Mathematical Theory Generated with the Vacuum.Net Theory

From the eternal round to closure as oscillation: twenty-two rungs, some proved in cubical Agda, some checked by computation

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Preface

This book grows mathematics from below. It starts with movement. In the beginning there is a direction, <- . ->: a point with a way out and a way back. Without movement nothing happens, so the movement has no start: it is an eternal round. The Foundations of the theory begin with a first distinction [1]. This book starts from the round: a distinction is a still picture of it. It then lets the net grow, one rung at a time. At each rung it asks one question. Which field of mathematics already has a name for what the net has just made?

The order of the book is the order of the net, not the order of history. History found these structures in no fixed order. A study of the theory against the history of mathematics found no significant relation between the order of the theory's chain and the dates of the results it uses [2]. Here the order comes from the net. The names come from the fields.

The book has two kinds of mathematician in it. The seer works with space, movement and the whole, and comes first. The reasoner works in order, step by step. Rung 0 is seen; the ladder is reasoned. The book shows where the two meet and where they do not. Its round S^1 is the seer's circle, a point and a loop, taken up to deformation. Its circle of places is the reasoner's circle, a set of points. It proves that these are different types. If the circle of places is $\mathbb{R}/\mathbb{Z}$, the step from the second to the first would be the shape modality of cohesive type theory [9, 84]. For the net that step is open: the net has no cohesive structure yet.

Working from below solves a problem that working from above could not. When a named concept is taken first and then written as trits, its trit word depends on how it is written down [3]. When the net generates the structure first, the word comes first. The name is added afterwards.

How to read this book

Each chapter is one rung, in three steps. Seen: what the net makes, as a picture or a movement, and the name mathematics already has for it. Reasoned: what is proved, step by step. Back to the whole: what the result shows about the whole, and what stays open. Every statement under Reasoned carries one of four labels.

- **Proved in Agda.** A theorem in one of the cubical Agda files of this project, accepted by the type checker under --safe, without postulates [15]. The Agda name is given.
- **Checked by computation.** A finite fact recomputed in Python, with the script named.
- **Known theorem.** An established result of mathematics, cited to its source. It is not reproved here.
- **Argument (on paper).** A proof written out in the text. It is not checked by the type checker. It says what a formal proof would have to show. It is not counted as proved.

Readings are interpretations that link the net to a field or to a tradition. They belong to seeing: what the net is taken to show. They stand under Back to the whole, marked "Reading:", and are never counted as proved.

The goal is derivation. The book tries to derive mathematics step by step from the net. Where the derivation stops, it names the smallest assumption that is still needed. These stopping points are results in their own right: they show exactly what the net does not yet give.

A word on method. Matching a rung to a field shows where mathematics has already put a name on a structure of the net. It does not show that the theory is true. The book claims only this: the structures arise in this order from one rule, and each already has a name. Where a rung needs a hypothesis, the hypothesis is quoted from the theory with its number. The book adds two of its own at Rung 11 (H1, H2). At Rung 14 it takes the real numbers as an input. The chapter “Beyond Rung 21” builds the places of an interval from the net and proves Bishop’s criterion for the equality of their values, on integers. Later chapters build Bishop-regular sequences in the rationals (modulus $1/(2\cdot 3^k)$); the Cauchy reals are not built.

The Agda files are listed in Table A, with the start of their sha256 hash. They type-check with Agda 2.8.0 and the cubical library v0.9 [7, 14]. Names inside the files are Dutch. Stroom is a stream. Kop is its first trit. Staart is the rest of the stream. Fase is the set of places. Spiegel is the mirror. Voor is a digit put in front. Begrensd is bounded. Derde and Tweede are the ×3 and the ×2 ladder. Zonnen are the suns. Geen-keuze is no choice.

Rung	The net	Field that names it	Status
0	Movement: the eternal round	Circle S^1, connectedness	Agda + library
1	Three directions	windings −1, 0, +1 in $\mathbb{Z}$; Boolean algebra as a still picture	Agda
2	The return (N1)	Circle, integers as windings	Agda + library
3	Direction (trit rule)	$\mathbb{Z}_3$, F_3, Kleene logic	Agda
4	Words (T12)	Balanced ternary	Agda
5	Window (T2–T4)	Fox colouring, AG(n,3), cap sets	Agda + computation
6	Three closures (T7)	$\mathbb{Z}_3$ with mirror, S_3	Agda
7	Closing everywhere (T8–T10)	Linear cellular automata, circulants, $d^3 = 0$	Agda + computation + argument (on paper)
8	Seams (T11)	Sheaves (reading)	Agda
9	Closed without a start (T13)	Necklaces, Lyndon words	Computation
10	The plane (T14)	Eisenstein integers	Computation
11	Mirror and ring in one node	Modular group, braids	Agda + computation + cited
12	Two ladders (T15–T18)	Continued fractions, the comma	Computation
13	Into three dimensions (T19–T22)	Knots, SU(2), Hopf	Agda (maps to Rung 11 and S^1); complement cited; + embedding for the rest
14	Coupling (T23)	Analysis, Laplace’s method	Computation; + energy
15	Free path (T24)	Random walks, Pólya	Computation; + walk
16	Closure on itself	Clifford algebra; $d \circ d = 0$; $d^3 = 0$	Computation; + Dirac; Agda via 7
17	Two registers	Quaternions, spectral theory	Computation; + Maxwell
18	Measure	Dimensional analysis	Computation; + Larson
19	Loss has an address	Onsager, PSD matrices	Cited; + thermodynamics
20	Numbers without end	Signed-digit reals, computable analysis	Agda (average at finite depth), computation, cited; +

Rung	The net	Field that names it	Status
			infinite streams
21	Closure as oscillation	Difference equations, crystallographic restriction	Agda, computation, cited; + integer sum 0

Table 1. The twenty-two rungs. “+” names the hypothesis a rung adds to the net.

Before Euclid, and after

Many have tried to order mathematics. Table 0 sorts the attempts by the form of their order. The ladder of this book is a list in the order of generation: each item comes from the previous one by one rule, and the place in the list is the depth.

Ordering	Form	Examples
From axioms	Tree with one root	Euclid; Frege and Peano; Russell and Whitehead; Zermelo
From structures	Lattice of mother structures	Bourbaki
From relations	Network of arrows	Eilenberg and Mac Lane; Grothendieck; Lawvere
From paths	Space of types	Martin-Löf; Voevodsky (homotopy type theory)
By strength or symmetry	Ranking	Klein (Erlangen programme); reverse mathematics
By subject	Catalogue	Mathematics Subject Classification
By generation	List, one rule from item to item	Pāṇini and Piṅgala in method; this book

Table 0. Ways of ordering mathematics. Sources: Euclid [74], Russell and Whitehead [75], Bourbaki [76], Klein [77], Eilenberg and Mac Lane [78], Lawvere [79], Grothendieck [80], Martin-Löf [81], reverse mathematics [50], MSC [56].

An early generative work is Indian. Pāṇini's grammar, around the fourth century BCE, produces the words of Sanskrit from about four thousand short rules [67]. Computer science later saw a formal grammar in it [68]. Piṅgala, in the third or second century BCE, gives a procedure to list all metres of a given length as words of short and long syllables. He also gives a rule to find the place of any pattern in that list [67, 69]. Brahmagupta, in 628, gives rules for three kinds of number: fortune, debt and zero [73]. These are the method, the address and the three values of this book, found independently of the Greek line of axioms.

Two lines run through the history. The Indian and Chinese line generates: rules produce words, and each word gets a place. The Greek and European line deduces: theorems follow from axioms, and later the whole is ordered into trees and lattices. Grothendieck stands between them. He looked at relations rather than objects. Through topos theory and Lawvere, that line contributes to homotopy type theory, the language of this book. Its main roots are Martin-Löf's type theory and Voevodsky's univalence [79, 80, 81]. The two lines were never separate. Indian numerals with zero reached Europe through the Islamic world, and the Yijing reached Leibniz through the Jesuits [70]. Whether the Kerala series reached Europe is not established [71].

Each chapter names its precursors where they are known.

Rung 0. Movement: the eternal round

Seen

In the beginning there is movement. It has a direction: <- . ->, a point with a way out and a way back. Nobody was there at the start, but without movement nothing happens. So the movement never stops and never began. It is an eternal round.

Algebraic topology and homotopy type theory (MSC 55, 03). The circle S^1 is exactly this: one point, base, and one movement, loop, that returns to it [4]. The circle is connected: every place on it is reached from the point. The type fixes one point, base, as a reference; it has no time in it.

Precursors. Kauffman reads the imaginary unit as an oscillation, a value that alternates in time [82]. Spencer-Brown's re-entry gives such an oscillating value [10]. In this book the oscillation is not reached at the end but given at the start.

Martin-Löf, who founded the type theory beneath homotopy type theory, traced the order of conceptual priority backwards. From mathematics he went to proposition and truth, then to judgement, and ended at act and object. Rightness belongs first to the act, and an object is actual if an act with it has been performed [83]. Read this way, this book starts at the same place: the movement is the act, and a point or a trit is what the act leaves when seen still.

Reasoned

- Proved in Agda: a point without movement has only standing still; every return of the unit type is trivial (zonder-beweging, VacuumNetRound).
- Proved in Agda: every place on the round is reached from the point, base (geen-begin, VacuumNetRound, from the library's isConnectedS^1).

Back to the whole

Reading: The movement has no start and is eternal. S^1 has no time in it and fixes a base point as reference; that this point is no beginning is a reading, not a theorem.

The Foundations 9.2 begin with a first distinction [1]. This rung starts from the round, as the Preface does. The written theory has not yet been brought into line with it.

Rung 1. Three directions

Seen

Seen at one place, the round shows three directions: back (<-), the point (.), and out (->). These are the three trits T, 0 and 1. A trit is not a value but a still picture of the movement.

Group theory and logic (MSC 20, 03, 06). On the circle the three directions are the reversed loop, the constant path and the loop. Their windings are −1, 0 and +1. A distinction in the sense of Spencer-Brown cuts a space into two sides [10]. It is the still picture with the middle left out. Its algebra is Boolean.

Precursors. Spencer-Brown begins Laws of Form with the instruction to draw a distinction [10]. In this book his mark is not the start but a view of the round.

Reasoned

- Proved in Agda: the three directions have windings −1, 0 and +1, and out is not back (w-terug, w-punt, w-heen, heen≠terug, VacuumNetRound).
- Proved in Agda: the two sides of a mark do not coincide, ¬ (true ≡ false) (markering, VacuumNetLadder).
- Known theorem: the primary algebra of Laws of Form is a Boolean algebra [10].

Back to the whole

Reading: These three directions are the trits T, 0 and 1 of the theory.

A still picture alone has no motion. The next rung shows why the motion must be a round.

Rung 2. The return

Seen

The theory states N1: there is one strand, and every distinction is a loop [1]. A movement that goes out and comes back along the same way leaves nothing behind. Only a round that comes back by another way leaves a trace. That is why the eternal movement is a round.

Algebraic topology and group theory (MSC 55, 20). The windings of the circle are the integers. Licata and Shulman proved this inside homotopy type theory [5].

Reasoned

- Proved in Agda: out and back along the same way cancels, loop · loop^{-1} = refl (heen-en-terug, VacuumNetRound).
- Proved in Agda: one round is not standing still, ¬ (loop ≡ refl) (rondgang-blijft, VacuumNetRound; also onderscheid, VacuumNetFoundation).
- Proved in Agda: every number of rounds is kept; n rounds equal m rounds only if n = m (rondes-verschillen, VacuumNetRound).
- Known theorem: the loops of the circle are the integers, $\Omega S^1 \simeq \mathbb{Z}$ [5, 14].

Back to the whole

Reading: Only a round leaves a trace, so the eternal movement is a round.

The loops are shown to be the trit words directly (Rung 4, VacuumNetHelix), without the library theorem $\Omega S^1 \simeq \mathbb{Z}$. The integers still serve as a measuring rod inside that proof.

Rung 3. Direction

Seen

At a return, the trit rule of the theory reads one of three answers [1]. The passage leaves as the first passage left (+1, written R), leaves the way the first passage came in (−1, written L), or does neither (0, written O). These are the three trits, read as digits of the trinity (T1).

Group theory, field theory and logic (MSC 20, 12, 03). The three trits add as the cyclic group of order three, $\mathbb{Z}_3$. With multiplication they form the field with three elements. As truth values with an open middle they form Kleene's strong three-valued logic [11].

Precursors. Brahmagupta (628) gave rules for fortune (dhana, +), debt (ṛṇa, −) and zero (śūnya): a debt taken from zero is a fortune, a fortune taken from zero is a debt [73]. That is the mirror of T12.1. Schemes with more than two answers are older still: the Jain sevenfold predication and the Buddhist four corners (catuṣkoṭi), used by Nāgārjuna. Reading them as many-valued logics is debated [72].

Reasoned

- Proved in Agda: the addition $\oplus$ of trits is commutative and associative ($\oplus$-comm, $\oplus$-assoc, VacuumNetLadder).
- Known theorem: $\mathbb{Z}_3$ is the unique group of order three.

Back to the whole

Foundations III.1 says: "The trits are therefore not directions that compose but digits that add." Its argument is aimed at one reading: "the same as the first" as neutral and "the reverse" as its own inverse, a structure of two values. This book does not use that reading. III.2 reads the trits as winding (1), rest (0) and counterwinding (T). The Agda map ℓ follows III.2: R is the loop, O is the constant path, L is the loop reversed.

For whole words the two readings meet. The map ρ sends a word to the winding of its value, and composing windings adds integers [5]. The carry of T1 is the scale step ×3 between places. For single trits they meet through the carry. ℓ R • ℓ R • ℓ R is three windings, while R ⊕ R ⊕ R is O in $\mathbb{Z}_3$. The digit is the winding modulo three; the rest, (s − d)/3, passes to the next scale (T1). Agda proves the digit part in general. The balanced residue modulo three is additive on $\mathbb{Z}$ (rest3-+). With the winding homomorphism of the library this gives, for any two loops p and q: the digit of p • q is the digit of p $\oplus$ the digit of q (cijfer-hom). For single trits the digit of ℓ d is d (cijfer-van-ℓ). So composing loops and adding digits agree for all loops (VacuumNetDigitWinding). The carry (s − d)/3 to the next scale is stated, not proved. This settles the question for the III.2 reading; III.1's objection concerns a different, two-valued reading. The physical reading of the trit rule stays open (IX.5).

Rung 4. Words

Seen

Trits in a row form a word. Every integer has exactly one balanced-ternary word (T12) [1]. Mirroring R and L gives the negative (T12.1).

Number theory and computer science (MSC 11, 68). Knuth analyses balanced-ternary arithmetic and its history [13].

Precursors. Piṅgala listed all words of two kinds of syllable and gave rules to find the place of a given word in the list: a unique address, with two values instead of three [67, 69]. Pāṇini generated words from rules [68]. Leibniz wrote numbers as words of 0 and 1 (1679, published 1703). Only later, through Bouvet, did he see the Yijing hexagrams as the same [70].

