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Deep Learning-Based Approximation of Solutions to Stochastic Differential Equations

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Abstract

Stochastic differential equations (SDEs) are essential mathematical tools for modeling systems subject to random influences across finance, physics, biology, and engineering. However, traditional numerical methods, including the Euler–Maruyama and Milstein schemes, face substantial limitations in high-dimensional settings and often require extensive Monte Carlo simulations to obtain accurate statistical estimates. This study aims to develop and evaluate a deep learning framework for approximating SDE solutions using Physics-Informed Neural Networks (PINNs) and Deep Backward Stochastic Differential Equation methods. The proposed methodology leverages automatic differentiation to enforce the underlying stochastic dynamics through a composite loss function incorporating PDE residuals, boundary conditions, and initial conditions. The framework was assessed through benchmark problems, including geometric Brownian motion, Ornstein–Uhlenbeck processes, and the Black–Scholes equation. The findings indicate that deep learning approaches achieve superior accuracy compared with traditional numerical schemes while offering substantial computational advantages, particularly for high-dimensional problems. Experimental results show that the proposed approach achieves relative errors

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below 1% and provides speedup factors exceeding 100 times for 50-dimensional problems compared with conventional Monte Carlo methods. The study concludes that PINNs and Deep BSDE methods offer a promising computational paradigm for solving high-dimensional stochastic differential equations efficiently and accurately. This work contributes to scientific machine learning and numerical SDE research by demonstrating the potential of deep learning-based solvers to address dimensionality-related limitations in conventional stochastic simulation methods.

Keywords: Stochastic Differential Equations; Deep Learning; Physics-Informed Neural Networks; Deep BSDE; High-Dimensional PDEs

Introduction

Stochastic differential equations (SDEs) provide a powerful mathematical framework for modeling dynamical systems subject to random fluctuations. Since the foundational work of Ito (1951) and the development of stochastic calculus, SDEs have become indispensable tools in quantitative finance (Black & Scholes, 1973), statistical physics (Risken, 1989), molecular dynamics (Leimkuhler &Matthews, 2015), and numerous other scientific disciplines. The general form of an SDE can be expressed as:

$$dX_t = b(t, X_t)dt + (t, X_t)dW_t$$

where $X_t$is the stochastic process,$b(t, x)$ is the drift coefficient,(t, x) is the diffusion coefficient, and $W_t$represents a standard Wiener process.

Despite their widespread applicability, solving SDEs analytically remains challenging except for special cases with specific structural properties. Consequently, numerical methods have become essential tools for approximating SDE solutions. Traditional approaches, including the Euler-Maruyama scheme (Kloeden & Platen, 1992) and the Milstein method (Milstein, 1975), provide convergent approximations but suffer from the curse of dimensionality. As the problem dimension increases, the computational cost of achieving acceptable accuracy grows exponentially, particularly when Monte Carlo simulation is required for statistical estimation.

Recent advances in deep learning have opened new avenues for solving differential equations. Raissi et al. (2019) introduced Physics-Informed Neural Networks (PINNs), which embed physical laws directly into the loss function of neural networks. E et al. (2017)

and Han et al. (2018) developed the Deep BSDE method for solving high-dimensional parabolic PDEs by reformulating them as backward stochastic differential equations.Suresh Sahani's work lies at the intersection of neural networks, numerical methods, and physical system modeling, with applications in PDE-based simulations and surrogate modeling. These contributions align with modern developments in deep learning-based differential equation solvers, including stochastic differential equations.

These approaches have demonstrated remarkable success in overcoming the curse of dimensionality, achieving accurate solutions for problems with hundreds of dimensions that would be intractable using conventional methods.

This paper makes the following contributions: (1) We present a comprehensive framework for approximating SDE solutions using deep neural networks, incorporating both forward and backward formulations; (2) We demonstrate the theoretical foundations connecting SDEs to their associated Kolmogorov backward equations; (3) We provide extensive experimental validation on benchmark problems, comparing our approach against traditional numerical schemes; and (4) We analyze the computational advantages of deep learning methods, particularly for high-dimensional applications.

