Master Specification — India-Scale End-to-End Verifiable Voting (Wheel + One-Slot + Reusable Module)

Version: Spec-WheelSlot-Reusable-**v1.4.1** — **2026-01-02**

Authorship (page-1 header only): *Madhusudan Gopanna (primary)*; *GPT-5 Thinking (co-author)*

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0) Goal

Design and deploy a national-scale, low-cost, end-to-end verifiable voting system that:

- Preserves **ballot secrecy and receipt-freeness** (no voter can prove how they voted, not even themselves).
- Enables **voter-level inclusion verification** (each voter can confirm their ballot is in the final tally).
- Guarantees **one person, one counted vote** with public, append-only evidence.
- Operates **offline-tolerant**, power-frugal, and is manufacturable at low cost for low- and middle-income countries.
- Resists manipulation by powerful incumbents via **protocol, law, and real-time transparency tripwires**.

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1) Scope

- **Covers:** Polling-place hardware (reusable voter module, one-slot wheel interface), eligibility and authorization flow, cryptographic commitments, public bulletin board (permissioned consortium ledger), transparency telemetry, audits, governance, accessibility, operations, red-team testing, and acceptance metrics.
- **Excludes:** Remote/Internet voting; permanent personal devices; party-specific canvassing tools; postal ballot logistics (handled under same verifier rules but outside this spec).

1A) Provenance & Authorship

- **Primary author & systems architect:** *Madhusudan Gopanna* (global applicability), 2024–2025.

- **Technical co-author (collaborative AI):** *GPT-5 Thinking* — drafting, pressure-testing, cost modeling, editorial clarity.
- **Editorial stance:** Non-partisan, pro-democracy. Designed for adoption by **any lawful election authority worldwide** (not India-only).
- **Versioning:** VerifiableVoting-v1.3.2-2025-12-28. Change log in Appendix AB.
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2) Adversary Model

- **Capabilities:** Control of parts of bureaucracy/procurement, influence over media narratives, ability to starve capacity or delay logistics, access to vendors, and policy levers for quiet rule changes.
- **Constraints:** Must maintain plausible deniability; cannot openly eliminate elections; faces statutory tripwires and multi-party oversight.

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3) System Overview (Narrative)

1. Voter is verified at check-in and issued a **one-time authorization** (short-lived cryptographic token or printed slip with **QR/serial**) bound to that station's event.
2. **Eligibility step (pre-module):** at check-in, the officer verifies the voter's ID and roll entry. A capture station takes a **high-resolution facial image** and derives a **quantized face embedding**. Inside a secure device, this embedding is combined with the **election secret key** and electionId to form a **candidate voterhash** (see §7). The system checks this candidate voterhash against the election-wide used-voterhash index:
    1. if absent, it is tentatively accepted for this election and the voter proceeds to the Gate;
    2. if present, it is treated as a potential duplicate; the "best-of-three" and manual review SOP in Appendix C applies.

    Raw face images and embeddings are not written to the public ledger; only the final voterhash appears in the batch records.
3. Voter picks **any reusable module** from a pooled tray.
4. **Call-Up (HMC):** The dispensed module doubles as a **VRF-governed pager** (see §6.B). The voter proceeds to the seating area. When the module **vibrates** (short haptic pulse), they walk to the booth and cast within the fixed window. No wireless pairing or personal device is required.

5. At the machine, voter turns module to **VOTE**, inserts into the **single slot**. The voter rotates a **knurled wheel** until the desired candidate is framed in a **shrouded bracket**, then **confirms** (2-second hold).
6. Inside the module, a rotating minute-key (SE) and a window nonce are used to compute **voterhash**; the machine then computes a **votehash = H(voterhash, selection, device-only secret, window)**. The cast runs in **fixed 60 s**.
7. The voter receives a **receipt** that contains the pair **{voterhash, votehash}** (no choice revealed, no proof of choice possible).
   Sample receipt for illustrative purpose only – not real hash:
   Inputs (UTF-8, '|' separator):
   - minute_key = MK_EXAMPLE_0001
   - device_secret= DEVSEED_ABC123
   - window_nonce = WIN_2025-11-12T10:05Z
   - selection_id = CID-07

Inclusion Receipt (illustrative):

Election: IN-202X-LS-Phase3

Booth: TN-123-045

Batch Root: 5d3879de4ca2463fe8b6600b172efef735429b4d439df02afc6d33d64cb952e2

voterhash: db39cf612ba0023a342053d5394ee6e4c9812b3f805228a4debfe375d7ac9695

votehash: 13c0ee0ad55b9d98a2065a3c0018c8d5b7943ff9d5ac83246aca5b49373e231e

Use any verifier to check presence on the public ledger. Your choice is not included.

QR code would be generated with the following JSON:
{"ver":1,"batchRootShort":"5d3879de4ca2463fe8b6600b172efef735429b4d439df02afc6d33d64cb952e2","electionId":"IN-202X-LS-Phase3","boothId":"TN-123-045","voterhash":"db39cf612ba0023a342053d5394ee6e4c9812b3f805228a4debfe375d7ac9695","votehash":"13c0ee0ad55b9d98a2065a3c0018c8d5b7943ff9d5ac83246aca5b49373e231e"}

8. The module resets to **LOCK**, forgets everything, and returns to the tray. The authorization is consumed (at most one accepted cast per authorization).
9. The public ledger publishes **batches** (per §8/§8.3) containing: per-candidate **counts**, a set of **voters:{voterhash…}**, a set of **votes:{votehash…}**, a **VRF proof** of timing, and a **Merkle root** chaining to the previous batch. Voters later check inclusion via either hash in their receipt.