Reasoned

- Proved in Agda: the words are exactly the windings of the loop, BT ≃ ΩS^1, and by univalence BT ≡ ΩS^1 (VacuumNetHoTT).
- Proved in Agda: the loop of a word is the winding of its value, ρ w ≡ intLoop (val w) (ρ≡intLoop, VacuumNetHoTT). The digit at each place is added by path composition; the rest of the word is traversed three times (×3), which is the carry to the next place.
- Proved in Agda, without the library theorem ΩS^1 ≃ ℤ and without the library fact that ΩS^1 is a set: the loops of the circle are the trit words (ΩS^1≃BT′). Over the base point lie the words; one turn around the loop is one step sucBT, an equivalence with inverse predBT (helixBT). A loop is sent to the word that ε becomes after transport (encodeBT). Going round the loop adds R with carry (encode-loop). This is the Licata–Shulman argument [5] with the net's own words as the fibre; decoding goes via intLoop ∘ val. Since the words form a set, it follows that the loops form a set too, in VacuumNetHelix.
- Proved in Agda: the set-truncation of the word type is not needed. The type BT^0, with only ε, _▷_ and stand, is a set by itself (isSetBT^0), because every word reads to a list with no O on top and reads back to itself (terug). It is equivalent to the truncated type and to ℤ (BT^0≃BT, BT^0≃ℤ, VacuumNetBT0). So the net's own rule, that a lone O on top falls away, is enough to make the words a set equal to ℤ.
- Proved in Agda: mirroring a word reverses its winding, ρ (mirror w) ≡ sym (ρ w) (spiegeling, VacuumNetFoundation).
- Checked by computation with the Agda value function val, least significant trit first: thirteen is R R R, three is O R, minus thirteen is L L L.

Back to the whole

The integers are still used as a measuring rod (val, toBT, intLoop). A proof with the words alone, without ℤ, is not done.

Rung 5. The window

Seen

Three successive trits form a window. A window closes when its sum is zero modulo three (T2). Exactly 9 of the 27 windows close (T3). A window closes exactly when its three trits are all equal or all different (T4) [1].

Knot theory, combinatorics and finite geometry (MSC 57, 05, 51). The same rule appears three times in mathematics. In knot theory it is Fox's three-colouring: at a crossing the arcs carry one colour or all three [12]. In finite geometry, three distinct points of the space F_3^n lie on a line exactly when they sum to zero. In additive combinatorics, the cap set problem asks for the largest set in F_3^n with no three distinct points that sum to zero, that is, with no line. Ellenberg and Gijswijt proved in 2017 that such a set has at most about 2.756^n points [16].

Reasoned

- Proved in Agda: a window closes exactly when its trits are all equal or all different, for all 27 windows (venster, VacuumNetLadder).
- Checked by computation: the closed triples in F_3^2 are its 12 lines, and in F_3^3 its 117 lines (bottomup_checks.py).
- Known theorem: the cap set bound of Ellenberg and Gijswijt [16].

Back to the whole

Reading: The rule is identical in the three fields, as a condition. That the fields therefore share more than this condition is a reading.

The cap set problem asks for the largest set without a closed window of three distinct trits. The theory has no answer to it yet.

Rung 6. Three closures

Seen

Every closed word reduces to nothing by removing three kinds of closure (T7) [1]. A standing is a single 0. A meeting is a trit and its mirror. A ring is three equal trits. Beside them stands the open pair: two equal nonzero trits. It does not close. It keeps a nonzero digit and may carry: 1 + 1 = 1T (T7.1).

Group theory (MSC 20). In $\mathbb{Z}_3$ the standing is the zero and the meeting is the inverse. The ring is the fact that every element has order dividing three. The open pair gives the mirror of x: x + x = −x. The mirror itself has order two. Rotation of order three and mirror of order two together are the symmetries of the trinity, the group S_3.

Reasoned

- Proved in Agda: x ⊕ spiegel x ≡ O (ontmoeting$_3$); x ⊕ x ⊕ x ≡ O (ring$_3$); x ⊕ x ≡ spiegel x (open-paar$_3$); spiegel (spiegel x) ≡ x (spiegel^2), all in VacuumNetLadder.
- Proved in Agda, on the loop: forward then back is no winding (meeting); a digit a scale up is three windings (ring); one step with carry is one winding more (openPair), in VacuumNetHoTT.
- Known theorem: $\mathbb{Z}_3$ with its mirror forms S_3.

Back to the whole

The equation x + x = −x is the arithmetic form of the open pair. That this is what T7.1 means is a reading.

Rung 7. Closing everywhere

Seen

A word may close in every window. The sum of the next window is the sum of this one, plus the trit that enters, minus the trit that leaves (T8) [1]. So a word closes everywhere exactly when its first window closes and it repeats with period three. For every length n ≥ 3 there are exactly nine such words. On a ring the count is nine when three divides n, and three otherwise (T9).

The theory then rewrites a ring. Each trit becomes minus the sum of its two neighbours (T10). Since 2 ≡ −1 modulo three, each trit becomes the mean of its neighbours. A ring stays fixed exactly when every window closes. For lengths 3 to 10, rings that are not fixed end in cycles, except 24 rings of length 4 and 24 of length 8, which come to rest.

Linear algebra over F_3, symbolic dynamics and cellular automata (MSC 15, 37B, 68Q80). The rewrite is a linear cellular automaton over $\mathbb{Z}_3$. Martin, Odlyzko and Wolfram worked out the algebra of such automata [25]. Its fixed points form the kernel of a circulant matrix with rows (1, 1, 1) [26]. The kernel has dimension two when three divides n, and one otherwise. The reason lies in the polynomial $x^2 + x + 1$, which over F_3 equals $(x - 1)^2$. The words that close everywhere form a shift of finite type with no freedom left: zero entropy [27].

Reasoned

- Proved in Agda: the window sum moves by the new trit minus the old one (propagatie); two closed windows in a row force the trit to repeat after three (periode); a trit is fixed by the rewrite exactly when its window closes (vast-punt), all in VacuumNetLadder2.
- Checked by computation: nine words for n = 3 to 9 (upper_checks.py).
- Checked by computation: nine or three rings, and five or three rotation classes, for n = 3 to 11.
- Checked by computation: 24 rings come to rest for n = 4 and for n = 8, and none for the other n from 3 to 10.
- Checked by computation: for n = 12, 6,552 rings come to rest (rest12.py). This goes beyond the range of T10.
- Checked by computation: the fixed space has size 9 or 3 for n = 3 to 12.
- Checked by computation (exact linear algebra): the count of rings that come to rest follows the rule below for every n from 3 to 48 (rest_rule.py). For n = 16 it is 24, for n = 36 it is 3,486,784,392.
- Proved in Agda: closing is a second difference. With D t = t(i+1) − t(i) over $\mathbb{Z}_3$, D^2 of three trits is their window sum (venster-is-D^2). D^3 of four trits is the last minus the first (D^3-is-periode), both in VacuumNetLadder3. So a constant word has D = 0, a word that closes everywhere has $D^2 = 0$, and a word of period three has $D^3 = 0$. This joins T8 and T9 in one chain: 3 ⊂ 9 ⊂ 27 rings when three divides n (ncomplex.py).
- Proved in Agda: among all 27 local linear rules t(i) ↦ a·t(i−1) + b·t(i) + c·t(i+1) over $\mathbb{Z}_3$, exactly two leave a trit in place precisely when its window closes (enige-twee, VacuumNetEigenform). One is the rewrite of T10, −(t(i−1) + t(i+1)). The other is t(i−1) − t(i) + t(i+1). The rewrite of T10 is the only one in which a trit does not read itself.
- Checked by computation: the same two rules, and no others, have as fixed points exactly the rings that close everywhere for all lengths 3 to 9 taken together (rule_search.py). For a single length this holds when three divides n; other lengths admit up to eight rules.

- Argument (on paper): the 27-window result is close to a tautology. A rule (a, b, c) works exactly when (a, b − 1, c) is a nonzero multiple of (1, 1, 1). The real choice is to allow only linear rules of radius one. Among those, the rule is forced up to a scalar.
- Known theorem: the kernel of a circulant matrix has dimension equal to the degree of the greatest common divisor of its polynomial with $x^n - 1$ [26].

Back to the whole

The Agda proofs are local: they concern one window. The counts for all n are argued on paper and computed here, not formalised.

Rings that come to rest are not limited to lengths 4 and 8. They occur exactly when four divides n. The count is 3^(2·3^v) · F − F, with F the number of fixed rings and 3^v the power of three in n. The proof is short. Read a ring as a polynomial modulo $x^n - 1$ over F_3. The rewrite is multiplication by $-(x^2 + 1)/x$, and R − I by $-(x - 1)^2/x$. Over F_3 the factor $x^2 + 1$ is irreducible. Its roots are the fourth roots of one, so it divides $x^n - 1$ exactly when four divides n, with multiplicity 3^v. That factor is where the rewrite is nilpotent. On all other factors the rewrite is invertible [25, 26]. Coming to rest means $(R - I)R^m t = 0$ for some m. That kernel is the fixed space plus the $x^2 + 1$ part, of dimension 2·3^v. The count follows.

This corrects the statement of T10, which lists only lengths 4 and 8 because it was computed up to length 10.

Rung 8. Seams

Seen

Two closed windows can be joined. Across the joint lie two new windows. The first closes exactly when the two first trits agree. The second closes exactly when the two last trits agree. So the seam closes only when both windows are the same (T11) [1]. Of the 81 ordered pairs, 9 seams close, 36 have one open window and 36 have two. Two different closed windows cannot be joined without tension.

Sheaf theory and cohomology (MSC 18F20, 55N30). A sheaf asks when local pieces fit into one global piece. The failure to fit is measured by cohomology [28]. Here each closed window is a local piece. The open windows at the seam are the failure to fit.

Reasoned

- Proved in Agda: a closed window is fixed by its first and last trit (this follows from vast-punt; midden names the middle); the seam closes exactly when first and last trits agree, for all 81 cases (naad, VacuumNetLadder2).
- Checked by computation: 9, 36 and 36 seams (upper_checks.py).

Back to the whole

Reading: The open windows at a seam as a cohomological obstruction.

The sheaf reading is untested. A real test would build the cohomology of a word and show that it counts the open seams.

Rung 9. Closed without a start

Seen

A closed strand has no first place. Read from a start, a word has length n. Read without a start, only its rotation class remains (T13) [1].

Combinatorics and algebra (MSC 05, 17, 68). Rotation classes of words are necklaces, counted by Burnside's lemma [24]. The primitive ones, which are not a repetition of a shorter word, are Lyndon words. Lyndon words form a basis of the free Lie algebra, by theorems of Chen, Fox and Lyndon and of Shirshov, both 1958 [21, 22].

Precursors. Piṅgala's tradition counted words of fixed length by kind; Halāyudha's commentary (10th century) gives the arithmetic triangle as meru-prastāra [67, 69].

Reasoned

- Checked by computation: ternary necklaces of length 1 to 6 number 3, 6, 11, 24, 51, 130, as in T13; primitive ones (Lyndon words) number 3, 3, 8, 18, 48, 116 (rungs_checks.py).
- Known theorem: Lyndon words give a basis of the free Lie algebra [21, 22].

Back to the whole

That the primitive closed strands of the net are a basis of a Lie algebra is a reading worth testing.

Rung 10. The plane

Seen

The three digits can also be used in the plane. Take the Eisenstein integers $a + b\omega$, with ω a cube root of one, and the base $\beta = 1 - \omega$. Subtract the balanced residue and divide by β. This gives a map T (T14) [1]. Every orbit of T ends either at 0 or at one of two fixed points, $\pm(1 + \omega)$ (proof below). These fixed points are sixth roots of one: a turn of 60°. An element has a finite word only if its orbit reaches 0. Not every element does: 2 goes to $2 + \omega$ and then to $1 + \omega$, where it turns for ever.

Algebraic number theory (MSC 11R, 11A63). The Eisenstein integers are the integers of the field $\mathbb{Q}(\sqrt{-3})$. The element $1 - \omega$ is the prime above three. Its residue field is $\mathbb{F}_3$, so its three residues are exactly the three trits. Three is, up to a unit, the square of this prime: $3 = -\omega^2(1 - \omega)^2$. Cubic reciprocity lives in this ring [29]. Number systems with bases in such rings are studied as canonical number systems [30].

Reasoned

- Checked by computation: $2 \to 2 + \omega \to 1 + \omega$ (upper_checks.py).
- Argument (on paper): every orbit of T ends at 0 or at $\pm(1 + \omega)$. First, $|1 - \omega| = \sqrt{3}$, and T subtracts a residue of size at most 1 before it divides by $1 - \omega$. So $|Tz| \le (|z| + 1)/\sqrt{3}$, which is smaller than $|z|$ as soon as $|z| \ge 2$. That is the case when the norm $a^2 - ab + b^2$ is at least 4. The norm then drops at every step, until it is at most 3. Second, the elements of norm at most 3 are 0, the six units and the six associates of $1 - \omega$. T keeps 0 and $\pm(1 + \omega)$ fixed. It sends the other four units to 0 within two steps, and the associates of $1 - \omega$ to units. So no other cycle exists.
- Checked by computation: for $|a|, |b| \le 60$ (14,641 elements) the norm drops at every step from norm 4 on. Every orbit ends at 0 (9,351 elements), at $1 + \omega$ (2,645) or at $-(1 + \omega)$ (2,645). No other cycle occurs. The 13 elements of norm at most 3 behave as stated (upper_checks.py).
- Checked by computation: for $|a|, |b| \le 40$, 1,788 of 6,561 elements (27.3 %) end in the turn; for $|a|, |b| \le 100$, 16,546 of 40,401 (41.0 %), as in T14.
- Known theorem: $\mathbb{Z}[\omega] / (1 - \omega) \cong \mathbb{F}_3$ and $3 = -\omega^2(1 - \omega)^2$ [29].
- Checked by computation: the bases β for which $-1, 0, 1$ are a complete residue system are exactly the elements of norm 3: the six associates of $1 - \omega$ (base_search.py). A complete residue system of size three needs $|\mathbb{Z}[\omega]/(\beta)| = N(\beta) = 3$, and three has one prime above it. So the residue system forces β up to a unit. The behaviour of T14 depends on the unit.
- Checked by computation: a nonzero fixed point $z = d/(1 - \beta)$ exists only when $1 - \beta$ is a unit. Among the six associates that holds for $1 - \omega$ and its complex conjugate $2 + \omega = 1 - \omega^2$ only (base_units.py). The other four associates end in cycles of period 2 or 4 instead. Complex conjugation leaves the digit unchanged and carries the dynamics of one base to the other. On conjugation-symmetric regions (norm at most 300 or 1,500) the two give the same share ending in the turn: 332 of 1,075 and 1,676 of 5,437. So requiring a turn that is a fixed point (period 1) forces the base up to complex conjugation. The differences seen earlier came from the square box, which conjugation does not preserve.

Back to the whole

Whether the share settles at a limit is open (IX.3). This rung is not formalised in Agda. It shows the limit of the address: in the line the trits give every number a word, in the plane they do not.

Rung 11. Mirror and ring in one node

Seen

Rung 6 gave a symmetry of order two and a ring of order three. On the three trit values they obey one more relation and give S_3. Now let both act at one node of the net, on everything that passes it. Write the node as a type with one point and two loops: S, which closes after two turns, and the ring, which closes after three. Nothing else is imposed. S is read here as a mirror; it is not the mirror of T12.1 (see Reading).

Rung 12 gives the ladder path. Up to sign, each R step is S followed by the ring, and each L step is S followed by the ring backwards. Does the net force the node to carry no further relation? Two hypotheses make it so. (H1) The steps can be undone. The ladder itself gives only forward steps. (H2) The node keeps distinct ladder paths apart. This is the unique address of T12, applied to the paths: distinct continued fractions stay distinct. Under H1 and H2 the argument runs as follows. A further relation would make a nontrivial normal subgroup of PSL(2, $\mathbb{Z}$) trivial at the node. Such a subgroup contains a hyperbolic element. Every hyperbolic element is conjugate to a positive R/L word. That word would then be the identity at the node, which H2 forbids. So, under H1 and H2, the free pairing is required by the ladders.

Number theory, hyperbolic geometry and knot theory (MSC 11F06, 20F05, 57K10). The free combination of a group of order two and a group of order three is the modular group PSL(2, $\mathbb{Z}$) [17]. Every element of it is written in one way only, as an alternation of the mirror and the ring turned forward or back. The braid group on three strands, B_3, is a central extension of it by $\mathbb{Z}$: B_3 divided by its centre is PSL(2, $\mathbb{Z}$). B_3 is also the knot group of the trefoil [18]. Modular forms on its congruence subgroups carry Wiles's proof of Fermat's Last Theorem [19]. Continued fractions are paths in this group [48].

