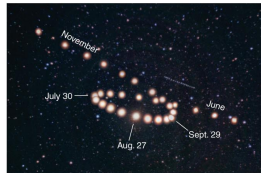
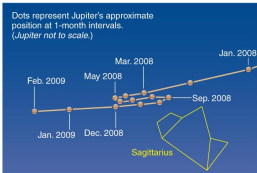
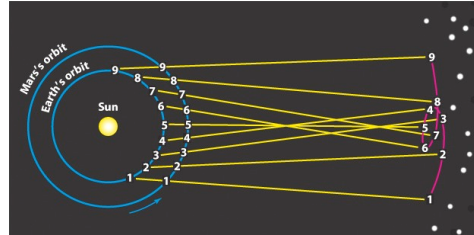


What was once so mysterious about planetary motion in our sky?

- Planets usually move slightly *eastward* from night to night relative to the stars. **You cannot see this motion on a single night.**
- But sometimes they go *westward* relative to the stars for a few weeks: **apparent retrograde motion**



We see apparent retrograde motion when we pass by a planet



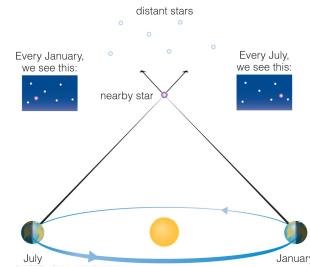
Although Mars moves steadily along its orbit, it appears (from Earth's perspective) to slow to a stop and move westward (retrograde) relative to the background stars as Earth passes it

Explaining Apparent Retrograde Motion

- Easy *for us* to explain: occurs when we “lap” another planet (or when Mercury or Venus laps us)
- But very difficult to explain if you think that Earth is the center of the universe!
- In fact, ancients considered but rejected the correct explanation*

Why did the ancient Greeks reject the real explanation for planetary motion?

- Their inability to observe **stellar parallax** was a major factor.



The Greeks knew that the lack of observable parallax could mean one of two things:

- Stars are so far away that stellar parallax is too small to notice with the naked eye
- Earth does not orbit Sun; it is the center of the universe

With rare exceptions such as Aristarchus, the Greeks rejected the correct explanation (1) because they did not think the stars could be *that* far away

Thus setting the stage for the long, historical showdown between Earth-centered and Sun-centered systems.

In what ways do all humans employ scientific thinking?

- Scientific thinking is based on everyday ideas of observation and trial-and-error experiments.

How did astronomical observations benefit ancient societies?

- Keeping track of time and seasons
 - for practical purposes, including agriculture
 - for religious and ceremonial purposes
- Aid to navigation

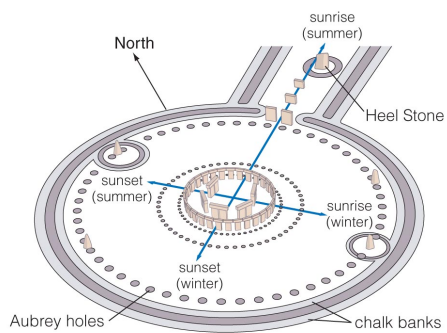
What did ancient civilizations achieve in astronomy?

- Daily timekeeping
- Tracking the seasons and calendar
- Monitoring lunar cycles
- Monitoring planets and stars
- Predicting eclipses
- And more...

- Egyptian obelisk:
Shadows tell time of day.



Stonehenge

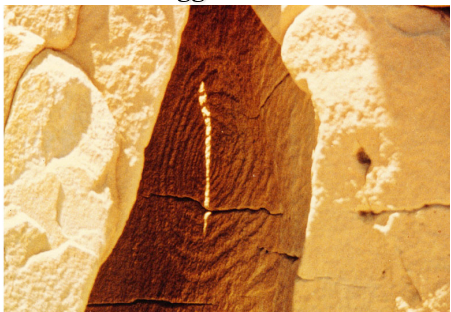


England: Stonehenge (1550 B.C.)



New Mexico: Anasazi kiva aligned north-south

The "Sun Dagger" of the Anasazi



SW United States: "Sun Dagger" marks summer solstice



Scotland: 4,000-year-old stone circle; Moon rises as shown here every 18.6 years.

