

How to Build a Planet

QTC-016 · From Quarks to Consciousness

The Universe, Life, and How We Found Out

Author: Juan Seguroloa

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Article Abstract

A planet is not assembled by following one recipe. It emerges from a disk whose solids condense, collide, drift, concentrate and sometimes collapse gravitationally, while growing bodies scatter one another and migrate through gas. Meteorites, protoplanetary disks, isotope systems, numerical dynamics and Earth's interior preserve different parts of that history. This article follows the chain from calcium-aluminium-rich inclusions and chondrules to planetesimals, embryos, differentiation and the Moon-forming impact. It separates observed structures from inferred planets, viable mechanisms from unique histories, and precise dates from the events those dates actually record. Earth was built, melted and chemically sorted through a stochastic sequence whose broad physics is secure but whose exact itinerary remains reconstructive. Building a planet is therefore a process, not an architectural plan.

In 60 Seconds

Young stars are surrounded by disks of gas and dust, but a ring or gap does not uniquely prove that a planet made it. In our Solar System, calcium-aluminium-rich inclusions mark the first known solids at 4567.30 ± 0.16 million years ago; they are a time zero, not the birthday of a completed Earth. Dust could stick into aggregates, yet bouncing, fragmentation and inward drift blocked simple growth. Concentration by gas-particle dynamics, including streaming instability, offers a route to gravitationally bound planetesimals, while pebble accretion can accelerate later growth under suitable conditions. Gravity then built embryos, scattered them and moved them through the gas disk. Impacts and aluminium-26 melted some bodies, separating metal cores from silicate mantles. Earth accreted from changing mixtures, and its water and late veneer remain partly disputed. The Moon most likely records a giant impact, but canonical, high-angular-momentum, synestia and immediate-satellite models solve different constraints. No single object preserves the whole sequence; the history is earned by agreement among independent archives.

Why This Question Matters

Planet formation connects the first stars to the first geology. Stellar nucleosynthesis supplied the elements, but disks, collisions, gravity and heat had to turn those elements into differentiated worlds. The evidence is unusually distributed: telescopes show other disks now, meteorites preserve early Solar System solids, isotope systems order events, computer models test dynamics, and planets reveal final structures. That distribution makes the subject a lesson in reconstruction. A mechanism can be

physically real without having dominated every region, and a precise number can date one closure or segregation event without dating the whole planet.

1. A Planet Is a Reconstruction, Not a Recipe

The Question

If no one watched Earth assemble, what makes planet formation more than a plausible story? Different archives preserve different operations, and the reconstruction becomes strong where disks, meteorites, dynamics and planetary interiors constrain the same sequence.

A finished planet hides much of its construction. Melting erases textures, impacts mix reservoirs and tectonics recycles crust. Researchers therefore do not read Earth as a complete diary. They compare young circumstellar disks, primitive meteorites, differentiated asteroids, planetary orbits, laboratory measurements and numerical models.[1] Each archive answers a narrower question than ‘how was Earth made?’, but their overlap can exclude many histories.

Disks around young stars are directly observed. HL Tau revealed bright and dark rings at extraordinary resolution, and the DSHARP survey showed that rings, gaps and other substructures are common in nearby disks.[2,3] Such structures can be produced by planets, but also by ice lines, pressure variations, magnetic effects or hydrodynamic instabilities. A gap is therefore evidence about disk structure, not an automatic planet detection.

The available time was limited. Infrared surveys show that the fraction of stars retaining inner dusty disks falls strongly over a few million years.[4] Gas giants must acquire most of their envelopes before the gas disperses, while rocky bodies can continue colliding later. ‘Planet formation time’ is consequently not one interval: solids, planetesimals, cores, atmospheres and final giant impacts obey different clocks.

This article reconstructs operations rather than narrating an inevitable march from dust to Earth. Condensation sorts matter; collisions can grow or destroy aggregates; gas can concentrate solids and move embryos; gravity makes accretion stochastic; heat differentiates bodies; isotopes and chemistry retain partial memories. The result is not a universal recipe but a constrained family of pathways.

