Measurement of Time

Peter Watson
(with extras from
Louis Marmet, NRC)

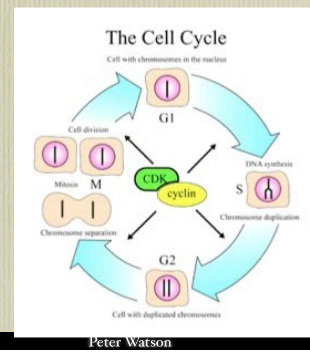
Mantua clock tower (1472) shows time, lunar phases, signs of zodiac

When did time start to matter?

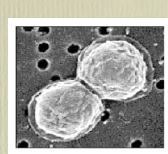
Work, eat, play, mate

- Sleep, play, mate

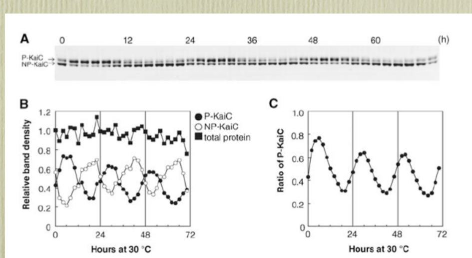
- Many biological processes require a coordinated sequence of events These events are repeated with a well defined period



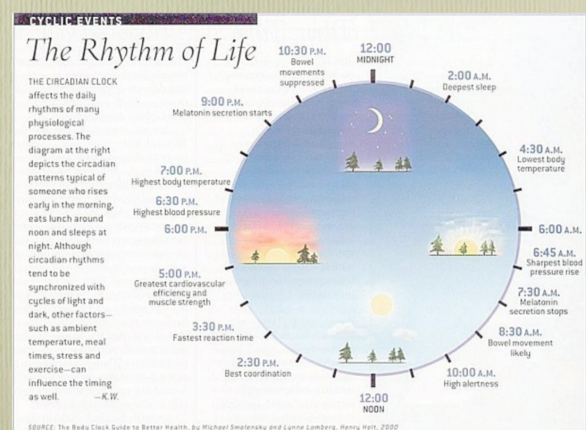
Biological Clocks



Circadian rhythms are controlled by biochemical networks
Even bacteria need to keep time: e.g CyanoBacteria
Eldon Emberley, SFU, finds 3 proteins give an oscillatory system with 24 hour period



Humans



- Natural cycle ~ 24 hours 11 minutes (average) but wide variations.
- Gets reset ("phase-locked") by light
- Mostly in hypothalamus: suprachiasmatic nucleus, but requires most of endocrine system to work
- Universal in mammals: mechanism can vary, and disappear in arctic animals
- As to moral courage, I have very rarely met with the two o'clock in the morning kind. I mean unprepared courage, that which is necessary on an unexpected occasion. (Napoleon)

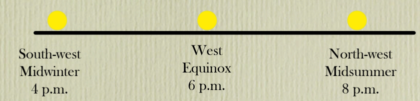
The first observatory (or the earliest we know about)

- Stonel
- Proba

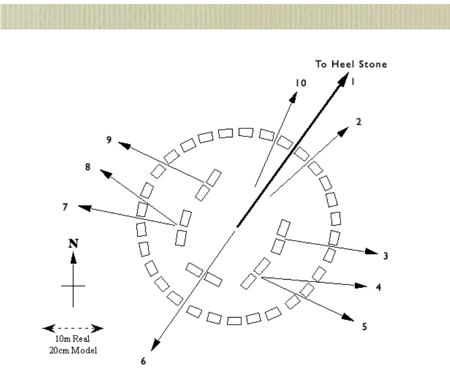
- Midsummer day: when the sun rises/sets in most northerly position: sunrise aligns with "heel stone"

•Measured at Stonehenge: important to define seasons and hence time to plant crops

Sunset



- Note that position varies more as you move away from the equator



- Alignments let you measure summer solstice

Midsummer sunrise
Winter moonrise low point
Midwinter Sunrise
Southern moonrise (minimum)
Southern moonrise (maximum)
Midwinter sunset
Northern moonset (minimum)
Northern moonset (maximum)
Winter moonrise high point

http://www.fas.harvard.edu/~scidemos/AstronomyAstrophysics/Stonehenge/Stonehenge.html

Chankillo

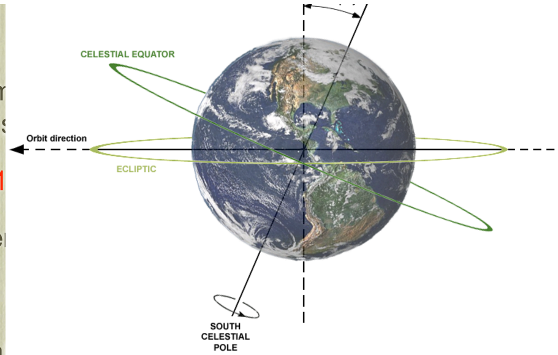
- Much later
- Row of 13 towers on a ridge in a desert in Peru

