Some Set Properties Underlying Geometry and Physics

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ABSTRACT. Volume and the Minkowski distances/p-norms (e.g., Manhattan and Euclidean distance) are derived from a set and limit-based foundation without referencing the primitives and relations of geometry. Sequencing a strict linearly ordered set in all n-at-a-time orders via successor/predecessor relations is a cyclic set of at most 3 members. Therefore, all other domain interval lengths have different types from a cyclic set of 3 distance domain interval lengths. Constant ratios between different types of interval lengths and the set proofs provide simpler derivations of the: spacetime, Newton's gravity, Coulomb's charge force, Planck-Einstein, Compton wavelength, de Broglie wavelength,, quantum-relativity gravity equations, and provide simple derivation of gravity (G), charge (k_e), and Planck (h) constants. All proofs are verified in Coq.

CONTENTS

1. Introduction

Mathematical analysis can construct differential calculus from a set and limit-based foundation without referencing the primitives and relations of Euclidean geometry, like straight line, angle, shape, etc., which provides a more rigorous foundation to calculus. But Euclidean volume in the Riemann integral, Lebesgue integral, measure theory, and distance in the vector magnitude and metric space criteria are definitions motivated by Euclidean geometry. [**Gol76**] [**Rud76**] Here, volume and distance is derived from a set and limit-based foundation.

An intuitive, set-based motivation of Euclidean volume is the number, v_c, of ordered combinations (n-tuples): $v_c = \prod_{i=1}^{n} |x_i|$, where $|x_i|$ is the cardinal of the countable, disjoint set, x_i. But, mathematical analysis textbooks do not provide proofs that $v_c = \prod_{i=1}^{n} |x_i| \Rightarrow v = \prod_{i=1}^{n} s_i$, where each set, x_i, is a set of subintervals of the interval, $[a_i, b_i] \subset \mathbb{R}$, and $s_i = b_i - a_i$. [**Gol76**] [**Rud76**]. In this article, a simple proof is provided that: $v_c = \prod_{i=1}^{n} |x_i| \Rightarrow v = \prod_{i=1}^{n} s_i$.

$v_c = \prod_{i=1}^{n} |x_i| = f(|x_1|, \cdots, |x_n|, n)$. If f is a bijective function, then $\exists\, d_c : d_c = f^{-1}(v_c, n)$ and $v_c = f(d_c, n) = f(|x_1|, \cdots, |x_n|, n)$. If $d_c = |x_1| = \cdots = |x_n|$, then $v_c = \prod_{i=1}^{n} |x_i| = \prod_{i=1}^{n} d_c = d_c^n$.

Where f is a bijective function, and where $d_c = |x_1| = \cdots = |x_n|$, it will be proved that $v_c = \sum_{j=1}^{m} v_{c_i} \Rightarrow \exists\, d, d_i \in \mathbb{R} : d^n = \sum_{i=1}^{m} d_i^n$. d is the ρ-norm (Minkowski distance), which will be proved to imply the metric space properties.

Sequencing the domain sets, $x_1, \cdots, x_n$, from $i = 1$ to n, is a strict linear (total) order, where a total order is defined in terms of successor and predecessor functions. Being able to sequence a set via successor and predecessor functions, in all n-at-a-time orders, requires a "symmetry" constraint, where every set member is either a successor or predecessor to every other set member. A strict linearly ordered and symmetric set will be proved to be a cyclic set, where $n \leq 3$.

Therefore, if $\{x_1, x_2, x_3\}$ is a strict linearly ordered and symmetric set of 3 "distance" dimensions, then another dimension, x_4, must have a different type (is a member of different set). Calculus divides domain intervals into the same number of subintervals, where each subinterval of a distance domain interval maps to a proportionate-sized subinterval of some other type of domain interval, which is expressed by a unit-factoring ratio, for example, *meters/second*.

Three constant, unit-factoring ratios, $r_c/t_c = c_t$, $r_c/m_c = c_m$, and $(r_c/q_c) = c_q$, combined with the results of the volume, distance, and 3D proofs provide simpler and shorter derivations of the, spacetime, Newton's gravity, Coulomb's charge force, Planck-Einstein, Compton wavelength, de Broglie wavelength, quantum-relativity gravity equations, and provide simple derivations of the gravity (G), charge (k_e), and Planck (h) constants. The ratios and proofs also simplify Einstein's field (general relativity) equations.

All the proofs in this article have been verified using using the Coq proof verification system [**Coq23**]. The formal proofs are in the Coq files, "euclidrelations.v" and "threed.v," at: https://github.com/treeck/RASRGeometry.

2. Ruler measure and convergence

A ruler (measuring stick) measures the size of each interval *approximately* as the sum of the nearest integer number, p, of size κ subintervals. The ruler is both an inner and outer measure of an interval.

DEFINITION 2.1. Ruler measure, $M = \sum_{i=1}^{p} \kappa = p\kappa$, where $\forall\, [a, b] \subset \mathbb{R}$, $s = b - a \,\wedge\, 0 < \kappa \leq 1 \,\wedge\, (p = floor(s/\kappa) \,\vee\, p = ceiling(s/\kappa))$.

THEOREM 2.2. *Ruler convergence:* $M = \lim_{\kappa \to 0} p\kappa = s$.

The formal proof, "limit_c_0_M_eq_exact_size," is in the file, euclidrelations.v.

PROOF. (epsilon-delta proof)
By definition of the floor function, $floor(x) = max(\{y : y \leq x,\, y \in \mathbb{Z},\, x \in \mathbb{R}\})$:

(2.1) $\forall\, \kappa > 0,\, p = floor(s/\kappa) \,\wedge\, 0 \leq |floor(s/\kappa) - s/\kappa| < 1 \,\Rightarrow\, |p - s/\kappa| < 1$.

