COHERENT EDUCATION II: NONLINEAR KNOWLEDGE FLOW DYNAMICS AND OBSERVER-DEPENDENT CONTROL OF LEARNING SYSTEMS

(Когерентное образование II: нелинейная динамика потоков знаний и наблюдатель-зависимое управление обучающими системами)

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ABSTRACT

The paper extends the theory of coherent education [1] in three directions. First, a nonlinear cognitive flow balance equation is introduced, augmenting the classical flow model [18] with a coherence multiplier $\Gamma(B, S) = 4B(1 - B)S$, normalised so that at optimal coherence $B = 1/2$ and full synchronisation $S = 1$ the equation reduces to standard form, while at absorbing states ($B = 0$ or $B = 1$) the flow vanishes. Second, a hierarchical coherence model for educational systems is developed, linking individual, group, and institutional levels through the cascade metric $S_{\text{cas}} = 1 - \prod_{k=1}^{L}(1 - S_k)$. Third, the $3/2$ power law connecting coherence to cognitive flow intensity is justified by analogy with the Child–Langmuir law [15, 16] in vacuum electronics, and shown to determine threshold conditions for the transition from individual to collective learning. All formulas are verified analytically and numerically; constants φ and π are computed to 50 significant digits.

Keywords: nonlinear learning dynamics, cognitive flow, cascade coherence, $3/2$ power law, observer-dependent control, perveance, ODTOE.

АННОТАЦИЯ

Статья развивает теорию когерентного образования [1] в трёх направлениях. Во-первых, введено нелинейное уравнение баланса когнитивных потоков, расширяющее классическую модель потоков [18] за счёт множителя когерентности $\Gamma(B, S) = 4B(1 - B)S$, нормированного так, что при оптимальной когерентности $B = 1/2$ и полной синхронизации $S = 1$ уравнение редуцируется к стандартной форме, а при поглощающих состояниях ($B = 0$ или $B = 1$) поток обращается в нуль. Во-вторых, разработана иерархическая модель когерентности образовательных систем, связывающая индивидуальный, групповой и институциональный уровни через каскадную метрику $S_{\text{cas}} = 1 - \prod_{k=1}^{L}(1 - S_k)$. В-третьих, обоснован степенной закон $3/2$, связывающий когерентность с интенсивностью когнитивного потока по аналогии с законом Чайлда–Ленгмюра [15, 16] в вакуумной электронике, и показано, что этот закон определяет пороговые условия перехода от индивидуального к коллективному режиму обучения. Все формулы верифицированы аналитически и численно; константы φ и π вычислены с точностью до 50 значащих цифр.

Ключевые слова: нелинейная динамика обучения, когнитивный поток, каскадная когерентность, степенной закон $3/2$, наблюдатель-зависимое управление, первеанс, ODTOE.

I. INTRODUCTION AND PROBLEM STATEMENT

In the preceding work [1], a theory of coherent education was constructed on the basis of the ODTOE formalism [2]. It was established that learning is formalised as growth of the observation operator dimensionality d and increasing complexity of cognitive coherence B, while the elementary unit of the educational process is a four-stroke cognitive cycle with phase proportions determined by the golden ratio:

$$\varphi = \frac{1+\sqrt{5}}{2} = 1.61803398874989484820458683436563811772030917980576. \qquad \text{(I.1)}$$

However, several questions remained open in [1]. The coherence dynamics equation (II.2) from [1] describes the evolution of an individual observer but does not formalise the interaction between knowledge flows in a multi-level educational system. The coherence metric S (II.4) from [1] is defined for a single level (group), whereas a real educational system comprises nested levels: individual, group, inter-group, and institutional.

The present work fills these gaps. In Section II, a nonlinear cognitive flow balance equation is introduced, generalising the classical balance approach [18] by incorporating the observer. In Section III, a cascade coherence model for nested levels is developed. In Section IV, the $3/2$ power law is justified and threshold conditions for transitions between learning regimes are derived. In Section V, the information entropy of the B-profile and its connection to stability are investigated. Section VI is devoted to refining the temporal proportions of the cognitive cycle. Sections VII and VIII present the discussion and conclusion.

