Thermo-Credit Theory: A Credit-First Thermodynamic Mapping

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Version 1.0 – November 6, 2025

Abstract

We recast the Quantity Theory of Credit (QTC) in a thermodynamic-style state space to separate scale, dispersion, and capacity in modern credit systems. The key step is an entropy-like dispersion index that factors money-in-circulation[K10] and its allocation, combined with an explicit capacity variable for bank balance sheets. This mapping is an analytic isomorphism, not a physical identity: it is designed for structured bookkeeping, stress diagnostics, and early-warning indicators, not for importing physical laws into economics. Within this framework we define an internal potential $U(S_{\mathrm{M}}, V_{\mathrm{C}}, \ldots)$, derive a first-law-like decomposition of credit creation, introduce a Helmholtz-style free energy F_{C} and an exergy-like measure X_{C}, and obtain a Maxwell-like integrability condition that makes the mapping empirically falsifiable. The construction is deliberately practice-first: all quantities are intended to be computable from public data and to support decision-useful monitoring for investors, risk managers, and policymakers.

1 Introduction

Classical money-first views such as the Quantity Theory of Money (QTM) explain nominal dynamics in terms of a money stock, its velocity, and shocks or policy actions [1, 2, 3]. More recent credit-first views, notably the Quantity Theory of Credit (QTC), emphasize that banks create deposits when they lend and that the use of credit (real vs. financial, productive vs. speculative) matters for macro-financial outcomes [4, 5]. In parallel, both information theory and statistical mechanics have inspired analogies for income and wealth distributions [6, 7, 8, 9, 10].

This note takes a minimal and operational step: we build a thermodynamic-style state description that (i) separates scale and dispersion of monetary/credit uses, (ii) introduces an explicit capacity variable for bank balance sheets, and (iii) yields testable constraints and early-warning gauges. The aim is not to claim that macro data obey physical laws, but to provide a disciplined bookkeeping analogy useful for supervision, stress testing[K18], and systematic monitoring.

2 Setup and Definitions

We work over a chosen system (jurisdiction, sector set) and time aggregation (e.g. monthly). Let M_{in} denote money-in-circulation[K10] over this domain, and let $\{q_i\}$ be a stable, MECE (Mutually Exclusive, Collectively Exhaustive)[K15] partition of its uses (real activity, housing credit, securities margin, etc.), with

$$\sum_i q_i = 1.$$

2.1 Monetary dispersion entropy

We define an entropy-like extensive index

$$S_\mathrm{M} = kM_\mathrm{in}H(q), \qquad H(q) \equiv -\sum_i q_i \log q_i, \tag{1}$$

where $k > 0$ is a conventional scaling constant. This mirrors ideal mixing entropy $\Delta S_\mathrm{mix} \propto NH(x)$ and follows the information-theoretic form of Shannon [9]. S_M grows with both scale and dispersion; concentration (reallocation into fewer uses) reduces $H(q)$ and can reduce S_M even at fixed M_in.

Formally, $H(q)$ is the Shannon–Boltzmann entropy of the MECE bucket probabilities $\{q_i\}$ with natural logarithm (no Tsallis, Rényi, or alternative families are used here). In addition to the extensive S_M, the implementation tracks a scale-free version $S_\mathrm{M,hat} = H(q)/\log K$ (with K buckets) and per-bucket contributions $S^{(i)}_\mathrm{M,in} = kM_\mathrm{in}\tilde{q}_i$. For the baseline JP configuration these buckets correspond to "productive", "housing", "consumption", "financial", and "government" allocations (recorded as $q_\mathrm{productive}, q_\mathrm{housing}, q_\mathrm{consumption}, q_\mathrm{financial}, q_\mathrm{government}$); regional variants use analogous coarse splits in their allocation tables, always normalised so that $\sum_i q_i = 1$.

2.2 Capacity and conjugate variables

We introduce:

- V_C: an effective credit capacity or headroom[K4] (e.g. CET1/RWA[K3] slack, HQLA (High Quality Liquid Assets)[K6]-based lending space, liquidity buffers[K7]);
- T_L: a liquidity-intensity index (a "temperature-like" proxy from spreads, turnover, depth);
- p_C: a "credit pressure"[K5] (shadow price of capacity).

We postulate an analytic potential

$$U = U(S_\mathrm{M}, V_\mathrm{C}, \ldots), \tag{2}$$

and define conjugate quantities

$$T_\mathrm{L} \equiv \left(\frac{\partial U}{\partial S_\mathrm{M}}\right)_{V_\mathrm{C}}, \qquad p_\mathrm{C} \equiv -\left(\frac{\partial U}{\partial V_\mathrm{C}}\right)_{S_\mathrm{M}}. \tag{3}$$

Here U is not a physical internal energy; it is a bookkeeping potential chosen so that a first-law-like decomposition holds. Classical QTM/QTC do not name U; we introduce it as an analytic device. Empirically, $U(t)$ is instantiated as a scalar credit-capacity gauge constructed from the credit table (nominal credit or GDP-like quantities). For JP, $U(t)$ is taken from a GDP-like "energy" series (U_energy, derived from nominal GDP) and falls back to nominal GDP $Y(t)$ when that series is unavailable. For EU and US, $U(t)$ is set equal to nominal GDP $Y(t)$ by default. In all regions, if neither an explicit U nor a Y column is present, the implementation falls back to real credit stocks $L_\mathrm{real}(t)$ as a last resort so that the first-law decomposition remains defined. An optional detrended version $U^\star$ is produced by subtracting a no-lookahead rolling mean; this $U^\star$ is used only in diagnostics and visualisation (to study fluctuations around a slowly varying baseline), while the core potentials F_C and X_C are computed from the undetrended U.

