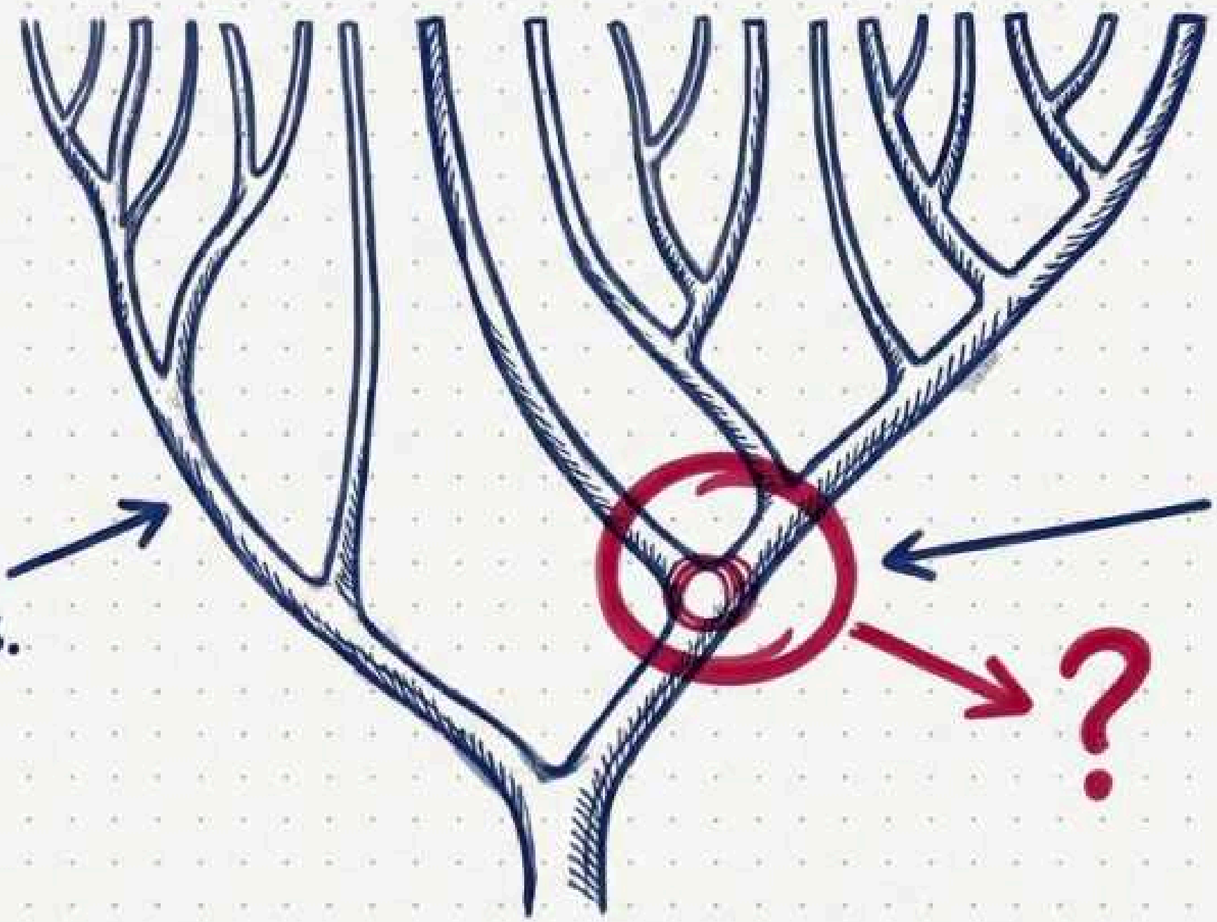
Lecture 3: Molecular Clocks & Deep Time

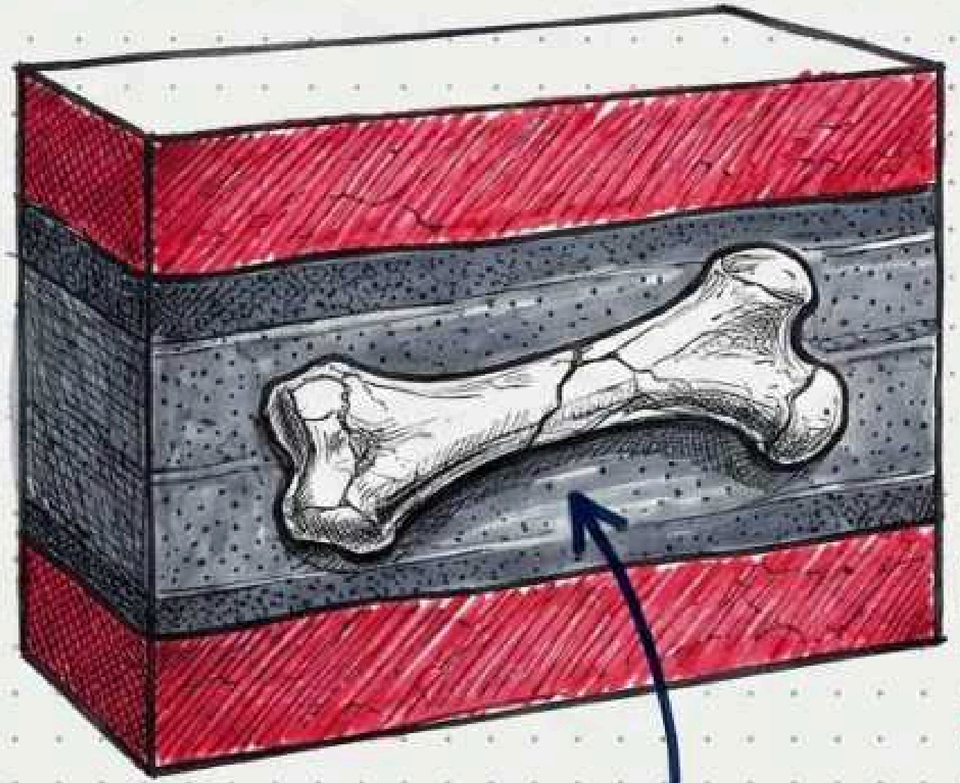
¶ 3.1



We measure deep time using two lines of evidence: **Rocks/Fossils** and **DNA/Proteins.** **DNA/Proteins.** We will see how they combine, and what happens when they clash.

