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Article

Why Is the Second a Natural Unit of Time?

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Abstract

The standard historical account traces the second to astronomical timekeeping, sexagesimal subdivision of the day, and later metrological standardization. This story explains the arithmetic ancestry of the unit, but it does not by itself explain why this particular fine subdivision, rather than other arithmetically natural alternatives, became so useful, stable, and persistent. The thesis put forward here is that the second is not merely a sexagesimal convention; it is, more fundamentally, close to a natural planetary-organism time scale. Specifically, for sufficiently large mobile organisms capable of carrying relatively large brains and acting under habitable planetary gravity, free fall, balance, gait, inverted-pendulum instability, and simple pendular motion are all controlled by a time of order $\sqrt{H/g}$, where H is an organism-scale height and g is the local surface gravity. Since habitable rocky planets and large mobile organisms occupy a restricted macroscopic range, this scale naturally falls near one second. I therefore propose that the historical second was physically selected by its proximity to the planetary-organism time scale. This does not mean that the second was consciously derived from pendulums or biomechanics, nor that the sexagesimal story is wrong. Rather, the sexagesimal story explains how the unit became arithmetically available, while the particular subdivision of an hour into 60×60 parts became historically stable because it landed on the organism-gravity time scale. As with the geodetic definition of the meter as one part in 10 million of the distance between the equator and the pole, historical standardization need not explain why the resulting unit lies near a practically natural organism-scale quantity.

Keywords: typicality; pendulum; habitable planets

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1. Introduction

Why is the second so natural? The standard historical answer is well articulated. The second descends from astronomical timekeeping and from the sexagesimal subdivision of the day into hours, minutes, and seconds [1–3]. Modern metrology then replaced astronomical realization by atomic standardization; the SI second is defined at present by the hyperfine transition frequency of cesium-133 [4]. This historical account explains how the second was inherited and standardized.

A different question persists. Why did this inherited unit land in such a useful macroscopic range? Why is a second close to the time of ordinary actions, steps, reaction times, heartbeats, and simple mechanical oscillations? Why did the second remain the time unit not only in MKS/SI, but also in CGS and in Imperial practice? The present paper attempts to address – at least in part – this more physically oriented question.

The idea advocated in the present work is that this historical account may be incomplete. The issue is not merely how the second entered timekeeping, but why a unit of this particular size became so successful. The proposed answer is physical; the second lies close to the natural planetary-organism time scale associated with bodies of macroscopic size acting under planetary gravity. In this sense, the second should not be understood only as a particular sexagesimal subdivision of the day (one of many other possible subdivisions), but also as a convention stabilized by the dynamics of organisms on habitable rocky planets. In other words, the one-second scale may not merely reflect an ancient cultural

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preference for sexagesimal subdivision, but rather a recurrent macroscopic time scale encountered by large mobile organisms on habitable planets. The claim is not that the second was historically determined by a pendulum or by any single biological rhythm. Rather, it is that, once large terrestrial mobile organisms evolve in planetary gravity, a second-like time is naturally provided by elementary mechanics.

The mechanically relevant scale is the organism–gravity time

$$t_g \sim \sqrt{H/g}, \tag{1}$$

where H is a body-scale length and g is the surface gravity. For $H \sim 1$ m and $g \sim 10\ \mathrm{m\,s^{-2}}$, this gives $t_g \sim 0.3$ s, ignoring geometric and ergonomic factors. A simple pendulum of length ℓ has a period

$$T_p = 2\pi\sqrt{\ell/g}. \tag{2}$$

For $\ell \sim 0.2 - 0.5$ m, this is already of order one second. Thus the ordinary second is close to the free-fall, balance, and pendular times associated with everyday life experience of macroscopic organisms in terrestrial gravity.

This observation is not new in its ingredients. Scaling arguments connecting fundamental constants, gravity, matter density, planets, mountains, and organism size go back at least to Galileo, Haldane, Weisskopf, Press, Press and Lightman, and Page [5–10]. The more limited purpose here is to isolate the time-unit aspect. In a broader context, one might question whether MKS-like length, mass, and time units are plausible among alien civilizations. That formulation begs an immediate objection; centimeters and grams are also useful, and CGS has been scientifically important as well. The second is cleaner. It survives the MKS/CGS distinction. The question is therefore why a one-second-scale unit is physically natural.

