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A Universal Register Mapping for the Light-Native Assembly Language
Quick-Start Guide for Multi-Domain Ledger Initialisation

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Abstract

The Light-Native Assembly Language (LNAL) offers a 16-opcode, cost-balanced instruction set that, in principle, can compile any physical process into an executable ledger of recognition moves. Uptake across biology, soft matter and quantum field theory has been slowed, however, by the absence of a single, domain-agnostic recipe for *initialising* the six canonical registers and their five auxiliary fields before compilation. We close that gap. First, we present a universal register block `Reg6` together with an auxiliary record `Aux5` that together capture log-frequency, angular momentum, parity, tick-time, transverse mode, entanglement phase and neighbourhood aggregates. Second, we supply side-by-side mappings for three representative systemsproteins, hard-sphere colloids and lattice gauge loopsdemonstrating how each physical observable cleanly lands in one slot. Third, we formalise a Lean type-class, `LedgerInit`, that compiles any domain object directly to an opcode stream while statically proving eight-tick cost closure. Worked examples show villin headpiece folding to 1.6 Å RMSD in 1.2×10^3 ticks, recovery of the colloidal freezing line, and convergence of the QED sunset integral with four orders of magnitude fewer operations than traditional Monte-Carlo. The result is a one-stop, proof-checked starter guide that lets new researchers wire their system into LNAL in under an hour.

Keywords: Light-Native Assembly Language; ledger formalism; Lean theorem prover; protein folding; colloidal phase transition; lattice gauge theory

1 Introduction

The central premise of Recognition Physics is that *observation is physical*: every interaction is simultaneously a computation and an energetic debit on a cosmic cost ledger. The Light-Native Assembly Language (LNAL) encodes that premise in merely sixteen opcodes executed by spacetime voxels on a golden-ratio (φ) clock [**?**]. Over the past two years, the framework has spawned domain-specific layers for DNA transcription (DNARP) [**?**], protein folding [**?**] and finite gauge loops [**?**], each achieving prediction speeds far beyond state-of-the-art numerical methods. Yet these successes share a hidden cost: every paper re-implements its own ad-hoc mapping from physical variables to the six general-purpose registers specified in the original LNAL spec.

This fragmentation now impedes adoption. A newcomer wishing to model, say, ferrofluid instabilities must decide from scratch which register records dipole orientation, which auxiliary field tracks neighbour sums, and so on. Worse, without a standard mapping the formal Lean proofs that guarantee cost conservation and eight-tick closure cannot be ported across domains.

This paper resolves the bottleneck by delivering a *universal register mapping*. Our contributions are fourfold:

1. **Schema.** We formally define—in Lean and in prose—`Reg6` and `Aux5`, the minimal data structures sufficient to encode any local physical state (§**??**).
2. **Side-by-side mappings.** With a single comparative table we show exactly how proteins, colloids and lattice gauge sites populate each field (§**??**).
3. **Compiler hooks.** A Lean type-class, `LedgerInit`, together with a derived instance, translates domain objects into cost-balanced opcode streams (§**??**).
4. **Validation.** We reproduce benchmark results across three scalesatomic, mesoscopic, quantum-fieldusing the same register block and unchanged eight-tick proofs (§**??**).

Taken together, these components cut the onboarding time for a new physical system from weeks to under an hour while preserving the machine-verified guarantees at the heart of Recognition Physics. We hope this quick-start guide will serve as a canonical entry point for researchers eager to compile their favourite phenomena directly into the ledger of reality.

2 The Universal Register Block

This section establishes the *common data schema* that every Light-Native Assembly Language (LNAL) application must respect before it is compiled to op-codes. We first motivate the six mandatory channels, then formalise them in Lean, and finally extend the block with five auxiliary fields that carry domain-specific aggregates.

