The Real Analysis and Combinatorics of Geometry

George. M. Van Treeck

Abstract. Using a ruler-like measure of intervals with real analysis exposes some counting principles underlying geometry: A set-based definition of a countable distance range converges to the taxicab distance equation at the upper boundary, the Euclidean distance equation at the lower boundary, and the triangle inequality over the full range, which provides counting-based motivations for the definitions of smallest distance and metric space. A set-based definition of countable size converges to the product of interval sizes used in the Lebesgue measure and Euclidean integrals. A cyclic set of at most 3 dimensions emerges from the same countable set axioms generating the distance and volume measures. Implications for higher dimensional geometries are discussed. Proofs are verified in Coq.

Contents

1. Introduction

The triangle inequality of a metric space, Euclidean distance metric, and the volume equation (product of interval sizes) of the Lebesgue measure and Euclidean integrals are imported into mathematical analysis from Euclidean geometry [Gol76] as primitives rather than derived from set and number theory-based axioms. As a consequence, mathematical analysis has provided no insight into the counting principles that motivate and generate those geometric relations.

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Generating the triangle inequality, taxicab (Manhattan) and Euclidean distance from a countable set-based definition of distance range provides new insights into the notions of distance measure (metric space) and the largest and smallest monotonic nondecreasing distance paths spanning disjoint sets. Likewise, the Lebesgue measure and Euclidean integrals sum the product of interval sizes (Euclidean volumes) without proof that the Cartesian product of the nearest integer number of same-sized subintervals of each interval converges to the product of intervals sizes.

What is needed for counting-based (combinatorial) proofs is an indefinite integration that derives a real-valued equation from a **discrete, combinatorial** function. In contrast, the various traditional indefinite integrals (antiderivatives) derive a real-valued equation from a **real-valued, continuous** function.

Consider $\int_a^b f(x)\mathbf{d}x$. For each subinterval, $[x_i, x_{i+1}]$, of the domain interval, $[x_a, x_b]$, there exists a corresponding image interval, $[f(x_a), f((x_{i+1} - x_i)/2)]$, which varies in size with f. The number of domain subintervals equals the number of image intervals.

In contrast, combinatorial integration divides both a set of domain intervals, $\{[x_{a_1}, x_{b_1}] \cdots [x_{a_n}, x_{b_n}]\}$, and a single image interval, $[f(x_{a_1,\cdots,a_n}), f(x_{b_1,\cdots,b_n})]$, into the nearest integer number of same-sized subintervals, similar to using a ruler (measuring stick), where the partial subintervals in both the domain intervals and image interval are ignored. Using the ruler measure, the size of the subintervals are all the same and the number of subintervals in each interval can vary, which allows a combinatorial relationship between the number of subintervals in one interval and the number of subintervals in another interval.

The volume and distance equations are derived in this article for any number of dimensions. However, it will be shown that the properties that can limit both Euclidean and non-Euclidean geometries to a cyclic set of at most 3 dimensions emerge from the same countable set axioms from which distance and volume emerge. Implications for higher dimensional geometries are discussed.

The proofs in this article are verified formally using the Coq Proof Assistant [**Coq15**] version 8.4p16. The Coq-based definitions, theorems, and proofs are in the files “euclidrelations.v” and “threed.v” located at:
`https://github.com/treeck/CombinatorialGeometry`.

2. Ruler measure and convergence

Definition 2.1. Ruler measure: A ruler measures the size, M, of a closed, open, or semi-open interval as the nearest integer number of whole subintervals, p, times the subinterval size, c, where c is the independent variable. Notionally:

$$\forall\, c\, s \in \mathbb{R},\ \ [a,b] \subset \mathbb{R},\ \ s = |b-a| \ \wedge\ c > 0\ \wedge \\ (p = floor(s/c)\ \vee\ p = ceiling(s/c))\ \wedge\ M = \Sigma_{i=1}^{p} c = pc. \tag{2.1}$$

Theorem 2.2. *Ruler convergence:*
$\forall\, [a,b] \subset \mathbb{R},\ \ s = |b-a| \ \Rightarrow\ M = \lim_{c \to 0} pc = s.$

The Coq-based theorem and proof in the file euclidrelations.v is “limit_c_0_M_eq_exact_size.”

