DWARF PLANETS ARE PLANETS, TOO: PLANETARY PEDAGOGY AFTER NEW HORIZONS: K. D. Runyon[1], P. T. Metzger[2], S. A. Stern[3] J. Bell[4], [1]Johns Hopkins APL, Laurel, MD, USA (kirby.runyon@jhuapl.edu). [2]University of Central Florida, Orlando, FL, USA. [3]Southwest Research Institute, Boulder, CO, USA. School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

Introduction: The last two decades have seen a shift in how scientists and the public understand the organization of the Solar System. The discovery of KBOs of comparable size to Pluto, beginning with Eris (erroneously thought at the time to be larger than Pluto) [1,2, 3], have revolutionized our understanding of the size distribution of round worlds. With more than 120 dwarf planets discovered since the early-2000s [4], a paradigm shift is needed regarding how students are taught the organization of the Solar System: it is no longer sufficient to teach students the names of nine (eight) planets' named after pagan gods and assume that any meaningful science education has occurred. We believe the International Astronomical Union (IAU) has done damage to the public understanding of solar system science with their 2006 vote on the definition of planets [5], which explicitly excludes dwarf planets as a planet category [6]. Taxonomical science is not legitimately advanced by democratic voting, but set by the precedent of a word's usage. We summarize events since 2006 which counter the IAU's action and suggest a new paradigm for solar system education to young students.

Geophysical Planet Definition: As proposed by Runyon et al. (2017) and Runyon and Stern (2018), the geophysical planet definition (GPD) states that a planet is 1) Round by self-gravity; 2) Has never undergone nuclear fusion; and 3) Matches the above criteria regardless of its orbit.

This definition classifies all dwarf planets and the solar system's 19 known round satellites as planets. Furthermore, this broad and inclusive definition highlights the diversity of planets and the many subcategories, which include 1) Terrestrial planets; 2) Giant planets (Gas giant planets and Ice giant planets); 3) Dwarf planets (Kuiper belt planets and one asteroid belt planet); 4) Satellite planets. This planetary categorization is implicit in the peer reviewed literature, is common in professional verbal usage, and is based on precedent rather than voting, unlike the IAU's planet definition [5,6]. Further, just as there is no formal lower-size cut-off for giant planets, we simply suggest that dwarf planets be defined as being smaller than Mercury, rather than whether they have "cleared their orbits," as the IAU suggests as the main dwarf planet criterion [5,6].

Anachronistic Reclassification of Asteroids as Non-Planets: Metzger et al. [7] demonstrated through a thorough literature review that asteroids were considered a class of planet until the 1950s, despite their numbering in the thousands and their mutual orbit-sharing. The change was heralded by the realization that different formation processes resulted in asteroids being geophysically distinct from larger planets. This is at odds with the supposedly historically-precedented IAU planet criterion that a planet must have cleared its orbit [6], or, informally, be otherwise gravitationally dominant [5].

Ignoring the IAU: (Il)legitimacy of Voting: The peer reviewed literature is replete with examples (at least 129) of professional planetary scientists implicitly use the GPD—not the IAU definition—when referring to round worlds. In such papers, authors commonly substitute the word "planet" for the body's proper name. We have found examples applying to Pluto, Titan, Europa, Earth's Moon, Ganymede, Ceres, Triton, Io, and other dwarf and satellite planets dating from both before and after the IAU's 2006 planet definition vote. This precedent amounts to ignoring the IAU and the orbital dynamics criterion. This professional precedent of using a liberal planet definition in the peer-reviewed literature is one that space-interested members of the general public and students should feel free to use. The taxonomical voting of the IAU [5,6] is thus undermined in its legitimacy and no action by the IAU is needed.

Public Engagement and Anecdotal Evidence Favoring the GPD: We conduct many public engagement events per year in schools, museums, science outreach interviews, and in informal social gatherings. A few examples can be found at the following web links.
http://www.astronomy.com/magazine/2018/05/an-organically-grown-planet-definition
https://www.youtube.com/watch?v=3WtwrowIQys&t=487s
https://www.space.com/41769-pluto-planet-definition-debate-rages-on.html
https://www.youtube.com/watch?v=3AFtgZP6Aa8
https://today.ucf.edu/pluto-planet-research
https://www.cbc.ca/news/technology/pluto-scientists-battle-planet-definition-1.4032382

In our experience, a very common conversation will go something like the following: "I'm a planetary scientist, and I explore lots of worlds in the solar system, including Pluto." "Is Pluto a planet again?" "Well, I consider Pluto a planet, along with more than 120 other similarly-sized planets in the solar system." "Good! I like keeping Pluto as a planet." The good-will engendered by such exchanges is consistent with the public sentiment and human intuition that small, round worlds, even as small as Pluto, should be categorized as planets. The broad diversity the GPD categorization implies, such as from tiny satellite planets like Enceladus, small

terrestrial planets such as Mercury, to gas giant planets like Saturn, teach us the fascinating complexity and diversity of nature. This parallels stellar diversity between, e.g., red dwarf stars and blue supergiant stars—both are stars, but differ by multiple orders of magnitude in size, mass, and lifetime.