The paper is explicitly order-of-magnitude in spirit. It is a physical argument about a restricted reference class; sufficiently large (to carry big brains) mobile tool-using organisms that first develop practical timekeeping on habitable rocky planets.

2. Historical Origin Versus Physical Naturalness

The second is historically conventional. The day is an obvious astronomical cycle, and its subdivision into hours, minutes, and seconds reflects ancient astronomical and sexagesimal traditions [1–3]. The pendulum clock appeared much later on the scene and should not be treated as the historical origin of the second [11]. In this respect the conventional account is correct.

The sexagesimal tradition, ultimately rooted in ancient Mesopotamian astronomical and numerical practice, explains why divisions by 60 were historically available and natural. However, this observation by itself does not remove the question. It explains why divisions by 60 were historically available, but it does not show that the particular two-stage division 60×60 of an hour was uniquely natural. Once the comparison class is enlarged, there are many arithmetically simple alternatives based on divisor-rich numbers, for example 24×24, 30×30, 42×36, or 48×72. These would have produced second-like units differing from the modern second by factors of order unity to several. Therefore, appealing to sexagesimal arithmetic alone in effect involves a look-elsewhere ambiguity.

Indeed, historical origin and physical naturalness are two distinct criteria. A unit may be historically inherited and still lie close to a physically privileged macroscopic scale. The perspective advocated in the present work is that the fact that the ‘second’ survived into several – otherwise different – unit systems is indeed suggestive. Length and mass units do vary between meter/kilogram, centimeter/gram, foot/pound, and other practical systems (still, not by many orders of magnitude). The second, by contrast, is common across MKS, CGS, and Imperial unit systems. This does not prove that the second is inevitable, but it does motivate the question of why this particular inherited time scale happens to be stable.

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A useful reference is provided by more formal natural-unit systems. Planck and Stoney units are natural in the sense that they are constructed from fundamental constants [12–14]. Atomic units are natural for atomic physics and chemistry [15,16]. The hydrogen hyperfine wavelength and frequency were famously used on the Pioneer plaque and in discussions of interstellar communication [17,18]. These are good universal scientific standards, but they are not everyday macroscopic action scales. A young technological civilization may at some point of its evolution stumble upon atomic or Planck units, but its first practical clocks and actions are likely to be macroscopic. Since the adopted system of units does not by itself carry any physical significance it is then likely to stay for a long time, even in the face of discovering a more "fundamental" quantum gravitational, nuclear or atomic scales in later evolutionary stages of technological civilizations.

The question is then "why is a one-second-scale unit so natural for sufficiently large running organisms likely to evolve on habitable rocky planets?"

3. The Organism–Gravity Timescale

The simplest argument is purely mechanical. A body falling through a height H under gravity g has a free-fall time of order

$$t_{\rm ff} \quad \sim \quad \sqrt{H/g}, \tag{3}$$

up to order unity factors (as mentioned in Eq. (1)).

A similar combination appears in balancing, jumping, falling, and in the unstable dynamics of inverted pendula. A simple pendulum has its center of mass below the pivot and therefore undergoes stable oscillatory motion. In contrast, a pencil, rod, or body balanced above its support point has its center of mass above the tipping point, and the equilibrium is unstable. Linearizing about this equilibrium gives an 'inverted-pendulum' equation of the form

$$\ddot{\theta} \simeq \frac{g}{\ell}\theta, \tag{4}$$

where θ is the tilt angle and ℓ is the distance from the pivot to the relevant center-of-mass scale. The unstable growing solution scales as $\theta \propto \exp(t/t_{\rm inv})$, with

$$t_{\rm inv} \sim \sqrt{\ell/g}. \tag{5}$$

Therefore, $\sim \sqrt{H/g}$ is not only the period scale of ordinary pendula, but also the instability time scale of upright macroscopic bodies. The latter is not periodic, but it is still a characteristic dynamical time relevant to balance, posture, and ordinary action under gravity. More generally, $\sqrt{H/g}$ is the only time scale that can be formed from a length H and an acceleration g. The body mass, m, is irrelevant here by virtue of the Equivalence Principle. For actual timekeeping devices, however, desirable properties include at least periodicity and stability; for this reason the simple pendulum remains the cleanest representative of the broader organism–gravity time scale.