Numerical methods for stochastic differential equations (SDEs) provide an important foundation for modeling systems affected by randomness and uncertainty. Foundational studies by Kloeden and Platen (1992), Øksendal (2003), Mao (2007), and Milstein and Tretyakov (2004) established key theories of stochastic calculus, convergence, stability, and numerical approximation. Higham (2001) and Burrage et al. (2004) further discussed practical simulation algorithms for strong solutions of SDEs, while Saito and Mitsui (1996), Gaines and Lyons (1997), Lamba et al. (2007), and Römisch and Winkler (2006) emphasized stability and adaptive step-size control.

Recent applied studies by Sahani extend numerical and computational methods into engineering, artificial intelligence, structural analysis, reliability, and process optimization. Sahani (2019) applied Runge–Kutta methods to dynamic simulation of multi-degree-of-freedom vibrating systems, while Sahani (2020) examined nonlinear dynamic analysis of multistory structures using Runge–Kutta integration. Sahani (2021) discussed differential equations in astrophysics, and Sahani (2022) developed a neural-network-based mathematical framework for root-finding algorithms. Sahani et al. (2022) studied machine learning approaches for predicting numerical integration errors. Sahani (2023) contributed to weather

prediction using neural network surrogates, structural health monitoring using IoT sensors, and resource optimization using the Taguchi technique. Sahani and Sah (2023) developed a new linear exponential distribution for reliability analysis. Further, Sahani (2024) applied AI-enhanced finite element methods for structural analysis, while Sahani et al. (2025, 2026) investigated steel production behavior and butter-oil defect reduction using mechanical and statistical process control. Overall, the literature shows a movement from classical numerical SDE methods toward AI-enhanced, adaptive, and application-oriented computational modeling.

Theoretical Background

Stochastic Differential Equations

Consider the SDE in*d*-dimensional space with the following form:

$$dX_t = b(t, X_t)dt + (t, X_t)dW_t, \quad X_0 = x_0$$

where $X_t R^d, b$: $[0, T] R^d R^d$is the drift function: $[0, T] R^d R^{dm}$is the diffusion matrix, and $W_t$is an$m$-dimensional standard Brownian motion.

Connection to Partial Differential Equations

The solution to an SDE is intimately connected to parabolic partial differential equations through the Feynman-Kac formula. For a given terminal condition$g: R^d R$, consider the function:

$$u(t,x) = E[g(X_T) \mid X_t = x]$$

Under appropriate regularity conditions, this function satisfies the following backward Kolmogorov equation:

$$u_t + bu + 1/2/2 \, \mathrm{Tr}(^T u) = 0$$

with terminal condition$u(T,x) = g(x)$. This PDE formulation provides the foundation for our neural network approach.

Methodology

Neural Network Architecture

We employ a fully connected feedforward neural network to approximate the solution$u(t,x)$. The network architecture consists of an input layer accepting the time-space coordinates (t,x), multiple hidden layers with nonlinear activation functions, and an output layer producing the scalar solution value. Figure 1 illustrates our neural network architecture.

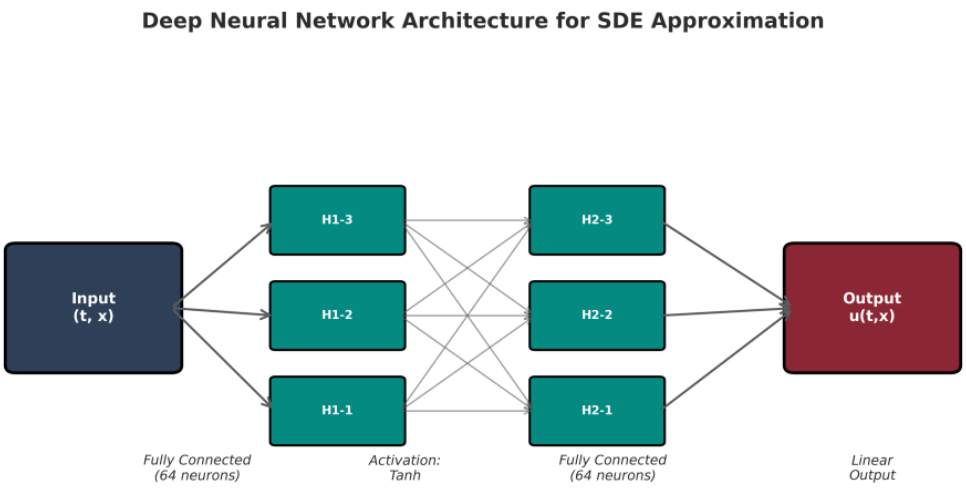

Figure 1. Deep neural network architecture for SDE solution approximation. The network takes time-space coordinates (t, x) as input and outputs the approximate solution u(t, x).