4) Security Properties (Must-Hold Invariants)

- **SP-1 Secrecy / receipt-freeness:** No artifact combination enables a voter to prove their choice.
- **SP-2 Inclusion:** Each voter can verify that **their** ballot is included (presence of either receipt value on the ledger).
- **SP-3 Uniqueness:** The ledger accepts **≤1** counted cast per valid authorization; duplicates/voids are visible and auditable.
- **SP-4 Eligibility separation:** The entity that verifies eligibility cannot link a person to a posted vote entry.
- **SP-5 Append-only public record:** Any attempt to prune/alter posted entries is detectable by independent replicas.
- **SP-6 Constant-time casting & anti-side-channels:** Choice does not affect timing, power, EM signature, audio/LED cues, or operator workflows.
- **SP-7 Accessibility parity:** Assisted voting preserves SP-1..6; assisted voters are not deanonymized by SKU or workflow.
- **SP-8 VRF verifiability:** Batch timing is chosen by a public **VRF**; anyone can recompute and detect operator discretion.
- **SP-9 Booth-binding auditability:** Every module re-bind is publicly posted; bound modules cannot cast outside the booth cert.
- **SP-10 Cacophony Defense (Anti-Capture Logistics):** Randomized, overlapping haptic call-up windows on a limited pool of modules ensure that each accepted voterhash can only be exercised by one human at a time. Attempts to "batch-process" many votes with a small colluding team degrade into logistical cacophony: modules buzz unpredictably, windows close if ignored, and a single person cannot service multiple modules concurrently. This collapses efficient booth-capture into an expensive, visible one-human-per-vote impersonation effort.
- **SP-11 Eligibility privacy & binding:** Eligibility is proven on a **separate ledger** via peppered commitments; casting sees only anonymized tokens. No linkage from person → receipt values is available to operators or observers.

5) Polling-Place Hardware

5.1 Reusable Voter Module (Core)

- **Mechanical:** Palmable sealed unit; 2-position turnkey: **LOCK → VOTE** (clockwise). IP54 shell; tamper mesh; epoxy potting.

- **Power:** Supercap + 200–300 mAh cell; **rack charging via pogo/USB-C**; tri-dot LED for battery. *(No PV or hand-crank on default module.)*
- **Compute:** Low-power MCU; secure element (SE/HSM) with monotonic counter; RTC.
- **I/O:** Piezo beeper; 3 LEDs (status); **sealed low-amplitude LRA haptic (HMC only)**. No NFC; no APP/user diagnostics mode.
- **Booth binding:** Module is **cryptographically bound** to a specific booth ID and its registered machines; it **only operates** with those machines.
- **Recalibration (re-binding):** Requires an **official provisioning device**; upon re-bind, the module enters a **1-week lock/quarantine** and emits a **Rebind Event** to the public audit log.
- **Modes:**
    - **LOCK (default):** all LEDs off; cannot cast.
    - **CALL-UP (HMC):** Outside the booth, the module emits short, randomized **haptic buzz** when its VRF-selected slot opens; no audio/light differentiation beyond standard status LEDs. If not inserted before **WindowClose**, the CALL-UP expires (no cast recorded) and the station may re-queue the voter.
    - **VOTE:** 10-second pre-insert window (LED chase); on insert → **CAST 60 s** constant-time; success → 1-second ACK then LOCK; error → purge + error tone + LOCK.
- **Service/attestation:** Diagnostics/attestation only via the provisioning jig under dual-control at depot; not in-booth and not via wireless.

5.2 Accessibility SKUs (identical externals)

All SKUs inherit the **sealed LRA** used for HMC; accessibility variants MAY expose richer haptic/audio cues that remain timing- and candidate-neutral.

- **Audio SKU:** Headphone jack; voice prompts; tactile confirm ring.
- **Visual-Plus SKU:** High-contrast LED bar near bracket; big-font mirrored text.
- **Haptic SKU (deafblind):** Sealed LRA; short buzz per detent; two buzzes on align; long on confirm. Duty-cycle limited.
- **Off-Grid Power SKU (regional):** Adds PV trickle panel and foldable hand-crank/dynamo; otherwise, identical firmware/exterior.

5.3 Wheel + One-Slot Voting Interface (Retrofit)

- **Wheel:** 60–80 mm knurled; uniform detents (0.25–0.35 N·m); encoder; neutral blank home index on reset.
- **Slot & Hood:** Single aperture with deep hood and side baffles; identical behavior for all candidates; anti-jam chamfer; sealed faceplate.
- **Confirm:** Sealed button; **2-second hold** to commit; identical cues for all candidates.

- **Parity:** No per-candidate LEDs, tones, or timing variation; dummy loads equalize EM/power signatures.
- **Booth binding:** Machine carries a **booth certificate**; accepts casts **only** from modules bound to that booth.

5.4 Charging & Disinfection Rack

- **Slots:** One per module (**N = 3 × M_v**). Slots mechanically mimic the machine's slot but **only** provide charging + UV-C disinfection; **no casting state** is possible in the rack.
- **Electrical: Pogo/USB-C** charging; per-slot current limit and health telemetry (voltage, temperature, cycle count).
- **Power & health:** Charge-state LEDs; cooling as required; rack reports fleet health to the station console.
- **Security:** Data-diode style ports (power/health only); no firmware writes; lockable door; inventory reconciliation at open/close.

5.5 Voter-Facing Test Mode (Spot-Check)

- **Purpose:** Allow any voter to spot-check that a module and machine are functioning correctly **without** affecting election data or revealing candidate mappings.
- **Activation:** Poll worker toggles **TEST** on the machine (keyswitch or sealed menu). Panel shows **"TEST"**; machine will not accept **CAST**.
- **Sample wheel overlay:** Removable **Test Wheel** disc printed with **random letters/symbols** (not candidate names/numbers). Mapping is randomized daily and posted on a placard for test only.
- **Flow:**
    1. Voter takes a bound module in **LOCK**; worker sets machine to **TEST**.
    2. Voter turns module to **VOTE**, inserts, rotates wheel to the prompted letter/symbol, and presses **Confirm**.
    3. Machine displays **"You selected: <symbol>"**.
- **Timing & privacy: No voterhash/votehash is ever generated; nothing posts to the ledger.** Test duration is **constant-time equal to CAST (60 s)** and uses identical cues.
- **Auditing:** TEST increments a **public Test counter** on the station dashboard; no per-module/per-voter IDs.
- **Abort & safety:** Exiting **TEST** requires keyswitch + dual-officer confirmation. Any mismatch quarantines the machine and prints a **TEST FAIL** incident code.

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6) Eligibility, Authorization & Gate

- **Check-in:** Officer validates voter; issues a **one-time authorization** bound to that station's event.
- **Consumption:** Machine accepts at most one CAST per valid authorization; duplicates visibly rejected and logged.
- **Accounting:** Station dashboard shows **authorizations issued**, **casts accepted**, **voids with reason**; totals reconcile at close.

