Key Ideas for Session on From the Earth to the Moon Video

I. Nature of Scientific reasoning
A. Understanding as connected experiences, patterns, and explanations

   Inquiry (Constructing explanations from patterns in experience)
      Arguments from evidence

   Experiences
      (data, phenomena, systems, objects, events)

   Patterns
      (generalizations, laws)

   Explanations
      (hypotheses, models, theories)

   Application (Using scientific patterns and theories to describe, explain, predict, design)
      Model-based reasoning

B. Importance of qualitative reasoning as a basis for quantitative reasoning
C. Rigor as consistent, detailed use of simple models (for example, this lesson does not include Snell’s Law, refraction by lenses, real and virtual images, etc.)

II. Importance of Student Reasoning
A. Specific misconceptions (for example, that we see out from our eyes)
B. Sense-making strategies
   • Procedural display: Following procedures that are personally meaningless to get correct answers
   • Narrative reasoning: Learning stories and steps in procedures
   • Practical reasoning: Finding and using patterns
   • Model-based reasoning: Connecting experiences, patterns, and models
C. Assessment and dialogue as key strategies for engaging students’ personal reasoning

III. Learning Cycles as a Way to Help Students Learn Difficult Content
A. Transfer of responsibility
B. Prerequisites for a learning cycle
C. Specific steps in learning cycles
Learning Cycle Requirements for Collecting Moon Rocks

1. Objective for Astronauts
   Collect the most informative rocks when they land on the moon.

2. Experiences, patterns, and explanations

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Application: Model-based Reasoning

Inquiry: Finding and Explaining Patterns in Experience

3. Pattern in Astronaut Practice

Initial Observations: Visual Survey of Site

Developing Tentative Explanation or Hypothesis
- What is the history of this site?
- What collection of rocks best represents all the stages in that history?

Collecting Rocks
- Guided by hypotheses

Geologists Develop More Complete Theories
- Explaining in ways that are consistent with all available data
Learning Cycle Requirements for Observing the Moon from Orbit

1. Objective for Astronauts
   Record details of lunar topography.

2. Experiences, patterns, and explanations

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Application: Model-based Reasoning

Inquiry: Finding and Explaining Patterns in Experience

3. Pattern in Astronaut Practice

   Initial Observations Visual Survey of Moon

   Developing Tentative Explanation or Hypothesis
   - Causes of lunar surface features and order in which they were formed

   Detailed Observations from Orbiting Module
   - Drawing the object and all the forces on it
   - Using arrows to represent ONLY forces (not direction of motion, etc.)

   Geologists Develop More Complete Theories
   - Explaining in ways that are consistent with all available data
Origins
by Peter Tyson

Whence our moon? Was it a chunk of Earth flung off in our planet's early history? Did the Earth capture a small, roaming planet in its gravity grip? Or did the moon fashion itself alongside our world from the same planetary batter? One of the Apollo program's chief scientific goals was to give lunar researchers the means to decide, once and for all, between these three main theories of how the moon formed.

What transpired in this "battle of the Big Three" after the last Apollo mission flew in 1972 surprised just about everyone. The story provides a revealing glimpse of the workings of the scientific process, while at the same time opening a window on the origins of what one lunar researcher has called "one of the most peculiar bodies in the solar system"—the moon.

The Big Three

Human beings have surely wondered about the moon since they had brains big enough to do so. Many cultures, from ancient times to the present day, have even worshipped it as a deity. The Greeks were perhaps the first to study our satellite scientifically. Using Earth's shadow on the moon during lunar eclipses as a guide, the third-century B.C. astronomer Aristarchus estimated it lay 60 Earth radii away. (It was a remarkable guess: in fact, the distance varies between 55 and 63 Earth radii, or 220,000 and 250,000 miles.) The biographer Plutarch went so far as to posit that people lived on the moon, whose dark regions, the Greeks thought, marked oceans and the bright areas land. Their belief survives in the Latin names—maria (seas) and terrae (lands)—by which we know these dark and light regions.

In the 1870s, Charles Darwin's son proposed that the Earth flung off a portion of itself that became the moon.

Modern scientific study of our neighbor began in 1610, when Galileo, training his spyglass on the moon, became the first person to see the dark and light regions for what they really were: vast plains and rugged mountains, respectively. Galileo's famous trial for heresy—for insisting that the Earth revolved around the sun rather than vice verse—apparently kept Descartes from publishing one of the first theories about the origin of the moon until 1664, long after his own death. (His theory was essentially an early version of the planet-capture theory.) Descartes left a fuller explanation for others, admitting "I have not undertaken to explain everything."