Reasoned

- Proved in Agda: in the node, twice the ring is the ring backwards ($\text{ring}^2 \equiv \text{ring}^{-1}$); S is its own inverse ($\text{spiegel} \equiv \text{spiegel}^{-1}$); the L step equals S followed by the ring twice (stap-L), in VacuumNetPairRing.
- Proved in Agda (by construction): a trit ±1 is the step "S, then the ring forward or back" (stap). Every trit word is a loop at the node (pad). So is the comma path of $\log_2 3$ (kommapad).
- Proved in Agda by computation with integer matrices: $S^2 = -I$ (S-paar); $(ST)^3 = -I$ (U-ring); $\sigma_1\sigma_2\sigma_1 = \sigma_2\sigma_1\sigma_2$ (vlecht); $a^2 = b^3$ (klaverblad), in VacuumNetLadder.
- Checked by computation: $R = S{\cdot}U$ and $L = S{\cdot}U^2$, up to sign, with $U = ST$ the ring; the comma path of 41 steps is the same matrix whether written in R and L or in mirror and ring; $T^{-1}LT^{-1} = S$, so R and L generate SL(2, $\mathbb{Z}$) (pair_ring_path.py, sb_path.py).
- Known theorem: PSL(2, $\mathbb{Z}$) $\cong C_2 * C_3$, with a unique alternating normal form [17]; the fundamental group of a node with two such loops is $C_2 * C_3$ by Seifert–van Kampen, also in homotopy type theory [49]; $B_3 / Z(B_3) \cong$ PSL(2, $\mathbb{Z}$) and B_3 is the trefoil group [18].
- Proved in Agda: every ladder path has a unique address, its Stern–Brocot fraction. Reading the address back gives the path (lees-adres), so distinct paths have distinct pairs (p, q) (adres-injectief). Mirroring a path, R ↔ L, turns p/q into q/p (spiegel-pad), all in VacuumNetLadderPath. This is H2 for positive words, at the level of pairs: the classical Stern–Brocot uniqueness, formalised. It also gives the inversion half of S.
- Proved in Agda: H2 holds in a node whose group is SL(2, $\mathbb{Z}$), a central ±1 extension of PSL(2, $\mathbb{Z}$) (the group is cited via van Kampen [49], not proved). The node SLKnoop has loops s and u

with $s^4 = 1$ and $s^2 = u^3$. Above it lies a family of integer 2 × 2 matrices; s and u act by right multiplication with S and U = ST (F, built with univalence). The ladder steps are exact words: R is s s s u and L is s s s u u. The loop of a ladder word, applied to the identity and to (1, 1), gives its Stern–Brocot pair (vector-pad, vw-adres). So distinct ladder words give distinct loops (H2-knoop). H1 holds because loops are paths. The node of Rung 11 is this node with s•s set to rest (naar11), all in VacuumNetSLNode.

- Proved in Agda: H2 holds in the node of Rung 11 itself. The fibre is the set of integer 2 × 2 matrices with M and −M identified (a set quotient). On it the mirror closes after two turns and the ring after three, so the family G over the node exists. Transport along a ladder word gives the product of its matrices, up to sign (tr-pad11). Starting from the identity, the absolute values of M·(1, 1) ignore the sign and give back the Stern–Brocot pair. So distinct ladder words give distinct loops in the node of Rung 11 (H2-knoop11, VacuumNetPSLNode).
- Argument (on paper): under H1 and H2 no relation beyond the two closures can hold. It uses two known facts about PSL(2, $\mathbb{Z}$): every nontrivial normal subgroup contains a hyperbolic element, and every hyperbolic element is conjugate to a positive R/L word [48].

Back to the whole

Reading: The matrix S, $z \mapsto -1/z$, as a mirror of the net. The mirror of T12.1 is negation, $z \mapsto -z$, which has determinant −1 and lies outside PSL(2, $\mathbb{Z}$). With the ring it gives PGL(2, $\mathbb{Z}$). S is negation followed by inversion. Inversion has a place in the net: mirroring a ladder path, R ↔ L, sends x to 1/x (proved in Agda, spiegel-pad). So S is the mirror of T12.1 applied twice: once to the value (negation) and once to the path (inversion).

H1 and H2 are proved, for SLKnoop and for the node of Rung 11 itself. For the node of Rung 11, any further relation would merge two addresses; that is argued from cited facts, not formalised. What stays open is that the net's node is this minimal node. S is read as the mirror applied to value and path together, and that double reading is not yet proved. That the node is the theory's first knot is still a reading.

Rung 12. Two ladders

Seen

Merging meetings doubles; merging rings triples (T15). The ladders ×2 and ×3 never meet exactly, because $2^n \neq 3^k$ (T16). Their best near-meetings are the closure depths (T17). At depth 12 the miss is the Pythagorean comma (T18) [1].

Diophantine approximation and the theory of tuning (MSC 11J). $\log_2 3$ is irrational. Its continued fraction gives the best approximations [20]. The comma is implied in the Sectio canonis, about 300 BCE, which shows that six whole tones exceed an octave [2].

Reasoned

- Proved in Agda: $2^n = 3^k$ only when n = k = 0 (geen-ontmoeting, VacuumNetComma). The proof is by parity, as in the theory.
- Checked by computation: $\log_2 3 = [1; 1, 1, 2, 2, 3, 1, 5, 2, 23, \ldots]$; convergent denominators 1, 2, 5, 12, 41, 53, 306, 665; the comma $3^{12}/2^{19}$ is 23.46 cents (rungs_checks.py).
- Known theorem: best approximations of the second kind are the convergents [20].

Back to the whole

T16 is formalised. The closure depths (T17) are not yet formalised in Agda.

Rung 13. Into three dimensions

Seen

The theory adds one hypothesis: the strand is embedded in three-dimensional space. Then the trefoil is the simplest configuration that cannot be undone (T19). It differs from its mirror (T20). An attached strand returns after 4π, not 2π (T21). The Hopf charge is conserved (T22) [1].

Part of this needs no space. Take one node with two loops, x and y. Run x twice and y three times. Neither x•x nor y•y•y is set to rest; they are set equal: x•x ≡ y•y•y. The space is built from two loops and one equation. Its homotopy type is that of the complement of the trefoil in S^3 [54]. Close the common loop, and the node of Rung 11 appears. So Rung 11 is this rung with its common loop set to rest.

Knot theory, Lie groups, singularity theory and algebraic topology (MSC 57K10, 22, 32S55, 55). The group of the space is $\langle x, y \mid x^2 = y^3 \rangle$, the trefoil group. The equation $x^2 = y^3$ is also the curve $z^2 = w^3$ in $\mathbb{C}^2$. Its link at the origin is the trefoil, and its complement fibres over the circle (Milnor) [55]. The modular group of Rung 11 is this group divided by its centre, the common loop. The double cover of rotations by unit quaternions gives the 4π return. The Hopf map generates $\pi_3(S^2) \cong \mathbb{Z}$ [23]. In homotopy type theory the Hopf fibration has been constructed, and Brunerie proved $\pi_4(S^3) = \mathbb{Z}/2$ [8].

Reasoned

- Proved in Agda: the space Klaverblad with x•x ≡ y•y•y maps to the node of Rung 11 (naar-knoop), and the common loop x•x becomes trivial there (centrum-weg). It maps to the circle with x as three windings and y as two (vezel); the common loop winds six times (centrum-6), all in VacuumNetTrefoil. On the fundamental group, vezel is the map of the Milnor fibration; vezel itself is a map, not a fibration.
- Known theorem: the 2-complex with group $\langle x, y \mid x^2 = y^3 \rangle$ has the homotopy type of the trefoil complement (Hatcher's mapping cylinders, after collapsing; both spaces are aspherical with the same group) [54]; the trefoil is the link of $z^2 = w^3$ and its complement fibres over the circle [55].
- Known theorem: $\pi_3(S^2) \cong \mathbb{Z}$, generated by the Hopf map; Hopf showed in 1931 that this map cannot be undone [23]. The result is also derived in homotopy type theory [8].
- Known theorem, proved in the cubical library [14] and checked in this environment: $\pi_3(S^2) \cong \mathbb{Z}$ ($\pi_3 S^2 \cong \mathbb{Z}$ in VacuumNetHopf). It goes through the Hopf fibration, whose fibre is the circle of Rung 2. The integer of T22 is this invariant; that it is conserved in physics is the theory's reading.
- Proved in Agda: the tension resolves one level up. Klaverblad maps to SLKnoop (x ↦ s, y ↦ u; naarSL). There s•s does not close: transport of the identity along s•s gives −I (ss-Id, paar-sluit-niet, VacuumNetOpenPair). The open pair carries a sign and closes after four turns (s^4, by definition of the node). It closes after two in the node of Rung 11, where M and −M are identified. So SLKnoop agrees with T7.1 that the open pair does not close; reading −I as its carry is a reading. Rung 11 as the reading in which the sign is forgotten is a reading too.
- Proved in Agda: crosswise, the loop with exponent two (x) carries three windings, and the loop with exponent three (y) carries two (winding-x, winding-y).
- Argument (on paper): vezel is the abelianisation of $\langle x, y \mid x^2 = y^3 \rangle$. The common loop has winding 6, so vezel modulo six factors through $\mathrm{PSL}(2, \mathbb{Z}) = C_2 * C_3$ and gives its abelianisation $\mathbb{Z}_2 \times \mathbb{Z}_3 \cong \mathbb{Z}_6$. (For $\mathrm{SL}(2, \mathbb{Z})$ it would be $\mathbb{Z}_{12}$.)

- Known theorem: the complement of the trefoil and that of its mirror are homeomorphic, by a map that reverses orientation; so the knot group cannot tell them apart [64]. Klaverblad therefore cannot see T20. Chirality needs orientation, which is what the embedding adds.
- Checked by computation: the Kauffman bracket of the three crossings gives the Jones polynomial $t + t^3 - t^4$ for one trefoil and $t^{-1} + t^{-3} - t^{-4}$ for its mirror (jones_trefoil.py) [65, 66]. They differ, so the trefoil is chiral. The writhe ±3 is not computed from an orientation; it is fixed by requiring integral powers of t, which is a consistency check. By the usual convention the first polynomial is the right-handed trefoil.
- Known theorem: the Alexander polynomial $t^2 - t + 1$ is the same for the trefoil and its mirror [64].

Back to the whole

Reading: X•x as the open pair and y•y•y as the ring. The open pair carries (T7.1); here it lands on the same loop as the ring. That this is the carry of T7.1 is a reading. There was a tension with Rung 11: there the order-two loop closes (spiegel²), which T7.1 does not allow for the open pair.

Reading (tested and weakened): the reading that Rung 11 is this rung "within one scale", with the carry dropped. Through the abelian map, dropping the carry (modulo three) leaves $\mathbb{Z}_3$. Then x has winding 3 and becomes nothing, and y becomes L. That is not even $\mathbb{Z}_6$, the abelianisation of the modular group. So this reading loses information that setting the common loop to rest keeps.

Reading, after the test: the two numbers of the theory meet here once, in the exponents 2 and 3, the open pair and the ring. The windings 3 and 2 follow from them (6/2 and 6/3). The common loop is 2·3 = 3·2. Rung 11 sets that common loop to rest. This is a reading, not a derivation.

Reading: Fox's rule of Rung 5 tells the trefoil from the unknot.

Reading: The 4π return of T21 in algebraic form. In SLKnoop, two turns of s give −I and four give the identity; the node of Rung 11 forgets the sign, and there two turns suffice. S acts on the hyperbolic plane as a half-turn [17], so two turns are a full turn there, and lift to −I. This has the shape of SU(2) over SO(3), where a rotation by 2π lifts to −1 and 4π returns. It is a shape match only: the fundamental group of PSL(2, $\mathbb{R}$) is $\mathbb{Z}$, not $\mathbb{Z}_2$ as for SO(3). Proved: s•s ≠ refl in SLKnoop (VacuumNetOpenPair); the shape match is a reading.

A space with the homotopy type of the knot complement comes without a space hypothesis. The knot as a curve in space, its chirality (T20) and the Hopf charge (T22) still need the embedding; the space of this rung cannot see chirality, as shown above. The 4π return (T21) has an algebraic shadow in SLKnoop, as a reading. They are not formalised. The equivalence of Klaverblad with the knot complement is cited, not proved.

Beyond the first knot

The next six rungs come from the coupling part of the Foundations and from the physics that continues them [1]. Each adds a hypothesis that the net does not supply. The hypothesis is named at the start of each chapter. From here on the net no longer grows from itself alone. What grows is still mathematics: each rung meets a field.

Rung 14. Coupling

Seen

Hypothesis: the energy density of the medium is $e(n) = (g_2/2)n^2 + (g_3/6)n^3$. The stiffness is its second derivative. Around a reference density it reads $g_eff = \bar{g}(1 + \gamma\delta)$ (T23) [1]. The stiffness is a function of the state, as N4 asks. The theory also defines the lever of a count: $\gamma = -\bar{n} \cdot \kappa_3/\kappa_2^2$, built from the mean and the second and third cumulants.

Analysis and asymptotics (MSC 26, 41, 60E). This is the first rung with real functions. Derivatives, Taylor expansion and convexity enter. The lever links a smooth energy to the fluctuations of a count. The link is Laplace's method [31].

Precursors. Infinite series for the sine, cosine and arctangent were found in Kerala by Mādhava around 1350, centuries before Newton and Leibniz [71].

Reasoned

- Checked by computation: the identities $g_eff = \bar{g}(1 + \gamma\delta)$ and $g_2 = \bar{g}(1 - \gamma)$, symbolically (upper_checks.py).
- Known theorem: Laplace's method for integrals with a large parameter [31].

Back to the whole

The link between the energy and the cumulants is taken from the theory [1]. It is not derived here, and Laplace's method is cited as the route it would take. The real numbers enter here as an input. The chapters "Beyond Rung 21" and "Beyond Rung 21 (b)" build the places of an interval from the net. Bishop's criterion for the equality of their values is proved on integers. That gives numbers, not functions: real functions, derivatives and Laplace's method are not built from the net. The formal identification with the Cauchy reals of [4] is not done either.

Rung 15. The free path

Seen

Hypothesis: the strand is a free path, a simple random walk on $\mathbb{Z}^d$ with d ≥ 3. A node counts its visits. The number of visits is geometric. Its lever is γ = −(1 + P_d)/P_d, where P_d is the chance to return (T24) [1].

Probability theory (MSC 60G50, 60J10). Pólya proved in 1921 that the walk returns for sure in one and two dimensions, and not for sure from three on [32]. Watson evaluated the triple integrals in closed form [33]. Through later work, including Montroll's, they give the return probability in three dimensions [34].

Reasoned

- Checked by computation: γ = −3.9365, −6.1759 and −8.3976 for d = 3, 4, 5 (upper_checks.py).
- Known theorem: Pólya's recurrence theorem [32]; Watson's integrals [33].

Back to the whole

Whether the lever of the free path is the coupling of the medium is open (IX.1).

Rung 16. Closure on itself

Seen

Hypothesis: Dirac's equation, written in Rowlands' nilpotent form [35, 36]. The operator is Q = ikE + ip + jm. Its square is $(E^2 - p^2 - m^2)$ times one. So $Q^2 = 0$ exactly on the mass shell (Physics T1) [1]. The theory reads this as closure applied to itself: a closure that closes again adds nothing.

Clifford algebras and spinors (MSC 15A66, 81R25); homological algebra (MSC 18G). Quaternions and vector units together form a Clifford algebra [37]. Nilpotence has a central place in one more field. In homological algebra, a boundary of a boundary is nothing: $d \circ d = 0$. All of homology and cohomology rests on that rule [38].

