

The Resource Ledger

EXTENDING DOUBLE-ENTRY TO PHYSICAL MASS

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ABSTRACT

For five hundred years, double-entry bookkeeping has made monetary value verifiable: every debit has its credit, and symmetry exposes error. For physical matter, the books have only ever closed on one side. Inflows are tracked at the resolution of the modern supply chain; outflows are aggregated into unidentified mass and compressed into a single line item — disposal cost. This paper argues that the consequence of this asymmetry is not primarily a problem of measurement but of time: unidentified matter defaults to incineration or landfill, terminals that consign it from the economic timescale to one that exceeds it by orders of magnitude. It then argues that the constraint that produced the asymmetry — a trust layer resting on human testimony, audited at a cost that keeps verification partial — is now lifting, through the convergence of direct physical observation, autonomous interpretation, and tamper-evident record substrates. It proposes the Resource Ledger: five principles forming a chain in which each closes the failure mode the previous one leaves open — paired entries extended to physical mass; observation as the origin of every entry; autonomous reconciliation; a verification premium, paid by newly structural sovereign demand, that makes coordinated misrepresentation unprofitable; and a compliance surface that pays the first node back before any network exists. The paper closes by naming four open problems — classification, aligned interest, tolerance, and cold start — as the research program that follows.

I. THE ASYMMETRY

Every transaction has two sides. This principle — double-entry bookkeeping — has been the foundation of monetary accounting for five hundred years. Every debit has its credit, every revenue its matching expense, every asset its offsetting liability and equity. This symmetry is what detects error, exposes fraud, and renders the whole of economic activity legible. Without it, the modern financial economy could not exist.

The same principle has been applied to physical mass in the academy — as the material balance of chemical engineering, as material flow analysis. But it has never been adopted as an operational standard of account. The flow of physical resources is recorded with a striking asymmetry. Inflows are captured at the resolution a supply chain provides. Outflows, apart from regulated streams such as hazardous waste, are barely recorded in structured form at all. Within one and the same accounting

system, incoming matter is tracked by item, by lot, by quantity. Supply-chain management, refined over decades, produced one of the most precise industrial information systems humanity has ever built. Outgoing matter is aggregated into mass whose kind has been lost — cubic meters of volume, counts of bags and containers, mixtures whose composition can no longer be told apart. At the level of the books, this aggregated mass is compressed further still, into a single line item: disposal cost. There is an industrial information system on the inflow side. There is nothing of comparable order on the outflow side.

Luca Pacioli codified double-entry bookkeeping in 1494. In that year, money moved onto two-sided books. Matter never made the move. Matter is still managed on the bookkeeping that money graduated from five hundred years ago.

The consequence of this asymmetry is not, in the first instance, a problem of measurement. It is a problem of time. When matter leaves the books unidentified, it cannot be routed to reuse, recovery, or recycling. Its default destination is incineration or landfill. These do not make matter disappear; they are terminals that consign it from humanity's economic timescale to one that vastly exceeds it. Matter that could have re-entered circulation within a few years is instead dispatched onto a return cycle measured in centuries or millennia.

This temporal deferral has functioned, across decades of accumulated industrial activity, not as a side effect but as a structural mechanism — the mechanism by which civilization has converted renewable cycles into irreversible depletion. Its scale has been measured. Of the roughly 106 billion tonnes of materials entering the global economy each year, only 6.9 percent is secondary material — recycled or reused; the remaining 93 percent is virgin, newly mined, felled, or extracted. And the share keeps falling: it stood at 9.1 percent in 2018. The absolute quantity recycled is growing. But the economy's total intake of materials grows faster, so the ratio retreats. The growth of the mass returning to the books is not keeping pace with the growth of the mass leaving them. The visible symptoms — the scarcity of resources, the accumulation of waste, the fact that as of 2025 seven of the nine planetary boundaries have been transgressed — are what this mechanism produces. Three variables determine whether a circular economy is possible: the rate of consumption, the stock retained within the economy, and the time of return. The first two have been partially tracked. The third has never been treated as an operational variable of account.