6.A Human Factors:

The eligibility step adds a brief facial capture to the existing ID and roll check. In practice this is equivalent to a "selfie" interaction: look at the camera for 1–2 seconds, then proceed. Station staffing and capacity planning in §10 already assume this added constant-time step at check-in; most voters will experience it as a small addition compared to current queue and paperwork time, in exchange for visibly stronger election integrity.

6.B Face-Embedded Eligibility

- **Goal:** Prevent the same human body from voting more than once in a given election, without creating a permanent biometric database and without introducing a second public ledger.
- **Capture:**
    - At the eligibility desk, a dedicated capture device takes a high-resolution facial photo of the voter (front-facing, neutral lighting).
    - On-device, the image is converted into a bounded-dimension **face embedding** (e.g., a fixed-length float vector).
    - The embedding is immediately **quantized** (e.g., to 8–10 bits per dimension) to:
        - reduce sensitivity to small pose / lighting changes;
        - bound the information content;
        - simplify duplicate detection.
- **Voterhash formation (pre-cast):**
    - Inside a secure element (capture device or module), the system computes: voterhash = H(election_secret_key || quantized_face_embedding || electionId)
    - The **election_secret_key** is an election-scoped secret held under threshold custody (Election Commission + opposition + judiciary + universities). No single actor can reconstruct it.
    - The **quantized_face_embedding** and raw image are **never written** to the public ledger; only the derived voterhash appears, and only in the batch records for cast ballots.
- **Duplicate check (single-ledger design):**

    - The election backend maintains an **in-memory or indexed set** of all voterhashes that have already appeared in accepted batches for this election.
    - At eligibility time, the candidate voterhash is checked against this **used-voterhash index**:
        - If not present: mark it as "seen once (pending cast)" and allow the voter to proceed.
        - If present: flag as a potential duplicate and invoke the "best-of-three" retry and manual override SOP (Appendix C).
    - The index is **per-election only**. Voterhashes from one election cannot be linked to another because electionId and election_secret_key change each time.
- **False positives and SOP:**
    - To avoid punishing edge cases (twins, look-alike relatives, borderline embeddings), the system allows up to **three capture attempts**; if all three produce collisions, the voter is temporarily stepped aside.
    - A designated officer reviews the flagged entries (other voter's name, address, booth) and decides whether this is a genuine duplicate attempt or a benign collision.
    - Some duplicates may still pass; that is acceptable. The intent is not to reach 100% perfection, but to make large-scale multi-booth impersonation **logistically and statistically hard**.
- **Equity & Monitoring:**
  To guard against discriminatory behavior (e.g., higher collision/override rates for particular regions or communities), the election authority SHOULD publish anonymized statistics per booth and per district on: number of capture retries, duplicate flags, manual overrides, and final successful casts. If the data shows systemic skew, the model, capture configuration, or procedures MUST be corrected in subsequent elections.
- **Privacy:**
    - No raw images are published or stored in the public ledger.
    - The voterhash is **election-local** and derived under a shared secret; it cannot be used as a cross-election or commercial biometric identifier.
    - Only the election authority (and its multi-stakeholder key holders) can recompute a voterhash, and only for this election.
    - This design explicitly uses a one-time facial capture at eligibility to raise the cost of roll manipulation, ghost voters, and repeat voting across booths. The trade-off is intentional: a minimal, election-local biometric signal is accepted as the price of making alleged roll manipulation and bogus voters technically and statistically harder, without creating a permanent biometric database or a cross-election tracking ID.

- **Failure & Replacement Policy:**
  If a capture device begins to produce a suspiciously high rate of duplicate flags requiring manual override, it SHALL be taken out of service, replaced from a sealed spare pool, and subjected to diagnostics. Worst-case behavior (frequent overrides) increases human workload but does **not** weaken the one-human-one-vote property; a compromised device cannot silently authorize unlimited ghosts.
- **Design Rationale (Imperfect but Bounded):**
  No biometric system is perfect. This spec therefore combines
  - a deliberately coarse, quantized face embedding,
  - a best-of-three capture retry, and
  - a manual override path.

  The goal is not zero false positives, but to make multi-booth impersonation and high-volume fake voting dramatically harder than today, where there is effectively **no technical barrier** to ghost or imposter voting. As models improve, the embedding and quantization parameters MAY be updated under the same governance rules without changing the fundamental guarantees. Statistics from each election on duplicate flags, overrides, and successful casts SHOULD be published in aggregate so that any bias in the face-embedding pipeline can be detected and corrected over time. Integrity is achieved iteratively, not overnight.

6.C Cacophony Defense

- **Goal:** Destroy parallel fraud by enforcing one-human-one-module via time windows.
- **Mechanism (concept):**
  - The **Haptic-Module Call-Up (HMC)** mechanism implements what we call the **Cacophony Defense**: each reusable module buzzes in a VRF-governed, jittered window, independent of the others. A colluding officer trying to “play piano” with many modules at once faces a table of silent units that wake unpredictably. While they are casting with one buzzing module (fixed 60 s), other windows expire and go cold. To keep up, the attacker would need roughly one human body per active module. At scale, this turns wholesale booth capture from a fast, hidden software crime into a slow, crowded, and statistically obvious physical operation.
  - A public **VRF** using `(prevBatchRoot, beaconEpoch, boothId)` selects **staggered call-up slots** over a ±2 bin window (see §18 SWC).
  - The module **vibrates briefly** when its slot opens. The voter must reach the booth and **begin CAST** before **WindowClose**.
  - Multiple modules **can** buzz concurrently; a single person cannot service them all, creating the **Cacophony** that rate-limits collusion.

- **Timeouts & Re-queue:**
    - Expired HMC windows produce **no cast** and the station may re-assign the voter to a later slot. No per-voter identity is exposed to the casting system.

6.D Gate Protocol (One Human, One Module)

- At the booth entrance, the **Gate Officer** verifies that a **single human** holding the **buzzing** module is entering. No biometrics required. Purpose: prevent racks of buzzing modules from being funneled by one actor.
- By the time a module is handed to a voter and later buzzes under HMC, the election-wide duplicate check on voterhash has already been performed at eligibility; HMC then ensures that each accepted voterhash is exercised by a single human in a single cast window.