Reasoned

- Checked by computation: $Q^2 = (E^2 - p^2 - m^2) \cdot 1$ as a symbolic 4×4 identity; the boundary of the boundary of a filled triangle is zero (upper_checks.py).
- Known theorem: Dirac's equation and its square [35]; $d \circ d = 0$ as the definition of a chain complex [38].
- Proved in Agda (Rung 7), locally on one window: closure on the trits is $D^2 = 0$, and period three is $D^3 = 0$. Rings of period three form a 3-complex in the sense of Mayer [45–47].

Back to the whole

Reading: $Q^2 = 0$ and $d \circ d = 0$ have the same form.

Rung 7 gives a first answer. On rings, the window sum is D^2, the square of the difference operator, and D^3 is the shift by three minus one. On rings of period three, $D^3 = 0$ but $D^2 \neq 0$. They form a 3-complex. The rings that close everywhere are its kernel of D^2. Such complexes were introduced by Mayer in 1942 [45]. Kapranov and Dubois-Violette developed them as generalised homology with d^N = 0 [46, 47]. On the 27 rings of period three, D is a single block of size three. There ker D^2 = im D and ker D = im D^2: the homology is zero. That D = shift − 1 gives D^3 = shift^3 − 1 over F_3 is Mayer's own mechanism. The trits carry the simplest 3-complex. Whether this adds more than a new name is open. Whether $Q^2 = 0$ of the Dirac rung is the same rule one level up is still a reading.

Rung 17. Two registers

Seen

Hypothesis: Maxwell's equations in his own quaternion form of 1873. Hamilton's operator gives one product with two parts: a scalar part, the convergence, and a vector part, the curl. Gibbs and Heaviside later split the product in two [1]. The theory reads the two parts as two readings of one closure. To keep orientation, a rule must use full quaternions (Physics T2, T3). A ring measure R_Q is the largest eigenvalue of an average of DD^T. It lies between ¼ and 1 and ignores the sign of each D (Physics T4).

Quaternion algebra, rotations and spectral theory (MSC 15A66, 15A18, 20G20). The sign invariance is the double cover of rotations by unit quaternions [39]. The ring measure is the same matrix that is used to average rotations: the mean rotation is the top eigenvector of the summed DD^T [40]. In the language of Clifford analysis, Maxwell's single product ∇A is the operator $d + \delta$ acting on A. The curl is the d part. The convergence is, up to sign, the δ part. That this is the net's one closure read twice is a reading.

Reasoned

- Checked by computation: the worked example gives $D_1 \cdot D_2 = 0.653$ and R_Q = 0.827 (upper_checks.py).
- Known theorem: q and −q give the same rotation [39]; the eigenvector form of the quaternion average [40].

Back to the whole

The theory itself marks this part as a correspondence. Maxwell's equations are translated into the net, not derived from it.

Rung 18. Measure

Seen

The net has no units. Its quantities are ratios. To compare with instruments, the theory follows Larson: space S and time T are two aspects of one motion. The map $\varphi(x, y, z) = (x - 3z, y + 3z)$ sends length, time and mass to powers of S and T (Physics T5) [1, 41]. Speed becomes S/T, energy T/S, mass T^3/S^3. The unit length and time are fixed by hydrogen.

Dimensional analysis as linear algebra over $\mathbb{Z}$ (MSC 00A73, 20K). Dimensions form a free abelian group. A change of units is a homomorphism. The Buckingham π theorem counts the dimensionless groups through the kernel of such a map [42]. Here the kernel of φ is generated by $M{\cdot}L^3/T^3$.

Reasoned

- Checked by computation: the images of speed, energy, momentum and mass, and the kernel (3, −3, 1) (upper_checks.py).
- Known theorem: Buckingham's π theorem [42].

Back to the whole

Reading: Larson's motion as the ground of units.

That the Balmer Hδ line falls at $9S_0$ holds by construction of the unit, as the theory says. It is a consistency, not a test.

Rung 19. Loss has an address

Seen

Hypotheses: local equilibrium per mesh, local balance, and the second law for every sub-volume. Then entropy production is $\sigma = \Sigma\, J \cdot X \geq 0$ at every location (Physics T6) [1]. In the linear regime $J = LX$. Onsager's symmetry of L needs one more hypothesis, microscopic reversibility [43]. With L symmetric, L is positive semidefinite. Every loss happens at a mesh with an address.

Non-equilibrium thermodynamics and matrix theory (MSC 80A, 15B48). Onsager proved the symmetry of L in 1931 [43]. De Groot and Mazur built the field on it [44]. The spectral theorem splits σ into sign-definite parts.

Reasoned

- Checked by computation: $\sigma = X^{T}LX \geq 0$ for 1,000 random positive semidefinite L (upper_checks.py). This is a sanity check of a known fact, not a test of the theory.
- Known theorem: Onsager reciprocity [43].

Back to the whole

All the content of this rung comes from its hypotheses. The net supplies only the address.

Rung 20. Numbers without end

Seen

One addition: words without end. Finite words do not give them; a stream is an infinite object, given coinductively, one digit at a time (see the chapter on infinity). Let a word go on without end: a stream of trits after the point. On the ×3 ladder, with digits −1, 0, 1, this is balanced ternary for real numbers. Cutting is rounding (III.2). Each number has one stream, except at countably many boundary points, where it has two. This is the unique address of T12, carried into the continuum.

That uniqueness has a price. Take x = 0.1TTT… and y = 0.0111…, both 1/6 from either side. However many digits of x and y are read, no digit of their average is fixed. The first digit depends on whether the average lies just above or just below 1/6, and no finite depth decides that. So on the ×3 ladder, adding numbers without end is not computable digit by digit.

On the ×2 ladder the same three digits behave differently. In base 2 with digits −1, 0, 1, almost every number has many streams. That redundancy is what makes addition work: each output digit needs about one more input digit. The continuum, read at finite depth, needs redundancy. The ×2 ladder with the three digits of the net is one way to get it; base 3 with five digits, −2 to 2, is another.

Computable analysis and computer arithmetic (MSC 03F60, 26, 65G, 68). Signed-digit representations were introduced by Avizienis for fast arithmetic [57]. Wiedmer showed that redundant signed digits make arithmetic on infinite expansions computable [58]. Ciaffaglione and Di Gianantonio built the reals from signed-digit streams in a proof assistant, with coinductive types [59]. The homotopy type theory book constructs the Cauchy reals as a higher inductive-inductive type [4].

Precursors. The ×2 ladder with words of two kinds goes back to Piṅgala [67, 69] and to Leibniz (1679), who later saw it in the Yijing [70]. The three digits on it are Avizienis's signed digits [57].

Reasoned

- Proved in Agda: mirroring a trit stream twice gives the same stream, by coinduction (spiegelS²). Defined: trit streams as a coinductive type, the digit-wise mirror (spiegelS) and reading at finite depth n (lees), in VacuumNetStream. The file does not yet link streams to real values.
- Checked by computation: for x = 0.1TTT… and y = 0.0111… in base 3, no digit of the average is fixed after 5, 10, 20 or 40 digits. In base 2 with digits −1, 0, 1, the first L digits of each input always fix at least L − 1 digits of the average: the uncertainty has width 2^(1−L) and a digit is safe while it is at most one half. A test on 3,000 random pairs with L = 25 agrees (continuum.py).
- Known theorem: redundant signed-digit expansions make addition computable with bounded lookahead [58]; signed digits themselves go back to Avizienis [57].
- Proved in Agda: the average of two signed-binary trit streams, with a carry c in {−2, …, 2} as a five-valued type. One step reads two digits and gives one digit e and a new carry, with c′ + 4e = 2c + x + y in all 45 cases (stap-ok). After any finite depth n, c + 4E = T, where E and T are the output and the input sum read as integers (invariant, gemiddelde-klopt). The same step is defined on streams by corecursion (gemS), all in VacuumNetAverage.
- Proved in Agda, in integers: T − 4E is one of −2, …, 2, namely the final carry (foutgrens). The first output digit is always 0 (eerste-O). The stream gemS′ read at depth n is the output list of the finite version (stroom-klopt), and E is the Horner value of that list (E-is-horner). Chaining these three: the stream gemS′ from carry 0, read at any depth n, satisfies T − 4E ∈ {−2, …, 2}.

- Argument (on paper): dividing by $4 \cdot 2^n$, the output at depth n lies within 2^(−n−1) of (x_n + y_n)/4, the value of the digits read, and within 2^(−n) of (x + y)/4. The bound is reached. Dropping the first digit gives the average (x + y)/2 with one digit of lookahead.
- Checked by computation: on 5,000 random pairs of 30 digits, the first output digit is always 0 and the average lies within 2^(−29) of (x + y)/2 (average_check.py).
- Proved in Agda: multiplying a word by one trit is mirroring, zeroing or keeping it, exactly (keer-trit-klopt). Shift-and-add over the digits of y, $P := 2P + y_i \cdot X$, gives exactly X·Y for the integer values X and Y of two words (product-klopt), in VacuumNetProduct.
- Checked by computation: for 1,000 random pairs, the first 24 digits of x and y allow at least 22 digits of x·y to be emitted safely (product_check.py). This is consistent with the bounded delay of the classical on-line multiplier [61]. The exact product of two n-digit prefixes has denominator 2^(2n); that no bounded state suffices follows from Muller [60] (next bullet).
- Known theorem (Muller): take radix r and signed digits $-\alpha, \ldots, \eta$ with $0 < \eta \leq r - 1$. Let a finite automaton compute a function on-line, most significant digit first. If the function has a piecewise continuous second derivative, it is piecewise affine with rational coefficients [60]. Addition and the average are affine; the five-state carry above is such an automaton. The product x·y is not affine. A multiplier therefore needs memory that grows with the depth [60, 61].
- Known theorem: with unique digit expansions, addition is not computable on streams, since an output digit can depend on the whole input. Redundant signed digits remove this [58, 90].

Back to the whole

Reading: With the three digits of the net, the two ladders of Rung 12 take different roles. The ×3 ladder names; the ×2 ladder computes.

The average is proved at every finite depth. The link between stream and finite version is proved. The integer values of the prefixes of a stream are formalised in VacuumNetValue and VacuumNetValue2. Bishop's criterion for the equality of two places is formalised in VacuumNetBishop and VacuumNetBishop2 (chapters "Beyond Rung 21" and "Beyond Rung 21 (b)"). That these values form Bishop-regular sequences in the rationals is proved in VacuumNetReal and VacuumNetRealEq (chapter "Beyond Rung 21 (b)"). Not formalised: their identification with the Cauchy reals of [4]. Multiplication is formalised only as exact integer arithmetic on prefixes; the digit stream of the product, with its growing state, is not. The field laws are not formalised. Here a real boundary appears. One step with a bounded carry gives at most the piecewise affine operations with rational coefficients, and not the product. Any finite-state reading, most or least significant digit first, has this limit [60]. T1 does not bound the carry: (s − d)/3 grows with the sum. So the limit belongs to finite-state reading, not to the net's rule. Whether the net itself prefers the ×2 ladder for the continuum, or only allows it, is open.

Rung 21. Closure as oscillation

Seen

One choice. A closed window has sum 0 modulo three (T2); over the integers its sum is −3, 0 or 3. Take, as a choice, the windows whose integer sum is exactly 0: a + b + c = 0. Write the second difference, (c − b) − (b − a). Then a + b + c = 0 says exactly that the second difference is −3 times the middle value. That is the discrete harmonic oscillator, y″ = −k·y with k = 3, exactly and with step one, not as a small-step approximation. A word whose windows all have integer sum 0 is a discrete circular motion with period three.

The oscillator t(i+1) = c·t(i) − t(i−1) is periodic over the integers for every start only for c = −1, 0, 1, with periods 3, 4 and 6. For c = 2 the motion is free (linear growth), for c = −2 it grows with alternating sign, and for |c| > 2 it grows faster; special starts can still repeat. The closure of the net is the first of the three: c = −1.

Difference equations and ordinary differential equations (MSC 39A, 34A); crystallography (MSC 20H15). The equation y″ = −y is the limit of the discrete oscillator as the step goes to zero [62]. Over the integers only rotations of order 1, 2, 3, 4 and 6 are possible: the crystallographic restriction [63]. The same orders are the orders of the elements of finite order in SL(2, $\mathbb{Z}$). There S has order 4 and ST order 6 (Rung 11).

Reasoned

- Proved in Agda: a + b + c = 0 exactly when (c − b) − (b − a) + 3b = 0, over $\mathbb{Z}$ (sluiten⇒trilling, trilling⇒sluiten). The step matrices [[c, −1], [1, 0]] for c = −1, 0, 1 have order 3, 4 and 6 (periode-3, periode-4, periode-6), all in VacuumNetOscillator.
- Checked by computation: from start (0, 1), the integer recurrence is periodic for c = −1, 0, 1 only (c from −3 to 3). With real step h and c = 2 − h^2, the orbit follows cos(iθ) to within 10^{-12} and the period tends to 2π/h (oscillator_check.py).
- Known theorem: an integer 2 × 2 matrix of finite order has order 1, 2, 3, 4 or 6 [63].

Back to the whole

Reading: The closure of the net is the discrete form of circular motion. This fits the theory's reading that the closed loop carries the motion that is light. It is a reading, not a derivation of physics.

The limit to y″ = −y needs real numbers (Rung 20) and is only computed here, not proved. General linear ordinary differential equations are not reached. The link between the period three of closure and the orders four and six of Rung 11 is a reading.

Beyond Rung 21. The continuum on the round

Seen

The round of Rung 0 has a direction and a count of turns. The question here is whether it also has places between: a continuous phase. Merging gives two ladders, ×2 and ×3 (T15). Seen on one round, with a turn of the ×2 ladder as the unit, each ×3 step moves $\log_2 3$ of a turn. A place is reached by a descent through the scales: at each scale one trit, and what is left goes on to the next scale (N5, T1). Two descents are the same place when their difference, carried scale by scale, stays in the window for ever. A place within one turn can be written as a trit stream, a balanced-ternary fraction of a turn. An oscillation is a movement that repeats a finite block of directions. A rotation closes when, after some number of steps, it is back where it began.

Homotopy type theory, dynamical systems and number theory (MSC 03, 37, 11). In the circle S^1 the paths from the point to itself are whole turns only: $\Omega S^1 \simeq \mathbb{Z}$ [5]. Half a turn is not a loop. The continuous circle, the real numbers modulo one, is a different object: a set of points. Shulman added a shape modality to homotopy type theory and proved that the shape of the continuous circle is S^1 [84]. In that sense the round is what is left of the continuous circle when only movement up to deformation is kept.

Precursors. Kauffman's eigenforms are fixed points of a self-referring operation [82]. Brouwer's free choice sequences are infinite sequences that follow no law [85].

Reasoned

- Proved in Agda: an oscillation is a fixed point of "put the block in front": per ≡ ervoor (a ∷ as) per (eigenvorm, VacuumNetPhase). Standing still is the oscillation with block 0 (stil-is-trilling).
- Checked by computation: a block W of length n gives the phase W/(3^n − 1), for all 1092 blocks up to length 6. Such phases have denominators prime to 3. The closing rotations of Rung 21 are a finite prefix followed by an oscillation: 1/4 = 0.(1T); 1/3 = 0.1000…; 1/6 = 0.0111… (phase_check.py).
- Known theorem: a number has an eventually periodic expansion in base three exactly when it is rational. A rotation by α closes after n steps exactly when nα is a whole number.
- Proved in Agda: the ladders ×2 and ×3 never meet exactly, $2^n = 3^k$ only for n = k = 0 (T16; geen-ontmoeting, VacuumNetComma). Hence $\log_2 3$ is irrational: if it were p/q, then 3^q = 2^p.
- Checked by computation: stepping the round by one ×3 step, measured in turns of the ×2 ladder ($\log_2 3$ of a turn), gives 5001 different phases (k = 0 to 5000). The largest gap between them shrinks to 0.0011 of a turn, and at 12, 53, 665 and 5000 points there are at most three gap lengths. The nearest returns come at the closure depths 1, 2, 5, 12, 41, 53, 306, 665 (comma_orbit.py).
- Known theorem: the multiples of an irrational step are dense on the round (Kronecker) [86]; they leave at most three gap lengths (the three-distance theorem) [87].
- Proved in Agda: the carried difference of two descents moves as r → 3r + (a − b). A run that stays in the window [−2, 2] for ever never reaches ±2; its rest stays in [−1, 1] (venster-p2, venster-m2, klein, VacuumNetLimit). "Same place" is an equivalence relation (≈-refl, ≈-sym, ≈-trans). The places of one turn form the set quotient Fase = Stroom / ≈. The descents 0.1TTT… and 0.0111… differ in their first trit, yet they are one place (twee-afdalingen-één-plek).

