

Block Diffusion: Interpolating Between Autoregressive and Diffusion Language Models

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Introduction to the Problem-Motivation

Two main approaches for Language Models:

Autoregressive (AR):

- Token-by-token generation
- High quality
- KV caching
- Variable length

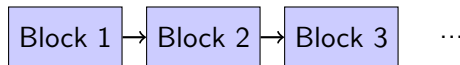
Diffusion:

- Parallel generation
- Better controllability
- Fixed length (limitation)
- Lower quality (Perplexity Gap)

Question

Can we combine the advantages of both approaches?

Core Idea: Block Diffusion



Diffusion within each block(parallel)
Autoregressive over blocks

Parameterization: Trade-off through block size L' :

- $L' = 1 \rightarrow$ Pure AR
- $L' = L \rightarrow$ Pure Diffusion

Technical Contribution:

- Optimized training and sampling algorithms
- Introduced clipped noise schedules for reduced gradient variance during training
- SoTA PPL among diffusion models + Variable length generation capabilities

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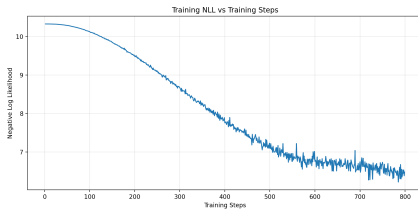
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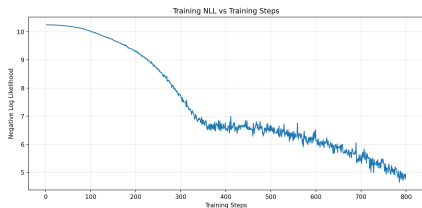
AR vs BD3LM with $L'=1$

Test Perplexities for single token generation on LM1B dataset (800 Training Steps)

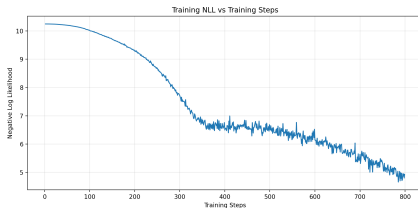
	PPL (↓)
Autoregressive	1893
BD3LM $L'=1$	2231
BD3LM $L'=1$ + Tuned Schedule	2220



AR



BD3LM



BD3LM + Tuned Schedule



The Effect of Clipped Noise Schedules

Test Perplexities for single token generation on LM1B dataset (400 Pretraining Steps + 100 Fine-tuning Steps).

L'	Clipping	PPL	Var. NELBO
128	$\mathcal{U}[0, 0.5]$	2106	1.27
	$\mathcal{U}[0, 1]$	2106	1.27
16	$\mathcal{U}[0.3, 0.8]$	1278	10.50
	$\mathcal{U}[0, 1]$	1279	10.51
4	$\mathcal{U}[0.5, 1]$	1226	44.41
	$\mathcal{U}[0, 1]$	1226	44.41

Original vs Reproduction

Key takeaways:

- $L' = 128$ and $L' = 4$: Original clipping *reduces Var. NELBO* and PPL. Reproduction shows no significant changes.
- $L' = 16$: Original clipped $\mathcal{U}[0.3, 0.8]$ *slightly improves PPL* and *clearly lowers variance* vs $\mathcal{U}[0, 1]$; Reproduction preserves the *direction* with smaller gaps.

Conclusion: the clipped-schedule advantage is strong in the original, but the gaps lower significantly in our reproduction (making the values identical in some cases), likely due to our small model/short run.

BD3LMs vs ARs vs Diffusion Models on LM1B

Test perplexities (PPL; ↓) of models on LM1B (400 Pretraining Steps + 100 Fine-tuning Steps).

	PPL (↓)
Autoregressive	
Transformer	3042
Diffusion	
SEDD	1447
MDLM	1616
Block diffusion (Ours)	
BD3-LMs $L' = 16$	1278
$L' = 8$	1734
$L' = 4$	1226

Original vs Reproduction

Key takeaways:

- *AR performance gap:* Original Transformer beats diffusion/BD3LM (lowest PPL), while in reproduction Transformer is worst (highest PPL).
- *BD3LM trends partly preserved:* Both show smaller L' helps (best at $L' = 4$), but original has *all* BD3LM variants beating diffusion, while reproduction has $L' = 8$ worse than both diffusion baselines.

