

Where the Supercurrent Closes

The Leiden Work of J. Aarts and K. Lahabi and the Closure Rule of the Vacuum.Net

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Abstract

For forty years, one laboratory in Leiden has asked where a supercurrent runs. Jan Aarts began with vortex lattices, ferromagnetic hybrids and the first π junction. His former student Kaveh Lahabi continued with disks, rings and a kagome superconductor. He now holds a Vidi grant to image how the collective wave flows.

Their results share one pattern. The supercurrent does not fill the material. It runs where a phase returns onto itself: around a vortex, along a rim, across a pair of domain walls, through a network of filaments.

The Vacuum.Net theory starts from that condition. Only what returns in phase persists. This essay sets the measurements beside the rule. Four results are computed here: the half-quantum fluxoid as two half-turns, the pairing of domain walls on a ring, the sign sequence $+$, 0 , $-$ of the π junction, and the number of closed configurations on a kagome lattice. That number is exactly one free trit per unit cell.

1. The Net in Brief

The picture is a fishnet in water. One strand runs everywhere and crosses itself. Where strands wind around each other, knots form. Between the strands lie meshes. Four words carry the theory: strand, winding, knot, mesh.

At every crossing the strand has one of three states: $+1$, 0 or -1 . This unit is the trit. Three crossings in a row form a window. A window is closed when its three values sum to zero, counted modulo 3. An open window carries tension. Only what closes, stays.

Three states on three places give 27 windows. Nine of them close:

- three equal values: $(+, +, +)$, $(0, 0, 0)$, $(-, -, -)$;
- three different values: the six orders of $(-, 0, +)$.

The other 18 are open.

A ring of three different values has no starting point. Six orders divided by three rotations give two rings. The left ring runs $- \rightarrow 0 \rightarrow +$. The right ring runs $+ \rightarrow 0 \rightarrow -$. They are mirror images.

Put a left ring against a right ring: $-, 0, +, +, 0, -$. The windows read:

Window	Sum	State
$(-, 0, +)$	0	closed

(0, +, +)	2	open
(+, +, 0)	2	open
(+, 0, -)	0	closed

One seam gives two open windows. They always come as a pair.

Give each trit a phase of 120° . A window then carries a total phase of (sum) $\times 120^\circ$. A sum of 0 or ± 3 gives a whole number of turns. A sum of ± 1 or ± 2 does not. The closed window is therefore the condition that the phase returns onto itself. This is the same condition that quantizes flux in a superconducting ring.

Two further statements are used below. Zero is not rest. It is the meeting of an act with its mirror: $+1$ and -1 together. And there are two ways to reach zero. One is meeting (two opposite values). The other is going round (three equal steps).

2. The Ring: Fluxoid Quantization Is the Closure Rule

A superconducting ring carries one condensate wave function. After one turn around the ring, the phase must return to itself. The phase winding is then $2\pi n$. The enclosed fluxoid is quantized:

$$\Phi' = n \cdot \Phi_0, \text{ with } \Phi_0 = h/2e = 2.0678 \times 10^{-15} \text{ Wb.}$$

Near T_c the free energy oscillates with the applied flux. The transition temperature and the resistance follow. These are the Little-Parks oscillations.

Take a ring with an inner area of $0.96 \mu\text{m}^2$. The field period is

$$\Delta B = \Phi_0 / A = 2.0678 \times 10^{-15} / 0.96 \times 10^{-12} = 2.15 \text{ mT.}$$

In the terms of the net, the ring is one winding. The quantum number n is its address. A state that does not close in phase does not exist. The rule is the same. Only the notation differs.

3. The Half-Quantum Fluxoid: Two Half-Turns

Yasui, Lahabi, Aarts, Maeno and co-workers milled microrings from single crystals of Sr_2RuO_4 (Physical Review B, 2017). They observed proper Little-Parks oscillations. With an added in-plane field, the peaks split. They read this as the half-quantum fluxoid.

The count is short. In an equal-spin triplet state, the order parameter has two components:

$$\Psi = \Delta (e^{i\theta \uparrow} | \uparrow \uparrow \rangle + e^{i\theta \downarrow} | \downarrow \downarrow \rangle).$$

Each component must be single-valued on its own. Around the ring, $\theta \uparrow$ winds by $2\pi \cdot m \uparrow$ and $\theta \downarrow$ winds by $2\pi \cdot m \downarrow$, with integers $m \uparrow$ and $m \downarrow$. The fluxoid follows the mean charge phase:

$$n' = (m \uparrow + m \downarrow) / 2.$$

Take $m \uparrow = 1$ and $m \downarrow = 0$. Then $n' = 1/2$. The charge phase winds by π . The spin axis rotates by π . Together they make one whole turn.

