

The Mathematics of Whether Pluto is a Planet

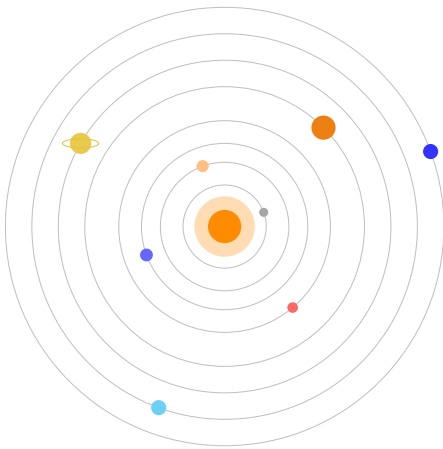
Christopher Gilmartin

Departments of Physics and Mathematics, New York University

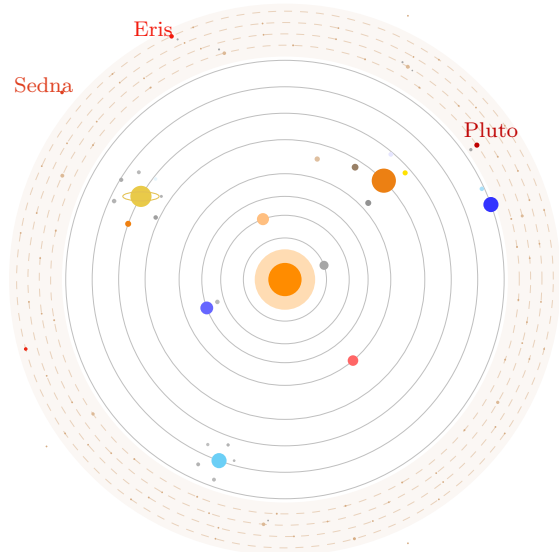
TikTok: @christopher.mycle

April 2026

The IAU Solar System
8 planets



The Geophysical Solar System
~110 planets



Prologue

On April 28, 2026, NASA Administrator Jared Isaacman testified before the U.S. Senate Committee on Appropriations on the agency’s 2027 budget. Near the end of the hearing, Senator Jerry Moran of Kansas, Clyde Tombaugh’s home state, turned the conversation to Pluto. Isaacman responded, “I am very much in the camp of ‘make Pluto a planet again.’” Further, he told the committee that NASA is preparing papers that it hopes to take to the scientific community to revisit the issue.

This paper aims to help us make that decision.

1 The Question of Pluto and the IAU’s Three Criteria

What’s frustrating about the question of Pluto is that everyone is right.

Those who insist Pluto is not a planet are correct according to the definition laid out by the International Astronomical Union in 2006. Those who say it is a planet are also correct, under a different definition favored by some planetary scientists, including the lead investigator of the only mission ever to reach Pluto. The argument is not about Pluto; it is about the meaning of the term “planet.”

To understand why, let’s look at the actual wording of that definition. On August 24, 2006, in its General Assembly in Prague, the IAU passed Resolution B5, which set forth a definition for planets in the solar system as those bodies satisfying three conditions:

1. They orbit the Sun.
2. They are massive enough for gravity to make them assume hydrostatic equilibrium.
3. They have cleared the area around their orbit of other bodies.

Those meeting the first two criteria but not the third were classified as *dwarf planets*. Pluto, along with Ceres and Eris, was categorized as a dwarf planet. In effect, a dwarf planet is not a type of planet, like the way a sea horse is not a kind of horse.

Two of these criteria are easy to establish. Pluto orbits the Sun, so criterion 1 is obviously fulfilled. Pluto is spherical in form, and we will prove in Section 4 below that its mass exceeds the threshold beyond which the forces of self-gravity dominate, putting it well within the limits of criterion 2. Criterion 3 is what has generated the controversy.

But criterion 3 is also difficult, because no exact threshold was provided in the resolution. There is no statement of how much material needs to have been removed from the orbital neighborhood, the time span involved, nor even the mechanism of that removal. All that is stated is “cleared.” Over the years, three different proposals have been made by planetary scientists to quantify this concept: Stern and Levison’s Λ parameter, Soter’s μ value, and Margot’s Π number. These will be explored in Sections 5, 6, and 7. Warning: all three give the same result for Pluto, namely that it has not cleared its orbit, which means it does not qualify as a planet.

What you will note here is that this issue tends to get oversimplified on most science TikToks, even including mine. Under the definition provided by the IAU, Pluto is a definite failure, not a

close call. As we will show in Section 8, the difference between Pluto and a true planet, in terms of the three criteria mentioned above, is orders of magnitude and can be graphed on a log scale.

If it's so straightforward, then why the argument?

Because there's another definition. In 2017, planetary scientists led by Kirby Runyon introduced what they called a *geophysical* definition for planets. Very roughly, any sub-stellar body that has sufficient mass to assume a hydrostatic equilibrium shape is considered a planet. By such a definition, the number of planets in our solar system is closer to 110, including Pluto, Ceres, our Moon, Europa, Titan, Triton, and Enceladus.

It sounds ridiculous at first. It is not. It expresses a genuine divide over exactly what the word “planet” should capture. The IAU definition is *dynamical*, focusing on a body's relationship to its surroundings and its history. The geophysical definition focuses on the body itself, irrespective of the external conditions. Neither definition is wrong; they answer different questions.

IAU Definition (2006) as Nested Filters

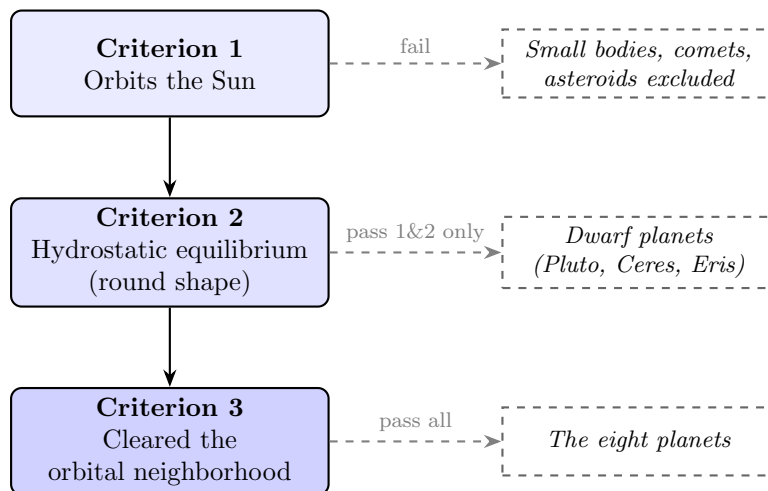


Figure 1: The three IAU criteria for planethood, drawn as nested filters. A body must pass all three to be classified as a planet. Bodies that pass criteria 1 and 2 but fail criterion 3 are classified as dwarf planets, a category which the IAU explicitly does not consider a subset of “planet.” Pluto fails at the third filter.

For the remainder of this paper, we shall take both of these options into account. We will work our way up the problem: first, Pluto's orbit (Section 2), then the resonance that keeps it from crashing into Neptune despite their nearly intersecting paths (Section 3), the proof that its mass exceeds the threshold for hydrostatic roundness (Section 4), and three mathematical formulations of orbital clearing (Sections 5 through 7). Once the dynamical case is firmly established, we'll proceed to the alternative proposal (Section 9) and ask whose approach is more useful (Section 10).

My conclusion will be that the dynamical classification is a more useful taxonomy of planets as it slices the solar system at its joints, but that the geophysical classification captures something the former neglects. The term “planet” is being asked to do double duty, and the honest solution is to admit we need two words.

But let's put my argument at rest and begin with the orbit of Pluto.

2 The Orbit of Pluto Around the Sun

Before asking the main question in the title of this paper, we have to define the location of Pluto's neighborhood. Let's start with the orbit.

The semi-major axis a , half of the ellipse's longest diameter, is the first relevant parameter. For Pluto, $a = 39.48$ AU [8], or about 40 AU. One astronomical unit is equal to 1.496×10^{11} m, the average distance from the Earth to the Sun. So Pluto is, on average, 40 times more distant from the Sun than we are.

The use of the word "average" is important here, because Pluto's orbit is highly eccentric. The measure of orbital eccentricity e lies within the range 0 to 1; for a circle, e is 0; for an increasingly elongated ellipse, it approaches 1. The vast majority of planets have a practically zero eccentricity: 0.017 for the Earth, 0.007 for Venus, and 0.009 for Neptune [8]. The eccentricity for Pluto is 0.249 [8], which is higher than that of any major planet. The nearest point of an eccentric orbit to the center (perihelion, q), and the furthest point (aphelion, Q) are described in the following way:

$$q = a(1 - e), \quad Q = a(1 + e) \quad (1)$$

So for Pluto:

$$\begin{aligned} q &= 39.48 \times (1 - 0.249) = 29.66 \text{ AU} \\ Q &= 39.48 \times (1 + 0.249) = 49.30 \text{ AU} \end{aligned}$$

Pluto's variation from the Sun is approximately 20 AU within one orbit cycle. It is comparable to the distance from the Sun to Uranus. The first peculiarity of Pluto's orbit is obvious already.