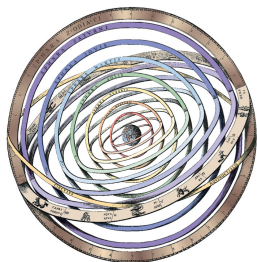


Macchu Pichu, Peru: Structures aligned with solstices.



Our mathematical and scientific heritage originated with the civilizations of the Middle East

Why does modern science trace its roots to the Greeks?



Greek geocentric model (c. 400 B.C.)

- Greeks were the first people known to make *models* of nature.
- They tried to explain patterns in nature without resorting to myth or the supernatural.

How did the Greeks explain planetary motion?

Underpinnings of the Greek geocentric model:

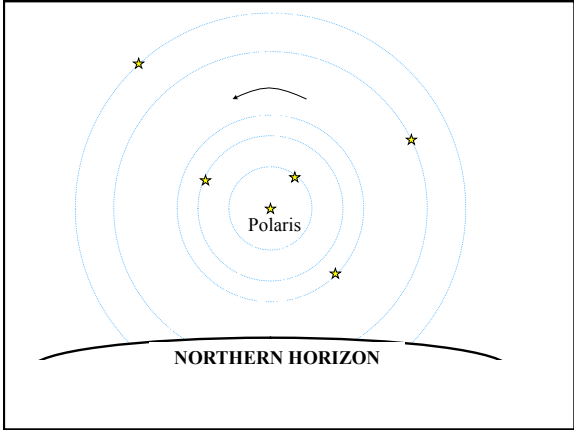
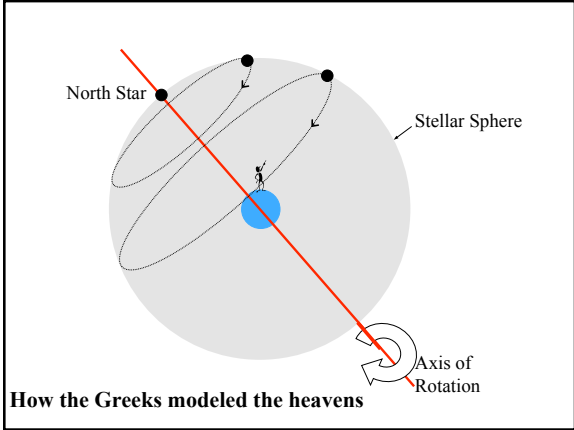


Plato



Aristotle

- Earth at the center of the universe
- Heavens must be "perfect": Objects moving on perfect spheres or in perfect circles.



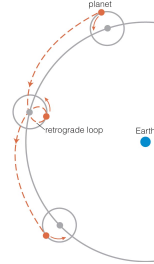

BUT - THERE WAS A COMPLICATION

- There were stars that appeared to move across the sky without staying in their respective constellations
- WANDERING STARS
 - (Greek word for wanderer is *planete*)

So how did the Greek model explain retrograde motion?

- Planets orbit Earth with a “circle on circle” motion (*epicycle*)
- Claudius Ptolemy created a fairly accurate but very complex version of this model, circa 140 AD

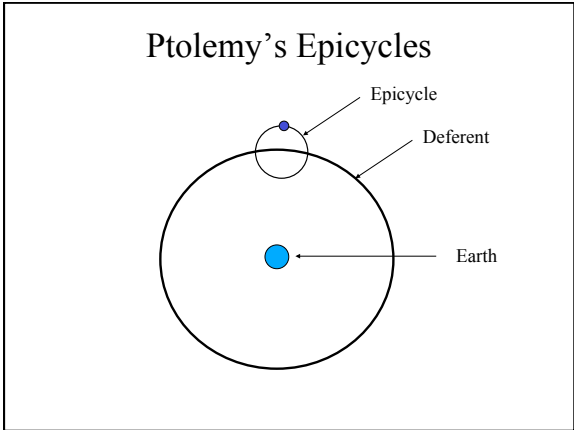
In Ptolemy's model, the planets orbit Earth on epicycles, resulting in periods of retrograde motion

