Predictive Compression Dynamics: A Methodological Framework for Computable Information-Driven Modeling

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Abstract

We present *Predictive Compression Dynamics* (PCD) as a *methodological framework* for building *computable* local functionals that drive dynamics by explicit gradient flow. Rather than postulating uncomputable principles, PCD starts from an *information-motivated* surrogate codelength $\widehat{\Phi}$ and specifies dynamics $\dot{x} \propto -\nabla\widehat{\Phi}(x)$ with all parameters preregistered. We study two concrete classes: (i) a *fixed-graph* functional

$$\widehat{\Phi}_E(x) = -\sum_{(i,j)\in E} \frac{m_i m_j}{\sqrt{\|x_i - x_j\|^2 + a^2}},$$

and (ii) a *smooth kernel* functional

$$\widehat{\Phi}_K(x) = -\sum_{i<j} m_i m_j \, K_\sigma(\|x_i - x_j\|),$$

with K_σ compactly supported and C^1. The first provides a transparent sandbox; the second avoids neighbor-set discontinuities and guarantees well-posedness. In the dilute two-body limit both produce an attractive $1/r^2$ *form* (after calibration), while the softening a regularizes collisions. These are *operational, information-motivated models*, not new claims about gravity; familiar “Plummer-like” roll-offs serve here as *sanity checks*, not phenomenological predictions. We give preregistered algorithms, an explicit model–data codelength decomposition, and clear falsification criteria for model instances. The framework supports reproducible exploration of *computable* compression-driven dynamics across domains.

1 Positioning and Commitments

What this paper is: a disciplined way to construct and test *computable* local functionals $\widehat{\Phi}$ whose gradients define dynamics. We make code-level, preregistered choices explicit (domains, discretizations, kernels, parameters) and provide sanity checks.

What this paper is *not*: a claim of novel gravitational phenomenology, nor a derivation of GR/QM. Any resemblance of simple pair terms to familiar softened potentials is acknowledged and used only as a controlled testbed.

2 Operational Domain and Notation

We consider N point agents with positions $x_i \in \mathbb{R}^3$ and positive weights m_i (“masses”). Computations occur at finite precision: lattice spacing a_{grid} and b bits per coordinate stated *a priori*. A global calibration constant $G_{\text{eff}} > 0$ turns the dimensionless force into physical units.

3 Information-Motivated Functionals

Model–data decomposition (explicit). Following standard MDL reasoning, a description length splits as

$$L_{\text{tot}} = L(M) + L(D \mid M), \tag{3.1}$$

where $L(M)$ encodes the model/regularities and $L(D \mid M)$ the residual data given that model. A decrease $\Delta L_{\text{tot}} < 0$ corresponds to *realized compression.* In PCD we treat a computable, local $\widehat{\Phi}$ as a proxy for the *negative* of an achievable ΔL_{tot}; gradient descent in $\widehat{\Phi}$ heuristically implements compression.

3.1 Fixed-graph functional

Let $E \subset \{(i,j) : 1 \le i < j \le N\}$ be a symmetric, degree-bounded edge set (e.g. an initial kNN graph). Define

$$\widehat{\Phi}_E(x) = -\sum_{(i,j)\in E} \frac{m_i m_j}{\sqrt{\|x_i - x_j\|^2 + a^2}}, \qquad a > 0. \tag{3.2}$$

Sign convention: the minus sign ensures attraction under gradient descent. Softening a regularizes collisions. The force on i is

$$\begin{aligned} F_i^{(E)}(x) &= -\nabla_{x_i} \widehat{\Phi}_E(x) \\ &= -\sum_{\substack{j:\\ (i,j)\in E}} m_i m_j \, \frac{(x_i - x_j)}{\left(\|x_i - x_j\|^2 + a^2\right)^{3/2}}. \end{aligned} \tag{3.3}$$

In the two-body, $a \to 0$ limit with $(i,j) \in E$,

$$F_i^{(E)} \to -\, m_i m_j \, \frac{x_i - x_j}{\|x_i - x_j\|^3}, \tag{3.4}$$

i.e. an attractive $1/r^2$ *form* along the active edge. For physical units we use $F_i^{\text{phys}} = G_{\text{eff}} \, F_i^{(E)}$.

Remark (edge modeling). Forces vanish between pairs not in E; this is a *modeling choice* for locality/sparsity, not a universal law.

3.2 Smooth-kernel functional

To avoid kNN neighbor-set discontinuities, choose a compactly supported, C^1 radial kernel $K_\sigma : [0,\infty) \to \mathbb{R}_{\ge 0}$ with support $[0, R\sigma]$ (e.g. a Wendland C^2 kernel). Define

$$\widehat{\Phi}_K(x) = -\sum_{i<j} m_i m_j \, K_\sigma(\|x_i - x_j\|). \tag{3.5}$$

Then $F_i^{(K)}(x) = -\nabla_{x_i} \widehat{\Phi}_K(x)$ is continuous and locally Lipschitz (away from collisions if $K'_\sigma(0)$ finite). For $K_\sigma(r) \sim (r^2 + a^2)^{-1/2}$ near zero one recovers the same regularized two-body *form* as (3.4).