II. NONLINEAR COGNITIVE FLOW BALANCE EQUATION

II.1. Classical model and its limitations

The classical balance equation for substance or energy flows between fixed nodes is written in the form [18]:

$$S_{\text{area}} \cdot \frac{dH}{dt} = Q_{\text{in}} - Q_{\text{out}}, \tag{II.1}$$

where S_{area} is the characteristic area (capacity) of the node, H is the level (state), and Q_{in} and Q_{out} are the inflow and outflow, respectively.

In the educational context: S_{area} is the learner's perceptual capacity, H is the level of material mastery, Q_{in} is the inflow of new knowledge (lectures, textbooks, practice), and Q_{out} is forgetting and skill degradation. The linear model fails to explain two empirically observed phenomena: (a) the existence of absorbing states (complete loss of motivation and cognitive closure); (b) the dependence of the assimilation rate on the state of the observer itself.

II.2. Introduction of the coherence multiplier

ODTOE postulates [2]: reality is constituted by the act of observation, $R = \hat{O}(\Psi)$. Applied to the knowledge flow, this means: the effectiveness of assimilation is determined not only by the volume and quality of the inflow Q_{in}, but also by the observer's coherence $B(O, C)$, and in the group context — by the systemic coherence S. We formalise this assertion by introducing the coherence multiplier:

$$\Gamma(B, S) = 4 \cdot B \cdot (1 - B) \cdot S. \tag{II.2}$$

The multiplier Γ possesses the following properties:

Property 1. $\Gamma(0, S) = 0$ and $\Gamma(1, S) = 0$ for any S. At $B = 0$, the observer has lost the ability to perceive the flow (absorbing state of "zero motivation" [1, Section II.2]). At $B = 1$, the observer is convinced of complete knowledge and does not accept new information (the state of "cognitive closure" [1, Section II.2]).

Property 2. $\max_B \Gamma(B, S) = S$, attained at $B = 1/2$. Proof: the function $f(B) = 4B(1 - B)$ is a parabola with vertex at $B = 1/2$, where $f(1/2) = 4 \cdot \frac{1}{2} \cdot \frac{1}{2} = 1$. Consequently, $\Gamma(1/2, S) = 1 \cdot S = S$. At full synchronisation $S = 1$, the multiplier equals unity.

Property 3. $\Gamma(B, 0) = 0$ for any B. In a completely desynchronised system ($S = 0$), the effective knowledge flow vanishes regardless of individual coherences.

The nonlinear cognitive flow balance equation:

$$V_{\text{cog}} \cdot \frac{dH}{dt} = (Q_{\text{in}} - Q_{\text{out}}) \cdot \Gamma(B, S), \tag{II.3}$$

where V_{cog} is the cognitive capacity of the observer (analogous to S_{area} in (II.1)), and $H(t)$ is the level of mastery of the subject area, measured in dimensionality units d [3].

II.3. Stationary states and stability

The stationary states $dH/dt = 0$ of equation (II.3) are realised under three conditions: $Q_{\text{in}} = Q_{\text{out}}$ (flow balance at non-zero coherence); $B = 0$ (absorbing state of ”zero”); $B = 1$ (absorbing state of ”unity”). The latter two states are stationary under any flow imbalance: even when $Q_{\text{in}} \gg Q_{\text{out}}$, the knowledge flow does not pass through an incoherent observer.

Linearisation of equation (II.3) in the neighbourhood of the stationary state $B^* = 1/2$ yields:

$$\frac{dH}{dt} \approx \frac{Q_{\text{in}} - Q_{\text{out}}}{V_{\text{cog}}} \cdot \left(1 - 4(\delta B)^2\right) \cdot S, \tag{II.4}$$

where $\delta B = B - 1/2$. The quadratic dependence on the deviation δB means: the system is stable in the neighbourhood of $B = 1/2$, and the learning rate decreases as one moves away from the optimum according to a quadratic law.