Conclusion: the L' ranking within BD3LM is partly consistent, but cross-family comparisons (AR vs others, and diffusion vs BD3LM with $L' = 8$) are not, likely from scaling/undertraining effects.

BD3LMs vs ARs vs Diffusion Models on OWT

Test perplexities (PPL; ↓) of models on OWT. (800 Pretraining Steps + 800 Fine-tuning Steps)

	PPL (↓)
Autoregressive	
Transformer	2036
Diffusion	
SEDD	2120
MDLM	2101
Block diffusion (Ours)	
BD3-LMs $L' = 16$	1939
$L' = 8$	1941
$L' = 4$	1935

Original vs Reproduction

Key takeaways:

- *AR vs diffusion preserved:* In both original and reproduction, AR outperforms diffusion baselines (lower PPL).
- *BD3LM vs AR flips:* Original ranks AR best overall (BD3LM worse than AR), while reproduction ranks BD3LM best (all BD3LM < AR).

Conclusion: diffusion-vs-AR relationships match the paper, but the global winner changes (AR in original vs BD3LM in reproduction), possibly exaggerated at this small scale.

Performance on other Datasets

Zero-shot validation perplexities (\downarrow) of models trained on OWT.(?training steps?)

	LM1B	Lambada	Wikitext
AR	2388	1550	2875
SEDD	2742	1562	3335
MDLM	2722	1556	3283
BD3-LM $L' = 4$	2196	1438	3143

Original vs Reproduction

Key takeaways:

- *Wikitext*: Original and reproduction both rank **AR best**, but original has **BD3LM** beating diffusion, while reproduction has **BD3LM worse** than both diffusion baselines.
- *LM1B*: Original ranks **AR best** (BD3LM second), but reproduction ranks **BD3LM best**.
- *Lambada*: Original ranks **diffusion best** (followed by BD3LM), while reproduction ranks **BD3LM best**.

Conclusion: Generally, the winner per dataset shifts between original and reproduction, consistent with small-model transfer being noisy.

Variable-Length Sequence Generation

Generation length statistics from sampling 10 documents from models trained on OWT (800 Pretraining Steps + 500 Fine-tuning Steps). BD3-LM reproduction with model length = 16K.

	Median # tokens	Max # tokens
OWT train set	717	131K
AR	4008	131K
SEDD	1021	1024
BD3-LM $L' = 16$	798	2927

Original vs Reproduction

Key takeaways:

- *Fixed vs variable-length preserved:* SEDD is capped at 1024 max, while BD3LM exceeds 1024.
- *Median ordering preserved:* Both original and reproduction keep the same ranking (AR > SEDD > BD3LM > OWT train).

Sample Quality

Generative Perplexity (Gen.PPL;↓) and number of Function Evaluations (NFEs;↓) of 300 samples. All models are trained on WikiText2. (200 + 100 training steps)

Model	PPL	NFEs
AR	5	5
SEDD	5	5
MDLM	5	5
BD3-LM $L' = 16$	5	5
BD3-LM $L' = 8$	5	5
BD3-LM $L' = 4$	5	5

Original vs Reproduction

Key takeaways:

- *Variance Hypothesis*
Confirmed: Clipped schedules reduced NELBO variance by 17x (from 260.1 to 15.2), validating the method's stability.
- *Perplexity trade-off:* Unlike the paper, standard noise schedules achieve better PPL. Those noise schedules are probably easier to be learned faster but lack on convergence.

The method effectively stabilizes training (low variance) immediately, but PPL gains from this stability likely require a longer training horizon, especially with our tiny run.