Where That Leaves Us

Planet formation is known by joining incomplete archives rather than by finding one pristine record. Observed disks establish environments, meteorites preserve early solids, dynamics tests possible itineraries and planetary interiors reveal later sorting. The next step is to ask how the disk made different starting materials available without fixing every object's fate.

2. The Disk Sorted Matter Without Fixing Its Fate

A cooling Solar nebula did not condense every element at once. Equilibrium calculations rank solids by the temperatures and pressures at which they become stable: refractory calcium- and aluminium-bearing phases appear before more volatile materials.[5] This ‘condensation sequence’ is a chemical reference, not a literal conveyor belt. Transport, repeated heating, kinetics and inherited presolar grains complicate every radial map.

Calcium-aluminium-rich inclusions, or CAIs, preserve the earliest high-temperature solids yet dated. Their Pb–Pb age of 4567.30 ± 0.16 million years provides the conventional time zero for Solar System chronology.[6] It does not date a completed Sun, Earth or disk. It dates crystallization of specific inclusions whose minerals retained the relevant isotope record.

Chondrules are millimetre-scale droplets that were melted and cooled before being incorporated into many chondritic meteorites. Some Pb–Pb results overlap the CAI interval, while other chronometers and samples extend chondrule production later.[7,8] The thermal events that made them remain an open problem: shocks, current sheets, planetesimal collisions and other mechanisms reproduce different subsets of the evidence.

Meteorites therefore preserve materials that formed at different places, temperatures and times and were later mixed into one rock. A carbonaceous chondrite is not an untouched sample of one orbital radius, and an enstatite chondrite is not simply a parcel labelled ‘inner disk’. Chemical families and isotopic anomalies constrain reservoirs, but transport prevents a one-dimensional distance-to-composition rule.

Where That Leaves Us

The disk created chemical and chronological structure, but transport repeatedly blurred it. CAIs provide a precise first-solid reference, not Earth's birthday, while chondrules record later or overlapping heating whose cause remains unsettled. Before gravity could assemble planets from these ingredients, small solids had to cross a growth problem that simple sticking could not solve.

3. Dust Had to Cross a Growth Barrier

The Question

If grains begin smaller than sand and planets end thousands of kilometres wide, why not let collisions do all the work? Because the same gas and impacts that bring particles together can make them bounce, fragment or spiral into the star.

Micrometre grains can stick through surface forces, and laboratory work maps regimes of sticking, bouncing, fragmentation, erosion and mass transfer.[9,10] The outcome depends on composition, porosity, size, velocity and impact geometry. There is no single collision speed at which ‘dust stops growing’, and icy aggregates need not behave like compact silicate ones.

Gas orbits slightly below the local Keplerian speed because pressure helps support it. Solids therefore feel a headwind, lose angular momentum and drift inward. Particles with stopping times comparable to an orbit drift especially rapidly, while repeated collisions can stall at a bouncing barrier.[9,10] The familiar ‘metre-size barrier’ names a dynamical regime, not a universal one-metre diameter.

The streaming instability provides a collective route. Particle feedback on gas can concentrate solids into dense filaments; if a concentration becomes self-gravitating, it can collapse into planetesimals.[11,12] Simulations often produce an initial mass distribution dominated by bodies tens to hundreds of kilometres across, but the result depends on local solid abundance, pressure gradients, turbulence, self-gravity and numerical resolution.[13]

This is a viable mechanism, not proof that every planetesimal formed that way. Pressure traps, vortices, turbulent concentration and collisional paths may contribute in different environments.

Once seeds exist, pebble accretion can accelerate growth because gas drag helps passing particles lose energy and be captured, yet its efficiency depends on particle size, embryo mass, disk thickness and relative velocity.[14,15]

Where That Leaves Us

Dust growth is not one uninterrupted sequence of adhesive collisions. Aerodynamic drift, bouncing and fragmentation create barriers, while collective concentration and pebble capture offer conditional routes around them. The dominant mixture of routes remains open. Once gravity bound solids into planetesimals, however, a different regime began: bodies could focus impacts, scatter neighbours and rearrange the disk.

