It’s About Time Notes

Contents

NIST Notes

Ancient Calendars

- Ice-age hunters in Europe >20k years ago scratched lines & gouged holes in sticks & bones, possibly counting days between phases of mon
- 5k years ago, Sumerians in Tigris-Euphrates valley in today's Iraq had calendar that divided year into 30 day months, divided day into 12 periods (each = 2 of our hours), divided these periods into 30 parts (each 4 of our minutes)
- No written records of Stonehenge, built >4k years ago in England, but its alignments show its purposes apparently included determination of seasonal/celestial events, such as lunar eclipses, solstices, etc
- Earliest Egyptian calendar was based on moon's cycles
  - Later Egyptians realized that "Dog Star" in Canis Major (we call Sirius) rose next to Sun every 365 days, about when annual inundation of Nile began
  - Devised 365 day calendar, begun ~3100 BCE, seems to be 1 of earliest years recorded in history
- Before 2000 BCE, Babylonians used year of 12 alternating 29 day & 30 day lunar months, 354 day year
- Mayans relied on Sun, Moon, Venus, to establish 260 day & 365 day calendars
  - This culture & its related predecessors spread across Central America between 2600 BCE & 1500 CE, reaching apex between 250 & 900 CE
  - Left celestial-cycle records indicating their belief that creation of world occurred in 3114 BCE
  - Calendars later became portions of great Aztec calendar stones

Early Clocks

Sun Clocks

- Obelisks were built as early as 3500 BCE
- Moving shadows formed a kind of sundial, enabling people to partition day into morning & afternoon
- Obelisks also showed year's longest & shortest days when shadow at noon was shortest/longest of year
- Later, additional markers around base of monument would indicate further subdivisions of time
- Another Egyptian shadow clock/sundial, possibly 1st portable timepiece, came into use ~1500 BCE
- Device divided a sunlit day into 10 parts + 2 "twilight hours" in morning & evening
- When long stem w/5 variably spaced marks was oriented east & west in the morning, an elevated crossbar on east end cast a moving shadow over the marks
- At noon, device was turned in the opposite direction to measure the afternoon "hours"
- Merkhet = oldest known astronomical tool, was an Egyptian development of around 600 BCE
- A pair of merkhets was used to establish a north-south line (or meridian) by aligning them w/Pole Star
    - They could be used to mark off nighttime hours by determining when certain other stars crossed meridian
- In quest for better year-round accuracy, sundials evolved from flat horizontal/vertical plates to more elaborate forms
- One version was hemispherical dial, a bowl-shaped depression cut into a block of stone, carrying a central vertical gnomon (pointer) & scribed w/sets of hour lines for different seasons
- Hemicycle, said to have been invented ~300 BCE, removed useless half of hemisphere to give an appearance of a half-bowl cut into the edge of a squared block

- By 30 BCE, Vitruvius could describe 13 diff sundial styles in use in Greece, Asia Minor, Italy

Elements of a Clock

- Regular, constant, repetitive process/action to mark off equal increments of time
- Means of keeping track of increments of time & displaying the result

Water Clocks

- Among earliest timekeepers that didn't depend on the observation of celestial bodies
- One of the oldest was found in the tomb of Egyptian pharaoh Amenhotep I, buried around 1500 BCE
- Later named clepsydras ("water thieves") by Greeks, who began using them ~325 BCE, these were stone vessels w/sloping sides that allowed water to drip at a nearly constant rate from a small hole near bottom
- Other clepsydras were cylindrical/bowl-shaped containers designed to slowly fill w/water coming in at a constant rate
- Markings on the inside surfaces measured the passage of "hours" as the water level reached them
- These clocks were used to determine hours at night, but may have been used in daylight as well
- Another version consisted of a metal bowl w/a hole in the bottom; when placed in a container of water the bowl would fill & sink in a certain time
- These were still in use in North Africa in 20th century
- More elaborate & impressive mechanized water clocks were developed between 100 BCE & 500 CE by Greek & Roman horologists & astronomers
- Added complexity was aimed at making the flow more constant by regulating the pressure, & at providing fancier displays of passage of time

- Some water clocks rang bells & gongs, others opened doors & windows to show little figures of people, or moved pointers, dials, astrological models of the universe
- A Macedonian astronomer, Andronikos, supervised the construction of his *Horologion*, known today as Tower of the Winds, in Athens marketplace in the 1st half of the 1st century BCE
- Octagonal structure showed scholars & shoppers

Julian Day

- Continuous count of days since beginning of Julian Period used primarily by astronomers
- Starts Jan 1 4713 BC (Julian calendar), lasts for 7980 years
    - After 7980 years # starts from 1 again
    - 4713 BC because Indiction, Golden Number, & Solar Number = 1
        - In 1st year together, chosen bc preceded all historical dates
    - 15 (indiction cycle) x 19 (Metonic cycle) x 28 (Solar cycle) = 7980 years
- **Julian Day Number (JDN)** = integer assigned to a whole solar day in Julian day count starting from noon GMT, w/Julian day # 0 assigned to day starting at noon on Jan 1, 4713 BC, proleptic Julian calendar (Nov 24, 4714 BC, in Gregorian)
    - Julian day number for day starting at 12:00 UT on January 1, 2000, = 2,451,545
- **Julian Date (JD)** = JDN for preceding noon in GMT + fraction of day since that instant
    - Expressed as JDN w/decimal fraction added
    - May also refer, outside of astro, to day-of-year # (ordinal date) in Gregorian calendar, esp in computer programming, military & food industry, or may refer to dates in Julian calendar
    - If given JD is “May 12, 1629,” means that date in Julian calendar (May 22, 1629, in Gregorian calendar)

  - Outside of astro/historical context, if a given JD = 40 this most likely means 40th day of a given Gregorian year, namely Feb 9
  - But potential for mistaking "JD = 40" to mean an astro JDN (or year 40 AD in Julian calendar, or even duration of 40 astronomical Julian years) is justification for preferring terms "ordinal date" or "day-of-year" instead
- Julian Period = chronological interval of 7980 years beginning 4713 BC
  - Been used by historians since intro in 1583 to convert between diff calendars

History

- Invented by French scholar Joseph Justus Scaliger in 1583, at time of Gregorian calendar reform, as it's multiple of 3 calendar cycles used w/Julian calendar
  - Julian could refer to Scaliger's father, Italian scholar Julius Caesar Scaliger
  - Book V of his *Opus de Emendatione Temporum* ("Work on the Emendation of Time"): "We've called it Julian merely because it's accommodated to Julian year"
    - So Julian refers to Julius Caesar, who introduced Julian calendar in 46 BC
- Astronomer John Herschel, in book *Outlines of Astronomy,* 1st published in 1849, added counting of days elapsed from beginning of Julian Period
  - Astronomers adopted his "days of Julian period" in late 19th century, but used meridian of Greenwich instead of Alexandria, after former was adopted as Prime Meridian after International Meridian Conference in Washington in 1884
  - Now become standard system of JDN
- French mathematician & astronomer Pierre-Simon Laplace
  - 1st expressed time of day as a decimal fraction added to calendar dates in his book, *Traité de Mécanique Céleste*, in 1799

- Other astronomers added fractions of day to JDN to create JD, typically used by astronomers to date astronomical observations, eliminating complications resulting from using standard calendar periods like eras/years/months
    - 1890, 1st introduced into variable star work by Edward Charles Pickering, of Harvard College Observatory
- Begin at noon bc when Herschel recommended them, astronomical day began at noon
    - Astronomical day had begun at noon ever since Ptolemy chose to begin days in his astronomical periods at noon
    - Chose noon bc transit of Sun across observer's meridian occurs at same apparent time every day of year, unlike sunrise/sunset, which vary by several hours
    - Midnight not considered bc couldn't be accurately determined using water clocks

Variants

Reduced JD	JD-2400000	• More recent starting pt sometimes used • Ex: dropping leading digits to fit into limited computer memory w/adequate amount of precision
Modified JD	JD-2400000.5	• Introduced by Smithsonian Astrophysical Observatory in 1957 to record orbit of Sputnik • Epoch of OpenVMS, using 63-bit date/time, postponing next Y2K campaign to July 31, 31086, 02:48:05.47 • Defined relative to midnight
Truncated JD	JD-2440000.5	• Introduced by NASA/Goddard in 1979 as part

		of a parallel grouped binary time code (PB-5) for spacecraft applications • 4-digit day count from MJD 40000 (May 24, 1968) represented as a 14-bit binary # • Since code was limited to 4 digits, recycled to 0 on MJD 50000 (Oct 10, 1995), which gives a long ambiguity period of 27.4 years • Only whole days represented • Time of day is expressed by a count of seconds of a day + optional ms, microseconds & nanoseconds in separate fields • Later PB-5J was introduced which increased field to 16 bits, allowing values up to 65535, which will occur in year 2147 • 5 digits recorded after TJD 9999
Dublin JD	JD-2415020	• # of days elapsed since epoch of solar & lunar ephemerides used from 1900-1983, Newcomb's Tables of the Sun & Ernest W. Brown's *Tables of the Motion of the Moon* (1919) • This epoch was noon UT on Jan 0, 1900, which is same as noon UT on Dec 31, 1899 • DJD was defined by International Astronomical Union at their meeting in Dublin, Ireland, in 1955
Chronological JD	JD+0.5+tz	• Recently proposed by Peter Meyer • Has been used by some students of calendar

		& in some scientific software packages • Usually defined relative to local civil time, rather than UT, requiring a time zone (tz) offset to convert • Days start at midnight • Users of CJD sometimes refer to Julian Date as **Astronomical Julian Date** to distinguish it
Lilian Date	floor (JD-2299159.5)	• Count of days of Gregorian calendar & not defined relative to Julian Date • Integer applied to a whole day; day 1 was Oct 15, 1582 (day Gregorian calendar went into effect) • Original paper defining it has no mention of time zone/time-of-day • Named for Aloysius Lilius, principal author of Gregorian calendar
ANSI Date	floor (JD-2305812.5)	• Defines Jan 1, 1601, as day 1 • Used as origin of COBOL integer dates • This epoch is beginning of previous 400 year cycle of leap years in Gregorian calendar, which ended w/year 2000
Rata Die	floor (JD-1721424.5)	• System (family of 3 systems) used in book *Calendrical Calculations* • Uses local timezone, & day 1 is Jan 1, 1, that is, 1st day of Christian/Common Era in proleptic Gregorian calendar

Unix Time	86400(JD-2440587.5)	• Count of seconds
Mars Sol Date	JD-24055221.02749	• Count of Martian days
Heliocentric JD		• Same as Julian day but adjusted to frame of reference of Sun ○ Can differ from JD by ~498s, that being time it takes Sun's light to reach Earth • Ordinary JD sometimes = **Geocentric Julian Day (GJD)** to distinguish it

Calculations

- Integer division is used exclusively (remainder of all divisions dropped)
- Months (M) Jan-Dec = 1-12
- For year (Y), astro year numbering used, thus 1 BC=0, 2 BC=−1, 4713 BC=−4712
- D = day of month
- JDN pertains to noon occurring in corresponding calendar date