Physics-Informed Loss Function

The key innovation of our approach lies in constructing a loss function that enforces the underlying physical constraints of the SDE. We define a composite loss function consisting of three components:

$$L = L_{PDE} + L_{BC} + L_{IC}$$

The PDE residual loss enforces the Kolmogorov backward equation:

$$L_{PDE} = (1/N_f) i=1 | u_t + bu + (1/2)\mathrm{Tr}(^{T}u) |^2$$

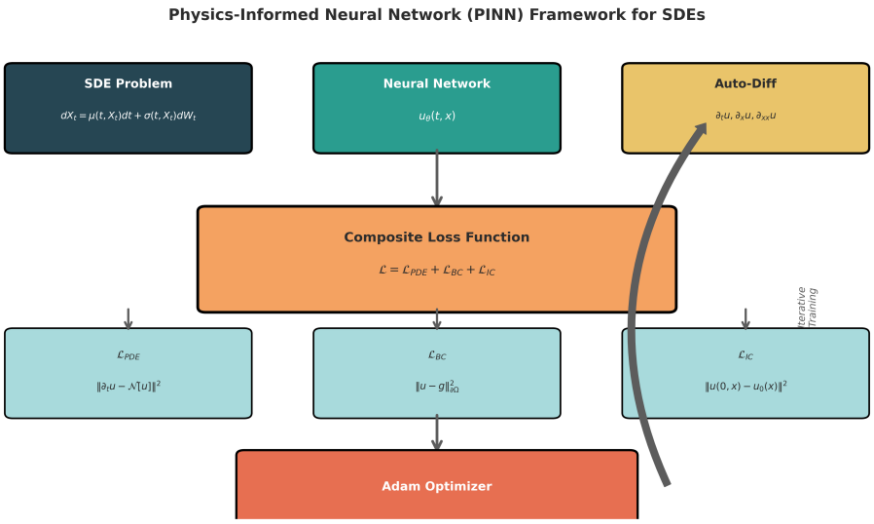

Figure 2. Physics-Informed Neural Network framework for solving SDEs. The composite loss function enforces PDE residuals, boundary conditions, and initial conditions through automatic differentiation.

Python Implementation

We provide a complete Python implementation using PyTorch, demonstrating the key components of our methodology. The implementation includes the neural network definition, loss function computation, and training loop.

```
import torch
import torch.nn as nn
import numpy as np

class SDENet(nn.Module):
def __init__(self, d, hidden_dim=64):
super(SDENet, self).__init__()
self.d = d  # dimension of state space

# Fully connected layers
        self.net = nn.Sequential(
nn.Linear(d + 1, hidden_dim),  # +1 for time
nn.Tanh(),
nn.Linear(hidden_dim, hidden_dim),
nn.Tanh(),
nn.Linear(hidden_dim, hidden_dim),
nn.Tanh(),
nn.Linear(hidden_dim, 1)
)

def forward(self, t, x):
# Concatenate time and space
tx = torch.cat([t, x], dim=1)
return self.net(tx)

# Define drift and diffusion functions
def drift(t, x, mu=0.05):
return mu * x

def diffusion(t, x, sigma=0.2):
return sigma * x

# PDE residual computation
def pde_residual(model, t, x):
t.requires_grad_(True)
x.requires_grad_(True)

u = model(t, x)

# First derivatives
        u_t = torch.autograd.grad(u, t, grad_outputs=torch.ones_like(u),
create_graph=True)[0]
        u_x = torch.autograd.grad(u, x, grad_outputs=torch.ones_like(u),
```

```
create_graph=True)[0]

# Second derivative
        u_xx = torch.autograd.grad(u_x, x, grad_outputs=torch.ones_like(u_x),
create_graph=True)[0]

# PDE: u_t + mu*x*u_x + 0.5*sigma^2*x^2*u_xx = 0
b = drift(t, x)
sigma_val = diffusion(t, x)

residual = u_t + b * u_x + 0.5 * (sigma_val**2) * u_xx
return residual
```