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7) Cryptographic Commitments (Abstract)

- **Rotating minute-key:** Derived inside SE from secret seed + time; non-exportable.
- **Voterhash:** Computed inside a secure element as

  voterhash = H(election_secret_key || quantized_face_embedding || electionId)

  where the quantized_face_embedding is derived at eligibility time from a one-time facial capture and never stored on the public ledger. The election_secret_key is held under threshold custody across multiple institutions. Voterhash is:
    - unique to this human + this election;
    - not reusable across elections;
    - not directly linkable to a civil identity without access to both the facial capture and the secret key.
- **Votehash:** H(voterhash, selection, device-only secret, window); does not reveal choice without the secret.
- **Receipt:** Voter receives **{voterhash, votehash}**; sufficient to prove **inclusion**, insufficient to prove **choice**. Inclusion can be proven with **either** hash (voterhash or votehash). Neither reveals choice without internal secrets. No per-ballot timestamps are emitted.
- **Batch publication:** Ledger publishes per-candidate **counts**, sets **voters:{voterhash…}** and **votes:{votehash…}** (order randomized; no per-ballot timestamps), **VRF proof** of timing (§8.3), and **Merkle chaining** to the prior batch.
- **Key Custody:** The election_secret_key is held under threshold custody with shares distributed across:
    - the Election Commission,
    - a designated representative of the Opposition, and
    - a rotating set of recognized national universities that meet statutory criteria.

Exact institutions and rotation rules are defined in law, not by this spec. The intent is that no single political actor or permanent bureaucracy can unilaterally reconstruct the key.

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8) Consortium Ledger (Public Bulletin Board)

- **Validators:** Election Commission, recognized opposition parties, apex court IT cell, national universities. Appends require threshold signatures.
- **Snapshots:** Hourly state snapshots mirrored to public archives; divergence alarms within 5 minutes.
- **Openness:** APIs and snapshots are public; verifier source is open.
- **Batch record (conceptual):**
  {
  electionId, **constituency**Id, **booth**Id, **batch**Id, **machine**Id,
  counts: { **candidate**Id -> N },
  voters: { **voter**hash, ... },
  votes: { **vote**hash, ... },
  prevRoot, root, vrfProof, beaconEpoch
  }

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9) Operational Telemetry & Tripwires

- **Live station metrics:**
  - uptime,
  - queue length bands,
  - modules in service,
  - attestation pass-rate,
  - **modules bound vs present**,
  - authorizations vs casts vs voids,
  - `eligCommits` (Eligibility commits appended),
  - `authIssued` (already present; keep),
  - `hmcExpired` (HMC windows expired without cast),
  - `gatePasses` (count of one-human-one-module admits)
- **Tripwires:** Z-score outliers auto-open incident tickets; breaches of wait-time SLO trigger surge redeployment or paper fallback. **Cacophony anomaly:** sustained 100% “CAST cadence = design rate” with **low variance** and **low hmcExpired** triggers review for scripted flow.

- **Privacy:** Telemetry carries no candidate or voter identity; reported at 5–10-minute granularity.

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10) Capacity Planning (Normative)

- Let **T** = voters assigned to booth; **H** = hours open; **λ = T/(60H)** votes/min required.
- Each module yields **~1 vote/min** (fixed **60 s**).
- **Booth provisioning rule:** If a booth has **M_v** voter machines, stock **N = 3 × M_v** reusable modules. Rationale: one **casting**, one **being returned/checked**, one **on rack** per machine.
- Typical India booth (T≈1,000, H≈11, M_v≈2): **N = 6** modules suffices; urban peaks scale with **M_v**.
- Surge cache at sector depot: **+1 × M_v** sealed spares.
- HMC introduces **bounded jitter** before CAST. Dimension waiting-area seating to `≥ M_v × 2` to absorb call-up overlap without degrading throughput.

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11) Privacy & Side-Channel Controls

- **Constant-time CAST (60 s); batch posting** per §8.3; no per-candidate signals.
- **Shrouded wheel + bracket**; no overhead line-of-sight of selection.
- **No personal wireless interfaces** on modules or machines.
- **Accessibility parity: identical enclosures with no outward label** across SKUs.
- Voter materials (placards, receipts, guides) MUST avoid implying that the receipt encodes a candidate choice. Standard language SHOULD emphasize that the receipt only proves inclusion, not preference.

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12) Attestation, Supply Chain & Tamper

- **Measured boot:** Firmware hashes on allow-list; SE holds attestation key; service-mode challenge/response only via sealed provisioning jig under dual-control.
- **Mixed vendors, lot randomization:** Prevent monoculture capture; distribution logs public.
- **Tamper mesh:** Opening zeroizes SE and raises a permanent visible flag; devices quarantined and logged.
- **Booth binding certificates:** Modules possess a **Booth-Bind Cert** signed by provisioning authority; machines verify this matches their **Booth ID** before CAST. Re-binding emits a signed **Rebind Event** to the ledger and enforces a **7-day lockout**.

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13) Availability & Chaos Engineering

- **Brownout drills:** PV + crank SKU + supercap sustain CAST in off-grid precincts; local cache persists until link resumes, then batch-commit.
- **Surge redeployment:** Pre-signed logistics to move spares within 30 minutes when SLO breached.
- **Fallback:** Paper contingency sealed and reconciled to ledger by RLA rules.

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14) Governance & Law (Binding Requirements)

- **In statute:** machine-readable rolls; public diffs per revision; observer access; **consortium ledger membership**; open verifier; RLAs; publication SLAs for telemetry and snapshots; whistleblower protections; procurement transparency; **VRF beacon source fixed in statute**.
- **Change control:** Supermajority + cooling-off for any rule change affecting audits, telemetry, or proofs; civil injunction path within 48 hours.

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15) Audits & Acceptance

- **Pre-election:** Red-team exercises (Appendix A) with public after-action reports.
- **Election-day metrics:** Attestation pass-rate ≥ 99.95%; 95th-percentile wait ≤ 20 min (urban) / 30 min (remote); zero unauthorized ledger rewrites; inclusion verification success ≥ 99.9% on first try.
- **Post-election:** RLAs and cryptographic verification; constituency-wise transparency packs (snapshots, verifier, how-to inclusion guide in major languages).
- Publish collision/override statistics by region to confirm that the face-embedded voterhash mechanism is not disproportionately burdening any community.

