 meter

Standards Used Worldwide
SI Units

- The seven basic standards
  - ✓ Length—meter (m)
  - ✓ Time—second (s)
  - ✓ Amount of substance—(mole)
  - ✓ Electric Current—ampere (A)
  - ✓ Temperature—kelvin (K)
  - ✓ Luminous intensity—candela (cd)
  - ✓ Mass—kilogram (kg)

- All based on natural phenomena and five fundamental constants*

* Planck's constant (h), Boltzmann's constant (k or k_B), Avogadro's number (N_A), speed of light (c) and charge on the electron (e)

Back to the subject!

Ever use…


RADIO
MEDIA
PHONE
TONE
MAP
NAV
TRAFFIC
SETUP
10:57
LTE
30
MPH
Dexter Ave N toward
McGraw St
6th Ave N
ooh la la (feat. Greg...
Run The Jewels
Waverly Pl N
10:59 ETA
2 min
1.1 mi
AC

Global Navigation Satellite Systems (GNSS)

- GPS (United States)
  - ✓ Operational 1995, military only
  - ✓ Operational 1983, civilian use
- GLONASS (Russia); 1995
- BeiDou ["Big Dipper"] (China); 2020
- Galileo (EU); 2023
- QZSS (Japan)—regional, global in development
- IRNSS (India))—regional, global in development

The American GPS System

- 38 satellites, 32 operational
  - ✓ In orbit at an altitude of 12,552 miles
  - ✓ Circle the earth at a speed of 8,724 miles/hour*
  - ✓ Each satellite contains a synchronized atomic clock

* Two orbits per day

The American GPS System

- Each satellite transmits:
  - ✓ The satellite's ID
  - ✓ Orbital data for all the satellites
  - ✓ Orbital information for that specific satellite
  - ✓ Very precise time information for that satellite
- Signals from 4 satellites are needed for calculating*:
  - ✓ Latitude and longitude
  - ✓ Altitude
  - ✓ (Time is given and synchronizes the GPS's quartz clock)

* The receiver (GPS) works by calculating the distance to 4+ satellites URL URL URL URL

Accuracy of Common GPS Devices

- Cars: ±10-50 feet
- Smartphones: ±16 feet
- Handheld GPS units: ±10 feet
- U.S. Military systems ±3 feet* (?)
- Real-Time Kinematic (RTK) GPS systems ±1 inch

* Corrections made to account for the speed of light in the atmosphere

Things now get

Unintuitive

Time Dilation

- Time Dilation is the difference in **elapsed time** as measured by two atomic clocks, one on earth—the other in a satellite (*clocks appear to be out of sync*):
  - ✓ The clocks will show different times due to a difference in **speed** between the clocks (Einstein's Special Relativity)