Multiply both sides of inequality 2.1 by κ:

$$(2.2) \qquad \forall\, \kappa > 0, \quad |p - s/\kappa| < 1 \quad \Rightarrow \quad |p\kappa - s| < |\kappa| = |\kappa - 0|.$$

$$(2.3) \quad \forall\, \epsilon = \delta \quad \wedge \quad |p\kappa - s| < |\kappa - 0| < \delta$$
$$\Rightarrow \quad |\kappa - 0| < \delta \quad \wedge \quad |p\kappa - s| < \epsilon \quad := \quad M = \lim_{\kappa \to 0} p\kappa = s. \quad \square$$

The following is an example of ruler convergence for the interval, $[0, \pi]$: $s = \pi - 0$, and $p = floor(s/\kappa) \Rightarrow p \cdot \kappa = 3.1_{\kappa=10^{-1}}, 3.14_{\kappa=10^{-2}}, 3.141_{\kappa=10^{-3}}, ..., \pi_{\lim_{\kappa \to 0}}$.

LEMMA 2.3. $\forall\, n \geq 1, \quad 0 < \kappa < 1 \quad \Rightarrow \quad \lim_{\kappa \to 0} \kappa^n = \lim_{\kappa \to 0} \kappa$.

PROOF. The formal proof, "lim_c_to_n_eq_lim_c," is in the Coq file, euclidrelations.v.

$$(2.4) \quad n \geq 1 \quad \wedge \quad 0 < \kappa < 1 \quad \Rightarrow \quad 0 < \kappa^n < \kappa \quad \Rightarrow \quad |\kappa - \kappa^n| < |\kappa| = |\kappa - 0|.$$

$$(2.5) \quad \forall\, \epsilon = \delta \quad \wedge \quad |\kappa - \kappa^n| < |\kappa - 0| < \delta$$
$$\Rightarrow \quad |\kappa - 0| < \delta \quad \wedge \quad |\kappa - \kappa^n| < \delta = \epsilon \quad := \quad \lim_{\kappa \to 0} \kappa^n = 0.$$

$$(2.6) \qquad \lim_{\kappa \to 0} \kappa^n = 0 \quad \wedge \quad \lim_{\kappa \to 0} \kappa = 0 \quad \Rightarrow \quad \lim_{\kappa \to 0} \kappa^n = \lim_{\kappa \to 0} \kappa. \qquad \square$$

3. Volume

DEFINITION 3.1. A countable n-volume is the number of ordered combinations (n-tuples), v_c, of the members of n number of disjoint, countable domain sets, x_i:

$$(3.1) \quad \exists\, n \in \mathbb{N}, \; v_c \in \{0, \mathbb{N}\}, \; x_i \in \{x_1, \cdots, x_n\} : \; \bigcap_{i=1}^{n} x_i = \emptyset \; \wedge \; v_c = \prod_{i=1}^{n} |x_i|.$$

THEOREM 3.2. *Euclidean volume,*

$$(3.2) \quad \forall [a_i, b_i] \in \{[a_1, b_1], \cdots [a_n, b_n]\}, \; [v_a, v_b] \subset \mathbb{R}, \; s_i = b_i - a_i, \; v = v_b - v_a :$$
$$v_c = \prod_{i=1}^{n} |x_i| \quad \Rightarrow \quad v = \prod_{i=1}^{n} s_i.$$

The formal proof, "Euclidean_volume," is in the Coq file, euclidrelations.v.

PROOF.

$$(3.3) \quad v_c = \prod_{i=1}^{n} |x_i| \Leftrightarrow v_c \kappa = (\prod_{i=1}^{n} |x_i|)\kappa \Leftrightarrow \lim_{\kappa \to 0} v_c \kappa = \lim_{\kappa \to 0} (\prod_{i=1}^{n} |x_i|)\kappa.$$

Apply the ruler (2.1) and ruler convergence (2.2) to equation 3.3:

$$(3.4) \quad \exists\, v, \kappa \in \mathbb{R} : v_c = floor(v/\kappa) \quad \Rightarrow \quad v = \lim_{\kappa \to 0} v_c \kappa = \lim_{\kappa \to 0} (\prod_{i=1}^{n} |x_i|)\kappa.$$

Apply lemma 2.3 to equation 3.4:

$$(3.5) \quad v = \lim_{\kappa \to 0} (\prod_{i=1}^{n} |x_i|)\kappa = \lim_{\kappa \to 0} (\prod_{i=1}^{n} |x_i|)\kappa^n = \lim_{\kappa \to 0} (\prod_{i=1}^{n} |x_i|\kappa).$$

Apply the ruler (2.1) and ruler convergence (2.2) to s_i:

$$(3.6) \quad \exists\, s_i, \kappa \in \mathbb{R} : floor(s_i/\kappa) = |x_i| \quad \Rightarrow \quad \lim_{\kappa \to 0} (|x_i|\kappa) = s_i.$$

$$(3.7) \quad v = \lim_{\kappa \to 0} (\prod_{i=1}^{n} |x_i|\kappa) \; \wedge \; \lim_{\kappa \to 0} (|x_i|\kappa) = s_i \; \Rightarrow \; v = \prod_{i=1}^{n} s_i \qquad \square$$

4. Distance

DEFINITION 4.1. Countable distance, $d_c : d_c \in \mathbb{Z}_{\geq 0}, f(d_c, n) = v_c \Leftrightarrow f^{-1}(v_c, n) = d_c$, where v_c a countable volume (3.1) and $d_c = |x_1| = \cdots = |x_n|$.