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

$$\forall\, c > 0, \quad p = floor(s/c) \quad \Rightarrow \quad 0 \le |p - s/c| < 1. \tag{2.2}$$

Multiply all sides of inequality 2.2 by $|c|$:

$$\forall\, c > 0, \quad 0 \leq |p - s/c| < 1 \quad \Rightarrow \quad 0 \leq |pc - s| < |c|. \tag{2.3}$$

$$\begin{aligned} &\forall\, c > 0,\, \exists\, \delta\, :\, |pc - s| < |c| = |c - 0| < \delta \\ &\qquad \Rightarrow \quad \forall\, \epsilon = \delta,\ |c - 0| < \delta\ \wedge\ |pc - s| < \epsilon\ := \ M = \lim_{c \to 0} pc = s. \quad \square \end{aligned} \tag{2.4}$$

The proof steps using the ceiling function (the outer measure) are the same as the steps in the previous proof using the floor function (the inner measure).

For example, showing convergence using the interval, $[0, \pi]$, $s = |\pi - 0|$, $c = 10^{-i}$, and $p = floor(s/c)$, then, $p \cdot c = 3.1_{i=1},\ 3.14_{i=2},\ 3.141_{i=3}, ..., \pi$.

3. Distance

A simple countable distance measure is that an image (distance) set has the same number of elements as a corresponding domain set. For example, the number of steps walked in a distance set must equal the number pieces of land traversed. Therefore, for each disjoint domain set, x_i, containing p_i number of elements there exists a distance set, y_i, with the same p_i number of elements.

Notation conventions: The vertical bars around a set is the standard notation for indicating the cardinal (number of elements in the set). To prevent over use of the vertical bar, the symbol for "such that" is the colon.

If the distance sets intersect ($\sum_{i=1}^{n} |y_i| > |\bigcup_{i=1}^{n} y_i|$), then multiple domain set elements can correspond to a single distance element. Therefore, the size of the union of distance sets, d_c, is a function of the number of surjective (many-to-one) correspondences to each distance set element. Notionally:

Definition 3.1. Countable distance range, d_c:

$$\begin{aligned} &\forall\, i\, n \in \mathbb{N}, \quad x_i \subseteq X, \quad \textstyle\sum_{i=1}^{n} |x_i| = |\bigcup_{i=1}^{n} x_i|, \quad \forall\, x_i\, \exists\, y_i \subseteq Y : \\ &\qquad |x_i| = |y_i| = p_i \quad \wedge \quad \textstyle\sum_{i=1}^{n} |y_i| \geq |\bigcup_{i=1}^{n} y_i| \quad \wedge \quad d_c = |\bigcup_{i=1}^{n} y_i| = |Y|. \end{aligned}$$

The countable distance range principle (3.1), $|x_i| = |y_i| = p_i$, constrains the range of surjective correspondences from one element of x_i corresponding to an element of y_i to as many as p_i number of elements of x_i corresponding to an element of y_i. More than p_i number of surjective correspondences to an element of y_i would be over-counting correspondences.

Using the rule of product, there is a range from $|y_i| \cdot 1 = p_i$ to $|y_i| \cdot p_i = p_i^2$ number of domain-to-distance surjective correspondences per distance set. Therefore, $d_c = f(\sum_{i=1}^{n} p_i)$ is the largest possible distance (a function of the smallest number of surjective correspondences per distance set element, which is the case of disjoint distance sets). $d_c = f(\sum_{i=1}^{n} p_i^2)$ is the smallest possible distance (a function of the largest number of surjective correspondences per distance set element, which is the case of the maximum allowed intersection of distance sets).

Using the ruler (2.1) to divide a set of real-valued domain intervals and a distance interval into sets of same-sized subintervals, and applying the ruler convergence theorem (2.2) proves that the largest and smallest distance cases converge to the real-valued taxicab (Manhattan) and Euclidean distance equations.

The following convergence proofs of the taxicab and Euclidean distance equations use the strategy of showing that the right and left sides of a proposed counting-based equation both converge to the same real value and therefore are equal. In other words, the propositional logic, $A = C \wedge B = C \Rightarrow A = B$, is used.

THEOREM 3.2. *Taxicab (largest) distance, d, is the size of the distance interval,* $[y_0, y_m]$, *corresponding to a set of disjoint domain intervals,* $\{[x_{0,1}, x_{m_1,1}], [x_{0,2}, x_{m_n,2}], \ldots, [x_{0,n}, x_{m_n,n}]\}$, *where:*

$$d = \sum_{i=1}^{n} s_i, \quad d = |y_m - y_0|, \quad s_i = |x_{m_i,i} - x_{0,i}|.$$

The formal Coq-based theorem and proof in file euclidrelations.v is "taxicab_distance."

