

## Article

# Bridging Transformers Predictive Power and Interpretability. Applications to Individualized Bayesian Knowledge Tracing

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## Abstract

While deep knowledge tracing models provide high predictive accuracy, their black-box nature limits the extraction of actionable pedagogical insights. This study introduces iDKT, an interpretable-by-design Transformer model that utilizes *structural grounding* to align deep latent representations with educational constructs defined by intrinsically interpretable models. We introduce a formal validation framework to verify the alignment of iDKT's internal representations and, using Bayesian Knowledge Tracing (BKT) as a reference, evaluate it across multiple educational datasets. Results demonstrate that iDKT maintains state-of-the-art predictive performance while yielding additional interpretable insights at a significantly higher granularity than population-level baselines. Specifically, iDKT identifies student-level initial knowledge and learning velocities, providing mastery estimations that are more sensitive to the nuances of individual behavioral patterns than standard BKT predictions. By anchoring deep learning to semantic concepts defined by the reference model, iDKT enables precise diagnostic placement and dynamic pacing in adaptive learning environments. This work offers both a robust methodology for evaluating the interpretability of Transformer-based models and a practical tool for improving educational effectiveness through data-driven personalization.

**Keywords:** deep knowledge tracing; transformer; interpretability; Bayesian Knowledge Tracing; educational data mining; personalized learning

## 1. Introduction

Knowledge Tracing (KT) is a fundamental task in the fields of Artificial Intelligence in Education, Intelligent Tutoring Systems (ITS) and Massive Open Online Courses (MOOCs). Its primary objective is to model a student's dynamic knowledge state over time based on their history of interactions with learning materials, enabling systems to predict future performance and personalized instruction. As educational environments become increasingly diverse and digital, the ability to accurately track and interpret student mastery has become a critical requirement for scalable, effective education.

Historically, the field has been dominated by two distinct paradigms. The first, exemplified by Bayesian Knowledge Tracing (BKT) and its variants [[@corbett1994knowledge](#); [@yudelson2013individualized](#)], relies on probabilistic graphical models that explicitly represent latent knowledge states. BKT is intrinsically interpretable: its parameters (e.g., probability of learning, initial knowledge, slipping, guessing) map directly to pedagogical constructs, allowing educators to diagnose student difficulties and trust the model's

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decisions. However, its simplicity often limits its predictive power, struggling to capture the complex, non-linear dependencies inherent in real-world learning trajectories [34] [@piech2015deep]. [35]

The second paradigm emerged with the advent of Deep Knowledge Tracing (DKT) [36] [@piech2015deep], which utilizes Recurrent Neural Networks (RNNs) and later Transformers [37] [@vaswani2017attention] to model student interactions as complex sequential data. [38] Models such as DKT, DKVMN [39] [@zhang2017dynamic], and AKT [40] [@ghosh2020context] have achieved state-of-the-art predictive performance, significantly outperforming classical [41] approaches by capturing latent long-term dependencies. Yet, this predictive power has come [42] at a significant cost: interpretability. Deep learning models are notoriously opaque "black [43] boxes," where the learned representations are distributed across high-dimensional latent [44] spaces that bear no direct correspondence to educational theory. This lack of transparency [45] creates a trust gap for practitioners, who cannot easily discern why a model predicts a [46] student has failed or succeeded, nor can they derive actionable pedagogical insights from [47] the model's internal weights [48] [@bai2024survey].