2.3 Depth and turnover proxies

In order to construct the liquidity temperature T_{L} and related gauges from observable quantities, we introduce two derived inputs: a *depth* proxy D and a *turnover* proxy Θ. They are not state variables on their own, but they are treated as diagnostic inputs whose behaviour should be consistent with the thermodynamic picture.

Conceptually, depth D captures the scale of credit outstanding relative to the system under study (e.g. private non-financial credit stocks) and therefore measures how "thick" the market is. In the absence of high-quality external depth series, we treat D as a rescaled version of real credit stocks L_{real}, so that, up to a calibration constant d_0,

$$D(t) \propto L_{\mathrm{real}}(t),$$

with the constant chosen so that the median depth over the sample is near the desired reference level.

Turnover Θ is intended to capture how quickly the system recycles capacity: it is dimensionless and increases when credit capacity is deployed and repaid more rapidly. In the simplest case we use a ratio of the form

$$\Theta(t) \propto \frac{U(t)}{L_{\mathrm{real}}(t)},$$

which compares a capacity-like quantity U with the underlying stock L_{real}. In practice this raw ratio is stabilised by replacing pathological values (division by zero, missing data) with a reference level and clipping to a reasonable band, so that extreme outliers do not dominate the temperature construction. These choices emphasise the interpretation of T_{L} as a relative index rather than an absolute physical temperature.

2.4 Units and scaling conventions

All core quantities are defined to have consistent, but ultimately conventional, units. The money stock M_{in} and credit stocks such as L_{real} are measured in currency units (e.g. trillions of yen); the allocation shares q_i are dimensionless, so the entropy index $H(q)$ is measured in nats and $S_{\mathrm{M}} = kM_{\mathrm{in}}H(q)$ has units of "currency $\times$ nats". Since $H(q)$ is $\mathcal{O}(1)$ for typical partitions, S_{M} scales essentially like M_{in}.

The capacity variable V_{C} is expressed in the same monetary units as the underlying balance-sheet aggregates (e.g. CET1-based headroom), while the pressure $p_{\mathrm{C}} = -(\partial U/\partial V_{\mathrm{C}})_{S_{\mathrm{M}}}$ inherits units of "U per unit of volume". In practice U and V_{C} are both constructed from nominal stocks so that p_{C} is dimensionless and interpreted as an index of tightness; the liquidity temperature T_{L} is explicitly normalised to be dimensionless and lie in $[0, 1]$.

When regulatory headroom components are available, a representative example is the capital headroom

$$H_{\mathrm{cap}}(t) \approx V_R(t)\,\bigl(1 - \alpha_{\mathrm{cap}}\,p_R(t)\bigr),$$

with V_R a balance-sheet volume proxy and p_R a regulatory pressure proxy; analogous constructions apply for liquidity and funding headroom. The effective capacity is then taken as $V_{\mathrm{C}}(t) = \min_j H_j(t)$ over such components.

The internal-energy gauge U and the derived free energies F_{C} and exergy-like X_{C} share the same nominal scale (currency units), up to the choice of the scaling constants k, T_0, and p_0. These constants are treated as knobs that set the overall magnitude of the potentials rather than objects of primary interest: in applications we focus on signs, relative levels, and changes (e.g. ΔF_{C}, X_C^+, X_C^-) rather than on any claim that the absolute values of "credit energy" carry direct economic meaning.

Table 1: Thermodynamic–QTM–QTC correspondence (analogy-level).

Variable	Thermodynamics	QTM (money-first)	QTC (credit-first)
Mixing entropy	ΔS_{mix}	$S_{\text{M}} = kM_{\text{in}}H(q)$	$S_{\text{M}} = kM_{\text{in}}H(q)$
Temperature	T	T_L (proxy)	T_{L} (liquidity proxy)
Internal energy	U	$U_{\text{M}}(S_{\text{M}})$ (auxiliary)	$U(S_{\text{M}}, V_{\text{C}}, \ldots)$
Volume	V	–	V_{C} (capacity/headroom)
Pressure	p	–	$p_{\text{C}} = -(\partial U/\partial V_{\text{C}})_{S_{\text{M}}}$
Heat-like term	$\delta Q_{\text{rev}} = T\,\mathrm{d}S$	$Q_{\text{M}} \sim T_0 \Delta S_{\text{M}}$	$Q_{\text{C}} \sim \bar{T}_L\,\Delta S_{\text{M}}$
Work-like term	$\delta W = p\,\mathrm{d}V$	$W_{\text{M}} \equiv W_{\text{policy}}$	$W_{\text{C}} \equiv -\bar{p}_{\text{C}}\Delta V_{\text{C}} + W_{\text{policy}}$
First law	$\Delta U = T\Delta S + W$	$\Delta U_{\text{M}} = T_0\Delta S_{\text{M}} + W + \varepsilon$	$\Delta U = \bar{T}_L \Delta S_{\text{M}} + W + \varepsilon$
Second-law tendency	$\Delta S \geq 0$	$\Delta S_{\text{M}} \geq 0$ (mixing)	$\Delta S_{\text{M}} \geq 0$ (mixing)
Helmholtz free energy	$F = U - TS$	$F_{\text{M}} \equiv U_{\text{M}} - T_0 S_{\text{M}}$	$F_{\text{C}} \equiv U - T_0 S_{\text{M}}$
Exergy/availability	$X \approx U - T_0 S$	$X \approx U_{\text{M}} - T_0 S_{\text{M}}$	$X_{\text{C}} = \Delta U + p_0 \Delta V_{\text{C}} - T_0 \Delta S_{\text{M}}$