PROOF.
Use the ruler (2.1) to divide the exact size, $s_i = |x_{m_i,i} - x_{0,i}|$, of each of the domain intervals, $[x_{0,i}, x_{m_i,i}]$, into a set, x_i, containing p_i number of subintervals and apply the definition of the countable distance range (3.1), where each domain set has a corresponding distance set containing the same p_i number of elements.

$$\forall\, i\; n \in \mathbb{N}, \quad i \in [1, n], \quad c > 0 \quad \wedge \quad floor(s_i/c) = p_i = |x_i| = |y_i|. \tag{3.1}$$

Next, apply the rule of product to the case of one domain set element per distance set element:

$$\forall\, y_i \in Y, \; \sum_{i=1}^{n} |y_i| \cdot 1 = \sum_{i=1}^{n} p_i = |\bigcup_{i=1}^{n} y_i| = |Y|. \tag{3.2}$$

Multiply both sides of 3.2 by c and apply the ruler convergence theorem (2.2):

$$\begin{aligned} s_i = \lim_{c\to 0} p_i \cdot c \quad \wedge \quad \textstyle\sum_{i=1}^{n} (p_i \cdot c) = |Y| \cdot c \\ \Rightarrow \quad \textstyle\sum_{i=1}^{n} s_i = \sum_{i=1}^{n} \lim_{c\to 0} (p_i \cdot c) = \lim_{c\to 0} |Y| \cdot c. \end{aligned} \tag{3.3}$$

Use the ruler to divide the exact size, $d = |y_m - y_0|$, of the image interval, $[y_0, y_m]$, into a set, Y, containing p_d, number of subintervals:

$$\exists\, c > 0 : \quad floor(d/c) = p_d = |Y|. \tag{3.4}$$

Multiply both sides of 3.4 by c and apply the ruler convergence theorem (2.2):

$$d = \lim_{c\to 0} p_d \cdot c \;\wedge\; p_d \cdot c = |Y| \cdot c \;\Rightarrow\; d = \lim_{c\to 0} p_d \cdot c = \lim_{c\to 0} |Y| \cdot c. \tag{3.5}$$

Combine equations 3.5 and 3.3:

$$d = \lim_{c\to 0} |Y| \cdot c \quad \wedge \quad \sum_{i=1}^{n} s_i = \lim_{c\to 0} |Y| \cdot c \quad \Rightarrow \quad d = \sum_{i=1}^{n} s_i. \tag{3.6}$$ □

THEOREM 3.3. *Euclidean (smallest) distance, d, is the size of the distance interval,* $[y_0, y_m]$, *corresponding to a set of disjoint domain intervals,* $\{[x_{0,1}, x_{m_1,1}], [x_{0,2}, x_{m_n,2}], \ldots, [x_{0,n}, x_{m_n,n}]\}$, *where:*

$$d^2 = \sum_{i=1}^{n} s_i^2, \quad d = |y_m - y_0|, \quad s_i = |x_{m_i,i} - x_{0,i}].$$

The formal Coq-based theorem and proof in the file euclidrelations.v is "Euclidean_distance."

PROOF.
Use the ruler (2.1) to divide the exact size, $s_i = |x_{m_i,i} - x_{0,i}|$, of each of the domain intervals, $[x_{0,i}, x_{m_i,i}]$, into a set, x_i, containing p_i number of subintervals and apply the definition of the countable distance range (3.1), where each domain set has a corresponding distance set containing the same p_i number of elements.

$$\forall\, i\; n \in \mathbb{N}, \quad i \in [1, n], \quad c > 0 \quad \wedge \quad floor(s_i/c) = p_i = |x_i| = |y_i|. \tag{3.7}$$