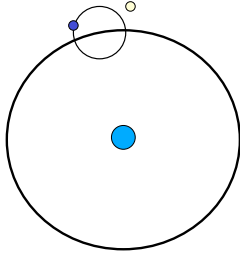
Ptolemy

The most sophisticated geocentric model was from Ptolemy (A.D. 100-170) — the **Ptolemaic model**:

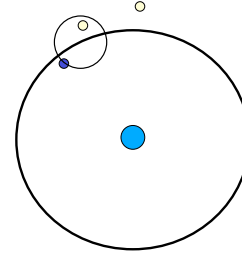
- Sufficiently accurate to remain in use for 1,500 years.
- Arabic translation of Ptolemy's work named *Almagest* (“the greatest compilation”)



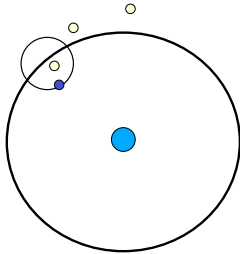
Ptolemy's Epicycles



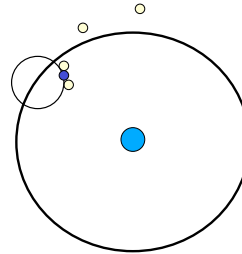
Ptolemy's Epicycles



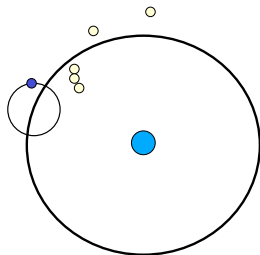
Ptolemy's Epicycles



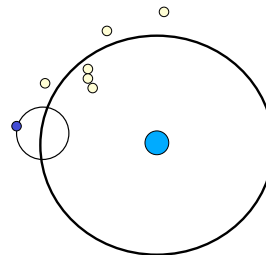
Ptolemy's Epicycles



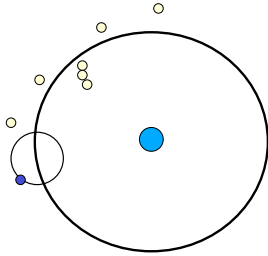
Ptolemy's Epicycles



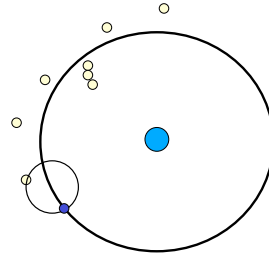
Ptolemy's Epicycles



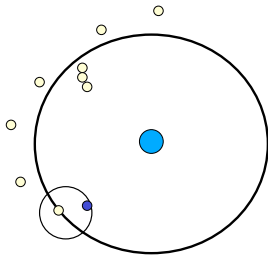
Ptolemy's Epicycles



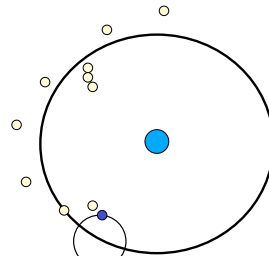
Ptolemy's Epicycles



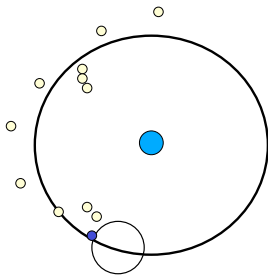
Ptolemy's Epicycles



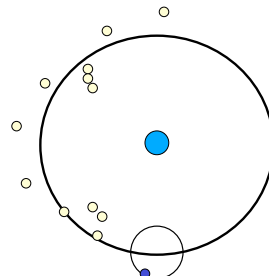
Ptolemy's Epicycles



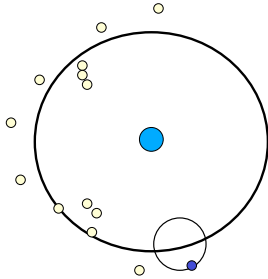
Ptolemy's Epicycles



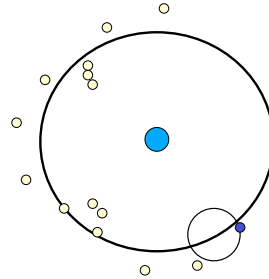
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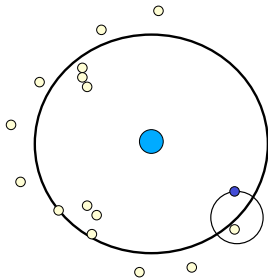
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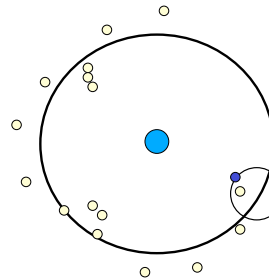
Ptolemy's Epicycles