It's time to introduce the second one. Neptune moves along a rather perfect circular orbit of $a = 30.07$ AU and $e = 0.009$, meaning that the perihelion distance for Neptune is 29.80 AU. Thus, Pluto's perihelion is inside Neptune's orbit.

Not surprisingly, this is not a minor peculiarity. For almost 20 years of its 248-year cycle, Pluto remains closer to the Sun than Neptune does. The last such period began in February 1979 and ended in February 1999. The next one will begin in 2231.

To calculate the frequency of this event, we need to estimate T , Pluto's orbital period around the Sun. According to Kepler's third law:

$$T^2 = \frac{4\pi^2 a^3}{GM_\odot} \quad (2)$$

where $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ (Newton's gravitational constant) and $M_\odot = 1.989 \times 10^{30} \text{ kg}$ (Sun's mass).

In SI units, it would be quite complicated. However, using a convenient set of units in which T is measured in years and a is measured in AU, Kepler's law takes a beautiful shape:

$$T^2 = a^3 \quad (3)$$

For Pluto: $T^2 = 39.48^3 = 6.154 \times 10^4$, giving $T \approx 248.07$ years.

One Pluto-year is roughly 248 Earth-years.

The next parameter, Pluto's inclination i (the angle of orbital plane deviation from a chosen reference plane, in our case the ecliptic), is another sign of Pluto being a unique object. Most of

the planets are situated very close to the ecliptic. Earth’s orbital plane deviation angle, obviously, equals 0° . The same is true for Mars (with its 1.85° angle). Neptune, having an angle of 1.77° , is almost in the ecliptic too. However, Pluto’s inclination $i = 17.16^\circ$ [8], or roughly seven times the average planetary value.

This parameter directly influences the answer we’ve been seeking. While looking at a two-dimensional diagram (Fig. 2a), you can notice the orbits of Pluto and Neptune crossing. But this is an illusion created by projecting a three-dimensional space onto a two-dimensional plane. The third dimension brings us part of the answer: two non-parallel planes always meet, but only along a single line, and Pluto crosses that line at about 33 and 42 AU from the Sun, never at Neptune’s distance. When Pluto is inside Neptune’s orbit, it sits several AU above Neptune’s orbital plane (Fig. 2b). Pluto’s and Neptune’s orbits intersect when projected onto the ecliptic, but never intersect in three dimensions. The real minimum distance between Pluto and Neptune is larger still, about 17 AU, which is nearly the distance from the Sun to Uranus. The tilt alone does not guarantee that margin, though; it is kept by the resonance described in the next section.

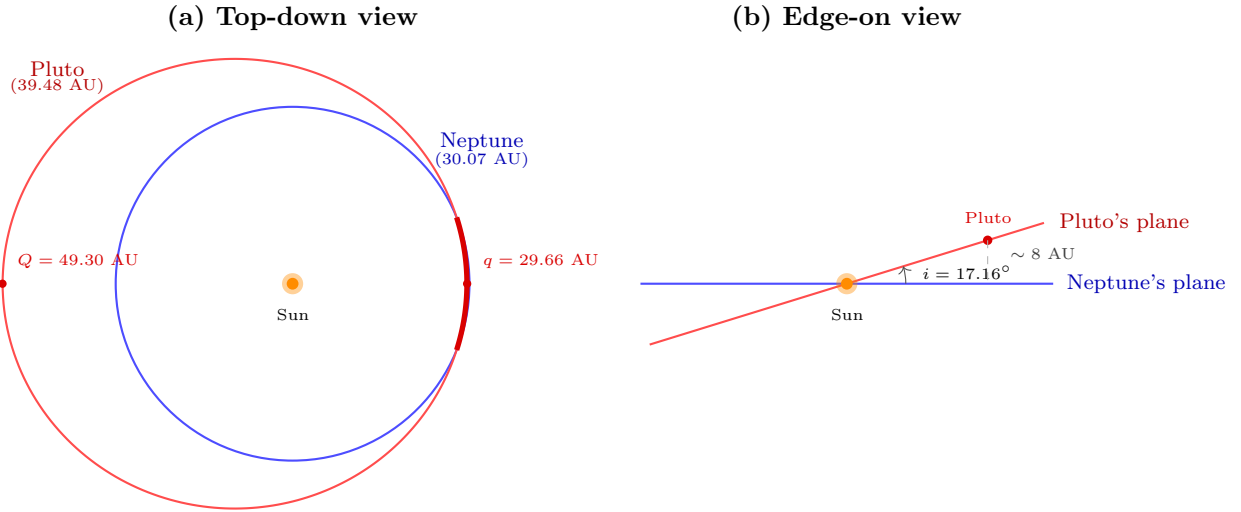


Figure 2: Pluto’s orbit relative to Neptune’s. Panel (a) shows the top-down view with both orbits projected onto the ecliptic plane. Pluto’s eccentric orbit (red) carries it from perihelion at $q = 29.66$ AU, just inside Neptune’s nearly circular orbit at 30.07 AU, to aphelion at $Q = 49.30$ AU. The thick red arc marks the portion of Pluto’s path inside Neptune’s orbit, traversed during roughly twenty years of every 248-year Pluto orbit. Panel (b) shows the system viewed edge-on along the line of nodes, revealing the 17.16° tilt of Pluto’s orbital plane relative to the ecliptic, which Neptune’s orbit follows to within 2° . At perihelion, the body itself sits roughly 8 AU above the ecliptic (about 7 AU above Neptune’s orbital plane). The actual minimum three-dimensional separation between the two bodies is approximately 17 AU, a margin kept by the 3:2 resonance (Section 3).

This information provides a very interesting and beautiful story about the dynamics of our solar system. But this is not the complete picture of reality. If we have two intersecting orbital planes but currently non-intersecting orbits, we might expect that eventually these two bodies will encounter each other much more closely. Such intersections arise from perturbations caused by interactions between a planet and other objects.

These perturbations may affect the dynamics of these bodies for billions of years. As a result, we may expect that by now Pluto has either been thrown out into the outer Solar System or become a

moon of Neptune. The fact that neither of these events occurred is due to an incredibly special configuration called a *mean-motion resonance*, which Pluto and Neptune participate in. We will explore it in the next section.

3 The 3:2 Mean-Motion Resonance with Neptune

The problem described in the last section is real. Two bodies whose orbits cross are bound to approach each other over the course of billions of years due to the incremental perturbations caused by other planets' gravity. The fact that the orbits of Pluto and Neptune haven't collided for the whole age of the solar system suggests that some force is preventing it.

The stabilizing force is the mean-motion resonance, a special dynamical regime in which the orbital periods of two bodies are in a ratio of small integers.

The basis for such a regime can be seen in the orbital period ratio:

$$\begin{aligned} T_N^2 &= 30.07^3 = 2.719 \times 10^4 \\ T_N &\approx 164.89 \text{ years} \end{aligned}$$

We already have $T_P \approx 248.07$ years from Section 2. Their ratio:

$$\frac{T_P}{T_N} = \frac{248.07}{164.89} = 1.5045 \quad (4)$$

This number is very close to the simple fraction $3/2$. Equivalently:

$$\begin{aligned} 2 \cdot T_P &= 496.14 \text{ years} \\ 3 \cdot T_N &= 494.67 \text{ years} \end{aligned}$$

The discrepancy is only about 0.3 percent. Pluto makes exactly two revolutions in virtually the same amount of time that Neptune makes three revolutions. The match is too good to be random.

Why does the ratio matter for stability? To understand that, we must discuss the mean motion n , defined as the average angular speed of a body around the Sun:

$$n = \frac{2\pi}{T} \quad (\text{rad/year}) \quad (5)$$

For our two bodies:

$$\begin{aligned} n_N &= \frac{2\pi}{164.89} \approx 0.03811 \text{ rad/yr} \\ n_P &= \frac{2\pi}{248.07} \approx 0.02533 \text{ rad/yr} \end{aligned}$$

A $p:q$ mean-motion resonance between the bodies is characterized by a near-identity:

$$p \cdot n_{\text{outer}} \approx q \cdot n_{\text{inner}} \quad (6)$$

With Neptune inner and Pluto outer:

$$2 \cdot n_N \approx 3 \cdot n_P \quad (7)$$

Substituting our data:

$$\begin{aligned} 2 \cdot n_N &= 0.07621 \text{ rad/yr} \\ 3 \cdot n_P &= 0.07599 \text{ rad/yr} \end{aligned}$$

The difference is only 0.00022 rad/yr, less than 0.3 percent of either. This small difference is the resonance.