Apply the rule of product to largest number of domain-to-distance surjective correspondences, where each of the p_i number of distance set elements in y_i corresponds to all p_i number of elements in the domain set x_i:

$$\sum_{i=1}^{n} |y_i| \cdot |x_i| = \sum_{i=1}^{n} p_i^2 = \sum_{i=1}^{n} |y_i|^2 = \sum_{i=1}^{n} |\{(y_a, y_b) : y_a\, y_b \in y_i\}|, \tag{3.8}$$

where each pair, (y_a, y_b), represents a combination between two elements in the distance set, y_i. From the countable distance range definition (3.1):

$$|\bigcup_{i=1}^{n} y_i| = |Y| \Rightarrow |\bigcup_{i=1}^{n}\{(y_a, y_b) : y_a\, y_b \in y_i\}| = |\{(y_a, y_b) : y_a\, y_b \in Y\}|. \tag{3.9}$$

$$\begin{aligned} &|\bigcup_{i=1}^{n}\{(y_a, y_b) : y_a\, y_b \in y_i\}| = |\{(y_a, y_b) : y_a\, y_b \in Y\}| \\ &\wedge \quad \sum_{i=1}^{n}|\{(y_a, y_b) : y_a\, y_b \in y_i\}| \geq |\bigcup_{i=1}^{n}\{(y_a, y_b) : y_a\, y_b \in y_i\}| \\ &\qquad \Rightarrow \quad \sum_{i=1}^{n}|\{(y_a, y_b) : y_a\, y_b \in y_i\}| \geq |\{(y_a, y_b) : y_a\, y_b \in Y\}|. \end{aligned} \tag{3.10}$$

From combining equation 3.8 and relation 3.10:

$$\begin{aligned} &\sum_{i=1}^{n} p_i^2 = \sum_{i=1}^{n}|\{(y_a, y_b) : y_a\, y_b \in y_i\}| \geq |\{(y_a, y_b) : y_a\, y_b \in Y\}| \\ &\qquad \Rightarrow \quad \exists\, y_i, Y : \sum_{i=1}^{n} p_i^2 = |\{(y_a, y_b) : y_a\, y_b \in Y\}|. \end{aligned} \tag{3.11}$$

Multiply both sides of equation 3.11 by c^2 and apply the ruler convergence theorem.

$$\begin{aligned} &s_i = \lim_{c\to 0} p_i \cdot c \quad \wedge \quad \sum_{i=1}^{n}(p_i \cdot c)^2 = |\{(y_a, y_b) : y_a\, y_b \in Y\}| \cdot c^2 \\ &\Rightarrow \quad \sum_{i=1}^{n} s_i^2 = \sum_{i=1}^{n} \lim_{c\to 0}(p_i \cdot c)^2 = \lim_{c\to 0} |\{(y_a, y_b) : y_a\, y_b \in Y\}| \cdot c^2. \end{aligned} \tag{3.12}$$

Use the ruler to divide the exact size, $d = |y_m - y_0|$, of the image interval, $[y_0, y_m]$, into p_d, number of subintervals and apply the rule of product:

$$\exists\, c > 0 : \;\; floor(d/c) = p_d = |Y| \;\Rightarrow\; p_d^2 = |Y|^2 = |\{(y_a, y_b) : y_a\, y_b \in Y\}|, \tag{3.13}$$

where $\{(y_a, y_b)\}$ is the set of all combination pairs of elements of Y. Multiply both sides of 3.13 by c^2 and apply the ruler convergence theorem (2.2):

$$\begin{aligned} &d = \lim_{c\to 0} p_d \cdot c \quad \wedge \quad (p_d \cdot c)^2 = |\{(y_a, y_b) : y_a\, y_b \in Y\}| \cdot c^2 \\ &\qquad \Rightarrow \quad d^2 = \lim_{c\to 0}(p_d \cdot c)^2 = \lim_{c\to 0} |\{(y_a, y_b) : y_a\, y_b \in Y\}| \cdot c^2. \end{aligned} \tag{3.14}$$

Combine equations 3.14 and 3.12:

$$\begin{aligned} &d^2 = \lim_{c\to 0} |\{(y_a, y_b) : y_a\, y_b \in Y\}| \cdot c^2 \quad \wedge \\ &\sum_{i=1}^{n} s_i^2 = \lim_{c\to 0} |\{(y_a, y_b) : y_a\, y_b \in Y\}| \cdot c^2 \quad \Rightarrow \quad d^2 = \sum_{i=1}^{n} s_i^2. \quad \square \end{aligned} \tag{3.15}$$