II. THE CONVERGENCE

The turn began outside of technology. In the late 2020s, the political standing of physical resources changed structurally. What had been treated as an environmental matter — governed by voluntary effort, by ESG disclosure frameworks, by the moral authority of sustainability — was redefined as a question of economic sovereignty. Beginning in 2023, a major exporting nation progressively tightened controls on the outflow of critical minerals. Gallium, germanium, graphite, antimony, tungsten, a set of medium and heavy rare earths, and the processing technology for rare earths and lithium batteries came under restriction in turn. Materials that had been traded as commodities became instruments of strategic power. The waste materials present within a nation's own borders,

until then managed as a cost, were reappraised as a domestic source of supply. The urban accumulation of metals, plastics, and organics was no longer a waste stream to be processed at the lowest price. It was a strategic stock, and its accurate inventory became a matter of national concern. And an inventory demands verification. There is no resource sovereignty over unobserved mass. A stockpile that cannot be verified is not a stockpile.

The institutional response began with frameworks. The Global Circularity Protocol, launched at COP30 in November 2025 by the World Business Council for Sustainable Development and the One Planet Network (hosted by UNEP), is the first voluntary, science-based, globally harmonized framework for companies to measure, manage, and communicate their circular performance. The European Union's Digital Product Passport begins its phased rollout across 2026 and 2027 under the Ecodesign for Sustainable Products Regulation, in force since July 2024; its underlying DPP Registry is to stand up by July 2026, and the first product-level passport to be mandated is the battery passport, applying from February 2027 under the EU Battery Regulation. Each requires disclosure, at the level of the product, of material composition, origin, and end-of-life pathway. ISO/IEC Joint Technical Committee 5 was established in 2026 to develop global standards for the Digital Product Passport. GS1 Digital Link, identifier-resolution protocols, and sector-specific data ontologies have begun to converge toward a common basis for exchanging material information across organizations and jurisdictions.

Every one of these frameworks rests on a shared premise: that information about physical matter — its composition, its movement, its destination — can be trusted. Yet none of them builds the foundation of that trust. What they specify is which information, in which format, by whom, and when it is disclosed. How the physical truth beneath it is to be observed, recorded, and verified — independently of the party disclosing it — they do not specify. The present structure is a layer of structured disclosure laid over a base of self-declaration and audited assertion. The base itself remains what it has always been: human testimony about physical reality. However refined, the frameworks of the 2020s operate without the trust layer they tacitly presuppose.

The technical question, five centuries in the asking, was never how to apply double-entry to physical mass. It was how to make information about physical mass trustworthy in the first place. Double-entry rests on the premise that what is recorded reflects what occurred. For monetary transactions, that premise could be secured by institutional design. Banks, courts, accounting firms, and statutory audit formed a dense chain of mutual verification, closing the distance until a recorded figure was very nearly synonymous with the transaction behind it. For physical mass, no equivalent chain existed. Matter moves through trucks, gates, and machines. Its movement is attested by humans. Verification is performed after the fact, by other humans, on a sample — so it is infrequent, and beyond that point it does not pencil out. Since the manifest was invented, this structure has not changed. A human attests; a human audits; the cost of verification is high enough that verification is always partial.

No country has demonstrated both the reach and the limits of this structure at greater scale than Japan. Japan universalized its industrial-waste manifest in the 1990s and has operated it for more than three decades: a paired-entry system of testimony, in which generator and processor issue and return matching slips for every consignment, at roughly seventy million manifests a year — one of the