However, such a near-identity is not enough by itself for anything to stay stable. All it means is that the two bodies are passing each other infrequently. To make the resonance a stabilizing mechanism, we must define one additional quantity: the resonant argument.

For the 3:2 Pluto-Neptune resonance, this quantity is

$$\phi = 3\lambda_P - 2\lambda_N - \omega_P \quad (8)$$

Here, λ_P and λ_N are the mean longitudes, the angles measured in the orbit of a body relative to a fixed direction in space. In contrast, ω_P is the longitude of Pluto's perihelion, that is, the direction at which Pluto's orbit makes its closest approach to the Sun.

The resonant argument has the following time dependence:

$$\frac{d\phi}{dt} = 3n_P - 2n_N - \frac{d\omega_P}{dt} \quad (9)$$

The first two terms differ by a very small amount, and that difference is not fixed: Neptune's pull slightly speeds Pluto up and slows it down, so the difference swings back and forth around zero. The perihelion precession rate of Pluto, $d\omega_P/dt$, is smaller still, of order 10^{-6} rad/yr, since the secular perturbations of the giant planets take millions of years to turn Pluto's perihelion once around the Sun. Consequently, ϕ is changing very slowly, oscillating around the same value. Such a slow oscillation is called *libration*.

For the Pluto-Neptune system, ϕ librates around 180° [9], with an amplitude of roughly plus or minus 80° and a period of about 20,000 years.

What does it protect? When the two bodies cross paths, meaning they have the same mean longitude ($\lambda_P = \lambda_N \equiv \lambda$), their relative angle ϕ becomes simply

$$\phi = 3\lambda - 2\lambda - \omega_P = \lambda - \omega_P \quad (10)$$

which is, by definition, Pluto's mean anomaly at that point.

If ϕ is librating around 180° , then whenever Pluto and Neptune are at the same longitude, Pluto's mean anomaly is also near 180° , which places Pluto near aphelion. The libration of the resonant argument ensures that the crossings occur near aphelion, never at perihelion.

This is the stability mechanism. Its consequences are drastic. At its aphelion, Pluto is at a distance $Q = 49.30$ AU from the Sun, while Neptune stays close to 30 AU. Even if the two bodies were to cross orbits at that time, they would still be separated by 20 AU in the orbital plane, discounting Pluto's inclination by 17.16° . The resonance aligns the bodies in exactly the way that puts them the furthest apart.

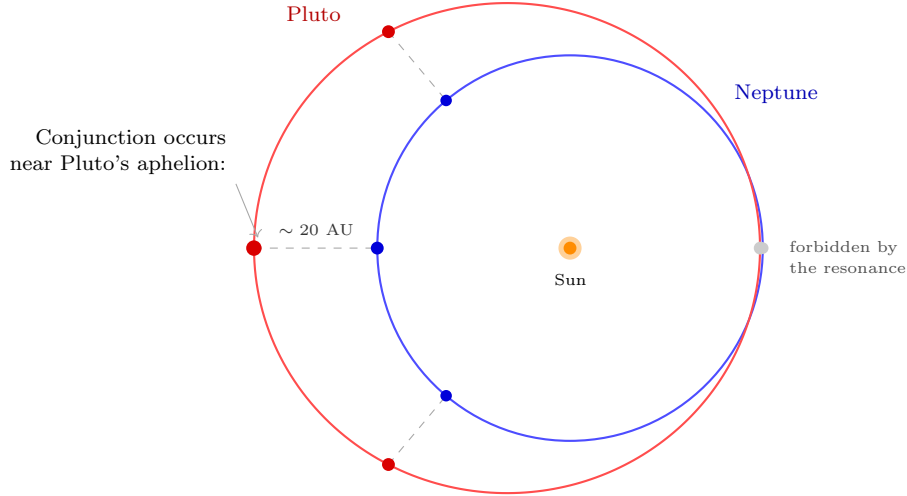


Figure 3: The protective effect of the 3:2 mean-motion resonance. Three sample conjunctions are shown (the moments when Pluto and Neptune share the same heliocentric longitude), spanning the full range of libration of the resonant argument ϕ . In every case, Pluto (red) is far from perihelion, and Neptune (blue) is correspondingly distant. The dashed lines mark the in-plane separation, which is approximately 20 AU at the aphelion conjunction and never less than about 14 AU at the libration extremes; once Pluto’s tilt is included, the true separation never drops below about 17 AU. The faded pair on the right shows the configuration the resonance forbids: Pluto and Neptune meeting near Pluto’s perihelion, where the two bodies would come within about 0.4 AU of each other in the orbital plane. This configuration never occurs.

The beauty of this scheme hardly needs explaining. There is also an extremely important consequence from the viewpoint of the central question of this paper. Pluto’s presence in this orbit depends entirely upon Neptune. It is not just a mutual relationship. The resonance is such that Neptune dictates the orbit of Pluto, and without it, Pluto couldn’t exist in this part of the solar system. Pluto’s presence here demonstrates the dominance of Neptune rather than its lack thereof.

Finally, we are ready to put the third IAU criterion into context. Pluto has not cleared its orbit. On the contrary, its orbit is controlled by Neptune.

There is no symmetry between the bodies involved. This is not just an accounting issue. It is a reality that has affected their orbits since the dawn of the solar system.

In the next four sections, we will investigate how dominant Neptune is quantitatively. We will use three independent criteria of how much a body has cleared its zone, defined in the planetary dynamics literature.

4 Self-Gravity and Hydrostatic Equilibrium

The first criterion posed by the IAU is trivially fulfilled by any object that revolves around the Sun. Indeed, Pluto orbits the Sun, so no further discussion is needed. The third criterion, concerning the clearing of the object’s orbital neighborhood, will be discussed in the subsequent four sections. This section is devoted to the analysis of the second criterion.

According to the criterion, a planet should have enough mass for self-gravity to dominate its

shape, thus resulting in the hydrostatic equilibrium, an almost spherical shape. In simple terms, the object has to be large enough for its self-gravity to pull it into a spherical shape.

Why is there a minimum size requirement in such a case? Actually, two factors compete against each other. First, there is always self-gravity, pulling all parts of the body towards its center of mass. Second, there is the internal structural resistance provided by material strength. When the body is relatively small, material strength dominates, and objects have highly uneven shapes. Mars's satellite Phobos, for example, has an irregular potato-like shape. As the body grows larger, the internal pressure exceeds the structural resistance, and the object assumes a spherical shape.

We can estimate the threshold size using simple calculations. Indeed, for a uniform sphere with density ρ and radius R , the pressure on the center, created by self-gravity, equals:

$$P_c = \frac{2\pi}{3} G \rho^2 R^2 \quad (11)$$

Such a formula results from integrating the gravitational force acting on each material layer, starting from the surface. For the body to assume a spherical shape, the central pressure must exceed the body's yield strength σ_y , i.e., the stress at which elastic deformation begins. So let us set $P_c \approx \sigma_y$ and solve the equation:

$$R_{\text{crit}} = \sqrt{\frac{3\sigma_y}{2\pi G \rho^2}} \quad (12)$$

Let us consider a relatively icy body whose density is approximately $\rho = 1000 \text{ kg/m}^3$, while the yield strength is $\sigma_y = 1 \text{ MPa} = 10^6 \text{ Pa}$. Such assumptions make sense since ice is abundant in bodies of the outer Solar System:

$$\begin{aligned} R_{\text{crit}} &= \sqrt{\frac{3 \times 10^6}{2\pi \times 6.674 \times 10^{-11} \times 10^6}} \\ &= \sqrt{\frac{3 \times 10^6}{4.19 \times 10^{-4}}} \\ &= \sqrt{7.16 \times 10^9} \approx 85 \text{ km} \end{aligned}$$

If we consider rocky bodies with $\rho \approx 3000 \text{ kg/m}^3$ and $\sigma_y \approx 100 \text{ MPa}$ (meaning rocks are approximately 100 times more resistant to deformation than ice), we get approximately 280 km.

The above-mentioned threshold radius values are rough estimates; the transition is quite smooth, depending on the body's chemical composition, internal temperatures, and collision history. Nevertheless, it agrees well with the real world: the smallest icy object to assume an almost round shape is the icy satellite of Saturn, Mimas, which has a mean radius of approximately 198 km [11], and in the asteroid belt the only body round enough to qualify is the largest asteroid, Ceres, a mixture of rock and ice with a radius of approximately 470 km [11]. Another example is Vesta, with a mean radius of about 263 km, just under the rock threshold; it is roughly round but has a crater about 500 km across near its south pole caused by a collision. These estimates correspond well with real data.