- From observation sites the towers line up with sunrise and sunset
- Can tell date to within 2-3 days. (Ivan Ghezzi and Clive Ruggles)

Need some definitions (roughly as the Babylonians might have used them)

- Year: interval between (e.g) most northerly sunrises. ~365 1/4 days
- (lunar) Month: interval between (e.g.) full moons ~ 29 1/2 days
- Solar day: interval between times when the sun is due south = 24 hours (defn)
- Sidereal day: interval between (e.g.) Sirius being due south = solar day - 4 minutes

- Midsumm
  day, sun s
- 20th or 21
- Midwinte
- 21st/22nd



- Spring/fal equinox: sun is over equator,
  night & day are equal (roughly)
- 20th/21st March 22nd/23rd Sept

But note

- Year is not a whole # ofdays
- Year is not a whole # of lunar months
- However 19 years = 235 lunar months (+ 2 hours): Metonic cycle
- Most societies fudge 12 months = 1 year by adding in extra days.

Babylonian

- 12 lunar months + extra short month

MS 4151
List of month names for the Lagash (Larsa?) calendar, including the extra 13th month. Babylonia, 2000-1600 BC

e.g Chinese

- Months are alternately 29 & 30 days
- Gives year of 354 1/3 days
- Add in intercalary month every second or third year to re-align year and month
- Sun also passes through 12 zodiacal constellations in year (Aries, Pisces, Aquarius ...) or roughly 1/month

1. The months are lunar months. This means the first day of each month beginning at *midnight* is the day of the astronomical dark moon.
2. Each year has 12 regular months, which are numbere... sequence (1 to 12) and have alternative names. Every second or third ... n intercalary month which may come after any regular month ... number as the preceding regular month, but is designated int...
3. Every other jiéqì of the Chinese solar ye... o an entry of the sun into a sign of the tropical zodiac (a pri... sp).
4. The sun always passes the winte... s Capricorn) during month 11.
5. If there are 12 months betw... sive occurrences of month 11, not counting either month 11 ... hese 12 months must be a month during which the sun r... e same zodiac sign throughout (no principal term or cu... it). If only one such month occurs, it is designated interc... such months occur, only the first is designated intercalary. N... dars before true motions of the sun were used for naming (i.e. ... or in years where there is no double-cusp month in that yea... or following years (i.e., usually), the following rule suffices... no principal term (or cusp) in it is designated intercalary.

Are you confused?

e.g Hebrew calendar

- Lunar months
- Intercalary month added 7 times in 19 years
- gives `6939.550 days`
- `vs 6939.750 days`

e.g Roman calendar

- Romulus: 10 months of 30 or 31 days + 61 days of winter
- Numa: 12 months of 28-31 days, totalling 355, so add 22 or 23 days to Feb. every 2^{nd} year
- Julius Ceasar: essentially modern calendar with leap years adding one day to Feb every 4 years

Babylon: Mul Apin tablet

http://www.mesopotamia.co.uk/astronomer/explore/exp_set.html

On the 1st of Nisannu the Hired Man becomes visible.
On the 20th of Nisannu the Crook becomes visible.
On the 1st of Ayyaru the Stars become visible.
On the 20th of Ayyaru the Jaw of the Bull becomes visible.
On the 10th of Simanu the True Shepherd of Anu and the Great Twins become visible.
On the 5th of Du'uzu the Little Twins and the Crab become visible.
On the 15th of Du'uzu the Arrow, the Snake, and the Lion become visble; 4 minas is a daytime watch, 2 minas is a nighttime watch.
On the 5th of Abu the Bow and the King become visible.
On the 1st of Ululu [. . . .]
On the 10th of Ululu the star of Eridu and the Raven become visible.
On the 15th of Ululu Shu-pa, Enlil, becomes visible.
On the 25th of Ululu the Furrow becomes visible

Sundials

- Good to few minutes but
- ...Position of the noon sun in the sky varies throughout the year:

It moves against the fixed stars because the earth orbits the sun the earths axis is tilted

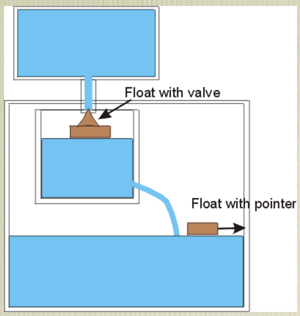
- it also moves in the sky at a given time of day: (i.e. the time of noon varies by about 8 minutes) because the earth moves at varying speeds in its orbit,
- so we actually need a **better** clock than the sun to measure this

A tutulemma. Photo from Side, by Tunc Tezel

Combines sun's position through year with an eclipse

Water-clock (probably first non-astro clock)

- www.mlahanas.de/ Greeks/Clocks.htm
- Water in a container drains out through small hole: problem is that the flow is non-uniform.
- Hence keep container full with valve so as to have constant pressure
- clepsydra (= "water thief")



Eclipses

Tablet with a list of eclipses between 518 BC and 465 BC, mentioning the death of king Xerxes.
British Museum, London

Why do these matter?