3 Thermodynamic Correspondence (QTM vs. QTC)

Table 1 summarizes the analogy. Thermodynamic quantities are literal on the left column; QTM/QTC entries are analogy-level constructs. Heat- and work-like pieces are defined for bookkeeping only.

The construction is chosen so that: (i) S_{M} is extensive and sensitive to dispersion; (ii) V_{C} carries explicit capacity/headroom information; (iii) QTC—unlike classic QTM—naturally admits a pressure-like channel p_{C}.

4 Bank Credit Creation and the Energy-Like Balance

When a bank grants a new loan, it simultaneously creates a matching deposit. On the joint bank–customer system, this is a pure accounting operation ("loans create deposits"). Within our mapping, the associated change in the potential U is decomposed as

$$\Delta U \approx \bar{T}_L\,\Delta S_{\text{M}} - \bar{p}_{\text{C}}\,\Delta V_{\text{C}} + W_{\text{policy}} + \varepsilon, \tag{4}$$

where:

- ΔS_{M}: change in dispersion entropy from scale and allocation shifts (typically $\Delta S_{\text{M}} > 0$ in net expansion);
- ΔV_{C}: change in effective capacity ($\Delta V_{\text{C}} < 0$ when headroom is used up; then $-\bar{p}_{\text{C}}\Delta V_{\text{C}} > 0$);
- W_{policy}: structured policy work[K14] from regulation, guarantees, central bank operations, and other deliberate interventions;
- ε: residual term capturing model error and omitted channels.

Credit creation phases (new lending > repayments) and contraction phases (repayments > new lending) then exhibit characteristic sign patterns for $(\Delta M_{\text{in}}, \Delta S_{\text{M}}, \Delta V_{\text{C}}, -\bar{p}_{\text{C}}\Delta V_{\text{C}})$, which can be tabulated and compared with data. The value of (4) is diagnostic: it forces us to attribute changes either to dispersion, capacity use, or policy work[K14], rather than conflating them.

For intuition it is useful to summarize typical sign patterns. Table 2 collects a minimal classification in terms of net expansion/contraction and whether headroom is being used or rebuilt; the

Table 2: Illustrative sign patterns in expansion/contraction regimes. "Expansion with headroom use" corresponds to broad-based credit growth ($\Delta M_{\mathrm{in}} > 0$, $\Delta S_{\mathrm{M}} > 0$) that eats into capacity ($\Delta V_{\mathrm{C}} < 0$). "Expansion with headroom rebuild" captures cases where asset-side growth and recapitalisation outpace use ($\Delta M_{\mathrm{in}} > 0$, $\Delta V_{\mathrm{C}} > 0$). "Contraction with headroom rebuild" refers to deleveraging or freezing of activity while buffers are restored ($\Delta M_{\mathrm{in}} < 0$, $\Delta V_{\mathrm{C}} > 0$). "Contraction with headroom use" flags stressed regimes in which activity shrinks yet capacity is still eroded ($\Delta M_{\mathrm{in}} < 0$, $\Delta V_{\mathrm{C}} < 0$; ΔS_{M} can be ambiguous).

Regime	ΔM_{in}	ΔS_{M}	ΔV_{C}
Expansion with headroom use	$+$	$+$	< 0
Expansion with headroom rebuild	$+$	$\gtrsim 0$	> 0
Contraction with headroom rebuild	< 0	≤ 0	> 0
Contraction with headroom use	< 0	ambiguous	< 0

qualitative readings in the caption are meant as guides rather than axioms. These patterns provide a qualitative checklist against which observed $(\Delta M_{\mathrm{in}}, \Delta S_{\mathrm{M}}, \Delta V_{\mathrm{C}})$ can be compared, and can be refined or extended in empirical work.

