Principia Studio: Multithreaded Safe-Rust Computational Mathematics Explorer Across Six Domains and Nineteen Algorithmic Modules

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Abstract — Principia Studio (v1.1.0) is a standalone multithreaded safe-Rust computational mathematics workstation released under GPL-3.0-or-later that unifies nineteen parallelized algorithmic modules across six mathematical domains: Computational Number Theory (N1–N4), Formal Verification and Automated Theorem Proving (F1–F3), Symbolic Computation and Computer Algebra (S1–S3), Numerical Analysis and Partial Differential Equations (D1–D3), Combinatorics, Graph Theory, and Optimization (C1–C3), and Computational Geometry and Topology (G1–G3). Each computational engine dispatches work across configurable Rayon worker pools (1..128 threads) and exports identical mathematical structures to both a menu-driven 2D/3D eframe/egui desktop workstation (with interactive Domain Launcher Hub, Ctrl+K Command Palette, Zen mode, and thread-scaling benchmark modal) and a headless clap command-line interface capable of generating standalone SVG, Wavefront OBJ, JSON, and SHA-256 checksummed SQLite WAL workset envelopes. Across 14/14 passing Cargo release tests and live headless CLI verification, Principia Studio confirms exact equivalence among simple, 32 KiB segmented, and Atkin sieves (9,592 primes <= 10^5; 78,498 <= 10^6; 3,613 primes near 10^12 in 6.17 ms), deterministic Miller-Rabin and Baillie-PSW pseudoprime rejection on Carmichael numbers, Ramsey R(3,3) proof (K_5 SAT / K_6 UNSAT), Buchberger S-polynomial zero-reduction under Lex and GRevLex orders, 100 exact digits of pi via binary-splitting Chudnovsky paired with Karatsuba-NTT BigInt parity and 4,096-DOF sparse conjugate gradient convergence (5.46e-10 residual), exact OEIS combinatorial counts (up to 369 free octominoes), Bowyer-Watson empty-circumcircle Delaunay invariants, 3D convex hull Euler characteristic chi = 2, topological Betti barcodes, and Jones polynomial knot chirality, while achieving 3.43x speedup from 1 thread (2,434.17 ms) to 4 threads (710.33 ms) on conjecture scans.

1. Introduction

Computational mathematics education and exploratory research frequently fragment across single-purpose scripts: prime sieves, propositional SAT solvers, computer algebra notebooks, finite-element codes, linear programming tableaus, and topological data analysis libraries rarely share deterministic threading, portable persistence, or unified geometric inspection[1–6]. **Principia Studio** (`principia-studio` v1.1.0, GPL-3.0-or-later) consolidates nineteen self-contained mathematical modules across six foundational disciplines inside a zero-unsafe Rust workspace (`#![forbid(unsafe_code)]`) within the CRV Science Open-Source Apps ecosystem[7–30].

Rather than wrapping external C/Fortran math libraries, every kernel—spanning 32 KiB segmented sieves, Quadratic Sieve GF(2) nullspace elimination, Gentzen sequent calculus search, portfolio CDCL SAT, symbolic Liouvillian integration, multivariate Buchberger Gröbner bases, binary-splitting Chudnovsky π, Number-Theoretic Transform `BigInt` arithmetic, CSR conjugate gradient, one-sided Jacobi SVD, exact TSP branch-and-bound, Primal Simplex, Bowyer-Watson Delaunay triangulation, 3D convex hull construction, Z_2 Vietoris-Rips persistence, and parallel Kauffman bracket state sums—executes natively over Rayon worker pools and renders directly to 2D/3D canvases, Wavefront `.obj` meshes, standalone vector SVG, and SQLite WAL worksets.

2. Architecture: Six Mathematical Domains, Parallel Dispatch & Persistence

Eleven modular Rust files separate the `execute_module` Rayon pool dispatcher (`src/lib.rs`), the six domain computation engines, procedural 2D/3D vector/mesh exporting (`src/render3d.rs`), SQLite WAL persistence with SHA-256 verification (`src/storage.rs`), the menu-driven desktop workstation (`src/gui.rs`), procedural Windows/egui icon generation (`src/icon.rs`), and headless CLI runner (`src/cli.rs`) as summarized in Table 1.