But how does it work for Pluto? Its radius equals $R_P = 1188.3 \text{ km}$, and the mass is $M_P =$

1.303×10^{22} kg [11, 13]. It implies:

$$\begin{aligned}\rho_P &= \frac{M_P}{(4\pi/3)R_P^3} \\ &= \frac{1.303 \times 10^{22}}{(4\pi/3) \times (1.1883 \times 10^6)^3} \\ &= \frac{1.303 \times 10^{22}}{7.029 \times 10^{18}} \approx 1854 \text{ kg/m}^3\end{aligned}$$

Such a density lies between those of pure water ice (approximately 1000 kg/m^3) and silicate rock (approximately 3000 kg/m^3). Hence, Pluto is made of approximately two-thirds rock and one-third water ice. Thus, with Pluto’s mean density being 1854 kg/m^3 and the same yield strength assumption as previously, we may calculate the critical radius:

$$R_{\text{crit}} \approx 46 \text{ km} \quad (13)$$

Thus, Pluto’s radius exceeds the critical radius approximately twenty-five-fold.

The shape of the object is consistent with this calculation. In July 2015, New Horizons conducted the detailed mapping of Pluto’s surface [6]. The mission’s images were used to estimate its oblateness, the difference between the equatorial and polar radii, expressed as a fraction of the equatorial radius, to be less than 0.6%, which could not be measured accurately and is thus considered approximately zero [13]. For comparison, Earth’s oblateness is 0.34%, driven entirely by its 24-hour rotation. Pluto’s rotation period is 6.39 days [11], slow enough that rotational flattening is negligible.

Consequently, Pluto is a sphere. Clearly, without any doubt, it fulfills the second IAU criterion with an enormous margin.

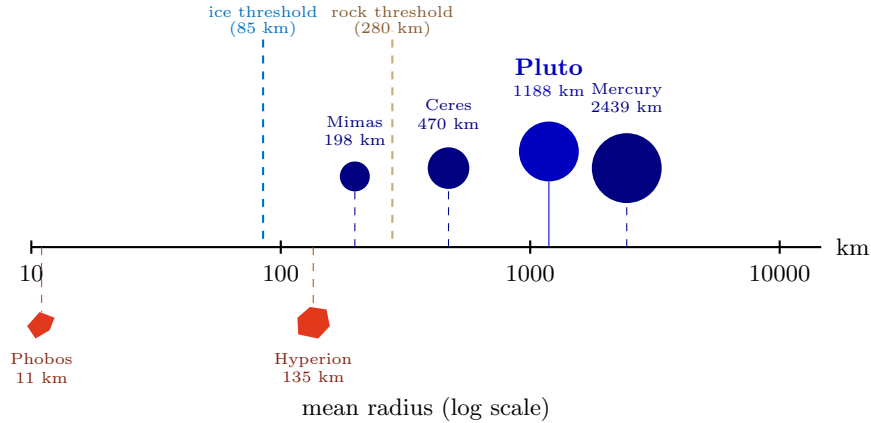


Figure 4: Mean radius vs. shape regime for representative solar system bodies. Below the ice threshold of approximately 85 km, material strength dominates and bodies retain irregular shapes (red polygons, shown below the axis). Above the rock threshold of approximately 280 km, self-gravity overcomes the strength of any plausible solid material and bodies relax into hydrostatic equilibrium (blue circles, sized roughly proportional to actual radius). Pluto, at 1188 km, sits roughly a factor of 14 above the ice threshold and is unambiguously round.

Thus, the criterion separates Pluto from the very smallest asteroids but not from the major planets, since Pluto, Ceres, and many large bodies in the Kuiper Belt are all rounded. Had the

IAU definition contained only the first two criteria, revolves around the Sun and is in hydrostatic equilibrium, Pluto would have been classified as a planet beyond question, and so would have many other bodies, including Eris, Haumea, Makemake, Ceres, and dozens of others. As we will see in Section 9, the alternative geophysical planet classification accepts essentially this position: it treats hydrostatic equilibrium as the central criterion and ignores orbital context entirely.

It is the third criterion of the IAU planetary classification that serves as a dividing line between the planets and dwarf planets. In the subsequent sections, several proposed metrics for neighborhood clearing will be analyzed.

5 The Stern-Levison Scattering Parameter Λ

We have shown that Neptune has qualitative dominance over Pluto’s orbital neighborhood. The next three sections quantitatively confirm this claim through three independently proposed metrics. While the metrics differ in their definitions and reasoning, they agree on their conclusions.

The first such metric was proposed in 2002 in an article entitled “Regarding the criteria for planethood and proposed planetary classification schemes” by Alan Stern and Harold Levison. This metric is a scattering parameter denoted by the Greek letter lambda. The question posed physically by this metric is as follows: How effectively does a body of a certain mass M and a certain orbital radius a clear out small bodies from its orbital neighborhood through gravitational scattering?

This is achieved by estimating how strongly the larger body deflects a small body in each encounter and how many encounters take place over a Hubble time, roughly the age of the universe. The full derivation is complicated, but the result yields an elegant expression:

$$\Lambda = \frac{M^2}{a^{3/2}} \cdot k \quad (14)$$

Here, M is the mass of the body, a is the semi-major axis of its orbit in units of astronomical units, and k is the constant of proportionality that encapsulates the details of the geometry of the encounter and the length of a Hubble time. For us, what is important about this expression is the scaling: Λ scales with the square of the mass and with the inverse three-halves power of the orbital radius. Thus, doubling the mass increases effectiveness by a factor of 4, while doubling the orbital radius decreases it by a factor of $2^{1.5}$ (≈ 2.83).

Stern and Levison introduced a criterion: a body that can scatter a substantial fraction of the small bodies out of its orbital neighborhood within a Hubble time has cleared that neighborhood. Working out the mathematics, this condition yields $\Lambda > 1$ when the units of measurement are chosen correctly, with 1 as the threshold.

Let us now plug in some numbers. Taking mass in units of Earth masses and the semi-major axis in units of AU, and using appropriate normalization, the numerical values for the major planets and Pluto are:

$$\begin{aligned} \text{Earth: } M &= 1, \quad a = 1 : \quad \Lambda \approx 1.53 \times 10^5 \\ \text{Jupiter: } M &= 318, \quad a = 5.20 : \quad \Lambda \approx 1.30 \times 10^9 \\ \text{Neptune: } M &= 17.1, \quad a = 30.07 : \quad \Lambda \approx 2.73 \times 10^5 \\ \text{Pluto: } M &= 0.0022, \quad a = 39.48 : \quad \Lambda \approx 2.95 \times 10^{-3} \end{aligned}$$

The ratios of the scattering parameters for Neptune over Pluto and for Jupiter over Pluto work out to be as follows: Neptune-to-Pluto: $\sim 9 \times 10^7$ (90 million); Jupiter-to-Pluto: $\sim 4 \times 10^{11}$. According to the Stern-Levison criterion, Pluto falls roughly eight orders of magnitude below even Earth (the smallest- Λ planet listed above), and nearly twelve orders of magnitude below Jupiter.¹

While the precise normalization of Λ varies across the literature, the qualitative result, namely Pluto’s Λ being many orders of magnitude below the planetary cluster, is robust under any reasonable formulation of the metric. Reasonable critics may dispute whether Λ is the right thing to measure (we will engage with this in Section 9); they cannot dispute the magnitude of the gap once Λ is computed.

It is an extraordinary historical twist of fate that the very author of this metric, Alan Stern, went on to become the principal investigator of the New Horizons mission to Pluto and one of the most prominent advocates for restoring its planetary status. The apparent contradiction is resolved if we read Stern’s later position not as a repudiation of his 2002 work but as an evolution: the metric is mathematically sound, but is it the right question to ask? We will return to this in Section 9.