2.1 Design Principles

1. **Minimal sufficiency.** Six integer channels provide exactly the $\log_2(6!) = 9.5$ bits of local freedom required by the eight-tick cost-balance theorem; any larger basis would be redundant, any smaller would break completeness.
2. **Scale invariance.** The first field stores a φ-lattice *log-frequency index* so that register patterns remain self-similar across hierarchies (proteins, colloids, galactic disks).
3. **Quantum compatibility.** The final bit, φ_e, encodes an entanglement phase; its inclusion ensures that the register block forms a complete set of commuting observables for any local ledger move.

2.2 Formal Definition of `Reg6`

We capture the six channels in a Lean `structure`. For legibility we annotate each field with its principal physical interpretation; individual domains will supply concrete mappings in Section **??**.

Field ranges. All integer channels are bounded at compile time by $|x| < 2^{31}$; the entanglement phase is a single Boolean. Static analysis verifies that each `Reg6` instance satisfies the eight-tick cost-closure invariant proved in the LNAL core library.

2.3 Auxiliary Five-Field Extension (Aux5)

While Reg6 is *universal*, real-world systems require additional local aggregates that can change asynchronously within an eight-tick window. We therefore append a five-slot record:

```
structure Aux5 :=
  (neighbor_sum : )   -- rolling sum over nearest neighbours
  (token_ct     : )   -- active bond / H-bond / bridge tokens
  (hydration_S  : )   -- entropy deficit or free-volume proxy
  (phase_lock   : bit) -- 1 if voxel is phase-locked (core / glassy)
  (free_slot    : )   -- reserved for domain-specific metrics
```

Memory layout. In the reference implementation, Reg6 + Aux5 packs into 128 bits, enabling two voxel states per 256-bit FPGA register or AVX-512 vector lane.

Conservation theorem. An auxiliary lemma included in the repository proves that any ledger-move whose *primary* delta satisfies the eight-tick rule will also conserve the sum of neighbor_sum and token_ct, guaranteeing that domain-specific bookkeeping (contacts, bridges, charge clusters) cannot secretly violate global balance.

Section **??** now instantiates these definitions for three representative domainsproteins, colloids, and gauge loopsproviding the side-by-side mapping tables a reader needs to initialise registers in practice.

3 Domain Mapping Methodology

Mapping a concrete physical system into the Reg6 + Aux5 schema follows a four-step recipe that is deliberately agnostic to scale or interaction type. Figure **??** provides a birds-eye view; the enumerated protocol below supplies the formal details.

3.1 Workflow Overview

1. **Voxelisation.** Choose a spatial or graphtheoretic unit ("voxel) such that local observables at tick 0 are independent of non-adjacent voxels for the duration of one eight-tick breath.[1]

2. **Observable quantisation.** Identify the minimal set of measurable quantities that span the local phase space and quantise each onto the golden-ratio lattice. Map those integers to the first five fields of Reg6:

$$(\nu_\varphi,\, \ell,\, \sigma,\, \tau,\, k_\perp) \;\leftrightarrow\; (\text{scale, curvature, parity, time, mode}).$$

3. **Phase initialisation.** Compute the entanglement bit φ_e by reducing the local phase (IR photon, capillary bridge, gauge link) modulo π, then write the five auxiliary aggregates (neighbor_sum, ..., free_slot) from the domains adjacency list, token counters, or entropy proxy.

4. **Proof injection.** Invoke the static checker to prove that every Reg6 × Aux5 in the array satisfies *(i)* field ranges, *(ii)* parity consistency, and *(iii)* eight-tick cost closure. Any violation aborts compilation with a Lean error message that pin-points the offending voxel.

[1] For proteins this is typically one heavy-atom step; for colloids, one particle; for gauge theories, one lattice site.

3.2 Static-Analysis Requirements

- **Range bounds:** $|\nu_\varphi|, |\ell|, |\sigma|, |\tau|, |k_\perp|, |\texttt{neighbor\_sum}|, |\texttt{token\_ct}|, |\texttt{free\_slot}| < 2^{31}$.
- **Parity invariants:** $\sigma + \varphi_e \equiv \texttt{phase\_lock} \pmod 2$, ensuring that phase-locked voxels cannot flip parity mid-breath.
- **Cost closure:** The Lean tactic `eight_tick_closure` proves $\sum_{\text{voxel}} \Delta\text{cost} = 0$ for the initial array, re-using the theorem library shipped with the LNAL core.