4.1. Minkowski distance (ρ-norm).

THEOREM 4.2. *Minkowski distance (ρ-norm):*

$$v_c = \sum_{j=1}^m v_{c_i} \quad \Rightarrow \quad \exists\, d, d_i \in \mathbb{R} : d^n = \sum_{i=1}^m d_i^n.$$

The formal proof, "Minkowski_distance," is in the Coq file, euclidrelations.v.

PROOF. Apply the countable distance definition (4.1) to the assumption:

$$(4.1) \quad v_c = \prod_{i=1}^n |x_i| = \prod_{i=1}^n d_c = d_c^n \quad \wedge \quad v_{c_i} = \prod_{j=1}^n |x_{i_j}| = \prod_{i=1}^n d_{c_i} = d_{c_i}^n$$
$$\wedge \quad v_c = \sum_{j=1}^m v_{c_i} \quad \Rightarrow \quad d_c^n = \sum_{j=1}^m d_{c_i}^n.$$

Multiply both sides of equation 4.1 by κ and take the limit:

$$(4.2) \qquad d_c^n = \sum_{j=1}^m d_{c_i}^n \quad \Leftrightarrow \quad \lim_{\kappa \to 0} d_c^n \kappa = \lim_{\kappa \to 0} \sum_{j=1}^m d_{c_i}^n \kappa.$$

Apply lemma 2.3 to equation 4.1:

$$(4.3) \quad \lim_{\kappa \to 0} d_c^n \kappa = \lim_{\kappa \to 0} \sum_{j=1}^m d_{c_i}^n \kappa \quad \wedge \quad \lim_{\kappa \to 0} \kappa^n = \lim_{\kappa \to 0} \kappa$$
$$\Leftrightarrow \lim_{\kappa \to 0} d_c^n \kappa^n = \lim_{\kappa \to 0} \sum_{j=1}^m d_{c_i}^n \kappa^n \Leftrightarrow \lim_{\kappa \to 0}(d_c \kappa)^n = \lim_{\kappa \to 0} \sum_{j=1}^m (d_{c_i} \kappa)^n.$$

Apply the ruler (2.1) and ruler convergence theorem (2.2) to equation 4.3:

$$(4.4) \quad \exists\, d, d_i : d_c = floor(d/\kappa), \; d = \lim_{\kappa \to 0} d_c \kappa$$
$$\wedge \quad d_{c_i} = floor(d_i/\kappa), \; d_i = \lim_{\kappa \to 0} d_{c_i} \kappa \quad \Rightarrow$$
$$d^n = \lim_{\kappa \to 0}(d_c \kappa)^n = \lim_{\kappa \to 0} \sum_{j=1}^m (d_{c_i} \kappa)^n = \sum_{j=1}^m d_i^n. \quad \square$$

4.2. Distance inequality.
The formal proof, distance_inequality, is in the Coq file, euclidrelations.v.

THEOREM 4.3. *Distance inequality*

$$\forall\, n \in \mathbb{N}, \; v_a, v_b \geq 0 : \; (v_a + v_b)^{1/n} \leq v_a^{1/n} + v_b^{1/n}.$$

PROOF. Expand $(v_a^{1/n} + v_b^{1/n})^n$ using the binomial expansion:

$$(4.5) \quad \forall\, v_a, v_b \geq 0 : \quad v_a + v_b \leq v_a + v_b +$$
$$\sum_{i=1}^n \binom{n}{k}(v_a^{1/n})^{n-k}(v_b^{1/n})^k + \sum_{i=1}^n \binom{n}{k}(v_a^{1/n})^k(v_b^{1/n})^{n-k} = (v_a^{1/n} + v_b^{1/n})^n.$$

Take the nth of both sides of the inequality 4.5:

$$(4.6) \; \forall\, v_a, v_b \geq 0, n \in \mathbb{N} : v_a + v_b \leq (v_a^{1/n} + v_b^{1/n})^n \Rightarrow (v_a + v_b)^{1/n} \leq v_a^{1/n} + v_b^{1/n}. \quad \square$$

4.3. Distance sum inequality.
The formal proof, distance_sum_inequality, is in the Coq file, euclidrelations.v.

THEOREM 4.4. *Distance sum inequality*

$$\forall\, m, n \in \mathbb{N}, \; a_i, b_i \geq 0 : \; \left(\sum_{i=1}^m (a_i^n + b_i^n)\right)^{1/n} \leq \left(\sum_{i=1}^m a_i^n\right)^{1/n} + \left(\sum_{i=1}^m b_i^n\right)^{1/n}.$$

PROOF. Apply the distance inequality (4.3):

$$(4.7) \quad \forall\, m, n \in \mathbb{N}, \; v_a, v_b \geq 0 : \quad v_a = \sum_{i=1}^m a_i^n \quad \wedge \quad v_b = \sum_{i=1}^m b_i^n \quad \wedge$$
$$(v_a + v_b)^{1/n} \leq v_a^{1/n} + v_b^{1/n} \quad \Rightarrow \quad \left(\left(\sum_{i=1}^m a_i^n\right) + \left(\sum_{i=1}^m b_i^n\right)\right)^{1/n} =$$
$$\left(\sum_{i=1}^m (a_i^n + b_i^n)\right)^{1/n} \leq \left(\sum_{i=1}^m a_i^n\right)^{1/n} + \left(\sum_{i=1}^m b_i^n\right)^{1/n}. \quad \square$$

4.4. Metric Space. All Minkowski distances (ρ-norms) have the properties of metric space.

The formal proofs: triangle_inequality, symmetry, non_negativity, and identity_of_indiscernibles are in the Coq file, euclidrelations.v.