3.3 A minimal codelength view

Interpreting $-\widehat{\Phi}$ as a surrogate *gain in description length* when nearby pairs are represented jointly, if the expected residual codelength per pair scales like a decreasing $\ell(r_{ij})$, then

$$L_{\text{tot}} \approx \text{const} + \sum_{(i,j)} \ell(r_{ij}), \quad \Rightarrow \quad \widehat{\Phi} \;\propto\; -\sum_{(i,j)} \ell(r_{ij}).$$

We refrain from claiming exact MDL optimality; $\widehat{\Phi}$ is an *operational proxy* to be tested.

4 Dynamics and Preregistration

All parameters ($a_{\text{grid}}, b, a, \sigma, \Delta t, m_i, \gamma, T, \text{seeds}$) are fixed *before* experiments.

Deterministic gradient flow.

$$x_i^{(t+\Delta t)} = x_i^{(t)} + \Delta t\, F_i(x^{(t)}), \quad F_i \in \{F_i^{(E)}, F_i^{(K)}\}. \tag{4.1}$$

Underdamped Langevin.

$$m_i \ddot{x}_i = F_i(x) - \gamma\, \dot{x}_i + \xi_i(t), \quad \langle \xi_i(t)\xi_j(t')\rangle = 2\gamma k_B T\, \delta_{ij}\delta(t-t'). \tag{4.2}$$

5 Sanity Checks (not phenomenology)

Two-body limit. With $a \to 0$ and a single interacting pair, (3.4) holds (after calibration G_{eff}).
Softening expansion (corrected). For $r = \|x_i - x_j\| \gg a$,

$$\frac{r}{(r^2+a^2)^{3/2}} = \frac{1}{r^2}\left(1 - \frac{3a^2}{2r^2} + O\left(\frac{a^4}{r^4}\right)\right), \tag{5.1}$$

hence

$$\|F_i^{(E)}\| = m_i m_j \frac{r}{(r^2+a^2)^{3/2}} \overset{r \gg a}{=} m_i m_j \frac{1}{r^2}\Big(1 - \frac{3a^2}{2r^2} + \dots\Big). \tag{5.2}$$

We use (5.1) solely to verify numerics; *no claim* is made that nature exhibits such a roll-off at any laboratory scale.

6 Well-posedness

For $a > 0$ and bounded degree, $\widehat{\Phi}_E \in C^1(\mathbb{R}^{3N} \setminus \{x_i = x_j\})$ and $F^{(E)}$ is locally Lipschitz away from collisions; similarly $F^{(K)}$ is continuous and locally Lipschitz for C^1 kernels with bounded derivative at 0. If kNN is used with dynamic neighbors, forces are only piecewise smooth; then employ (i) hysteresis for neighbor swaps, (ii) temporal smoothing of weights, or (iii) prefer the smooth kernel model (3.5).

7 A Preregistered Model Card (example)

Domain. $a_{\text{grid}} = 10\,\mu\text{m}$, $b = 16$.
Functional. $\widehat{\Phi}_K$ with Wendland C^2 kernel of scale $\sigma = 0.5\,\text{mm}$; softening $a = 50\,\mu\text{m}$.
Dynamics. Underdamped with ($m_i \equiv 1, \gamma = 0.1, T = 300\,\text{K}$), $\Delta t = 1 \times 10^{-3}\,\text{s}$.
Calibration. G_{eff} fit once in a dilute two-body sandbox at $r \gg a$.
Sanity checks. Verify (3.4) form and (5.1) numerically; report seeds and residuals.

8 What to Falsify (for a given instance)

Given fixed ($\widehat{\Phi}$, params), the instance is falsified if:
(F1) Two-body trajectories disagree with the calibrated $1/r^2$ *form* beyond stated error under identical numerical conditions.
(F2) Kernel vs. fixed-graph variants yield statistically inconsistent small-r behavior not explainable by topology (violates within-class robustness).
(F3) The chosen code-length proxy (e.g. $-\widehat{\Phi}$ vs. an external structural complexity metric) fails to correlate in controlled tests.
These are *model-level* falsifiers; they do not purport to test fundamental physics.

9 Discussion and Scope

PCD supplies a reproducible route from *computable* information-motivated functionals to concrete dynamics. Simple pairwise terms coincide with well-known softened interactions; this is a feature for validation, not a novelty claim. The framework can be extended to richer $\widehat{\Phi}$ (e.g. graph Laplacians, learned local codes) with the same preregistration discipline.

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References

References

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A Schematic Field (single edge)

Figure 1: Attractive field along the active edge for (3.2); magnitude regularized near particles by a.

B Units and the corrected far-field

With x in length units, (3.2) has units of inverse length. The calibrated constant G_{eff} supplies force units so that $F^{\mathrm{phys}} = G_{\mathrm{eff}} F$. The large-$r$ expansion used for numerical validation is (5.1) and (5.2).