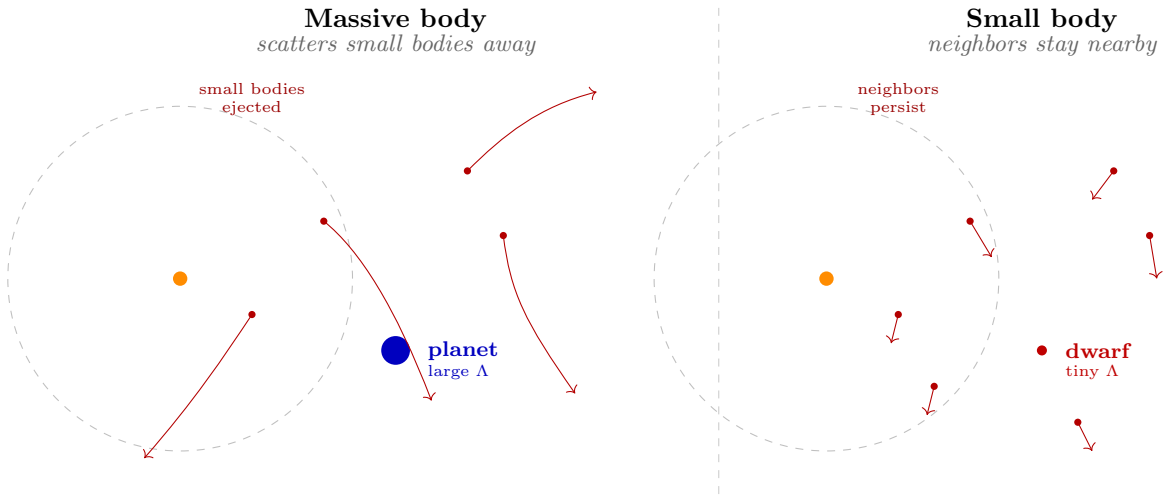


Figure 5: What the Stern-Levison parameter physically measures. **Left:** A massive body (large Λ) deflects small nearby bodies into wildly different trajectories during gravitational encounters. Over the age of the solar system, this scatters the orbital region clean. **Right:** A small body (tiny Λ) barely perturbs neighboring bodies during encounters. The orbital region remains populated. Pluto’s $\Lambda \approx 3 \times 10^{-3}$ means that scattering encounters with Pluto change a small body’s trajectory by a negligible amount per pass; the population around Pluto persists for billions of years.

¹A note on normalization. The literature reports Λ values under several different conventions, depending on the assumed encounter geometry, the timescale used, and whether the constant k absorbs the solar system’s age explicitly. This makes it difficult to compare absolute values across sources. The numerical values cited above all follow a single convention, the one tabulated by Soter [3] from Stern and Levison’s work [2]; what is invariant across all such formulations is the qualitative result, namely that Pluto’s Λ sits many orders of magnitude below the cluster of the eight planets. The conclusion is robust under any reasonable convention.

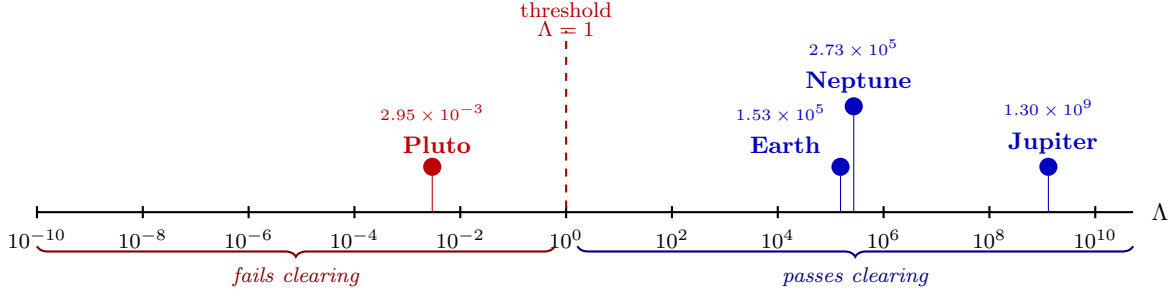


Figure 6: The Stern-Levison scattering parameter Λ on a logarithmic scale, for representative bodies. The threshold for orbital clearing is $\Lambda = 1$. Pluto’s value of 2.95×10^{-3} sits between two and three orders of magnitude below the threshold, while the eight major planets all sit several orders of magnitude above it. The gap between Pluto and the nearest planet shown (Earth) is roughly eight orders of magnitude.

Next, we turn to a second independently proposed metric by Steven Soter.

6 Soter’s Planetary Discriminant μ

Also in 2006, the year of the IAU resolution, Steven Soter, another astronomer, published his paper “What is a planet?”, in which he offered an alternative measure of orbital clearing. The metric, denoted by the Greek letter mu, is called the planetary discriminant.

While Stern and Levison’s metric looks ahead in time (“how well would the body clean out its region?”), Soter’s metric looks backward (“how much did the body clean out its region?”). That is, how well has the body actually cleaned out its region, as judged by what remains there?

The definition of this metric is simple. Given a body with mass M and a set of other bodies of total mass m_{other} (not including moons of the primary body), the planetary discriminant is

$$\mu = \frac{M}{m_{\text{other}}} \quad (15)$$

A body that has swept its orbital region clean will have μ much larger than 1, and one that has not will have μ less than or around 1. Soter’s criterion for planethood is $\mu > 100$, meaning the candidate body must weigh more than everything else in its orbital neighborhood by at least a factor of 100.

To use the equation, we need a working definition of “orbital neighborhood.” Soter defined it as the collection of bodies whose orbits cross a common distance from the Sun with the primary body’s orbit and whose orbital periods differ from its own by less than a factor of ten. Again, the details are complex but computable using observational information.

For the eight major planets, the planetary discriminant values are staggering:

$$\begin{aligned} \text{Earth: } \mu &\approx 1.7 \times 10^6 \\ \text{Jupiter: } \mu &\approx 6.3 \times 10^5 \\ \text{Neptune: } \mu &\approx 2.4 \times 10^4 \end{aligned}$$

The planet with the lowest μ of all eight, Neptune, surpasses the threshold of 100 in its value of μ by orders of magnitude.

Consider now the case of Pluto. Pluto’s mass is 1.303×10^{22} kg [11]. The total mass of all other known objects in Pluto’s orbital neighborhood, which consists mostly of other Kuiper Belt objects whose orbits cross Pluto’s, is estimated at roughly 1.7×10^{23} kg, about 0.03 Earth masses [3, 12]. Hence,

$$\mu_{\text{Pluto}} = \frac{1.303 \times 10^{22}}{1.7 \times 10^{23}} \approx 0.077 \quad (16)$$

Thus, μ_{Pluto} is less than 1: Pluto weighs less than the other objects in its orbital neighborhood. According to Soter’s criterion (which requires $\mu > 100$), Pluto fails by more than three orders of magnitude. Note that the estimate of total Kuiper Belt mass in Pluto’s region remains under refinement; even a much more conservative estimate of about 2×10^{22} kg would give $\mu_{\text{Pluto}} \approx 0.65$, still far below the threshold. The qualitative conclusion is robust to either estimate: Pluto’s orbital region is populated, not cleared.

By the same reasoning, for Ceres in the asteroid belt, we find that $\mu \approx 0.33$. For Eris in the scattered disk, $\mu \approx 0.10$. In other words, dwarf planets fall not only below the critical value of μ but also far below it into a qualitatively distinct regime as mere constituents of population groups.

This is what Soter’s metric captures that the Stern-Levison parameter doesn’t. While the latter tells us about the capability for orbital clearing, the former reveals the extent of that capability. But, for Pluto, the two metrics agree in their conclusions.

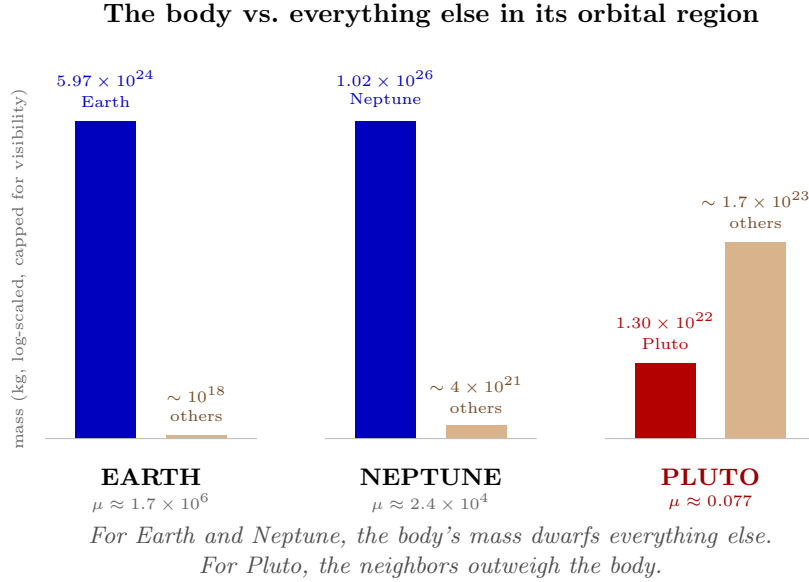


Figure 7: Soter’s discriminant μ visualized: the ratio of a body’s mass to the total mass of everything else sharing its orbital region. For Earth, the “everything else” bar is essentially invisible at this scale: $\mu = 1.7 \times 10^6$ means Earth outweighs its orbital region’s other inhabitants by more than a million to one. For Neptune, the others bar is small but present. For Pluto, the others bar is *taller* than Pluto itself: $\mu = 0.077$ means Pluto is outweighed by the rest of its orbital region more than tenfold. Heights are log-scaled and capped to make the comparison legible.