THEOREM 4.5. *Triangle Inequality:*
$d(s_1, s_2) = (\sum_{i=1}^{2} s_i^p)^{1/p} \quad \Rightarrow \quad d(u, w) \leq d(u, v) + d(v, w).$

PROOF. $\forall\, p \geq 1, \quad k > 1, \quad u = s_1, \quad w = s_2, \quad v = w/k:$

$$(4.8) \qquad (u^p + w^p)^{1/p} \leq ((u^p + w^p) + 2v^p)^{1/p} = ((u^p + v^p) + (v^p + w^p))^{1/p}.$$

Apply the distance inequality (4.3) to the inequality 4.8:

$$(4.9) \quad (u^p + w^p)^{1/p} \leq ((u^p + v^p) + (v^p + w^p))^{1/p} \;\wedge\; (v_a + v_b)^{1/n} \leq v_a^{1/n} + v_b^{1/n}$$
$$\wedge \quad v_a = u^p + v^p \quad \wedge \quad v_b = v^p + w^p$$
$$\Rightarrow \quad (u^p + w^p)^{1/p} \leq ((u^p + v^p) + (v^p + w^p))^{1/p} \leq (u^p + v^p)^{1/p} + (v^p + w^p)^{1/p}$$
$$\Rightarrow \quad d(u, w) = (u^p + w^p)^{1/p} \leq$$
$$(u^p + v^p)^{1/p} + (v^p + w^p)^{1/p} = d(u, v) + d(v, w). \quad \square$$

THEOREM 4.6. *Symmetry:* $d(s_1, s_2) = (\sum_{i=1}^{2} s_i^p)^{1/p} \quad \Rightarrow \quad d(u, v) = d(v, u).$

PROOF. By the commutative law of addition:

$$(4.10) \quad \forall\, p : p \geq 1, \quad d(s_1, s_2) = (\sum_{i=1}^{2} s_i^p)^{1/p} = (s_1^p + s_2^p)^{1/p}$$
$$\Rightarrow \quad d(u, v) = (u^p + v^p)^{1/p} = (v^p + u^p)^{1/p} = d(v, u). \quad \square$$

THEOREM 4.7. *Non-negativity:* $d(s_1, s_2) = (\sum_{i=1}^{2} s_i^p)^{1/p} \quad \Rightarrow \quad d(u, w) \geq 0.$

PROOF. By definition, the length of an interval is always ≥ 0:

$$(4.11) \qquad \forall\, [a_1, b_1], [a_2, b_2], \quad u = b_1 - a_1, \; v = b_2 - a_2, \quad \Rightarrow \quad u \geq 0, \; v \geq 0.$$

$$(4.12) \qquad p \geq 1, \; u, v \geq 0 \quad \Rightarrow \quad d(u, v) = (u^p + v^p)^{1/p} \geq 0. \qquad \square$$

THEOREM 4.8. *Identity of Indiscernibles:* $d(u, u) = 0.$

PROOF. From the non-negativity property (4.7):

$$(4.13) \quad d(u, w) \geq 0 \quad \wedge \quad d(u, v) \geq 0 \quad \wedge \quad d(v, w) \geq 0$$
$$\Rightarrow \quad \exists\, d(u, w) = d(u, v) = d(v, w) = 0.$$

$$(4.14) \qquad\qquad d(u, w) = d(v, w) = 0 \quad \Rightarrow \quad u = v.$$

$$(4.15) \qquad\qquad d(u, v) = 0 \quad \wedge \quad u = v \quad \Rightarrow \quad d(u, u) = 0. \qquad \square$$

4.5. The properties limiting a set to at most 3 members.

DEFINITION 4.9. Totally ordered set:

$$\forall\, i\, n \in \mathbb{N},\ i \in [1, n-1],\ \forall\, x_i\, \in \{x_1, \ldots, x_n\},$$
$$successor\ x_i = x_{i+1}\ \wedge\ predecessor\ x_{i+1} = x_i.$$

DEFINITION 4.10. Symmetry (every set member is sequentially adjacent to every other member):

$$\forall\, i,\, j,\, n \in \mathbb{N},\ \forall\, x_i,\, x_j \in \{x_1, \ldots, x_n\},\ successor\ x_i = x_j\ \Leftrightarrow\ predecessor\ x_j = x_i.$$

THEOREM 4.11. *A strict linearly ordered and symmetric set is a cyclic set.*

$$i = n\ \wedge\ j = 1\ \Rightarrow\ successor\ x_n = x_1\ \wedge\ predecessor\ x_1 = x_n.$$

The formal proof, "ordered_symmetric_is_cyclic," is in the Coq file, threed.v.

PROOF. A total order (4.9) assigns a unique label to each set member and assigns unique successors and predecessors for all set members except for the successor of x_n and the predecessor of x_1. Therefore, the only member that can be a successor of x_n, without creating a contradiction, is x_1. And the only member that can be a predecessor of x_1, without creating a contradiction, is x_n. Applying the symmetry property (4.10):

(4.16) $i = n\ \wedge\ j = 1\ \wedge\ successor\ x_i = x_j\ \Rightarrow\ successor\ x_n = x_1.$

Applying the definition of the symmetry property (4.10) to conclusion 4.16:

(4.17) $successor\ x_i = x_j\ \Rightarrow\ predecessor\ x_j = x_i\ \Rightarrow\ predecessor\ x_1 = x_n.$ □

THEOREM 4.12. *An ordered and symmetric set is limited to at most 3 members.*

The formal proofs in the Coq file threed.v are:

Lemmas: `adj111, adj122, adj212, adj123, adj133, adj233, adj213, adj313, adj323, and not_all_mutually_adjacent_gt_3.`

The following proof uses Horn clauses (a subset of first order logic), which makes it clear which facts satisfy a proof goal.

PROOF.
It was proved that an ordered and symmetric set is a cyclic set (4.11).