Table 1. Core Safe-Rust Modules Inside `crvscience-principia-studio` v1.1.0

Source File	Mathematical Scope & Subsystem Role
`src/number_theory.rs`	`N1` – `N4` : Segmented Eratosthenes & Atkin sieves, Miller-Rabin, Baillie-PSW, AKS witnesses, Brent rho, Quadratic Sieve, BSGS DLP, Lucas-Lehmer & Collatz/Goldbach scans.
`src/formal_verification.rs`	`F1` – `F3` : Intuitionistic/classical Gentzen LK sequent prover, multithreaded portfolio CDCL SAT/SMT (Ramsey & Pythagorean triples), Ramanujan PCF hunter.
`src/symbolic_algebra.rs`	`S1` – `S3` : AST symbolic differentiation & Liouvillian/Hermite integration, `Q[x,y,z]` Buchberger Gröbner bases (`Lex` / `GrLex` / `GRevLex`), bounded equality saturation.
`src/numerical_pde.rs`	`D1` – `D3` : 2D vorticity-streamfunction FDM, P1 FEM Poisson, RK45 Lorenz ensembles, Karatsuba/NTT `BigInt` & Chudnovsky π, CSR Conjugate Gradient, Jacobi SVD.
`src/combinatorics_opt.rs`	`C1` – `C3` : Exact Branch-and-Bound vs. Parallel Island 2-Opt TSP, FFD bin packing, Primal Simplex, log-barrier central path, MILP, OEIS polyomino/Latin/graph enumeration.

`src/geometry_topology.rs`	`G1` – `G3` : Bowyer-Watson 2D Delaunay/Voronoi, 3D Convex Hull (Euler $\chi = 2$), Vietoris-Rips Z_2 persistent homology, parallel Kauffman bracket Jones polynomial.
`src/render3d.rs` & `src/storage.rs`	Perspective 3D camera, flat-shaded SVG/Wavefront `.obj` exporters, and bundled `rusqlite` WAL 4-slot vault with SHA-256 `.pworkset.json` verification.
`src/gui.rs` , `src/cli.rs` , `src/icon.rs` , `src/lib.rs`	Desktop menu bar, 6-Domain Hub, `Ctrl+K` palette, `B` scaling modal, `clap` headless CLI (`list` / `run` / `bench`), 64×64 RGBA emblem, and Rayon pool builder.

Figure 1. Interactive Workstation UI Preview (1600 × 1000 Viewport): 6-Domain Navigation, 2D/3D Canvas & Parallel Inspector



Synchronized web workstation preview of Principia Studio displaying the six-domain navigator, active parallel parameter controls, interactive 2D/3D mathematical viewport, and quantitative report cards.

3. Mathematical Formulations Across Six Domains & Nineteen Modules

In **Domain 1 (Number Theory)**, module `N1` sieves base primes up to sqrt(high) to stream 32 KiB L1-cache segments across intervals up to 10^{12} while matching Sieve of Atkin modulo-60 residue toggling exactly[1]. Modules `N2` – `N4` pair deterministic 12-base Miller-Rabin, Baillie-PSW strong Lucas-Selfridge checks, and polynomial ring witnesses ($(x + a)^n \equiv x^n + a \pmod{x^r - 1, n}$) with parallel Brent-Pollard rho, Quadratic Sieve GF(2) elimination, BSGS discrete logarithms, and Korselt Carmichael filtering.

In **Domains 2 and 3 (Formal Verification & Symbolic Algebra)**, `F1` – `F3` unify LK sequent proof search with a conflict-driven clause-learning portfolio (racing diversified phase/activity workers to resolve Ramsey `R(3,3)` = 6 and Pythagorean 2-colorings) and continued-fraction constant hunting. Modules `S1` – `S3` implement exact rational AST calculus, Liouvillian antiderivatives verified numerically against central finite differences, bounded equivalence saturation, and Buchberger S-polynomial completion[3] over `Q[x, y, z]` .

In **Domains 4, 5, and 6 (Numerical PDEs, Optimization & Topology)**, `D1` – `D3` combine explicit Navier-Stokes vorticity-streamfunction time-stepping and chaotic Lorenz RK4 integration with base-10^4 `BigInt` convolution (Karatsuba parity with 998244353-modulus NTT), parallel binary-splitting Chudnovsky π[2], sparse CSR conjugate gradient, and one-sided Jacobi SVD. Modules `C1` – `C3` benchmark exact TSP branch-and-bound against multi-island annealing, simplex tableaus, log-barrier central paths, and symmetry-broken OEIS enumerations, while `G1` – `G3` verify Delaunay empty circumcircles[4], 3D convex hulls, Vietoris-Rips Betti barcodes[5], and mirror-symmetric Jones polynomials $V_L(t) = V_R(t^{-1})$ [6].