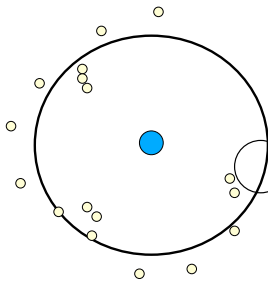
Ptolemy's Epicycles



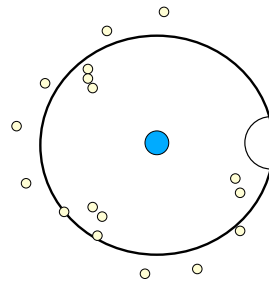
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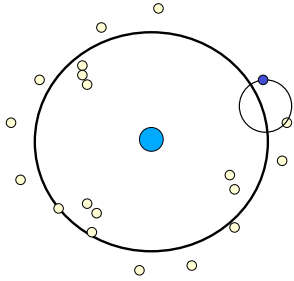
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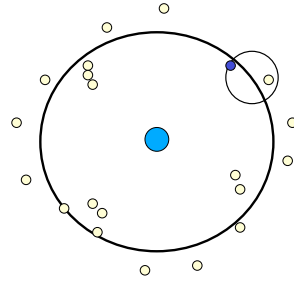
Ptolemy's Epicycles



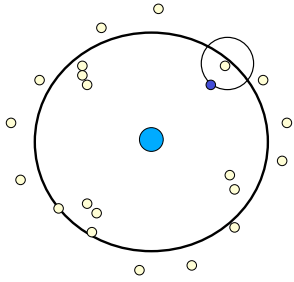
Ptolemy's Epicycles



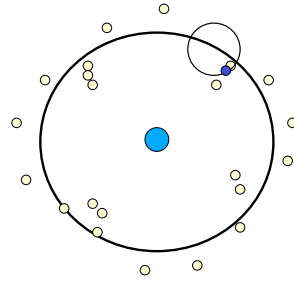
Ptolemy's Epicycles



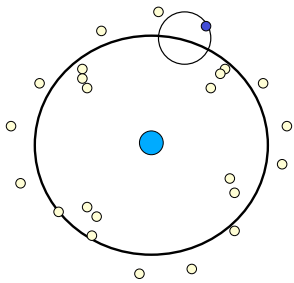
Ptolemy's Epicycles



Ptolemy's Epicycles

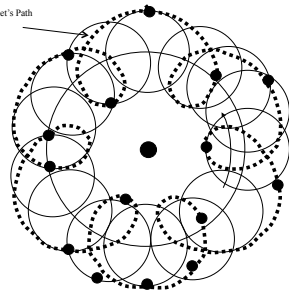


Ptolemy's Epicycles



Ptolemy's Epicycles

Where is retrograde motion occurring?




Ptolemy's Epicycles

Where is retrograde motion?

Planet's Path

How did Copernicus, Tycho, and Kepler challenge the Earth-centered idea?

Copernicus (1473 – 1543 AD) was Polish

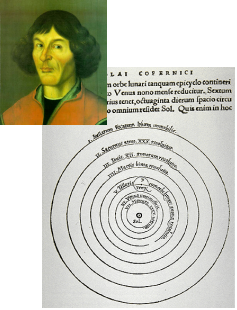


He is known for sun-centered model of the solar system or universe

The Copernican Revolution

The Copernican Hypothesis

- Proposed **Sun-centered model (published 1543)**
- Simpler way to explain retrograde motion
- Used model to determine layout of solar system
- But . . .
- Model was no more accurate than Ptolemy's model in predicting planetary positions, because still used *perfect circles for orbits*




The most important consequence of the Copernican hypothesis

- By placing the Sun at the center, Copernicus made Earth move along an orbit like the other planets
- This **revolutionized humanity's view of its place in the Universe**
- We are not at the center of the Universe!**

Tycho Brahe (1546-1601) was Danish

Had artificial wooden and silver noses

Rumored to have died when his bladder burst



He is know for being the world's best naked-eye astronomer

What do we mean by “Greatest Naked-eye Astronomer?”