DEFINITION 4.13. (Cyclic) Successor of m is n:

(4.18) $Successor(m, n, setsize) \leftarrow (m = setsize \wedge n = 1) \vee (n = m + 1 \leq setsize).$

DEFINITION 4.14. (Cyclic) Predecessor of m is n:

(4.19) $Predecessor(m, n, setsize) \leftarrow (m = 1 \wedge n = setsize) \vee (n = m - 1 \geq 1).$

DEFINITION 4.15. Adjacent: member m is sequentially adjacent to member n if the successor of m is n or the predecessor of m is n. Notionally:
(4.20)
$Adjacent(m, n, setsize) \leftarrow Successor(m, n, setsize) \vee Predecessor(m, n, setsize).$

Every member is adjacent to every other member, where $setsize \in \{1, 2, 3\}$:

(4.21) $\quad Adjacent(1,1,1) \leftarrow Successor(1,1,1) \leftarrow (m = setsize \wedge n = 1).$

(4.22) $\quad Adjacent(1,2,2) \leftarrow Successor(1,2,2) \leftarrow (n = m + 1 \leq setsize).$

(4.23) $\quad Adjacent(2,1,2) \leftarrow Successor(2,1,2) \leftarrow (n = setsize \wedge m = 1).$

(4.24) $\quad Adjacent(1,2,3) \leftarrow Successor(1,2,3) \leftarrow (n = m + 1 \leq setsize).$

(4.25) $\quad Adjacent(2,1,3) \leftarrow Predecessor(2,1,3) \leftarrow (n = m - 1 \geq 1).$

(4.26) $\quad Adjacent(3,1,3) \leftarrow Successor(3,1,3) \leftarrow (n = setsize \wedge m = 1).$

(4.27) $\quad Adjacent(1,3,3) \leftarrow Predecessor(1,3,3) \leftarrow (m = 1 \wedge n = setsize).$

(4.28) $\quad Adjacent(2,3,3) \leftarrow Successor(2,3,3) \leftarrow (n = m + 1 \leq setsize).$

(4.29) $\quad Adjacent(3,2,3) \leftarrow Predecessor(3,2,3) \leftarrow (n = m - 1 \geq 1).$

Member 2 is the only successor of member 1 for all $setsize \geq 3$, which implies member 3 is not ($\neg$) a successor of member 1 for all $setsize \geq 3$:

(4.30) $\quad \neg Successor(1, 3, setsize \geq 3)$
$$\leftarrow Successor(1, 2, setsize \geq 3) \leftarrow (n = m + 1 \leq setsize).$$

Member $n = setsize > 3$ is the only predecessor of member 1, which implies member 3 is not ($\neg$) a predecessor of member 1 for all $setsize > 3$:

(4.31) $\quad \neg Predecessor(1, 3, setsize \geq 3)$
$$\leftarrow Predecessor(1, setsize, setsize > 3) \leftarrow (m = 1 \wedge n = setsize > 3).$$

For all $setsize \geq 3$, some elements are not ($\neg$) sequentially adjacent to every other element (not symmetric):

(4.32) $\quad \neg Adjacent(1, 3, setsize > 3)$
$$\leftarrow \neg Successor(1, 3, setsize > 3) \wedge \neg Predecessor(1, 3, setsize > 3). \quad \square$$

5. Applications to physics

From the 3D proof (4.12), dividing a set of domain intervals into the same number of subintervals, a 3-dimensional distance subinterval length, r, maps to proportionate subinterval lengths of other types, t (time), m (mass), and q (charge):

(5.1) $$r = (r_c/t_c)t = (r_c/m_c)m = (r_c/q_c)q.$$

5.1. Spacetime equations. From the volume proof (3.2), two disjoint distance intervals, $[0, r]$ and $[0, r']$, define a 2-volume. From the Minkowski distance proof (4.2), the distance interval lengths, r and r', are inverse functions of two 2-volumes, v and v' having the sizes, $v = r^2$ and $v' = r'^2$. And if r and r' are independent, then $\exists\, r_{total} : r_{total}^2 = r^2 + r'^2$. And if dependent, then either $\exists\, r_\nu : r^2 = r'^2 + r_\nu^2$ or $r'^2 = r^2 + r_\nu^2$. The same equations result from any case – only the notation differs. For traditional notation, the $r^2 = r'^2 + r_\nu^2$ case is chosen. And from the 3D proof (4.12), for some non-distance type, τ:

(5.2) $\quad \exists\, \mu,\, \nu \in \mathbb{R} : r = \mu\tau \quad \wedge \quad r_\nu = \nu\tau \quad \wedge \quad \exists\, r_\nu \in \mathbb{R} : r^2 = r'^2 + r_\nu^2$
$$\Rightarrow \quad (\mu\tau)^2 = r'^2 + (\nu\tau)^2 \quad \Rightarrow \quad r' = \sqrt{(\mu\tau)^2 - (\nu\tau)^2} = \mu\tau\sqrt{1 - (\nu/\mu)^2}.$$

Local (proper) distance, r', contracts relative to coordinate distance, r, as $\nu \to \mu$:

(5.3) $\qquad r' = \mu\tau\sqrt{1-(\nu/\mu)^2} \quad \wedge \quad \mu\tau = r \quad \Rightarrow \quad r' = r\sqrt{1-(\nu/\mu)^2}.$

Coordinate length, τ, dilates relative to local length, τ', as $\nu \to \mu$:

(5.4) $\qquad \mu\tau = r'/\sqrt{1-(\nu/\mu)^2} \quad \wedge \quad r' = \mu\tau' \quad \Rightarrow \quad \tau = \tau'/\sqrt{1-(\nu/\mu)^2}.$

Where τ is time, one form of the flat Minkowski spacetime event interval is:

(5.5) $\quad \mathrm{d}r^2 = \mathrm{d}r'^2 + \mathrm{d}r_\nu^2 \quad \wedge \quad \mathrm{d}r_\nu^2 = \mathrm{d}x_1^2 + \mathrm{d}x_2^2 + \mathrm{d}x_3^2 \quad \wedge \quad \mathrm{d}(\mu\tau) = \mathrm{d}r$

$$\Rightarrow \quad \mathrm{d}r'^2 = \mathrm{d}(\mu\tau)^2 - \mathrm{d}x_1^2 - \mathrm{d}x_2^2 - \mathrm{d}x_3^2.$$

Note: τ could also represent mass or charge.