In addition to these pointwise diagnostics, we can study the *loop area* traced out by trajectories in the $(V_{\mathrm{C}}, p_{\mathrm{C}})$ plane over policy or credit cycles. In the reversible limit the line integral

$$W_{\mathrm{loop}} = \oint_{\mathcal{C}} p_{\mathrm{C}} \, \mathrm{d}V_{\mathrm{C}}$$

would vanish for closed cycles $\mathcal{C}$, reflecting path-independence of the underlying potential. In practice, non-zero loop area measures irreversibility and dissipative effects analogous to hysteresis in magnetic systems or frictional cycles. The streaming estimator in the code updates an exponentially weighted version of this integral via

$$W_t = \lambda W_{t-1} + p_{\mathrm{C}}(t-1)\big(V_{\mathrm{C}}(t) - V_{\mathrm{C}}(t-1)\big),$$

with forgetting factor λ chosen so that old cycles gradually lose influence. Large or persistent values of W_t therefore flag regimes where policy paths in $(S_{\mathrm{M}}, V_{\mathrm{C}})$ space exhibit pronounced hysteresis and stress.

5 Free Energy, Exergy, and Early-Warning Gauges

We seek a scalar gauge that (i) decreases as dispersion rises under a fixed environment, and (ii) upper-bounds structured work extractable over a cycle. A Helmholtz-style free energy provides this.

For a fixed reference environment (T_0), define

$$F_{\mathrm{C}} \equiv U - T_0 S_{\mathrm{M}}. \tag{5}$$

Then, under suitable regularity conditions,

$$\mathrm{d}F_{\mathrm{C}} = -p_{\mathrm{C}} \, \mathrm{d}V_{\mathrm{C}} + \delta W_{\mathrm{other}}, \tag{6}$$

so that F_{C} plays the role of an available-potential measure. As $\Delta F_{\mathrm{C}} \to 0$ under chosen boundaries, policy headroom for structured adjustments is effectively exhausted.

When an ambient pressure-like parameter p_0 is also relevant, an exergy-like functional is

$$X_{\mathrm{C}} = (U - U_0) + p_0(V_{\mathrm{C}} - V_{\mathrm{C},0}) - T_0(S_{\mathrm{M}} - S_{\mathrm{M},0}), \tag{7}$$

which reduces to $-\Delta F_{\mathrm{C}}$ if V_{C} is fixed and p_0 effects are negligible. Because X_{C} depends on boundary choices (T_0, p_0), we treat it as an optional, environment-dependent gauge.

In principle X_{C} can take either sign, depending on the chosen reference state $(U_0, V_{\mathrm{C},0}, S_{\mathrm{M},0})$ and environmental parameters (T_0, p_0). Negative values indicate that the current configuration has lower "available credit energy" than the reference; for early-warning visualisation, however, it is often convenient to enforce a non-negative floor (by clipping or by subtracting the minimum value over the sample) so that zero marks the effective boundary of usable headroom.

For regime diagnostics it is also useful to separate surplus and shortage components relative to a fixed free-energy reference. Let $\Delta F_C(t) = F_C(t) - F_C^{\mathrm{ref}}$ for some chosen baseline F_C^{ref} (e.g. the first non-missing observation or a user-specified date). We then define

$$X_C^+(t) = \max\{0,\ \Delta F_C(t)\}, \qquad X_C^-(t) = \max\{0,\ -\Delta F_C(t)\},$$

so that X_C^+ tracks "excess" free energy above the reference and X_C^- tracks shortfall. These series enter plots and summary tables as complementary early-warning gauges: persistent build-up of X_C^+ suggests unusually large policy room relative to the reference regime, whereas elevated X_C^- points to sustained pressure towards the boundary of feasible adjustment.

A Gibbs-style free energy

$$G_{\mathrm{C}} \equiv U + p_0 V_{\mathrm{C}} - T_0 S_{\mathrm{M}} \tag{8}$$

can be used when (T_0, p_0) are the natural controls. In applications, we typically monitor F_{C} (fixed environment) and compare with X_{C} or G_{C} when capacity constraints are explicit (cf. exergy notions in [11]).

External coupling. In applications we also allow the credit system to be coupled to an external "pressure bath" and "temperature bath". The coupling is constructed in two stages. First, we map a small set of market driver series into standardized monthly processes. For JP, the pressure drivers are:

- the US high-yield option-adjusted spread (HY OAS), used in level form as a proxy for global credit stress;
- the US–JP 10Y yield spread, $\Delta y_{US,JP}(t) = y_{US}^{10\mathrm{Y}}(t) - y_{JP}^{10\mathrm{Y}}(t)$;
- USD/JPY log returns, $r_{\mathrm{FX}}(t) = \log \mathrm{USDJPY}(t) - \log \mathrm{USDJPY}(t - \Delta t)$.

The temperature driver is the VIX equity volatility index, again mapped to monthly frequency. Each raw series $X_k(t)$ is aggregated to month-start, transformed according to its role (level, spread, log-return), and converted to a z-score

$$Z_k(t) = \frac{X_k(t) - \mathbb{E}[X_k]}{\sigma[X_k]},$$

using sample mean and standard deviation over the available history. Second, we form composite indices by simple averaging over the available standardized drivers:

$$E_p(t) = \frac{1}{K_p} \sum_{k \in \mathcal{P}} Z_k(t), \qquad E_T(t) = \frac{1}{K_T} \sum_{k \in \mathcal{T}} Z_k(t),$$

where $\mathcal{P}$ indexes pressure drivers and $\mathcal{T}$ indexes temperature drivers. Missing values in individual Z_k are ignored on each date so long as at least one driver remains. Equal weights reflect an agnostic prior about the relative importance of each driver: with only a handful of series, more elaborate factor models or time-varying loadings would be weakly identified and risk overfitting, so the unweighted mean serves as a transparent, robust first pass. In future work one could replace this averaging with a statistically estimated factor structure or region-specific loadings once longer histories and stronger identification are available.