In the net, one turn of a half-integer carrier is half a closure. The whole closure needs a second half. The half-quantum fluxoid shows exactly that: half in charge, half in spin, closed only as a pair.

4. Spontaneous Junctions: Walls Come in Pairs

Sr_2RuO_4 is a candidate chiral superconductor. Its order parameter can turn left or right. Domains of opposite chirality can coexist. At a wall between them the condensate is suppressed. The wall can act as an intrinsic Josephson junction.

Yasui, Lahabi and co-workers (npj Quantum Materials, 2020) found such junctions in homogeneous rings. Rings with a sharp transition at 1.5 K showed critical-current oscillations with the period of one flux quantum, like a dc SQUID with two junctions. Rings with a broad transition near 3 K showed no junctions and plain Little-Parks oscillations. Order-parameter simulations placed stable walls across both arms.

A parity count settles the number. Chirality has two values. Each wall reverses it. A path around the ring returns to its starting chirality. It must therefore cross an even number of walls. The smallest nonzero even number is two.

This matches the measurement: two junctions, or none.

It also matches the seam of Section 1. A left ring placed against a right ring gives two open windows. They come as a pair. In the ring of Sr_2RuO_4 the pair is visible as two junctions that no one fabricated.

5. The π Junction: The Register in One Device

In 2001 Ryazanov, Oboznov, Rusanov, Veretennikov, Golubov and Aarts reported the first π junction (Physical Review Letters). The device was $\text{Nb} / \text{Cu}_{0.48}\text{Ni}_{0.52} / \text{Nb}$ with a ferromagnetic layer near 22 nm thick.

On cooling, the critical current fell to zero and rose again. The authors showed that the coupling changes sign. Above the crossover the junction is in the 0 state. Below it is in the π state. The crossover appears where the thermal energy and the exchange energy are of the same order.

Write the critical current with its sign. On cooling it runs

$$+I_c \rightarrow 0 \rightarrow -I_c.$$

The coupling passes through all three trit values. The zero is not a third phase of the junction. It is the point where the 0 coupling and the π coupling meet and cancel. That is the net's reading of 0: an act meeting its mirror.

The π state itself is a half-turn. Across the junction the phase jumps by π . This is the third appearance of the same object: the half-quantum fluxoid of Section 3, the chiral wall of Section 4, and now the π coupling.

6. Domain Walls: Closure by Difference

A ferromagnet suppresses superconductivity through its exchange field. In a uniform magnet the field points one way. Rusanov, Hesselberth, Aarts and Buzdin (Physical Review Letters, 2004) studied Nb on permalloy. They found a clear enhancement of superconductivity in a field window of about 0.5 mT. In that window the permalloy switches and many domains are present.

Their explanation: inside a wall, a Cooper pair samples many magnetization directions at once. The pair-breaking partly averages out. The condition is that the wall width matches the coherence length: $\delta w \approx \xi_S(T)$. In microstructured samples without walls, the effect is absent.

In the net there are two kinds of closed window. One holds three equal values. The other holds three different values. A uniform magnet is a window of one value: it carries tension. A wall offers different directions within one coherence length. The pair then sees a window that closes by difference.

The fit is strict. The wall must have the size of the pair. That is selection by fit: what matches returns in phase, what does not, scatters.

7. The Rim Selects

The same group found, over thirty years, that the boundary decides where superconductivity lives.

- **1991.** Maj and Aarts showed that in a Nb/NbZr multilayer the outer layers determine the parallel critical field.
- **2017.** Lahabi and co-workers built a disk-shaped Josephson junction with a ferromagnetic vortex (Nature Communications). The supercurrent split into two channels. Moving the vortex with a field moved the current.
- **2022.** In Nb/Co disks the long-range triplet current ran in narrow channels at the rim, below 80 nm wide (Nano Letters). The boundary between superconductor and vacuum played a central role. By changing the spin texture, both 0 and π channels appeared in one device.
- **2024.** With the half-metal $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$, the triplet current was again confined to the rim of disks. In bars it was uniform. The rim current belonged to the disk geometry, not to the mechanism that generated the triplets (Physical Review Research).