5.2. Newton's gravity force and the constant, G. From equation 5.1:

(5.6) $\quad \forall\, m_1, m_2, m, r \in \mathbb{R} : m_1 m_2 = m^2 \quad \wedge \quad m = (m_c/r_c)r$

$$\Rightarrow \quad m_1 m_2 = ((m_c/r_c)r)^2 \quad \Rightarrow \quad (r_c/m_c)^2 m_1 m_2/r^2 = 1.$$

(5.7) $\qquad r = (r_c/t_c)t = ct \;\Rightarrow\; mr = (m_c/r_c)(ct)^2 \;\Rightarrow\; ((r_c/m_c)/c^2)mr/t^2 = 1.$

(5.8) $\quad ((r_c/m_c)/c^2)mr/t^2 = 1 \quad \wedge \quad (r_c/m_c)^2 m_1 m_2/r^2 = 1$

$$\Rightarrow \quad F := mr/t^2 = ((r_c/m_c)c^2)m_1 m_2/r^2 = Gm_1 m_2/r^2,$$

where Newton's constant, $G = (r_c/m_c)c^2$, conforms to the SI units: $m^3 \cdot kg^{-1} \cdot s^{-2}$.

5.3. Coulomb's charge force and constant, k_e. From equation 5.1:

(5.9) $\quad \forall\, q_1, q_2, q, r \in \mathbb{R} : q_1 q_2 = q^2 \quad \wedge \quad q = (q_c/r_c)r$

$$\Rightarrow \quad q_1 q_2 = ((q_c/r_c)r)^2 \quad \Rightarrow \quad (r_c/q_c)^2 q_1 q_2/r^2 = 1.$$

(5.10) $\qquad r = (r_c/t_c)t = ct \;\Rightarrow\; mr = (m_c/r_c)(ct)^2 \;\Rightarrow\; ((r_c/m_c)/c^2)mr/t^2 = 1.$

(5.11) $\quad ((r_c/m_c)/c^2)mr/t^2 = 1 \quad \wedge \quad (r_c/q_c)^2 q_1 q_2/r^2 = 1$

$$\Rightarrow \quad F := mr/t^2 = ((m_c/r_c)c^2)(r_c/q_c)^2 q_1 q_2/r^2.$$

(5.12) $\quad r_c/t_c = c \quad \wedge \quad F = ((m_c/r_c)c^2)(r_c/q_c)^2 q_1 q_2/r^2$

$$\Rightarrow \quad F = (m_c(r_c/t_c^2))(r_c/q_c)^2 q_1 q_2/r^2 = k_e q_1 q_2/r^2,$$

where Coulomb's constant, $k_e = (m_c(r_c/t_c^2))(r_c/q_c)^2$, conforms to the SI units: $N \cdot m^2 \cdot C^{-2}$.

5.4. 3 fundamental constants. c_t, c_m, and c_q.

(5.13) $\qquad\qquad\qquad c_t = r_c/t_c \approx 2.99792458 \cdot 10^8 m\ s^{-1}.$

(5.14) $\qquad G = (r_c/m_c)c_t^2 \quad \Rightarrow \quad c_m = r_c/m_c \approx 7.4261602691 \cdot 10^{-28} m\ kg^{-1}.$

(5.15) $\quad k_e = ((m_c/r_c)c_t^2)(r_c/q_c)^2 \Rightarrow \quad c_q = r_c/q_c \approx 8.6175172023 \cdot 10^{-18} m\ C^{-1}.$

5.5. The work constants. The ratios c_t/c_m and c_t/c_q yields 3 work constants, k_t, k_m, and k_q that are the basis of particle-wave behavior:

$$(5.16) \quad r/t = r_c/t_c, \quad r/m = r_c/m_c \quad \Rightarrow \quad (r/t)/(r/m) = (r_c/t_c)/(r_c/m_c) \quad \Rightarrow$$
$$(mr)/(tr) = (m_c r_c)/(t_c r_c) \quad \Rightarrow \quad mr = m_c r_c = k_m, \quad tr = t_c r_c = k_t.$$

$$(5.17) \quad r/t = r_c/t_c, \quad r/q = r_c/q_c \quad \Rightarrow \quad (r/t)/(r/q) = (r_c/t_c)/(r_c/q_c) \quad \Rightarrow$$
$$(qr)/(tr) = (q_c r_c)/(t_c r_c) \quad \Rightarrow \quad qr = q_c r_c = k_q, \quad tr = t_c r_c = k_t.$$

5.6. Planck-Einstein equation: Applying both the direct proportion ratio (5.1), $r/t = r_c/t_c = c$, and the work ratio (5.16), $mr = m_c r_c = k_m$:

$$(5.18) \quad m(ct)^2 = mr^2 \ \wedge \ m = m_c r_c/r = k_m/r \quad \Rightarrow \quad m(ct)^2 = (k_m/r)r^2 = k_m r.$$

$$(5.19) \quad m(ct)^2 = k_m r \quad \wedge \quad r/t = r_c/t_c = c$$
$$\Rightarrow \quad E := mc^2 = k_m r/t^2 = (k_m(r/t))\,(1/t) = (k_m c)(1/t) = hf,$$

where the Planck constant $h = k_m c$ and the frequency $f = 1/t$.