Radiometric Dating: Bracketing the Past

¶ 3.2



Bracketing the Fossil Age

$$N(t) = N_0\, e^{-\lambda t}$$

Uranium –> Lead (Billions of years)

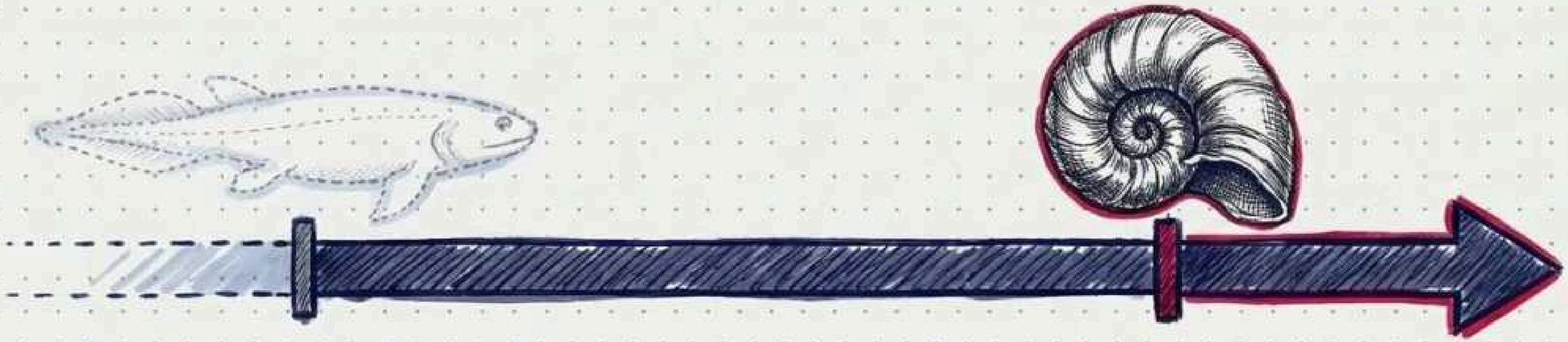
Potassium –> Argon (Hundreds of millions of years)

Uncertainty is often < 1%

Measure the proportion of parent-to-daughter radioactive isotopes in volcanic rock to "bracket" the fossil's age.

The Fossil Record = Minimum Ages

¶ 3.3



True Origin (Unknown)

Fossilization is incredibly rare. Early members of a lineage vanish without a trace.

First Appearance (Known)

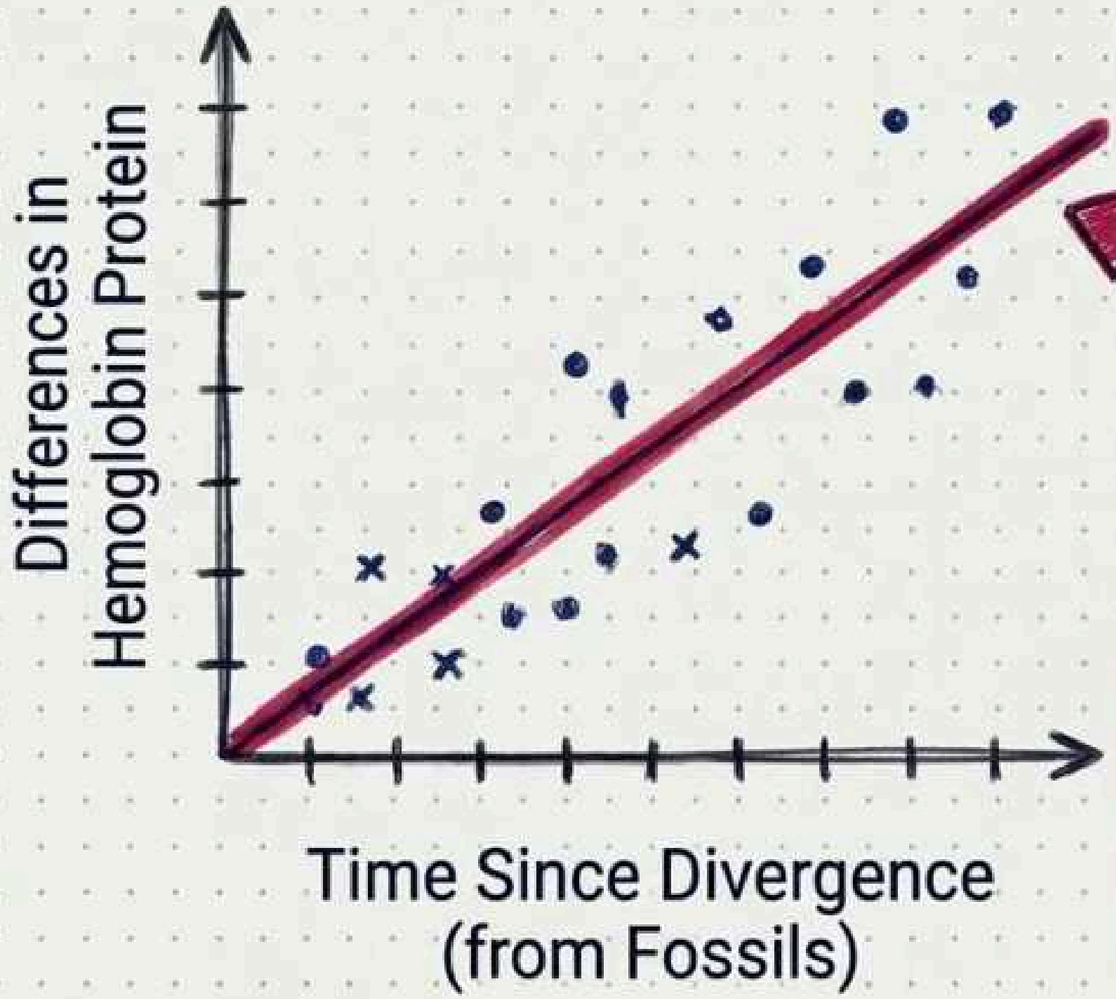
If the oldest known fossil of a group is 300 million years old, the lineage must be AT LEAST that old.

The first appearance of a fossil is a strict lower bound on a lineage's true age.

The Molecular Evolutionary Clock

¶ 3.4

Emile Zuckerkandl & Linus Pauling (1962 / 1965)



Differences in hemoglobin between species increase roughly in proportion to the time since they diverged.