largest ledgers of matter ever run. Its operation has shown two things. The first is a limit of scope. The manifest covers only industrial waste consigned to third parties. The burnable waste that leaves offices and shops every day — commercial general waste, some twelve million tonnes a year — sits outside the national paired entries, apart from the separate control slips and reduction plans some municipalities impose. And the industrial side has a gap of the same shape. A manifest comes into being only at the moment matter is consigned to a third party; what a generator treats within its own premises involves no consignment, and so has no ledger. Of the roughly 370 million tonnes of industrial waste generated annually, the consigned share that reaches the manifest is about 160 million — less than half. This ledger records only transfers. Transformations and retentions go unobserved. The second is a limit of method. Even inside the ledger, the system succeeded in defining a chain of responsibility, yet mixtures of ambiguous kind continued to cross markets and borders under changed names, and beneath transactions that closed lawfully on paper, the actual destination of matter went unasked. Thirty years of operation established that paired entries are necessary but not sufficient. As long as both sides are testimony, symmetry merely replicates the lie symmetrically.

The change of the late 2020s was not a single technology but the simultaneous availability of three components, whose combination dissolves the dependence on human testimony. The first is direct physical observation: weighing systems integrated into collection and haulage vehicles, image recognition that identifies material composition without a purpose-trained model, sensor networks deployable at the cost of consumer electronics. The second is autonomous interpretation: agentic AI that resolves the ambiguity of observational data, detects discrepancies between declared and observed values, and can act on those discrepancies without a human in the loop, within rules defined in advance. The third is a record substrate that is tamper-evident and controlled by no single party — such that no participant can rewrite a recorded observation after the fact. This property may be realized by a distributed ledger, but is not limited to one; the requirement is functional, not technological, and several distinct approaches now meet it at industrial throughput and cost. None of the three resolves the trust problem alone. A sensor without autonomous interpretation still produces data requiring human review. Interpretation atop a record that is not tamper-evident can only produce conclusions its custodian may overturn. A record without direct observation merely formalizes the human testimony that was the source of the problem to begin with. The convergence of the three is what constitutes the change.

The dissolution of human testimony does not happen at once. It proceeds in stages, as the trust layer matures. In the present configuration, sensors perform direct observation, but human review remains in the loop for the edge cases that exceed what current models can interpret. As models improve, and as accumulated observation trains against the long tail of physical reality, that loop contracts. Human involvement moves from confirming individual judgments to designing the rules by which judgments are made, and to handling the disputes those rules cannot resolve. The endpoint is not the elimination of human judgment but the relocation of it — from inside every transaction to outside the system as a whole. The Resource Ledger is built for this trajectory, not for any single point along it.

What this convergence makes possible for the first time is to apply double-entry to physical mass at the resolution and continuity the principle demands: to observe inflows and outflows directly, to record them on a substrate no single party controls, and to reconcile them through an autonomous

process that converges on physical fact without depending on any single testimony. The asymmetry named at the outset — the precision of inflow records and the loss of outflow detail — was not born of anyone's negligence or a flaw of design. Human testimony and audit, the only machinery of trust then available, could support records only up to that resolution. Outflow records are coarse because that was the ceiling. That ceiling is now being raised.

III. THE PROPOSAL

What is proposed here is not new in its conception. More than twenty years ago, William McDonough and Michael Braungart, in *Cradle to Cradle* and the subsequent work on Intelligent Materials Pooling, set out the operating logic of an economy in which materials circulate through shared pools — an economy in which multiple parties deposit, withdraw, and replenish, across defined periods of use. That vision was specified at the level of design principle and business architecture. What could not be specified then, and what the vision required, was the operational foundation to make such pools trustworthy at scale: the means by which a deposit is verified, a withdrawal is recorded, and a discrepancy between declared and observed values is resolved without dependence on any single party. What is proposed here is that foundation. The Resource Ledger is the protocol layer the material pool has been waiting for.

The five principles that follow are not parallel requirements. They are a chain. Each principle closes the failure mode that the one before it cannot. With five, the chain closes.

1. Extending double-entry to matter

The first principle is the extension of double-entry to physical mass. Every transaction on the ledger records the movement of matter as paired entries: an outflow from one node and an inflow to another, equal in mass, equal in composition, equal in time. When the entries do not balance, the transaction is incomplete, and it remains unsettled until the discrepancy is resolved. This is not double-entry itself. It carries into material flow the principle of verification that double-entry brought to accounting — the mechanism by which symmetry exposes error. The idea of material balance has long existed in chemical engineering; the core of the proposal here is to recast it not as a method of after-the-fact analysis but as a continuous verification protocol that operates on every transaction.