CALPURNIA: When beggars die, there are no comets seen;

The heavens themselves blaze forth the death of princes. *Julius Caesar*

(Chinese astronomers Hi and Ho executed for failing to predict eclipse in 2134 BC).

GLOUCESTER These late eclipses in the sun and moon portend no good to us: though the wisdom of nature can reason it thus and thus, yet nature finds itself scourged by the sequent effects.....

....

EDMUND I am thinking, brother, of a prediction I read this other day, what should follow these eclipses.

EDGAR Do you busy yourself about that?

EDMUND I promise you, the effects he writes of succeed unhappily; as of unnaturalness between the child and the parent; death, dearth, dissolutions of ancient amities; divisions in state, menaces and maledictions against king and nobles; needless diffidences, banishment of friends, dissipation of cohorts, nuptial breaches, and I know not what.

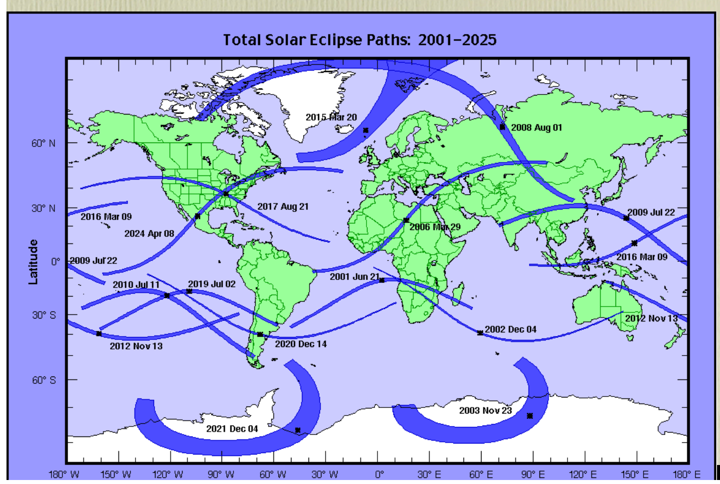
EDGAR How long have you been a sectary astronomical?

Text

And they even mattered to artists

St Benedict, by Cosmas Damian Asam 1735

Eclipse preediction



Saros cycle

- Eclipses repeat after 18 years and 11.3 days.
- The .3 days shifts the eclipse about 110º degrees west.
- Also some saros sequences start at the south and drift North, others at the North and drift South.
- This means that the cycle is very complex: can only see it after many years.
- Why is it so complicated? Need to combine

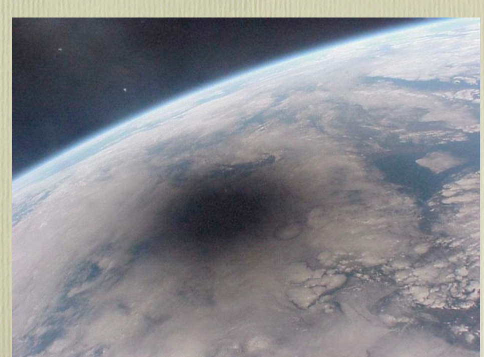
I. Earths rotation

II. Moons orbit (not quite circular)

III. Earth's orbit (ditto)

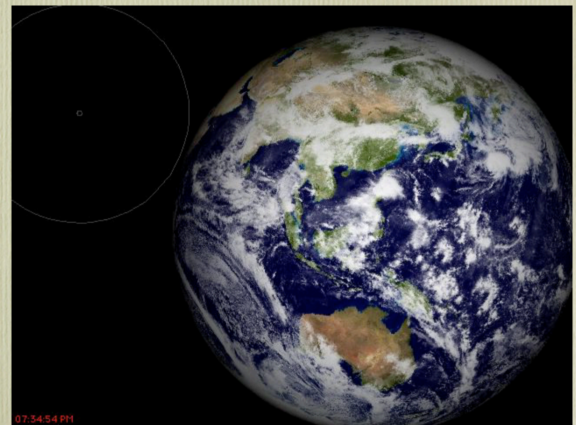
IV. <u>and</u> the plane of the moons orbit precesses

Eclipse of 1999 seen from Mir

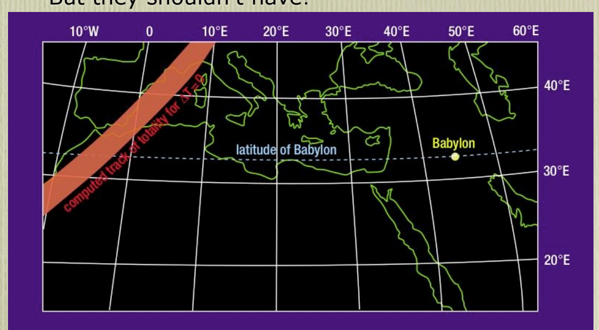


Babylonians observed total eclipse 15 April 136 BC.

and they would even have seen it from the moon !