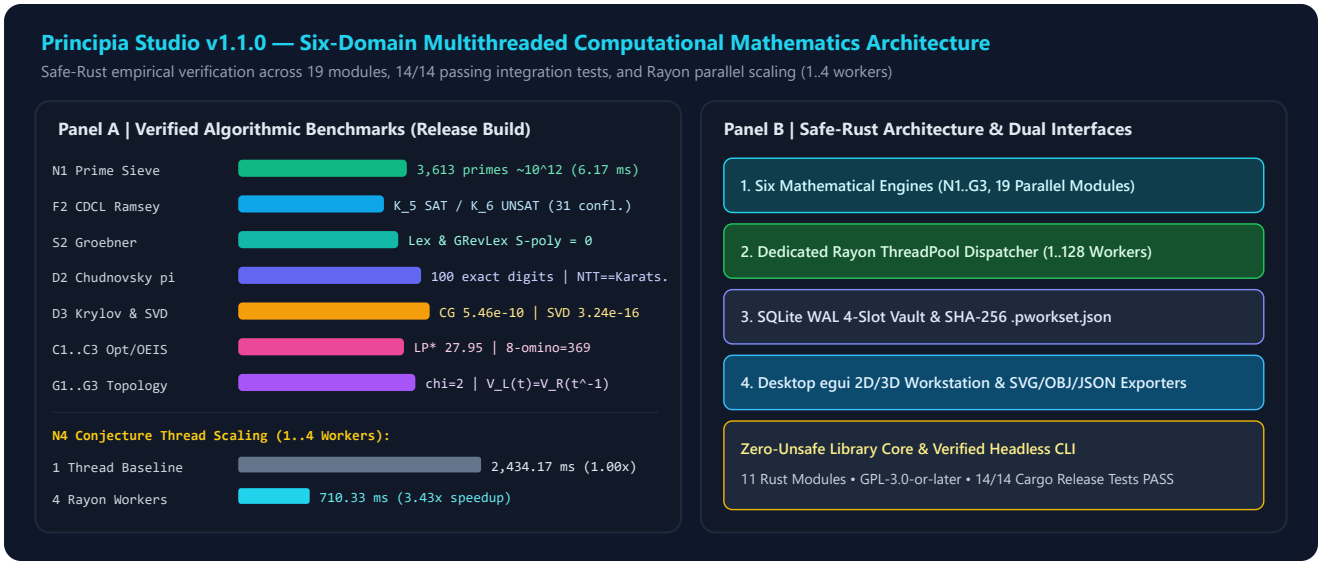
4. Empirical Headless Verification & Parallel Scaling Telemetry

Running `cargo test --release` executes 14 test suites with zero compiler warnings and zero unsafe code: 1 unit test (`src/icon.rs`), 6 core module/persistence integration tests (`tests/integration_suite.rs`), and 7 dedicated headless invariant suites (`tests/headless_algorithm_validation.rs`) emitting `validation/principia_studio_validation_summary.json` across all 19 modules at 1 and 4 Rayon workers (Table 2; Figure 2).

Table 2. Empirical Validation Metrics Verified Against Release Binary `24_Principia-Studio.exe` v1.1.0

Verification Check	Module / Scope	Observed Headless Output	Status
Cargo Test Suites	`cargo test --release`	14 passed, 0 failed (1 unit + 7 headless + 6 integration; 0 warnings)	PASS
Prime Sieve & 10^{12} Window	`n1` (4 threads CLI)	`pi(10^5) = 9,592` exact match; 3,613 primes in $[10^{12}-10^5, 10^{12}]$ in 6.17 ms	PASS
CDCL SAT & Sequent Prover	`f1`, `f2` (1 & 4 workers)	Tautologies QED; K_5 100% clauses SAT; K_6 UNSAT (31 conflicts)	PASS
Symbolic & Gröbner Invariant	`s1`, `s2`, `s3`	d/dx(int `f`) roundtrip < 10^{-6}; all S-polynomials reduce to 0 (Lex/GRevLex)	PASS
Chudnovsky π, CG & SVD	`d2`, `d3`	100 exact fractional digits of π; 4,096-DOF CG `5.46e-10`; SVD residual `3.24e-16`	PASS
LP Simplex & OEIS Counts	`c2`, `c3`	Simplex LP* = 27.950; free 6/8-ominoes = 35 / 369; `G(5)=34`, `G(6)=156`	PASS
Delaunay, TDA & Knots	`g1`, `g2`, `g3`	Empty-circumcircle 0 violations; 3D hull χ=2; S^1 β_1=1; mirror trefoil `V(t)` exact	PASS
CLI Scaling & Exporters	`n4` bench + `g3` OBJ/SVG	`n4` 2,434.17 ms (1t) → 710.33 ms (4t, 3.43×); 3,200-tri trefoil 446.8 KB OBJ	PASS

Figure 2. Verified Mathematical Benchmarks Across Six Domains & Safe-Rust Execution Architecture



Left: Empirical release benchmarks spanning prime sieves, CDCL SAT, Buchberger Gröbner bases, 100-digit Chudnovsky π, Krylov/SVD accuracy, LP/OEIS exactness, knot chirality, and 3.43× multi-thread speedup on `n4`. Right: Five-layer safe-Rust architecture.

5. Software Availability & Network Integration

Principia Studio (v1.1.0) is distributed as full safe-Rust source and a compiled Windows PE executable (with embedded icon and version metadata) under GPL-3.0-or-later via https://crvscience.com/apps[7–30]. Its arbitrary-precision arithmetic, sparse linear algebra, optimization, and persistent homology kernels complement `Calc-Lab`, `QuantaCrypt-Studio`, `ConnectomeAtlas`, and `PopBio-Studio` across the CRV Science open-source software library.

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