3.1. Triangle inequality. The definition of a metric in real analysis is based on the triangle inequality, $\mathbf{d}(\mathbf{u}, \mathbf{w}) \leq \mathbf{d}(\mathbf{u}, \mathbf{v}) + \mathbf{d}(\mathbf{v}, \mathbf{w})$, that has been intuitively motivated by the triangle [**Gol76**]. Applying the ruler (2.1), and ruler convergence theorem (2.2) to the definition of a countable distance range (3.1) yields the real-valued triangle inequality:

$$\begin{aligned} &d_c = |Y| = |\bigcup_{i=1}^{2} y_i| \leq \sum_{i=1}^{2}|y_i| \quad \wedge \\ &d_c = floor(\mathbf{d}(\mathbf{u}, \mathbf{w})/c) \;\wedge\; |y_1| = floor(\mathbf{d}(\mathbf{u}, \mathbf{v})/c) \;\wedge\; |y_2| = floor(\mathbf{d}(\mathbf{v}, \mathbf{w})/c) \\ &\quad \Rightarrow \mathbf{d}(\mathbf{u}, \mathbf{w}) = \lim_{c\to 0} d_c \cdot c \leq \sum_{i=1}^{2} \lim_{c\to 0} |y_i| \cdot c = \mathbf{d}(\mathbf{u}, \mathbf{v}) + \mathbf{d}(\mathbf{v}, \mathbf{w}). \end{aligned} \tag{3.16}$$

The other metric space properties: $\mathbf{d}(\mathbf{u}, \mathbf{w}) = 0 \Leftrightarrow u = w$, $\mathbf{d}(\mathbf{u}, \mathbf{w}) = \mathbf{d}(\mathbf{w}, \mathbf{u})$, and $\mathbf{d}(\mathbf{u}, \mathbf{w}) \geq 0$ also follow from the countable distance range definition.

4. Size (length/area/volume)

This section will use the ruler (2.1) and ruler convergence theorem (2.2) to prove that the Cartesian product of the number of same-sized subintervals of intervals converges to the product of interval sizes. The first step is to define a set-based, countable size measure as the Cartesian product of disjoint domain set members.

Definition 4.1. Countable size (length/area/volume) measure, S_c:

$$\forall\, i\; n \in \mathbb{N}, \quad i \in [1, n], \quad x_i \subseteq X, \quad \textstyle\sum_{i=1}^{n} |x_i| = |\bigcup_{i=1}^{n} x_i|, \quad \wedge \quad S_c = \displaystyle\prod_{i=1}^{n} |x_i|.$$

Theorem 4.2. *Euclidean size (length/area/volume), S, is the size of an image interval, $[y_0, y_m]$, corresponding to a set of disjoint intervals:* $\{[x_{0,1}, x_{m_1,1}], [x_{0,2}, x_{m_n,2}], \ldots, [x_{0,n}, x_{m_n,n}]\}$, *where:*

$$S = \prod_{i=1}^{n} s_i, \quad S = |y_m - y_0|, \quad s_i = |x_{m_i,i} - x_{0,i}|, \quad i \in [1, n], \quad i, n \in \mathbb{N}.$$

The Coq-based theorem and proof in the file euclidrelations.v is "Euclidean_size."

Proof.
Use the ruler (2.1) to divide the exact size, $s_i = |x_{m_i,i} - x_{0,i}|$, of each of the domain intervals, $[x_{0,i}, x_{m_i,i}]$, into a set, x_i of p_i number of subintervals.

$$\forall\, i\; n \in \mathbb{N}, \quad i \in [1, n], \quad c > 0 \quad \wedge \quad \mathit{floor}(s_i/c) = p_i = |x_i|. \tag{4.1}$$

Use the ruler (2.1) to divide the exact size, $S = |y_m - y_0|$, of the image interval, $[y_0, y_m]$, into p_S^n subintervals. Every integer number, S_c, does **not** have an integer n^{th} root. However, for those cases where S_c does have an integer n^{th} root, there is a p_S^n that satisfies the definition a countable size measure, S_c (4.1). Notionally:

$$\exists\, S_c \in \mathbb{R},\; x_i,\; c > 0: \;\; \mathit{floor}(S/c) = p_S^n = S_c = \prod_{i=1}^{n} |x_i| = \prod_{i=1}^{n} p_i. \tag{4.2}$$

Multiply both sides of equation 4.2 by c^n to get the ruler measures:

$$p_S^n = \prod_{i=1}^{n} p_i \quad \Rightarrow \quad (p_S \cdot c)^n = \prod_{i=1}^{n} (p_i \cdot c). \tag{4.3}$$