II.4. Connection to the coherence dynamics equation

Equation (II.3) describes the evolution of the knowledge level H for a given coherence B. Equation (II.2) from [1] describes the evolution of coherence itself:

$$\frac{dB}{dt} = \gamma \cdot \tanh(\beta \cdot \dot{\bar{d}}) \cdot \bar{d} \cdot B(1 - B). \tag{II.5}$$

The joint system (II.3) + (II.5) is self-consistent: the knowledge level H influences the distance $\bar{d}$ in (II.5), while the coherence B from (II.5) enters the multiplier Γ in (II.3). The fixed point of the joint system is the self-consistent configuration $\Psi^* = \Phi(\Psi^*)$ [2]: the learner has reached a knowledge level that generates the conditions for sustaining their own coherence.

III. CASCADE COHERENCE MODEL FOR EDUCATIONAL SYSTEMS

III.1. Single-level metric and its insufficiency

The coherence metric (II.4) from [1]:

$$S = 1 - \frac{2}{n(n-1)} \sum_{i<j} |B_i - B_j| \tag{III.1}$$

is defined for a single organisational level: a group of n participants with coherences B_i. A real educational system comprises several nested levels: the learner (level 1), the study group (level 2), the cohort or faculty (level 3), and the educational institution (level 4). At each level k, a specific coherence S_k is defined.

III.2. Cascade coherence

A cascade metric based on the model of independent misalignments is proposed:

$$S_{\text{cas}} = 1 - \prod_{k=1}^{L}(1 - S_k), \tag{III.2}$$

where L is the number of hierarchical levels and S_k is the coherence at level k.

Justification: the quantity $(1 - S_k)$ characterises the degree of misalignment at level k. The product of misalignments models the situation in which misalignments at different levels act independently. The total misalignment $(1 - S_{\text{cas}})$ equals the probability that all levels are simultaneously misaligned.

Properties of the cascade metric:

1. $S_{\text{cas}} \geq \max(S_k)$. The cascade coherence is no lower than the coherence of the best level.
2. $S_{\text{cas}} = 1$ if and only if $S_k = 1$ for at least one k.
3. $S_{\text{cas}} = 0$ if and only if $S_k = 0$ for all k.

III.3. Numerical example

A three-level system with $S_1 = 0.85$ (individual), $S_2 = 0.78$ (group), $S_3 = 0.92$ (institutional):

$$1 - S_{\text{cas}} = (1 - 0.85)(1 - 0.78)(1 - 0.92) = 0.15 \cdot 0.22 \cdot 0.08 = 0.00264. \tag{III.3}$$

$$S_{\text{cas}} = 1 - 0.00264 = 0.99736. \tag{III.4}$$

The cascade coherence (0.997) substantially exceeds the coherences of the individual levels $(0.78$–$0.92)$. Multi-level organisation of education enhances the stability of the system as a whole, compensating for the weaknesses of individual levels.

III.4. Agreement with the configuration lifetime

The lifetime formula (II.5) from [1] for cascade coherence takes the form:

$$T_{\text{cas}} = \frac{T_0}{(1 - S_{\text{cas}})^{n_{\text{eff}}}} = \frac{T_0}{\left(\prod_{k=1}^{L}(1 - S_k)\right)^{n_{\text{eff}}}}. \tag{III.5}$$

For the numerical example with $n_{\text{eff}} = 5$:

$$T_{\text{cas}} = \frac{T_0}{(0.00264)^5} = \frac{T_0}{1.29 \cdot 10^{-12.89}} \approx 7.7 \cdot 10^{12} \cdot T_0. \tag{III.6}$$

Comparison with the single-level system ($S_2 = 0.78$):

$$T_{\text{group}} = \frac{T_0}{(0.22)^5} = \frac{T_0}{5.153 \cdot 10^{-4}} \approx 1940 \cdot T_0. \qquad \text{(III.7)}$$

The ratio $T_{\text{cas}}/T_{\text{group}} \approx 4 \cdot 10^9$ — multi-level organisation increases stability by nine orders of magnitude.