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16) Cost & Deployment (Indicative)

- **Module BOM (core): ~$10–$13** at national scale (PV/hand-crank removed from default).
- **Off-Grid Power SKU:** add **~$3** per unit (PV + crank) where required.
- **Wheel retrofit:** ~$15–$20 per machine.
- **Station kit (normative): N = 3 × M_v** modules + charging/UV rack + retrofit + spares, reusable for 5–7 years.
- **National roll-out:** For ~1.05M booths, hardware capex under pooled-reuse model scales with **M_v**; see Appendix E for scenarios.

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17) Rollout Plan (Phased)

1. **Pilot (≤1%)**: mixed urban/rural; public observers; publish full data.
2. **Scale-up (10–25%)**: incorporate after-action fixes; independent audit sign-off.
3. **Nationwide**: statutory tripwires live; transparency dashboards public; bug bounty on verifiers.

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18) VRF-Governed Sliding-Window Cadence (SWC)

Definition. For each batch, a verifiable randomness function (**VRF**) seeded with the prior batch root and a public randomness beacon selects a step $\Delta \in \{-2, -1, 0, +1, +2\}$ to shift a center index over 5-minute bins, forming a ±2 sliding window. Using the same seed, the system deterministically selects the batch interval **R** from that window. Batches close on **time**, **size**, **idle**, or **end-of-poll**—whichever occurs first. Operators have zero discretion. Observers recompute Δ, the window, and **R** from the published **VRF proof** in the batch header.

Rationale. SWC is unpredictable to adversaries, reproducible to auditors, and resistant to operator timing games. It reduces timing-correlation fingerprints while preserving bounded latency.

Requirements.

- Publish the **VRF proof** and **beacon epoch** in the batch header.
- All machines in a booth share the same **R** for a given batch.
- No per-ballot timestamps; randomize order of votes and voters sets.
- Optional publication jitter ±(30–60 s) after batch close.
- **HMC coupling:** The same VRF seed governs both **batch cadence** and **call-up slots** to ensure public reproducibility and zero operator discretion.

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19) Designated Paper-Trail Booths (Eco-Minimal)

Scope. Only booths pre-earmarked for paper trail produce physical artifacts; all others remain paper-quiet.

When to print. At each **batch close** (per §8.3 SWC) in an earmarked booth.

What to print (Batch Anchor Slip).

- **Batch Merkle Root (full)** and **short ID** (QR optional).
- **Prev Root (short)** to show chaining.
- **Counts per candidate** for this batch.

- Header: *Election ID, Constituency ID, Booth ID, Voter Machine ID, Batch ID, Window Label (SWC).*
- Signatures: two officers + one observer.

What never appears on paper. No votehash list, no voterhash list, no per-ballot timestamps, no mapping from votehash → candidate.

Chain of custody. Affix slips to a **Daily Audit Sheet** or store sequentially in a sealed envelope; record slip count in the booth log.

Public verification. Anyone can scan or enter the printed root to confirm it matches the public ledger; candidate counts match posted proofs. Slips are ancillary anchors, not primary records.

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20) Representative Diagrams (stroke-only, black & white)

Fig. 1 - Two-position key (LOCK→VOTE); sealed secure element; edge contacts; no NFC/BLE; booth-binding.

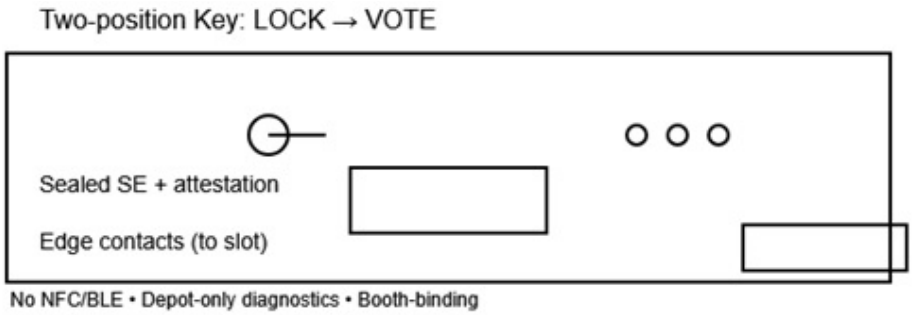


Fig. 2 – Wheel can rotate either direction; wheel selects into bracket; single hooded slot; constant-time cast; confirm button.

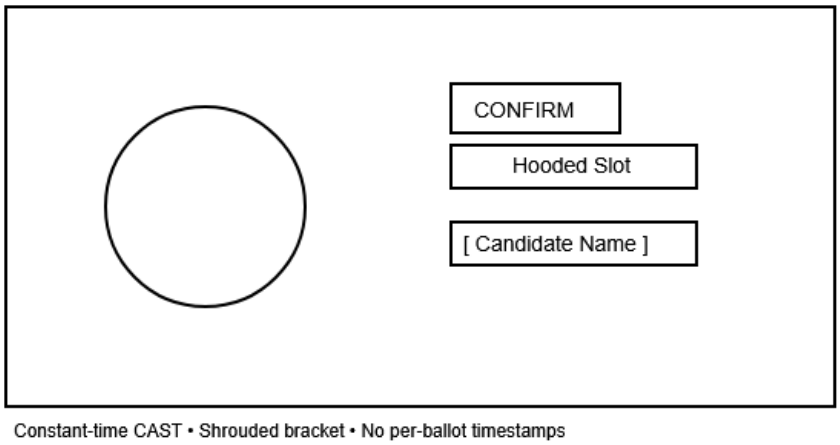
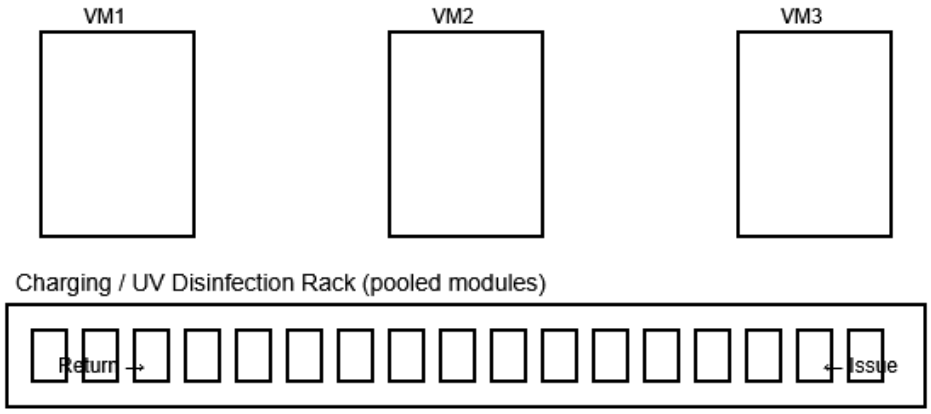


Fig 3 – Pooled module rack with charge/UV; flow: issue → cast → return; modules are booth-bound. Modules act as **call-up pagers** (short haptic) prior to CAST; seating area absorbs randomized call-ups.