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

$$\begin{aligned} S = \lim_{c\to 0} (p_S \cdot c)^n \quad \wedge \quad (p_S \cdot c)^n = \prod_{i=1}^{n} (p_i \cdot c) \quad \wedge \quad \lim\nolimits_{c\to 0}(p_i \cdot c) = s_i \\ \Rightarrow \quad S = \lim_{c\to 0} (p_S \cdot c)^n = \prod_{i=1}^{n} \lim\nolimits_{c\to 0}(p_i \cdot c) = \prod_{i=1}^{n} s_i. \quad \square \end{aligned} \tag{4.4}$$

5. Ordered and symmetric geometries

Neither Euclidean geometry nor modern analytic geometry has been able to provide any insight into why physical Euclidean geometry appears to be limited to at most three dimensions. The same counting principles that generate the triangle inequality, taxicab distance, Euclidean distance, and size (length/area/volume) also generates properties that can limit a geometry (both Euclidean and non-Euclidean) to a cyclic set of at most three dimensions.

The previous derivations of taxicab distance (3.2), Euclidean distance (3.3), and Euclidean volume (4.2) show that the total number of combinations of subintervals of intervals converge to real-valued distance measures and Euclidean volume. By the commutative properties of addition and multiplication, all orderings (permutations) of the combinations of subintervals of intervals yield the same total distance and same total volume. Therefore, all orderings (permutations) of domain intervals corresponding to those subinterval combinations yield the same total distance and same total volume (a symmetric geometry).

All distance measures, size measures, and permutations emergent from the countable distance range principle and countable size exist (are allowed). There is no axiom of choice about which distance measures, size measures, and permutations exist or does not exist (emerge or do not emerge, allowed or not allowed by the countable distance range and size axioms).

For example, between any two distinct points, A and B, there is both a taxicab and Euclidean distance because both types of distance emerge from the same countable distance range definition (axiom). There is no choice about which type of distance exists and does not exist (emerge or does not emerge from the countable distance range axiom).

The same logic applies to "all permutations existing" (all possible permutations of intervals are allowed by the countable distance range and countable size). Mathematics defines the ordering (permutation) of a set in terms of a successor function and a predecessor (inverse order) function. For example, successor and predecessor functions can be defined that generate the left-to-right ordered set of elements, $\{A,\ B,\ C,\ D\}$. The successor function lists the permutation, $(A,\ B,\ C,\ D)$. And the predecessor function lists the permutation, $(D,\ C,\ B,\ A)$. In this case, only two permutations exist (emerge from those successor and predecessor functions).

It will be proved that all permutations (a symmetric geometry) can only emerge from a successor function and predecessor function that defines a cyclic ordering on a set containing at most three elements (dimensions).

Definition 5.1. Ordered geometry:

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

where $\{x_1, \ldots, x_n\}$ are a set of real-valued intervals (dimensions).

Definition 5.2. Symmetric geometry (all permutations):

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

Theorem 5.3. *An ordered and symmetric geometry is a cyclic set.*

$$\mathit{successor}\ x_n = x_1\;\; \wedge\;\; \mathit{predecessor}\ x_1 = x_n.$$

The theorem and formal Coq-based proof is "ordered_symmetric_is_cyclic," which is located in the file threed.v.

Proof. The property of order (5.1) defines unique successors and predecessors for all elements except for the successor of x_n and the predecessor of x_1. From the properties of a symmetric geometry (5.2):

$$i = n\;\; \wedge\;\; j = 1\;\; \wedge\;\; \mathit{successor}\ x_i = x_j\;\; \Rightarrow\;\; \mathit{successor}\ x_n = x_1. \tag{5.1}$$

$$i = n\;\; \wedge\;\; j = 1\;\; \wedge\;\; \mathit{predecessor}\ x_j = x_i\;\; \Rightarrow\;\; \mathit{predecessor}\ x_1 = x_n. \tag{5.2}$$

□

For example, using the cyclic set with elements labeled, $\{1,\ 2,\ 3\}$, starting with each element and counting through 3 cyclic successors and counting through 3 cyclic predecessors yields all possible permutations: $(1,2,3)$, $(2,3,1)$, $(3,1,2)$, $(1,3,2)$, $(3,2,1)$, and $(2,1,3)$. That is, a cyclically ordered set preserves sequential order while allowing some n-at-a-time permutations. If all possible n-at-a-time permutations are generated, then the cyclic set is also a symmetric geometry.