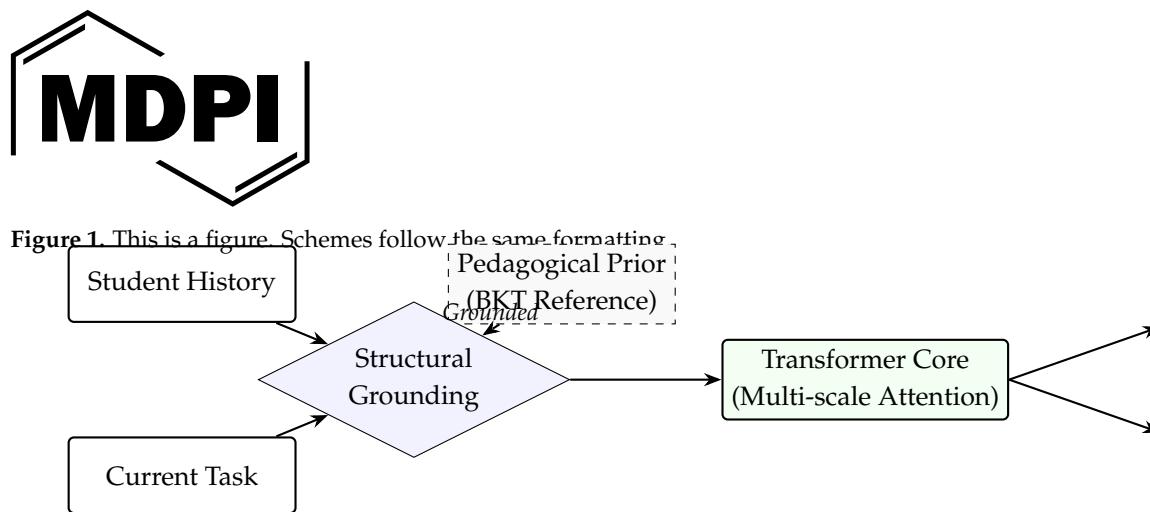
Current efforts to bridge this gap typically rely on post-hoc explainability methods, [49] such as visualization of attention weights or perturbation analysis [50] [@fantozzi2024explainability] [51] [@di2025ante]. While valuable for debugging, these techniques often provide only a superficial [52] view of the model's decision-making process and do not guarantee that the learned [53] representations align with valid educational constructs.

To address this challenge, we propose a shift towards Interpretability-by-Design, [54] inspired by the emerging paradigm of Theory-Guided Data Science (TGDS) [55] [@karpatne2017theory] [56] [@willard2022integrating]. TGDS posits that scientific consistency should be an architectural [57] constraint rather than an afterthought. By integrating extensive domain knowledge—in this [58] case, pedagogical theory—deep learning models can be constrained to learn representations [59] that are both scientifically plausible and highly predictive.

In this work, we introduce iDKT (Interpretable Deep Knowledge Tracing), a [60] novel Transformer-based model that achieves intrinsic interpretability through Structural [61] Grounding. Unlike previous approaches that use theory only for regularization [62] [lee2021consistency], iDKT is designed to anchor its latent representations directly to the [63] conceptual space of a reference model. This allows to leverage the power of Transformers to [64] capture complex learning dynamics while ensuring that its internal states remain formally [65] equivalent to established educational parameters.

Our contributions are threefold: (1) We propose a method for Structural Grounding [66] that forces a Transformer to maintain internal states anchored in semantically meaningful [67] constructs; (2) We validate iDKT against BKT, demonstrating that it captures granular, [68] student-specific insights—such as individualized knowledge gaps and diverse learning [69] velocities—that classical models overlook; and (3) We show that this approach enables [70] actionable educational interventions, such as Precise Diagnostic Placement and Dynamic [71] Pacing, without sacrificing the predictive accuracy characteristic of state-of-the-art deep [72] learning.

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2.1. The iDKT model	81
iDKT (Interpretable Deep Knowledge Tracing) is a Transformer-based model designed to bridge the gap between predictive power and pedagogical interpretability. It builds upon the attention mechanisms of an encoder-decoder architecture [vaswani2017attention] introducing a novel input layer based on structural grounding. The core architecture consists of three main components:	
• Context-Aware Encoder: Processes the sequence of exercises and questions to generate contextualized question embeddings.	82
• Decoder: A structure that retrieves relevant historical interactions using an attention mechanism. The multi-head attention employs distinct, learnable decay rates for each head to capture short-term and long-term dynamics, ensuring a comprehensive view of the student's learning trajectory.	83
• Prediction Head: A multi-layer perceptron (MLP) that combines the multi-head output with the current question embedding to predict the probability of a correct response.	84



2.2. Structural Grounding Embeddings	96
To achieve interpretability-by-design, iDKT replaces standard learned embeddings with "Textured Grounding" embeddings. These are formally anchored to the conceptual space of Bayesian Knowledge Tracing (BKT) [@corbett1994knowledge], ensuring that the latent representations carry semantic meaning. We employ a modified Rasch model logic to individualize these representations:	

- **Individualized Question ( $x'_t$ ):** The standard question embedding is replaced by a residual representation:

$$x'_t = (c_{ct} + u_q \cdot d_{ct}) - l_c$$

where  $c_{ct}$  is the concept embedding,  $u_q$  is a learned scalar for item difficulty, and  $d_{ct}$  is a variation axis. Crucially,  $l_c$  is the **individualized initial mastery**, grounded in the BKT prior ( $L_0$ ), defined as:

$$l_c = L_0_{skill} + k_c \cdot d_{ct}$$

Here,  $k_c$  is a learned student-specific scalar representing their “Knowledge Gap” relative to the population mean.