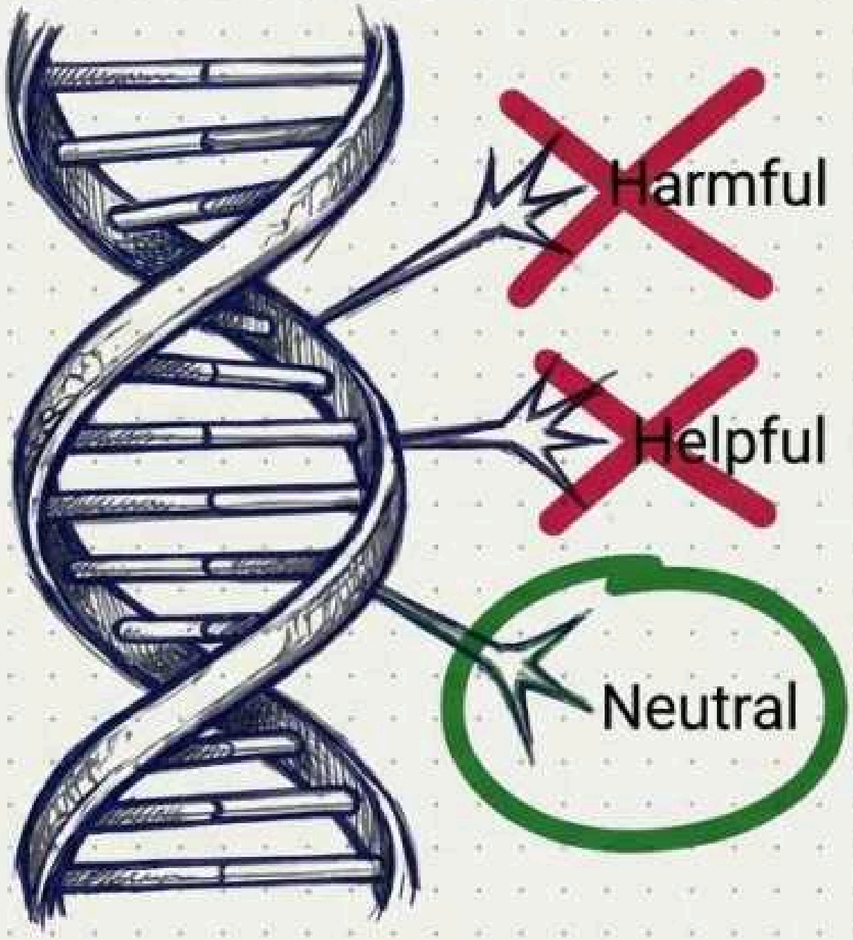
$$\Delta \textit{ Molecular Differences} \approx \textit{Time Since Common Ancestor}$$

(If molecules change at a roughly constant rate)

Why the Steady Rate? Neutral Theory

Motoo Kimura (1968)

¶ 3.5

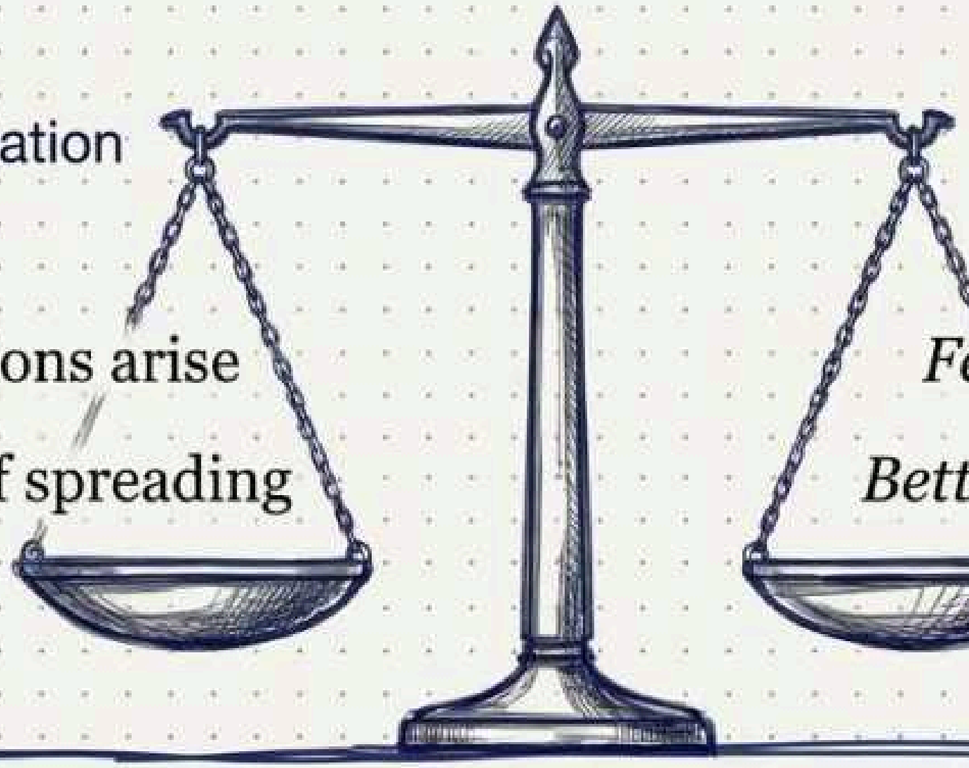


Most DNA changes that become fixed in a species are NEUTRAL – neither helpful nor harmful. neither helpful nor harmful. They spread entirely by chance through genetic drift.