- Checked by computation: 6560 numbers with two different expansions all stay in the window. 3000 pairs of different numbers all leave it, within two scales of $\log_3(1/|x - y|)$ (limit_check.py).
- Known theorem: classically, signed-digit streams up to equal value are exactly the points of the interval [−1/2, 1/2] [58, 59].
- Proved in Agda: let V n s be the first n trits of s read as a whole number. After n steps the rest is $3^n \cdot r + (V\ n\ s - V\ n\ t)$ (rest-is-V, VacuumNetValue). So the same place gives $|V\ n\ s - V\ n\ t| \le 1$ at every scale, and $|V\ n\ s - V\ n\ t| \le 2$ at every scale gives the same place (≈→begrensd, begrensd→≈). On the ×2 ladder the same holds with the bounds 2 and 4 (VacuumNetValue2).
- Known theorem: a real number in Bishop's sense is a sequence of rationals q_n with $|q_n - q_m|$ bounded by a fixed modulus. Two such sequences are equal when their distance tends to zero with that modulus [88].
- Argument (on paper): the sequence $V\ n\ s / 3^n$ is of this kind. The tail bound $|V\ m\ t| \le (3^m - 1)/2$ gives $|V\ n\ s / 3^n - V\ m\ s / 3^m| < 1/(2 \cdot 3^m)$ for $m \le n$. So the value of a place is a Bishop real number.
- Proved in Agda: bounded difference of the truncated values is the same place (≈→begrensd, begrensd→≈ in VacuumNetValue). "Same place" is also Bishop's criterion on these integer values. The distance of $V\ n\ s / 3^n$ and $V\ n\ t / 3^n$ goes to zero (≈→bishop, bishop→≈ in VacuumNetBishop; chapter "Beyond Rung 21 (b)").
- Argument (on paper) and computation: if s and s′ are the same place, then $|V\ n\ s \cdot V\ n\ t - V\ n\ s' \cdot V\ n\ t| \le 3^n/2$. So the product sequences $V\ n\ s \cdot V\ n\ t / 9^n$ are equal in Bishop's sense. The product is an operation on values (product_value_check.py, 4000 pairs). As an operation on streams it needs memory that grows with depth [60]; a finite window of rests cannot carry it.
- Argument (on paper): suppose every real number in [−1/2, 1/2] had a ×3 place. Its first trit decides $x \le 1/6$ or $x \ge 1/6$. Applied to $x = 1/6 + \max(-1/3, \min(1/3, y))$, this decides $y \le 0$ or $y \ge 0$ for every real y. That is the principle LLPO [89], which constructive mathematics does not prove. Signed-digit places, as on the ×2 ladder, are admissible: every computable real has one, computed from it [90].
- Proved in Agda: on the ×2 ladder with trits the same construction works, with the rest moving as $r \to 2r + (a - b)$. "Same place" is again an equivalence relation, and an endless run stays in [−2, 2] ($\approx_2$-refl, $\approx_2$-sym, $\approx_2$-trans, klein, VacuumNetArith). The average of Rung 20 respects "same place" in each argument (gem-l, gem-r). So it is an operation on the places themselves (gemF on Fase_2). The mirror respects "same place" on both ladders, and mirroring twice is the identity on places (spiegelF_2, spiegelF_3, spiegelF_3^2).
- Checked by computation: on the ×3 ladder the first digit of a sum can depend on a digit arbitrarily far down. For $x = 0.0(1^n)1$ and $y = 0.0(0^n)e$, the first digit of x + y is 0 for e = 0 and 1 for e = 1, for every n up to 30. On the ×2 ladder, 2000 random averages agree with (x + y)/2 to within 2^{-38} (base3_add_check.py).
- Known theorem: a signed-digit system in radix r is redundant only when it has more than r digits [57]. Three digits are redundant in radix 2, not in radix 3; in radix 3 two expansions exist only at special points such as 0.0111… = 0.1TTT…, and those points are what block computation. Redundancy is needed for digit-by-digit arithmetic with bounded lookahead [58].

Back to the whole

Reading: A finite prefix followed by an oscillation gives exactly the rational phases, and these are the phases of the closing rotations. They lie dense on the round but are countable.

Reading: Classically the ×3 places are all real numbers of their interval. Constructively they can be so only if LLPO holds; LLPO with countable choice is enough. The ×2 places need no omniscience principle for reals given as Bishop sequences; for the Cauchy quotient, countable choice is used. The ladders divide the work again: ×3 for addresses, ×2 for computing and for the full continuum.

Reading: The two ladders divide the work. The ×3 ladder gives nearly unique addresses and places (two only at special points, identified by ≈). The ×2 ladder, with the same three digits, gives computation.

Reading: The limit step is a path. A set quotient adds an identification, a path, between any two descents that end at the same place. So the continuum of one turn is made of descents and of the movement between descents that meet. This fits the start of the book: movement first.

Reading: The net has its own movement that never closes. What does not close at one scale goes on as tension (N2), as material for the next scale (N5), or as a carry (T1). Read with T16, and under the hypothesis of T15, this descent would never end and never repeat. The whole closes (N1); its parts need not.

From closing alone, with a finite prefix, the net gives the rational phases. Its own movement that never closes gives, classically, every phase as a limit. Constructively that needs LLPO (see the Reading above). The limit step is built from the net: places are descents, identified when their carried difference stays in the window. Their equality is Bishop's criterion on the integer values, proved on the natural numbers and integers (VacuumNetBishop, VacuumNetBishop2). That the values are Bishop real numbers is argued on paper. The average and the mirror act on places; the product acts on values. Three things are left. First, the identification with the Cauchy reals of [4] is not formalised; constructively it needs countable choice [4, 88]. Second, the conversion from ×3 to ×2 places is argued on paper and computed (chapter "Beyond Rung 21 (c)"), not proved in Agda. Third, a stream product with finite memory is impossible [60]; that is a result, not a gap. Shulman's modality remains another route [84].

The author asks whether the comma keeps the round going. The mathematics gives something close to it. If the two ladders met exactly, their joint movement would repeat. Because of the comma it never repeats, and it comes as close as one likes to every phase.

Beyond Rung 21 (b). Same place and Bishop's criterion

Seen

A place is a descent through the scales. At each scale there is one trit, and the rest goes on to the next scale. Two descents are the same place when the rest they carry stays in the window for ever. The chapter "Beyond Rung 21" showed that this is the same as a bounded difference of the truncated values.

This chapter asks for more. In constructive analysis two approximations are equal when their distance goes to zero. The question is whether "same place" is the same as that.

Constructive analysis (MSC 03F60, 26E40). In Bishop's analysis a real number is a sequence of rationals with a modulus of convergence. Two such sequences are equal when their distance tends to zero [88]. Here the sequence is V n s / 3^n, and on the ×2 ladder V n s / 2^n. Signed-digit streams give such sequences [57, 59].

Reasoned

- Proved in Agda: on the ×3 ladder, "same place" is equivalent to Bishop's criterion on the integer values. BishopEq s t says this: for every k there is an N such that, for all n ≥ N, |V n s − V n t|·3^k ≤ 3^n. The two directions are ≈→bishop and bishop→≈ (VacuumNetBishop). Everything is in the natural numbers and the integers. The files define no rational numbers, no Bishop sequences and no real numbers.
- Proved in Agda: the same on the ×2 ladder, with 2^n, for the own notion of "same place" of that ladder (VacuumNetBishop2).
- Proved in Agda: the key step is a growth lemma (grow+). Suppose the difference V m s − V m t is at least 3 at some scale m. That is outside the window. Then at scale m + j it is at least 1 + 2·3^j. So the bound roughly triples at every scale. This contradicts Bishop's criterion at k = m. On the ×2 ladder the bound is 5 and the growth is 2 + 3·2^j.
- Proved in Agda: the converse. If the places are the same, the difference is at most 1 at every scale (≈→begrensd in VacuumNetValue). On the ×2 ladder it is at most 2 (VacuumNetValue2). So the criterion holds with N = k, and with N = k + 1 on the ×2 ladder (≈→bishop in VacuumNetBishop and VacuumNetBishop2).
- Known theorem: a real number in Bishop's sense is a sequence of rationals with a modulus of convergence. Two such sequences are equal when their distance tends to zero [88].
- Argument (on paper): the sequence V n s / 3^n has a modulus of convergence. The tail bound |V m t| ≤ (3^m − 1)/2 gives |V n s / 3^n − V m s / 3^m| < 1/(2·3^m) for m ≤ n. So the value of a place is a Bishop real number. By the criterion above, "same place" then means "same real number" in Bishop's sense.
- Proved in Agda: the tail bound in integers. V (m + k) s = 3^k · V m s + V k t, where t is s without its first m digits (V-som). So 2·|V (m + k) s − 3^k · V m s| ≤ 3^k − 1 (staart-grens, VacuumNetTail). Dividing by 3^(m+k) gives the bound above. That division is made in Agda in VacuumNetReal.
- Proved in Agda: the value is a Bishop real number, in the rationals of the library. Put x s n = V n s / 3^n and e k = 1/(2·3^k). Then |x s m − x s n| ≤ e m + e n for all m and n (regulier). Two places s and t are the same exactly when |x s k − x t k| ≤ 1/3^k for all k (≈→gelijk, gelijk→≈). Each step is reduced to an inequality between integers over one common denominator. All in VacuumNetReal. The modulus is 1/(2·3^k), not Bishop's 1/k; the two are equivalent after reindexing, and that step is on paper.

- Proved in Agda: equality in the form “the difference goes to zero” is an equivalence relation, and two places are the same exactly when their sequences are equal in that form. So the map from places to the regular sequences, divided by this equality, is injective (naar-reëel$_2$-inj, VacuumNetRealEq). For regular sequences this equality agrees with Bishop’s; that step is on paper.

Back to the whole

Reading: The set of places is the set of reals of the interval that have a ×3 address, as Bishop sequences up to Bishop equality. It is a set of sequences. It is not yet the type of Cauchy reals of [4].

Not formalised: that the equality of VacuumNetRealEq agrees with Bishop’s for regular sequences (on paper), that every real of the interval is a place, and the identification with the Cauchy reals of [4]. The library cubical v0.9 does not contain the Cauchy reals. Constructively the second needs countable choice [4, 88]. That every real of the interval has a ×3 place is a reading in the chapter “Beyond Rung 21”: it needs LLPO.

Beyond Rung 21 (c). Functions on places

Seen

A function on places must give the same answer for two descents that are the same place. If it does, it is a function on the set of places, Fase. The simplest candidates are the digit operations: mirror a digit, put a digit in front, take the first digit off.

Quotients and the functions out of them (MSC 03E, 18A, 54A). A function out of a set quotient is a function on representatives that respects the relation. This is the defining property of the set quotient in homotopy type theory [4].

Reasoned

- Proved in Agda: a function on streams has a modulus if the first m(n) input digits fix the first n output digits. The identity, constants and composition have one; the mirror has modulus n, a digit in front n − 1, and the shift n + 1. So the shift is continuous on streams, but it does not respect “same place” (VacuumNetModulus).
- Proved in Agda: for every stream s and every n, $2 \cdot |V\ n\ s| \le 3^n - 1$ (L1, VacuumNetCount).
- Proved in Agda: the property Resp f, “f respects same place”. The identity, composition, constants and the mirror have it (Resp-id, Resp-comp, Resp-const, Resp-spiegel in the module Derde of VacuumNetFunctions, for the ×3 ladder). A function with the property gives a function on Fase, [s] ↦ [f s] (induce). Composition is respected (induce-comp).
- Proved in Agda: putting a digit in front respects “same place” (Resp-voor, module Derde). On values this is x ↦ (x + d)/3. The same holds on the ×2 ladder ($Resp_2$-voor, module Tweede).
- Proved in Agda: if two streams are the same place and have the same first digit, their tails are the same place (staart-resp, module Derde).
- Proved in Agda: taking the first digit off does not respect “same place” (staart-not-Resp, module Derde). The streams 0.1TTT… and 0.0111… are the same place, both 1/6 (a and b in VacuumNetLimit). Their tails are TTT… and 111…, with the values −1/2 and 1/2. These are two different places (¬alL≈alR, by the difference of the values at depth 2). On the ×2 ladder the same happens. The streams 0.1TTT… and 0.000… are both 0. Their tails TTT… and 000… are not the same place (staart-not-$Resp_2$, module Tweede). Not proved: that no map on Fase has [s] ↦ [staart s]. That needs the quotient to be effective, which the files do not show.
- Argument (on paper): on the ×3 ladder the shift separates only the two ends of the interval. Suppose two streams with different first digits are the same place. Their tails then differ in value by exactly 1. A tail has a value in [−1/2, 1/2]. So the tails have the values −1/2 and 1/2. They are TTT… and 111…. If the two ends are glued, the shift is a function. It is the map x ↦ 3x mod 1 on the circle.
- Proved in Agda: the step above, without values. A rest +1 or −1 that never leaves the window fixes both streams: they are TTT… and 111… (p1-uniek, m1-uniek). So if s and t are the same place and their first digits differ, their tails are TTT… and 111…, in one order or the other (staart-verschil). Glue the two ends: Kring is the set of streams (not of places) up to “same place” or “one is TTT… and the other 111…”. Then [s] ↦ [staart s] is a function on Kring (schuif), and every place is a point of Kring (naar-kring). All in VacuumNetCircle. Proved in Agda: Kring is equivalent to the set of places with the two ends glued (Kring≃KringF, VacuumNetCircleFase). Kring is a set and the round S^1 of Rung 0 is not, so they are not equivalent (¬Kring≃S^1). The circle here is a set of points, not the homotopy type of Rung 0. Not proved: that Kring is $\mathbb{R}/\mathbb{Z}$ as a set (constructively that may need countable choice), and that schuif is x ↦ 3x mod 1 on it.