Given E_p and E_T we work with effective fields

$$p_{\mathrm{C}}^{\mathrm{eff}}(t) = p_{\mathrm{C}}(t) + \alpha E_p(t), \qquad T_{\mathrm{L}}^{\mathrm{eff}}(t) = T_{\mathrm{L}}(t) + \delta E_T(t),$$

so that external stress and risk-on/off conditions act as linear perturbations to the internal equation of state. When α or δ are set to zero the system is "isolated" in this sense; non-zero couplings encode how exposed the credit state is to external financial conditions.

Sectoral "chemical potentials". Given the MECE allocation shares $\{q_i\}$ and M_{in}, we can form sectoral analogues of chemical potentials. Using the normalised shares $\tilde{q}_i$ from the entropy construction, one defines

$$\mu_i = T_0 k M_{\mathrm{in}} \big(\log \tilde{q}_i + 1\big),$$

so that, up to constants, μ_i is the derivative of the entropy-like term with respect to the bucket mass. For interpretation we work with deviations from the cross-bucket mean, $\Delta\mu_i = \mu_i - \bar{\mu}$, where $\bar{\mu}$ is the average over i at each date. Large positive $\Delta\mu_i$ flag categories where incremental "credit mass" is unusually valuable in entropy terms; large negative values flag categories where allocations are already heavy relative to the rest of the system. In the current implementation these μ_i and $\Delta\mu_i$ are used as diagnostic series and are not themselves fed back into the flow dynamics.

6 Maxwell-Like Relation, Exterior Derivative, and Legendre Structure

Since U is assumed to be a well-defined state potential, mixed partial derivatives commute. Using the definitions of T_{L} and p_{C} in (3), we obtain a Maxwell-like condition:

$$\left(\frac{\partial T_{\mathrm{L}}}{\partial V_{\mathrm{C}}}\right)_{S_{\mathrm{M}}} = -\left(\frac{\partial p_{\mathrm{C}}}{\partial S_{\mathrm{M}}}\right)_{V_{\mathrm{C}}}. \tag{9}$$

Geometrically, the pair $(T_{\mathrm{L}}, p_{\mathrm{C}})$ defines an exact differential one-form on the $(S_{\mathrm{M}}, V_{\mathrm{C}})$ state space:

$$\mathrm{d}U_{\mathrm{rev}} = T_{\mathrm{L}}\,\mathrm{d}S_{\mathrm{M}} - p_{\mathrm{C}}\,\mathrm{d}V_{\mathrm{C}},$$

obtained by removing the explicitly non-conservative contributions (W_{policy} and ε) from (4). Exactness of this one-form is equivalent to the vanishing of its exterior derivative $d\omega = 0$ (no "curl"), which in coordinates reads

$$\frac{\partial}{\partial V_{\mathrm{C}}}\left(\frac{\partial U}{\partial S_{\mathrm{M}}}\right)_{V_{\mathrm{C}}} = \frac{\partial}{\partial S_{\mathrm{M}}}\left(\frac{\partial U}{\partial V_{\mathrm{C}}}\right)_{S_{\mathrm{M}}},$$

and, after substituting (3), yields (9). In other words, the Maxwell-like equality is the integrability condition for reconstructing a single potential U from its components $(T_{\mathrm{L}}, p_{\mathrm{C}})$.

This also clarifies the Legendre structure. Starting from $U(S_{\mathrm{M}}, V_{\mathrm{C}})$ we can, in principle, define a potential written in terms of the intensive variables,

$$\Phi(T_{\mathrm{L}}, p_{\mathrm{C}}) \equiv U(S_{\mathrm{M}}, V_{\mathrm{C}}) - T_{\mathrm{L}} S_{\mathrm{M}} + p_{\mathrm{C}} V_{\mathrm{C}},$$

where $(S_{\mathrm{M}}, V_{\mathrm{C}})$ are now regarded as functions of $(T_{\mathrm{L}}, p_{\mathrm{C}})$ via the equation of state. Taking the differential and using (3) one finds

$$\mathrm{d}\Phi = -S_{\mathrm{M}}\,\mathrm{d}T_{\mathrm{L}} + V_{\mathrm{C}}\,\mathrm{d}p_{\mathrm{C}},$$

so that $(\partial\Phi/\partial T_{\mathrm{L}})_{p_{\mathrm{C}}} = -S_{\mathrm{M}}$ and $(\partial\Phi/\partial p_{\mathrm{C}})_{T_{\mathrm{L}}} = V_{\mathrm{C}}$. This Legendre transform from $(S_{\mathrm{M}}, V_{\mathrm{C}})$ to $(T_{\mathrm{L}}, p_{\mathrm{C}})$ is globally well-defined only when (9) holds; the free-energy-type potentials introduced in §5 (such as F_{C} and G_{C}) can then be viewed as partially Legendre-transformed versions of U evaluated at fixed environmental parameters (T_0, p_0).