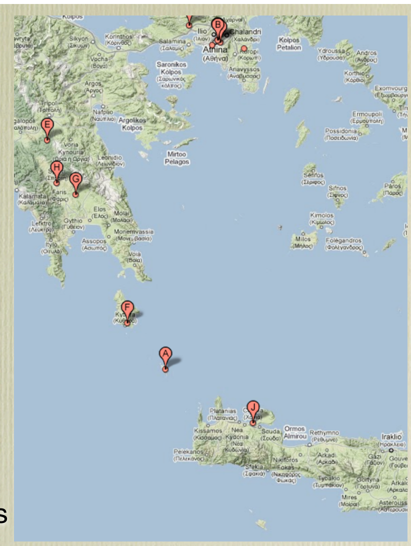
Observed total Eclipse 15 April 136 BC.
and they would even have seen it from the moon !
But they shouldn't have!



4: Computed track of totality for the eclipse of 15 April in 136 BC, assuming a fixed length of day (ΔT = 0). This track lies more than 50° to the west of Babylon, where totality was actually observed.

- Earth's rotation has slowed down, by 1/100 sec/century, because of tidal effects! i.e. earth isn't a very good time-keeper

Antikythera



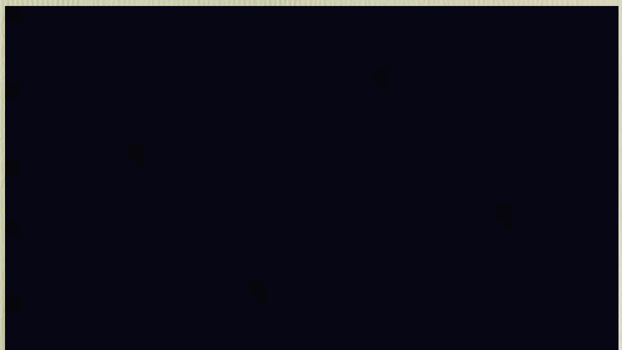
- Wreck full of sculptures

Antikythera Mechanism

- Found in 1901
- probably late second century BC.
- National Archaeological Museum in Athens: wikipedia
- So what is it?

- X-rays show very complex structure
- Many (at least 30) gears: one has 47 teeth !!!!

This may be how it works



- Shows Metonic sequence (235 lunar months = 19 solar years + 2 hours)
- Shows Saros eclipse cycle (223 lunar months)
- But not programmable
- No driving mechanism

The descendants

- The Orrery
- (Vatican Museum)

Clock

Display:

Shows the number of time intervals

Counter

Oscillator:

generates identical time intervals

Louis Marmet

Pendulum Clock

Invented by Huyghens (1656)
Look at the Foucault pendulum in the entrance to Herzberg building: [Watch the animation.]

- Period:

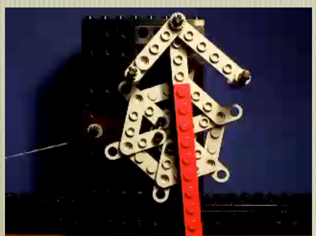
$$P = 2\pi\sqrt{\frac{L}{g}}$$

- So 1 metre simple pendulum should have period of ~1s?
- Accuracy ~ 1 minute/day

Need three Ingredients

Pendulum

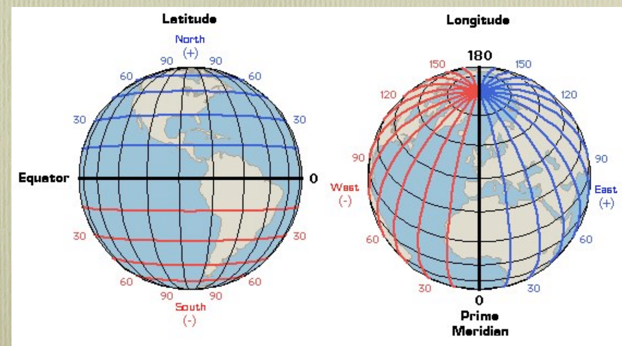
Power supply: usually gravity)



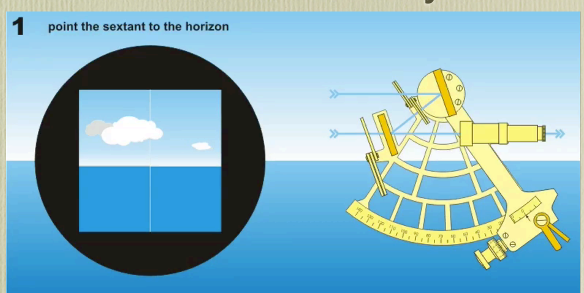
Escapement: must transfer energy to pendulum to keep it swinging

Chronometer

At sea, need to determine latitude and longitude: see Longitude (Dava Sobel)



Latitude is “easy”



- Need to be able to measure south (compass)
- and postion of sun (or star) wrt horizon
- astrolabe or sextant

Longitude problem: error on longitude typically 100 km (!) in 18th century.