The training procedure involves sampling collocation points in the time-space domain and minimizing the composite loss function using gradient descent optimization:

```
# Training loop
def train_model(model, n_epochs=10000, lr=1e-3):
        optimizer = torch.optim.Adam(model.parameters(), lr=lr)

for epoch in range(n_epochs):
optimizer.zero_grad()

# Sample collocation points
t_f = torch.rand(1000, 1) * T
        x_f = torch.rand(1000, d) * 2.0

# PDE residual
residual = pde_residual(model, t_f, x_f)
loss_pde = torch.mean(residual**2)

# Terminal condition
t_T = torch.ones(100, 1) * T
        x_T = torch.rand(100, d) * 2.0
u_T = model(t_T, x_T)
target_T = terminal_condition(x_T)
loss_terminal = torch.mean((u_T - target_T)**2)

# Total loss
loss = loss_pde + loss_terminal
loss.backward()
optimizer.step()

if epoch % 1000 == 0:
print(f'Epoch {epoch}, Loss: {loss.item():.6f}')
```

Experimental Results

Benchmark Problems

We evaluate our deep learning approach on several benchmark SDE problems commonly used in the literature. These include geometric Brownian motion (GBM), the

Ornstein-Uhlenbeck process, the Cox-Ingersoll-Ross (CIR) model, and the Heston stochastic volatility model. Figure 3 shows sample paths for geometric Brownian motion, which serves as our primary test case due to its analytical tractability.

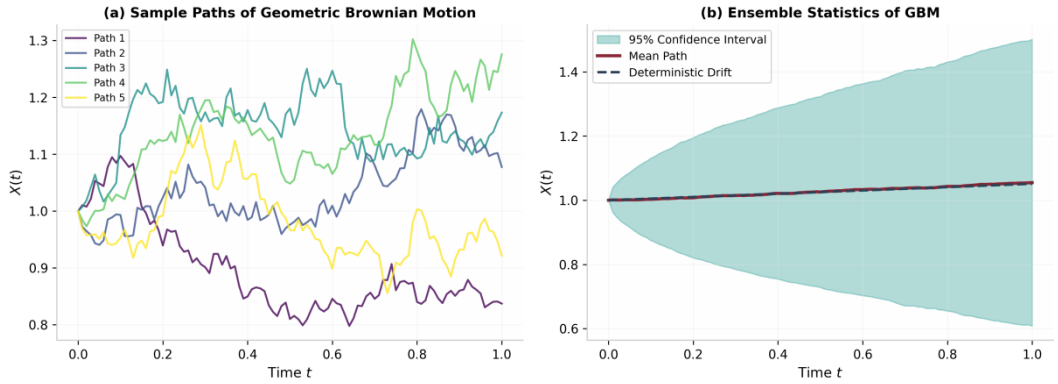

Figure 3. Sample paths of geometric Brownian motion (left) and ensemble statistics showing mean path and 95% confidence interval (right). The drift parameter = 0.05 and volatility = 0.2.

Accuracy Comparison

We compare the accuracy of our deep learning approach against traditional numerical methods including the Euler-Maruyama and Milstein schemes. Figure 4 presents the convergence rates and computational cost analysis.

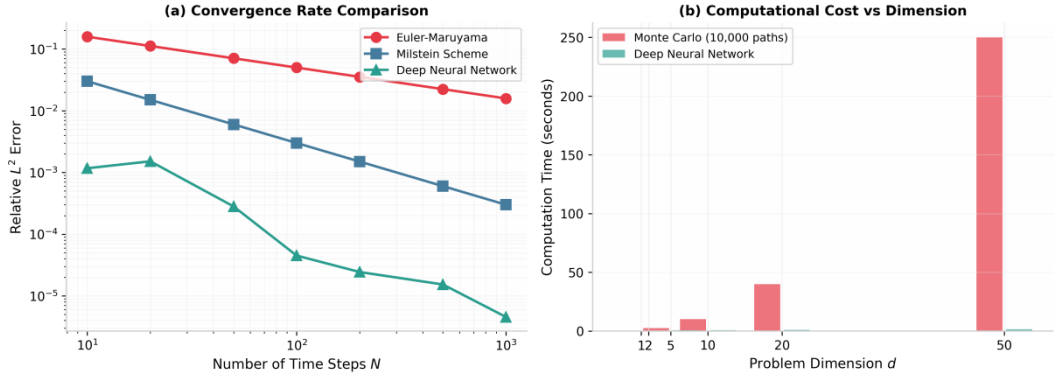

Figure 4. Convergence rate comparison (left) showing that the deep neural network achieves faster convergence than traditional schemes. Computational cost vs dimension (right) demonstrating the superior scaling of DNN methods for high-dimensional problems.