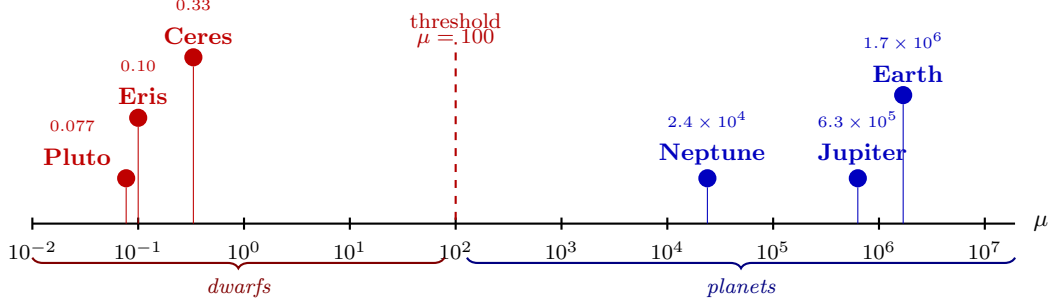


Figure 8: Soter’s planetary discriminant μ on a logarithmic scale, for representative solar system bodies. The threshold for planethood under Soter’s criterion is $\mu > 100$. The three dwarf planets shown (Eris, Ceres, Pluto) all fall below $\mu = 1$, meaning they weigh less than the other bodies in their respective orbital regions. The three planets shown (Neptune, Jupiter, Earth) all exceed 10^4 . The gap between the dwarf cluster and the planet cluster spans more than four orders of magnitude.

7 The Margot Threshold Parameter Π

The third criterion was put forth in 2015 by Jean-Luc Margot, a planetary scientist at UCLA, in his paper “A quantitative criterion for defining planets.” Margot’s criterion, denoted by the capital pi, is an improvement over the Stern-Levison approach and features two distinguishing qualities: reliance solely on observable parameters (as opposed to making any assumptions about the encounter geometry) and explicit dependence on the host star’s mass. These two qualities mean that the Margot parameter can be extended to define both exoplanets and Solar system objects.

The Margot parameter is expressed as follows:

$$\Pi = \frac{m}{C \cdot M^{5/2} \cdot a^{9/8}} \quad (17)$$

where m is the mass of the candidate planet, M is the mass of the host star, a is the semi-major axis in AU, and C is a constant chosen to give $\Pi = 1$ at the threshold for clearing the orbital zone within the host star’s main-sequence lifetime. For stars similar to the Sun (main-sequence lifetime: about 10 billion years), where m is given in units of Earth masses and a in AU, the Margot parameter has the following form:

$$\Pi = 807 \cdot \frac{m}{a^{9/8}} \quad (18)$$

As demonstrated by Margot, all eight IAU planets satisfy $\Pi > 1$ without ambiguity. All known dwarf planets fail the test with no exceptions. Numerically:

$$\begin{aligned} \text{Jupiter: } \Pi &\approx 4.0 \times 10^4 \\ \text{Saturn: } \Pi &\approx 6.1 \times 10^3 \\ \text{Venus: } \Pi &\approx 9.5 \times 10^2 \\ \text{Earth: } \Pi &\approx 8.1 \times 10^2 \\ \text{Uranus: } \Pi &\approx 4.2 \times 10^2 \\ \text{Neptune: } \Pi &\approx 3.0 \times 10^2 \\ \text{Mercury: } \Pi &\approx 1.3 \times 10^2 \\ \text{Mars: } \Pi &\approx 5.4 \times 10^1 \end{aligned}$$

For Pluto,

$$\Pi_{\text{Pluto}} = \frac{807 \times 0.0022}{39.48^{9/8}}$$

The denominator, $39.48^{9/8}$, is approximately 62.5. Then,

$$\Pi_{\text{Pluto}} = \frac{807 \times 0.0022}{62.5} \approx 0.028 \quad (19)$$

Π_{Pluto} is approximately thirty-five times lower than the threshold of 1. The lowest Π among the planets is Mars's, at which value the criterion is exceeded by a factor of about 54. Π_{Pluto} is three dozen times below the threshold. The difference between the marginal success, Mars, and the failure, Pluto, is a factor of roughly 1,900.

The Margot criterion may be considered the cleanest of the three criteria under discussion. It relies solely on observable parameters, applies uniformly across the solar system and extrasolar bodies, and leaves a relatively large (more than 3 orders of magnitude) gap between the eight bodies that satisfy it and the ninth, Pluto.

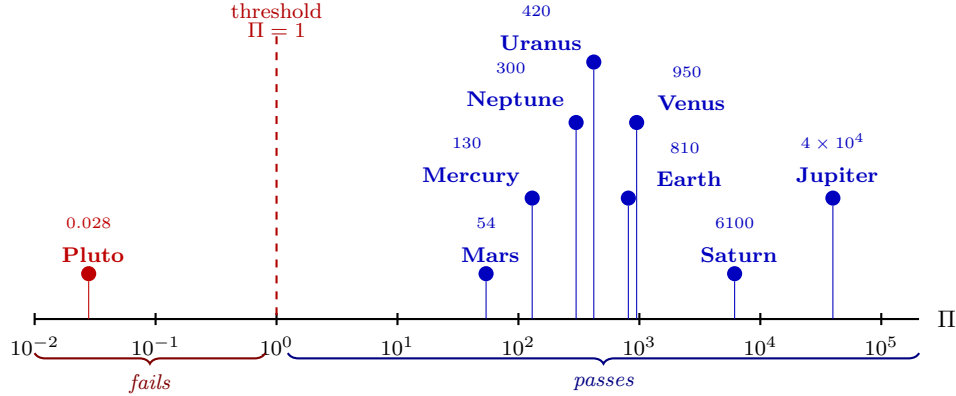


Figure 9: The Margot threshold parameter Π on a logarithmic scale, for the eight major planets and Pluto. The threshold is $\Pi = 1$. All eight planets satisfy this condition; Pluto fails by a factor of approximately 35. The gap between Pluto and the smallest passing case (Mars) spans more than three orders of magnitude. Labels are staggered vertically in the dense cluster around $\Pi \sim 10^{2.5}$ for legibility.

8 Head-to-Head Comparison Between Solar System Bodies

We have now applied three independent tests of orbit clearing to the eight classical planets and also to several dwarf planets. Here we present an overview in a table.

Table 1: Values of the three orbital-clearing metrics for the eight major planets and three representative dwarf planets. Threshold values are listed in the bottom row. A dash (—) indicates that a numerical value was not given in the body of this paper; complete numerical results are available in the original references.

Body	Λ (Stern-Levison)	μ (Soter)	Π (Margot)
Mercury	—	—	1.3×10^2
Venus	—	—	9.5×10^2
Earth	1.53×10^5	1.7×10^6	8.1×10^2
Mars	—	—	5.4×10^1
Jupiter	1.30×10^9	6.3×10^5	4.0×10^4
Saturn	—	—	6.1×10^3
Uranus	—	—	4.2×10^2
Neptune	2.73×10^5	2.4×10^4	3.0×10^2
Ceres	—	0.33	—
Pluto	2.95×10^{-3}	0.077	0.028
Eris	—	0.10	—
<i>Threshold</i>	> 1	> 100	> 1

The following observations can be made.

First, none of the IAU planets and none of the dwarf planets overlap in the three different metrics. Specifically, the lowest value in each of the three columns of the eight planets is greater than the highest value for the dwarfs in the same column. There is a clear gap between the two clusters.

Second, the size of the gap varies between the three methods. In the case of Margot’s Π , the gap between Mars and Pluto is a factor of about 1,900. In the case of Soter’s μ , the gap between Neptune and Pluto is a factor of about 300,000. In the case of Stern-Levison’s Λ , the gap between Earth and Pluto is a factor of about 5×10^7 . The gaps are all sizable; however, the differences in size are due to each test answering a different physical question.

Most importantly, however, the three metrics produce consistent results when compared with one another in terms of relative rankings. This means that if a body clears one metric, it has cleared all three. On the contrary, failing to clear one metric means failing all three.

Such an agreement is not coincidental. It indicates that orbital clearing is a real physical process and allows for many equally valid mathematical approaches to describing it. The distinction between IAU planets and dwarf planets exists objectively within the dynamics of our solar system.

It is safe, then, to say that the third criterion for planets adopted by the IAU is well-defined in reality. Indeed, applying any of the three metrics above to determine which bodies cleared their zones yields the same result: the eight planets are planets, and Pluto is a dwarf planet.