No telescope!!



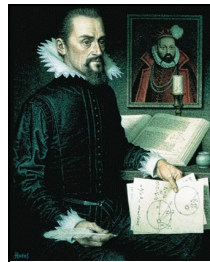
Tycho Brahe, the master observer

- Observed positions of over 700 stars and the planets using a “state-of-the-art” observatory
- Uraniborg – “The Castle of Urania”
 - First custom-built observatory
- More precise than had ever been done
- Accurate to ~1 arcminute
- **No telescopes!**
- Not a Copernican, but his observations ended up being crucial in dethroning the Earth-centered idea

Tycho Brahe (1546-1601)



- Compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
- Still could not detect stellar parallax, and thus still thought Earth must be at center of solar system (but recognized that other planets go around Sun)
- Hired Kepler, who used Tycho's observations to discover the truth about planetary motion.



Johannes Kepler (1571 – 1630) was German

He was a deeply religious man and a family man.

He was rumored to have hated Tycho Brahe and was in the relationship for the data. With that data he changed the understanding of motion of heavenly bodies forever.

He was also a writer, who wrote children stories about the heavens.

How did Kepler further the Copernican Revolution?

- Kepler tested Copernicus' theory with Tycho's observations
- Found that circular orbits could not predict the planets' positions accurately
- Had to modify the theory!
- Led him to try *ellipses* instead



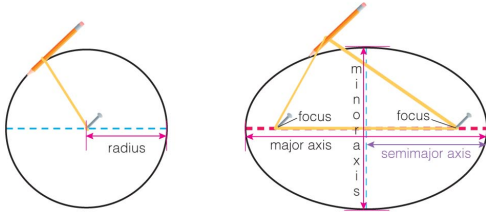
Johannes Kepler (1571-1630)

- An 8-arcminute discrepancy

“If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.”

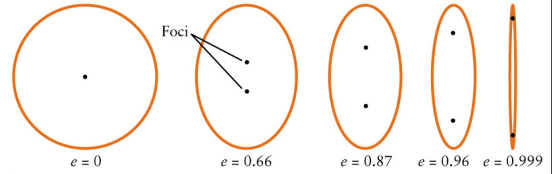
Kepler's Three Laws of Planetary Motion

What is an Ellipse?



An ellipse looks like an elongated circle

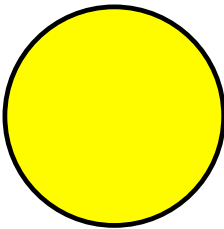
Eccentricity of an Ellipse



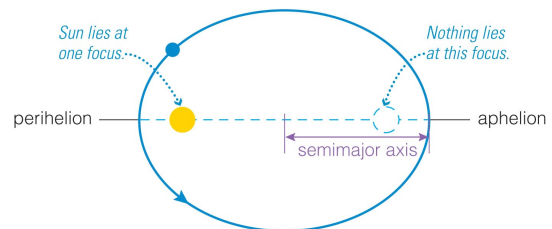
- An orbital eccentricity of 0 is a perfect circle while an eccentricity close to 1.0 is nearly a straight line
- Most of the planets' orbits have low eccentricity - i.e. "nearly circular"

What is the shape of Earth's orbit around the Sun?

Earth, $e = 0.016$

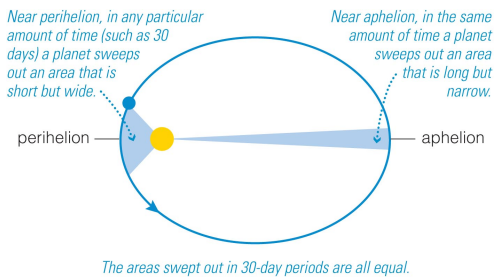


Kepler's First Law: The orbit of each planet around the Sun is an *ellipse* with the Sun at one focus.



The heavens do not move in perfect circles!

Kepler's Second Law: As a planet moves around its orbit, it sweeps out equal areas in equal times.