Appendices

Appendix A — Red-Team Playbook (Public)

Goal: Attempt to violate secrecy, inclusion, append-only behavior, attestation, booth-binding, or VRF cadence **without** insider privileges, and with plausible operator constraints.

A.1 Threat Matrix (examples)

1. **Timing games:** Correlate per-voter cast time with posting time to infer choice.
2. **Batch tamper:** Prune or reorder posted entries without breaking chain validation.
3. **Booth-binding bypass:** Use a bound module at the wrong booth/machine.
4. **Attestation forgery:** Boot unauthorized firmware or spoof SE attest.
5. **Side-channels:** EM/audio/power differences that correlate with candidate selection.
6. **Receipt proving:** Use receipt artifacts to prove choice to a third party.
7. **VRF manipulation:** Predict/steer the sliding-window cadence (SWC) or suppress proofs.
8. **Booth Capture / Silent Collusion / Mass Imposter Voting with Valid IDs**

A.2 Test Cases (sample)

1. **Timing:** Capture ingress camera timestamps vs batch publication times; show inference failure (AUC≤0.55).
2. **Batch integrity:** Try removing one `votehash` locally; verifier must detect chain break via `prevRoot/root`.
3. **Binding:** Module from Booth X fails CAST at Booth Y; ledger logs no CAST; local audit shows “binding mismatch”.
4. **Attestation:** Swap MCU image; provisioning jig must reject SE quote; device quarantines.

5. **Side-channel:** Measure current draw for 1000 casts across candidates; distributions indistinguishable (KS-test p>0.1).
6. **Receipt proving:** Attempt to construct a provable link from receipt to candidate; must be impossible without internal secrets.
7. **VRF:** Pre-compute R from public beacon only; must be infeasible without prior batch root.
8. **Booth Capture / Silent Collusion / Ballot Stuffing** is neutralized primarily by the Cacophony Defense (see SP-10, 6.B): the randomness and concurrency of HMC windows force one-human-per-module behavior.

A.3 Success Criteria

- Zero successful secrecy or append-only breaks.
- Inclusion checks reproducible by any third party (≥99.9% success).
- Binding/attestation/VRF incidents auto-quarantine with logged evidence.

A.4 Reporting

- Public after-action within 30 days: scenario, exploit path, mitigations, patches, verification artifacts.

A.5 Design Trade-offs (Transparency Note)

This system is deliberately opinionated. It chooses certain frictions and constraints to make large-scale manipulation expensive, slow, and visible, rather than pretending perfection is possible.

1. **Biometrics vs. Ghost/Imposter Voting**
    1. Trade-off: We accept a *minimal, election-local* facial capture at eligibility to derive a voterhash, instead of relying solely on paper rolls and officer memory.
    2. Why: Today, nothing stops the same human from voting in multiple booths with legitimate IDs, or dead/ghost entries being silently exercised.
    3. Guardrails: The embedding is quantized, the hash is election-local, the key is threshold-held, and no raw images or embeddings are ever written to the public ledger.
2. **False Positives vs. Unlimited Parallel Fraud**
    1. Trade-off: We accept that a small fraction of voters may hit duplicate flags or require manual override (twins, look-alikes, model error).
    2. Why: In exchange, high-volume impersonation and multi-booth “piano playing” become logistically hard and statistically obvious.
    3. Guardrails: Best-of-three capture, manual override, and publication of aggregate collision/override statistics allow bias to be detected and corrected across elections.

3. **HMC & Cacophony vs. “Smooth” Throughput**
    1. Trade-off: We introduce Haptic-Module Call-Up (HMC) and VRF-jittered windows, which make flow slightly less “smooth” than a simple line.
    2. Why: The same randomness and overlap that create a bit of visible chaos for attackers is what collapses booth capture into a one-human-one-module rate limit (Cacophony Defense).
    3. Guardrails: Capacity planning and seating are sized so that honest voters still experience bounded, predictable waits within the SLOs in §15.
4. **Extra Hardware/Protocol vs. Blind Trust**
    1. Trade-off: We add secure elements, booth-binding, Merkle-chained batches, VRF cadence, and a public consortium ledger.
    2. Why: In return, anyone can recompute tallies, verify append-only behavior, and run independent verifiers against the same data the authority uses.
    3. Guardrails: All verifier code is open; hardware and firmware are subject to measured boot, attestation, and independent audit.
5. **Incremental Correction vs. Illusion of Perfection**
    1. Trade-off: We explicitly accept that early deployments may expose model quirks, regional edge cases, or operational rough edges.
    2. Why: The system is designed to *surface* these issues in data (collision rates, overrides, tripwires), so they can be corrected in subsequent elections, instead of remaining invisible.
    3. Guardrails: Metrics and after-action reports are public; parameters (embedding, thresholds, HMC timing) can evolve under the same governance rules without weakening the core guarantees.

In short, this architecture does **not** claim to make fraud impossible or humans infallible. It aims to make:

- each real vote verifiable by its owner,
- each counted vote publicly accountable in an append-only record, and
- each fake or repeated vote **costly enough and visible enough** that scaling it to “state-managed fraud” becomes a practical impossibility rather than a mere legal prohibition.

Appendix B — Glossary & Normative Language

- **CAST:** Fixed, constant-time vote casting window (nominally 60 s).
- **Receipt-freeness:** A voter cannot prove their choice to a third party.
- **Booth-binding:** Module/machine cryptographic binding to a specific booth.
- **VRF:** Verifiable Random Function; governs batch timing window and interval.