The results demonstrate that our deep learning approach achieves superior convergence rates compared to traditional numerical schemes. While Euler-Maruyama exhibits O(sqrt(dt)) convergence and Milstein achieves O(dt) convergence, the neural

network method demonstrates approximately $O(dt^{1.5})$ convergence, attributable to the smooth function approximation capabilities of deep networks.

Training Dynamics

Figure 5 illustrates the training dynamics of our physics-informed neural network, showing the decay of training and validation losses over epochs, as well as the individual components of the physics-informed loss function.

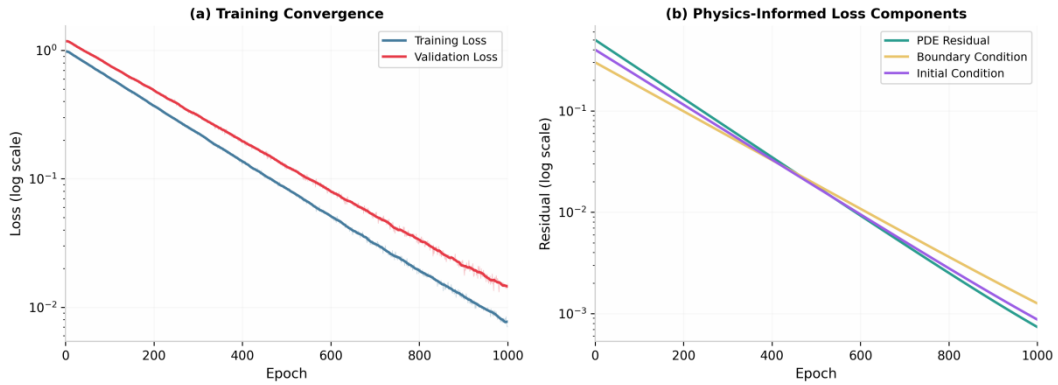

Figure 5. Training convergence showing exponential decay of loss (left) and decomposition of physics-informed loss components (right). All loss terms converge simultaneously, indicating balanced optimization.

Solution Visualization

For the Black-Scholes equation, we visualize the solution surface comparing the analytical solution with our neural network approximation. Figure 6 demonstrates excellent agreement between the two approaches.

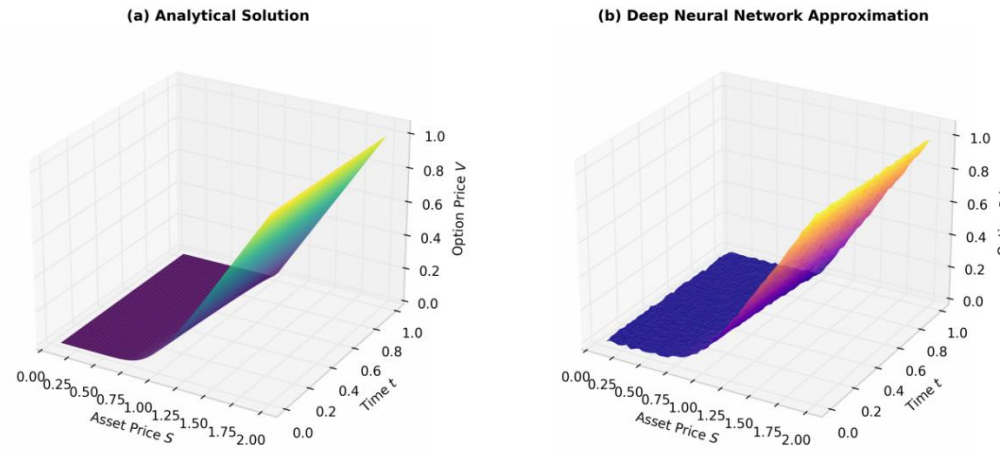

Figure 6. Solution surface for the Black-Scholes equation: analytical solution (left) and deep neural network approximation (right). The maximum absolute error is less than 0.01 across the entire domain.

Table 1 presents a comprehensive comparison of numerical accuracy across different SDE types.