- Known theorem: on the circle the map x ↦ kx mod 1 is a standard expanding map. The full shift on k symbols is its symbolic model, up to a countable set of ambiguous points [91].
- Argument (on paper): a conversion from ×3 to ×2 digits that keeps the place. Write A_i for the value V i s of the first i input digits. Write B_j for the value V j c of the first j output digits. Put $Q_j(i) = 2^j \cdot A_i - 3^i \cdot B_j$. Let n be the least number with $3^n \geq 2^{j+1}$. It depends on j only. Put $N = 3^n$ and $P = 2^j$. The output digit e is +1 if $4 \cdot Q_j(n) \geq N$, −1 if $4 \cdot Q_j(n) \leq -N$, and 0 otherwise. Then $B_{j+1} = 2 \cdot B_j + e$. The digit depends on a finite prefix of the input.
- Argument (on paper): the invariant is $2 \cdot |Q_j(i)| \leq 2 \cdot 3^i + 2^j$ for all i. It holds for j = 0, because $B_0 = 0$, $Q_0(i) = A_i$ and $|A_i| \leq (3^i - 1)/2$. An invariant stated only at depth n is not inductive. It must hold for all i.
- Argument (on paper): the step from j to j + 1. Let d be the next input digit. Then $Q_j(i + 1) = 3 \cdot Q_j(i) + P \cdot d$ and $Q_{j+1}(i) = 2 \cdot Q_j(i) - 3^i \cdot e$. Put $q = Q_j(n)$. Then $N \geq 2P$. The bound on the tail of the input gives, for $i \geq n$, $|Q_j(i) - 3\text{^}(i-n) \cdot q| \leq P \cdot (3\text{^}(i-n) - 1)/2$. For $i < n$ it gives $|3\text{^}(n-i) \cdot Q_j(i) - q| \leq P \cdot (3\text{^}(n-i) - 1)/2$. To show: $|2 \cdot Q_j(i) - 3^i \cdot e| \leq 3^i + P$ for all i.
- Argument (on paper): the case e = 0. Then $|4q| < N$. For $i \geq n$: $2 \cdot |Q_j(i)| < 3^i/2 + P \cdot 3\text{^}(i-n) - P$. This is at most $3^i + P$, since $2P \leq N$. For $i < n$: $2 \cdot |Q_j(i)| < 3^i/2 + P$. So the bound holds.
- Argument (on paper): the case e = +1. Then $4q \geq N$. The upper bound $2 \cdot Q_j(i) \leq 2 \cdot 3^i + P$ is the invariant for j. The lower bound is $2 \cdot Q_j(i) \geq -P$. For $i \geq n$: $Q_j(i) \geq 3\text{^}(i-n) \cdot (N/4 - P/2) + P/2 \geq P/2$. For $i < n$: $Q_j(i) > 3^i/4 - P/2$. The case e = −1 is the mirror image.
- Argument (on paper): the output keeps the value. Divide the invariant by 3^i and let i go to infinity. This gives $|2^j \cdot x - B_j| \leq 1$, where x is the value of the input place. So the output has the value x.
- Proved in Agda: a conversion by rounding. Let n(j) be the least n with $3^n \geq 2^{j+1}$. Let B(s, j) be the integer nearest to $2^j \cdot V(n(j), s) / 3\text{^}n(j)$. The output digit e_j = B(s, j+1) − 2·B(s, j) lies in {−1, 0, 1}, so the output is a stream of ×2 digits (VacuumNetConvert, dstep). Its value at depth j is B(s, j) (convert-V). It keeps the value to within the rounding error: $2 \cdot |2^j \cdot V(n(j), s) - 3\text{^}n(j) \cdot V(j, \text{convert } s)| \leq 3\text{^}n(j)$ (convert-waarde). If s and t are the same place on the ×3 ladder, then convert s and convert t are the same place on the ×2 ladder (convert-resp). The proof needs no invariant over all i. The rounding is by division with remainder (VacuumNetRondaf). The integer inequalities are checked by explicit slack certificates and the ring solver. Not proved: that the value of convert s, as a real number, is the value of s. That needs the real numbers.
- Argument (on paper): the greedy conversion respects “same place”. Let s and t be the same place. By ≈→begrensd the input values differ by at most 1 at every depth. The invariant for s and for t gives $3^i \cdot |\Delta B_j| \leq 2^j \cdot |\Delta A_i| + 2 \cdot 3^i + 2^j$. At i = n this is $|\Delta B_j| \leq 2 + 2^{j+1}/3^n$. Now $3^n \geq 2^{j+1}$, and 3^n is odd. So $3^n > 2^{j+1}$, and $|\Delta B_j| \leq 2$ for every j. The lemma begrensd→≈ of VacuumNetValue2 accepts differences up to 4. The window of the ×2 ladder is [−4, 4]. The range [−2, 2] is only that of an endless run. So the lemma applies directly. The two outputs are the same place.
- Checked by computation (w1_check.py): 5970 streams, no violation of the invariant. 3002 pairs of streams that are the same place: the largest difference of the output values was 1.

Back to the whole

Reading: The maps of the net that change the scale and are functions on places go inwards. Putting a digit in front contracts by the factor 3, or 2. The way back, taking a digit off, is a correspondence and not a function. This fits the start of the book. One can go to finer scales without a choice. To come back one must choose between the two names of a point.

The greedy conversion argued above is not in Agda. A different conversion, by rounding, is (VacuumNetConvert). Continuity is defined on streams (VacuumNetModulus), not on places. Its link with “same place” is not proved. Function spaces, norms and a topology on Fase are not built. The

average (VacuumNetArith) is a function on places in each argument. The product is not a function on streams with bounded memory [60].

Beyond Rung 21 (d). Counting: which ladder measures

Seen

Count the words of depth n by the value they give. On the ×3 ladder each whole number in the window has one word of depth n. So the cells of depth n are of equal size. On the ×2 ladder many words give the same value. That ladder is redundant, and its cells are not of equal size.

Combinatorics and measure (MSC 11A63, 28A). Balanced ternary is the representation of the integers with the digits −1, 0, 1 [13]. Lebesgue measure on an interval is the limit of the uniform measure on cells of width 3^{-n}.

Reasoned

- Known theorem: with n digits from {−1, 0, 1}, each whole number from $-(3^n - 1)/2$ to $(3^n - 1)/2$ is represented exactly once [13]. So the 3^n words of depth n on the ×3 ladder correspond one to one to the integer window. The cells have width 3^{-n}.
- Proved in Agda: the same, for every depth n. Put $H\ n = (3^n - 1)/2$. Then $3^n = 2 \cdot H\ n + 1$ (pow3-H). If $3x + a = 3y + b$ with digits a, b, then $a = b$ and $x = y$ (cijfer-eenduidig). So $V\ n\ s = V\ n\ t$ gives the same first n digits (V-inj, V-inj-lees), and the converse holds (V-prefix). $V\ n\ s$ lies in the window $[-H\ n, H\ n]$ (V-in-venster). Every integer of the window is $V\ n\ s$ for some stream (venster→V). All in VacuumNetWindow.
- Checked by computation (measure_check.py): at depth 8 the ×3 words give 6561 different values for 6561 words. The four quarters of the interval hold 0.2500, 0.2500, 0.2501 and 0.2500 of the words. On the ×2 ladder at depth 12, 531441 words give only 8191 different values. The four quarters hold 0.1667, 0.3333, 0.3333 and 0.1667 of the words.
- Argument (on paper): the uniform digit measure on the ×3 words gives every cell of depth n the mass 3^{-n}, which is its width. So in the limit it is Lebesgue measure on the interval. The same digit measure on the ×2 words does not: at depth 12 its quarters hold 0.1667, 0.3333, 0.3333 and 0.1667 of the words (computed above).

Back to the whole

Reading: The ×3 ladder measures and the ×2 ladder computes. The average respects “same place” on the ×2 ladder, and the mirror on both. So the ladders divide the work: ×3 for addresses and measure, ×2 for computation. This sharpens the reading in the chapter “Beyond Rung 21”.

The count at every depth is in Agda (VacuumNetWindow). It is stated as a one-to-one map onto the window, not as a count with finite types. The cell width 3^{-n} is not a number in the files. The limit measure, integration, the space L^2 and Fourier analysis are not reached. Table 4 gives the obstacles.

Beyond Rung 21 (e). Two suns: the double cover of the round

Seen

The round of Rung 0 is one point and one movement. A cover of the round puts a set over every point. The question here is what happens to that set after one passage over a spot. It may come back as it was, or it may come back changed.

Covering spaces in homotopy type theory (MSC 55R10, 57M10). A family of sets over the circle S^1 is a covering. The nontrivial double cover has a set of two elements over the point, and the loop swaps them [4, 5]. Jaina astronomy has a doctrine of two suns [94, 95].

Reasoned

- Proved in Agda: the double cover Zonnen of S^1. Over the point lie two suns, Bhārata and Airāvata (the names as in [94]). One passage over a spot (the loop) swaps them (tweede-verschijning). Two passages bring each sun back (derde-verschijning, twee-rondes-terug). One passage never returns a sun to itself (één-ronde-anders). All in VacuumNetTwoSuns.
- Proved in Agda: no single sun can be chosen at every spot of the round, varying continuously with the spot (geen-keuze: Zonnen has no section). The proof is by transport. There are no postulates.

Back to the whole

Reading: Lishk [94] reports the Jaina doctrine like this. One sun cannot go round and appear again the next morning, since it still has three of four quarters to travel. So there are two suns, half an orbit apart. The primary text [95] was not read for this book. The double cover models the consequence. The second appearance at a spot belongs to the other sun, and the third to the first. The book does not claim that the doctrine says more than this.

Reading: Without proof, the second assumption of the book (the choice of one base of a conjugate pair, Rung 10) has the same shape. A pair is a fibre of two points. Choosing one point is a section. The double cover says that a section over the whole round does not exist. So the choice may be local and not a law. The monodromy of the conjugate pair is not computed.

Not modelled: the half-orbit offset as a deck transformation, the four quarters, real time, Mount Meru and the two moons. The file models only what is stated above.

Beyond Rung 21 (f). Nets as objects of a topos: what is known, what is proved, what is open

Seen

Question: can the net be read as an object of an ∞-topos, with the places Fase as its discrete part and the real line as its shape? This chapter collects what is known and states exactly what the Agda files prove. It builds no topos.

The rest rule on a ring of trits is r(t)_i = −(t_(i−1) + t_(i+1)) over F3. Its nilpotent part exists when 4 divides the length n. Its dimension is 2·3^v and its index is 3^v for a power 3^v fixed by n (computed, n = 3 to 48).

Semantics. Shulman [95] shows that every Grothendieck (∞,1)-topos models Book homotopy type theory with strict univalent universes. The caveats are his: ZFC with inaccessible cardinals, an initiality principle, and an interpretation only. Orton and Pitts [96] model cubical type theory in toposes that carry an interval-like object. That is not every ∞-topos. So a proof in Cubical Agda is not automatically valid in every ∞-topos. Transfer needs a check per file that the file is expressible in Book HoTT. This check is not done.

Cohesion. Shulman [84] adds modalities to HoTT. In real-cohesive HoTT the shape of the topological circle is the higher inductive circle. Myers [97] treats such modalities in a framework for fibrations. Schreiber [9] gives cohesive ∞-topoi.

Reasoned

- Proved in Agda: seam and diagonal. Two closed windows of two trits are glued at a seam when the closing test of Rung 8 passes on both sides. The seam closes exactly when the two windows are equal (naad-gelijk, naad-refl in VacuumNetNaadGelijk). The obstruction to gluing is therefore a boundary difference only. This weakens the reading “seam tension is cohomology” at this level. No sheaf cohomology is built.
- Proved in Agda: the nilpotent shell, index 1. On rings of every length the rest rule has kernel equal to the shell, the zero set of x^2+1, where t(i+2) = −t(i) (VacuumNetRestKern). For the ring of four trits the same is proved in VacuumNetRestRing. The index 3^v is computed in Python only.
- Proved in Agda: the rest rule with step k, written Rk, satisfies Rk three times = Rk of 3k, for every integer k (macht3). Hence the 3^v-th power of the rule with step 1 equals Rk with step 3^v (Pmacht). Rk is zero exactly on the shell f(i+k+k) = −f(i) at scale k (VacuumNetRestIndex). This is the Frobenius identity $(x^2+1)^3 = x^6+1$ in characteristic 3. Not proved: that the generalised kernel of the rule on a ring of a given length is the kernel of its 3^v-th power.
- Argument (on paper): Rowlands’ words with their product form a finite group, of order 2^(n+1) at length n. A finite non-trivial group has no injective homomorphism into the integers, which have no torsion. So no injective map from these words to the integer values of places can respect the product. A map that respects the product must be found among finite quotients or in a different place structure. This is an obstruction, not a map.
- Computed: the count of rings that come to rest follows the formula 3^(2·3^v)·F − F, with F as in the Python check rest_rule.py, for n = 3 to 48.

Back to the whole

Reading: The link between this nilpotent rule and Rowlands’ $Q^2 = 0$ is a reading (C3 of the Ninth Edition). Rowlands and Diaz use binary words and a carry-free product. The net uses places and

carry. A set-level bijection of their words with places on the ×2 ladder holds for n = 1 to 6 (checked). Their product is not the net's.

Open: a value map from Fase to the Dedekind reals in real-cohesive HoTT. Open: a shape modality for the net, since the net has no cohesive structure yet. Open: cohomology of seams beyond the diagonal lemma. Open: transfer of the Cubical Agda files to Book HoTT. Open: an independent check by a person.

How much infinity the ladder needs

Reverse mathematics measures how strong the axioms behind a theorem must be [50]. It gives an order that has nothing to do with the net. If the order of the rungs matches the order of strength, that is convergence from an independent side.

Table 2 gives an estimate per group of rungs. It is an estimate from the kind of statement, not a reverse-mathematics proof. The Agda proofs themselves run in a much stronger theory; the table concerns what the statements need.

Rungs	What the statements are about	Estimated system	Basis
0–4	Finite types, $\mathbb{Z}_3$, words, $\mathbb{Z}$ as windings	EFA	Finite checks and integer arithmetic
5	Windows; lines of F_3^n; cap set bound	EFA (expected)	Arithmetical statement; elementary polynomial method; formalised in Lean [53]
6–10	$\mathbb{Z}_3$ with mirror; circulants over F_3; seams; necklaces; $\mathbb{Z}[\omega]$	EFA	Linear algebra over finite fields and counting
11	PSL(2, $\mathbb{Z}$), braids, normal forms	EFA	Finitely presented groups, words
12	$2^n \neq 3^k$, convergents, comma; $\log_2 3$ itself	EFA; RCA_0 for $\log_2 3$	Convergents are integer arithmetic; $\log_2 3$ is a real number
13	Trefoil group; SU(2), 4π; $\pi_3(S^2) \cong \mathbb{Z}$	EFA for the group; RCA_0 for SU(2); RCA_0–WKL_0 for $\pi_3(S^2)$ (uncertain)	Topological statement via coded maps; a simplicial version is arithmetical, strength unknown
14–15	Real functions, Laplace's method; random walks	RCA_0	Basic real analysis of explicit functions [50]
16–19	Clifford and quaternion algebra; eigenvalues; Onsager	RCA_0	Linear algebra over $\mathbb{R}$ and $\mathbb{C}$ with explicit entries [50]
20–21	Trit streams, average with lookahead; oscillation periods	RCA_0	Streams as functions $\mathbb{N} \to \{-1, 0, 1\}$; finite automata
Beyond 21	Places as streams up to ≈; Bishop's criterion on integer values; ×3 places as all reals	BISH for ≈ and integer values; LLPO (with countable choice) for ×3 places to be all reals	Constructive analysis [88, 89]

Table 2. Estimated strength of the rungs. EFA: elementary arithmetic. PRA: primitive recursive arithmetic. RCA_0: recursive comprehension.

Martin-Löf separates actual truth, a proof that has been made, from potential truth, a proof that can be made [83]. Read in his terms, the discrete ladder up to Rung 19 needs only infinity of the second kind: windings that can always be added. From Rung 20 on the book uses streams, given coinductively one digit at a time, and set quotients of them. These are infinite objects, but each is used only through its finite prefixes. This is a reading; Martin-Löf speaks of truth, not of infinity.

Three findings follow.

- At a coarse resolution the order does not go down. Up to Rung 11 the statements are discrete. Real numbers first appear at Rungs 12 and 13 ($\log_2 3$, SU(2)), and dominate from Rung 14, where the hypotheses from physics begin. With only two or three levels, this is weak evidence.

- Up to Rung 11, and for the integer part of Rungs 12 and 13, the statements are about finite or discrete objects. Elementary arithmetic is expected to suffice. Friedman conjectures this for all finitary theorems of mainstream mathematics, and Avigad shows how far it reaches in number theory and combinatorics [52].
- RCA_0 and WKL_0 prove no Π^0_2 sentence that primitive recursive arithmetic does not prove (Parsons; Friedman). Simpson reads this as a partial realisation of Hilbert's programme [51]. RCA_0 suffices for Rungs 14 to 19 only because their functions and series are explicit, with computable bounds. In general form, Laplace's method needs WKL_0 (a maximum of a continuous function) and monotone convergence needs ACA_0. So the arithmetical content of every rung is finitistically reducible. This is compatible with the theory's position that finite depth is enough. It is not evidence for it: Hilbert's "finitistic" is not the theory's "finite depth", and statements about real numbers are not Π^0_2.