The first moon-origin theory to gain a solid foothold was put forth in 1878. That year, George Howard Darwin, son of the famous evolutionist, proposed that Earth spun so rapidly in its early years that the sun's gravity eventually yanked off a chunk of an increasingly elongated Earth; that chunk became the moon. Four years later, the geologist Osmond Fisher added a juicy addendum: The Pacific ocean basin marks the scar left behind where our future satellite ripped away. The so-called "fission" theory became the accepted wisdom well into the 20th century, as this quirky, 1936 U.S. Office of Education script for a children's radio program attests:

The Darwin-Fisher model eventually met with competition from two other theories. In 1909, an astronomer with the all-American name of Thomas Jefferson Jackson See proposed that the moon was a wandering planet that had been snared by Earth's gravity, like a fly in a spider web. The third theory, advocated by the astronomer Edouard Roche among others, was coaccretion. In this model, the Earth and the moon formed independently, side by side as it were, from the same material that formed all the planets of our solar system.
Some clever scientist eventually dubbed the Big Three "daughter" (fission), "spouse" (capture), and "sister" (coaccretion). Which family member would win out?

**Apollo's Impact**

By the end of the Apollo program, lunar scientists had elucidated many aspects of the moon's history, giving them clues unavailable to the likes of Darwin or See. Selenology, the study of the origin of the moon, had taken off. Most of the new evidence came from the more than 800 pounds of moon rocks retrieved by the American and Russian lunar missions.

In many ways, the moon turned out to be quite different from Mother Earth. Anybody can see that, of course: It's airless, colorless, lifeless. But the differences run deeper. It is compositionally different, with fewer volatile elements—those that tend to boil off at high temperature. The moon might have inherited such differences—maria rocks contain no water, for instance, unlike volcanic rocks on our planet—from the impactor. The lunar samples also suggest that much of the moon may have once been molten; no definitive evidence exists that the Earth ever melted to such a degree. And while one-quarter its size, the moon has but one percent of our planet's mass, and its density more closely resembles that of Earth's mantle rather than the planet as a whole. Lunar scientists in the immediate post-Apollo years explained these discrepancies by postulating that the moon had but a tiny core. In 1998, the Lunar Prospector, NASA's first mission to the moon since Apollo, confirmed that the moon's core indeed comprises less than three percent of its mass. (By contrast, Earth's core represents 30 percent of its mass.)

In other ways, the Earth and moon have remarkably similar characteristics. Studies of radiogenic elements and isotopes in lunar rocks reveal that the two bodies are roughly the same age, 4.5 billion years old. They also came from the same neighborhood: Unlike those in all meteorites ever analyzed, the nonradioactive, stable isotopes of oxygen in moon and Earth rocks match like blood types, implying the two spheres formed at the same radial distance from the sun. Indeed, results from Apollo showed the pair to be more intimately connected than previously thought. "Apollo tied together for the first time the history of the moon with the history of the Earth," says William Hartmann of the Planetary Science Institute in Tucson, Arizona. "It showed us that we live in a system, the Earth-moon system."

In fact, it's a pairing unlike any other in the solar system. Our moon is far more massive relative to Earth, for example, than the satellites of all other planets save Pluto (whose moon, Charon, is half its size). The Earth-moon system also has an unusually high angular momentum—that is, the sum of the our planet's rotational velocity and the speed at which the moon orbits the Earth.

So how do the Big Three stand up in the face of all the new evidence? Not well, it turns out. The fission theory might explain the moon's lack of a large core and the oxygen-isotope similarity, astronomers say, but calculations show that the Earth would have to have had four times its present angular momentum—a lightning-fast rotational speed that astronomers cannot square in their models. Add to that the understanding reached decades ago that the Pacific basin formed less than 70 million years ago and therefore could not possibly have spawned the moon, and the Darwin-Fisher model suddenly comes up short.