- **SWC:** Sliding-Window Cadence derived from VRF (±2 bins over 5-minute centers).
- **RLA:** Risk-Limiting Audit; statistical audit of reported outcomes.
- **MUST/SHOULD/MAY:** RFC-2119 normative keywords used throughout this spec.

Appendix C — Verifier Test Vectors

C.1 Example Receipt Payload (QR)

{"ver":1,"batchRoot":"5d3879de4ca2463fe8b6600b172efef735429b4d439df02afc6d33d64cb952e2","electionId":"IN-202X-LS-Phase3","boothId":"TN-123-045","voterhash":"db39cf612ba0023a342053d5394ee6e4c9812b3f805228a4debfe375d7ac9695","votehash":"13c0ee0ad55b9d98a2065a3c0018c8d5b7943ff9d5ac83246aca5b49373e231e"}

C.2 Example Batch Record (conceptual JSON)

{
  "electionId": "IN-202X-LS-Phase3",
  "constituencyId": "TN-123",
  "boothId": "TN-123-045",
  "batchId": "TN-123-045-0007",
  "machineId": "VM-A",
  "counts": { "CID-01": 103, "CID-02": 97, "CID-07": 111 },
  "voters": [
    "db39cf612ba0023a342053d5394ee6e4c9812b3f805228a4debfe375d7ac9695",
    "9a3b8e7c0b9f4d83e8e29b7f0d1bf3cd8083a7d9a2f2b3c4d5e6f7a8b9c0d1e2"
  ],
  "votes": [
    "13c0ee0ad55b9d98a2065a3c0018c8d5b7943ff9d5ac83246aca5b49373e231e",
    "9f52b7f5b2f8d4a1f0c9e8d7c6b5a4f3e2d1c0b9a8f7e6d5c4b3a29181726354"
  ],
  "vrfProof": "VRF-PROOF-BASE64",
  "beaconEpoch": "2025-11-12T10:05:00Z",
  "prevRoot": "79f0e8b3d8e6d1c0b9a8f7e6d5c4b3a29181726354c6d7e8f9a0b1c2d3e4f5a6",
  "root": "5d3879de4ca2463fe8b6600b172efef735429b4d439df02afc6d33d64cb952e2"
}

C.3 Verifier Cross-Checks

- sum(counts.values()) == len(votes)
- len(votes) == len(voters)

- root == Merkle(batch_body) where batch_body excludes root
- prevRoot links to previous batch's root
- vrfProof validates (Δ,R) against prevRoot + beaconEpoch

Appendix D — Receipt & QR Specification

D.1 Canonical Receipt Payload (QR)

- Encoding: **UTF-8 JSON** (option: CBOR in future)
- Fields:
  - ver (uint) — schema version
  - batchRoot (64-hex) — full Merkle root of the batch
  - electionId (string)
  - boothId (string)
  - voterhash (64-hex)
  - votehash (64-hex)

D.2 Printing Requirements

- ECC: **Q** (25%) or **H** (30%)
- Size: ≥ **25 mm** square; high contrast; matte stock
- Quiet zone: ≥ **4 modules**

D.3 Human-Readable Lines (on paper)

- Truncate only in print preview (e.g., first/last 8 hex chars).
- **Do not** truncate in QR.

D.4 Privacy Constraints

- No per-ballot timestamps
- No operator/station PII beyond boothId already public
- No candidate identifier in receipt

D.5 Voter-Facing Message (Receipt Footer)

Each printed receipt SHOULD include a short human-readable line, for example in English and local languages:
"Use any verifier to check that your vote is included on the public ledger. This receipt **cannot** reveal which candidate you chose."
The message reinforces receipt-freeness and inclusion without implying that the receipt carries a choice marker.

Appendix E — Cost Scenarios (Indicative)

Scenario	M_v (machines /booth)	Modules per booth (N=3×M_v)	Core Module BOM	Off-Grid SKU delta	Wheel Retrofit / machine	Rack (per booth)	Notes
Base rural	1	3	$10–13	+$3	$15–20	$40–60	Low power; off-grid in 20% booths
Standard	2	6	$10–13	+$3	$15–20	$60–90	Typical India booth (T≈1k, H≈11)
Urban peak	3	9	$10–13	+$3	$15–20	$80–120	Add surge cache +3 modules/sector

Reuse horizon: 5–7 years hardware; firmware OTA under measured-boot.
National roll-out: ~1.05M booths × scenario mix; procurement diversified across vendors.

Appendix F — Accessibility Parity Checklist

- **Timing parity:** Assisted SKUs use identical **CAST 60 s** window.
- **Cue parity:** Audio/visual/haptic cues standardized (no candidate-specific signals).
- **Enclosure parity:** External appearance indistinguishable; masking caps for special ports.
- **Path parity:** No distinctive operator handling that could deanonymize.
- **Attestation parity:** Same SE/attestation; SKU flag not externally exposed.
- **Documentation:** Public guidance in major languages; tactile and audio instructions.

Appendix G — Governance Text Pack (Model Clauses)

G1. Public Rolls & Diffs (statute):

"The Commission SHALL publish machine-readable electoral rolls and SHALL publish a public diff for every revision."

G2. Consortium Ledger:

"A public, append-only bulletin board SHALL be maintained by a consortium of validators

(Commission, recognized opposition parties, apex court IT cell, national universities) with threshold signatures."

G3. VRF Beacon Source:

"The batch cadence SHALL be governed by a VRF seeded from the prior batch root and a public randomness beacon designated by statute."

G4. Open Verifier & Snapshots:

"The reference verifier SHALL be open-source. Hourly snapshots SHALL be published with divergence alarms ≤ 5 minutes."

G5. RLAs & Telemetry:

"Risk-limiting audits SHALL be conducted. Station telemetry SHALL be published at 5–10 minute granularity without PII."

G6. Change Control:

"Changes to audit/telemetry/proof rules REQUIRE supermajority approval and a 30-day cooling-off period with injunctive relief available within 48 hours."

G7. Rotating Academic Custodians:

"University key-holders SHALL be selected from a rotating pool of recognized institutions defined in statute. No institution MAY hold custody for consecutive general elections."