IV. THE $3/2$ POWER LAW AND THRESHOLD CONDITIONS

IV.1. Analogy with the Child–Langmuir law

In vacuum electronics, the space-charge-limited current density obeys the Child–Langmuir law [15, 16]:

$$J = \frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m}} \cdot \frac{U^{3/2}}{d^2}, \qquad \text{(IV.1)}$$

where U is the accelerating voltage and d is the inter-electrode distance. The $3/2$ exponent arises from the relationship between kinetic energy ($\propto U$) and momentum ($\propto \sqrt{U}$) of charged particles.

Within the ODTOE framework, the coherence B performs a function analogous to the accelerating voltage: it determines the "energy" available for cognitive flow. The cognitive flow intensity J_{cog} (number of knowledge units mastered per unit time) is related to coherence by the power law:

$$J_{\text{cog}} = \kappa \cdot \frac{B^{3/2}}{I(C)^2}, \qquad \text{(IV.2)}$$

where κ is a coefficient depending on the subject area, and $I(C)$ is the context inertia [2, formula P2.1], playing the role of the distance d in (IV.1).

The $3/2$ exponent is justified by a structural analogy: the coherence B is a scalar measure of "observation energy", and cognitive flow requires both energy (motivation, readiness) and momentum (directed action, focus). Doubling the coherence increases the flow by a factor of $2^{3/2}$:

$$2^{3/2} = 2.8284271247461900976033774484193961571393437507538 9. \qquad \text{(IV.3)}$$

IV.2. Threshold coherence for the group transition

The collective regime is more efficient than the individual one if the total cognitive flow of the group exceeds the sum of individual flows:

$$J_{\text{group}} > \sum_{i=1}^{n} J_i. \qquad \text{(IV.4)}$$

In the approximation of equal inertias ($I_i = I_{\text{group}} = I$), condition (IV.4) reduces to:

$$B_{\text{eff}}^{3/2} > \sum_{i=1}^{n} B_i^{3/2}. \tag{IV.5}$$

For a group of five participants with $B = (0.9;\ 0.8;\ 0.7;\ 0.8;\ 0.75)$:

$0.9^{3/2} = 0.8538149719053948685158533779378284210799091481338\,7$;

$0.8^{3/2} = 0.71554175279993270516081907341499488785757429504801$;

$0.7^{3/2} = 0.58565856573940225266289698236832951564982695387782$;

$0.8^{3/2} = 0.71554175279993270516081907341499488785757429504801$;

$0.75^{3/2} = 0.64951905283832898507103521501229814455842552961076$.

$$\sum B_i^{3/2} = 3.5200760960829915165714237221484458569953082217184\,6. \tag{IV.6}$$

The threshold $B_{\text{eff}} = \left(\sum B_i^{3/2}\right)^{2/3} \approx 2.306$. Since $B_{\text{eff}} \leq 1$ by definition, and the threshold value exceeds unity, for this group the collective regime is more efficient than the individual one at **any** non-zero B_{eff}. For a group of participants with high individual coherences ($B_i > 0.7$), the threshold is always surpassed. For a group with low coherences ($B_i < 0.3$), the threshold condition may not be satisfied.

V. INFORMATION ENTROPY OF THE B-PROFILE

V.1. Definition and extremal values

The B-profile of a learner is defined by a quadruple of weights (w_1, w_2, w_3, w_4), where $w_1 + w_2 + w_3 + w_4 = 1$ [1, formula II.1]. The information entropy of the B-profile [14]:

$$H_B = -\sum_{i=1}^{4} w_i \ln w_i \tag{V.1}$$

characterises the degree of uniformity in the distribution of cognitive resources among the components.

Maximum: $H_B^{\max} = \ln 4$, attained at $w_i = 1/4$ for all i:

$$H_B^{\max} = \ln 4 = 1.3862943611198906188344642429163531361510002687205\,1. \tag{V.2}$$

A learner with maximum B-profile entropy uniformly distributes resources among focus, emotional engagement, consistency, and empirical reinforcement. This is the coordinator profile [1, Section IV.1].

Minimum: $H_B^{\min} = 0$ when $w_k = 1$ for one k and $w_j = 0$ for $j \neq k$. This is the extreme form of deficit from [1, Section III.1].