Limits. The table is an estimate. Rung 13 is uncertain. Onsager reciprocity is a physical principle; only its matrix content is placed here. The estimate concerns provability, not what exists.

Coverage of the subject classification

The Mathematics Subject Classification has 63 top-level areas [56]. Each area was placed on the rungs where the net meets it, or marked as a gap. The full list is in msc_coverage.csv. Placing an area means that at least one structure of the area appears on a rung. It does not mean that the area is generated.

- Met: 17 areas, through a structure on a rung that is proved or computed. They include logic, combinatorics, number theory, field theory, linear algebra, group theory, algebraic topology, knot theory and dynamical systems.
- Met by citation only: 3 areas (17, 32, 33).
- Met via a hypothesis: 7 areas (16, 22, 35, 60, 78, 80, 81). They appear only once a hypothesis from physics or analysis is added (Rungs 13 to 19).
- Met weakly: 11 areas (06, 08, 14, 26, 28, 30, 31, 34, 52, 54, 82). One structure appears, cited or read, but nothing of the area's own theory.
- Not applicable: 3 areas (00, 01, 97).
- Gaps: 22 areas. Analysis on continua: 42–47, 49, 58. Geometry: 53. K-theory: 19. Statistics: 62. Applications: 70, 74, 76, 83, 85, 86, 90–94.

About a third of the gaps (8 of 22) lie in analysis on continua. Several others (19, 90, 91, 94) are on the discrete side. The match with Table 2, where real numbers enter late and through hypotheses, therefore holds only in part. The ladder is strongest on the discrete side of mathematics and weakest on the continuous side. The continuum of one interval is built (chapter "Beyond Rung 21"). The next rungs, if they exist, must go beyond it: differential equations, function spaces and differential geometry.

Table 4 lists, for the gaps in analysis and geometry, what a next rung would have to overcome.

Where the derivation stopped

The goal of the book is derivation. Each time it stopped, the missing piece was named. Table 3 lists every stopping point, what was missing, and what became of it. The labels are those used during the work. Resolved points are proved in the files of the appendix or computed by its scripts.

Point	Where it stopped	What was missing	Status
V-a	Rung 4: loops as words	A reading of $\mathbb{Z}$ as words, not as a given set	Resolved: loops are words; $\mathbb{Z}$ is only a measuring rod (Helix, BT0)
V-b	Rung 3: digit and winding	A link between the trit and the loop	Resolved: digit = winding modulo three, for all loops (DigitWinding). The carry (s − d)/3 is stated, not proved; the physical reading is open (IX.5)
V-c	Rung 7: the rewrite rule	Why this rule and not another	Resolved up to a scalar among linear radius-one rules; non-linear rules open
V-d	Rung 10: the base 1 − ω	Why this base	Resolved by computation, given a fixed-point turn (period 1), up to complex conjugation; the choice of one of the pair is not derived
V-e	Rung 11: the node	Free pairing of mirror and ring	H1 and H2 proved for SLKnoop and for the node of Rung 11 (SLNode, PairRing, PSLNode). Free pairing argued from cited facts, not formalised. Open: that the net's node is this minimal node
T10	Rung 7 (T10)	A consistent rest rule	Corrected by the rest rule (rest_rule.py)
V-g′	Rung 13: the open pair	Whether the open pair closes	Resolved in SLKnoop: it does not close (OpenPair), as T7.1 says. In the node of Rung 11 it closes after two turns
V-h	Rung 20: product of streams	A finite automaton for the product	Not possible: the product needs growing memory (Muller 1994). Prefix product proved exact (Product)
Open 1	Rung 20: value of a stream	A real number for an infinite trit word	Proved in Agda for the integer values V n s: same place = bounded difference (VacuumNetValue, VacuumNetValue2) = Bishop's criterion (VacuumNetBishop, VacuumNetBishop2). Argument (on paper): V n s / 3^n is a Bishop sequence; every computable real has a ×2 place [90]. Reading: all reals have a place; on the ×3 ladder that needs LLPO. Average and mirror act on places; the product acts on values. Proved in Agda: the tail bound in integers (VacuumNetTail). Proved in Agda: the value is a Bishop real in the rationals, and same place = Bishop equality of these sequences (VacuumNetReal). Proved in Agda: the map from places to reals is injective (VacuumNetRealEq). Not formalised: the Cauchy reals of [4]
Open 2	Rung 13 (T20): chirality	Left and right trefoil apart	Open: the knot group cannot see it; the embedding is needed

Point	Where it stopped	What was missing	Status
Open 3	Coverage	22 MSC areas	Open: 8 of the 22 are analysis on continua (Coverage chapter)
Open 4	Beyond Rung 21: functions on places	Which stream functions are functions on places	Proved in Agda: Resp, the induced map and the digit in front. Taking a digit off does not respect “same place”, on both ladders (VacuumNetFunctions). Open: continuity and function spaces
Open 5	Beyond Rung 21: conversion from ×3 to ×2	A stream function that keeps the place	Argument on paper (chapter Beyond Rung 21 (c)) and computed (ladder_convert_check.py, w1_check.py). Not in Agda. Work package W-1 in WORKPLAN.md
Open 6	Beyond Rung 21: measure	Lebesgue measure on places	Checked by computation (measure_check.py): at finite depth the ×3 cells are uniform and the ×2 cells are not. Known theorem: balanced ternary represents each integer of the window once [13]. Proved in Agda for every depth (VacuumNetWindow). The limit measure is not in Agda. Reading: the ×3 ladder measures and the ×2 ladder computes
Open 7	Rung 10: the base	Why one base of the conjugate pair	Open. Reading (by analogy): the double cover of the round has no global section, proved in VacuumNetTwoSuns. That the conjugate pair behaves like it is not shown: its monodromy is not computed

Table 3. Stopping points of the derivation.

The stopping points sharpen the goal. Four groups of assumptions remain. First, the net’s node is the minimal node of Rung 11. Second, one base is chosen among a conjugate pair. Third, space is embedded at Rung 13. Fourth, the hypotheses of Rungs 14 to 21 hold: physical for Rungs 14 to 19, infinite streams at Rung 20, closure read as oscillation at Rung 21. Rung 12 rests on the hypothesis IX.4. The continuum chapter also uses the stream hypothesis of Rung 20 and, for its reading of the comma, T15. The places of an interval, with Bishop’s criterion for the equality of their values proved on integers, are built from the net in the continuum chapters. The real line is not built: the ×3 places are all reals only under LLPO. The values are Bishop-regular sequences of rationals (VacuumNetReal). Three things are open. The identification with the Cauchy reals of [4] is missing. The field operations are missing, since only the ×2 average and the mirror act on places. Real functions are missing. Up to Rung 13, the rest is proved or computed, as each chapter states; readings are marked as readings.

Where the ladder goes next

The theory names its own open questions (IX.1–IX.5) [1]. Each is a rung that is not yet climbed.

- IX.1: is the lever of the free path the coupling of the medium? This joins Rungs 14 and 15.
- IX.2: which rewrite dynamics is its own fixed point? On the register of Rung 7 it is answered for local linear rules of radius one. The fixed points are the rings that close everywhere. Only two such rules have that property, and the rewrite of T10 is the one in which a trit does not read itself. Non-linear rules are not covered. For the whole net it is open.
- IX.3: does the share of turning elements in the plane settle? This is Rung 10.
- IX.4: when does a strand merge in equal blocks? This is the hypothesis of Rung 12.
- IX.5: the physical reading of the trit rule. Does the passage that leaves a node the way the first passage left it give the digit +1, the reverse −1, and any other 0? This touches the open point of Rungs 3 and 4.

Some fields are met only weakly or not at all (see the coverage chapter). The real numbers enter at Rungs 12 to 14 as an input. The chapter “Beyond Rung 21” later builds the places of an interval from the net. It gives them Bishop’s criterion for the equality of their values. Algebraic geometry is met only through one cited curve. Category theory is met only through homological algebra (Rung 7) and a reading (Rung 8). Two routes lead there. Homotopy type theory is the internal language of higher toposes, so category theory is close. Schreiber’s cohesive homotopy type theory reaches differential geometry and gauge fields [9]. Rungs 7 and 16 point to a third route. The trits carry the simplest 3-complex, with $d^3 = 0$. Whether generalised homology with d^N = 0 adds more than a new name here is open.

Candidate rungs 22 to 28: a programme, not a derivation

A text generated by Google's AI system, supplied by the author, proposed seven further rungs, 22 to 28. It also marked eight gaps of the coverage table as "resolved". This book does not adopt the text. None of its points is resolved by a file that the type checker accepts.

Table 4 lists, for each proposed rung, what this book already has and what blocks the step. Where a point could be checked, it was checked. The result is a programme, not a derivation.

Rung	Proposed	In this book	What blocks it
22	Function spaces and topology (MSC 46, 47, 54). Functions that respect "same place". The shift as an operator	Functions that respect "same place", the induced map, the digit in front (VacuumNetFunctions)	The shift does not respect "same place" on the interval (proved). With the two ends glued it is x ↦ 3x mod 1 (argued on paper, W-3). No topology and no modulus of continuity are defined. A norm needs real values, and the Cauchy reals are not formalised
23	Measure and integration (MSC 28, 42). Cylinder measure 3^{-n} or 2^{-n}. The integral as a limit of averaged sums. Fourier analysis from Kronecker density	A count at finite depth: uniform on ×3, not on ×2 (measure_check.py)	On the ×2 ladder the 3^n words cannot all have mass 2^{-n}, since the masses would sum to $(3/2)^n$. The integral divides 3^n words by 2^n. The ×2 cells are not uniform. Kronecker density (Rung 12) gives density, not a measure. Equidistribution of the multiples of an irrational number is Weyl's theorem [115]. It is stated for Lebesgue measure, and a measure on places is not built
24	Differential operators and equations (MSC 34, 35, 39). A scaling limit of the difference operator. Wave and heat equation from the shift registers	The discrete oscillator and $D^3 = 0$ (Rungs 7 and 21)	A limit needs reals and derivatives on places. The shift does not respect "same place" on the interval (with the ends glued it is x ↦ 3x mod 1, argued on paper). The wave and heat equations are not derived
25	Differential geometry (MSC 53, 58). Manifolds from windows glued along closed seams. Curvature as the density of open seams	Seams (Rung 8). The circle and its double cover (VacuumNetTwoSuns)	Charts $\mathbb{R}^d$ need a dimension d, which the net does not give. There is no smooth structure and no calculus of transitions. Curvature is not defined
26	Calculus of variations (MSC 49, 90). Action as summed dissipation. The optimal path minimises loss	The thermodynamic hypothesis of Rung 19 only	The minimum of a path cost on a finite graph is a shortest-path problem, solved by dynamic programming [116]. A calculus of variations needs a continuum: function spaces and derivatives (rungs 22 and 24). Physical least action is stationary, not always minimal. The rung rests on the physics of Rung 19
27	Algebraic K-theory and N-complexes (MSC 18, 19). K_0 from N-complexes. K_1 as automorphisms of the modular node	$D^3 = 0$ (Rung 7). The modular group (Rung 11)	K_1 is the abelianisation of the stable linear group, not a group of automorphisms. $K_1(\mathbb{Z})$ has two elements [92]. The abelianisation of SL(2, $\mathbb{Z}$) has twelve [93]. That of PSL(2, $\mathbb{Z}$), the group of Rung 11, has six. K_0 of N-complexes is not defined in the text
28	Statistics and stochastic	Random walks and Pólya	A martingale needs a probability space

Rung	Proposed	In this book	What blocks it
	processes (MSC 60, 62). A random trit at each scale as a martingale. Inference of the energy density	recurrence as input (Rung 15). Counts at finite depth	on infinite streams and conditional expectations. Chapter (d) gives uniform digits (mean zero) only as counts at finite depth. The dimension d, and the link between walks on $\mathbb{Z}^d$ and trit streams, are not explained. There is no estimator and no data model

Table 4. Proposed rungs 22 to 28 and what blocks them. Source of the proposals: a text generated by Google's AI system, supplied by the author. Checks: Claude (Anthropic).

Two obstacles are proved or computed in this book: the shift does not respect "same place", and the ×2 and ×3 ladders have different cell sizes at finite depth (computed). The other obstacles are read from the definitions and from known theorems. They are not new results.

Limits

- The loops-equal-words step does not rely on the library theorem (VacuumNetHelix), and the set-truncation is not needed (VacuumNetBT0). Both proofs still use the integers as a measuring rod. Altenkirch and Scoccola [6] define the integers as a higher inductive type without set-truncation. That is one way to lift this limit. It has not been tried here.
- The Agda proofs of Rungs 7 and 8 are local, on one window or one seam. The rule for rings that come to rest is argued on paper and checked exactly up to n = 48, not formalised.
- Rung 11: H1 and H2 are proved in Agda, for SLKnoop and for the node of Rung 11 itself. The rung rests on the assumption that the net's node is the minimal node, on cited theorems (Stern–Brocot, van Kampen, the group of the node, normal subgroups of PSL(2, $\mathbb{Z}$)) and on reading S as a mirror. The matrix check of the braid relation is not faithful for B_3.
- Rungs 9, 10 and 14 to 19 are checked by computation or cited. They are not formalised. Rung 12 is formalised for T16 only (VacuumNetComma); Rung 13 in part (VacuumNetTrefoil, VacuumNetOpenPair, VacuumNetHopf). Rungs 20, 21 and the continuum chapter are formalised as their bullets state.
- From Rung 13 on, every rung adds a hypothesis. Rungs 16 to 19 rest on physics: Dirac, Maxwell, Larson and thermodynamics. The theory itself marks Rung 17 as a correspondence.
- The readings that link a rung to a field are readings. The strongest is that the node of Rung 11 is the first knot. It needs its own proof. That $Q^2 = 0$ of the Dirac rung equals the $d^3 = 0$ of the trits is also still a reading.
- All formal work and all checks were made by the same AI system. A second AI system (DeepSeek) reviewed version 3.0. Its points on readings, on the digit and direction readings, on hypotheses and on Rung 11 are addressed where noted. An independent check by a person is still needed.
- A modulus of continuity for functions on streams is defined (VacuumNetModulus). Functions on places are built only for the mirror, the digit in front, the average on the ×2 ladder, and their composites. The conversion from ×3 to ×2 places is argued on paper (chapter "Beyond Rung 21 (c)") and tested by computation (w1_check.py). A different conversion, by rounding, is proved in Agda (VacuumNetConvert).
- The counts of chapter (d) are in Agda as a one-to-one map onto the window (VacuumNetWindow). The measure is not. The shift on the circle (VacuumNetCircle) is a function on a glued quotient. This quotient equals the places with the ends glued (VacuumNetCircleFase). It is not the round S^1 of homotopy type theory (proved); that it is $\mathbb{R}/\mathbb{Z}$ is not proved. The tail bound (VacuumNetTail) is in integers; the step to the rationals and to Bishop reals is in VacuumNetReal. Equality of reals is an equivalence relation and the map from places is injective (VacuumNetRealEq). The Cauchy reals of [4] are not built.
- The candidate rungs of Table 4 are a programme. No rung above 21 is derived.
- The readings from other traditions (chapter (e) and the last appendix) are readings and search notes. No theorem depends on them.

Conclusion

In its first eleven rungs, 0 to 10, the net leads to a row of known structures. They are the circle and the integers, the field with three elements and balanced ternary. Next come the setting of the cap set problem and linear cellular automata over F_3. Then follow the gluing rule of closed windows, necklaces, and the limit of the address in the Eisenstein integers.