Converting Julian/Gregorian Calendar Date to JDN

- Algorithm is valid at least for all positive JDNs
- Doesn't follow NASA/US Naval Observatory - convention in these systems being that Gregorian Calendar didn't exist before date October 15, 1582 (Gregorian)
- Effectively back-dates Gregorian onto Julian for dates before intro of Gregorian calendar
    - So any calculations made w/this formula before Oct 15, 1582, won't agree w/these previous ephemerides
- To calculate

- Express date as Y (year), M (month #, Jan = 1, Feb = 2, etc), D (day of month)
- If month is Jan/Feb, subtract 1 from year to get new Y
  - Add 12 to month to get new M
- Drop fractional part of all results of all multiplications & divisions, let
  - A = Y/100
  - B = A/4
  - C = 2-A+B
  - E = 365.25(Y+4716)
  - F = 30.6001(M+1)
  - JD=C+D+E+F-1524.5
- This is JDN for beginning of date in question at 0 hours, GMT
- Will always give you half day extra because Julidan Day begins at noon GMT

- Or
  - a=[14-month12]
  - y=year+4800-a
  - m=month+12a-3
  - For date in Gregorian calendar
    - JD=day+[153m+25]+365y+[y4]-[y100]+[y400]-32045
  - For date in Julian calendar
    - JD=day+[153m+25]+365y+[y4]-32083
  - JD is Julian Date that starts at noon TT on specified date
  - Algorithm works fine for AD dates
    - If want to use for BC, must convert BC year to negative year (10 BC = -9)
    - Works correctly for all dates after 4800 BC (all positive Julian Day)

Convert Other Way

- For Gregorian calendar

- a=JD+32044
- b=[4a+3146097]
- c=a-[146097b4]

- For Julian calendar
  - b=0
  - c=JD+32082
- Then
  - d=[4c+31461]
  - e=c-[1461d4]
  - m=[5e+2153]
  - day=e-[153m+25]+1
  - month=m+3-12[m10]
  - year=100b+d-4800+[m10]

Finding Day of Week Given JDN

- JDN mod 7
  - 0 = Mon
  - 1 = Tues
  - 2 = Wed
  - 3 = Thurs
  - 4 = Fri
  - 5 = Sat
  - 6 = Sun

Gregorian Calendar From JDN

- Algorithm by Richards to convert JDN (J) to date in Gregorian calendar
  - Doesn't state which dates algorithm is valid for
- All variables are integer values, notation "*a* div *b*" = integer division

Variable	Value	Variable	Value
y	4716	v	3

j	1401	u	5
m	2	s	153
n	12	w	2
r	4	B	274277
p	1461	C	-38

- *f=J=j=(((4J+B)div146097)3)div4+C*
- *e=rf+v*
- *g=mod(e,p)div r*
- *h=ug+w*
- ***D**=(mod(h,s)) div u +1*
- *M=mod(h div s + m,n)+1*
- *Y=(e div p)-y+(n+m-M) div n*
- D, M, Y, are #'s of day, month, year

Doomsday Rule

- John Conway, inspired by Lewis Carroll's work on perpetual calendar algorithm
- Takes advantage of each yr having a certain day of the week (doomsday) upon which certain easy-to-remember dates fall
    - 1/3 (common years), 1/4 (leap years), 1/11 (leap years), 2/14, 2/22 (leap years), 2/28, 2/29 (leap years), 3/14, 3/21, 4/4, 5/9, 6/6, 7/4. 7/11, 8/8, , 9/5, 10/10, 10/31, 11/7, 12/12, 12/26, and the last day of Feb all occur on the same day of the week in any given year
- Applying algorithm:
    - Determine "anchor day" for century
        - These alternate in 400 yr cycle w/a pattern of 5, 3, 2, 0, 5, 3, 2, 0,...the 1900s have an anchor day of 3 and the 2000s of 2
        - Remaining centuries can be extrapolated from this pattern

        - Anchor-day for a century also corresponds to the doomsday for the 00 year of that same century, so if this is the case, can skip next step
        - For Gregorian:
            - 5 x (cmod4) + Tuesday = anchor
        - For Julian:
            - 6 x (cmod7)mod7 + Sunday = anchor
        - c = year/100
    - Use anchor day to calc doomsday for yr
        - Take only the last 2 digits of the yr
        - Add 11 only if original yr was odd
        - Divide year by 2
        - If year is odd after division, add 11 to make it even
        - Take this remaining number mod7, subtract this from 7
        - Add anchor day and subtract 7 if necessary
        - 2037->37 (cut out year)->48 (add 11)->24 (divide by 2)->3 (mod 7)->4 (subtract from 7)->6(2 for anchor day)
        - 1938->38 (cut out year)->19 (divide by 2)->30 (add 11)->2 (mod 7)->5 (subtract from 7)->8 (3 for anchor-day)->1 (subtract 7)
        - 1848->48 (cut out year)->24 (divide by 2)->3 (mod 7)->4 (subtract from 7)->9 (5 for anchor-day)->2 (subtract 7)
        - Alternately, can look up in table
    - Determine if leap-year
        - This can be skipped if desired month is not Jan or Feb
        - Otherwise, see above for detailed rules on leap-years for the Gregorian calendar
    - Choose closest date out of ones that always fall on doomsday
    - Count # of days (mod 7) btwn that date and the date in ques to arrive at the day of the week
        - Calc diff btwn desired date & nearby date & add/subtract it from doomsday

        - Use mod 7 to bring result into range of 0-6 to get day of week
        - Ex: Jan 13, 1848
            - Doomsday of 1848 = 2
            - Since it's Jan, pay extra attention to fact that it's a leapyear (divisible by 4 and not divisible by 100)
            - Since Jan 4 is near 13 & is doomsday for leapyear, we calc that the 13th is 9 days after the 4th
            - (9+2)mod7=11mod7=4, so Thurs
- Noneday, Sansday (Sunday), Oneday, Twosday, Treblesday, Foursday, Fiveday, Six-a-day
- For purpose of this calc, centuries considered to begin on 00 yrs
- Caveat: method intended for yrs CE/AD; variation needed for BCE/BC

Zeller's Congruence Method

- For Gregorian
    - h=(q+13(m+1)5+K+K4+J4-2J) mod7
- For Julian
    - h=(q+13(m+1)5+K+K4+5-J) mod7
- *h*: day of week (0 = Saturday, 1 = Sunday, 2 = Monday, ..., 6 = Friday)
- *q*: day of month
- *m*: month (3 = March, 4 = April, 5 = May, ..., 14 = February)
- *K*: year of century (year mod 100)
- *J* is zero-based century (actually (year/100))
    - For example, zero-based centuries for 1995 and 2000 are 19 and 20 respectively (not to be confused w/common ordinal century enumeration which indicates 20th for both cases)
- Note: In this algorithm January & February are counted as months 13 and 14 of the previous year
    - If it's 2 February 2010, the algorithm counts the date as the 2nd day of the 14th month of 2009 (02/14/2009 in DD/MM/YYYY format)

Dominical Letter Method

- DD = (3 - DL)mod7
- A=1, B=2, …, G=0

Doomsday	Dominical Letter
Sunday	C, DC
Monday	B, CB
Tuesday	A, BA
Wednesday	G, AG
Thursday	F, GF
Friday	E, FE
Saturday	D, ED

For Julian:

- Find remainder when year is divided by 28, look up in following table

Remainder	Dominical Letter
0	DC
1	B
2	A
3	G
4	FE
5	D

6	C
7	B
8	AG
9	F
10	E
11	D
12	CB
13	A
14	G
15	F
16	ED
17	C
18	B
19	A
20	GF
21	E
22	D
23	C
24	BA
25	G

26	F
27	E

Table of Dominical Letters For Years

Years	1600 2000	1700 2100	1800 2200	1900 2300
00	BA	C	E	G
01 29 57 85	G	B	D	F
02 30 58 86	F	A	C	E
03 31 59 87	E	G	B	D
04 32 60 88	DC	FE	AG	CB
05 33 61 89	B	D	F	A
06 34 62 90	A	C	E	G
07 35 63 91	G	B	D	F
08 36 64 92	FE	AG	CB	ED
09 37 65 93	D	F	A	C
10 38 66 94	C	E	G	B
11 39 67 95	B	D	F	A
12 40 68 96	AG	CB	ED	GF
13 41 69 97	F	A	C	E

14 42 70 98	E	G	B	D
15 43 71 99	D	F	A	C
16 44 72	CB	ED	GF	BA
17 45 73	A	C	E	G
18 46 74	G	B	D	F
19 47 75	F	A	C	E
20 48 76	ED	GF	BA	DC
21 49 77	C	E	G	B
22 50 78	B	D	F	A
23 51 79	A	C	E	G
24 52 80	GF	BA	DC	FE
25 53 81	E	G	B	D
26 54 82	D	F	A	C
27 55 83	C	E	G	B
28 56 84	BA	DC	FE	AG

Table for Days of the Year

Days	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 8 15 22 (29)	A	D	D	G	B	E	G	C	F	A	D	F
2 9 16 23 (30)	B	E	E	A	C	F	A	D	G	B	E	G

3 10 17 24 (31)	C	F	F	B	D	G	B	E	A	C	F	A
4 11 18 25	D	G	G	C	E	A	C	F	B	D	G	B
5 12 19 26	E	A	A	D	F	B	D	G	C	E	A	C
6 13 20 27	F	B	B	E	G	C	E	A	D	F	B	D
7 14 21 28	G	C	C	F	A	D	F	B	E	G	C	E

Odd +11 Method

- Let T be year's last 2 digits
- If T is odd, +11
- Let T=T/2
- Let T=Tmod7
- Count forward T leters from century's dominical latter to get year's dominical letter
- y+11(ymod2)2

Rule of De Morgan's

- Add 1 to given year
- Take quotient found by dividing given year by 4 (neglecting remainder)
- Take 16 from centurial figures of given year if that can be done
- Take quotient of III divided by 4 (neglecting remainder)
- From sum of I, II, and IV, subtract III
- Find remainder of V divided by 7: this is the number of the Dominical Letter, supposing A, B, C, D, E, F, G to be equivalent respectively to 6, 5, 4, 3, 2, 1, 0
- (year+(year/4)+(year/400)-(year/100)-1)mod7
- (y+(y/4)+5(c mod4)-1)mod7

Formula Derived From Gauss's Algorithm

- For Gregorian:

    - DL=(ymod4x2+ymod7x4+cmod4x2)mod7
- For Julian:
    - DL=(ymod4x2+ymod7x4+cmod7+2)mod7
- DL = dominical letter (A=1,...,G=0)
- y = (year-1)mod100
- c = (year-1)/100
- Note: for a leap year, 2nd letter = 1st letter -1

Astronomical Clock

- Clock w/special mechanisms & dials to display astronomical info, such as relative positions of Sun, moon, zodiacal constellations, & sometimes major planets

Definition

- Term is loosely used to refer to any clock that shows, in addition to time of day, astro info
    - Could include location of Sun & moon in sky, age & phase of moon, position of Sun on ecliptic & current zodiac sign, sidereal time, & other astronomical data such as moon’s nodes (for indicating eclipses) or a rotating star map
- Term shouldn’t be confused w/astronomical regulator, a high precision but otherwise ordinary pendulum clock used in observatories
- Astronomical clocks usually represent solar system using geocentric model
    - Center of dial is often marked w/disc or sphere representing Earth, located at center of solar system
    - Sun is often represented by a golden sphere (as it initially appeared in Antikythera Mechanism, back in 2nd century BC), shown rotating around Earth once a day around a 24-hour analog dial
    - This view accords both w/daily experience & w/philosophical world view of pre-Copernican Europe