The governing identity is conservation. For any node in the network, over any defined period, the matter that entered equals the matter that left plus the change in matter retained within it. Inflow equals outflow plus the change in stock. The identity holds because mass is conserved. The ledger does not impose this constraint; it records it. What the ledger adds is the requirement that the identity be reconciled at the level of identifiable matter rather than aggregated mass, and that the reconciliation occur continuously rather than after the fact.

The identity requires two boundaries to be defined: a temporal boundary and a material boundary. The temporal boundary sets the period over which inflow, outflow, and change in stock are reconciled — an hour, a day, a year, chosen by the implementation. The change in stock over the period is the difference between the stock balance at the period's end and at its start; matter present before the

period begins is treated as an opening condition and is not counted as flow. The material boundary defines what counts as retained within the node — inventory, matter embodied in fixed assets, matter contained in long-lived products. Both boundaries are chosen by the implementation, but within a boundary once defined, the identity holds exactly. Unless the boundary is defined, the principle cannot be applied. Once it is defined, at whatever scale, the conservation equation is exact.

Three categories of entry suffice to describe any flow. A **transfer** records matter moving from one node to another; both nodes make an entry, in opposite directions. A **transformation** records matter changing form within a node; the entry pairs input matter with output matter and any residue. A **retention** records matter remaining within a node across a period; the entry persists until that matter is transferred or transformed. Every physical movement, every chemical change, every accumulation into stock can be expressed as a combination of these three.

What everyday language calls consumption is, on this ledger, a species of transformation. Combustion does not erase matter: fuel is transformed into flue gas and ash, and food into biomass, breath, and residue. Matter used as energy still goes somewhere as mass. Conservation is never broken; what breaks is tracking. An implementation, in defining its material boundary, therefore also chooses how releases to air and water are handled — entered as outflows to an environmental node within the boundary, or recorded as exits across it, at which point tracking ends. Either way, an exit is entered as an exit. The only thing this ledger does not contain is silent disappearance.

But the limit of what symmetry guarantees must be stated precisely. In double-entry, what symmetry exposes is error. It does not expose lies. A fabricated transaction balances perfectly. This is what the accounting of money spent five hundred years learning, and it is why the chain of banks and audits was built outside the books. Paired entries are a grammar of verification, not a guarantee of truth. The next principle exists because of this gap.

2. Observation as the ledger's origin

The second principle is that entries on the ledger are generated from physical reality itself, not from a declaration about reality. Every transfer, transformation, and retention is observed, at the place and moment it occurs, by an instrument whose role is to register a material fact. The observation is not the basis for an entry made by someone; the observation *is* the entry. No human testimony intervenes between the physical event and its record.

This is a structural inversion of the trust layer. Under the conventional structure, the source of the entry is a declaration — made by a party with an interest in what the declaration says — and that declaration, if it is verified at all, is verified by another party. The Resource Ledger inverts this. The source is the observation; a declaration, where one exists, is confirmed against the observation. Where the two diverge, the observation prevails. The chain of testimony, refined over five hundred years but always constrained by the cost of verification, is replaced by a chain of observation whose cost falls year over year.

For this principle to function, one condition is required: independence must reside in the chain of observation, not in any single instrument. Self-weighting by the party generating an outflow is, on its

own, instrumented testimony. It becomes an observation when it is cross-checked against the independent weighing of the next party in the flow — the receiver, the hauler, the processor — each registering the same physical event from a different position of interest. Independence is not a property of a sensor; it is a property of the network that several sensors compose in series. Any single observation carries sensor error, sampling error, variation in composition and moisture. A single observation captures not the truth but an estimate with a tolerance. It is the linking and mutual cross-checking of several independent observations that makes the estimate converge on physical fact.