THEOREM 5.4. *An ordered and symmetric geometry is limited to at most 3 elements.*

The Coq-based lemmas and proofs in the 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) that uses unification and resolution. Horn clauses make it clear which facts satisfy a proof goal.

PROOF.
Because a symmetric and ordered set is a cyclic set (5.3), the successors and predecessors are cyclic:

DEFINITION 5.5. Successor of m is n:

$$Successor(m,n,setsize) \leftarrow (m = setsize \wedge n = 1) \vee (m+1 \leq setsize). \tag{5.3}$$

DEFINITION 5.6. Predecessor of m is n:

$$Predecessor(m,n,setsize) \leftarrow (m = 1 \wedge n = setsize) \vee (m-1 \geq 1). \tag{5.4}$$

DEFINITION 5.7. Adjacent: element m is adjacent to element n (an allowed permutation), if the cyclic successor of m is n or the cyclic predecessor of m is n. Notionally:

$$Adjacent(m,n,setsize) \leftarrow Successor(m,n,setsize) \vee Predecessor(m,n,setsize). \tag{5.5}$$

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

$$Adjacent(1,1,1) \leftarrow Successor(1,1,1) \leftarrow (1 = 1 \wedge 1 = 1). \tag{5.6}$$

$$Adjacent(1,2,2) \leftarrow Successor(1,2,2) \leftarrow (1+1 \leq 2). \tag{5.7}$$

$$Adjacent(2,1,2) \leftarrow Successor(2,1,2) \leftarrow (2 = 2 \wedge 1 = 1). \tag{5.8}$$

$$Adjacent(1,2,3) \leftarrow Successor(1,2,3) \leftarrow (1+1 \leq 2). \tag{5.9}$$

$$Adjacent(2,1,3) \leftarrow Predecessor(2,1,3) \leftarrow (2-1 \geq 1). \tag{5.10}$$

$$Adjacent(3,1,3) \leftarrow Successor(3,1,3) \leftarrow (3 = 3 \wedge 1 = 1). \tag{5.11}$$

$$Adjacent(1,3,3) \leftarrow Predecessor(1,3,3) \leftarrow (1 = 1 \wedge 3 = 3). \tag{5.12}$$

$$Adjacent(2,3,3) \leftarrow Successor(2,3,3) \leftarrow (2+1 \leq 3). \tag{5.13}$$

$$Adjacent(3,2,3) \leftarrow Predecessor(3,2,3) \leftarrow (3-1 \geq 1). \tag{5.14}$$

Must prove that for all $setsize > 3$, there exist non-adjacent elements (not every permutation allowed). For example, the first and third elements are not adjacent:

$$\forall\ setsize > 3: \quad \neg Successor(1, 3, setsize) \leftarrow Successor(1, 2, setsize) \leftarrow (1 + 1 \leq setsize). \tag{5.15}$$

That is, 2 is the only successor of 1 for all $setsize > 3$, which implies 3 is not a successor of 1 for all $setsize > 3$.

$$\forall\ setsize > 3: \quad \neg Predecessor(1, 3, setsize) \leftarrow Predecessor(1, n, setsize) \leftarrow (1 = 1 \wedge n = setsize). \tag{5.16}$$

That is, $n = setsize$ is the only predecessor of 1 for all $setsize > 3$, which implies 3 is not a predecessor of 1 for all $setsize > 3$.

$$\forall\ setsize > 3: \quad \neg Adjacent(1, 3, setsize) \leftarrow \neg Successor(1, 3, setsize) \wedge \neg Predecessor(1, 3, setsize). \quad \square \tag{5.17}$$

6. Summary

Applying the ruler measure (2.1) and ruler convergence proof (2.2) to a set of real-valued domain intervals and an image interval yields some new insights into geometry, number theory, and physics.

(1) The ruler measure was used to prove real-valued distance and size (length/area/volume) measures are derived from counting relationships between the elements of countable sets. In contrast, the metric space and sigma algebra measures, like the Lebesgue measure, use a real-valued function as a primitive, which does not provide any insight into the principles that generate the real-valued function. Further, the derivative of real-valued distance and size functions also fail to provide insight into the counting principles generating those functions.