History

- Altho not a clock in traditional sense, 2nd century BC antikythera mechanism of ancient Greece was used to calculate positions of Sun, moon, stars at any given point by use of complex mechanical gears
- Research in 2011 & 2012 led an expert group of researchers to posit that European astro clocks are descended from tech of antikythera mechanism
- As Cicero later wrote in 1st century BC, Archimedes & Posidonius's orrery achieved virtually the same thing
- In 11th century, Song Dynasty Chinese horologist, mechanical engineer, & astronomer Su Song created a water-driven astronomical clock for his clock-tower of Kaifeng City
- Su Song is noted for having incorporated an escapement mechanism & earliest known endless power-transmitting chain drive for his clock-tower & armillary sphere to function (for more info see water clock)
- Contemporary Muslim astronomers & engineers also constructed a variety of highly accurate astronomical clocks for use in their observatories, such as castle clock (water-powered astro clock) by Al-Jazari in 1206, & astrolabic clock by Ibn al-Shatir in early 14th century
- Early development of mechanical clocks in Europe isn't fully understood, but there's general agreement that by 1300-1330 there existed mechanical clocks (powered by weights rather than by water & using an escapement) which were intended for 2 main purposes
    - For signalling & notification (timing of services & public events)
    - For modeling solar system
    - Latter is an inevitable development, bc astrolabe was used both by astronomers & astrologers, & it was natural to apply a clockwork drive to rotating plate to produce working model of solar system
- Astro clocks by Richard of Wallingford in St Albans during 1330s & by Giovanni de Dondi in Padua between 1348-1364 are masterpieces of their type

- They no longer exist, but detailed descriptions of their design & construction survive, & modern reproductions have been made
- Wallingford's clock may have shown Sun, moon (age, phase, node), stars & planets, & had, in addition, wheel of fortune & indicator of state of tide at London Bridge
- De Dondi's clock was 7-faced construction w/107 moving parts, showing positions of Sun, moon, 5 planets, as well as religious feast days
- Both these clocks, & others like them, were probably less accurate than their designers would have wished
    - Gear ratios may have been exquisitely calculated, but their manufacture was somewhat beyond mechanical abilities of the time, & they never worked reliably
    - Timekeeping mechanism in nearly all these clocks until 16th century was simple verge & foliot escapement, which had errors of at least half an hour a day
- Astro clocks were built as demo/exhibition pieces, to impress & educate/inform
- Challenge of building these masterpieces meant that clockmakers would continue to produce them, to demonstrate their technical skill & their patrons' wealth
- Philosophical message of an ordered, heavenly-ordained universe, which accorded w/Gothic era view of world, helps explain their popularity
- Growing interest in astro during 18th century revived interest in astronomical clocks, less for philosophical message, more for accurate astro info that pendulum-regulated clocks could display

Su Sung's Cosmic Engine

- Science Museum (London) has scale model
- Su Sung, Chinese polymath, designed & constructed in China in 1092
- This great astro hydromechanical clock tower was ~10 m high (~30 ft) & featured clock escapement & was indirectly powered by rotating wheel either

w/falling water & liquid mercury which doesn't freeze during sub-0 temps & flows freely allowing operation of clock during winter

- Full-sized working replica in Republic of China (Taiwan)'s National Museum of Natural Science, Taichung city
    - 12 m (39 ft) high

Al-Jazari's Castle Clock

- Most sophisticated water-powered astro clock
- Considered to be early example of programmable analog computer in 1206
- 3.3 m (11 ft) high
- Had multiple functions alongside timekeeping
    - Included display of zodiac & solar & lunar orbits & pointer in shape of crescent moon which traveled across top of gateway, moved by hidden cart & causing automatic doors to open, each revealing a mannequin, every hour
- Possible to re-program length of day & night every day in order to account for changing lengths of day & night throughout year
- Also featured 5 musician automats who automatically played music when moved by levers operated by hidden camshaft attached to water wheel
- Other components of castle clock included main reservoir w/float, float chamber & flow regulator, plate & valve trough, 2 pulleys, crescent disc displaying zodiac, 2 falcon automata dropping balls into vases

Strasbourg

- Housed 3 diff astro clocks since 14th century
- 1st clock was built between 1352 & 1354 & stopped working sometime at beginning of 16th century
- 2nd clock was then built by Herlin, Conrad Dasypodius, Habrecht brothers, & others, between 1547 & 1574
- Stopped working in 1788/1789 (apparently stopped working gradually, each component being disconnected one after other)

- After 50 year lapse, new clock built by Jean-Baptiste Schwilgué (1776–1856) + ~30 workers
    - Housed in case of 2nd clock
    - Shows many astronomical & calendrical functions (including what is thought to be 1st complete mechanization of part of computus needed to compute Easter) as well as several automata

Prague

- One of most famous of this type is Old-Town Hall clock in Prague, Czech Republic
- Also known as Prague orloj
- Central portion was completed in 1410
- 4 figures are set in motion at hour, w/Death (represented by skeleton) striking time
- On hour there's a presentation of statues of Apostles at doorways above clock, w/all 12 presented at noon
- 1870: calendar display was added below clock
- During WW2 clock was nearly destroyed by Nazi fire
- Townspeople are credited w/heroic efforts in saving most of the parts
- Gradually renovated until 1948
- In 1979 clock was once more cleaned & renovated
- According to local legend city will suffer if clock is neglected & its good operation is placed in jeopardy

Olomouc

- Olomouc = former capital of Moravia in eastern part of Czech Republic
- Impressive exterior astro clock on main town square
- Rare example of heliocentric astro clock
- A legend dates its construction to year 1422

    - In historic sources it’s 1st mentioned in 1517
- Clock was remodelled approx once every century
    - 1898 the astrolabe was replaced w/heliocentric model of solar system
- When retreating Nazi German army passed through Olomouc in final days of war in May 1945 they opened fire on old astronomical clock, leaving only a few pieces (that can now be seen in local museum)
    - As a result of serious damage the clock was reconstructed in style of socialist-realism in 1st years of communist rule in Czechoslovakia (1948-early 1950s)
    - Religious & royal figures were replaced w/athletes, workers, farmers, scientists & other members of proletariat, while glockenspiel was altered to play 3 pieces of traditional local music
- Lower dial represents earthly sphere
    - Indicates minute, hour, day, month, year, phase of moon
- Upper dial represents heavenly sphere
    - Shows star map, Sun, Earth, planets, against background of 12 houses of zodiac
- 3rd & highest level = saints & apostles once paraded during daily musical display at noon
    - Their role is now performed by faded-looking volleyball players, auto mechanics & factory workers
- Intricate background mosaic covers clock's entire height of 14 m & has representations of 12 seasons & traditional festivals; the ride of kings & procession of maidens
- Olomouc astronomical clock was featured in opening scenes of the film “The Joke” based on the book by Milan Kundera

Stará Bystrica

- During reconstruction of town square, astro clock was built in municipality
    - Completed in 2009
- Shape of stylized form of Our Lady of Sorrows, patron of Slovakia

- Described as largest wooden statue of Slovakia
- Exterior is decorated by statues of important figures from Slovakia's history: Prince Pribina, King Svatopluk, Anton Bernolák, Ľudovít Štúr, Milan Rastislav Štefánik, Andrej Hlinka
- Each hour, statuettes of saints connected w/Slovakia appear: Cyril, Methodius, Andrew-Zorard, Benedict, Gorazd, Bystrík & Adalbert
- Bells of clock carry names Sv. Juraj (St. George) & Riečnická Madona (Our Lady of Riečnica); the 1st is rung to indicate time, 2nd accompanies saints
- This astronomical clock is only one in Slovakia
- Astro part of clock consists of an astrolabe displaying astrological signs, positions of Sun & Moon, & lunar phases
- Clock is controlled by computer using DCF77 signals

Astronomical Clock of Taqi al-Din

- Ottoman Turkish engineer Taqi al-Din described weight-driven clock w/verge and foliot, a striking train of gears, alarm, & representation of moon's phases in his book *The Brightest Stars for Construction of Mechanical Clocks* written around 1565
- Clock also displayed zodiac

Lund

- Astro clock in Lund Cathedral in Sweden, *Horologium mirabile Lundense* was made around 1425, probs by clockmaker Nicolaus Lilienveld in Rostock
- After it had been in storage since 1837, was restored & put back in place in 1923
- Only upper, astro part is original, while some of other remaining medieval parts can be seen at Cathedral museum
- When it plays, one can hear *In Dulci Jubilo* from smallest organ in church, while 7 wooden figures, representing 3 magi & servants pass by

Besançon, France

- Made in 1860 by Auguste-Lucien Vérité of Beauvais
- Expresses theological concept that during each second of day the Resurrection of Christ transforms existence of man & of world
- 5.8 meters high, 2.5 meters wide, 30,000 mechanical parts
- 70 dials provide 122 indications including seconds, hours, days, years
- Perpetual & can register up to 10,000 years, including adjustments for leap year cycles
- Immediately after he finished Besançon commission, Vérité built a larger more elaborate clock for Beauvais Cathedral in his home town

Beauvais, France

- In Beauvais Cathedral
- Built by Auguste-Lucien Vérité over a period of 4 years, from 1865 to 1868 as a follow-up to his elaborate clock at Besancon
- 12 m high, 6 m wide, contains over 90,000 individual parts
- 52 dials that display times of sunrise, sunset, moonrise, moonset, phases of moon, solstices, position of planets, current time in 18 cities around world, & tidal hours
- Has a case that blends Romanesque & Byzantine styles & is crowned by a multi-tiered Celestial City w/68 automatons that animate, at striking of each hour, to enact Last Judgement

Copenhagen

- City hall in Copenhagen has a complete astro clock, set in an interior glass cabinet
- Clock was designed over period of 50 years by amateur astronomer & professional clockmaker Jens Olsen
- Some of components (such as computus) were inspired by Strasbourg clock, which was studied by Olsen
- Assembled from 1948-1955

- Between 1955 & 1997, clock underwent complete restoration by Danish watchmaker & conservator Søren Andersen

The Rasmus Sørnes Clock

- Arguably the most complicated of its kind ever constructed, the last of a total of 4 astronomical clocks designed & made by Norwegian Rasmus Sørnes (1893–1967), is characterized by its superior complexity compactly housed in a casing w/modest measurements of 0.70 x 0.60 x 2.10 m
- Features include locations of Sun & moon in zodiac, Julian calendar, Gregorian calendar, sidereal time, GMT, local time w/DST & leap year, solar & lunar cycle corrections, eclipses, local sunset & sunrise, moonphase, tides, sunspot cycles & a planetarium including Pluto's 248 year orbit & 25800 year period of polar ecliptics (precession of Earth's axis)
- All wheels are in brass & gold plated
- Dials are silver plated
- Sørnes also made necessary tools & based his work on his own observations of firmament
- This remarkable timepiece will probs be the last one ever to be designed & made by hand by 1 single person as true craftsmanship & work of art
- The result, outstanding for its performance & accuracy, remains a symbol of transition from mechanical age, Sørnes' electromechanical pendulum system pointing forward into age of digital clocks
- Having been exhibited at Time Museum in Rockford, Illinois, & at The Chicago Museum of Science and Industry, clock was sold in 2002 & its current location is not known
- The Rasmus Sørnes Astronomical Clock no.3, precursor to Chicago Clock, his tools, patents, drawings, telescope & other items, are exhibited at Borgarsyssel Museum in Sarpsborg, Norway