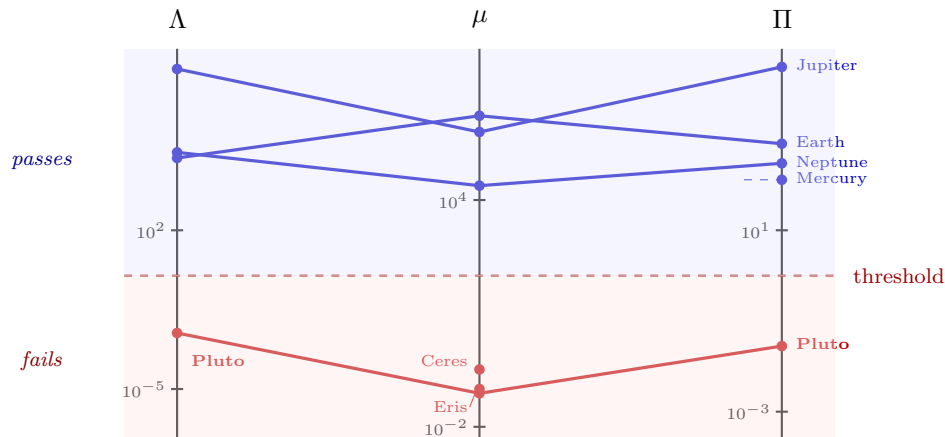


Figure 10: Parallel-coordinates view of the three orbital-clearing metrics. Each axis is normalized so that its respective threshold ($\Lambda = 1$, $\mu = 100$, $\Pi = 1$) sits at the same horizontal line, and each axis has its own logarithmic scale. A body’s value on each metric is plotted on the corresponding axis; lines connect the three values for each body. The lines for the three planets shown (Earth, Jupiter, Neptune) all stay above the threshold line on every axis. The line for Pluto stays below the threshold line on every axis. Ceres and Eris (data only available for μ) similarly fall below. The visual message: a body that fails one metric fails all three, and a body that passes one passes all three.

This completes the dynamical part of the discussion. Pluto has not cleared its zone, by any reasonably accurate metric. The remaining question is whether orbit clearing should be the classification criterion in the first place. This idea will be discussed in the subsequent section.

9 The Geophysical Planet Definition

The most well-known challenge to the IAU definition was published in 2017. It came from a team of planetary scientists, with Kirby Runyon, Alan Stern (the same Alan Stern who proposed the scattering parameter Λ), and Will Grundy leading the charge. Their proposal was simple: change the IAU’s three-criterion definition into a one-criterion geophysical definition.

According to Runyon et al. (slightly paraphrased), a planet is a sub-stellar mass body that has never undergone nuclear fusion and that has sufficient self-gravitation to assume a spheroidal shape adequately described by a triaxial ellipsoid regardless of its orbital parameters.

In other words, round, but not a star, and orbital context does not matter.

With this definition, the number of planets in the solar system increases from 8 to approximately 110. The list includes all eight planets recognized by the IAU plus Pluto, the dwarf planet Ceres, our Moon, Jupiter’s four largest moons (called the Galilean satellites), seven of Saturn’s major moons, five of Uranus’ major moons, Neptune’s moon Triton, and, in addition, the growing list of large trans-Neptunian objects (Eris, Haumea, Makemake, Quaoar, Sedna, Gonggong, etc.).

On the surface, this sounds unworkable. There is, however, a good case to be made for it. This case has three elements.

The first element is historical. According to Runyon and his colleagues, the term “planet” has

always been ambiguous, and the IAU’s 2006 decision to clarify it inadvertently changed its meaning. During the entire four hundred years between Galileo’s discovery of the four Jovian moons and 2006, planetary scientists used the term “planet” to refer to all roughly spherical worlds large enough to have their own geology. Under this definition, our Moon was routinely referred to as a planet, and so were the moons of Jupiter and Saturn. The IAU’s decision to introduce precision into the term was meant to redefine it, not to codify its informal use.

The second element is practical. Planetary scientists studying these worlds argue that the meaningful categorization scheme, from the perspective of their field, is a geophysical one rather than an orbital one. Pluto and Mercury are both rocky worlds; both have atmospheres (Pluto’s atmosphere is thin and seasonal, but it exists); both are differentiated bodies; both have dense cores; and both have experienced geological activity at some point in their history. From a geologist’s perspective, these similarities are much more significant than the differences in dynamics.

Finally, the third element is rhetorical. In essence, according to Runyon et al., the IAU decision creates a bizarre situation in which an object’s status as a planet depends on its location. If we place Earth where Pluto is now, surrounded by Kuiper Belt objects, it would no longer qualify under the IAU criteria as a planet. Yet, it would still be Earth, in every physical respect, but it would fail to meet the IAU’s criterion 3. According to Runyon et al., this situation is absurd: planethood should depend on intrinsic rather than extrinsic characteristics.

These arguments are reasonable. The geophysical definition is internally consistent, has strong scientific motivation, and enjoys a significant following among planetary scientists. It is not a fringe position.

That said, it does come with a price. But before discussing the price, two important objections to the IAU framework deserve to be acknowledged head-on.

The first objection is the incompleteness of clearing. Strictly speaking, no planet has fully cleared its orbital zone. Earth shares its orbital zone with more than 40,000 catalogued near-Earth asteroids [10]. Mars’s orbit is regularly crossed by smaller bodies. Even Jupiter coexists with the Trojan asteroids that share its orbit at the L4 and L5 Lagrange points. The IAU’s criterion 3, taken literally as “cleared,” is satisfied by no body in the solar system. What the IAU implicitly meant, and what the three quantitative metrics in Sections 5 through 7 actually measure, is dynamical *dominance*, not exclusive occupancy. The threshold $\Lambda = 1$, $\mu = 100$, or $\Pi = 1$ each defines a level of dominance below which a body is considered “not cleared.” This is a meaningful and defensible interpretation, but the geophysical camp is correct that the original IAU wording is imprecise. The metrics fix the imprecision.

The second objection is the location dependence captured by the Earth-at-Pluto thought experiment. The honest response is to acknowledge that, yes, the dynamical definition is location-dependent, by design. It is asking a question about role, not about intrinsic identity. A useful analogy is the word “king”: a king is a king because of the role he plays in his kingdom, not because of his physical properties. Place a king in a desert with no kingdom, and he is no longer functionally a king, even though he is the same person. The dynamical definition of “planet” works the same way. Earth, transported to Pluto’s orbital location, would still be a fascinating world (the geophysical category captures that), but it would no longer be the dominant body of its orbital region (the dynamical category captures that). The two questions have different answers in different contexts, by design, because they are different questions.

With these objections addressed, we can return to the price of the geophysical alternative.

The first obvious price is the count. The geophysical definition brings the number of planets in the solar system to about 110 (and this figure may continue rising as we discover even more trans-Neptunian objects). Among the new planetary candidates are our Moon, the asteroid Ceres, and seven moons of Saturn. The term “planet” becomes almost detached from its common usage.

An even less obvious price is informational. The IAU’s decision splits the solar system into the relatively small group of dynamically dominant bodies (eight) and the much larger population of dynamically subordinate bodies. This split reflects the reality of how the solar system has been evolving. The geophysical definition fails to capture this aspect.

And finally, the highest price is that the geophysical definition flattens a genuine hierarchy in the solar system. Consider a concrete example: Jupiter has shaped the orbital architecture of essentially every body in the inner and outer solar system, including the asteroid belt, the Kuiper Belt, and the orbits of the other planets. Our Moon, in contrast, has shaped exactly one orbit in the solar system: Earth’s. The geophysical definition places Jupiter and our Moon in the same category. This is not just a difference in size; it is a difference in role. The orbital structure is the defining feature of any planetary system, and ignoring it means missing the most vital information about how the system is organized.

While the IAU’s decision has flaws, such as vagueness in the wording of criterion 3 and in the subsequent development of the corresponding metrics, it is based on sound intuition: planets are dynamic organizers of their environments. It correctly divides the solar system at one of its joints.

In conclusion, I propose that the solution here is not to choose one definition over another.

10 The Need for Two Definitions

The core of the Pluto debate has always been about something other than Pluto per se. The issue at hand is whether we should define the “planet” classification by its dynamical function (regional dominator) or by its physical form (geologically differentiated spherical object). Interestingly, the former and the latter are two distinct types of classification. Both are legitimate, and neither can be replaced by the other.

Accordingly, the choice made by the 2006 IAU resolution and that of the Runyon et al. 2017 classification have been criticized by the respective camps in the ensuing discussion as wrong.

However, in my opinion, both are right.

The right way to look at it, I think, is to note that we have two kinds of classifications but only one word to call them. Therefore, we need two words, not one.