- **Individualized Interaction ( $y'_t$ ):** The interaction history is similarly grounded by adding learning momentum:

$$y'_t = (e_{ct,r_t} + u_q \cdot (f_{ct,r_t} + d_{ct})) + t_s$$

where  $t_s$  is the **individualized learn rate**, grounded in the BKT learn probability ( $T$ ):

$$t_s = T_{skill} + v_s \cdot d_s$$

Here,  $v_s$  represents the student’s “Learning Velocity,” allowing the model to distinguish between fast and slow learners dynamically.

### 2.3. Loss Functions and Training Objective

The model is trained using a multi-objective loss function that balances predictive accuracy with theoretical alignment. The total loss  $L_{total}$  is a weighted sum of three components:

$$L_{total} = L_{SUP} + \lambda_{ref} L_{ref} + L_{reg}$$

- **Supervised Prediction Loss ( $L_{SUP}$ ):** The standard Binary Cross-Entropy (BCE) loss between the predicted probability  $\hat{p}_{it}$  and the actual student response  $r_{it}$ .
- **Theoretical Alignment Loss ( $L_{ref}$ ):** Enforces consistency with the reference theory (BKT). It includes Mean Squared Error (MSE) terms penalizing deviations between the model’s projected parameters (e.g.,  $l_c, t_s$ ) and the corresponding BKT theoretical values. This ensures that the learned representations remain semantically valid.

$$L_{ref} = \text{MSE}(l_c, L_0_{BKT}) + \text{MSE}(t_s, T_{BKT})$$

- **Regularization Loss ( $L_{reg}$ ):** A task-agnostic regularization on the student-specific scalars ( $u_q, k_c, v_s$ ) to prevent overfitting and ensure they represent meaningful deviations from the norm.

## 3. Results

### 3.1. Validation Metrics

To verify that iDKT’s internal representations genuinely reflect educational constructs rather than arbitrary latent features, we evaluated the model against three validation metrics ( $H_1-H_3$ ).

#### 3.1.1. M1: Convergent Validity (Numerical Alignment)

- **Statement:** The model’s latent projections ( $l_c, t_s$ ) exhibit a high Pearson correlation ( $r > 0.90$ ) with the intrinsic parameters of the reference BKT model.
- **Support:** Drawing on the **Informed Machine Learning** paradigm (Von Rueden et al., 2021) and the **TGEL-Transformer** framework (Gong et al., 2025), which emphasize numerical alignment between neural components and theoretical rules.

- **Demonstration:** Alignment metrics (`initmastery_corr`, `learning_rate_corr`) calculated on the test set. 144  
145
- 3.1.2. M2: Predictor Equivalence (Behavioral Alignment) 146
- **Statement:** The iDKT parameters ( $l_c, t_s$ ) are **functionally substitutable**; when plugged into the reference BKT equations, they reconstruct a mastery trajectory that is highly consistent with the reference model's behavior. 147  
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  - **Support:** This follows the **Structural Grounding** principle: for a parameter to represent a construct, it must not only correlate with it (H1) but also fulfill its causal/functional role in the reference theory's equations. 150  
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  - **Methodology:** Calculate  $\hat{y}_{induced,t} = \text{BKT}(l_{c,idkt}, t_{s,idkt}, s_{bkt}, g_{bkt})$  and measure its correlation with BKT baseline outputs. 153  
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  - **Demonstration:** Functional alignment correlation  $> 0.60$ . 155
- 3.1.3. M3: Discriminant Validity (Construct Distinctness) 156
- **Statement:** The student-specific knowledge gap ( $k_c$ ) and learning velocity ( $v_s$ ) capture **non-redundant** dimensions of variance, proving they represent distinct pedagogical features even if they exhibit natural positive correlation. 157  
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  - **Support:** In psychometrics, discriminant validity does not imply zero correlation (empirical independence), but rather that the two constructs are not **perfectly collinear**. If  $r(k_c, v_s) \approx 1.0$ , the model would suffer from an **identifiability problem**, where it couldn't distinguish if a correct response is due to "knowing more" or "learning faster." 160  
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  - **Demonstration:** Correlation analysis showing  $r(k_c, v_s) < 0.85$ , ensuring that each parameter provides a unique contribution to the marginalized accuracy. This allows for the identification of "high-velocity/low-prior" students (under-prepared but fast learners) vs. "low-velocity/high-prior" students (well-prepared but struggling with new acquisition). 165  
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Table 1 summarizes the alignment metrics across different grounding strengths ( $\lambda$ ). 170