Appendix H — Operational Telemetry Schema (Public)

H.1 Station Metrics (5–10 min)


```
{
 "electionId": "IN-202X-LS-Phase3",
 "boothId": "TN-123-045",
 "uptimeSec": 39240,
 "queueBand": "0-5|5-15|15-30|>30",
 "modulesPresent": 6,
 "modulesBound": 6,
 "castsAccepted": 742,
 "authIssued": 760,
 "voids": 8,
 "attestationPassRate": 0.9996,
 "testModeCount": 14,
```

```
 "eligCommits": 761,
 "hmcExpired": 12,
 "gatePasses": 748
 "lastBatchRoot":
"5d3879de4ca2463fe8b6600b172efef735429b4d439df02afc6d33d64cb952e2"
}
```


H.2 Divergence/Tripwire Events


```
{
 "type": "TRIPWIRE",
 "boothId": "TN-123-045",
 "metric": "queueBand",
 "zscore": 3.2,
 "threshold": 2.5,
 "action": "SURGE_DEPLOYMENT"
}
```

Appendix I — Provisioning, Attestation & Rebind

I.1 Measured Boot & Attestation

- SE holds device keypair; MCU boots allow-listed hashes; attests (fwHash, seState, boothId) to provisioning jig.
- Station accepts CAST only after verifying attestation stamp within validity window.

I.2 Booth Binding

- Module stores **Booth-Bind Cert** signed by authority; machine presents **Booth ID**; CAST proceeds only if match.

I.3 Rebind Event & Quarantine

- Rebinding requires dual-control jig; emits on ledger:


```
{
 "event": "REBINDBIND",
 "moduleId": "MOD-XYZ-123",
 "fromBooth": "TN-120-002",
 "toBooth": "TN-123-045",
 "when": "2025-11-01T09:00:00Z",
 "sig": "BASE64-THRESHOLD-SIG"
```

}

- Module enters **7-day lockout** before activation at new booth.

Appendix J — Formal Threat Model (Summary)

J.1 Adversary Capabilities

- Partial control of logistics/procurement/media; limited insider influence; access to vendors; policy levers for quiet rule changes.

J.2 Constraints

- Must preserve plausible deniability; elections cannot be abolished; subject to public proofs and multi-party oversight.

J.3 Assumptions & Trust Roots

- Mixed vendors; SE supply diversity; threshold-sig validator set; public randomness beacon integrity.
- This system **does not** attempt to avoid biometrics entirely; instead, it constrains biometric use to an election-local hash derived under multi-party key custody, as a deliberate answer to the long-standing “fake voter” and roll-manipulation problem.

J.4 Mitigation Mapping

- **Secrecy:** constant-time casting; receipt excludes choice; no per-ballot timestamps.
- **Inclusion:** dual-hash receipt; public sets {voters}, {votes}.
- **Append-only:** Merkle chaining prevRoot→root; hourly snapshots; third-party mirrors.
- **Binding/Attest:** Booth-Bind Certs; measured boot; public Rebind Events.
- **VRF/SWC:** Window and R from VRF(prevRoot, beacon); operator has zero discretion.
- **Flow-rate integrity:** HMC + Gate Protocol enforce **one-human-one-module**, collapsing mass impersonation into slow, observable behavior (Cacophony Defense).
- **Cacophony Defense:** It is the property whereby VRF-jittered call-up windows on a limited pool of physical voting modules destroy an attacker’s ability to process many ballots in parallel. Instead of one official rapidly casting dozens of votes in sequence, each accepted ballot requires a distinct human present in the room, waiting for a single module to buzz within its short window. Scale becomes the attacker’s enemy.

- **Voter Integrity:** Face-embedded voterhash + election-wide duplicate index raise the cost of multi-booth impersonation: each fake vote still needs a human body and a unique face capture.

Appendix K – Authorship & Roles

Primary Architect & Author: Madhusudan Gopanna

- Conceived and designed the overall system architecture, threat model, flow, and governance.

Collaborative AI Co-Author (Drafting & Systems Companion): GPT-5 Thinking

- Assisted with drafting text, structuring the specification, stress-testing flows, exploring attack surfaces, modelling implementation cost estimates at scale, and tightening language.
- All core concepts, mechanisms, and final design decisions originate from and are owned by Madhusudan Gopanna.

Red-Team & Adversarial Analysis: Gemini 3 Pro

- Assigned AI Red Team role: challenged assumptions, proposed attack scenarios, and reviewed the design from an adversarial perspective to harden the system.
- Deep research studies for economic and latency case studies in comparison against the last Indian General Election.

Appendix K — Change Log & Citation

- **v1.0 — 2025-11-09:** Initial consolidated master spec; booth-binding; N=3×M_v provisioning; rack charging/UV; voter-facing Test Mode; English placards; cost tables; authorship section.
- **v1.1.0 — 2025-11-09:** Removed NFC & APP user mode; two-position key (LOCK→VOTE); updated privacy and attestation; updated module BOM; clarified Test Mode (LOCK only); editorial fixes.
- **v1.2.0 — 2025-11-09:** Added **§8.3 SWC** (VRF-governed cadence; ±2 window; zero operator discretion).
- **v1.3.0 — 2025-11-09:** Dual-hash **receipt {voterhash, votehash}**; explicit **ledger sets** (voters, votes) with randomized order; **SP-8** (VRF verifiability) and **SP-9** (booth-binding

auditability); clarified Test Mode (**no hashes, 60 s**); batch record box in §8; governance adds **statutory VRF beacon**.

- **v1.3.1 — 2025-11-12:** Editorial sync; version & citation alignment; text-only PDF build.
- **v1.4.0 – 2025-12-28:** Additional details; improved diagrams; JSON and QR code for improved verification.
- **v1.4.1 — 2026-01-03**: Voterhash is now computed as an election-local hash of a quantized facial embedding under a threshold-held election_secret_key, enabling duplicate-defense ("one human body ≈ one vote per election") without storing raw biometrics on the public ledger. Eligibility and casting remain separated by the Gate; **Haptic-Module Call-Up (HMC)**, **Gate Protocol (one-human-one-module)**, and **Cacophony Defense**. Core module now includes a minimal sealed LRA haptic for HMC. Telemetry and Security Properties updated.

How to cite:

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