Admiralty offered £20,000 ($10,000,000 today) to solve problem

If we know when the sun is a certain point in sky, can get longitude

(e.g. if it’s due south at 2 pm, we are 2/24*360 = 30° W of Greenwich)

So by measuring time accurately, can get position (first link between time and space!)

Not all were practical....

Design for a marine chair submitted to the Board of Longitude. Source: Cambridge University Library

- Could use Moons of Jupiter: act as astronomical timekeeper

Chronometer

- Need to determine time to better than 1 s/day
- Harrison (1721) constructed chronometer accurate to better than 1/5 s/day

Took him 20 years to collect reward!

Note that this depends on mechanical escapement mechanism

Photo Suat mEan FreeDigitalPhotos.net

A doctor's watch c 1815

Any sufficiently advanced technology is indistinguishable from magic (Arthur Clarke)

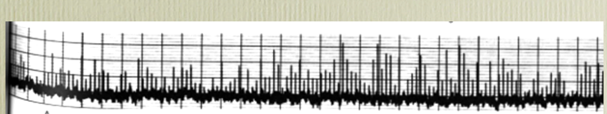
My watch (c 2009)

What's the difference?

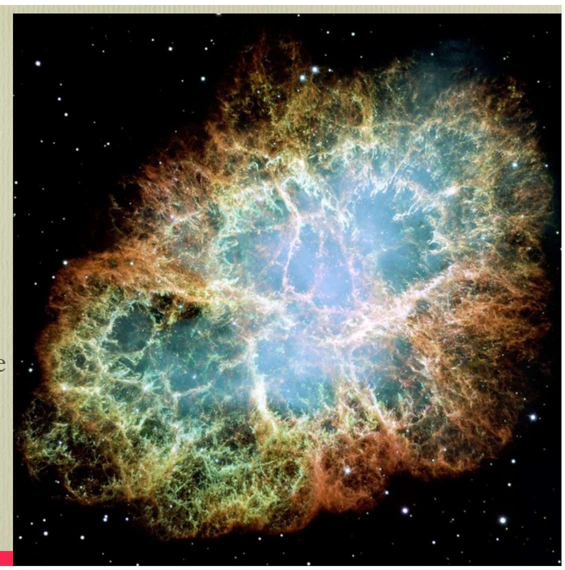
- **Power Source:** Coiled spring
- Mercury Battery
- **Time:** escapement mechanism
- Quartz crystal
- **Displays:** second hand + date wheel
- LCD
- **Setting:** listen to the church clock!
- Reset once a day by transmitter in Colorado Springs

Pulsars (1968)

- neither earth's orbit or rotation are sufficiently stable now: best astronomical timekeeper are pulsars, accidentally observed as pulsars (Jocelyn Bell etc)
- Very regular radio pulses,period of 4 s to 2 ms
- Note that height of pulse is very irregular



Best known is Crab. Known to be remnant from supernova in 1054 (seen by Chinese) Pulsar at centre has period of ~0.03s



And you can even listen to them

This is Vela

And this is PSR 0329+54

Period of Crab measured to be 0.03308471603 s
(i.e. stable to 1 part in billion)

Frequency and Period

Note for what follows:

•for repeated motions (e.g. Oscillators), Time and frequency are closely linked

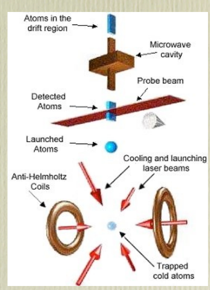
•Frequency = 1/Period

•So something that vibrates with a period of 0.5 s has a frequency of 2 Hertz (2 Hz)

$$F = \frac{1}{P}$$

Atomic Clocks

- Best is now at NRC: Caesium fountain clock better to 1 part in 10^{12} i.e. would lose or gain ~ hour over lifetime of universe: so accurate that the only comparison is one Cs clock to another!
- Works because atoms are isolated from each other, so don' influence each other
- Target is 1 part in 10^{15}: one minute in lifetime of universe