The reading is short. A closed rim is one winding. The disk offers a path that returns onto itself. The bar does not. The current takes the path that closes.

A memory element follows from the same principle (Fermin, Scheinowitz, Aarts and Lahabi, Physical Review Research, 2022). An elliptical junction switches with a 40 mT pulse between two stable textures: uniform, or a pair of vortices. Each texture gives a different critical current. In the net, each texture is a closed configuration with its own address. Writing means changing the state of the medium. The configuration then holds without power. That is the third axiom: what is closed carries memory.

8. The Vortex Lattice: A Net of Windings

In a type II superconductor, flux enters as vortices. Each vortex carries one flux quantum. Around its core the phase winds by 2π . Each vortex is one closed winding. The vortices form a triangular lattice with meshes between them. It is the most literal picture of the net that condensed matter offers.

Troyanovski, Aarts and Kes (Nature, 1999) imaged this lattice with scanning tunnelling microscopy at high flux densities. Two results stand out.

- With strong line defects, the lattice stays pinned until there are about twice as many vortices as defects. Beyond that, plastic creep begins.
- With weak point disorder, the vortices creep coherently along a principal axis of the lattice. Their speed is modulated with the lattice period.

The second result is the net's fourth axiom in action. The response of a winding is a function of the state of its surroundings. Here the speed of each vortex follows the period of the lattice it belongs to. The net moves as one.

9. The Kagome Superconductor: A Network of Windows

9.1 The measurements

The kagome lattice is a network of corner-sharing triangles. Every triangle is a group of three sites. In CsV_3Sb_5 , Lahabi's group found two things.

First, an unstructured flake contains its own network of Josephson junctions (Blom, Rog and co-workers, Nano Letters, 2026). It emerges below T_c . It shows quantized Shapiro steps. It survives nanostructuring and thermal cycling.

Second, a SQUID microscope shows the network directly (Rog, Blom and co-workers, arXiv 2026). Narrow supercurrent channels appear at T_c . They stay stable at all temperatures and currents. Their non-linear response fits junctions linked by filaments. The network is strong at light Sn doping ($x = 0.03$). In undoped flakes it is much weaker.

The network explains several anomalies reported for this family: intrinsic junctions, higher-charge pairing, and a superconducting diode effect without field.

9.2 The closure rule on the kagome lattice

Take a periodic kagome lattice of $L \times L$ unit cells. Each cell holds 3 sites and 2 triangles, one pointing up and one pointing down. There are $N = 3L^2$ sites and $2L^2$ triangles.

Put a trit on every site. Demand that every triangle closes: the sum of its three trits is 0 modulo 3. Each triangle gives one linear equation over the field $\text{GF}(3)$.

Count the solutions. Every site belongs to exactly one up-triangle and one down-triangle. The sum of all up-equations therefore equals the sum of all down-equations. That is one dependency. The rank of the system was computed directly:

L	sites	triangles	rank	free trits
2	12	8	7	5
3	27	18	17	10
4	48	32	31	17
6	108	72	71	37

The rank is $2L^2 - 1$. The number of free trits is $3L^2 - (2L^2 - 1) = L^2 + 1$.

The closure rule leaves exactly one free trit per unit cell: 3 closed configurations per cell.

9.3 Rings only

Now allow only rings: every triangle must carry three different values. This is the problem of colouring the kagome sites with three colours so that each triangle shows all three. It is equivalent to colouring the edges of the honeycomb lattice. Baxter (1970) solved it exactly. The number of states per honeycomb unit cell is

$$W^2 = \prod_{k \geq 1} (3k - 1)^2 / [(3k)(3k - 2)] = \mathbf{1.4610}.$$

A transfer-matrix count on strips of width 4 to 10 converges to the same value (1.414, 1.587, 1.482, 1.459 per cell). One honeycomb cell corresponds to one kagome cell.

So rings fill 1.461 of the 3 states per cell, or 49%. The rest is carried by windows of equal values.

9.4 Reading

The lattice already has the shape of the net. Each triangle is a window. The filaments are where the windows close along a path. The junctions are the open

windows between them.

The network needs light doping to appear in full. That is the fourth axiom: the response depends on the state of the medium. The junctions survive thermal cycling and nanostructuring. That is the third axiom: closed configurations keep their form.