It should be said that in most present implementations, observation is hybrid: the mass is registered by an instrument, while the choice of material class and the confirmation of the record remain in human hands. What the principle demands is not full automation from day one. It is that the center of gravity of the entry keep moving, without reversal, from declaration to observation.

But this cross-checking opens a new question. "From a different position of interest," it was just said. In the flow of matter, do the interests really differ? That question is the subject of the next principle.

3. Autonomous reconciliation

The third principle is that discrepancies on the ledger are resolved without recourse to an external authority. When linked observations of the same physical event diverge beyond tolerance, the resolution is made by a mechanism internal to the system. No regulator, no auditor, no court is summoned. According to rules defined in advance, the ledger either proceeds or it does not.

Three conditions make this possible. The first is the structural condition already established: observation is generated from a chain of parties, and no single party controls the recorded outcome. The second is that each party in the chain holds an economic interest in the accuracy of its own observation. A party whose observations persistently diverge from others bears a cost; a party whose observations persistently agree earns trust. Cost and trust are substantive: they govern access to future transactions and the terms on which counterparties will engage. The third is that the resolution rules themselves are unalterable by the parties they govern. The logic of how a discrepancy is evaluated, how trust is updated, whether an entry is confirmed or held, is written to a substrate that no participant in the flow can alter alone. Without this, the rules become a new site of testimony, and the inversion is undone at the level of the protocol.

But the limit of this mechanism must be confronted directly. Reconciliation in finance works adversarially because the payer's interest opposes the payee's. The service chain of matter is not built that way. The generator pays; the hauler and the processor are its contractors. There are structural moments in which every party in the chain profits when matter disappears at the lowest cost. Here the interests do not oppose; they align. The alignment is simple. Proper treatment costs real money. Take the fee for proper treatment, route the matter somewhere cheaper — a relabeled category, improper storage, a dump — and the difference is surplus. The generator prefers the lower quote and, once it has paid, has no incentive to confirm where the matter actually went. The mechanism described above detects instrument error and fraud by a single party. Against a coordinated misrepresentation — the whole chain agreeing on the same number — cross-checking is powerless. When everyone tells

the same lie, the books balance perfectly. This failure mode cannot be closed by verification technology. It is closed by the next principle.

What this leaves to humans is not the work of testimony but the work of design. And at the center of that design is a problem not of observation but of classification. Measuring matter has become comparatively easy. What is hard is defining what the measured thing is. Contaminated resin, a mixture of several polymers, packaging with food residue attached, a composite. Real matter does not come with clean boundaries of kind. The "identifiable matter" the ledger records does not exist self-evidently; it is constituted by an ontology of classification. How that ontology is defined, how matter with ambiguous boundaries is handled, how new materials are placed within an existing scheme — this cannot be solved by observation technology alone. It requires a system of classification and the collaboration of humans and machines that operate it. The role of human testimony, dense at the level of the transaction, is not eliminated but relocated to the level of the system as a whole. Inside the system, ledger entries are generated and confirmed without human intervention. Outside it, humans define the conditions under which the system runs.

4. The gravity field

The fourth principle concerns what breaks a coordinated lie. It is not verification. It is demand.

Bitcoin's miners behave honestly not because its participants are virtuous, but because the block reward makes honesty the most profitable strategy. Security comes not from morality but from a budget. In the Resource Ledger, the reward is the premium that verified matter earns over matter that carries only testimony. Matter whose observations are recorded directly on the ledger offers verifiable composition, traceable origin, auditable destination. Matter not so recorded offers testimony instead — the very form of evidence the substrate was designed to replace. The price difference between the two — the verification premium — is this ledger's security budget. When the premium for being verified exceeds the surplus a chain can capture by conspiring to make matter disappear cheaply, and only then, honest observation becomes the dominant strategy.