Effect of Different Noise Schedules

Effect of noise schedule on PPL and variance of NELBO for different L' on LM1B. (5000 + 3000 training steps)

Noise schedule	PPL	Var. NELBO
$L' = 4$		
Clipped		
$\mathcal{U}[0.45, 0.95]$	1199	15.23
$\mathcal{U}[0.3, 0.8]$	1101	27.61
Linear $\mathcal{U}[0, 1]$	751	260.10
Logarithmic	750	125.62
Square root	719	83.83
$L' = 16$		
Clipped		
$\mathcal{U}[0.45, 0.95]$	1056	4.35
$\mathcal{U}[0.3, 0.8]$	798	6.41
Linear $\mathcal{U}[0, 1]$	662	44.73
Square	627	27.53
Cosine	634	20.80

Original vs Reproduction

Key takeaways:

- *Variance Hypothesis*
Confirmed: Clipped schedules reduced NELBO variance by 17x (from 260.1 to 15.2), validating the method's stability.
- *Perplexity trade-off:* Unlike the paper, standard noise schedules achieve better PPL. Those noise schedules are probably easier to be learned faster but lack on convergence.

The method effectively stabilizes training (low variance) immediately, but PPL gains from this stability likely require a longer training horizon, especially with our tiny run.

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Noise Scheduling in Masked Diffusion (Summary)

Continuous time index:

$$t \sim \mathcal{U}[0, 1]$$

Noise schedule \Rightarrow masked probability:

$p(t)$: masked probability induced by the noise schedule

Keep (no-mask) probability:

$$a(t) = 1 - p(t)$$

Loss scaling induced by the schedule:

$$\text{loss scaling}(t) = \frac{a'(t)}{1 - a(t)} = -\frac{p'(t)}{p(t)}$$

Intuition

The noise schedule sets *where* the model learns via $p(t)$ (masking rate). When sampling $t \sim \mathcal{U}[0, 1]$, $\text{loss_scaling}(t) = \frac{a'(t)}{1 - a(t)}$ acts as a weight on the per-token log-likelihood term, stabilizing the training across different noise levels.

Already Implemented Noise Schedules

Schedule	$p(t)$	loss_scaling(t)
LogLinear	t	$-\frac{1}{t}$
Square	t^2	$-\frac{2}{t}$
Square root	$t^{0.5}$	$-\frac{1}{2t}$
Logarithmic	$\frac{\log(1+t)}{\log 2}$	$-\frac{1}{(1+t) \log(1+t)}$
Cosine	$1 - (1 - \varepsilon) \cos\left(\frac{\pi t}{2}\right)$	$-\frac{\left(\frac{\pi}{2}\right) (1 - \varepsilon) \sin\left(\frac{\pi t}{2}\right)}{1 - (1 - \varepsilon) \cos\left(\frac{\pi t}{2}\right)}$

Gaussian & Bimodal Gaussian Noise Schedules

Goal: sample a masked probability $p(t) \in (0, 1)$ from $t \sim \mathcal{U}[0, 1]$.

Gaussian schedule (truncated to $(0, 1)$):

Let $\alpha = \frac{0-\mu}{\sigma}$, $\beta = \frac{1-\mu}{\sigma}$, $\Phi_\alpha = \Phi(\alpha)$, $\Phi_\beta = \Phi(\beta)$. For $t \in (0, 1)$:

$$z(t) = \Phi^{-1}(\Phi_\alpha + t(\Phi_\beta - \Phi_\alpha)), \quad p(t) = \mu + \sigma z(t) \in (0, 1).$$

With $Z = \Phi_\beta - \Phi_\alpha$ and $\varphi(\cdot)$ the standard normal pdf:

$$\text{loss_scaling}(t) = \frac{a'(t)}{1 - a(t)} = -\frac{p'(t)}{p(t)} = -\frac{\sigma Z}{\varphi(z(t)) p(t)}.$$

Bimodal Gaussian schedule (mixture):