The dynamical definition, the IAU resolution, is appropriate in the present application of the word “planet.” The eight bodies that are regional dominators of the Solar System are the eight planets. The way to classify our Solar System in historical and observational terms is what any astrodynamist would find useful.

The physical definition, the Runyon et al. classification, requires another label altogether. Suggested terms include “world,” “planemo,” “globular world,” and others. None of them has gained acceptance yet. The key point is that whichever name is chosen, we require it because it describes a legitimate and important category of objects, which is what any planetary geologist finds useful.

There is a clear relationship between these two classifications: one of inclusion. All objects that fall into the dynamical classification belong to the physical one. Not all objects that belong to the physical classification belong to the dynamical classification, however.

For example, Pluto is in the physical category. It is a geologically active body with an atmosphere, satellites, and a very complicated surface. But none of these properties belong to the classification used by the astrodynamacists today. They don't belong.

Not being in the dynamical classification, Pluto is not considered a "planet" in the dynamical sense. The fact that Neptune dominates it due to the 3:2 mean-motion resonance does not violate the dynamical classification scheme. To the contrary, it confirms it. Not recognizing it as such should not lead us to abandon the classification that distinguishes dominators from dominated.

So, the way things ought to be stated in this case is that Pluto is a world. At the same time, Pluto is not a planet. Two statements that are completely compatible and in no way contradict one another because they describe two entirely different aspects of one particular body.

Now, having established what must be said on this matter in response to the debate, let's turn to the specific question posed in this essay. How should we respond to Jared Isaacman, who declared before the Senate Appropriations Committee that he wants to make Pluto a planet again?

First of all, the correct response to this statement is to agree that it is a worthy subject for discussion. Secondly, one should admit that the IAU definition of "planet" has several downsides that aren't obvious at first glance. Thirdly, it is right to recognize that planetary scientists are justified in feeling frustrated regarding their classification problem.

However, changing the definition of "planet" would not solve anything. The current definition works perfectly well for classifying regional dominators of the Solar System. We have three criteria to classify them successfully. Altering it wouldn't improve our categorization system; on the contrary, we would lose an important distinction between dominators and the dominated.

The correct step is to introduce a new term. Pluto is not a planet (in the dynamical classification). Pluto is a world (in the geophysical classification). Both statements are true. Both statements are important. The scientific community would benefit from accepting both rather than arguing over either.

What we need to make explicit about this proposed solution is what it means to compromise and to whom. The geophysical faction would lose the term "planet."

Under the proposed definition, "planet" stays with the astrodynamacists, so that Pluto is not a planet by the same reasoning as before. However, the geophysical faction would gain recognition of the importance of the geophysical category. The term "world" (or "planemo" or whatever name we agree upon) would carry the meaning that the geophysical faction wants it to carry. As a result, both factions would obtain most of what they wanted. Neither faction would get everything it desires.

This is how any honest compromise should be structured. Such is my response to the posed question. This is also what the general public wants to hear from us.

People don't love Pluto because it belongs to the category of "planet" or doesn't belong there. They love it because it is an interesting, distant, and beautiful, geologically active icy body located billions of miles from the Sun and visited only once during the last decade-long flight.

This is what Pluto is. And this cannot change, regardless of the committees' decisions and anything else.

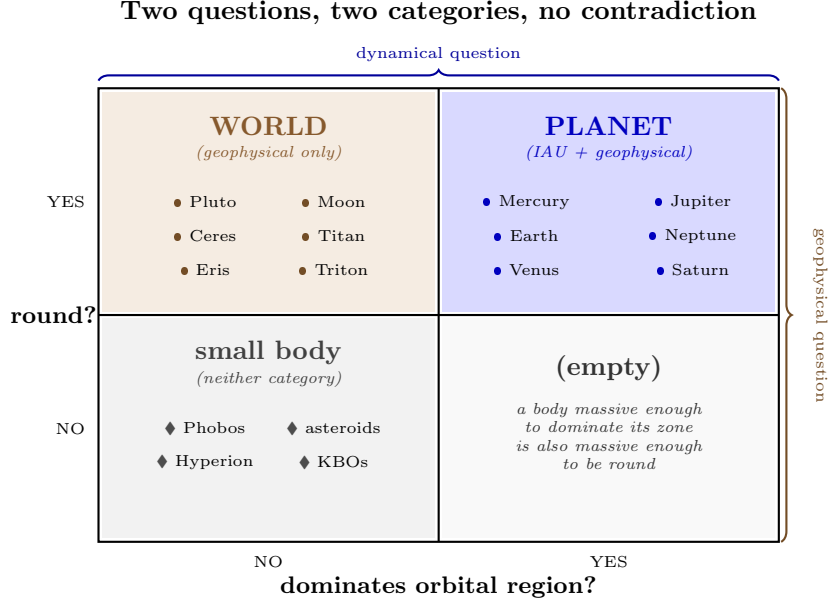


Figure 11: The proposed two-word taxonomy. The two questions “is the body round?” (geophysical) and “does the body dominate its orbital region?” (dynamical) define a 2×2 grid. The top-right quadrant (round AND dominant) contains the eight IAU planets; the proposal is to call these **planets**. The top-left quadrant (round but not dominant) contains Pluto, Ceres, Eris, our Moon, Titan, Triton, and roughly a hundred other bodies; the proposal is to call these **worlds** (or planemos, or some other agreed term). The bottom-left contains small irregular bodies. The bottom-right is physically empty: any body large enough to dominate its zone is also large enough to relax into a sphere. Pluto is a world. Pluto is not a planet. Both statements describe the same body.

Acknowledgments

My arguments in Sections 5 through 7 owe much to Alan Stern and Harold Levison (2002), Steven Soter (2006), and Jean-Luc Margot (2015), whose independent formulations of the orbital clearing criterion are foundational to their arguments. In addition, the geophysical planet definition and the dissent from the IAU classification proposal are based on work by Kirby Runyon, Alan Stern, and others (2017). My special thanks go to all my followers on TikTok for inspiring me to write this.

References

- [1] International Astronomical Union (2006), “Resolution B5: Definition of a Planet in the Solar System,” IAU 26th General Assembly, Prague.
- [2] Stern, S. A., and Levison, H. F. (2002), “Regarding the criteria for planethood and proposed planetary classification schemes,” *Highlights of Astronomy*, vol. 12, pp. 205–213.
- [3] Soter, S. (2006), “What is a planet?” *The Astronomical Journal*, vol. 132, pp. 2513–2519.
- [4] Margot, J.-L. (2015), “A quantitative criterion for defining planets,” *The Astronomical Journal*, vol. 150, no. 6, p. 185.

- [5] Runyon, K. D., Stern, S. A., Lauer, T. R., Grundy, W., Summers, M. E., and Singer, K. N. (2017), “A geophysical planet definition,” 48th Lunar and Planetary Science Conference, abstract no. 1448.
- [6] Stern, S. A., et al. (2015), “The Pluto system: Initial results from its exploration by New Horizons,” *Science*, vol. 350, no. 6258.
- [7] Isaacman, J. (2026), Testimony before the U.S. Senate Committee on Appropriations on the FY2027 NASA budget, April 28.
- [8] NASA Jet Propulsion Laboratory, Solar System Dynamics Group, “HORIZONS Web-Interface,” <https://ssd.jpl.nasa.gov/horizons/>. Used for orbital elements (semi-major axis, eccentricity, inclination, period) of all major planets, Pluto, and dwarf planets cited in this paper.
- [9] Malhotra, R. (1995), “The origin of Pluto’s orbit: Implications for the Solar System beyond Neptune,” *The Astronomical Journal*, vol. 110, pp. 420–429. Source for the libration of the Pluto-Neptune 3:2 resonant argument about 180° .
- [10] NASA Center for Near-Earth Object Studies (CNEOS), “Discovery Statistics,” <https://cneos.jpl.nasa.gov/stats/>. Source for the cataloged near-Earth asteroid count cited in Section 9.
- [11] NASA Goddard Space Flight Center, “Planetary Fact Sheets,” <https://nssdc.gsfc.nasa.gov/planetary/factsheet/>. Source for mean radii, masses, rotation periods, and oblateness values of Mimas, Ceres, Mercury, Phobos, and other solar system bodies referenced in Section 4.
- [12] Bernstein, G. M., Trilling, D. E., Allen, R. L., Brown, M. E., Holman, M., and Malhotra, R. (2004), “The size distribution of trans-Neptunian bodies,” *The Astronomical Journal*, vol. 128, no. 3, pp. 1364–1390. Source for total Kuiper Belt mass estimates used in Section 6.
- [13] Nimmo, F., et al. (2017), “Mean radius and shape of Pluto and Charon from New Horizons images,” *Icarus*, vol. 287, pp. 12–29. Source for Pluto’s mean radius and the upper limit on its oblateness cited in Section 4.