and

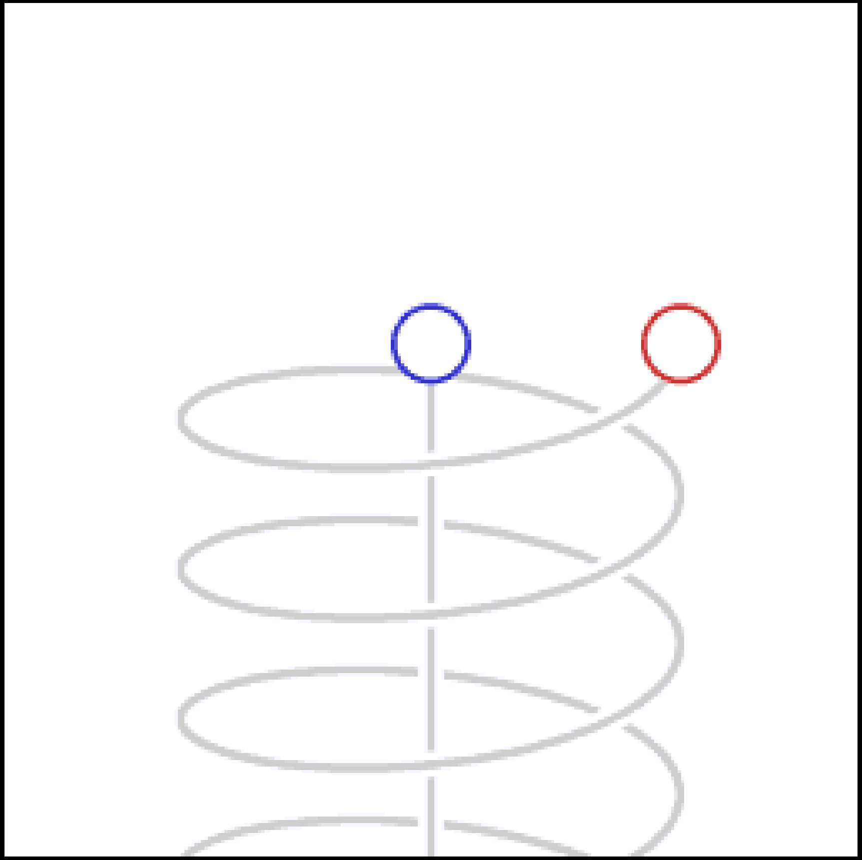
  - ✓ The clocks will show different times due to a difference in **gravitational potential** between the clocks' locations (Einstein's General Relativity)

Time Dilation (cont.)

- Consider a **clock in a satellite** circling the earth 12,552 miles above the earth and another **clock on the earth**:
  - ✓ due to speed of the satellite (8,724 miles/hour), its clock will lose 7.27 microseconds* each day
  - ✓ due to the lower gravitational potential of the clock in the satellite, its clock will gain 45.61 microseconds* each day
  - ✓ net effect, the clock on the satellite will gain 38.34 microseconds each day—relative to the clock on earth

* 1 second = 1,000,000 microseconds

See URL URL URL



Red ball has the clock on the satellite

Blue ball is where the clock on earth is

Notice the clock on the satellite (red) runs slower—gaining 38.62 μs/day

Time Dilation Formula—Speed Effect

Comparing two clocks: one on earth (at rest) the other (on the satellite) moving relative to the one on earth

$$\Delta t' = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Where:

Δt is the time interval
v is the speed of the satellite
c is the speed of light
$\Delta t'$ is the relative time
$\Delta t' - \Delta t$ is the amount of time dilation

For a time dilation calculator see URL

Time Dilation Formula—Gravitational Effect

$$\Delta t' = \Delta t \sqrt{1 - \frac{2GM}{rc^2}}$$

Where:

Δt' = The change in time in the gravitationally influenced reference frame

Δt = The change in time in a reference frame an infinite distance from any mass (a "standard" hour)

c = The speed of light 299,792,458 km/s

G = The gravitational constant $G = 6.6743 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$

M = The mass of the object being approached (such as Earth)

r = The distance from the object being approached

For a time dilation calculator go to URL

Comparing two clocks:

One on earth

The other on a satellite

Without Time Dilation Correction

- A GPS location would be meaningless after a several minutes
- The error in positioning would accumulate to about ±6 to 12 miles each day

OR

- **±40 to 90 feet each minute**
- **±200 to 450 feet in five minutes**

St. Lawrence River near Dorval

GPS

Without time dilation correction

Information About Atomic Clocks

- From Wikipedia URL
- NIST's Cesium Fountain Atomic Clocks URL
- From NASA URL
- How atomic clocks work URL
- MIT News URL
- Atomic clocks and astronomy URL URL

Suggested Reading

- *Longitude* by Dava Sobel
- *A Brief History of Time Keeping* by Chad Orzel
- *The Network of Time* by Alon Halperin
- *Why Time Flies: A Mostly Scientific Investigation* by Alan Burdick
- *The Order of Time* by Carlo Rovelli

All Done!

Thanks for your attention