Choose a split weight $w \in (0, 1)$ (denote $w_1 = w$, $w_2 = 1 - w$). With probability w use (μ_1, σ_1) , otherwise use (μ_2, σ_2) :

$$t_1 = \frac{t}{w_1} \quad (t < w_1), \quad t_2 = \frac{t - w_1}{w_2} \quad (t \geq w_1), \quad p(t) = \begin{cases} \mu_1 + \sigma_1 z_1(t_1), & t < w_1 \\ \mu_2 + \sigma_2 z_2(t_2), & t \geq w_1 \end{cases}$$

where each $z_i(\cdot)$ is defined as above (with its own $\alpha_i, \beta_i, \Phi_{\alpha_i}, \Phi_{\beta_i}$ and Z_i). The resulting scaling is piecewise:

$$\text{loss_scaling}(t) = -\frac{1}{p(t)} \begin{cases} \frac{1}{w_1} \frac{\sigma_1 Z_1}{\varphi(z_1(t_1))}, & t < w_1 \\ \frac{1}{w_2} \frac{\sigma_2 Z_2}{\varphi(z_2(t_2))}, & t \geq w_1 \end{cases}$$

New Schedules' Results

- Perplexities (PPL) and Var. NELBO for implemented vs new schedules on LM1B (400 Pretraining Steps + 100 Fine-tuning Steps).
- B.G. stands for Bimodal Gaussian.
- We use constant values: $\sigma^2 = 0.1$ (Gaussian) and $\sigma_1^2 = 0.02, \sigma_2^2 = 0.08$ (B.G.) for all experiments. Training under varying μ and μ_1, w_1 respectively.

Block Size	Already Implemented			Newly Implemented		
	Noise Schedule	PPL	Var. NELBO	Noise Schedule	PPL	Var. NELBO
128	Loglinear	2106	1.27	Gaussian ($\mu = 0.5$)	2115	1.29
	Loglinear $\mathcal{U}[0, 0.5]$	2106	1.27	Gaussian ($\mu = 0.6$)	2212	1.34
	Cosine	2154	1.31	B.G. ($\mu_1 = 0.3, w_1 = 0.6$)	2184	1.31
	Cosine $\mathcal{U}[0, 0.5]$	2150	1.30	B.G. ($\mu_1 = 0.1, w_1 = 0.6$)	2089	1.19
16	Loglinear	1279	10.50	Gaussian ($\mu = 0.5$)	1234	10.28
	Loglinear $\mathcal{U}[0.3, 0.8]$	1278	10.51	Gaussian ($\mu = 0.6$)	1235	10.31
	Cosine	1236	10.30	B.G. ($\mu_1 = 0.3, w_1 = 0.6$)	1254	10.42
	Cosine $\mathcal{U}[0.3, 0.8]$	1235	10.29	B.G. ($\mu_1 = 0.1, w_1 = 0.6$)	1295	10.59
4	Loglinear	1226	44.41	Gaussian ($\mu = 0.5$)	1250	46.76
	Loglinear $\mathcal{U}[0.5, 1]$	1226	44.41	Gaussian ($\mu = 0.7$)	1252	46.76
	Cosine	1228	45.28	B.G. ($\mu_1 = 0.3, w_1 = 0.6$)	1253	46.84
	Cosine $\mathcal{U}[0.5, 1]$	1229	45.26	B.G. ($\mu_1 = 0.1, w_1 = 0.6$)	1243	46.49

Using Bimodal Gaussian on Pretraining

We can also apply the Bimodal Gaussian noise schedule during pretraining.

The table reports, for each pretraining noise schedule, the *best* fine-tuning noise schedule we found, with the corresponding PPL and Var. NELBO (400 Pretraining Steps + 100 Fine-tuning Steps).

Block Size	Pretraining Schedule	Fine-tuning Schedule	PPL	Var. NELBO
128	Loglinear	B.G. ($\mu_1 = 0.1, w_1 = 0.6$)	2089	1.25
	Bimodal Gaussian	B.G. ($\mu_1 = 0.3, w_1 = 0.6$)	2070	1.19
16	Loglinear	Gaussian ($\mu = 0.5$)	1234	10.28
	Bimodal Gaussian	Cosine $\mathcal{U}[0.3, 0.8]$	1227	10.22
4	Loglinear	Loglinear	1226	44.41
	Bimodal Gaussian	Loglinear	1213	44.39