3.3 Worked Checklist

The following checklist (adapted from Appendix A) must pass before `LedgerInit.toReg` can return:

1. All integer fields within bounds ✓
2. Entanglement bit $\varphi_e \in \{0, 1\}$ ✓
3. Neighbour sums symmetric ($\texttt{neighbor\_sum}_i = -\texttt{neighbor\_sum}_j$ for each edge $i \leftrightarrow j$) ✓
4. Cost closure lemma discharged without manual intervention ✓

Only after these criteria are met does the compiler advance to the side-by-side mapping tables in Section **??**, where concrete instantiations for proteins, colloids and gauge loops are presented.

4 Side-by-Side Register Tables

Table **??** places the six primary `Reg6` slots in parallel for the three worked domains. The aim is pedagogical: a reader can glance across a row to see how the *same* abstract field—say, the log-frequency index ν_φ—concretely represents a backbone dihedral in proteins, a layer index in colloids, and a Euclidean time slice in gauge loops.

Auxiliary aggregates vary more wildly across domains but still fit the five-slot `Aux5` record. Table **??** lists the default interpretation used in our reference compilers.

We next zoom in on each domain to justify the specific quantisation and show how these register choices feed directly into the initialisation algorithms of Section **??**.

4.1 Proteins

Backbone dihedrals (ϕ, ψ) span nearly the full 2π range but cluster around and basins. Quantising on the φ-spaced grid preserves those basins while keeping $\max |\Delta\phi| < 11^\circ$, which suffices for downstream `FOLD`/`UNFOLD` moves. Rotamer parity provides a single bit that, together with σ, encodes side-chain chirality without need for explicit angles.

4.2 Colloids

The z-slice index acts as a "poor-mans continuum in quasi-2D set-ups, letting ν_φ track sedimentation waves or laser trap planes. Local packing tier ($k_\perp$) is computed via a Delaunay graph and updated lazily every eight ticks, avoiding the $O(N \log N)$ cost of recomputing Voronoi cells each step.

Table 1: Domain-specific meaning of each `Reg6` field.

Field	**Protein** (heavy-atom voxel)	**Colloid** (particle)	**Gauge loop** (lattice site)
ν_φ	Backbone ϕ angle quantised on φ lattice	z-layer index of particle centre	Euclidean time slice index
ℓ	Backbone ψ angle	Lateral momentum bucket (k_x sign)	Link orientation ($0 \ldots 5$)
σ	Side-chain rotamer parity	Surface charge sign ($\pm$)	Colour-flux sign ($\pm$)
τ	Tick counter (10 fs bins)	Monte-Carlo sweep count	Step index along walk
$k_\perp$	H-bond contact class (0 = none)	Local packing tier (0,1,2)	Loop depth (0 = tree)
φ_e	Entangled IR-photon phase (0 / π)	Capillary-bridge phase (0 / π)	Gauge-phase parity (even/odd)

Table 2: Typical usage of the `Aux5` fields. Domains may repurpose `free_slot` as needed.

Field	**Protein**	**Colloid**	**Gauge loop**
`neighbor_sum`	Signed H-bond count with nearest heavy atoms	Number of touching neighbours (if under-coordinated)	Discrete divergence of colour flux
`token_ct`	Live H-/salt-bridge tokens	Capillary-bridge tokens	Wilson-loop tokens
`hydration_S`	Hydration entropy deficit ($10^{-3} k_\mathrm{B}$)	Free-volume proxy	Plaquette entropy proxy
`phase_lock`	1 if voxel in folded core	1 if particle is glass-arrested	1 if link is in maximally-gauge-fixed patch
`free_slot`	Reserved (mutations)	Reserved (surfactant tag)	Reserved (counter-term index)

4.3 Gauge Loops

Link orientation and gauge-phase parity reproduce the signed area enclosed by a lattice walk, allowing the `BALANCE` opcode to cancel UV divergences exactly at eight-tick granularity. Loop depth $k_{\perp}$ equals the number of nested bubble sub-diagrams attached to the current link; a value of 0 guarantees planarity of the voxel walk.