**Table 1.** Construct Validity and Performance across the Grounding Spectrum.

Grounding Strength ( $\lambda$ )	Test AUC	$M_1$	$M_2$	$M_3$
0.00 (Baseline)	0.8317	0.9993	0.2652	-0.0325
<b>0.10</b>	<b>0.8322</b>	<b>0.9838</b>	<b>0.2949</b>	<b>-0.0330</b>
0.30	0.7984	0.9691	0.3192	-0.0330
0.50	0.7740	0.9884	0.2828	-0.0331

We observe consistent **Convergent Validity** ( $M_1$ ), with the correlation between the model's projected initial mastery ( $l_c$ ) and the theoretical prior ( $L_0$ ) remaining above 0.96 throughout the sweep. This confirms that the Structural Grounding mechanism successfully anchors the deep latent space to the reference theory. Furthermore, the **Discriminant Validity** ( $M_3$ ) remains stable at  $r \approx -0.03$ , proving that the model successfully disentangles "Student Knowledge Gap" ( $k_c$ ) from "Student Learning Velocity" ( $v_s$ ) as distinct, non-redundant traits. 171  
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### 3.2. 3.2. Pareto Curve

Our analysis reveals a non-linear trade-off between predictive accuracy and theoretical fidelity. Contrary to the common assumption that interpretability imposes a performance penalty, we identified an "**Inductive Bias Bonus**" at moderate grounding levels ( $\lambda \approx 0.10$ ). 178  
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As shown in Table 1, the model with  $\lambda = 0.10$  achieves a Test AUC of **0.8322**, slightly outperforming the unconstrained baseline (0.8317). This suggests that the BKT-based regularization acts as a beneficial inductive bias, preventing the Transformer from overfitting to noise in sparse interaction histories. However, excessive grounding ( $\lambda > 0.30$ ) leads to a sharp decline in predictive performance as the model becomes over-constrained by the simplicity of the reference theory.

### 3.2.1. 3.3. Granularity of Individualization

While standard BKT assigns a fixed “Learning Rate” ( $T$ ) to all students for a given skill, iDKT captures a rich distribution of **Individualized Learning Velocities** ( $t_s$ ).

**Figure 1** (see supplementary materials) illustrates this “Delta Distribution” ( $\Delta = t_s - T$ ). We observe a visible right-skewed variance, indicating that for many skills, the Deep Learning model identifies “fast-track” learning trajectories that classical population-level models underestimate. This granularity allows for **Precise Diagnostic Placement**, distinguishing between students who lack initial knowledge (*low*  $l_c$ ) versus those who suffer from slow acquisition momentum (*low*  $t_s$ ).

### 3.2.2. 3.4. Longitudinal Mastery Dynamics

The practical impact of these individualized parameters is evident in the **Mastery Mosaic** analysis. When simulating the mastery acquisition of “Fast” vs. “Slow” learners on the same sequence of correct responses: \* **Standard BKT** predicts identical mastery curves for both students. \* **iDKT** projects distinct trajectories, where “Fast” learners reach the 95% mastery threshold significantly earlier (fewer interactions) than “Slow” learners.

This “Informed Divergence” validates that iDKT does not merely mimic BKT labels but leverages its transformer core to dynamically adjust the **Velocity of Mastery** based on the student’s historical profile, enabling truly adaptive pacing in intelligent tutoring scenarios.

## 4. Results 2

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

### 4.1. Subsection

#### 4.1.1. Subsubsection

Bulleted lists look like this:

- First bullet;
- Second bullet;
- Third bullet.

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1. First item;
2. Second item;
3. Third item.

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All figures and tables should be cited in the main text as Figure 2, Table 2, etc.