Table Clocks

- Popular as showpieces

- To become a master clockmaker in 17th century Augsburg candidates had to design & build a ‘masterpiece’ clock, an astronomical table top clock of formidable complexity
- Examples can be found in museums, such as London's British Museum
- Currently Edmund Scientific among other retailers offer mechanical Tellurium clock, perhaps 1st mechanical astro clock to be mass marketed

Watches

- More recently, independent clockmaker Christiaan van der Klaauw created a wristwatch astrolabe, the “Astrolabium” in addition to “Planetarium 2000,” “Eclipse 2001” & “Real Moon”
- Ulysse Nardin also sells several astronomical wristwatches, “Astrolabium,” “Planetarium,” “Tellurium J. Kepler”

Others

Others

Belgium

- Sint-Truiden (Festraets’ astro clock)
- Lier. Zimmertoren

Croatia

- Split

Denmark

- Roskilde

France

- Beauvais. Beauvais astronomical clock
- Besançon. Astronomical clock (Besançon)

- Haguenau. Renaissance building of former chancellery (now housing the *Musée alsacien*) displays an astronomical clock on its facade.
- Lyon. The Lyon astronomical clock in Lyon Cathedral also has an astronomical clock from the 14th century.
- Ploërmel. Ploërmel astronomical clock
- Rouen. The Gros Horloge is a famous astronomical clock with a movement dating back to 14th century, though the facade is more recent. It is located in the Gros Horloge street.
- Versailles. The Passemant astronomical clock in the Palace of Versailles near Paris is a rococo astronomical clock sitting on a formal low marble base. It took 12 years for a clockmaker and an engineer to build and was presented to Louis XV in 1754.

Germany

- Stendal
- Münster. St. Paul's Cathedral, includes an astronomical clock of 1540, adorned with hand-painted zodiac symbols, which traces the movement of the planets, and plays a Glockenspiel tune every noon.
- Rostock. The Rostock astronomical clock in St. Mary's Church dating from 1472, built by Hans Düringer. Clock w/daily time, zodiac, moon phases, and month. Calendar, which is valid until 2017.
- Esslingen am Neckar. Old town hall.
- Esslingen am Neckar. At the headquarters of Festo, Professor Hans Scheurenbrand has constructed the *Harmonices Mundi*(named after Kepler's book of the same name), which consists of a technologically sophisticated astronomical clock, a world time clock, and a 74 bell glockenspiel.

Malta

- Valletta. The astronomical clock of Grandmaster's Palace (tower of the courtyard).

- Valletta. The astronomical clock of the "Yellow Room" in Grandmaster's Palace, this clock was made by Charles Andre' Boulle (17th Century).
- Valletta. The astronomical clock of St. John's Co-Cathedral.
- Midna. The astronomical clock is divided into two different quadrants in two towers of St. Paul's Cathedral.

Norway

- Oslo

Italy

- Messina. The Orologio astronomico di Messina. Multi-dial clock equipped with some of the most complex automata. Reconstructed between 1930 and 193, by the Ungerer Company of Strasbourg, on the base of an original dating from 1574. It is one of the largest astronomical clocks in the world.
- Trapani. The Orologio astronomico di Trapani (1570 and restored in 1596).
- Cremona. The Torrazzo, the bell tower of the Cremona Cathedral, contains the largest medieval clock in Europe.
- Mantua. The *Palazzo della Ragione* with the "Tower of the Clock"
- Venice. St Mark's Clock, in the clocktower on St Mark's Square, was built and installed by Gian Paulo and Gian Carlo Rainieri, father and son, between 1496 and 1499.
- Brescia, c.1540-50
- Padova. Clock by Jacopo Dondi dating 1344.

Poland

- Gdańsk. In St. Mary's Church there is the Gdańsk astronomical clock dating from 1464–1470, and built by Hans Düringer of Toruń. It was reconstructed after 1945.

Switzerland

- Bern. The Zytglogge is a famous astronomical clock from the 15th century situated in the landmark medieval tower of the same name.
- Sion
- Winterthur

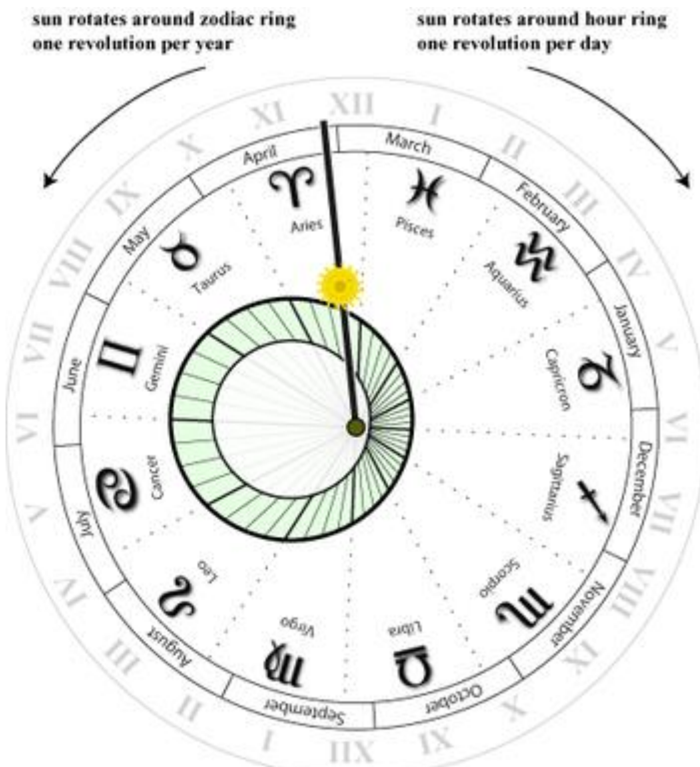
United Kingdom

- St Albans. A modern clock dating from 1995 built from notes by Richard of Wallingford held in the Bodleian Library, Oxford. On display in St Albans Cathedral.
- Durham. Prior Castell's Clock in Durham Cathedral
- Exeter. The Exeter Cathedral astronomical clock is one of the group of famous 14th to 16th century astronomical clocks to be found in the West of England. The main, lower, dial is the oldest part of the clock, probably dating from the 1480s.
- Hampton Court Palace. The Hampton Court astronomical clock is on the interior façade of the Main Gatehouse. It is a fine early example of a pre-Copernican astronomical clock.
- Leicester. The Leicester University astronomical clock is on the Rattray Lecture Theatre opposite the Physics department.
- Ottery St Mary. Ottery St Mary astronomical clock
- Wells. The Wells Cathedral clock is an astronomical clock in the north transept of Wells Cathedral, England. It can be dated to between 1386 and 1392.
- Wimborne. Wimborne Minster astronomical clock
- York. The York Minster astronomical clock, although modern, is a prime example of an astronomical clock, and was built to commemorate the RAF and Commonwealth nations' efforts in World War II.

Generic Description

Time of Day

- Most astro clocks have 24 hour analog dial around outside edge, numbered from I to XII then from I to XII again
- Current time is indicated by golden ball or picture of the Sun at end of a pointer
- Local noon is usually at top of the dial, & midnight at bottom
- Minute hands are rarely used
- Sun indicator/hand gives an approx indication of both Sun's azimuth & altitude



- For azimuth (bearing from North), top of dial indicates South, & 2 VI points of dial East & West
- For altitude, top is zenith & 2 VI & VI points define horizon
    - This is for astronomical clocks designed for use in the northern hemisphere
    - This interpretation is most accurate at the equinoxes
- If XII isn't at top of dial, of if #s are Arabic rather than Roman, then time may be shown in Italian hours (also called Bohemian, or Old Czech, hours)
- In this system, 1 o'clock occurs at sunset, & counting continues through the night & into the next afternoon, reaching 24 an hour before sunset

- In photograph of Prague clock shown above, time indicated by Sun hand is about noon (XII in Roman numerals), or about the 17th hour (Italian time in Arabic numerals)

Calendar & Zodiac

- This year is usually represented by 12 signs of zodiac, arranged either as a concentric circle inside 24 hour dial, or drawn onto a displaced smaller circle, which is a projection of ecliptic, path of Sun & planets through sky, & plane of Earth’s orbit
- Ecliptic plane is projected onto face of clock, & bc of Earth’s tilted angle or rotation relative to its orbital plane, it’s displaced from center & appears to be distorted
- Projection point for stereographic projection is North pole
- On astrolabes, South pole is more common
- Ecliptic dial makes 1 complete revolution in 23 hours 56 minutes (sidereal day), & will therefore gradually get out of phase w/hour hand, drifting slowly further apart during year
- To find date, find place where hour hand/sun disk intersects ecliptic dial
    - This indicates current star sign, Sun’s current location on ecliptic
- Intersection point slowly moves round ecliptic dial during year, as Sun moves out of 1 astrological sign into another
- If zodiac signs run around inside hour hands, either this ring rotates to align itself w/hour hand, or there’s another hand, revolving once/year, which points to Sun’s current zodiac sign

Moon

- Dial/ring indicating #’s 1 to 29 or 30 indicates moon’s age
- New moon = 0
- Waxes & become full around day 15
- Wanes up to 29 or 30

- Phase is sometimes shown by a rotating globe/black hemisphere, or a window that reveals part of a wavy black shape beneath

Hour Lines

- Unequal hours were result of dividing up period of daylight into 12 equal hours, & nighttime into another 12
- In Europe, there's more daylight in summer, & less night, so each of 12 daylight hours is longer than a night hour
- Similarly in winter, daylight hours are shorter, night hours are longer
- These unequal hours are shown by curved lines radiating from center
- Longer daylight hours in summer can usually be seen at outer edge of dial, & time in unequal hours is read by noting the intersection of Sun hand w/appropriate curved line

Aspects

- Astrologers placed importance on how Sun, moon, planets were arranged & aligned in sky
- If certain planets appeared at points of a triangle, hexagon, or square, or if they were opposite or next to each other, the appropriate aspect was used to determine the event's significance
- On some clocks you can see the common aspects - triangle, square, hexagon - drawn inside central disk, w/each line marked by symbol for that aspect, & you may also see signs for conjunction & opposition
- On an astrolabe, corners of diff aspects could be lined up on any of planets
- On a clock, disk containing aspect lines can't be rotated at will, so they usually show only aspects of Sun/moon

Dragon Hand: Eclipse Prediction & Lunar Nodes

- Moon's orbit isn't in same plane as Earth's orbit around Sun, but crosses it in 2 places
- Moon crosses ecliptic plane twice a month

  - Once when it goes up above plane
  - Again 15 or so days later when it goes back down below ecliptic
  - These 2 locations are ascending & descending lunar nodes
- Solar & lunar eclipses will occur only when moon is positioned near one of these nodes, bc at other times the moon is either too high or too low for an eclipse to be noticed from Earth
- Some astronomical clocks keep track of position of lunar nodes w/long pointer that crosses the dial
  - This so-called dragon hand makes 1 complete rotation around ecliptic dial every 19 years
  - When dragon hand & new moon coincide, moon is on same plane as Earth & Sun, & so there's every chance that an eclipse will be visible from somewhere on Earth