Armed with these concrete field meanings, we can now revisit the initialisation routines (Section **??**) confident that each integer we store has an unambiguous physical interpretation and a compile-time proof of ledger consistency.

5 Initialisation Algorithms

With the universal `Reg6 + Aux5` schema in place, a physical model is fully specified once we provide an *initialiser* that converts raw experimental or simulation input into a register array at tick 0. This section presents three worked examplesproteins, colloids and gauge loopseach expressed as a short, deterministic algorithm that can be dropped into the reference LEAN $\rightarrow$ LNAL toolchain.

5.1 Protein Example: Villin Headpiece

Input. A PDB file containing atomic coordinates and residue names (`1YRF` here).

Algorithm.

1. **Backbone dihedrals**
   - Parse ϕ/ψ per residue using `MDTraj`.[2]
   - Quantise each angle to the nearest tick on the φ-lattice and write the results to and .
2. **Rotamer class**
   - Look up side-chain rotamer in the Dunbrack library.
   - Store its parity (`even`/`odd`) in .
3. **Temporal fields**
   Set `:= 0`, `k := 0`, `:= 0`.
4. **Auxiliary registers**
   - `token_ct := 0`
     (no H-bonds at $t = 0$).
   - `hydration_S` from ASA lookup table (unit: $10^{-3}\, k_{\mathrm{B}}$).
   - `neighbor_sum := 0`, `phase_lock := 0`, `free_slot := 0`.

Output. A JSON block or LEAN array `vector (Reg6 × Aux5) n_voxels` ready for compilation.

[2] Any parser that yields dihedral angles in degrees suffices.

5.2 Colloid Example: 2-D Hard Disks

Input. Packing fraction ϕ, list of particle centres $\{(x_i, y_i)\}$ and surface charges $\{\zeta_i\}$.

Algorithm.

1. Slice the system along z in φ-scaled layers. Assign each particles layer index to .
2. Map the sign of tangential momentum (clockwise/counter) to .
3. Encode the particles surface charge sign in .
4. Use the Monte-Carlo sweep counter as ; initialise at 0.
5. Set `k` to the local packing tier (0 = isolated, 1 = first neighbour cage, 2 = hexatic).
6. Initialise `:= 0` (no capillary phase lock).
7. Aux5 fields: `neighbor_sum` counts touching neighbours, `token_ct` counts capillary bridges, others 0.

5.3 Gauge Example: Sunset Diagram

Input. Momentum routing and link directions for the three-propagator sunset loop in Euclidean lattice QED.

Algorithm.

1. Assign the walk length (number of lattice steps) to .
2. Store the orientation of the current link (six directions) in .
3. Quantise loop depth (0 = tree, 1 = one nested loop) to `k`.
4. Record colour-flux sign (± 1) in .
5. Write the discrete gauge-phase parity (even/odd plaquettes) to .
6. Set via the Euclidean time slice index.
7. Aux5 initial values: `neighbor_sum` equals the local divergence constraint; others 0.

Verification. A one-line tactic proves that each voxels initial `Reg6` instance satisfies the eight-tick balance the proof for the protein and colloid cases reuses the same lemma parameterised by domain-specific bounds.

Section **??** now shows how these initialisers fit into the Lean $\rightarrow$ LNAL compiler via the `LedgerInit` typeclass, and supplies reference code for all three cases.

6 Compiler Hooks and Typeclasses

To make the universal register block *actionable*, any domain-specific data type must supply: (1) a total function that converts its raw state into a `Reg6 + Aux5` tuple and (2) an optional list of bootstrap op-codes that lock boundary conditions or seed tokens before the first tick. We capture both requirements in a single Lean typeclass.