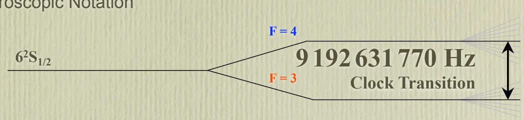
Louis Marmet

A faster atomic pendulum: ^{133}Cs atoms

Louis Marmet

Atomic oscillator: the ^{133}Cs atom

Spectroscopic Notation



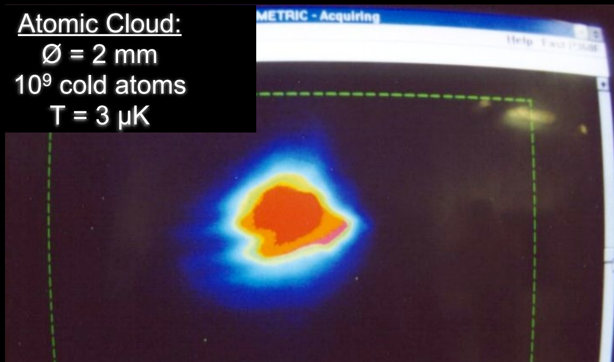
"Classical" Picture

Louis Marmet

Microwaves make the atoms oscillate

Cs Atoms in a Magneto-Optical Trap

Atomic Cloud:
Ø = 2 mm
10^9 cold atoms
T = 3 μK



Atomic Clock:
Accuracy 10^{-12} to 10^{-17}, after a few hours

Why is this precision needed?

Today's fast pace: from 0.001s to 0.000000001s

Synchronization of Power Networks: Uncertainty $\pm 1 \times 10^{-10}$

August 2003 Northeast Blackout – Great Lakes Region
http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/14021.htm

Time in Communications

Sharing bandwidth and time frames with a cell phone.

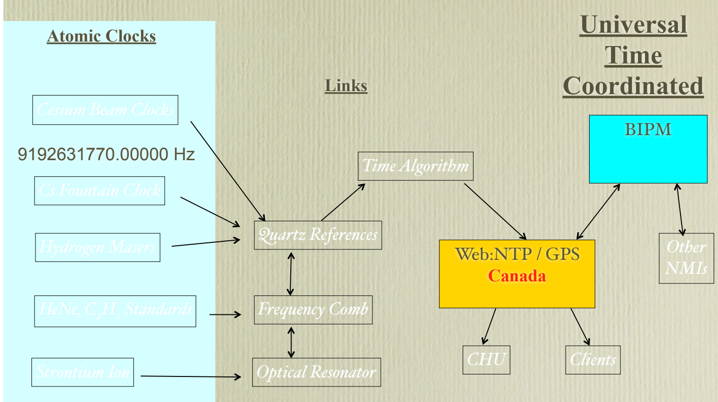
Computer synchronization

Computer transactions

Banks $$$$$$$$$$

NRC provides encrypted time-stamped secure NTP connections for banks at a cost of $110/yr!

Time dissemination



Subdivisions of time: Direct perception

- Roughly 1 / 10s = 100 ms, but depends very much on the stimulus

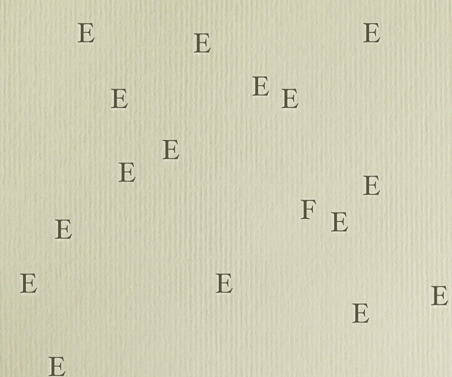
Perception of Time

- We are not very good ...

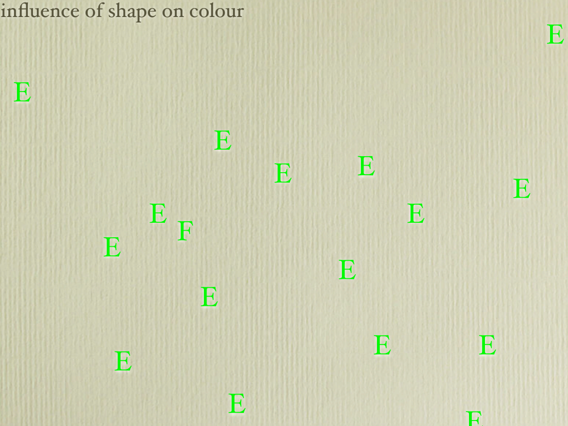
The influence of shape on colour

Find the “F”

The influence of shape on colour



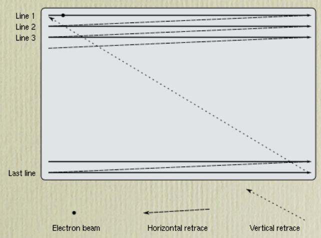
The influence of shape on colour



The influence of shape on colour

Limits:

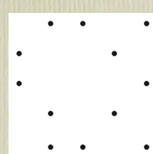
- Eyes can’t respond in much less than 1/20 s (= 50ms)
- Which is why we can watch TV



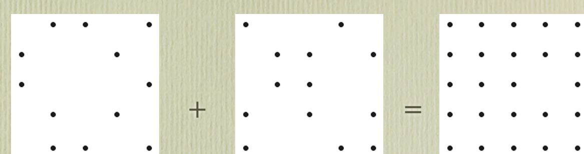
Picture as seen

- But shoot it too fast

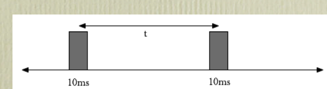
Brain will actually superimpose pictures if time is very short



Analyzing



If the gap t < 100 ms, see one image and can pick out missing spot
If the gap t > 100 ms, see two images, cannot pick out missing spot



Indirect perception via sounds

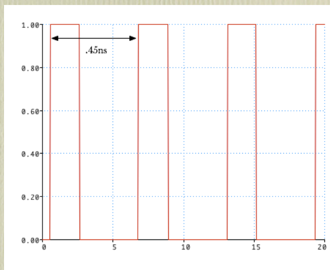
- We can hear notes in octaves: each octave is a doubling of frequency
- C Db D Eb E F Gb G Ab A Bb B

C	8.2	16.4	32.7	65.4	130.8	261.6	523.3	1046.5	2093.0	4186.0	8372.0
Db	8.7	17.3	34.6	69.3	138.6	277.2	554.4	1108.7	2217.5	4434.9	8869.8
D	9.2	18.4	36.7	73.4	146.8	293.7	587.3	1174.7	2349.3	4698.6	9397.3
Eb	9.7	19.4	38.9	77.8	155.6	311.1	622.3	1244.5	2489.0	4978.0	9956.1
E	10.3	20.6	41.2	82.4	164.8	329.6	659.3	1318.5	2637.0	5274.0	10548.1
F	10.9	21.8	43.7	87.3	174.6	349.2	698.5	1396.9	2793.8	5587.7	11175.3
Gb	11.6	23.1	46.2	92.5	185.0	370.0	740.0	1480.0	2960.0	5919.9	11839.8
G	12.2	24.5	49.0	98.0	196.0	392.0	784.0	1568.0	3136.0	6271.9	12543.9
Ab	13.0	26.0	51.9	103.8	207.7	415.3	830.6	1661.2	3322.4	6644.9	13289.8
A	13.8	27.5	55.0	110.0	220.0	440.0	880.0	1760.0	3520.0	7040.0	14080.0
Bb	14.6	29.1	58.3	116.5	233.1	466.2	932.3	1864.7	3729.3	7458.6	14917.2
B	15.4	30.9	61.7	123.5	246.9	493.9	987.8	1975.5	3951.1	7902.1	15804.3

- Roughly 20 Hz to 20 kHz
- O.K. 10 kHz for us!
- I.e. 50 ms down to 0.05 ms=50μs
- (why have we bothered to evolve this?)

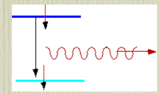
Electronics Directly

- Clock circuit in computer
- 2.8 GHz in this Mac:
- i.e. ~.35 nanoseconds (ns)



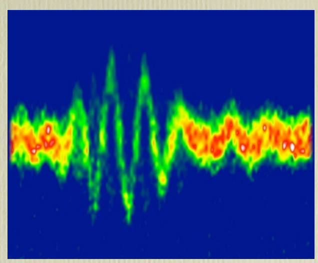
Atomic transitions

- E.g the laser pointer
- Atom makes transition from one level to another, emitting photon
- Typical time ~ 1 picosecond (ps)=10^{-12} s = 1/trillionth second=0.000000000001s



Pulsed lasers

- Paul Corkum at NRC/ Ottawa U developed techniques for cutting laser beams in few atto-second lengths:
- 1 attosecond (as)=10^{-18} s =0.000000000000000001s
- Allows still pictures of atoms



Particle Physics

- Reactions occur roughly at speed of light over the size of a proton
- Typical time ~ 10^{-24} s = 1/trillion-trillionth second =0.000000000000000000000001s
- 1 yoctosecond, except no-one ever calls it that

Planck time

- If we believe in superstring theory, they oscillate with a period
- $$t_p = \left(\frac{G\hbar}{c^5}\right)^{1/2} = 5.4\times10^{-44}s$$
- 0. 00000 00000 00000 00000 00000 00000 00000 00000 00005s
- Shortest time scale that makes any sense in physics

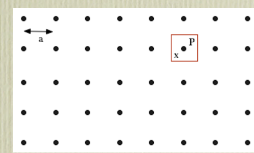
But wait a moment

- Can we really go on subdividing time?
- Is it really continuous or a succession of moments?
- Like a water-wave?