The payer of this premium did not exist before, but it is now taking its seat — the turn described in Part II created it. Export controls put a price on matter of proven provenance. The Digital Product Passport is converting verifiable material information into a condition of market access, and regulations that create statutory demand for certified secondary material itself — the EU's Packaging and Packaging Waste Regulation, with its mandated recycled content, and ReFuelEU Aviation, with its blending obligations for sustainable fuel — are already in force. End buyers under Scope 3 obligations are committing budgets at scale to certified secondary materials. Moral demand was optional and has left the stage; sovereign demand is structural and does not leave. That the ledger's honesty stands on this demand is no fragility of the design — it is the same architecture by which Bitcoin's security stands on the economic value of the block reward.

Once the demand is seated, propagation requires no persuasion. It proceeds by the gravitational pull of the mass already recorded on the substrate. When enough physical mass is recorded that the cost of staying outside exceeds the cost of connecting, every party that transacts with a connected node faces a structural choice: connect to the substrate, or lose access to that node's flows. The connected

counterparty is preferred for the same reason a signed contract is preferred to a verbal promise: the cost of verification is lower, the risk of dispute is lower, the speed of settlement is higher. In time, a party not connected to the substrate is not rejected. It is simply no longer chosen. The threshold is not a function of belief, of ideology, of environmental concern. It is a function of mass.

Here, one precedent teaches the requirement of substrate neutrality. That no single party may control the substrate is not idealism. Maersk loaded one of the world's largest volumes of shipping onto TradeLens, the platform it built with IBM; in 2023, it shut down. The official reason given was that full industry collaboration had not been achieved. Rival carriers never connected their flows to a substrate controlled by a competitor. Mass generates gravity, but when the substrate is owned by one of the participants, the same mass turns to repulsion. Neutrality is a survival condition, drawn from the lesson of consortium substrates that stopped one after another.

Yet gravity is a function of mass. Then when the mass is zero, the gravity is zero. Why does the first node connect? Answering that question is the work of the final principle.

5. The compliance surface

The answer lies outside the network. The first node does not connect for the network's sake. It connects to be paid back — alone, from day one.

The fifth principle is compatibility with the existing institutional frameworks that govern physical matter. The Resource Ledger does not seek to replace the manifests, reports, certificates, and disclosure documents that existing law and standards require. It generates them. Material information recorded at the substrate level is emitted, on demand, in the formats specified by regulators, certification bodies, and existing protocols. The substrate operates by its own logic — direct observation, paired entries, autonomous reconciliation. The presentation surface operates by the logic of whatever framework reads it. The two are designed to be independent, so that the protocol can serve any framework without being subordinate to any.

The consequence is that much of compliance ceases to be a separate activity. Reporting to the authorities remains for as long as the institutions require it — but its preparation stops being the assembly of a declaration and becomes an emission from the substrate. Once the substrate is written, it can be emitted into any required format without an additional declaration. And between private parties who share the ledger, the round-trip of reporting itself becomes unnecessary. The parties who read the report — regulators, auditors, certification bodies — receive it in the form they are accustomed to. They need not understand the substrate that generated it. Existing frameworks continue to operate; they simply become consumers of a more trustworthy source of information than the one they were designed to read. No replacement is demanded, and none is necessary. What changes is the quality of the information the existing frameworks receive.

And this compatibility is more than a courtesy of interoperability: it is the protocol's cold-start engine. The preparation of manifests, the filing of regulatory reports, the assembly of disclosures — administrative burdens that exist today disappear at the single connected node, without waiting for a

network to form. The first node's reason to connect lies not in the ledger's future but in that node's own income statement, today. The network's value rises afterward, with the mass recorded on it.

The five principles

These five are not a parallel list but a single chain. Symmetry exposes error. Observation removes testimony from the entry. Reconciliation detects instrument error and the fraud of a single party. Demand makes coordinated lies unprofitable. The compliance surface gives the first node a reason to connect on a day when no network exists. Each principle closes the failure mode the one before it leaves open, and with five, the chain closes. The claim of this paper is that these are the necessary minimum and the permissible maximum: with fewer, the material pool conceived twenty years ago cannot operate at scale; with more, the protocol intrudes on choices that belong to those who implement it. That claim itself stands open to the work and criticism that follow. What is specified here is the logic by which material flows can be recorded, verified, and settled without recourse to the trust layer that has constrained such systems for five hundred years. What is not specified is the form any particular implementation must take: the protocol is one, and the implementations will not be.