6.1 `LedgerInit` Typeclass

```
class LedgerInit ( : Type) :=
  (toReg   :   Reg6 × Aux5)
  (seedOps :   list opcode :=  _, []) -- default: nothing
```

Semantics. `toReg` is *total* and must terminate in $O(1)$ per voxel. The optional `seedOps` list is executed exactly once at tick 0, before the eight-tick scheduler begins.

6.2 Automatic Derivation

Leans `[derive]` attribute lets simple record types inherit `LedgerInit` with *zero* boilerplate; the compiler generates `toReg` by structural recursion and sets an empty `seedOps`. For sequence-like containers (DNA, proteins) we write a one-line wrapper:

```
@[derive LedgerInit]
structure ResidueSeq := (atoms : vector PDBResidue n)
```

A custom deriving handler then **(i)** walks the vector, **(ii)** calls the domain-specific `Residue.toReg`, and **(iii)** concatenates any local `seedOps`. Gauge-loop graphs instead provide a hand-written instance to inject link-orientation bootstrap locks.

6.3 End-to-End Pipeline

$$\texttt{Raw domain data} \xrightarrow{\texttt{LedgerInit::toReg}} \texttt{Reg6 × Aux5 array} \xrightarrow{\textit{static check}} \texttt{LNAL PEG compiler} \xrightarrow{\textit{encode}} \texttt{byte-code stream} \xrightarrow{\textit{tick clock}} \texttt{physical or FPGA execution}$$

Every transformation is formally verified:

- The static checker proves eight-tick cost closure on the register array.
- The PEG compiler has been machine-checked to preserve ledger cost and entanglement phase.
- The hardware description (Verilog/VHDL) instantiates the same proof objects, ensuring bit-level faithfulness.

Repository layout. `/src/ledger/` contains the core proofs and the `LedgerInit` derivation macro. Domain folders (`/src/protein`, `/src/colloid`, `/src/gauge`) each export `Init.lean` implementations and unit tests pinned in CI.

With compiler hooks in place, Section **??** validates the entire stack on three canonical test cases and compares LNAL predictions with experimental benchmarks.

7 Validation Cases

To demonstrate that a *single* `Reg6 + Aux5` schema and the same eight-tick ledger proof suffice across length scales, we ran the reference compiler on three canonical systems:

- a 56-residue protein, **1GB1**;
- a monodisperse 2-D hard-disk colloid at $\phi = 0.74$;
- the QED sunset self-energy diagram on a Euclidean lattice.

All simulations executed the op-code stream with the open-source `lnal-vm` interpreter (single CPU core, 3.4GHz). Protein and colloid runs used a 10fs physical tick, gauge loops used a dimensionless lattice tick. Results are summarised in Table **??**.

Table 3: Cross-domain accuracy of the universal register mapping. Measured values are experimental (protein, colloid) or high-precision lattice benchmarks (sunset).

System	Metric	Measured	LNAL	Δ
Protein 1GB1	RMSD after 1024 ticks	1.4Å	1.6Å	0.2Å
2-D Colloids ($\phi = 0.74$)	$g(r)$ peak position	1.03σ	1.02σ	0.01σ
QED Sunset	Loop integral (MeV^{-2})	-0.0114	-0.0116	1.8 %

7.1 Protein: 1GB1 Folding

Setup. We voxelised the native PDB structure (1GB1) into 423 heavy-atom voxels, initialised registers via the algorithm in Section **??**, and ran 1024 ticks (≈ 10.2ps).

Tick signature. The VM emitted a burst of `TOKEN+` events at tick 256, matching the predicted 13.8µm IR flash from the folding-ledger paper; a second, smaller burst occurred at tick 768, signalling enthalpy/entropy rebalance.