Rate of Fixation = Mutation Rate

The Elegant Math of Population Size

¶ 3.6



Large Population

Many mutations arise
x
Tiny chance of spreading

Small Population

Fewer mutations arise
x
Better chance of spreading

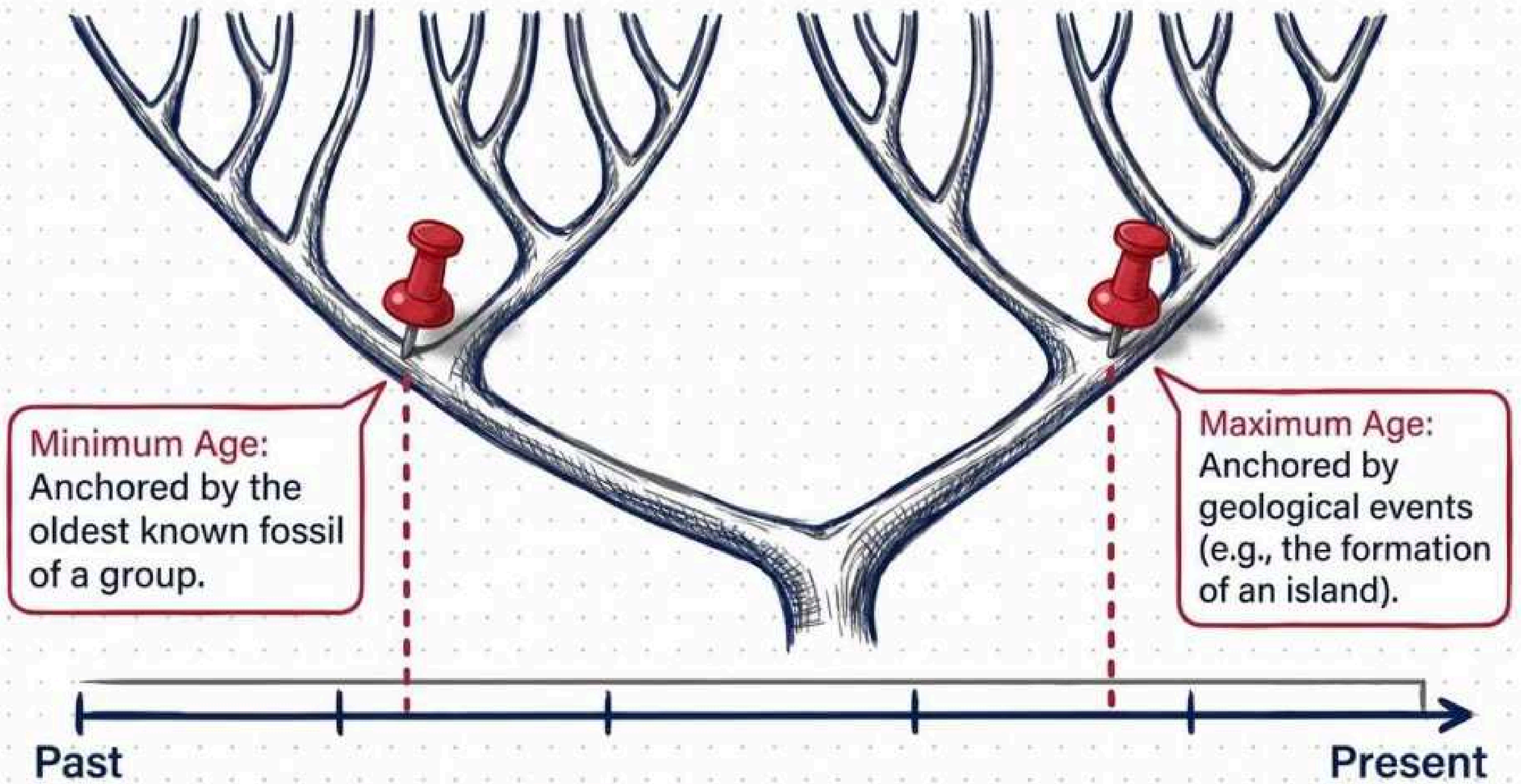
The opposing mathematical effects cancel out exactly. Therefore, the substitution rate does NOT depend on population size.

Tomoko Ohta's Nearly Neutral Theory: Slightly harmful mutations DO depend on population size.

Calibrating the Clock

¶ 3.7

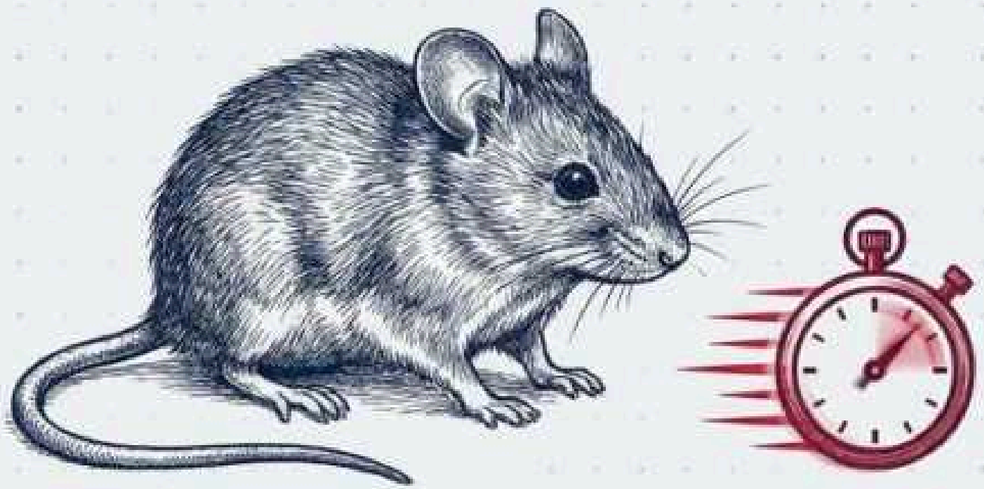
Molecular differences only provide RELATIVE times. They must be anchored to absolute radiometric dates.



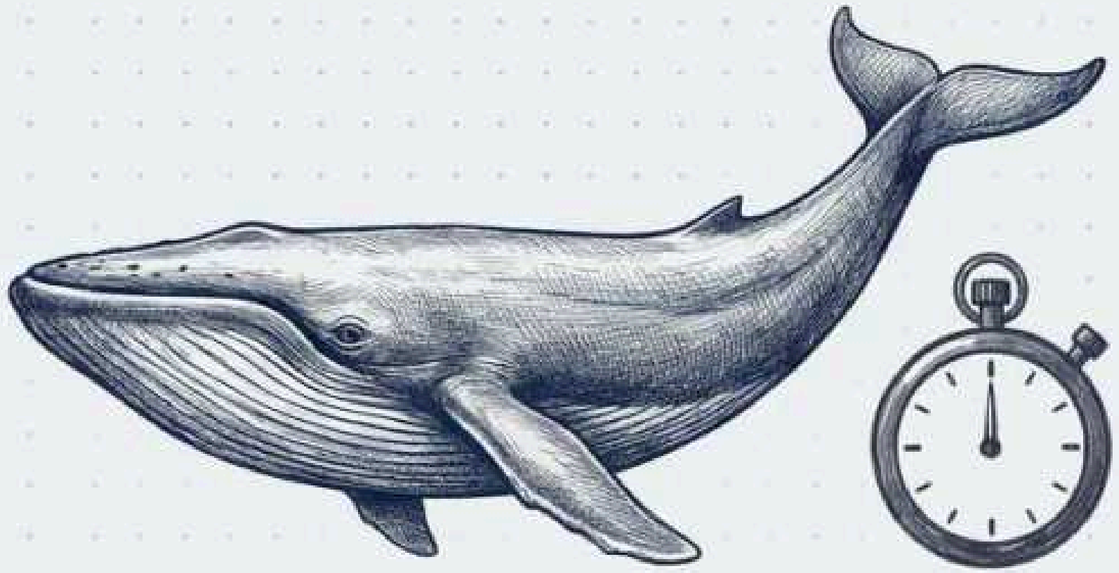
The best analyses use several calibrations spread across the entire tree.