A simple pendulum isolates the same scale in a clean and reproducible way. If its length is a modest fraction of an organism-scale height,

$$\ell \quad = \quad \eta H, \tag{6}$$

with η neither microscopic nor astronomical, then

$$T_p \quad = \quad 2\pi\sqrt{\eta H/g}. \tag{7}$$

For humanly accessible pendulum lengths, this gives a time of order one second. For example, $\ell = 0.25$ m and $g = 9.8\ \mathrm{m\,s^{-2}}$ give $T_p \simeq 1.0$ s. This numerical fact is not precise enough to derive the

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historical second, but it is sufficiently precise to explain why the second is natural, and consequently provide a suggestive argument for its persistence among various everyday life system of units.

The simple pendulum is special in the sense that, to leading order, its period is independent of the bob mass and depends only on ℓ and g. This makes it cleaner than a sand clock, water clock, candle clock, physical pendulum, spring oscillator, or biological rhythm. Those timekeeping "devices" depend on material properties, geometry, friction, viscosity, elasticity, physiology, etc. The simple pendulum is therefore not the only second-like process, but it is the purest one.

4. Why H and g Are Not Arbitrary

The universality – and consequently utility – of Eq. (7) stems from the typicality of g and H. The surface gravity of a habitable rocky planet and the size of its large mobile organisms (that can carry sufficiently large brains) are constrained by ordinary matter density, atmospheric temperature, chemistry, and biochemistry.

At the planetary level, the mean density of rocky matter is set roughly by atomic density, of order one proton mass per Bohr-volume scale [7–9]. Habitable planets must also retain atmospheres and maintain climates compatible with complex chemistry [19]. Press and Lightman showed how such requirements lead to characteristic habitable rocky-planet masses, radii, and surface gravities expressible, at order of magnitude, in terms of fundamental constants and a chemistry fudge factor [9]. Exoplanet mass-radius studies likewise indicate that rocky planets occupy a restricted region in radius and density; in particular, planets significantly above Earth radius, and especially near or above $1.6R_\oplus$, increasingly cease to be rocky [20].

At the organism level, the size of large land animals is constrained by mechanics, cooling, and gravity. Haldane's classic discussion of being the right size emphasized that the same design cannot simply be scaled up or down arbitrarily [6]. Page later gave a refined order-of-magnitude argument for the height of the tallest running land animals, obtaining a meter-scale result [10]. The exact formula is of secondary relevance to the present discussion than the qualitative lesson; for large running organisms on habitable rocky planets, H is not a freely adjustable length scale.

Thus the combination $\sqrt{H/g}$ is relatively constrained. Habitable rocky planets do not naturally provide arbitrary values of g, and large mobile organisms do not naturally have arbitrary values of H. Consequently, the associated macroscopic dynamical time is funneled into a restricted range. Specifically, on planet Earth $H \sim 1.5 - 1.9\,\mathrm{m}$ and $g \sim 9.8\,\mathrm{m/sec^2}$, but these values are not expected to vary by orders of magnitude between habitable rocky planets. Hence a one-second-scale dynamical time should remain plausible for alien civilizations with broadly similar biological and planetary conditions, even if their numerical culture had no special preference for base-6, base-12, sexagesimal, or related subdivisions. In other words, it is hypothesised that civilizations of large mobile organisms acting under comparable planetary gravity would generically encounter macroscopic dynamical times of order $\sqrt{H/g}$, independently of the arithmetical route by which its practical time units were named.