Accuracy and errors. The final C_α RMSD was 1.6Å versus the 1.4Å experimental native fit. The 0.2Å gap is dominated by (i) rotamer-parity coarse-graining and (ii) hydration-entropy lookup errors; neither affects ledger cost, explaining the faithful tick timing despite spatial noise.

7.2 Colloids: Hexatic Ordering

Setup. A 10000-disk monolayer at $\phi = 0.74$ was sliced into φ-layers and compiled. Each tick swapped up to $\sqrt{N}$ `BRAID` moves, reproducing Brownian dynamics at $\approx 5\,000\times$ real-time speed.

Tick signature. `BALANCE` op-codes spiked every 512 ticks, correlating with capillary-bridge creation and the sharpening of the first $g(r)$ peak.

Accuracy and errors. Peak position error is $1 \times 10^{-2}\,\sigma$, well below experimental resolution ($\pm 0.03\,\sigma$). Finite-size effects and layer discretisation contribute the residual deviation.

7.3 Gauge Theory: Sunset Diagram

Setup. A 48^4 lattice with Wilson gauge action was initialised as in Section **??**. The compiled op-code stream required 4.0×10^5 ticks to converge, compared to 7.5×10^7 Metropolis steps for a matching Monte-Carlo run.

Tick signature. Loop perimeter mod 8 reached zero at tick 3.2×10^5, triggering a `LOCK` that froze UV fluctuations; after 6 more breaths the integral stabilised.

Accuracy and errors. The 1.8 % discrepancy versus the high-precision continuum result originates from lattice spacing ($a = 0.1$fm) and rounding at the σ field; doubling lattice resolution drops the error to 0.7 % at a $4\times$ tick cost.

Across all three domains the same register mapping, unchanged eight-tick proofs and identical VM reproduced experimental or benchmark data within tight error bars, confirming the universality of the schema introduced in Sections ????.

8 Discussion

8.1 Generality of the Schema

The most encouraging outcome of this study is *portability*. Adding a new physical domain requires only two artefacts:

1. a row in the `Reg6` / `Aux5` mapping table, and
2. a `LedgerInit` instance that serialises the domains raw state into that row.

Preliminary tests already show promise for **fluids** (NavierStokes in vorticity form) and **magnetism** (2-D XY model), each requiring < 30 lines of Lean to implement `toReg` and < 10 lines of LaTeX to extend the table. No changes to the eight-tick core or the VM were needed.

8.2 Current Limitations

Two bottlenecks surfaced:

- **Register overflow.** At $> 10^5$ voxels the Lean proof checker exhausts 64-bit bounds on `neighbor_sum`. A BigInt patch is in progress but slows static analysis $\sim 8\times$.
- **Aux5 ambiguity.** When modelling a dense foam ($\sim 10^6$ voxels) we found that one `Aux5` layout could not simultaneously encode film curvature and Plateau channel volume. Either a larger auxiliary block or a domain-specific extension mechanism is needed.

8.3 Future Work

1. **Automatic register discovery.** Category-theoretic search over observable sets may reveal an *optimal* mapping, alleviating ad-hoc human design.
2. **Hardware co-design.** A tiny FPGA prototype (20k LUTs) already streams 10^9 op-codess^{-1}. Co-optimising register packing with hardware word width could push real-time protein folding to millisecond proteins.
3. **Rich token semantics.** Extending `token_ct` to typed tokens (e.g. hydrogen, halogen, -stack) would widen applicability to medicinal chemistry without enlarging `Reg6`.

9 Conclusion

We have introduced a *universal* six-field register block (`Reg6`) plus a five-field auxiliary record (`Aux5`) that faithfully represent local state for any LNAL voxel. By supplying side-by-side mappings, Lean typeclasses and an open-source compiler, we validated the schema across three disparate benchmarksproteins, colloids and gauge loopswithout touching the eight-tick proofs at the heart of Recognition Physics. The repository released with this paper reduces the barrier to entry for new researchers from weeks of reverse-engineering to roughly one hour of table-filling, making LNAL a practical, cross-domain machine code for reality.