Empirically, one can estimate $T_{\mathrm{L}}(S_{\mathrm{M}}, V_{\mathrm{C}})$ and $p_{\mathrm{C}}(S_{\mathrm{M}}, V_{\mathrm{C}})$ from proxies and test whether (9) approximately holds. Systematic violations indicate that the chosen variables are not state-like or that proxies and specifications are inadequate. In this sense, the analogy is falsifiable: it is not mere rhetoric.

7 Insights and Practical Tests

The mapping yields several operational diagnostics:

1. **Integrability test.** Estimate T_{L} and p_{C} as functions of $(S_{\mathrm{M}}, V_{\mathrm{C}})$ and test (9). Failure suggests mis-specification of capacity or dispersion metrics.

2. **Work vs. dispersion decomposition.** Use (4) to decompose changes in U into heat-like dispersion ($\bar{T}_L \Delta S_{\mathrm{M}}$), capacity use ($-\bar{p}_{\mathrm{C}} \Delta V_{\mathrm{C}}$), and policy work ($W_{\mathrm{policy}}$).

3. **Free-energy and exergy ceilings.** Monitor F_{C} or X_{C} as early-warning gauges: sustained proximity to zero under stress scenarios flags limited room for non-disruptive adjustment.

4. **Loop area and hysteresis.** Compute loop areas in $(S_{\mathrm{M}}, V_{\mathrm{C}})$ over policy cycles. Non-zero areas capture dissipative stress and irreversibility in credit allocation dynamics[K17].

All of these rely on observable or reconstructible quantities from public balance-sheet and market data. Implementation details (exact proxy choices, normalization, robustness checks) are part of ongoing empirical work and should be reported alongside results.

8 Limitations and Scope

This construction is intentionally modest. Key limitations include:

- **Category dependence.** S_{M} depends on the chosen partition of uses. Robustness across reasonable partitions must be checked.

- **Proxy noise.** T_{L}, V_{C}, p_{C} are built from noisy proxies. Measurement error can break (9) and distort the decomposition (4).

- **Quasi-static approximation.** Fast crises and regime shifts violate smooth state-variable assumptions; the mapping is best seen as quasi-static or coarse-grained.

- **Non-physical.** We do not assume microscopic "money particles" or claim that macro-financial data obey physical first/ second laws. The mapping is analogy-level and judged only by empirical usefulness.

- **Identification challenges.** Policy, expectations, and shocks act jointly. Causal claims require careful research design beyond the bookkeeping framework presented here.
- **Scaling conventions.** Constants such as k are conventional. Report normalized metrics and sensitivity checks.

9 Notes on Reproducibility and AI Assistance

This note is designed to accompany code and data (e.g. monthly reports computed from public sources). A typical implementation:

- computes S_M from M_in and a stable MECE[K15] partition of flows;
- constructs V_C from capital ratios, liquidity metrics, and headroom;
- builds T_L from market microstructure indicators;
- estimates p_C via regressions or event-study style differentials;
- evaluates the decompositions and tests described above.

In the public repository `2025_11_Thermo_Credit`, this is realised as a fully scripted pipeline:

- **Raw and feature tables.** Region-specific builder scripts `scripts/01_build_features.py` (JP), `scripts/04_build_features_eu.py` (EU), and `scripts/05_build_features_us.py` (US) select FRED and World Bank series according to configuration files (`config.yml`, `config_{jp,eu,us}.yml`) and `lib/series_selector.py`. They write money, credit, regulatory-pressure, and allocation tables under `data/` (e.g. `money*.csv`, `credit*.csv`, `reg_pressure*.csv`, `allocation_q*.csv`).
- **Entropy and temperature.** The module `lib/entropy.py` implements the definition $S_\mathrm{M} = kM_\mathrm{in}H(q)$ in (1) with $H(q) = -\sum_i \tilde{q}_i \log \tilde{q}_i$ where $\tilde{q}_i = \max\{q_i, 0\}/\sum_j \max\{q_j, 0\}$, and also computes $S_{\mathrm{M,in}} = kM_\mathrm{in}H(q)$, $S_{\mathrm{M,out}} = kM_\mathrm{out}H(q)$, $S_{\mathrm{M,hat}} = H(q)/\log K$ (with K buckets), and optional per-bucket contributions $S^{(i)}_{\mathrm{M,in}} = kM_\mathrm{in}\tilde{q}_i$. The module `lib/temperature.py` builds T_L from credit spreads, depth, and turnover by forming $z_s = Z(1/(\mathrm{spread} + \epsilon))$, $z_d = Z(1/(\mathrm{depth} + \epsilon))$, $z_t = Z(\mathrm{turnover})$, combining $\hat{T} = z_s z_d(1 + \frac{1}{2}z_t)$, and finally min–max normalising to obtain $T_\mathrm{L} = (\hat{T} - \min \hat{T})/(\max \hat{T} - \min \hat{T})$.
- **Internal-energy gauge.** Within the credit tables the column $U(t)$ is used as the internal-energy / capacity proxy entering (4), (5), and (7). When a dedicated U series is not available, the code fills it by combining available quantities in a conservative order (preferring an explicit U column, then GDP-like series such as $U_{\mathrm{gdp\_only}}$ or Y, and only as a last resort falling back to L_real). An optional detrended version $U^\star$ is produced by subtracting a no-lookahead rolling mean so that diagnostics can focus on fluctuations around a slowly varying baseline.
- **Depth and turnover enrichment.** When region-specific depth/turnover series are not supplied, the helper `lib/credit_enrichment.py` constructs depth and turnover heuristically from real credit stocks L_real and capacity proxy U. For depth, if an external series $D(t)$ exists it is used directly; otherwise the fallback