Atomic Clock

- Clock device that uses an electronic transition frequency in the microwave, optical, ultraviolet region of electromagnetic spectrum of atoms as a frequency standard for its timekeeping element
- Atomic clocks are most accurate time & frequency standards known, & are used as primary standards for international time distribution services, to control wave frequency of television broadcasts, & in global navigation satellite systems such as GPS
- Principle of operation of an atomic clock isn't based on nuclear physics, but rather on atomic physics
  - Uses microwave signal that electrons in atoms emit when they change energy levels
- Early atomic clocks were based on masers at room temp

- Currently, most accurate atomic clocks 1st cool atoms to near absolute 0 temp by slowing them w/lasers & probing them in atomic fountains in a microwave-filled cavity
    - Ex: NIST-F1 atomic clock, 1 of US's national primary time & frequency standards
- Accuracy depends on 2 factors
    - Temp of sample atoms
        - Colder atoms move much more slowly, allowing longer probe times
    - Frequency & intrinsic width of electronic transition
        - Higher frequencies & narrow lines increase precision
- National standards agencies in many countries maintain a network of atomic clocks which are intercompared & kept synchronized to an accuracy of 10^{-9} s/day (approx 1 part in 10^{14})
- These clocks collectively define a continuous & stable time scale, International Atomic Time (TAI)
- For civil time, another time scale is disseminated, Coordinated Universal Time (UTC)
    - UTC is derived from TAI, but approx synchronized, by using leap seconds, to UT1, which is based on actual rotations of Earth w/respect to solar time

History

- 1879: Idea of using atomic transitions to measure time 1st suggested by Lord Kelvin
- Magnetic resonance, developed in 1930s by Isidor Rabi, became practical method for doing this
- 1945: Rabi 1st publicly suggested that atomic beam magnetic resonance might be used as basis of a clock
- 1st atomic clock was an ammonia maser device built in 1949 at US National Bureau of Standards (NBS, now NIST)

- Less accurate than existing quartz clocks, but served to demonstrate the concept
- 1955: 1st accurate atomic clock, caesium standard based on a certain transition of Cs-133 atom, was built by Louis Essen at National Physical Laboratory in UK

- Calibration of caesium standard atomic clock was carried out by use of astronomical time scale ephemeris time (ET)
  - Led to internationally agreed definition of latest SI second being based on atomic time
- Equality of ET second w/(atomic clock) SI second has been verified to within 1 part in 10^{10}
- SI second thus inherits effect of decisions by original designers of ephemeris time scale, determining length of ET second
- Since beginning of development in 1950s, atomic clocks have been based on hyperfine transitions in hydrogen-1, cesium-133, rubidium-87
- 1st commercial atomic clock was Atomichron, manufactured by National Company
  - More than 50 were sold between 1956-1960
  - This bulky & expensive instrument was subsequently replaced by much smaller rack-mountable devices, such as Hewlett-Packard model 5060 caesium frequency standard, released in 1964
- In late 1900s 4 factors contributed to major advances in clocks
  - Laser cooling & trapping of atoms
  - So-called high-finesse Fabry–Pérot cavities for narrow laser line widths
  - Precision laser spectroscopy
  - Convenient counting of optical frequencies using optical combs
- In Aug 2004, NIST scientists demonstrated chip-scale atomic clock
- According to researchers, clock was believed to be 100th size of any other
- Requires no more than 125 mW, making it suitable for battery-driven applications
- This tech became available commercially in 2011

- Ion trap experimental optical clocks are more precise than current cesium standard

Mechanism

- Since 1967, International System of Units (SI) has defined second as duration of 9192631770 cycles of radiation corresponding to transition between 2 energy levels of Cs-133 atom
- This definition makes caesium oscillator the primary standard for time & frequency measurements, called cesium standard
- Other physical quantities (ex: volt & metre) rely on definition of second in their own definitions
- Actual time-reference of an atomic clock consists of an electronic oscillator operating at microwave frequency
- Oscillator is arranged so that its frequency-determining components include an element that can be controlled by a feedback signal
    - This feedback signal keeps oscillator tuned in resonance w/frequency of electronic transition of caesium/rubidium
- Core of atomic clock is a tunable microwave cavity containing gas
- In hydrogen maser clock gas emits microwaves (gas mases) on a hyperfine transition, field in cavity oscillates, & cavity is tuned for max microwave amplitude
- Alternatively, in a caesium/rubidium clock, beam/gas absorbs microwaves & cavity contains an electronic amplifier to make it oscillate
- For both types the atoms in gas are prepared in 1 electronic state prior to filling them into cavity
- For 2nd type the # of atoms which changes electronic states is detected & cavity is tuned for a max of detected state changes
- Most of complexity of clock lies in this adjustment process
    - Adjustment tries to correct for unwanted side-effects, such as frequencies from other electron transitions, temp changes, & spreading in frequencies caused by ensemble effects

  - 1 way of doing this is to sweep microwave oscillator's frequency across a narrow range to generate a modulated signal at detector
  - Detector's signal can then be demodulated to apply feedback to control long-term drift in radio frequency
  - In this way, the quantum-mechanical properties of atomic transition frequency of caesium can be used to tune microwave oscillator to same frequency, except for a small amount of experimental error
  - When a clock is 1st turned on, it takes a while for oscillator to stabilize
  - In practice, feedback & monitoring mechanism is much more complex than described above
- # of other atomic clock schemes are in use for other purposes
  - Rubidium standard clocks are prized for their low cost, small size (commercial standards are as small as 17 cm^3) & short-term stability
  - They are used in many commercial, portable & aerospace applications
  - Hydrogen masers (often manufactured in Russia) have superior short-term stability compared to other standards, but lower long-term accuracy
- Often, 1 standard is used to fix another
  - For example, some commercial applications use a rubidium standard periodically corrected by a global positioning system receiver
  - This achieves excellent short-term accuracy, w/long-term accuracy equal to (& traceable to) US national time standards
- Lifetime of a standard is an important practical issue
  - Modern rubidium standard tubes last more than 10 years, & can cost as little as $50
  - Caesium reference tubes suitable for national standards currently last ~7 years & cost about US $35000
  - Long-term stability of hydrogen maser standards decreases because of changes in cavity's properties over time
- Modern clocks use magneto-optical traps to cool atoms for improved precision

Physics Package Realisations

- # of methods exist for utilizing hyperfine atomic transitions
- These methods, w/their respective benefits & drawbacks, have influenced development` of commercial devices & laboratory standards
- By tradition, hardware that's used to probe atoms is called physics package

Atomic Beam Standard

- Atomic beam standard is a direct extension of Stern-Gerlach atomic splitting experiment
- Atoms of choice are heated in an oven to create gas, which is collimated into a beam
- This beam passes through a state-selector magnet A, where atoms of wrong state are separated out from beam
- Beam is exposed to an RF field at or near transition
- Beam then passes through a space before it is again exposed to RF field
- RF field & static homogeneous magnetic field from C-field coil will change state of atoms
- After 2nd RF field exposure atomic beam passes thru 2nd state selector magnet B, where atom state being selected out of beam at A magnet is being selected
- This way, detected amount of atoms will relate to ability to match atomic transition
- After 2nd state-selector a mass-spectrometer using an ionizer will detect rate of atoms being received
- Modern variants of this beam mechanism use optical pumping to transition all atoms to the same state rather than dumping half the atoms
- Optical detection using scintillation can also be used
- Most common isotope for beam devices Cs-133, but rubidium Rb-87 & thallium Tl-205 are examples of others used in early research

- Frequency errors can be made very small for a beam device, or predicted (such as the magnetic field pull of C-coil) in such a way that a high degree of repeatability & stability can be achieved
- This is why an atomic beam can be used as a primary standard

Atomic Gas Cell Standard

- Atomic gas cell standard builds on a confined reference isotope (often an alkali metal such as Rubidium-87 inside an RF cavity)
- Atoms are excited to a common state using optical pumping
  - When applied RF field is swept over hyperfine spectrum, gas will absorb pumping light, & a photodetector provides response
- Absorption peak steers fly-wheel oscillator
- Typical rubidium gas-cell uses rubidium-87 lamp heated to 108-110 degrees Celsius, & an RF field to excite it to produce light, where D1 & D2 lines are significant wavelengths
- Rb-85 cell filters out D1 line so that only D2 line pumps Rb-87 gas cell in RF cavity
- Among significant frequency pulling mechanisms inherent to gas cell are wall-shift, buffer-gas shift, cavity-shift, light-shift
- Wall-shift occurs as gas bumps into wall of glass container
- Wall-shift can be reduced by wall coating & compensation by buffer gas
- Buffer gas shift comes from reference atoms which bounce into buffer gas atoms such as neon & argon
  - These shifts can be both positive & negative
- Cavity shift comes from RF cavity, which can deform resonance amplitude response
  - This depends upon cavity centre frequency & resonator Q-value
- Light-shift = effect where frequency is pulled differently depending on light intensity, which often is modulated by temp shift of Rb lamp & filter cell
- There are thus many factors in which temp & ageing can shift frequency over time, & this is why a gas cell standard is unfit for a primary standard, but can

become a very inexpensive, low-power & small-size solution for a secondary standard or where better stability compared to crystal oscillators is needed, but not full performance of a Cs beam standard

- Rb gas standards have seen use in telecommunications systems & portable instruments

Active Maser Standard

- Active maser standard is a development from atomic beam standard in which observation time was incremented by using a bounce-box
- By controlling the beam intensity spontaneous emission will provide sufficient energy to provide a continuous oscillation, which is being tapped & used as a reference for a fly-wheel oscillator
- Active maser is sensitive to wall-shift & cavity pulling
- Wall-shift is mitigated by using PTFE coating (or other suitable coating) to reduce effect
- Cavity pulling effect can be reduced by automatic cavity tuning
- In addition the magnetic field pulls the frequency
- While not being long-term stable as caesium beams, it remains 1 of most stable sources available
- Inherent pulling effects makes repeatability troublesome & does prohibit its use as being primary standard, but it makes an excellent secondary standard
- Used as low-noise fly-wheel standard for caesium beam standards

Fountain Standard

- Development from beam standard where beam has been folded back to itself such that 1st & 2nd RF field becomes same RF cavity
- Ball of atoms is laser cooled, which reduces black body temp shifts
- Phase errors between RF cavities are essentially removed
- Length of beam is longer than many beams, but speed is also much slower such that observation time becomes significantly longer & hence higher Q value is achieved in Ramsey fringes

- Cesium fountains have been implemented in many laboratories, but rubidium has even greater ability to provide stability in fountain configuration

Ion Trap Standard

- Set of diff approaches, but their common property is that a cooled ion is confined in an electrostatic trap
- Hyperfine region of available electron is then being tracked similar to that of a gas cell standard
- Ion traps have been used for numerous ions
    - 199-Hg+ was early candidate
- Quantum logic spectroscopy of a single Al ion became most precise in 2008
- In 2010 an improved setup using Mg+ logic ion instead of Be was demonstrated

Power Consumption

- Power consumption of atomic clocks varies w/size
- Atomic clocks on scale of 1 chip require less than 30 mW
- US Time Standard atomic clocks, NIST-F1 & NIST-F2 use far greater quantities of power

Research

- Most research focuses on often conflicting goals of making clocks smaller, cheaper, more accurate, more reliable