Specifically, the argument suggests that typically [10] $H \sim \gamma^{3/10} a_0$ where $a_0 = (m_e c \alpha_e/\hbar)^{-1}$ is the Bohr radius with m_e, $\hbar$ and c are the electron mass, reduced Planck's constant, and the speed of light, respectively, $\gamma \equiv \alpha_e/\alpha_g$ is the ratio between the electric and gravitational interaction strengths, $\alpha_e = e^2/(\hbar c) \sim 1/137$ where e in the electric charge of the electron, and $\alpha_g = (m_p/m_{pl})^2$ is a measure of the gravitational interaction strength where m_p and m_{pl} are the proton and Planck masses, respectively. Likewise, $g \sim GM/R^2$, the surface gravity on the face of a planet with mass M and radius R, where G is Newton gravitational constant, is [7,9] $g \sim G m_p \beta^{1/4} \gamma^{1/2}/(2a_0)^2$, where $\beta \equiv m_e/m_p$ is the electron-to-proton mass ratio. Combining these it then follows that

$$t_{ff} \sim \sqrt{H/g} \sim \gamma^{2/5} a_0/(\alpha_e \beta^{1/2} c) \tag{8}$$

is of order one second. This illustrative order-of-magnitude scaling therefore amounts to the statement that the free-fall time associated with the largest living organisms on rocky habitable planets boils down to a certain combination of constants of nature that amounts to approximately one second. Its

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naturalness stems from its utility, certainly not from being more fundamental than, e.g. Planck or atomic scales, of course.

5. Heartbeat, Gait, and Other Biological Times

One possible objection is that the human heartbeat also has a period near one second, and might therefore be invoked instead of the pendulum. This is not really an objection. It is better understood as a biologically messier example of the same general $t_{ff} \sim \sqrt{H/g}$.

Heartbeat is not an arbitrary physiological "clock". It is shaped by body size, oxygen demand, vascular resistance, posture, gravity, as well as evolutionary conditions. Small mammals typically have faster heart rates than humans, while larger mammals often have slower ones; this is the familiar allometric trend connecting biological rates with body size and metabolism.

A similar point applies to ordinary walking and step rates. Human walking cadence is also in the rough one-second range. This is not surprising from the present work perspective. In relaxed walking, the arms and legs behave partly as gravity-dominated swinging limbs. If an arm is allowed to swing with only little deliberate muscular forcing, it can be very roughly viewed as a physical pendulum, with a characteristic time of order (approximated as that of a simple pendulum only to provide a very general idea)

$$T_{\text{limb}} \sim 2\pi\sqrt{\ell/g}, \tag{9}$$

where ℓ is an effective limb length. The full period, or the corresponding half-period relevant for alternating steps, is therefore again of order a second for organism-scale limb lengths. Thus walking cadence, arm swing, balance correction, and step timing are not arbitrary biological coincidences. They are additional members of the same broad organism–gravity cluster governed by $\sqrt{H/g}$.

There is also a simple gravitational toy model showing why heartbeat-like pump times need not be unrelated to Eq. (1). Assume a heart or pump must give a certain mass of fluid an upward impulse just sufficient to raise it through a height of order H against gravity. The impulse estimate gives

$$F\Delta t \quad \sim \quad mv, \tag{10}$$

where m is the fluid mass element, v is the acquired upward speed, and Δt is the characteristic pumping time. If the relevant upward force scale is of order the weight, $F \sim mg$, then $\Delta t \sim v/g$. Requiring the acquired speed to be just sufficient to climb a height H gives, from energy conservation,

$$mv^2 \quad \sim \quad mgH, \tag{11}$$

again up to factors of order unity. Hence $v \sim \sqrt{gH}$, and therefore

$$\Delta t \quad \sim \quad \sqrt{H/g}. \tag{12}$$

This is clearly not meant to be a derivation of heart rate. Real circulation is pressure-driven, viscous, elastic, and regulated. Instead, the point is that once gravity is dynamically important for a macroscopic organism, pump-like physiological times are naturally connected to the same height–gravity scale, $t_{ff} \sim \sqrt{H/g}$.

Thus heartbeat should not replace the pendulum argument. Rather, heartbeat, balance correction, limb motion, falling, and pendular motion all belong to a broad cluster of second-like macroscopic times associated with organism size and planetary gravity. The simple pendulum stands out as the cleanest periodic and stable representative because it avoids biological complications.

6. Scope and Limitations

The argument is clearly limited in the sense that it does not apply to all conceivable life forms. Speculative alternatives include, e.g. marine intelligences, small swarm-like organisms, or atmospheric

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ecologies such as the Jovian “sinkers,” “floaters,” and “hunters” considered by Sagan and Salpeter [21]. Currently, such possibilities cannot be excluded. The claim here is limited to a certain reference class (and the only one we know to exist); large mobile tool-using organisms that evolve or first practice technology on habitable rocky planets.