IV. THE FOUR PROBLEMS

This paper closes by stating what is not solved. Before this ledger can operate at scale, four problems must be solved.

First, the Classification Problem. Who defines what the measured thing is, and how? The "identifiable matter" the ledger records is an artifact constituted by an ontology of classification; real matter has no clean boundaries of kind. The design of the ontology, the adjudication of boundary cases, the placement of new materials — none of this yields to observation technology; it requires a classification scheme and its governance. The deepest difficulty of the circular economy lies not in the precision of measurement but in this classification.

Second, the Aligned-Interest Problem. In the service chain of matter, unlike in finance, there are structural moments when the parties' interests align rather than oppose. When the whole chain agrees on the same lie, cross-checking is powerless. This paper has given a structural answer — honesty becomes dominant when the verification premium exceeds the surplus of collusion (Principle 4). But the quantitative condition under which that inequality holds at every node has not been established.

Third, the Tolerance Problem. Every observation carries sensor error, sampling error, and variation in moisture and composition. Widen the tolerance to avoid false alarms, and the power of verification itself is lost. The signal-to-noise condition under which reconciliation is meaningful has not been established. This problem dictates where the ledger begins. The signal of verification exceeds the noise first in materials of high value density and stable category. Critical minerals, battery materials, electronic waste — the domain long called the urban mine is the precise intersection of where sovereign demand already exists and where the signal-to-noise ratio already works. The ledger begins there, and descends toward mixed waste as the cost of observation falls.

Fourth, the Cold-Start Problem. Before a network exists, who connects first? This paper has given a structural answer — the compliance surface pays the single node back from day one (Principle 5). But the condition under which single-node value exceeds the cost of connection depends on jurisdiction and industry, and its demonstration is still to come.

To two of these problems — aligned interest and cold start — this paper has given structural answers. Two — classification and tolerance — remain open and pass to the work that follows. The four are set out here by the paper itself because they are at once the pressure points of its argument and the path along which the research now proceeds.

C O D A

What has been proposed is an extension. The principle of double-entry, applied for five hundred years to monetary value, is now applied to physical mass. An outflow from one node is an inflow to another, equal in mass, equal in composition. It is recorded by observation rather than testimony, and kept honest not by authority but by the value of being verified.

The asymmetry named at the outset — inflows identified, outflows lost — was not born of anyone's will or neglect. It was the ceiling on what records a trust layer resting on human testimony could support, audited at a cost so high that verification could only ever be partial. That ceiling is now being raised. When matter is observed at the site of its movement, and that observation is reconciled without a central authority, outflow becomes as legible as inflow. The ledger closes on both sides.

The consequence is measured in time. Identified matter can be returned to use. Identified matter need not be consigned to a timescale that dwarfs the human economy by orders of magnitude. As the ledger extends into every domain through which matter moves, the return cycle of matter contracts toward the timescale of the economy that uses it. The symptoms of the present asymmetry — depletion, accumulation, the transgression of planetary boundaries — are, at root, the symptoms of matter kept to one side of the books.

Mass has always been conserved. What leaves is always somewhere. Matter had two sides from the beginning. The record is only now catching up to its symmetry.

Further work is planned to follow this paper: a specification defining the entry schema, the reconciliation rules, and the tolerance model in an open form; and an evidence paper answering the Tolerance Problem in numbers, with reconciliation data from a running implementation.

Hiroki Omura — 2026. This is a working paper, offered openly for citation and comment.

APPENDIX — A MINIMAL FORMAL CORE

This appendix sketches the formal core to be defined in the specification work that follows.