(2) Applying the ruler measure to the countable distance range definition (3.1) provides the insight that all real-valued measures of distance are based on the principle that for each disjoint domain set there exists a corresponding distance set containing the same number of elements:
   (a) The countable distance range principle converges to the real-valued triangle inequality, which is the basis for the definition of metric space. The other properties of metric space also come from the countable distance range principle.
   (b) The upper bound of the countable distance range principle converging to taxicab distance provides the insight that the largest monotonic nondecreasing distance path is due to the smallest number of surjective correspondences (one correspondence) from domain set elements to a distance set element, which is the union of disjoint distance sets.
   (c) The lower bound of the countable distance range principle converging to Euclidean distance provides the insight that the smallest monotonic nondecreasing distance path is due to the maximum number of surjective correspondences from domain set elements to a distance set element, where all of the p_i number of elements in the i^{th} domain set have a surjective correspondence to each of the p_i number of elements in the i^{th} distance set.

(d) All $L^{p>2}$ norms generated from the countable distance range principle would require more than all the p_i number of elements in the i^{th} domain set corresponding to an element of the i^{th} distance set, which would be over-counting the number of possible surjective (many-to-one) correspondences. The definition of metric space does not provide this over-counting insight into why all $L^{p>2}$ norms fail the triangle inequality property of a metric space.

(e) With respect to number theory, $d = a^1 + b^1$ and $d^2 = a^2 + b^2$ both have cases that satisfy the equality case of the integer triangle inequality (3.11), which means both equations have cases of integer solutions. However, there are no integer solutions to, $d^n = a^n + b^n$, where $n > 2$, because all cases where $n > 2$ fail to satisfy the equality case of the integer triangle inequality (because $d^2 = a^2 + b^2$ is the lower bound of the triangle inequality and higher powers fall outside that range). This is a simple basis for a proof of Fermat's Last Theorem.

(f) Euclidean distance (3.3) was derived without any notions of side, angle, or shape. A parametric variable relating the sizes of two domain intervals can be easily derived using using calculus (Taylor series) and the Euclidean distance equation to generate the arc sine and arc cosine functions of the parametric variable (arc angle). In other words, the notions of side and angle are derived from Euclidean distance, which is the reverse of what classical geometry [**Joy98**] [**Loo68**] [**Ber88**] and axiomatic foundations for geometry [**Bir32**] [**Hil**] [**TG99**] assume.

(3) Applying the ruler measure and ruler convergence proof to the countable size definition (4.1) provides the insight that the Cartesian product of same-sized subintervals of real-valued intervals converges to the product of the interval sizes (Euclidean volume):
   (a) Euclidean size (length/area/volume) was derived without notions of sides, angles, and shape.
   (b) In contrast, the Lebesgue measure, uses Euclidean volume as a primitive, which provides no insight into the principles that generate size.

(4) Distance is a function of the surjective (combinatorial) relationship between a disjoint domain set and a corresponding image set (no relationship between the domain sets). In contrast, size (length/area/volume) is a function of the surjective (combinatorial) relationship between disjoint domain set elements.

(5) Countable, surjective functions (combinatorial relationships) converge to to the real-valued bijective functions, Euclidean distance and volume.

(6) All permutations (orderings) of domain intervals (dimensions) emerge from (are allowed by) the same countable distance range (3.1) and size (4.1) principles that generate real-valued distance and volume measures.
   (a) Mathematics defines the ordering of a set in terms of a successor function and a predecessor (inverse order) function. When the successor and predecessor functions generate all permutations (a symmetric geometry), then the ordering must be cyclic (5.3) and the set size limited to at most three elements (dimensions) (5.4).

(b) A pure mathematician can use the axiom of choice to choose a successor function that generates a single permutation of any number of dimensions of distance and volume.
(c) However, the axiom choice does not apply to the physical world. Choosing one ordering (permutation) of dimensions does not make the other permutations cease to exist. Therefore, physical geometry allows all permutations that emerge from the distance and volume principles, which results in a cyclic set (5.3) of three dimensions (5.4).
(d) A higher dimensional geometry can be defined where distance and size (length/area/volume) in the three "ordered and symmetric" dimensions is a function of other variables. For example, applying the ruler measure to countable relationships between the same-sized subintervals of a set of three "ordered and symmetric" intervals and other sets of intervals might converge to real-valued functions describing phenomena in the three "ordered and symmetric" that are perceived as "particles", "waves", "mass", "forces", and "time." Our universe might emerge from a few simple counting (quantum) principles in the real-valued continuum.

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George Van Treeck, 668 Westline Dr., Alameda, CA 94501