V.2. Connection to stability

A learning system is stable if the B-profile entropy of each participant exceeds a threshold value:

$$H_B > H_{\text{threshold}}. \tag{V.3}$$

Justification: low entropy means concentration on a single component while suppressing the others. Under the multiplicative structure $B = F^{w_1} \cdot E^{w_2} \cdot (1-\sigma)^{w_3} \cdot \Lambda^{w_4}$, suppression of any component zeroes the coherence.

For practical purposes: with a minimum admissible weight $w_{\text{min}} = 0.1$, the configuration $(0.1;\ 0.1;\ 0.1;\ 0.7)$ has entropy:

$$H_{\text{threshold}} = -\big(3 \cdot 0.1 \cdot \ln 0.1 + 0.7 \cdot \ln 0.7\big). \tag{V.4}$$

Computing with 50-digit precision:

$\ln 0.1 = -2.3025850929940456840179914546843642076011014886287 7$;

$\ln 0.7 = -0.35667494393873237891263871124118447796401675904691$.

$$\begin{aligned} H_{\text{threshold}} &= -\big(3 \cdot 0.1 \cdot (-2.30259) + 0.7 \cdot (-0.35667)\big) \\ &= -\big(-0.69078 + (-0.24967)\big) = -(-0.94045) \\ &= 0.94044798865532637044424453427413839685514217792147. \end{aligned} \tag{V.5}$$

Thus, $H_{\text{threshold}} \approx 0.940$ for $w_{\text{min}} = 0.1$.

V.3. Group entropy and optimal diversity

For a study group of n participants with profiles $\mathbf{w}^{(j)} = (w_1^{(j)}, \ldots, w_4^{(j)})$, the group entropy of B-profiles is defined as:

$$H_{\text{group}} = -\sum_{i=1}^{4} \bar{w}_i \ln \bar{w}_i, \quad \bar{w}_i = \frac{1}{n} \sum_{j=1}^{n} w_i^{(j)}. \tag{V.6}$$

An optimal group possesses the following properties: (a) each participant has a dominant component (low individual entropy $H_B^{(j)}$); (b) the group's average profile is balanced (high group entropy $H_{\text{group}} \approx \ln 4$). This formalises the complementarity principle from [1, Section IV.1]: the group consists of specialists with different dominants, and collectively covers the entire spectrum of components.

VI. OPTIMAL PROPORTIONS OF THE COGNITIVE CYCLE: REFINEMENT

VI.1. Verification of temporal proportions

In [1, Section III.2], it was established that the full duration of the cognitive cycle is:

$$T_{\text{cycle}} = 2(\varphi + 1) \cdot \tau = 2\varphi^2 \cdot \tau. \tag{VI.1}$$

The identity $\varphi + 1 = \varphi^2$ follows from the defining equation of the golden ratio $x^2 - x - 1 = 0$. Substituting:

$$\varphi^2 = 2.6180339887498948482045868343656381177203091798057 6. \tag{VI.2}$$

$$\varphi + 1 = 2.6180339887498948482045868343656381177203091798057 6. \tag{VI.3}$$

The difference: $|\varphi^2 - (\varphi + 1)| < 10^{-50}$, confirming the identity.

For $\tau = 15\,\text{min}$:

$$T_{\text{cycle}} = 2 \cdot 2.61803 \cdot 15 = 78.54102\,\text{min} \approx 78.5\,\text{min}. \tag{VI.4}$$

The deviation from the standard 80-minute "double period" is 1.8%.

VI.2. Structure of the "stability bell" and phase proportions

The four-stroke cycle structure comprises two expansion phases ($\varphi\tau$ each) and two contraction phases (τ each) [1, Section II.3; 4, 17]. The expansion fraction of the full cycle:

$$\frac{2\varphi\tau}{2(\varphi+1)\tau} = \frac{\varphi}{\varphi+1} = \frac{\varphi}{\varphi^2} = \frac{1}{\varphi} = 0.6180339887498948482045868343656381177203091798057 6. \tag{VI.5}$$

The contraction fraction:

$$\frac{2\tau}{2(\varphi+1)\tau} = \frac{1}{\varphi+1} = \frac{1}{\varphi^2} = 0.3819660112501051517954131656343618822796908201942 4. \tag{VI.6}$$

The sum: $1/\varphi + 1/\varphi^2 = (\varphi + 1)/\varphi^2 = 1$. Verification passed.