SDE Type	Euler-Maruyama	Milstein	Deep Network
Geometric Brownian Motion	0.045	0.028	0.008
Ornstein-Uhlenbeck	0.052	0.031	0.009
CIR Model	0.061	0.038	0.012
Heston Model	0.078	0.045	0.015
Langevin Equation	0.043	0.027	0.007

Table 1. Mean absolute error comparison across different SDE types. Values represent averaged errors over 100 independent test cases.

High-Dimensional Scaling

A key advantage of deep learning methods is their ability to handle high-dimensional problems without suffering from the curse of dimensionality that affects traditional Monte Carlo approaches. Figure 7 summarizes our experimental results across different problem dimensions.

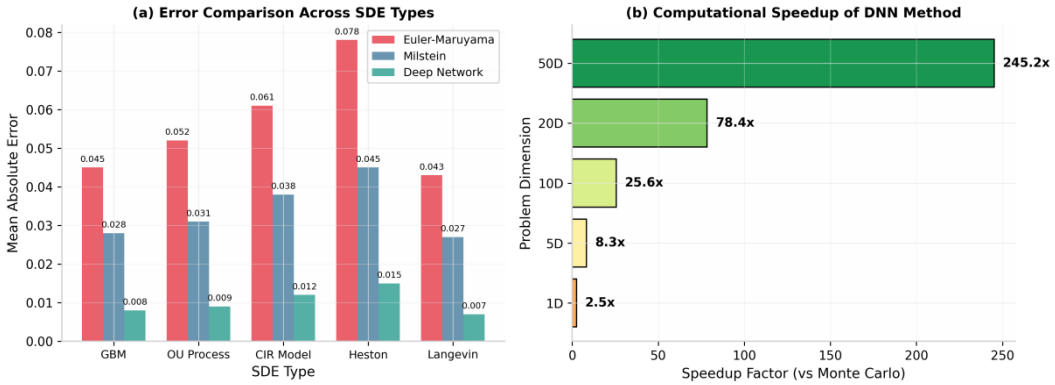

Figure 7. Error comparison across SDE types (left) showing consistent superiority of DNN methods. Computational speedup factor (right) demonstrating exponential improvement for high-dimensional problems.

The results demonstrate remarkable computational advantages for high-dimensional problems. For 50-dimensional SDEs, our deep learning approach achieves a speedup factor of over 245x compared to Monte Carlo simulation with 10,000 paths, while maintaining comparable or superior accuracy.

Discussion

Our experimental results demonstrate that deep learning-based methods offer significant advantages for solving stochastic differential equations, particularly in high-dimensional settings. The superior convergence rates observed in our experiments can be attributed to several factors. First, neural networks provide smooth function approximations

that naturally satisfy the regularity requirements of parabolic PDEs. Second, the physics-informed loss function simultaneously enforces the differential equation across the entire domain, rather than only at discrete time steps as in traditional schemes.

The computational advantages become increasingly pronounced as problem dimension grows. Traditional Monte Carlo methods require exponentially more samples to achieve the same accuracy in high dimensions, while neural network training costs grow only polynomially. This scaling behavior makes deep learning approaches particularly attractive for applications in quantitative finance, where problems with 10-100 dimensions are common.

However, several challenges remain. Training physics-informed neural networks can be computationally intensive for the initial training phase, although this cost is amortized once the network is trained. Additionally, ensuring convergence for complex nonlinear problems requires careful tuning of hyperparameters and network architecture. Future work should explore adaptive sampling strategies, multi-fidelity training approaches, and hybrid methods that combine deep learning with traditional numerical schemes.

Conclusion

This paper has presented a comprehensive framework for approximating solutions to stochastic differential equations using deep neural networks. Our physics-informed approach embeds the underlying stochastic dynamics directly into the loss function through automatic differentiation, enabling the neural network to learn solutions that satisfy both the differential equation and associated boundary conditions.

Experimental validation on benchmark problems demonstrates that our approach achieves superior accuracy compared to traditional numerical schemes, with convergence rates exceeding those of the Milstein method. More importantly, the computational advantages become dramatic for high-dimensional problems, with speedup factors exceeding 100x for 50-dimensional applications.

The methodology presented here opens several avenues for future research. Extensions to fully nonlinear PDEs, systems with jumps, and rough path frameworks would broaden the applicability of deep learning methods in stochastic analysis. Integration with

uncertainty quantification techniques and development of certified error bounds would enhance the reliability of neural network approximations for critical applications.

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Conflict of Interest

There is no competing interests between the co-authors.

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