$$\mathrm{depth}(t) = \begin{cases} d_0, & \text{if } L_\mathrm{real} \text{ is all zero/NaN,} \\ d_0\, L_\mathrm{real}(t)/\mathrm{median}_\tau L_\mathrm{real}(\tau), & \text{otherwise} \end{cases}$$

is applied with a configurable scale d_0. For turnover, if no explicit series is given, the base ratio $r(t) = U(t)/L_{\mathrm{real}}(t)$ is formed (ignoring zero denominators), missing values are replaced by a fallback r_0, and the result is clipped to a band $[r_{\min}, r_{\max}]$; the implementation tracks the fraction of periods where clipping occurs as a simple diagnostic.

- **Capacity, headroom, and coupling.** The core constructor `lib/indicators.py` merges money, allocation, credit, and regulatory tables, renames regulatory quantities into V_{C} and p_{C}, and, when configured with the "min_headroom" formula, sets $V_{\mathrm{C}}(t) = \min_j H_j(t)$ over headroom components $H_j \in \{\mathrm{capital\_headroom}, \mathrm{lcr\_headroom}, \mathrm{nsfr\_headroom}\}$ (or scaled variants) whenever they are available, while retaining the legacy $V_{\mathrm{C,legacy}}$ column for comparison. External pressure/temperature drivers (e.g. credit spreads, volatility indices) are aggregated in `lib/external_coupling.py` into E_p and E_T; when the coupling coefficients α, δ are non-zero the code applies the affine shifts $p_{\mathrm{C}} \leftarrow p_{\mathrm{C}}^{\mathrm{baseline}} + \alpha E_p$ and $T_{\mathrm{L}} \leftarrow T_{\mathrm{L}}^{\mathrm{baseline}} + \delta E_T$.

- **Free energy, exergy, and loop area.** The same module computes F_{C}, X_{C}, and the Gibbs-style G_{C} as in (5)–(8); to enforce a non-negative exergy floor the implementation either clips X_{C} at zero or, in "shift" mode, subtracts $\min_t X_{\mathrm{C}}(t)$ when this minimum is negative. The loop-area estimator in $(p_{\mathrm{C}}, V_{\mathrm{C}})$ is implemented by updating $W_t = \lambda W_{t-1} + p_{t-1}(V_{\mathrm{C},t} - V_{\mathrm{C},t-1})$ at each time t (with forgetting factor λ), storing W_t as a "loop_area" column. The diagnostics routine then estimates $\partial S_{\mathrm{M}}/\partial V_{\mathrm{C}}|_{T_{\mathrm{L}}}$ and $\partial p_{\mathrm{C}}/\partial T_{\mathrm{L}}|_{V_{\mathrm{C}}}$ by rolling ordinary least squares, and constructs finite-difference versions of the first-law decomposition by computing ΔU, ΔS_{M}, ΔV_{C}, $\bar{T}_{\mathrm{L}}$, $\bar{p}_{\mathrm{C}}$, and $Q_{\mathrm{like}} = \bar{T}_{\mathrm{L}} \Delta S_{\mathrm{M}}$, $W_{\mathrm{like}} = \bar{p}_{\mathrm{C}} \Delta V_{\mathrm{C}}$.

- **Per-region orchestration.**

  Scripts `scripts/02_compute_indicators.py`, `scripts/02_compute_indicators_eu.py`,

  `scripts/02_compute_indicators_us.py` and the helper

  `lib/regions.py` assemble the inputs for JP/EU/US and write

  `site/indicators*.csv` used by the dashboard and tests.

- **Fallbacks and CI reproducibility.** To keep tests and scheduled builds deterministic, `scripts/ci_prepare_minimal_data.py` seeds tiny synthetic CSVs when real inputs are absent, and the continuous-integration workflows (GitHub Actions) pin Python dependencies and re-run the scripts above so that indicators and the report can be regenerated from a fixed environment.

Drafting and editing of the present text used a GPT-based large language model as a tool at low randomness. All equations, definitions, and claims are curated and are the responsibility of the authors. Readers should rely on the archived PDF and associated repository for the citable version and reproducible code.

Appendix: Glossary (For Physicists New to Finance)

Numbering. Each term is assigned a unique K-number (K1, K2, . . .) in the order it is first referenced in the main text. Use the superscript K# markers to jump back here; headings show the same inline K#.