Optical Clocks

- New tech, such as femtosecond frequency combs, optical lattices, & quantum info, have enabled prototypes of next-generation atomic clocks
- These clocks are based on optical rather than microwave transitions
- Major obstacle to developing an optical clock is difficulty of directly measuring optical frequencies
- Problem has been solved w/development of self-referenced mode-locked lasers, commonly referred to as femtosecond frequency combs

- Before demo of frequency comb in 2000, terahertz techniques were needed to bridge gap between radio & optical frequencies, & systems for doing so were cumbersome & complicated
- W/refinement of frequency comb, these measurements have become much more accessible & numerous optical clock systems are now being developed around world
- As in radio range, absorption spectroscopy is used to stabilize an oscillator (in this case, a laser)
- When optical frequency is divided down into countable radio frequency using a femtosecond comb, bandwidth of phase noise is also divided by that factor
- Altho bandwidth of laser phase noise is generally greater than stable microwave sources, after division it is less
- 2 primary systems under consideration for use in optical frequency standards are single ions isolated in an ion trap & neutral atoms trapped in an optical lattice
- These 2 techniques allow atoms/ions to be highly isolated from external perturbations, thus producing an extremely stable frequency reference
- Optical clocks have already achieved better stability & lower systematic uncertainty than best microwave clocks
- Puts them in position to replace current standard for time, cesium fountain clock
- Atomic systems under consideration include Al+, Hg+/2_, Hg, Sr, Sr+/2+, In+/3?, Mg, Ca, Ca+, Yb+/2+/3+, Yb
- Rare-earth element ytterbium (Yb) is valued not so much for its mechanical properties but for its complement of internal energy levels
- Estimated amount of uncertainty achieved corresponds to Yb clock uncertainty of ~1s over lifetime of universe so far, 15 bil years, according to scientists at Joint Quantum Institute (JQI) & University of Delaware in Dec 2012
- In 2013 optical lattice clocks (OLCs) were shown to be as good as or better than cesium fountain clocks

- 2 optical lattice clocks containing ~10k atoms of strontium-87 were able to stay in synchrony w/each other at precision of at least 1.5×10^{-16}, which is as accurate as experiment could measure
- These clocks have been shown to keep pace w/all 3 of caesium clocks at Paris Observatory
- 2 reasons for possibly better precision
    - Frequency is measured using light, which has a much higher frequency than microwaves
    - By using many atoms, any errors are averaged
- Using ytterbium atoms, a new record for stability w/precision of 1.6×10^{-18} was published on August 22, 2013
- At this stability, the 2 optical lattice clocks NIST research team used would differ less than one 10th of a second over age of universe
    - 10 times better than previous experiments
- Clock relies on 10k ytterbium atoms cooled to 10 microkelvin & trapped in an optical lattice
- A laser at 578 nm excites atoms between 2 of their energy levels
- Having established stability of clocks, researchers are studying external influences & evaluating remaining systematic uncertainties, in hope that they can bring clock's accuracy down to level of its stability
- An improved OLC was described in a 2014 Nature paper

Quantum Clocks

- March 2008, physicists at NIST described quantum logic clock based on individual ions of beryllium & aluminium
- Clock was compared to NIST’s mercury ion clock
- Most accurate clocks that had been constructed, w/neither clock gaining nor losing time at a rate that would exceed a second in over a billion years
- In Feb 2010, NIST physicists described a second, enhanced version of quantum logic clocks based on individual ions of Mg & Al
- Considered world’s most precise clock

    - Offers more than twice the precision of original

Evaluated Accuracy

- In 2011, NPL-CsF2 caesium fountain clock operated by National Physical Laboratory (NPL), which serves as UK primary time & frequency standard, was improved regarding 2 largest sources of measurement uncertainties (distributed cavity phase & microwave lensing frequency shifts)
- As of 2011 this resulted in an evaluated frequency uncertainty reduction from 4.1×10^{-16} to 2.3×10^{-16} (lowest value for any primary national standard at the time)
- At this frequency uncertainty, NPL-CsF2 is expected to neither gain nor lose a second in more than 138 million years
- NIST-F2 caesium fountain clock operated by National Institute of Standards & Technology (NIST) was launched in April 2014, to serve as a new US civilian time & frequency standard, along w/NIST-F1 standard
- NIST-F2 was designed using lessons learned from NIST-F1
- Key advance is that vertical flight tube is now chilled inside container of liquid nitrogen, at -193 °C (-315.4 °F)
- This cycled cooling dramatically lowers background radiation & reduces some of very small measurement errors that must be corrected in NIST-F1

Applications

- Development of atomic clocks has led to many scientific & technological advances such as worldwide system of precise position measurement (GPS)
- Applications in Internet which depend critically on frequency & time standards
- Atomic clocks are installed at sites of time signal radio transmitters
- Used at some long wave & medium wave broadcasting stations to deliver a very precise carrier frequency
- Atomic clocks are used in many scientific disciplines, such as for long-baseline interferometry in radio astronomy

Global Positioning System

- Provides very accurate timing & frequency signals
- GPS receiver works by measuring relative time delay of signals from min of 4, but usually more, GPS satellites, each of which has at least 2 onboard caesium & as many as 2 Rb atomic clocks
- Relative times are mathematically transformed into 3 absolute spatial coordinates & 1 absolute time coordinate
- Time is accurate to within ~50 nanoseconds
- Inexpensive GPS receivers may not assign a high priority to updating display, so displayed time may differ perceptibly from internal time
- Precision time references that use GPS are marketed for use in computer networks, laboratories, cellular communications networks, & do maintain accuracy to within ~50ns

Time Signal Radio Transmitters

- Radio clock is a clock that automatically synchronizes itself by means of gov radio time signals received by a radio receiver
- Many retailers market radio clocks inaccurately as atomic clocks, altho the radio signals they receive originate from atomic clocks, they aren't atomic clocks themselves
- They're inexpensive time-keeping devices w/accuracy of ~1s
- Instrument grade time receivers provide higher accuracy
- Such devices incur transit delay of approx 1 ms for every 300 km (186 mi) of distance from radio transmitter
- Many govs operate transmitters for time-keeping purposes

Hourglass

- Sandglass/sand timer/sand watch/sand clock/egg timer
- Measures passage of a few min/hour of time

- 2 connected vertical glass bulbs allowing regulated trickle of material from top to bottom
- Once top bulb is empty, can be inverted to begin timing again
- Factors affecting time measured include amt of sand, bulb size, neck width, sand quality
- Alternatives to sand are powdered eggshell & powdered marble (sources disagree on best material)
- In modern times, hourglasses are ornamental/used when an approx measure suffices, as in egg timers for cooking/board games

History

Antiquity

- Origin is unclear, altho unlike predecessor, 1st referenced use:
  - According to American Institute of NY
    - Clepsammia/sandglass was invented at Alexandria ~150 BC
  - According to Journal of British Archaeological Association
    - So called clepsammia were in use before time of St Jerome (335 AD) & 1st representation of hourglass it is in a sarcophagus dated c. 350 AD, representing wedding of Peleus & Thetis, discovered in Rome in 18th century, studied by Wincklemann in 19th century, who remarked hourglass held by Morpheus in his hands

Middle Age

- Disappears until it's been re-introduced in medieval Europe
- By 8th century it's mentioned by monk named Luitprand, who served at cathedral in Chartres, France
- Not until 14th century that hourglass was seen commonly, earliest firm evidence being depiction in 1338 fresco Allegory of Good Government by Ambrogio Lorenzetti
- Use of marine sandglass has been recorded since 14th century

- Written records about it were mostly from logbooks of European ships
- In same period it appears in other records & lists of ships stores
- Earliest recorded reference that can be said w/certainty to refer to marine sandglass dates from c. 1345, in a receipt of Thomas de Stetesham, clerk of King's ship La George, in reign of Edward III of England
- Marine sandglasses were very popular on board ships, as they were most dependable measurement of time while at sea
- Unlike clepsydra, motion of ship while sailing didn't affect hourglass
- Fact that hourglass also used granular materials instead of liquids gave it more accurate measurements, as clepsydra was prone to get condensation inside it during temp changes
- Seamen found that hourglass was able to help them determine longitude, distance east/west from certain point, w/reasonable accuracy
- Found popularity on land as well
- As use of mechanical clocks to indicate times of events like church services became more common, creating 'need to keep track of time,' demand for time-measuring devices inc
- Hourglasses were essentially inexpensive, as they required no rare tech to make & their contents weren't hard to come by, & as manufacturing of these instruments became more common, their uses became more practical
- Commonly seen in use in churches, homes, workplaces to measure sermons, cooking time, time spent on breaks from labor
- Bc they were being used for more everyday tasks, model of hourglass began to shrink
- Smaller models were more practical & very popular as they made timing more discreet
- After 1500 AD, hourglass wasn't as widespread as it had been
    - Due to development of mechanical clock, which became more accurate, smaller & cheaper, & made keeping time easier
- Hourglass didn't disappear entirely

- Altho became relatively less useful as clock tech advanced, hourglasses remained desirable in their design
- Some of most famous hourglasses are 12-hour hourglass of Charlemagne of France & hourglasses of Henry VIII of England, made by artist Holbein in 16th century
    - Oldest known surviving hourglass resides in British Museum in London
- Not until 18th century did Harrison brothers, John & James, come up w/marine chronometer that significantly improved on stability of hourglass at sea
- Taking elements from design logic behind hourglass, were able to invent a marine chronometer that was able to accurately measure journey from England to Jamaica, w/only a miscalculation of 5 s, in 1761

Design

- Shape behind hourglass has hardly any written evidence of why its external form is shape that it is
- Glass bulbs used, however, have changed in style & design over time
- While main designs have always been ampoule in shape, bulbs weren't always connected
- 1st hourglasses were 2 separate bulbs w/cord wrapped at their union that was then coated in wax to hold piece together & let sand flow in between
- Not until 1760 that both bulbs were blown together to keep moisture out of bulbs & regulate pressure within bulb that varied the flow

Material

- Many didn't use sand
- Combo of powdered marble, tin/lead oxides, pulverized/burnt eggshell
- Over time, diff textures of granule matter were tested to see which gave most constant flow within bulbs

- Later discovered that for perfect flow to be achieved ratio of granule bead to width of bulb neck needed to be 1/12 or more but not greater than ½ neck of bulb

Practical Uses

- Early dependable, reusable, accurate measure of time
- Rate of flow of sand is independent of depth in upper reservoir, & instrument won't freeze in cold weather
- From 15th century onwards, being used in range of applications at sea, in church, in industry & in cookery
- During the voyage of Ferdinand Magellan around globe, 18 hourglasses from Barcelona were in ship's inventory, after trip being authorized by emperor Charles V
  - Job of ships' page to turn hourglasses & thus provide times for ship's log
  - Noon was reference time for navigation, which didn't depend on glass, as Sun would be at its zenith
- # of sandglasses could be fixed in a common frame, each w/diff operating time, as in a 4-way Italian sandglass likely from 17th century, in collections of The Science Museum in South Kensington, London, which could measure intervals of ¼, ½, ¾, & 1 hour (which were also used in churches, for priests & ministers to measure lengths of sermons)