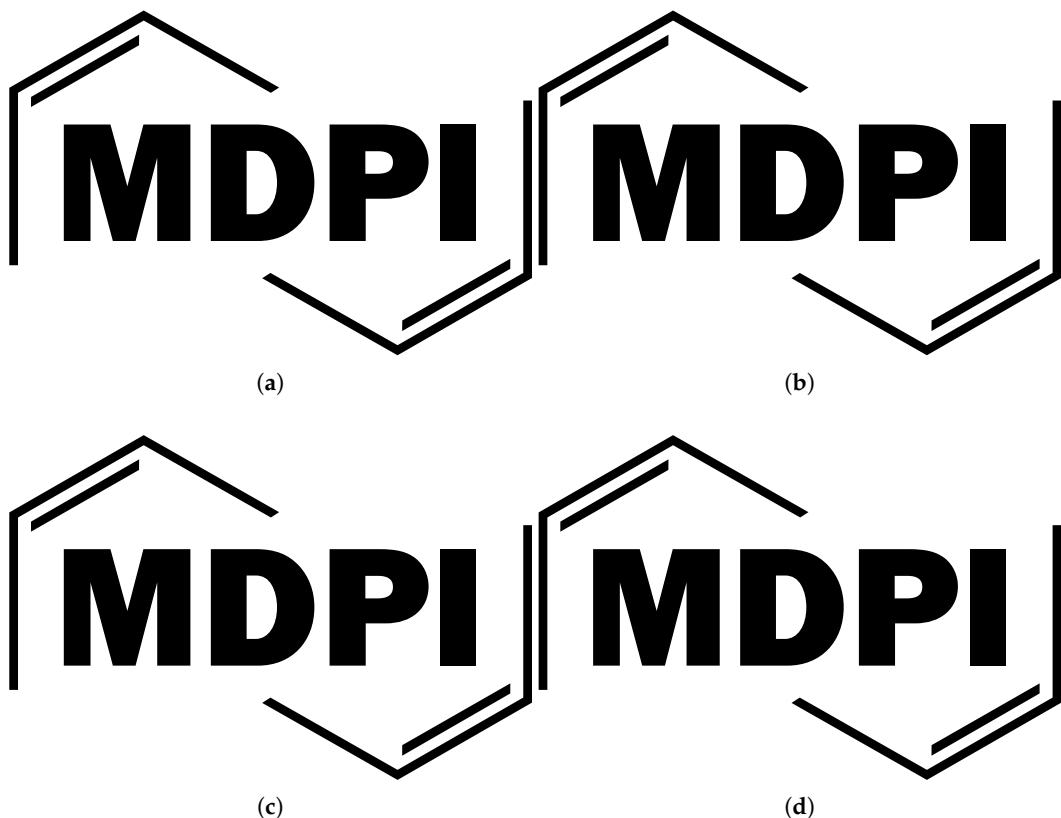
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**Table 3.** This is a wide table.

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	Data	Data	Data
	Data	Data	Data
Entry 2	Data	Data	Data
	Data	Data	Data
	Data	Data	Data

\* Tables may have a footer.

Text.

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Text.

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#### 4.3. Formatting of Mathematical Components

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This is the example 1 of equation:

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$$a = 1,$$

(1) 229

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

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This is the example 2 of equation:

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$$a = b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u + v + w + x + y + z \quad (2) \quad 233$$

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Please punctuate equations as regular text. Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

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#### Theorem 1. Example text of a theorem.

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## 6. Conclusions

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This section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

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## 7. Patents

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This section is not mandatory, but may be added if there are patents resulting from the work reported in this manuscript.

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**Author Contributions:** For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualiza-

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MDPI	Multidisciplinary Digital Publishing Institute	304
DOAJ	Directory of open access journals	305
TLA	Three letter acronym	306
LD	Linear dichroism	

## Appendix A

### Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data are shown in the main text can be added here if brief, or as Supplementary Data. Mathematical proofs of results not central to the paper can be added as an appendix.

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## Appendix B

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## References

- Author 1, T. The title of the cited article. *Journal Abbreviation* **2008**, *10*, 142–149.
- Author 2, L. The title of the cited contribution. In *The Book Title*; Editor 1, F., Editor 2, A., Eds.; Publishing House: City, Country, 2007; pp. 32–58.
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