Entry. An entry on the ledger is the tuple

$$e = (n_{\text{from}}, n_{\text{to}}, t, c, m, o, i)$$

where n_{from} and n_{to} are the origin and destination nodes, t the time of observation, c the material class under the classification ontology, m the mass, o the identifier of the observation, and i the identifier of the instrument that generated it. A transformation entry sets $n_{\text{from}} = n_{\text{to}}$ and pairs a set of input classes with a set of output classes, residue included. A retention entry is expressed as the stock balance $S_n(c, t)$ of node n in class c .

Conservation identity. For any node n , material class c , and period $[t_0, t_1]$:

$$\sum \text{inflow}(n, c) - \sum \text{outflow}(n, c) = S_n(c, t_1) - S_n(c, t_0) \pm \tau(c)$$

where $\tau(c)$ is the class-specific tolerance, defined as the composition of moisture, sampling, and instrument error. The design of τ is the Tolerance Problem itself (Part IV), and is to be calibrated against operating data in the work that follows.

State machine. An entry has three states:

pending → confirmed | disputed

An entry is confirmed when its pair reconciles within $\tau(c)$. When the pair does not arrive within its window, or the divergence exceeds $\tau(c)$, the entry moves to disputed and does not settle until the source of the divergence is identified. Each party's trust value is updated as a function of its agreement history and is reflected in its future terms of trade. The form of the trust-update function is left to the specification.

Sources

- Codification of double-entry: Luca Pacioli, *Summa de arithmetica, geometria, proportioni et proportionalità* (Venice, 1494) — the first printed systematic treatise on double-entry bookkeeping. Pacioli codified the method; he did not invent it.
- Global material throughput and circularity: ~106 billion tonnes entering the global economy annually; secondary-material share 6.9%, down from 9.1% in 2018. Circle Economy & Deloitte, *Circularity Gap Report 2025* (May 2025); reaffirmed in CGR 2026.
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- Critical-mineral export controls (China, 2023–2025): gallium and germanium (2023), graphite (2023), antimony (2024), tungsten (2025), medium and heavy rare earths and processing technology for rare earths and lithium batteries (2023–2025).
- Global Circularity Protocol: WBCSD and the One Planet Network (hosted by UNEP), launched at COP30, November 2025.

- EU DPP / ESPR: ESPR in force July 2024; DPP Registry due July 2026; battery passport applying from February 2027 under the EU Battery Regulation (2023/1542).
- ISO/IEC JTC 5, Digital Product Passport: established 2026, secretariat DIN.
- Japan's manifest system: introduced by administrative guidance in 1990; legally mandated for specially controlled industrial waste from April 1993 (1991 revision); extended to all industrial waste in December 1998, when the electronic manifest (JWNET) also began operation; electronic use mandated for large generators of specially controlled waste from April 2020. Scope: industrial waste consigned to third parties only (Waste Management Act, Art. 12-3). Volume: ~70 million manifests/year; ~47.5 million electronic in FY2025 (67.9%). Of ~374 million tonnes of industrial waste generated (FY2022), ~160 million tonnes consigned out is manifested; self-treatment on the generator's premises (e.g., on-site dewatering and incineration of sludge) involves no consignment and generates no manifest. ~11.9 million tonnes of commercial general waste falls outside the national manifest, though some municipalities impose their own control slips and reduction plans on large generators. MOE / JWNET.
- Statutory demand for secondary materials: EU Packaging and Packaging Waste Regulation, PPWR (Regulation (EU) 2025/40, in force February 2025; recycled-content targets for plastic packaging from 2030); ReFuelEU Aviation (Regulation (EU) 2023/2405; SAF blending obligations from January 2025).
- TradeLens: the Maersk–IBM blockchain trade platform; discontinuation announced 29 November 2022, offline by Q1 2023. Official reason: "the need for full global industry collaboration has not been achieved... not reached the level of commercial viability" (Maersk, 2022).
- McDonough & Braungart, *Cradle to Cradle* (North Point Press, 2002); Intelligent Materials Pooling (2001–2002).