Modern Practical Uses

- No longer widely used for keeping time, some institutions maintain them
- Both houses of Australian Parliament use 3 hourglasses to time certain procedures, such as divisions
- Sandglass is still widely used as kitchen egg timer
  - For cooking eggs, a 3-min timer is typical, hence name "egg timer" for 3-min hourglasses
- Egg timers are sold widely as souvenirs

- Sand timers are also sometimes used in games such as Pictionary & Boggle to implement a time constraint on rounds of play, & provide a sense of urgency to game of Quicksand

Symbolic Uses

- Unlike most other methods of measuring time, hourglass concretely represents present as being between past & future, & this has made it an enduring symbol of time itself
- It, sometimes w/addition of metaphorical wings, is often depicted as a symbol that human existence is fleeting, & that "sands of time" will run out for every human life
- Used thus on pirate flags, to strike fear into hearts of pirates' victims
- In England, sometimes placed in coffins, graced gravestones for centuries
- Also used in alchemy as a symbol for hour
- Former Metropolitan Borough of Greenwich in London used an hourglass on its coat of arms, symbolising Greenwich's role as origin of GMT
- District's successor, Royal Borough of Greenwich, uses 2 hourglasses on its coat of arms

Modern Symbolic Uses

- Recognition of hourglass as symbol of time has survived its obsolescence as a timekeeper
- American television soap opera *Days of Our Lives*, since 1st broadcast in 1965, has displayed an hourglass in its opening credits, w/narration, “Like sands through the hourglass, so are the days of our lives,” spoken by Macdonald Carey
- Various computer graphical user interfaces may change pointer to an hourglass during a period when program is in middle of a task, & may not accept user input
- During that period other programs, for ex in diff windows, may work normally

- When such an hourglass doesn't disappear, it suggests a program is in an infinite loop & needs to be terminated, or is waiting for some external event (such as user inserting a CD)
- Unicode has an HOURGLASS symbol at U+231B (⌛)

Hourglass Motif

- Bc of its symmetry, graphic signs resembling an hourglass are seen in art of cultures which never encountered such objects
- Vertical pairs of triangles joined at apex are common in Native American art; both in N America, where it can represent, for ex, body of Thunderbird or (in more elongated form) an enemy scalp, & in S America, where it's believed to represent a Chuncho jungle dweller
- In Zulu textiles they symbolize a married man, as opposed to a pair of triangles joined at base, which symbolize married woman
- Neolithic examples can be seen among Spanish cave paintings
- Observers have even given name "hourglass motif" to shapes which have more complex symmetry, such as a repeating circle & cross pattern from Solomon Islands
- Both members of Project Tic Toc, from TV series Time Tunnel & Challengers of the Unknown use symbols of hourglass representing time travel/time running out

Pulsar Clock

- Clock which depends on counting radio pulses emitted by pulsars
- Pulsar clock in Gdańsk
    - 1st pulsar clock in world was installed in St Catherine's Church, Gdańsk, Poland, in 2011
    - 1st clock to count time using signal source outside Earth
    - Consists of a radiotelescope w/16 antennas, which receive signals from 6 designated pulsars
    - Digital processing of pulsar signals is done by an FPGA device

- Pulsar clock in Brussels
    - On Oct 5, 2011, a display showing exact time of pulsar clock was installed in European Parliament in Brussels, Belgium

ab urbe condita

- "***ab urbe condita***" (related to "***anno urbis conditae***"; **A. U. C.**, **AUC**,**a.u.c.**; also "***anno urbis***", short **a.u.**) is a Latin phrase meaning "from the founding of the City (Rome)"
- traditionally dated to 753 BC.
- AUC is a year-numbering system used by some ancient Roman historians to identify particular Roman years.
- Renaissance editors sometimes added AUC to Roman manuscripts they published, giving the false impression that the Romans usually numbered their years using the AUC system.
- The dominant method of identifying Roman years in Roman times was to name the two consuls who held office that year.
- The regnal year of the emperor was also used to identify years, especially in the Byzantine Empire after 537 when Justinian required its use. Examples of continuous numbering include counting by regnal year, principally found in the writings of German authors, for example Mommsen's *History of Rome*, and (most ubiquitously) in the Anno Domini year-numbering system.

Significance

- From Emperor Claudius (reigned 41–54 AD) onwards,Varro's calculation (see below) superseded other contemporary calculations.
- Celebrating the anniversary of the city became part of imperial propaganda.
- Claudius was the first to hold magnificent celebrations in honour of the city's anniversary, in 48 AD, 800 years after the founding of the city

Calculation by Varro

- The traditional date for the founding of Rome of 21 April 753 BC, was initiated by Varro

Relationship with Anno Domini

- 1 ab urbe condita = 753 Before Christ or BC
- 2 AUC = 752 BC
- 749 AUC = 5 BC
- 750 AUC = 4 BC (Death of Herod the Great)
- 753 AUC = 1 BC
- 754 AUC = 1 Anno Domini
- 755 AUC = 2 AD
- 759 AUC = 6 AD (Quirinius becomes governor of Syria)
- 2206 AUC = 1453 AD (Fall of Constantinople)
- 2700 AUC = 1947 AD
- 2753 AUC = 2000 AD
- 2768 AUC = 2015 AD
- 2778 AUC = 2025 AD
- 2800 AUC = 2047 AD
- 2813 AUC = 2060 AD
- 3000 AUC = 2247 AD

Relativity

- Relativity postulate = laws of physics are same for observers in all inertial reference frames & no one frame is preferred over any other
- Speed of light postulate = speed of light in vacuum has same value *c* in all directions & in all inertial reference frames

Relativity of Simultaneity

- If 2 observers are in relative motion, they won't, in general, agree as to whether 2 events are simultaneous
- If 1 observer finds them to be simultaneous, the other generally won't

- Simultaneity is not an absolute concept but rather a relative one, depending on motion of observer
- t=vx'c2 (simultaneous events in *S'*)

Relativity of Time

- Time interval between 2 events depends on how far apart they occur in both space & time (their spatial & temporal separations are entangled)
- Proper time/proper time interval = when 2 events occur at the same location in an inertial reference frame, the time interval between them, measured in that frame
- Measurements of the same time interval from any other inertial reference frame are always greater
- Time dilation = amount by which a measured time interval is greater than the corresponding proper time interval
    - t=t01-(v/c)2
        - *t*: time observed in other reference frame
        - t0: time in observer's own reference frame (rest time)
        - *v*: speed of moving object
        - *c*: speed of light in a vacuum
- : speed parameter
- Lorentz factor: =11-2=11-(v/c)2
- t=t0

Relativity of Length

- Proper length/rest length = length of an object measured in the rest frame of the object
- Measurements of length from any reference frame that's in relative motion parallel to that length are always less than proper length
- Length contractions occur only along direction of relative motion
- L=L01-v2c2=L0
- LL0 =vt0vt=1

Relativity of Mass

- m=m01-v2c2=m0
    - m0: “rest mass”

Lorentz Transformation Equations

- Valid at all physically possible speeds
- x'=(x-vt)
- y'=y
- z'=z
- t'=(t-vx/c2)

Galilean Transformation Equations

- Approx valid at low speeds
- x'=x-vt
- t'=t

Relativity of Velocities

- Relativistic velocity transformation
    - u=u'+v1+u'v/c2
- Classical velocity transformation
    - u=u'+v
- xt=u, velocity of particle as measured in *S*
- x't'=u', velocity of particle as measured in *S’*

Doppler Effect for Light

- Shift in detected frequency
- Proper frequency of source = frequency that’s measured by an observer in the rest frame of the source
- f=f01-1+ (source & detector separating)

- f: frequency detected by an observer moving w/velocity relative to that rest frame
- f0: proper frequency
- =vc
- When direction of v is directly toward source, change signs in front of both

- Low-speed Doppler effect
  - f=f0(1-+122) (source & detector separating, 1
- Astronomical Doppler effect
  - v=0c (radial speed of light source, vc)
    - 0: proper wavelength (wavelength associated with f0)
    - : wavelength Doppler shift of light source
    - If light source is moving toward us, then is shorter than 0, is negative, & Doppler shift is called a blue shift
- Transverse Doppler effect
  - f=f01-2
  - T=T01-2=T0
    - T0: proper period of source

A New Look at Energy

- Mass energy = energy associated with mass of object
  - E0=mc2
- Total energy
  - Total energy of an isolated system can't change
  - E0i=E0f+Q
  - Mic2=Mfc2+Q
- Kinetic energy
  - K=mc2(-1)
- Momentum & kinetic energy
  - p2=2Km (classical)
  - E2=(pc)2+(mc2)2

Time Standards

- Time standard = a specification for measuring time: either the rate at which time passes; or points in time; or both
- In modern times, several time specifications have been officially recognized as standards, where formerly they were matters of custom and practice
  - An example of a kind of time standard can be a time scale, specifying a method for measuring divisions of time
  - A standard for civil time can specify both time intervals and time-of-day
- Standardized time measurements are made using a clock to count periods of some cyclic change, which may be either the changes of a natural phenomenon or of an artificial machine
- Historically, time standards were often based on the Earth's rotational period
- From the late 17th century to the 19th century it was assumed that the Earth's daily rotational rate was constant
- Astronomical observations of several kinds, including eclipse records, studied in the 19th century, raised suspicions that the rate at which Earth rotates is gradually slowing and also shows small-scale irregularities, and this was confirmed in the early twentieth century
- Time standards based on Earth rotation were replaced (or initially supplemented) for astronomical use from 1952 onwards by an *ephemeris time* standard based on the Earth's orbital period and in practice on the motion of the Moon
- Invention in 1955 of the caesium atomic clock has led to the replacement of older & purely astronomical time standards, for most practical purposes, by newer time standards based wholly or partly on atomic time
- Various types of second & day are used as the basic time interval for most time scales
- Other intervals of time (minutes, hours, years) are usually defined in terms of these 2

Time Standards Based On Earth Rotation

- **Apparent solar time** ('apparent' is often used in English-language sources, but 'true' in French astronomical literature) is based on the solar day, which is the period between one solar noon (passage of the real Sun across the meridian) & the next
  - A solar day is approximately 24 hours of mean time
  - Because the Earth's orbit around the sun is elliptical, and because of the obliquity of the Earth's axis relative to the plane of the orbit (the ecliptic), the apparent solar day varies a few dozen seconds above or below the mean value of 24 hours
  - As the variation accumulates over a few weeks, there are differences as large as 16 minutes between apparent solar time and mean solar time
  - However, these variations cancel out over a year
  - There are also other perturbations such as Earth's wobble, but these are less than a second per year
- **Sidereal time** is time by the stars
  - A sidereal rotation is the time it takes the Earth to make one revolution with respect to the stars, approximately 23 hours 56 minutes 4 seconds
  - For accurate astronomical work on land, it was usual to observe sidereal time rather than solar time to measure mean solar time, because the observations of 'fixed' stars could be measured and reduced more accurately than observations of the Sun (in spite of the need to make various small compensations, for refraction, aberration, precession, nutation and proper motion)
  - It is well known that observations of the Sun pose substantial obstacles to the achievement of accuracy in measurement
  - In former times, before the distribution of accurate time signals, it was part of the routine work at any observatory to observe the sidereal times of meridian transit of selected 'clock stars' (of well-known position and movement), and to use these to correct observatory clocks running local mean sidereal time; but nowadays local sidereal time is usually generated by computer, based on time signals