- Magnify by 1000: OK
- Magnify by 1000000: OK
- Magnify by 1000000000: start seeing molecules

Is time continuous?

- Is space?
- Suppose space is discrete at some scale a: say 1 attometre (1/1000 size of a proton)
- Then sizes smaller than this have no meaning



Is time continuous?

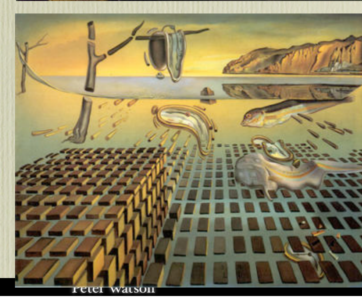
- Hence time scales shorter then $a/c \sim 10^{-27}$ s have no meaning
- Which is roughly the kind of limit we have now
- If space or time is quantized in some way, the reality is probably much more complicated

Text

- How Dali changed “the Persistence of Memory

into

- “The Disintegration of the Persistence of Memory”



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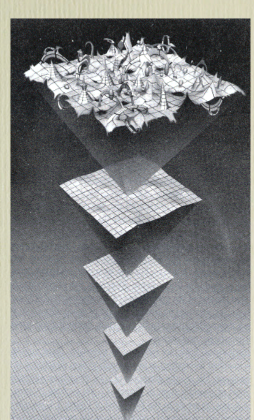
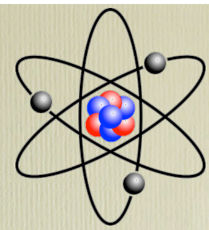


The Nucleus as a Clock

- Nuclei consist of (roughly equal) number of neutrons and protons
- Atomic Number Z = charge on nucleus= $N_{protons}$
- This defines chemistry
- Mass number $A = N_{protons} + N_{neutrons}$
- Isotopes: nuclei with different A but same Z.

PW

Notation



- We need to have some way to describe the nucleus we are talking about
- Lithium nucleus has 3 protons and 4 neutrons so

$^{7}_{3}Li_{4}$

However you can always figure out the $N_{neutron}$ so $^{7}_{3}Li$

Name implies Z, so simply ^{7}Li

Wikisource

Radioactive Decays

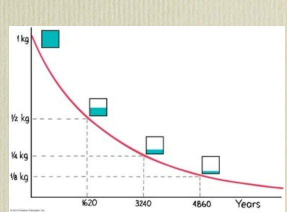
- All radioactive decays have a similar behaviour.
- The decay occurs totally at random
- probability of decay is proportional to the number of nuclei:
- This reduces the number of nuclei available to decay
- Half-life: time taken for half the nuclei to decay.

PW

- Half-life: time taken for half the nuclei to decay
- e.g. ^{13}N has half-life of 10 minutes

$^{13}N \Rightarrow {}^{13}C + e^{+} + \nu$

- If we start with 1000 nuclei, how much would be left after 30 minutes?
- after 10 minutes ~500 atoms
- after 20 minutes ~250 atoms
- after 30 minutes ~125 atoms



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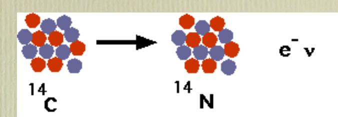
Carbon dating



- In the atmosphere, some of the $^{14}N \Rightarrow {}^{14}C$ by cosmic rays.
- This gets incorporated in living things, substituting for ^{12}C
- When the object dies, no more ^{14}C is absorbed,
- What is already there decays back to ^{14}N, with a half-life of 5700 years.

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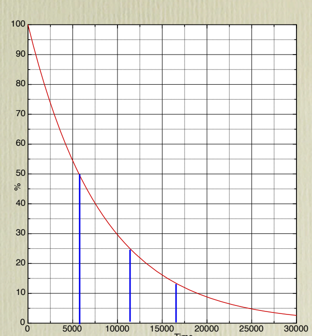
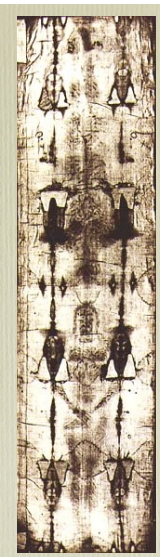
Carbon Dating

- 50% of atoms are left after 5700 years
- 25% after 11400
- 12.5% after 16100 etc



Turin Shroud

- (supposedly used to wrap Christ in when he was lowered from the Cross)
- Proportion of ^{14}C which is 89.5% of that of current materials.
- $\Rightarrow$ age of about 800 yrs



WIkipedia

How about large time intervals?

- Much less interesting for now
- Human lifetime ~ $2x10^9$s = 2 Gigasecond = 2Gs ~88 years
- Lifetime of the universe ~ $5x10^{17}$s = 0.5 exasecond = .5 Es ~14 billion years