4. Gravity Built Embryos and Rearranged Them

A planetesimal's gravity enlarges its effective collision target by focusing passing bodies toward it. The largest objects can initially grow faster than their neighbours, followed by oligarchic growth in which separated embryos dominate local feeding zones.[16] Those labels describe regimes in models, not a universal sequence with fixed boundaries.

When the gas disk fades, embryos and planetesimals continue through many-body dynamics. Numerical accretion experiments produce impacts, ejections and radial mixing; small changes in starting orbits can yield different final planets.[17] Mars's small mass, Earth's composition and the asteroid belt therefore constrain an ensemble of histories rather than selecting one deterministic replay.

Gas adds systematic torques. A low-mass planet excites waves and exchanges angular momentum with the disk, so migration is a physical expectation, not an exceptional rescue mechanism.[18] The direction and rate depend on disk temperature, density, viscosity and the planet's mass. Reconstructing a specific Solar System itinerary requires more than establishing that migration occurs.

The Grand Tack proposes that Jupiter migrated inward and then outward after resonance with Saturn, truncating material near Mars and repopulating the asteroid belt.[19] It is an active hypothesis, not a recorded voyage. Isotopic differences between carbonaceous and non-carbonaceous meteorites indicate long-lived reservoir separation; one influential interpretation links that barrier to Jupiter's early growth.[20] The inference is powerful but does not uniquely trace every kilometre of Jupiter's path.

Compact multiplanet systems observed by Kepler demonstrate that other disks often built architectures unlike ours.[21] Their existence does not falsify Solar System models; it removes any assumption that one outcome is inevitable. Migration, collisions and disk structure can produce multiple stable endpoints from similar starting ingredients.

Where That Leaves Us

Gravity turned seeds into an unstable population of embryos whose histories depended on neighbours and gas. Migration is expected, but the Grand Tack and Jupiter's exact itinerary remain reconstructions constrained by Mars, meteorites and the asteroid belt. Growth also released heat, so accretion did more than increase mass: it began separating planets chemically and physically.

5. Growth Also Melted and Differentiated Worlds

Accretion converts impact energy into heat. Compression, core formation and repeated collisions add more, while short-lived radionuclides can dominate the heating of small bodies formed early. The discovery of excess magnesium-26 in meteorites established that aluminium-26 was present in the early Solar System.[22] With a half-life near 0.7 million years, its effect depended sharply on when a body assembled.

Early-formed planetesimals containing enough aluminium-26 could melt and separate metal from silicate. Hf–W chronometry indicates that some asteroidal parent bodies differentiated within the first few million years.[23,24] Later or smaller bodies could remain partly unmelted. ‘Planetesimal’ therefore does not imply one internal state, and primitive meteorites can coexist chronologically with differentiated fragments.

A magma ocean permits dense metal to sink and silicate reservoirs to separate as crystallization proceeds.[25] Earth's present seismic structure — crust, mantle, liquid outer core and solid inner core — demonstrates large-scale differentiation, although the Preliminary Reference Earth Model describes today's radial properties, not a direct movie of core formation.[26]

Hafnium prefers silicate while tungsten prefers metal. Their isotope system can therefore constrain the timing of metal–silicate separation, but the inferred age depends on accretion history, impact equilibration, initial isotope composition and how much metal and silicate exchanged during each event.[23,24,27] A quoted ‘core formation age’ is a model-dependent timescale, not necessarily one instantaneous date.

Differentiation also changes what later evidence can survive. Metal carries siderophile elements into cores; volatile elements can escape or redistribute; mantle reservoirs can be mixed by impacts. The planet that emerges is not merely a larger aggregate. Its construction changes the archive used to reconstruct the construction.

Where That Leaves Us

Planetary growth generated heat as well as mass. Aluminium-26, impacts and segregation differentiated some early bodies rapidly, while others remained primitive. Earth's layers prove extensive sorting, but isotope-derived timescales depend on how accretion and equilibration are modelled. Those complications become central when asking exactly which changing mixture actually became Earth.