5.7. Compton wavelength equation: From equations 5.16 and 5.19:

$$(5.20) \quad\quad\quad mr = k_e \quad \Rightarrow \quad r = k_m/m = k_m c/mc = h/mc.$$

5.8. de Broglie wavelength equation: From equations 5.2 and 5.7:

$$(5.21) \quad v = r'/t = c\sqrt{1 - (v/c)^2} \quad \wedge \quad r = h/mc \quad \Rightarrow \quad r = (h/mv)\sqrt{1 - (v/c)^2}.$$

5.9. Work constant values:

$$(5.22) \quad\quad\quad k_m = m_c r_c = h/c \approx 2.21022 \cdot 10^{-42} \ kg \ m.$$

$$(5.23) \quad\quad\quad k_t = t_c r_c = k_m/(c_t/c_m) \approx 5.47493 \cdot 10^{-78} \ s \ m.$$

$$(5.24) \quad\quad\quad k_q = q_c r_c = (c_t/c_q)k_t \approx 1.90466 \cdot 10^{-52} \ C \ m.$$

5.10. Quantum-special relativity extensions to Newton's gravity force. The total mass of a particle is $m = \sqrt{m_0^2 + m_{ke}^2}$, where m_0 is the rest mass and m_{ke} is the kinetic energy-equivalent mass. Applying both the direct proportion ratios (5.1) and the work ratios (5.16):

$$(5.25) \quad m_0 = (m_c/r_c)r \quad \wedge \quad m_{ke} = m_c r_c/r \quad \wedge \quad m = \sqrt{m_0^2 + m_{ke}^2}$$
$$\Rightarrow \quad m = \sqrt{((m_c/r_c)r)^2 + ((m_c r_c)/r)^2}.$$

$$(5.26) \quad \exists\, m : m_1 m_2 = m^2 = ((m_c/r_c)r)^2 + ((m_c r_c)/r)^2$$
$$\Rightarrow \quad m_1 m_2/(((m_c/r_c)r)^2 + ((m_c r_c)/r)^2) = 1.$$

Newton's gravity force in the local frame of reference comes from the spacetime equation, 5.2:

$$(5.27) \quad\quad r' = \sqrt{(ct)^2 - (vt)^2} \quad \Rightarrow \quad m_0 r' = (m_c/r_c)((ct)^2 - (vt)^2).$$

$$(5.28) \quad m_0 r' = (m_c/r_c)((ct)^2 - (vt)^2) \quad \Rightarrow \quad ((r_c/m_c)/(c^2 - v^2))m_0 r'/t^2 = 1.$$

(5.29) $((r_c/m_c)/(c^2 - v^2))m_0 r'/t^2 = 1$

$$\wedge \quad m_1 m_2/(((m_c/r_c)r)^2 + ((m_c r_c)/r)^2) = 1$$

$$\Rightarrow \quad F := m_0 r'/t^2 = ((m_c/r_c)(c^2 - v^2))m_1 m_2/(((m_c/r_c)r)^2 + ((m_c r_c)/r)^2).$$

5.11. Quantum-special relativity extensions to Coulomb's charge force.

Applying $m = (m_c/q_c)q$ to the quantum-relativistic gravity equation (5.10):

(5.30) $$F = (m_c/q_c)^2 (m_c/r_c)(c^2 - v^2)q_1 q_2/(((m_c/r_c)r)^2 + ((m_c r_c)/r)^2).$$

6. Insights and implications

(1) Volume and distance derived from the same abstract, countable set of n-tuples provides a single set and limit-based foundation under integration, measure theory, the vector magnitude, and the metric space axioms without relying on the geometric primitives and relations in Euclidean geometry [**Joy98**], axiomatic geometry [**Lee10**], and vector analysis [**Wey52**].

(2) The definition of a complete metric space ignores the intimate relation between distance and volume. A more sufficient definition of a distance measure is distance as the inverse (bijective) function of volume (**??**).

(3) Euclid's proof that Euclidean distance is the smallest distance between two distinct points equate Euclidean distance to a straight line, where it is assumed that the straight line length is the smallest distance [**Joy98**]. And proofs that the straight line length is the smallest distance equate the straight line length to Euclidean distance.

Without using the notion of a straight line: Euclidean volume was derived from a set of n-tuples (3.2). And all distance measures derived from Euclidean 2-volumes (areas) are Minkowski distances (4.2), where $n \in \{1, 2\}$: $n = 1$ is the Manhattan (largest) distance case, $d = \sum_{i=1}^{m} s_i$. $n = 2$ is the Euclidean (smallest) distance case, $d = (\sum_{i=1}^{m} s_i^2)^{1/2}$. Hilbert spaces allow non-integer values of n (fractals). In that case, $1 \leq n \leq 2$ and d decreases monotonically as n goes from 1 to 2.

(4) The left side of the distance sum inequality (4.4),

(6.1) $$(\sum_{i=1}^{m}(a_i^n + b_i^n))^{1/n} \leq (\sum_{i=1}^{m} a_i^n)^{1/n} + (\sum_{i=1}^{m} b_i^n)^{1/n},$$

differs from the left side of Minkowski's sum inequality [**Min53**]:

(6.2) $$(\sum_{i=1}^{m}(a_i^n + b_i^n)^{\mathbf{n}})^{1/n} \leq (\sum_{i=1}^{m} a_i^n)^{1/n} + (\sum_{i=1}^{m} b_i^n)^{1/n}.$$

The two inequalities are only the same where $n = 1$. The distance sum inequality is a more fundamental inequality because its proof does not require convexity and Hölder's inequality that are required to prove the Minkowski sum inequality. And the distance sum inequality is derived from the definitions of volume and distance, which makes it more directly related to geometry.