Planetary Pedagogy for Teachers and Parents: Our impression is that many children's books and curricula blithely teach a seemingly small, simple solar system composed of the Sun and eight or nine planets. Then, a few facts about each planet (only eight or nine planets) are presented. As a new pedagogical framework, we suggest that students learn three zones of the Solar System, with different types of planets in each zone with different bulk compositions. This stands in contrast to teaching a long list of planet names. This new paradigm is analogous to the teaching of the periodic table of the elements: rather than memorizing a list of names, the natural organizational structure should be emphasized (Figure 1).

Zone 1: The Inner Solar System: Terrestrial planets with metallic cores formed close to the Sun in the warm inner solar system. Mercury, Venus, Earth, the Moon, Mars, and Ceres are terrestrial, satellite, and dwarf planets in the inner solar system.

Zone 2: The Middle Solar System: Giant planets with massive gaseous envelopes with rocky/metallic cores swept up large amounts of material during planetary formation. All are orbited by often multiple satellite planets, each of which has significant water and other ices on their surfaces, indicative of the cold conditions at these solar distances. The middle solar system giant and satellite planets are Jupiter (Io, Europa, Ganymede, Callisto), Saturn (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Iapetus), Uranus (Miranda, Ariel, Umbriel, Titania, Oberon), and Neptune (Triton).

Zone 3: The Outer Solar System: At distances greater than 30 AU from the Sun, even "supervolatiles" are often frozen as ices, sometimes in vapor pressure equilibrium with tenuous atmospheres. While there are over 120 dwarf planets in the 3rd zone, the 10 largest are Pluto, Eris, Makemake, 2007 OR10, Haumea, Charon (also a satellite planet with Pluto), Quaoar, Sedna, Orcus, and 2002 MS4 [4]. Notably, Pluto and Charon form the only double planet in the solar system because the system's barycenter is between both planets. This organizational structure highlights the great planetary diversity within a unified framework showcasing the processes of planetary formation and solar system evolution. Curricula and textbooks should reflect this.

Conclusion: The memorable phrase, "Ignore the IAU; dwarf planets are planets, too," captures the sentiment presented here and is justified from geophysical arguments and from the long precedent set in the professional literature. Teaching the zones and the diversity of the types of planets to students and the general public will better serve planetary science education, aligning what is taught to what is practiced by planetary scientists.

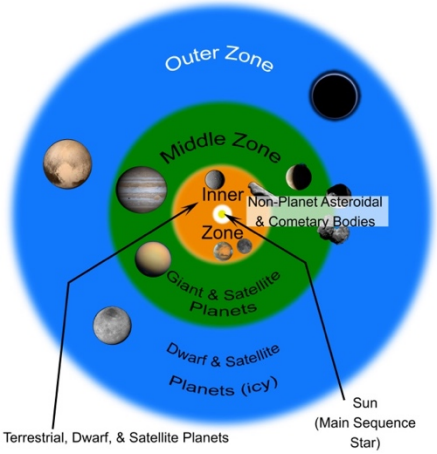

Figure 1. Teaching the zones of the solar system with the diversity of the types of planets in each zone will give students and members of the public a clearer picture of the natural organization and processes found in nature rather than memorizing eight or nine planet's names.

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References: [1] Brown, M.E., Trujillo, C.A., Rabinowitz, D.L. (2005). *Discovery of a Planetary-sized Object in the Scattered Kuiper Belt*. ApJ Letters, 635:L97–L100. [2] Brown, M.E., et al. (2006). *Direct Measurement of the Size of 2003 UB313 from the Hubble Space Telescope*. ApJ Letters, 643, 1. [3] Nimmo, F., et al. (2017). Mean radius and shape of Pluto and Charon from New Horizons images. Icarus, doi: 10.1016/j.icarus.2016.06.027. [4] Brown, M., personal website, "How many dwarf planets are there in the outer solar system?" Accessed 29 April 2019, http://web.gps.caltech.edu/~mbrown/dps.html#table. [5] Ekers, R., (2019). The Prague IAU General Assembly, Pluto, and the IAU Process. Proc. IAU Symp., doi:10.1017/S1743921319000115. [6] IAU, 2006, Voting results. Accessed 29 April 2019, https://www.iau.org/news/pressreleases/detail/iau0603/. [7] Metzger, P.T., Sykes, M.V., Stern, A., Runyon, K. (2019). The reclassification of asteroids from planets to non-planets. Icarus, doi: 10.1016/j.icarus.2018.08.026.

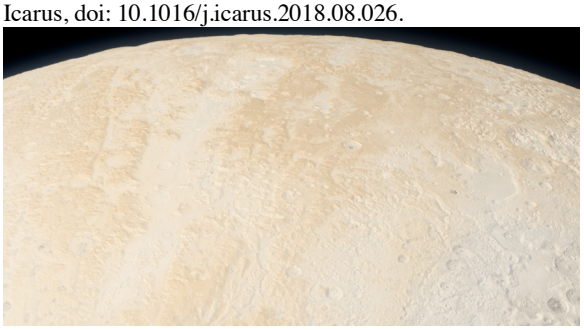

Figure 2. New Horizons stares over the north polar region of the planet Pluto. Credit: NASA/APL/SwRI.