These are proved in Agda or checked by computation. Two steps looked like choices of the theory: the rewrite of Rung 7 and the base $1 - \omega$ of Rung 10. Both are now forced, within stated limits. Among local linear rules of radius one, the rewrite is forced up to a scalar; it is the one in which a trit does not read itself. The base is forced up to a unit; requiring a turn that is a fixed point leaves only $1 - \omega$ and its complex conjugate, which behave alike; the other associates end in 2- or 4-cycles. Rung 11 follows from Rung 12 under two named hypotheses and the assumption that the net's node is the minimal node. Rungs 9 and 10 are checked on finite ranges.

In the next three rungs the net meets the settings of the modular group and the comma. It reaches a 2-complex whose homotopy type is that of the trefoil complement (cited), without a space hypothesis. With the hypothesis of embedding in space, it meets the knot itself and the Hopf charge. These are cited or read.

In Rungs 14 to 19 each step adds a hypothesis from physics. The fields that meet the net there are analysis, probability and Clifford algebra. Quaternion spectral theory, dimensional analysis and the theory of positive matrices follow. Rung 20 adds words without end, the trit streams. Rung 21 reads closure as oscillation.

History found each of these fields on its own. Here they come one after another, from one rule and the hypotheses named.

Two findings came out of the work itself. First, the theory states that rings come to rest only at lengths 4 and 8. In fact they come to rest exactly when four divides the length. This is argued on paper and checked by exact linear algebra up to length 48. Second, closure on the trits is a second difference: $D^2 = 0$. Period three is $D^3 = 0$. So the trits carry the simplest 3-complex, already at Rung 7. Whether that adds more than a new name is open.

The continuum part builds the places of one interval from the net. A place is a descent through the scales. Two descents are the same place when the rest they carry stays in the window. At depth n the value is one to one onto the integer window. The value of a place is a regular sequence of rationals, and the map from places into these sequences, up to "the difference goes to zero", is injective. With the two ends glued the shift is a function, on a circle that is a set of points and not the round S^1 of Rung 0. Putting a digit in front is a function on places; taking one off is not. The double cover of the round has no global choice of one sun.

So the answer to the question of this book is this. The framework is assumed: homotopy type theory, checked in cubical Agda. Inside it, and from the assumptions named below, the net derives the following. The circle and the integers. Balanced ternary with its closed windows. The modular group, and the trefoil group (cited). The exact product on prefixes. The places of one interval, as descents up to "same place", with Bishop's criterion for the equality of their values. Oscillation with the periods 3, 4 and 6. It does not derive function spaces, integration, differential equations, differential geometry, K-theory or statistics. Table 4 gives the obstacle for each.

Four groups of assumptions remain. First, the net's node is the minimal node of Rung 11. Second, one base is chosen from a conjugate pair. Third, the embedding in space at Rung 13. Fourth, the hypotheses of Rungs 14 to 21: physical up to Rung 19, streams at Rung 20, oscillation at Rung 21. Rung 12 rests on the hypothesis IX.4, and the continuum chapters use T15. The book is therefore not

a complete derivation of mathematics, and it does not claim to be. It is a ladder with every stopping point named.

Tool disclosure. The Agda files, the computations and this text were made with the AI system Claude (Anthropic) under the direction of the author. The author chose the method and decides what counts as a result.

Appendix: the formal files

All 47 files check with Agda 2.8.0 and the cubical library v0.9, under --safe, without postulates. The file All.agda imports all of them. Each needs the library file vn.agda-lib (depend: cubical-0.9). Table A lists them with the start of their sha256 hash.

File	sha256 (first 8)	Content
VacuumNetCircleFase.agda	cb11695f	the circle is the set of places with the ends glued; it is not the round S^1
VacuumNetRealEq.agda	48f1e5bf	equality of reals is an equivalence relation; places map injectively into the reals
VacuumNetReal.agda	6a737ba1	the value of a place as a Bishop real in the rationals; same place = Bishop equality
VacuumNetWindow.agda	34307572	counting at finite depth: V n is one to one onto the window
VacuumNetCircle.agda	62415b19	the shift is a function on the circle with the ends glued
VacuumNetTail.agda	08aa0bf6	tail bound of the value in integers
VacuumNetModulus.agda	9ab000ac	modulus of continuity for stream functions
VacuumNetCount.agda	b6c1e776	bound on the value at depth n, lemma L1
VacuumNetConvertLem.agda	a18e5934	integer lemmas for the conversion
VacuumNetConvert.agda	5db9de2d	×3 to ×2 conversion by rounding respects same place
VacuumNetRondaf.agda	981491d5	nearest integer by division with remainder
VacuumNetRestIndex.agda	ac723fde	rest rule with step k: third power = step 3k; index 3^v; shell at scale k
VacuumNetRestRing.agda	ce0070e5	rest rule on a ring of four trits: kernel = shell
VacuumNetRestKern.agda	6c15f576	rest rule on rings of every length, index 1: kernel = shell
VacuumNetNaadGelijk.agda	e1961ded	seam closes iff the two windows are equal
VacuumNetBishop.agda	06431484	same place = Bishop's criterion on the integer values, with the growth lemma, ×3)
VacuumNetBishop2.agda	75afd916	the same on the ×2 ladder
VacuumNetFunctions.agda	9997905f	functions on places: Resp, induced map, digit in front; the shift does not respect "same place", on both ladders)
VacuumNetTwoSuns.agda	3f8be249	double cover of the round: two suns, no global choice)
VacuumNetValue.agda	28206a57	value of a place: rest = difference of truncated values; same place = bounded difference (×3)
VacuumNetValue2.agda	30a3a6ec	the same on the ×2 ladder
VacuumNetArith.agda	df1401d6	same place on the ×2 ladder; average and mirror act on places (continuum chapter)
VacuumNetLimit.agda	833ded5c	the limit step: same place, window, Fase as quotient (continuum chapter)
VacuumNetComma.agda	ffeb7703	T16: the ladders ×2 and ×3 never meet exactly (Rung 12, continuum chapter)
VacuumNetPhase.agda	28a3ae24	oscillation as eigenform, standing still (Beyond Rung 21)
VacuumNetRound.agda	24bb8edb	movement as an eternal round, three directions, return

File	sha256 (first 8)	Content
		(Rungs 0, 1, 2)
VacuumNetHoTT.agda	2df88f8c	words BT, BT ≃ ℤ, BT ≃ ΩS¹ (Rungs 2, 4)
VacuumNetFoundation.agda	4cecefe3	onderscheid, mirror, spiegeling (Rungs 2, 4)
VacuumNetDictionary.agda	93e49953	disc, dunce cap, cross-cap, torus as two loops (earlier dictionary)
VacuumNetLadder.agda	fdc01e18	markering, ⊕, venster, three closures, matrices of Rung 11 (Rungs 1, 3, 5, 6, 11)
VacuumNetLadder2.agda	17f6ed9b	propagatie, periode, vast-punt, naad (Rungs 7, 8)
VacuumNetLadder3.agda	2345f5bf	closure as second difference, D³ (Rung 7)
VacuumNetEigenform.agda	f68a2f9b	the two eigenform rules (Rung 7)
VacuumNetBT0.agda	fce0a495	words without set-truncation (Rung 4)
VacuumNetHelix.agda	7e85b27a	loops are words, without the library theorem (Rungs 2, 4)
VacuumNetDigitWinding.agda	c4fd707b	digit = winding modulo three, for all loops (Rung 3)
VacuumNetLadderPath.agda	7dd5f53c	unique addresses of ladder paths, path mirror (Rungs 11, 12)
VacuumNetPairRing.agda	2fbdc537	node with mirror and ring, comma path (Rung 11)
VacuumNetSLNode.agda	3b2c0aad	H1 and H2 in SLKnoop (Rung 11)
VacuumNetPSLNode.agda	1897f38c	H2 in the node of Rung 11 itself
VacuumNetTrefoil.agda	b21d16a8	Klaverblad, maps to Rung 11 and to S¹ (Rung 13)
VacuumNetOpenPair.agda	3fab67b3	the open pair does not close (Rung 13)
VacuumNetHopf.agda	b62cf6f2	$\pi_3(S^2) \cong \mathbb{Z}$ from the library (Rung 13)
VacuumNetStream.agda	7fe9dcb6	trit streams, mirror (Rung 20)
VacuumNetAverage.agda	e2b8c3e9	average of streams, error bound in integers (Rung 20)
VacuumNetProduct.agda	860ccb24	exact product on prefixes (Rung 20)
VacuumNetOscillator.agda	a683dd28	closure as oscillation, periods 3, 4, 6 (Rung 21)

Table A. The Agda files of this book.

Computations are Python 3 scripts. They use sympy, mpmath and numpy. Each script prints the numbers quoted in the chapters. The scripts are:

- bottomup_checks.py, rungs_checks.py, upper_checks.py, rest12.py, rest_rule.py
- ncomplex.py, rule_search.py, base_search.py, base_units.py, sb_path.py
- pair_ring_path.py, continuum.py, average_check.py, product_check.py, oscillator_check.py
- jones_trefoil.py, phase_check.py, comma_orbit.py, limit_check.py, base3_add_check.py
- ladder_convert_check.py, product_value_check.py, trit_adres.py, trit_families.py, measure_check.py, w1_check.py

Reviews. Every chapter was checked by a separate AI agent that had not written it, following the author's Respondent–Judge protocol. The formal results of the continuum part, and 29 central lemmas before them, were compared with their statements in this book in the same way. Its corrections are worked into the text. A second AI system (DeepSeek) reviewed version 3.0. The reports are in the dossier. No person other than the author has checked the work. The author is a mathematician and takes responsibility for the result.

Appendix: status at a glance

Part	Status	Where
Rungs 0 to 13: circle to trefoil	Proved in Agda, computed or cited, as each chapter states. Four groups of assumptions remain	Chapters for Rungs 0 to 13; Table 3
Rungs 14 to 19	Computed or cited. Each rung adds a hypothesis from physics	Chapters for Rungs 14 to 19
Rungs 20 and 21: streams, oscillation	Proved in Agda for the statements each chapter lists	Chapters for Rungs 20 and 21
Places and their value	Proved in Agda: same place = bounded difference = Bishop's criterion on the integer values. Also: the value is a regular sequence of rationals, and two places are the same exactly when these sequences are Bishop-equal	Beyond Rung 21; Beyond Rung 21 (b)
Functions on places	Partly proved in Agda. Putting a digit in front is a function. Taking a digit off does not respect "same place"	Beyond Rung 21 (c)
Counting at finite depth	Proved in Agda: V n is one to one from the words of depth n onto the integer window. The limit measure is not reached	Beyond Rung 21 (d)
The shift on the circle	Proved in Agda: with the two ends glued, the shift is a function. The glued set equals the places with the ends glued. It is a set, so it is not the round S^1 of homotopy type theory (proved, 4.7). It is the circle as a set of points; that it is $\mathbb{R}/\mathbb{Z}$ is not proved	Beyond Rung 21 (c)
Double cover of the round	Proved in Agda. The link to Jaina astronomy is a reading	Beyond Rung 21 (e)
Conversion from ×3 to ×2 places	Proved in Agda for a conversion by rounding. The greedy conversion stays on paper. Work package W-1	Beyond Rung 21 (c); Table 3
Identification with the Cauchy reals	Bishop reals: proved in Agda. Places map one to one into the regular sequences up to equality ("the difference goes to zero"). The Cauchy reals of homotopy type theory, countable choice and onto-ness are not formalised	Beyond Rung 21 (b); Table 3
Areas of the classification	22 of 63 are gaps. Table 4 lists candidate rungs with their obstacles	Coverage chapter; Table 4
Independent check by a person	None yet	Limits

Table S. What is proved, computed, argued or open.

What "complete" means here

The book is complete in one sense only. Every point where the derivation stopped is named, and every statement under "What is established" carries one of five labels.

It is not a complete derivation of mathematics. Of the 63 top-level areas of the classification, 22 are gaps. The book starts from four named groups of assumptions and does not remove them.

Appendix: readings from other traditions

These are search notes. They are not results. No rung and no theorem depends on them. They are kept for later work. Each entry names its sources and its status.

Nāsadīya Sūkta

The hymn Ṛgveda 10.129 asks what there was before the first distinction. It ends in doubt about whether anyone knows [96]. This is the question of the Preface. Status: reading.

Saptabhaṅgī: sevenfold predication

The Jaina doctrine of syād-vāda gives seven ways to state a thing. It is. It is not. It is and is not. It is indescribable. And the three combinations of the indescribable with the first three. Seven is $2^3 - 1$: the non-empty combinations of three basic predicates [97, 98, 99].

Many formalisations exist. Some use probability [97, 98]. Some use many-valued and modal logic [100, 101]. One uses a one-valued logic [103]. One reads it as a dialectical logic shared with the Buddhist catuṣkoṭi [102]. One gives a contextual seven-valued logic for quantum systems [105]. Balcerowicz doubts that formalising makes sense [104].

In the sources found on 16 and 17 November 2026, none uses homotopy type theory. A formalisation in cubical type theory with an interval is not built here. It would be a separate piece with its own version number. Status: lead.

Spanda

Kashmir Shaivism calls the first stir of the absolute a pulsation, spanda, before any distinction [106, 107]. The Preface also puts a pulsation before the distinction. Status: reading.

Negation as a source of meaning

Dignāga's apoha explains meaning by exclusion [108]. The Navya-Nyāya treats negation and double negation with care [109]. Both take negation as more than the opposite of a statement. Status: lead for a later piece. No claim is made.

Lunar mansions and the calendar

Lists of 27 lunar mansions (nakṣatra) exist, and lists of 28 that add Abhijit [110]. The number 27 is 3^3. That is a coincidence of numbers until a step to the net is shown. The Vedāṅga Jyotiṣa has a five-year cycle that adds two months, to keep the lunar and the solar year in step [111]. That is the problem of the comma at Rung 12: no whole number of lunar months fits a whole number of solar years. Status: reading, not tested. The step from 27 and 28 to the net is a suggestion only.

The Indus script

The author keeps a separate paper on the Indus script. It uses Parpola's star and fish reading of signs [112] and a nakṣatra notation. That paper is a search and not a claim. This book neither tests nor uses it. Whether the script writes a language is disputed [113, 114].

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The theory behind every rung. The chapters cite N1, N4, the trit rule, T2–T4, T7, T7.1, T8–T11, T12, T12.1, T13, T14, T15–T24, Physics T1–T6 and IX.1–IX.5.

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[14] The agda/cubical library, version 0.9. https://github.com/agda/cubical
Supplies the circle, its winding theorem, the dunce cap and the torus used in the Agda files.

[15] Konstapel, J. (2026). VacuumNetBishop.agda, VacuumNetBishop2.agda, VacuumNetFunctions.agda, VacuumNetTwoSuns.agda, VacuumNetValue.agda, VacuumNetValue2.agda, VacuumNetArith.agda, VacuumNetLimit.agda, VacuumNetComma.agda, VacuumNetPhase.agda, VacuumNetRound.agda, VacuumNetHoTT.agda, VacuumNetFoundation.agda, VacuumNetDictionary.agda, VacuumNetLadder.agda, VacuumNetLadder2.agda, VacuumNetLadder3.agda, VacuumNetPairRing.agda, VacuumNetLadderPath.agda, VacuumNetBT0.agda, VacuumNetEigenform.agda, VacuumNetTrefoil.agda, VacuumNetStream.agda, VacuumNetAverage.agda, VacuumNetProduct.agda, VacuumNetDigitWinding.agda, VacuumNetOscillator.agda, VacuumNetHelix.agda, VacuumNetSLNode.agda, VacuumNetPSLNode.agda, VacuumNetOpenPair.agda, VacuumNetHopf.agda and All.agda. Constable Research, Leiden.
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