Kepler's SECOND LAW

- A line drawn from the planet to the Sun sweeps out equal areas in equal times
- **orbital speed is not constant for an ellipse only for a circle**
- **planets move faster when near the Sun (perihelion)**
- **planets move slower when they are far from the Sun (aphelion)**

Kepler's Third Law

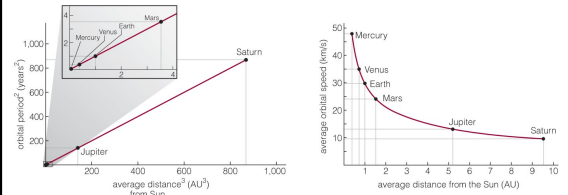
The size of the orbit determines the orbital period – more distant planets orbit the Sun at slower average speeds, obeying the relationship

$$p^2 = a^3$$

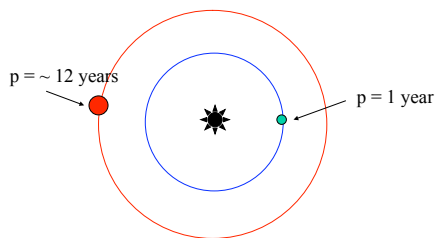
p = orbital period in years

a = avg. distance from Sun in AU

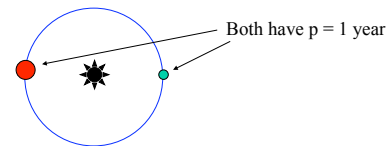
Graphical version of Kepler's Third Law



- The size of the orbit determines the orbital period
 - planets that orbit near the Sun orbit with shorter periods than planets that are far from the Sun



- The size of the orbit determines the orbital period
 - planets that orbit near the Sun orbit with shorter periods than planets that are far from the Sun
 - MASS DOES NOT MATTER



In-class Activities: Kepler's 2nd and 3rd Laws

- Work with a partner!
- Read the instructions and questions carefully.
- Discuss the concepts and your answers with one another. Take time to understand it now!!!!
- Come to a consensus answer you both agree on.
- If you get stuck or are not sure of your answer, ask another group.
- If you get really stuck or don't understand what the question is asking, ask me.

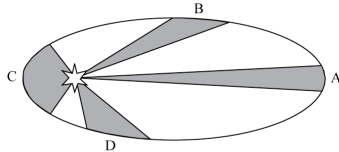
According to Kepler's second law, a planet with an orbit like Earth's would:

- move faster when further from the Sun.
- move slower when closer to the Sun.
- experience a dramatic change in orbital speed from month to month.
- experience very little change in orbital speed over the course of the year.
- none of the above.

The planet in the orbit shown below obeys Kepler's Laws.

During how many portions of the planet's orbit (A, B, C and D) would the planet be speeding up the entire time?

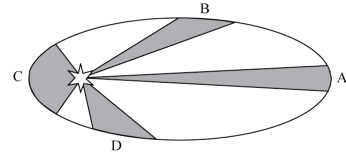
- A. Only during one of the portions shown.
- B. During two of the portions shown.
- C. During three of the portions shown.
- D. During four of the portions shown.
- E. None of the above.



The planet in the orbit shown below obeys Kepler's Laws.

During which of the portions of the planet's orbit would the planet experience an increase in speed for at least a moment?

- A. Only during one of the portions shown.
- B. During two of the portions shown.
- C. During three of the portions shown.
- D. During four of the portions shown.
- E. None of the above.



Which of the following best describes what would happen to a planet's orbital speed if its mass were doubled but it stayed at the same orbital distance?

- a) It would orbit half as fast.
- b) It would orbit less than half as fast.
- c) It would orbit twice as fast.
- d) It would orbit more than twice as fast.
- e) It would orbit with the same speed.

If a small weather satellite and the large International Space Station are orbiting Earth at the same altitude above Earth's surface, which of the following is true?

- a) The large space station has a longer orbital period.
- b) The small weather satellite has a longer orbital period.
- c) Each has the same orbital period.

An asteroid orbits the Sun at an average distance $a = 4$ AU. How long does it take to orbit the Sun?

- A. 4 years
- B. 8 years
- C. 16 years
- D. 64 years