9.5 Higher charge: 4e and 6e

Ge and co-workers (Physical Review X, 2024) measured CsV_3Sb_5 rings. At low temperature the flux period was $h/2e$. On warming it became $h/4e$, and near the onset $h/6e$. In larger rings $h/4e$ did not appear; the period went from $h/2e$ directly to $h/6e$.

For the ring of $0.96 \mu\text{m}^2$ the periods are:

- $h/2e$: 2.15 mT
- $h/4e$: 1.08 mT
- $h/6e$: 0.72 mT

Give each pair a phase step of 120° . Three pairs then close in the same two ways as a window. Either they carry 0° , 120° and 240° (the ring), or three equal steps (going round). A charge of $6e$ is a window of three pairs. A charge of $4e$ is the meeting of two. Which of the two appears at which ring size is a count that remains to be made.

10. Mosaic, Interface and the First Heavy Fermion

Three older lines in Aarts's work complete the picture.

Manganites. Fäth, Freisem, Menovsky, Tomioka, Aarts and Mydosh (Science, 1999) imaged a doped manganite with tunnelling spectroscopy. Metallic and insulating patches coexisted on a submicron scale. The texture survived 9 T. The transition does not happen uniformly. Closed regions grow until they connect. In the net, open and closed meshes lie side by side, and the pattern holds its form.

Oxide interfaces. LaAlO_3 and SrTiO_3 are both insulators. Their interface conducts. Aarts's group grew such interfaces by sputtering and studied how electrons are trapped there (Physical Review Letters, 2020). Two layers that do not conduct support a third that does. In the oldest form of the theory this is mutual support: two things that have arisen carry the next.

CeCu₂Si₂. In 1979 Steglich, Aarts and co-workers reported superconductivity in CeCu_2Si_2 (Physical Review Letters). It was the first unconventional superconductor. It forms from heavy quasiparticles amid strong magnetism, with $T_c = 0.7 \text{ K}$. Lattice vibrations do not account for it. No external binding agent is needed in the net either. What returns in phase stays.

11. Direction

The register of the net records sums. Two orders with the same sum can still differ. Towards each other closes. Away from each other opens. The theory needs a quantity that records order.

CsV_3Sb_5 shows a superconducting diode effect without field: the critical current depends on direction. The sum is the same, the response is not. This is the clearest laboratory place to look for that quantity.

12. Where the Count Continues

Rings of three and six. The net counts that a ring of three different values cannot grow by one site. It grows by three, to six. A ring of six splits into two rings of three. The Leiden group mills rings from single crystals, prints junctions with an electron beam, and works in a material whose lattice is made of triangles and hexagons. The count can be put on a chip.

The shape of zero. In the net, zero is a meeting and not a state. In a π junction the crossover should then be a single point where $|I_c|$ touches zero, not an interval. The published $I_c(T)$ curves allow this count.

The kagome number. One free trit per cell is a computed property of the closure rule. The SQUID microscope sees which paths close. Comparing the density of closed paths with the count of Section 9 is the next step.

The Vidi microscope. Lahabi's new project aims to show how the collective wave of a quantum material flows. That is an image of where closure lies.

13. Method

Every number in this essay was recomputed. The flux periods follow from h/Q_e divided by the ring area. The half-quantum fluxoid follows from single-valuedness per spin component. The wall parity follows from the two-valued chirality. The kagome rank was computed by Gaussian elimination over $GF(3)$ for $L = 2, 3, 4$ and 6 . Baxter's product was evaluated to two million factors and checked by transfer matrices on strips of width $4, 6, 8$ and 10 .

Status of the statements:

- **Source:** all measurements in Sections 2 to 11.
 - **Proved:** fluxoid quantization; the half-quantum count; wall parity; the kagome rank $2L^2 - 1$ for the sizes computed; Baxter's result.
 - **Computed:** flux periods; free trits per cell; the 49% share of rings.
 - **Reading:** fluxoid as winding; half-quantum fluxoid, chiral wall and π coupling as the seam; the π crossover as the trit sequence; walls as closure by difference; rim, vortex lattice and kagome network as the net; $4e$ and $6e$ as meeting and going round.
 - **Open:** the $4e/6e$ count by ring size; the shape of the π crossover; the measured density of closed paths in kagome flakes; rings of three and six.
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Annotated References

The net

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