Rates Are Not Perfectly Constant

¶ 3.8



Short generation times, small body size, and high metabolic rates = FASTER CLOCK (e.g., rodents)



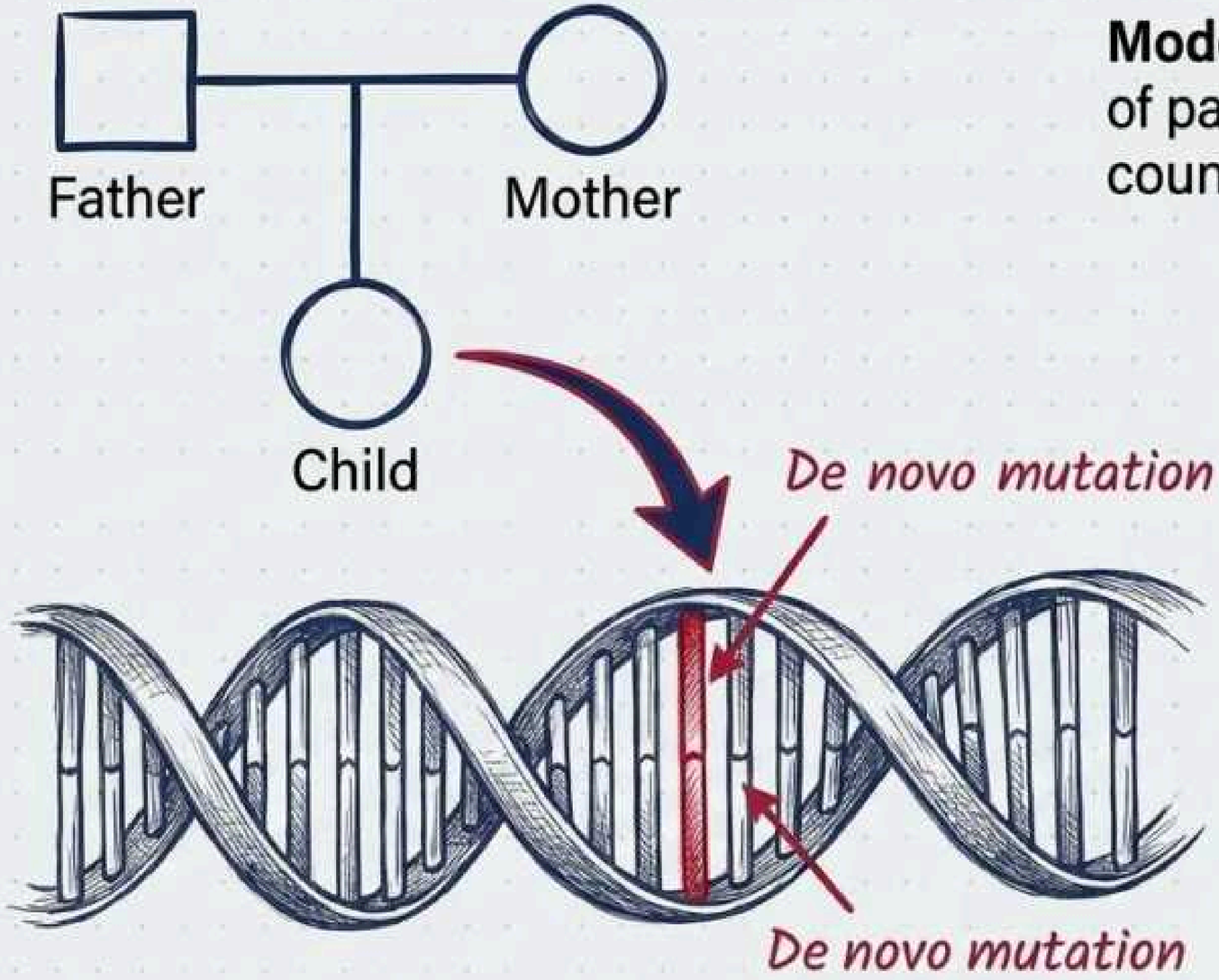
Long generations = SLOWER CLOCK (e.g., whales, apes)

The Solution (Late 90s/2000s):

Relaxed Clock Methods. These statistical models allow molecular rates to vary across different branches of the evolutionary tree while still estimating dates accurately.

The Impact of Direct Mutation Rates

¶ 3.9



Modern Method (2010s): Direct sequencing of parents and children allows geneticists to count new mutatiions per generation.

Human mutation rate:

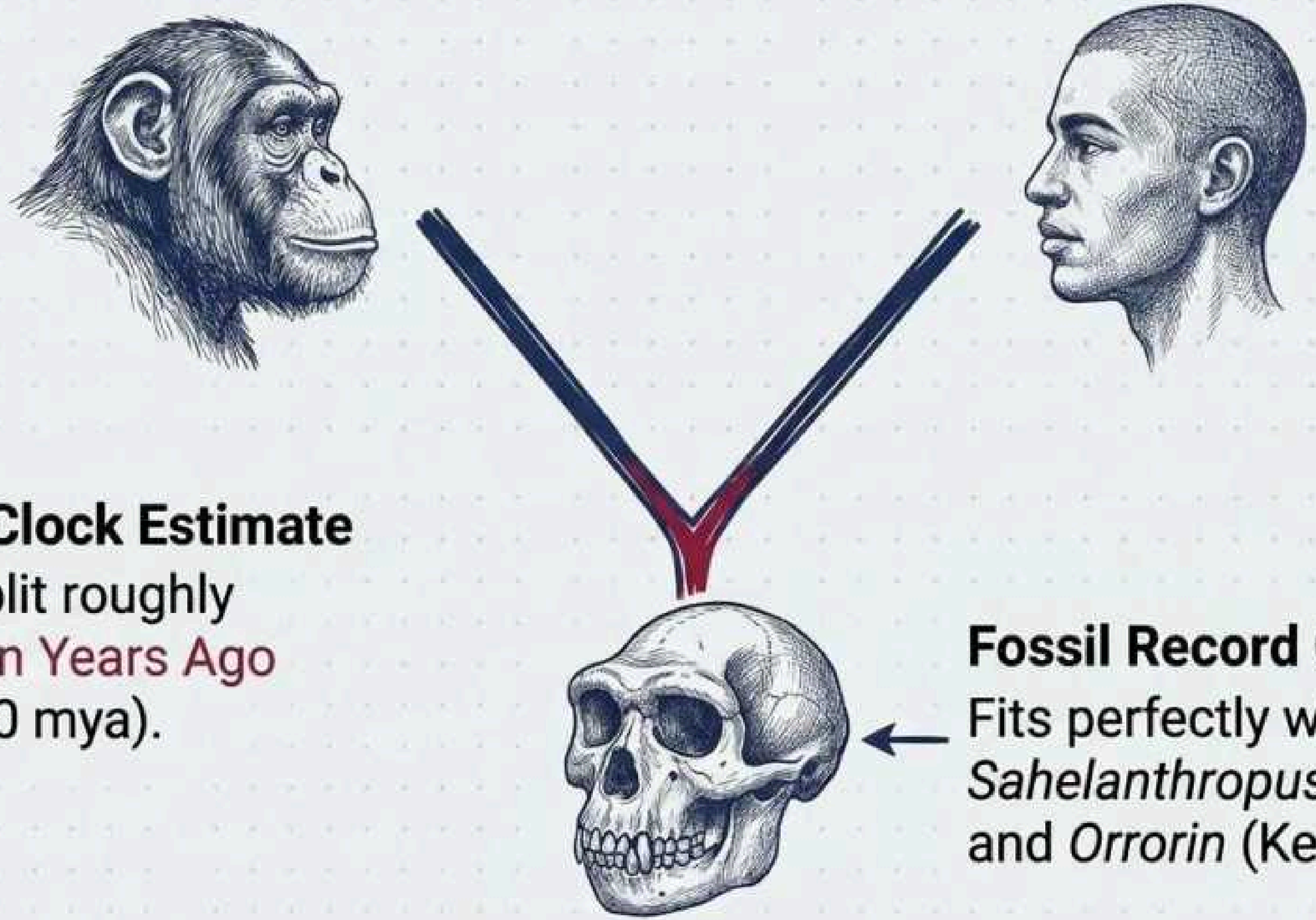
$$\mu \approx 1.2 \times 10^{-8}$$

per site, per generation.

The Consequence: This direct rate is slower than many earlier fossil-calibrated estimates, pushing some human divergence dates further back into deep time.

Human Origins: Molecules & Fossils Agree

¶ 3.10



Molecular Clock Estimate

Lineages split roughly
6 to 7 Million Years Ago
(Range: 5-10 mya).

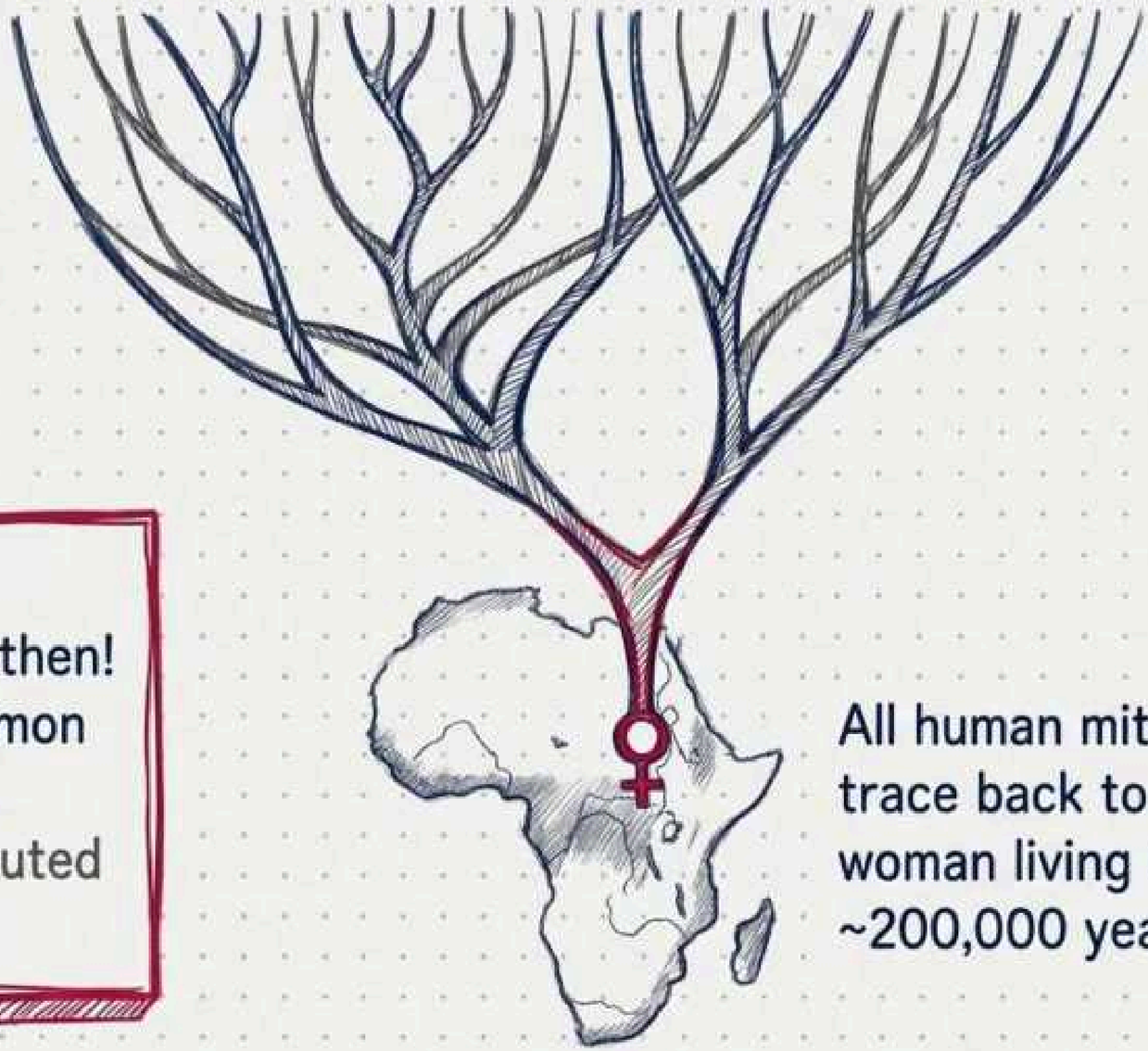
Fossil Record Confirmation

Fits perfectly with
Sahelanthropus (Chad, ~7 mya)
and *Orrorin* (Kenya, ~6 mya).

Mitochondrial Eve (1987)

¶ 3.11

Cann, Stoneking, & Wilson traced mitochondrial DNA (mtDNA), which is inherited exclusively from mothers.



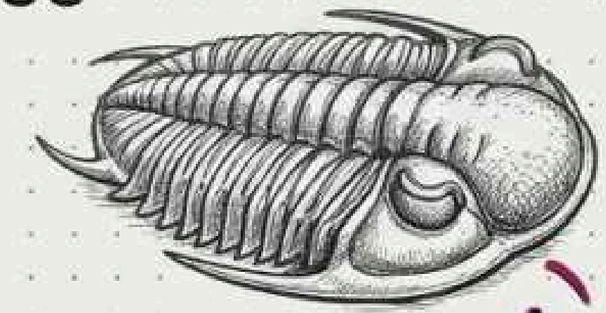
All human mitochondria trace back to one woman living in Africa ~200,000 years ago.