6. Earth Accreted as a Changing Mixture

The Question

Which meteorite is the ingredient list for Earth? None. Isotopes and elements point to several related reservoirs, while differentiation, volatile loss and late additions changed what the surviving mantle can reveal about the material that arrived.

Earth's isotopic composition is closest in several systems to non-carbonaceous inner-Solar-System materials, especially enstatite chondrites, but no meteorite group reproduces every element and isotope while also accounting for core formation.[28] Accretion models therefore allow the mixture

and oxidation state of impactors to change through time, with metal–silicate equilibration during successive collisions.[27,28]

Water exposes the ambiguity. Hydrogen, nitrogen and noble gases constrain possible carriers, yet comets, carbonaceous asteroids, enstatite-like material, nebular gas and later processing can overlap in selected isotope ratios.[29] Enstatite chondrites contain enough hydrogen to make an inner-Solar-System contribution plausible,[30] while comet 67P has a D/H ratio more than three times terrestrial ocean water, excluding it as a simple universal source but not excluding all comets.[31]

A matching D/H ratio is not a shipping label. Atmospheric escape, mantle exchange, parent-body alteration and mixing can change inventories and ratios. The origin of Earth's water and other volatiles is therefore contested at the level of proportions and delivery paths, even though multiple sources and later processing are established parts of the problem.

Highly siderophile elements should have followed metal into Earth's core. Their mantle abundance is commonly interpreted as material added after major core formation — a 'late veneer'. [32] Converting that abundance into a mass and timing requires assumptions about metal equilibration, mantle mixing and impactor composition. The veneer is a model, not a visible final coat.

Accretion, magma oceans and impacts may also have lost and redistributed volatiles. The surviving Earth is a filtered product: source composition, impact sequence, oxidation, differentiation and escape all contribute. That is why a successful reconstruction must fit isotopes, elemental abundances, dynamics and the present interior together.

Where That Leaves Us

Earth was assembled from a changing and processed mixture, not copied from one meteorite class. Isotopes constrain reservoirs, while water and the late veneer retain contested proportions and model dependence. The largest surviving clue to the final accretionary stages is the Moon, whose similarity to Earth demands a giant impact without selecting one unique version of it.

7. The Moon Records a Giant Impact, Not One Settled Scenario

The Question

If the giant-impact explanation is widely accepted, why do papers still propose very different collisions? Because forming a satellite is only one constraint: a successful history must also match angular momentum, chemistry, isotopes and later orbital evolution.

A collision between the growing Earth and a planetary embryo is the leading class of explanations for the Moon. The canonical calculation used a roughly Mars-sized impactor near the end of accretion and placed silicate debris into orbit while Earth's iron-rich core survived.[34] It naturally explains a small lunar core and angular momentum, but early versions made much of the disk from the impactor.

Lunar and terrestrial rocks are extraordinarily similar in several isotope systems. Some measurements identify small oxygen-isotope differences,[39] while others find indistinguishable values at higher precision and infer vigorous mixing.[40] Either way, the resemblance is a central

constraint: models must explain why a collision involving two differentiated bodies did not leave a simply foreign Moon.

One solution uses an impactor with an Earth-like composition or a collision that mixes target and impactor efficiently.[35] High-angular-momentum scenarios begin with a faster-spinning Earth and later remove excess angular momentum through resonance.[36] These models expand the allowed collisions, but they transfer part of the explanation into the probability of starting compositions and later orbital evolution.

The synestia model proposes a hot, extended, rapidly rotating structure in which the Moon accretes from vapor and condensate connected to Earth.[37] Very high-resolution simulations have also produced a Moon-mass satellite placed into orbit almost immediately after impact.[38] Both are active hypotheses. Each solves selected dynamical and compositional constraints while introducing conditions that require further testing.

The exact impact geometry, impactor composition, thermal state and date remain open. ‘The giant impact’ should therefore name a well-supported explanatory class, not one frozen animation. The scientific progress lies in using new isotope and dynamical constraints to eliminate versions, not in pretending that every successful simulation is the same history.