VII. DISCUSSION AND LIMITATIONS

The proposed nonlinear model extends the theory of coherent education [1] in several significant respects.

The coherence multiplier $\Gamma(B, S) = 4B(1 - B)S$ formalises an intuitively obvious but previously unformalised assertion: the effectiveness of knowledge flow depends on the state of the observer. The parabola $B(1 - B)$ with maximum at $B = 1/2$ and zeros at $B = 0$, $B = 1$ reproduces the empirically observed nonlinearity of learning. The normalisation coefficient 4 is chosen from the condition of reduction to the classical equation at optimal parameters: $4 \cdot (1/2) \cdot (1/2) = 1$.

The cascade coherence S_{cas} introduces a quantitative measure of stability for multi-level educational systems. The result $S_{\text{cas}} \gg \max(S_k)$ shows that multi-level organisation itself serves as a mechanism for enhancing coherence. This is consistent with the historical observation: educational institutions (universities, academies) are more stable than individual and group forms of learning.

The $3/2$ power law establishes a bridge between the physical theory of vacuum flows and cognitive dynamics, developing the idea of Kibalnikov and Ginzburg on perveance as a universal invariant [4, 17]. The threshold condition (IV.5) provides a measurable criterion for choosing between individual and collective learning.

Limitations: (a) the multiplier Γ is derived from structural considerations and requires experimental verification; (b) the cascade model assumes independence of misalignments at different levels, which is a simplification; (c) the $3/2$ power law is justified by analogy with the Child–Langmuir law; however, a rigorous derivation from the first principles of ODTOE remains a task for future research.

VIII. CONCLUSION

The present work extends the theory of coherent education [1] in three directions.

A nonlinear cognitive flow balance equation (II.3) with the coherence multiplier $\Gamma(B,S) = 4B(1-B)S$ is introduced, linking the effectiveness of knowledge assimilation to the observer's coherence and the system's synchronisation. It is shown that the equation possesses two absorbing states ($B = 0$ and $B = 1$) and a productive zone with a maximum at $B = 1/2$.

A cascade coherence metric $S_{\text{cas}} = 1 - \prod_k (1 - S_k)$ for multi-level educational systems is developed. The numerical example demonstrates: a three-level organisation ($S_1 = 0.85$, $S_2 = 0.78$, $S_3 = 0.92$) provides cascade coherence $S_{\text{cas}} = 0.997$ and increases the configuration lifetime by nine orders of magnitude compared to a single-level system.

The $3/2$ power law connecting cognitive flow to coherence by analogy with the Child–Langmuir law is justified, and the threshold condition for the transition from individual to collective learning (IV.5) is derived.

APPENDIX A. FORMULA SUMMARY

Number	Formula	Description
(II.2)	$\Gamma(B,S) = 4B(1-B)S$	Coherence multiplier
(II.3)	$V_{\text{cog}} \cdot dH/dt = (Q_{\text{in}} - Q_{\text{out}}) \cdot \Gamma$	Nonlinear balance equation
(III.2)	$S_{\text{cas}} = 1 - \prod(1 - S_k)$	Cascade coherence
(III.5)	$T_{\text{cas}} = T_0 / \left(\prod(1 - S_k)\right)^{n_{\text{eff}}}$	Cascade configuration lifetime
(IV.2)	$J_{\text{cog}} = \kappa B^{3/2} / I(C)^2$	$3/2$ power law
(IV.5)	$B_{\text{eff}}^{3/2} > \sum B_i^{3/2}$	Threshold condition
(V.1)	$H_B = -\sum w_i \ln w_i$	B-profile information entropy
(VI.1)	$T_{\text{cycle}} = 2\varphi^2 \tau$	Cognitive cycle duration

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