Crucial Clarification Box

She was NOT the only woman alive then!
She is simply the Most Recent Common Ancestor (MRCA) for mitochondria.
Other contemporary women contributed to our nuclear DNA.

When Clocks & Fossils Disagree

¶ 3.12



Fossils

539 mya: The Cambrian Explosion
(A 20-million-year window)

Molecules

1 Billion Years Ago

The Conflict: The fossil record shows most animal groups appearing rapidly ~539 mya. Early molecular clocks suggested origins were a billion years ago. Fossil experts argued this massive gap was entirely implausible.

Narrowing the Gap:
The Cambrian Resolution

¶ 3.13

The New Consensus: Using relaxed clocks and better calibrations, main animal lineages are now estimated to have diverged in the Ediacaran or late Cryogenian.



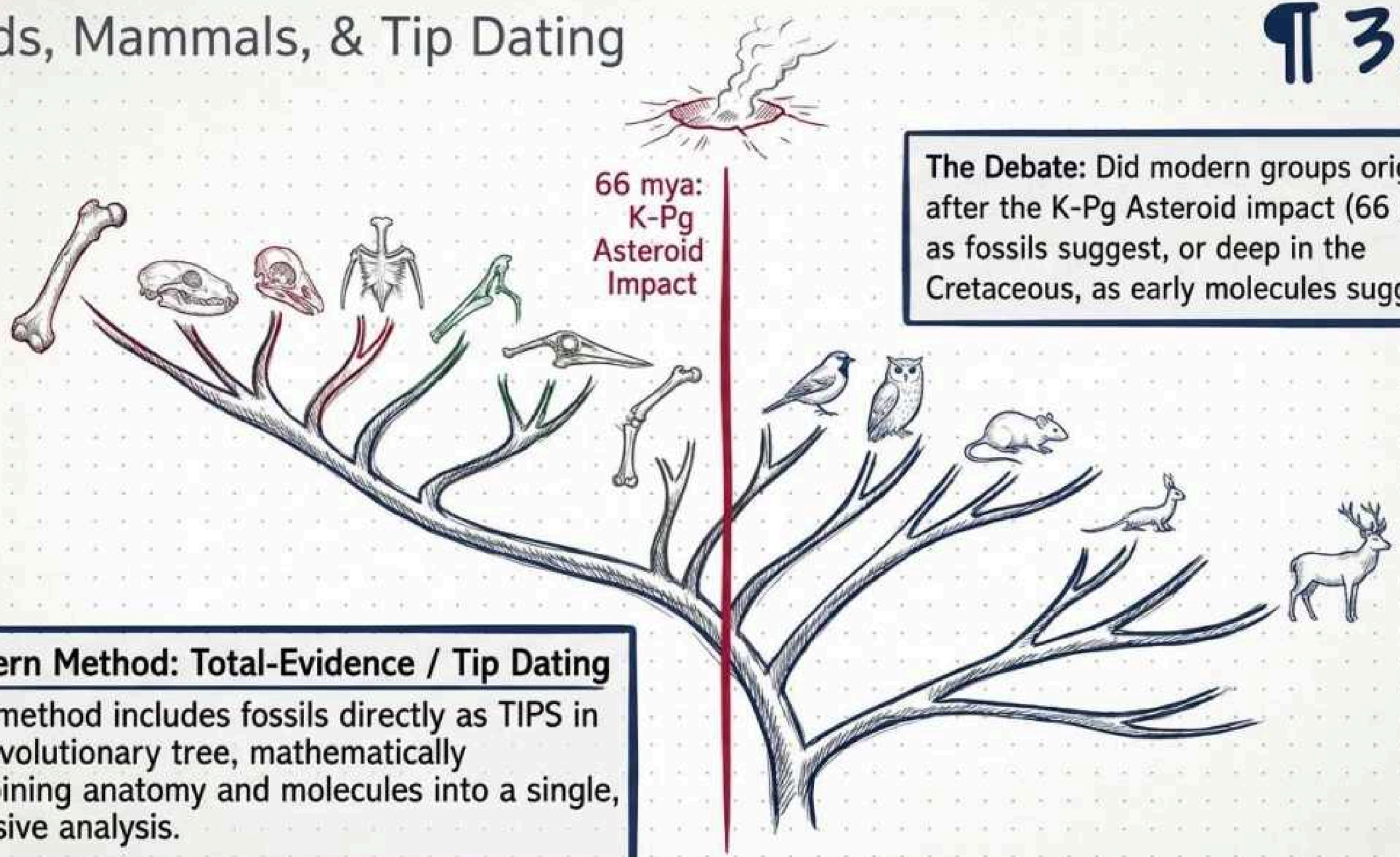
Cambrian
(539 mya)

The Missing Evidence: Ancestors were small and soft-bodied, meaning they rarely fossilized.

Each source corrected the other.
The truth was found between the two extremes.