- **Mean solar time** was originally apparent solar time corrected by the equation of time
    - Mean solar time was sometimes derived, especially at sea for navigational purposes, by observing apparent solar time and then adding to it a calculated correction, the **equation of time**, which compensated for two known irregularities, caused by the ellipticity of the Earth's orbit and the obliquity of the Earth's equator and polar axis to the ecliptic (which is the plane of the Earth's orbit around the sun)
- **Greenwich Mean Time** (**GMT**) was originally mean time deduced from meridian observations made at the Royal Greenwich Observatory (RGO)
    - The principal meridian of that observatory was chosen in 1884 by the International Meridian Conference to be the Prime Meridian
    - GMT either by that name or as 'mean time at Greenwich' used to be an international time standard, but is no longer so; it was initially renamed in 1928 as Universal Time (UT) (partly as a result of ambiguities arising from the changed practice of starting the astronomical day at midnight instead of at noon, adopted as from 1 January 1925)
    - The more current refined version of UT, UT1, is still in reality mean time at Greenwich
    - Greenwich Mean Time is still the legal time in the UK (in winter, and as adjusted by one hour for summer time)
    - But Coordinated Universal Time (UTC) (an atomic-based time scale which is always kept within 0.9 second of UT1) is in common actual use in the UK, and the name GMT is often inaccurately used to refer to it
- **Universal Time** (**UT**) is a time scale based on the mean solar day, defined to be as uniform as possible despite variations in Earth's rotation
    - **UT0** is the rotational time of a particular place of observation
        - It is observed as the diurnal motion of stars or extraterrestrial radio sources
    - **UT1** is computed by correcting UT0 for the effect of polar motion on the longitude of the observing site

        - It varies from uniformity because of the irregularities in Earth's rotation

Time Standards for Planetary Motion Calculations

- Ephemeris time and its successor time scales described below have all been intended for astronomical use, e.g. in planetary motion calculations, with aims including uniformity, in particular, freedom from irregularities of Earth rotation
- Some of these standards are examples of dynamical time scales and/or of coordinate time scales
- **Ephemeris Time** (**ET**) was from 1952 to 1976 an official time scale standard of the International Astronomical Union
    - Dynamical time scale based on the orbital motion of the Earth around the Sun, from which the ephemeris second was derived as a defined fraction of the tropical year
    - This ephemeris second was the standard for the SI second from 1956 to 1967, and it was also the source for calibration of the caesium atomic clock; its length has been closely duplicated, to within 1 part in 10^{10}, in the size of the current SI second referred to atomic time
    - This Ephemeris Time standard was non-relativistic and did not fulfil growing needs for relativistic coordinate time scales
    - It was in use for the official almanacs and planetary ephemerides from 1960 to 1983, and was replaced in official almanacs for 1984 and after, by numerically integrated Jet Propulsion Laboratory Development Ephemeris DE200 (based on the JPL relativistic coordinate time scale T_{eph})
    - For applications at the Earth's surface, ET's official replacement was Terrestrial Dynamical Time (TDT), since redefined as Terrestrial Time (TT)
    - For the calculation of ephemerides, TDB was officially recommended to replace ET, but deficiencies were found in the definition of TDB (though

    - not affecting T_{eph}), and these led to the IAUdefining and recommending further time scales, Barycentric Coordinate Time (TCB) for use in the solar system as a whole, and Geocentric Coordinate Time (TCG) for use in the vicinity of the Earth
    - As defined, TCB (as observed from the Earth's surface) is of divergent rate relative to all of ET, T_{eph} and TDT/TT;[7] and the same is true, to a lesser extent, of TCG
    - The ephemerides of sun, moon and planets in current widespread and official use continue to be those calculated at the Jet Propulsion Laboratory (updated as from 2003 to DE405) using as argument T_{eph}
- **Terrestrial Dynamic Time (TDT)** replaced Ephemeris Time and maintained continuity with it
    - TDT is a uniform atomic time scale, whose unit is the SI second. TDT is tied in its rate to the SI second, as is International Atomic Time (TAI), but because TAI was somewhat arbitrarily defined at its inception in 1958 to be initially equal to a refined version of UT, TT is offset from TAI, by a constant 32.184 seconds
    - The offset provided a continuity from Ephemeris Time to TDT
    - TDT has since been redefined as Terrestrial Time (TT)
- **Barycentric Dynamical Time** (**TDB**) is similar to TDT but includes relativistic corrections that move the origin to the barycenter
    - TDB differs from TT only in periodic terms
    - The difference is at most 2 milliseconds
    - In 1991, in order to clarify the relationships between space-time coordinates, new time scales were introduced, each with a different frame of reference
    - Terrestrial Time is time at Earth's surface
    - Geocentric Coordinate Time is a coordinate time scale at Earth's center
    - Barycentric Coordinate Time is a coordinate time scale at the center of mass of the solar system, which is called the barycenter
    - Barycentric Dynamical Time is a dynamical time at the barycenter

- **Terrestrial Time** (**TT**) is the time scale which had formerly been called Terrestrial Dynamical Time
  - It is now defined as a coordinate time scale at Earth's surface
- **Geocentric Coordinate Time** (**TCG**) is a coordinate time having its spatial origin at the center of Earth's mass
  - TCG is linearly related to TT as: TCG - TT = L_G * (JD -2443144.5) * 86400 seconds, with the scale difference L_G defined as 6.969290134e-10 exactly
- **Barycentric Coordinate Time** (**TCB**) is a coordinate time having its spatial origin at the solar system barycenter
  - TCB differs from TT in rate and other mostly periodic terms
  - Neglecting the periodic terms, in the sense of an average over a long period of time the two are related by: TCB - TT = L_B * (JD -2443144.5) * 86400 seconds
  - According to IAU the best estimate of the scale difference L_B is 1.55051976772e-08

Constructed Time Standards

- **International Atomic Time** (**TAI**) is the primary international time standard from which other time standards, including UTC, are calculated
  - TAI is kept by the BIPM (International Bureau of Weights and Measures), and is based on the combined input of many atomic clocks around the world, each corrected for environmental and relativistic effects
  - It is the primary realisation of Terrestrial Time
- **Coordinated Universal Time** (**UTC**) is an atomic time scale designed to approximate Universal Time
  - UTC differs from TAI by an integral number of seconds
  - UTC is kept within 0.9 second of UT1 by the introduction of one-second steps to UTC, the "leap second"
  - To date these steps have always been positive
- **Standard time** or **civil time** in a region deviates a fixed, round amount, usually a whole number of hours, from some form of Universal Time, now usually UTC

    - The offset is chosen such that a new day starts approximately while the sun is crossing the nadir meridian
    - Alternatively the difference is not really fixed, but it changes twice a year a round amount, usually one hour, see Daylight saving time

Other Time Scales

- Julian day number is a count of days elapsed since Greenwich mean noon on 1 January 4713 B.C., Julian proleptic calendar
- The Julian Date is the Julian day number followed by the fraction of the day elapsed since the preceding noon
- Conveniently for astronomers, this avoids the date skip during an observation night
- Modified Julian day (MJD) is defined as MJD = JD - 2400000.5
- An MJD day thus begins at midnight, civil date
- Julian dates can be expressed in UT, TAI, TDT, etc. and so for precise applications the timescale should be specified, e.g. MJD 49135.3824 TAI

Time Related Songs + Lyrics

Bill Hayley - Rock Around the Clock

- Bill Hayley's version of *Rock Around The Clock* became an anthem for the rebellious youth of the 50s
- Reached the #1 spot in the US and in the UK, & was also listed as #158 on Rolling Stone magazine's 500 Greatest Songs of All Time
- *When the clock strikes two, three and four,*
  If the band slows down we'll yell for more,
  We're gonna rock around the clock tonight,
  We're gonna rock, rock, rock, 'til broad daylig

The Chambers Brothers - Time Has Come Today

- Since its release in 1967 by The Chamber Brothers, *Time Has Come Today* has been covered time & time again by numerous artists including The Ramones, Joan Jett, & even by Bo Bice on American Idol

- Throughout the song, the sound of a cowbell can be heard, which is said to represent the sound of a ticking clock
- *Now the time has come*

  There's no place to run

  I might get burned up by the sun

  But I had my fun

Chicago - Does Anyone Know What Time It Is

- Originally written by Robert Lamm, *Does Anybody Know What Time It Is* comes off of Chicago's debut album, The Chicago Transit Authority
- Following the success of the songs, *Make Me Smile* and *25 or 6 to 4*, *Does Anybody Know What Time It Is* became the band's 3rd straight hit single
- *Does anybody really know what time it is?*

  Does anybody really care?

Cyndi Lauper - Time After Time

- As the 2nd single off of Cyndi Lauper's album, She's So Unusual, *Time After Time* is one of Cyndi's most successful hits
- The song was nominated for Song of the Year at the 1985 Grammy Awards, but lost out to Tina Turner's *What's Love Got To Do With It*
- Since its release, the song has been covered by more than 120 different artists
- *Lying in my bed I hear the clock tick and think of you*

  Caught up in circles confusion--Is nothing new

Coldplay - Clocks

- Off of Coldplay's 2nd album, A Rush of Blood To the Head, *Clocks* was built off of a piano riff that popped into vocalist Chris Martin's head
- When they wrote the song, they had already recorded 10 songs for their 2nd album, so *Clocks* was pushed aside as something to work on for the 3rd album
- After the band's manager heard the song, he encouraged them to rework it & put it on A Rush of Blood To the Head

- *Confusion never stops*
  Closing walls and ticking clocks

Foo Fighters - Times Like These

- As the 2nd single off of Foo Fighters' album, One By One, *Times Like These* is one of Foo Fighters' most well known songs
- The beginning lyric, "I'm a new day rising," is a reference to *New Day Rising* by one of Grohl's favourite bands, Hüsker Dü
- *It's times like these you learn to live again*
  It's times like these you give and give again
  It's times like these you learn to love again
  It's times like these time and time again

Foreigner - Feels Like the First Time

- Off of their debut album Foreigner, released in 1977, *Feels Like the First Time* was the band's debut single
- Thanks to other hits such as *Cold as Ice* & *Long, Long Way From Home*, the album ended up selling over 4 million copies in the US
- *I have waited a lifetime, spent my time so foolishly*
  But now that I found you, together we'll make history

Jim Croce - Time in a Bottle

- Sadly for Jim Croce, he was never able to see the success of his song, *Time In a Bottle*
- Reached the top spot on the Billboard charts in 1973 3 months after Croce died in a plane crash
- *If I could save time in a bottle*
  The first thing that I'd like to do
  Is to save every day 'til eternity passes away
  Just to spend them with you

Owl City - Good Time

Pink Floyd - Time

- *Time* by Pink Floyd comes off of epic The Dark Side of the Moon
- At beginning of the song, various clocks can be heard, followed by a 2-minute drum solo by Nick Mason
- Time is the only song on the album credited to all 4 members of the band
- *Ticking away the moments that make up a dull day*
  You fritter and waste the hours in an offhand way

Rocky Horror Picture Show - Time Warp

- Famously known for appearance in cult classic, The Rocky Horror Picture Show
- Since its release, the song has been covered/remade by many including Kidz Bop Kids, Alvin + Chipmunks, Glee
- *He had a pickup truck, and the devil's eyes*
  He stared at me and I felt a change
  Time meant nothing, never would again