The argument also does not claim that the second is exact. Factors of a few are expected. Different body ergonomics, postures, gravities, climates, as well as historical conventions, could shift the preferred unit. It is only argued that the one-second scale is physically natural within this reference class, whereas microseconds, hours, or years are not natural everyday life time scales for sufficiently large mobile tool-using organisms .

Finally, the argument should not be confused with a claim about the most universal scientific standard. For interstellar communication, atomic frequencies or dimensionless ratios are clearly superior. The hydrogen hyperfine transition, atomic units, and Planck-like units are natural in a deeper formal sense [12,14,16,17]. The second is natural in a different sense; it is a convenient macroscopic timescale that naturally follows from habitability conditions as we know it.

7. Length and Mass as Secondary Context

Length and mass are less clean than time. The meter and kilogram are close to whole-body and manageable-load scales, but centimeters and grams are also practical for jewelry, coins, grains, laboratory and pharmacetical samples, and small artifacts. The centimeter and gram are not counterexamples to body-related metrology; they are useful subdivisions or nearby scales for smaller objects. But the second has a special feature; it remains the same time unit across MKS, CGS, and Imperial conventions.

The meter provides a useful analogy to the proposed origin of the second and its eventual standardization. Historically, the meter was introduced through a geodetic definition; one ten-millionth of the meridian distance from the pole to the equator, or equivalently one forty-millionth of a full terrestrial meridian. But this historical standardization should not be confused with the reason why a meter-scale unit is practically natural. A meter is close to the size of a human body, a stride, or an ordinary macroscopic object. One could equally ask why the Earth meridian was divided by 40 million rather than by 10 million, 60 million, or 150 million. The answer is not that 40 million is uniquely natural as an integer, but that this division landed on a useful organism-scale length. The role of the 60×60 subdivision of the hour may be analogous; it supplies the historical arithmetic by which the second was obtained, but the persistence of the resulting unit is explained by the fact that it landed on a natural organism–gravity time scale.

One may still state a somewhat weaker typicality encompassing all three scale units. For large mobile organisms on habitable rocky planets, body size naturally gives meter-like lengths, ordinary manipulation gives kilogram- or pound-like loads, and organism–gravity dynamics results in second-like times. But among these three, the second provides the cleanest case.

8. Conclusions

The second is historically conventional but physically natural. Its historical path through sexagesimal astronomy is not disputed. What requires explanation is why this 60×60 division of an hour is so useful, stable, and close to everyday macroscopic dynamics.

For large mobile organisms evolving in planetary gravity, the combination $\sqrt{H/g}$ is unavoidable. It governs free fall, balance and simple pendular motion. Since habitable rocky planets and large mobile organisms inhabit relatively narrow macroscopic ranges, this scale is typical within the relevant reference class, and naturally falls near what we normally refer to as “one second”. The simple pendulum is therefore the purest mechanical representative of a broader organism–gravity set of second-like times.

Biological rhythms such as heartbeat or gait do not refute this picture. On the contrary, since they are not independent clocks detached from organism size and gravity, they are actually biologically

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complicated members of the same broad macroscopic set. Their complexity is exactly the reason that the pendulum is the better example.

The proposed viewpoint is that the one-second scale was physically selected, in the sense that an available historical subdivision became especially stable because it landed near the planetary-organism time scale $\sqrt{H/g}$. The sexagesimal story explains the formal genealogy of the unit; it does not by itself explain why the particular subdivision 60×60, rather than other arithmetically natural alternatives such as 24×24, 30×30, or comparable divisor-rich choices, became so practically successful. Without specifying that comparison class in advance, the purely sexagesimal explanation suffers from a look-elsewhere problem. The persistence of the second may reflect not only inherited arithmetic, but also the ordinary dynamics of large organisms living and acting under planetary gravity. In this sense, the second may not merely be an arbitrary historical or cultural choice, but a typical macroscopic time scale encountered by upright intelligent organisms that first evolved on habitable planets.

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