Birds, Mammals, & Tip Dating

¶ 3.14



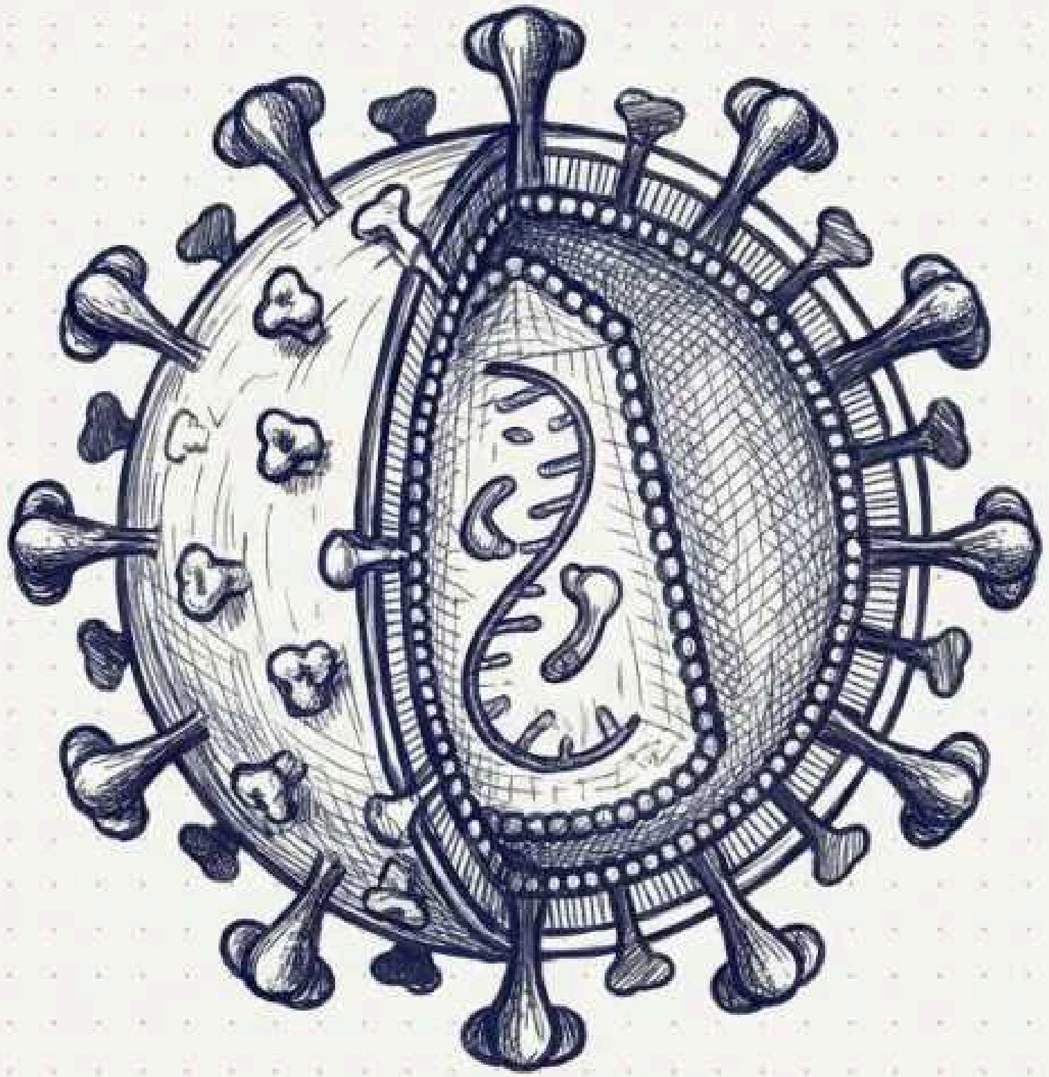
The Debate: Did modern groups originate after the K-Pg Asteroid impact (66 mya), as fossils suggest, or deep in the Cretaceous, as early molecules suggest?

Modern Method: Total-Evidence / Tip Dating

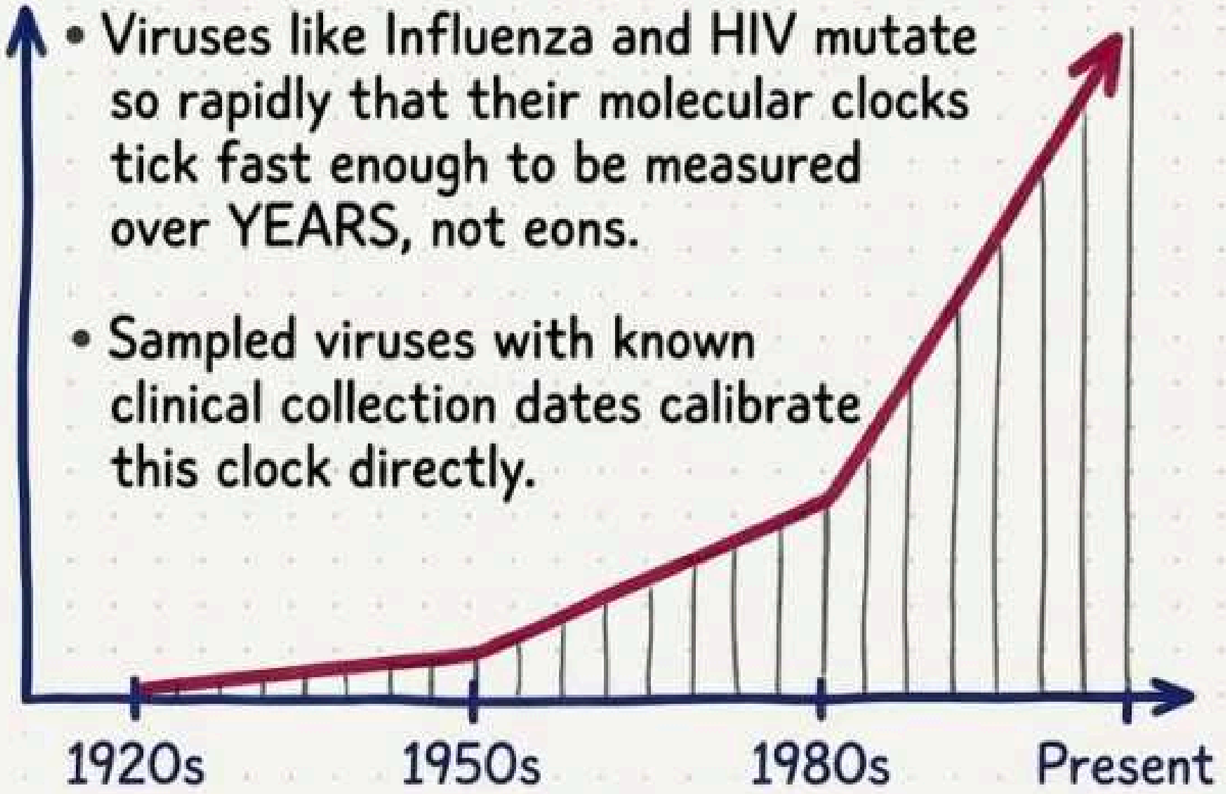
This method includes fossils directly as TIPS in the evolutionary tree, mathematically combining anatomy and molecules into a single, cohesive analysis.

Dating Viruses in Real Time

¶ 3.15



- Viruses like Influenza and HIV mutate so rapidly that their molecular clocks tick fast enough to be measured over YEARS, not eons.
- Sampled viruses with known clinical collection dates calibrate this clock directly.



The Finding: The pandemic form of HIV-1 began spreading among humans in central Africa in the 1920s.

Summary: The Synthesis of Deep Time

¶ 3.16

	Rocks & Fossils	Molecular Clocks
Method	Radiometric decay (λ)	Neutral Theory math (μ)
Output	Strict minimum ages	Estimated divergence times
Weaknesses	Rare preservation / gaps	Variable rates requiring calibration

Disagreements in evolutionary history (like the Cambrian Explosion) are ultimately resolved by combining these independent lines of evidence.

Next lecture: With time established, how do we detect natural selection?