See's capture theory suffers as well. The idea that Earth's gravity caught a rogue planet might explain the compositional differences between the two bodies. But, then, why doesn't the moon have its own regular-sized core? And why the oxygen-isotope similarity if the two formed in different parts of the solar system? Finally, most modelers deem the chance that a speeding planet would gracefully ease into Earth's embrace rather than slam into it or career off into space too remote for consideration.
Coaccretion led the pack through the 1970s, because, for one thing, it doesn't require a low-probability event like capture. But today it faces the same problem regarding the core. As Hartmann says, "It's very hard to imagine the two bodies growing together but somehow the Earth magically gets all the stuff with the iron in it and the moon doesn't get any." Even more troublesome, experts say, the theory cannot account for the enormous angular momentum we see in the Earth-moon system today.

The Big Whack

Rather than clarifying the issue of the moon's origin, the Apollo data only complicated it. As Hartmann declared in Origin of the Moon, a 1984 book he co-edited with two other researchers, "neither the Apollo astronauts, the Luna vehicles, nor all the king's horses and all the king's men could assemble enough data to explain the circumstances of the moon's birth." Many felt something else was needed.

It came in the mid-1970s, when a new theory of lunar origin began to emerge. It rose phoenix-like from the ashes of constraints not adequately met in tests of the three other models. First, Hartmann, along with Planetary Science Institute colleague Don Davis, determined that a roving planetoid, large enough to blast off enough mantle material to make the moon, could have struck the Earth shortly after its formation. (Previous work had held that the solar system had long since run out of planet-sized meteors.) Working independently, Alastair Cameron and William Ward of Harvard University concluded that an impact from a body at least as large as Mars could have supplied the rough material for the moon and also given our bipartite system its angular momentum.

The "Big Whack" theory was born. The giant-impact hypothesis, as it's more formally known, initially had little impact of its own. If Nature abhors a vacuum, researchers generally abhor catastrophic solutions to geophysical problems, Hartmann says; such solutions are too tidy. So the theory languished for a decade. As Robin Canup, an astrophysicist at the Southwest Research Institute in Boulder, Colorado, put it, "At first it was seen as ad hoc, probably unlikely, possibly ridiculous." But in 1984, a seminal conference devoted to the moon's origin that was held in Kona, Hawaii jumpstarted research.

Canup, for one, leapt in with both feet beginning in the mid-1990s. Cameron's models had left off after the giant impact, when a debris cloud from which the moon would arise formed around Earth. She extended the modeling from debris cloud to finished moon. Canup's calculations showed that most debris from the collision would either fall back to Earth or fly off into space, leaving only 20 to 50 percent to make a moon. The Big Whack, she figured, required a much bigger whacker—one two to three times the mass of Mars. But that resulted in an Earth spinning at two to two and a half times its present angular momentum. She addressed that problem by introducing a Big Whack II: a second impactor that hit Earth against the grain of our planet's rotation millions of years after the first, thus slowing its spin.

In contrast to the Big Three, the Big Whack stands up nicely against what we now know of the moon. According to theoretical models, the impact would have destroyed the impactor, sending most of its remains, along with huge amounts of the Earth's mantle, into an Earth-orbiting debris cloud that ultimately coalesced into the moon. This would explain the reduced density of the moon, which is believed to be composed of two-thirds impactor and one-third Earth mantle. And it explains its tiny core: Since the models suggest that all of the impactor's core wound up in the Earth's core, the moon must have got its core iron from later, smaller impacts. By the same token, Earth got its additional volatile elements from later impacts from comets and
carbonaceous meteors. Finally, the Big Whack can account well for the Earth-moon's angular momentum and even our planet's odd, 23.5-degree tilt off the ecliptic plane (the invisible platter on which nearly all planets orbit the sun).

While currently the frontrunner, the Big Whack needs more work. Many would like to see it account somehow for the oxygen-isotope similarity, which, by definition, would seem to argue against an impactor formed elsewhere in the solar system. Canup, for her part, has a running list of research questions she'd like to see addressed. These include: Make the Big Whack model work with just a single impact, rather than the more ad hoc multiple. Explain the formation of Charon, Pluto's moon, which scientists have postulated might also have been the offspring of a giant impact. And finally, chemically match the moon's characteristics with what would have happened in the proto-lunar debris cloud.

"If we can get to a point where we can naturally explain with our theoretical models the chemical signatures and elemental abundances in the lunar material," Canup says, "to me that's the nail in the coffins of the other theories." Cameron concurs. "Quite independently of the giant-impact theory," he says, "they were sealed long ago."

Peter Tyson is Online Producer of NOVA.