Where That Leaves Us

The Moon strongly supports a late giant collision, yet no single impact geometry owns that conclusion. Canonical, high-angular-momentum, synestia and immediate-satellite models distribute the constraints differently. Their competition is productive because lunar isotopes, angular momentum and thermal history can rule out implementations even when the explanatory class itself broadly survives.

8. What the Evidence Can and Cannot Rebuild

Lunar zircons yield ages near 4.51 billion years. Barboni and colleagues interpreted uranium–lead ages and hafnium isotopes as evidence that the Moon formed within about 60 million years of Solar System time zero.[41] That conclusion joins mineral crystallization to a model of lunar differentiation; the measured zircon ages are not a direct timestamp stamped onto the impact itself.

Highly siderophile elements provide another route. Jacobson and colleagues used the relation between late-accreted mass and dynamical clearing to estimate a Moon-forming time near 95 ± 32 million years after Solar System formation.[33] This is a statistical model tied to a late-veener proxy, not the same measurement as the lunar-zircon constraint. Agreement or tension must preserve that distinction.

Meteorite isotopes also connect present asteroid classes to source reservoirs. Hydrogen and nitrogen systematics constrain volatile carriers,[42] while returned particles from Itokawa establish a direct link between an S-type asteroid and ordinary chondrites.[43] Such successes justify comparative planetology, but one linked asteroid does not collapse every meteorite family into one place of origin.

Numerical accretion experiments show why exact replay is unlikely. Stochastic impacts change feeding zones, volatile delivery, rotation and final composition even under similar broad

conditions.[17,44] Models are strongest when they reproduce distributions and correlated constraints, not when one aesthetically convincing run is treated as Earth's recovered biography.

The reconstruction therefore has layers: observed disk structures; measured meteorite textures, chemistry and isotopes; experimentally calibrated physical processes; dynamical and geochemical models; and present planetary properties. A precise age belongs to a mineral, reservoir separation or closure event before it belongs to a planet. QTC-017 takes up how isotope clocks earn those ages, their assumptions and their cross-checks.

Where That Leaves Us

No archive rebuilds Earth alone. Dates, chemical reservoirs, interiors and simulations become persuasive when they constrain compatible operations while retaining different failure modes. The broad sequence from disk solids to a differentiated Earth and giant impact is robust; the exact itinerary remains reconstructive. The next article asks how isotope clocks make its chronology quantitative.

What We Know, and How

- Young stars commonly retain structured disks of gas and dust, while a ring or gap is not uniquely a planet signature.[2–4]
- CAIs provide a 4567.30 ± 0.16 Ma first-solid reference; they do not date a completed Earth.[6]
- Dust collisions, gas drag and collective particle–gas dynamics make several physically tested routes from grains to planetesimals.[9–15]
- Gravity, migration, impacts and aluminium-26 can grow, rearrange, melt and differentiate planetary bodies.[16–27]
- Earth and Moon constraints require a changing accretion mixture and a late giant-impact class without selecting one unique scenario.[28–41]

What We Still Don't Know

- Which planetesimal-forming route dominated at each disk location and time.
- Which specific migration history produced Mars, the asteroid belt and the terrestrial feeding zones.
- The proportions and delivery paths of Earth's water and other volatiles.
- The Moon-forming impact's exact geometry, impactor composition, thermal state and date.

What Could Change Our Minds

- Resolved disk observations that uniquely connect substructures to embedded planets or to non-planetary mechanisms.
- Laboratory and numerical convergence showing one planetesimal-forming route dominates across realistic disk conditions.
- New returned samples with reservoir-defining isotopes and known geological context.
- A lunar-impact model that simultaneously matches isotopes, chemistry, angular momentum, thermal evolution and absolute chronology without special tuning.

If You Remember Only One Thing

Planets emerge through several coupled mechanisms, and Earth's history is credible only where disks, meteorites, isotopes, dynamics and interiors constrain the same sequence without pretending to recover one inevitable recipe.

Related Articles

- QTC-004 — Where Were the Atoms in Your Body Made?
- QTC-015 — The Stars We Have Never Seen
- QTC-017 — How We Learned to Date the Past

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