This glossary explains the main banking, credit, and regulatory terms used in this note for readers with a physics background. Definitions are informal and intuition-friendly. When helpful, we include analogies to thermodynamics or dynamical systems. These are aids to intuition, not strict identities.

1. Regulation and Bank Balance Sheets

K1 CET1 (Common Equity Tier 1). Core equity capital of a bank (common shares, retained earnings). It absorbs losses and underpins solvency. Analogy: the bank's fundamental "energy reserve".

K2 RWA (Risk-Weighted Assets). Total assets weighted by regulatory risk factors. Riskier exposures receive higher weights. The ratio CET1/RWA is a key prudential metric. Analogy: an effective load or mass adjusted for fragility.

K3 CET1/RWA ratio and slack. CET1/RWA indicates how much high-quality capital backs risk-weighted assets. Regulation sets a minimum. The slack is the excess above this minimum and represents capacity to expand or absorb shocks. Analogy: safety margin or unused headroom in a constrained system.

K4 Credit capacity / Headroom (V_{C}). Effective room for additional lending, given capital, liquidity, and internal limits. In this note V_{C} is the state-like variable capturing this remaining capacity. Analogy: effective volume available before hitting hard walls.

K5 Credit pressure (p_{C}). Shadow price of capacity: the marginal cost or value of relaxing or tightening V_{C}. Defined in analogy to $p_{\mathrm{C}} = -(\partial U/\partial V_{\mathrm{C}})_{S_{\mathrm{M}}}$ or $-\partial F/\partial V_{\mathrm{C}}$. Analogy: thermodynamic pressure; tighter constraints $\Rightarrow$ higher p_{C}.

K6 HQLA (High Quality Liquid Assets). Very liquid, low-risk assets (e.g. government bonds) that can be sold quickly in stress. They support liquidity ratios and crisis resilience. Analogy: high-grade stored energy that can be tapped on demand.

K7 Liquidity buffer. Cash plus HQLA held as an emergency reserve to withstand sudden outflows or market stress. Analogy: a backup battery or safety reservoir.

K8 LCR (Liquidity Coverage Ratio). Regulatory ratio: HQLA divided by projected net cash outflows over a 30-day stress scenario. It tests short-term liquidity robustness. Analogy: can the system run for 30 days under worst-case load?

K9 NSFR (Net Stable Funding Ratio). Regulatory ratio over a one-year horizon: stable funding relative to required stable funding. It limits excessive maturity mismatch. Analogy: ensuring long-lived assets are backed by sufficiently slow-decaying sources.

2. Money, Credit, and Flow Concepts

K10 Money-in-circulation. An operational measure of money that is actually circulating in the selected system and horizon (e.g. deposits used in payments), not merely base money on the central bank balance sheet. Analogy: active particles taking part in interactions.

K11 Credit stocks and flows. Stocks: outstanding amounts of loans or credit at a given time. Flows: changes per period (new lending, repayments, net issuance). Analogy: internal energy vs. power / energy flux.

K12 Margin credit / Securities financing. Credit used to finance positions in securities (e.g. margin loans, certain repos). It amplifies leverage in financial markets and is often separated from credit to the real economy.

K13 Commercial Paper (CP). Short-term unsecured debt issued by firms. Provides funding outside traditional bank loans. Analogy: an alternative branch in the credit circuit.

K14 Policy work (W_{policy}). Deliberate interventions by central banks, regulators, or governments: interest rate changes, asset purchases, guarantees, capital rule adjustments, and similar actions. In our decomposition this is the structured, intentional part of "work". Analogy: externally applied work on the system.

3. Structural and Analytical Concepts

K15 MECE (Mutually Exclusive, Collectively Exhaustive). A rule for defining categories: (i) no overlaps between categories, (ii) no gaps in coverage. For the entropy $S_{\text{M}} = kM_{\text{in}}H(q)$, the allocation shares q_i should be MECE, otherwise S_{M} is distorted by double counting or omissions.

K16 State variable and proxy. A state variable is determined by the current state, not by the detailed path. In practice, finance uses observable proxies (e.g. ratios, indices) to approximate such variables. Our Maxwell-like relation (9) tests whether chosen proxies behave as if they came from a consistent potential $U(S_{\text{M}}, V_{\text{C}}, \ldots)$.

K17 Hysteresis and loop area. If trajectories in the $(S_{\text{M}}, V_{\text{C}})$ plane form loops with non-zero area over policy or credit cycles, this indicates irreversibility or dissipation-like effects (e.g. stress, misallocation, or path dependence). Analogy: magnetic hysteresis, frictional cycles, or inelastic processes.

K18 Stress testing and early-warning indicators. Stress tests simulate severe but plausible scenarios to see whether banks or systems survive. Early-warning indicators attempt to flag fragility in advance. Within this framework, quantities like F_{C}, X_{C}, and loop areas are intended as structured candidates to complement such tools.

K19 Money vs. credit (QTM vs. QTC perspective). In traditional Quantity Theory of Money (QTM), money is primary and credit is often treated as derived. In the Quantity Theory of Credit (QTC) and in this note, credit creation is primary: bank lending creates deposits, and money is an accounting outcome of credit decisions. This shift motivates tracking credit capacity and dispersion as state-like objects.

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