(5) The derivations of the spacetime equations, in this article (5.1), differ from other derivations:

  (a) The derivations, here, do not rely on the Lorentz transformations or Einsteins' postulates [**Ein15**]. The derivations do not even require the notion of light.

   (b) The derivations, here, rely only on the Euclidean volume proof (3.2), the Minkowski distances proof (4.1), and the 3D proof (4.12), which provides the insight that the properties of physical space creates a maximum speed and the spacetime equations.

   (c) The same derivations are also valid for spacemass and spacecharge.

(6) The flat spacetime interval equation was derived from a 2-dimensional equation (5.5). which is generalized to: $\mathrm{d}r'^2 = \alpha_1\mathrm{d}(\mu\tau)^2 - \mathrm{d}r_\nu^2$, where $\mathrm{d}r_\nu^2 = \alpha_2\mathrm{d}x_1^2 + \alpha_3\mathrm{d}x_2^2 + \alpha_4\mathrm{d}x_3^2$. The 4×4 metric tensor, $g_{\mu,\nu} = diag(\alpha_1, -\alpha_2, -\alpha_3, -\alpha_4)$, in Einstein's field equations, can be simplified to the 2×2 metric tensor, $g_{i,j} = diag(\alpha_1, -1)$. The 2×2 metric tensor allows using a 2-dimensional Gaussian curvature, which is much simpler to calculate than the 4-dimensional Ricci curvature. And the 2×2 tensors reduce the number of independent equations to solve.

(7) The gravity (5.8), charge (5.12), and Planck (5.19) constants were all derived from more fundamental constants, $r_c/t_c = c_t$, $r_c/m_c = c_m$, $(r_c/q_c) = c_q$, and $m_c r_c = k_m$ (where k_m was derived from the ratio of c_t/c_m (5.16)). And all depend on the speed of light constant, c_t: For example, $G = c_m c_t^2$, $k_e = (c_q^2/c_m)c_t^2$, and $h = k_m c_t$.

(8) The constant, direct proportion ratios, c_t, c_m, and c_q, were used to derive the inverse proportion (work) ratios, k_t, k_m, and k_q. But k_t, k_m, and k_q can also be used to derive c_t, c_m, and c_q.

(9) Algebraic manipulation of Coulomb's constant, $k_e = ((m_c/r_c)c^2)(r_c/q_c)^2 = (m_c(r_c/t_c^2))(r_c/q_c)^2$, contains the term, r_c/t_c^2, which suggests a maximum acceleration constant for particles having mass.

(10) Applying the constant ratios to derive Newton's gravity force (5.2) and Coulomb's charge force (5.3) equations provide:

   (a) Derivations that do not assume the inverse square law or Gauss's flux divergence theorem as a cause of the inverse square law. **Note:** In Einstein's field equations, the components of the Ricci and metric tensors have the units, $1/\text{distance}^2$, Einstein's constant, $k = (4\pi G)2/c^4$, and the mass density component of the energy-stress tensor [**Wey52**] are assumptions of the inverse square law and Gauss's flux divergence.

   (b) The first derivations to show that the inverse square law and the property of force as mass times acceleration are the result of the conversion ratios, $r = (r_c/t_c)t = (r_c/m_c)m$.

(11) The quantum-special relativity extension to Newton's gravity equation (5.28) makes empirically verifiable predictions.

   (a) In Newton's gravity force, Gauss's gravity law, and Einstein's field equations, the force, $F \to \infty$ as the distance, $r \to 0$. But, the quantum component of the quantum-special relativity equation causes $F \to 0$ as $r \to 0$. Where the distance between two point-like particles is less than approximately 10^{-6} m, the gravity force should be measurably smaller than at 10^{-4} m. If the quantum effect is measurable, then:

     (i) There are no black hole singularities.

     (ii) The small, finite gravity wall allows radioactivity and quantum tunneling.

(b) Further, Newton's gravity constant, G, Gauss's gravity constant, $4\pi G$, and Einstein's gravity constant, $k = 8\pi G/c^4$, [**Wey52**], are only valid where the local velocity, $v = 0$. The special relativity component replaces G with "$((m_c/r_c)(c^2 - v^2)) = c_m(c_t^2 - v^2)$" in the local frame of reference.

But example, in the local frame of reference, an observer on a star orbiting the fringe of a galaxy at relativistic speeds will measure a slower gravitational acceleration than predicted by a constant G. And, in the coordinate frame of reference, for example, an observer on earth would measure a faster gravitational acceleration of that same star orbiting that distant galaxy than predicted by G.

(12) There is no constant ratio mapping a discrete value to a continuously varying value. Therefore, the discrete spin states of two quantum entangled particles and the polarization states of two quantum entangled photons are independent of continuously varying distance and time interval lengths.

(13) The inner product space in vector spaces, Riemann manifolds, etc. assumes any number of possible dimensions. For example, the Gram-Schmidt process is a method to find an orthogonal vector for any n-dimensional vector [**Coh21**]. None of those disciplines have exposed the properties that can limit a geometry to 3 dimensions.

But the set-based, first-order logic proof that a strict linearly ordered and symmetric set is a cyclic set of at most 3 members (4.12) is the simplest and most logically rigorous explanation for observing only 3 dimensions of physical space: simpler and more rigorous than parallel dimensions that cannot be detected and simpler and more rigorous than extra dimensions rolled up into infinitesimal balls that are too small to detect.

(a) Higher order dimensions must have different types (members of different sets).

(b) Each of 3 ordered and symmetric dimensions of space can have at most 3 sequentially ordered and symmetric state values, for example, an ordered and symmetric set of 3 vector orientations, $\{-1, 0, 1\}$, per dimension of space and at most 3 spin states per plane, etc.

If the states are not sequentially ordered (a bag of states), then a state value is undetermined until observed (like Schrodinger's cat being both alive and dead until the box is opened).

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