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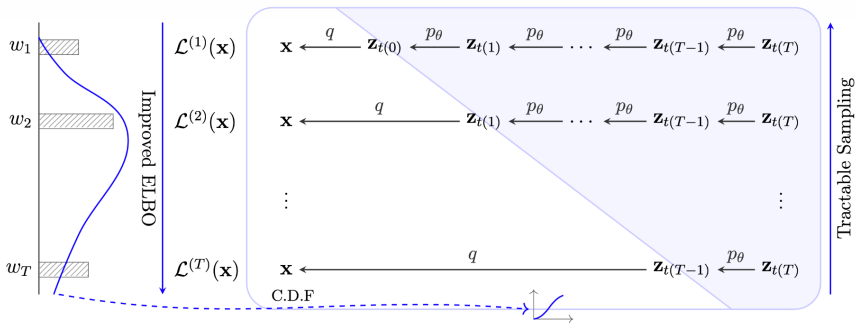
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Reweighted Losses are Better Variational Bounds



Diffusion objectives: $\mathcal{L}^{\bar{w}}(\mathbf{x}) = \lim_{T \rightarrow \infty} \sum_{i=1}^T w_i \mathcal{L}^{(i)}(\mathbf{x}) = \int_0^1 \tilde{w}(t) \mathbb{E}_{q(\mathbf{z}_t|\mathbf{x})} [L_{\text{denoise}}(\mathbf{z}_t, \mathbf{x}, t)] dt + C$

Reweighted Losses for Masked Diffusion

- Initial Reweighted NELBO:

$$\mathcal{L}^{\tilde{w}}(\mathbf{x}) = - \int_0^1 \tilde{w}(t) \frac{\alpha'_t}{1 - \alpha_t} \mathbb{E}_{q(\mathbf{z}_t|\mathbf{x})} \left[\delta_{\mathbf{z}_t, m} \cdot \mathbf{x}^\top \log \mu_\theta(\mathbf{z}_t) \right] dt$$

- Reparameterization trick: $\lambda(t) = \log \frac{\alpha_t}{1 - \alpha_t}$:

$$\mathcal{L}^{\hat{w}}(\mathbf{x}) = - \int_0^1 \hat{w}(\lambda(t)) \frac{\alpha'_t}{1 - \alpha_t} \mathbb{E}_{q(\mathbf{z}_t|\mathbf{x})} \left[\delta_{\mathbf{z}_t, m} \cdot \mathbf{x}^\top \log \mu_\theta(\mathbf{z}_t) \right] dt$$

Name	$\lambda(t)$	$\hat{w}(\lambda)$	$\tilde{w}(t)$
EDM		$p_{\mathcal{N}(2.4, 2.4^2)}(\lambda) \frac{e^{-\lambda + 0.5^2}}{0.5^2}$	$w(\lambda(t))$
IDDPM	$\log \frac{\alpha_t}{1 - \alpha_t}$	$\text{sech}(\frac{\lambda}{2})$	$2\sqrt{\alpha_t(1 - \alpha_t)}$
Sigmoid		$\text{sigmoid}(-\lambda + k)$	$\frac{1 - \alpha_t}{1 - (1 - e^{-k})\alpha_t}$
FM		$e^{-\frac{\lambda}{2}}$	$\sqrt{\frac{1 - \alpha_t}{\alpha_t}}$
Simple		-	$-\frac{1 - \alpha_t}{\alpha'_t}$

Reweighted Losses Results

Extended Table 3: Test Perplexities

PPL (\downarrow)						
Autoregressive						
Transformer	1221					
Diffusion						
SEDD	1403					
MDLM	1370					
Block diffusion	Base	IDDPM	EDM	Sigmoid ($k = 0$)	FM	Simple
BD3-LMs $L' = 16$	1345	8048.88	1593.4	1150.15	76213	53070
$L' = 8$	1210	7954.17	1569.75	1078.57	109169	36010741760
$L' = 4$	1176	7857.33	1565.6	1093.7	67332	2396260

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Conclusion

Initial reproduction

In our initial reproduction, we observed noticeable gaps compared to the paper's reported results, largely due to insufficient training.

Impact of our extensions

By identifying and applying our two extensions, we were able to improve performance.

Impact of using more resources

With sufficient training compute, our results are consistent with the trends reported in the paper.

This table shows test perplexities of models on OWT (3000 Pretraining Steps + 3000 Fine-tuning Steps).

Model	PPL
AR	402
SEDD	575
MDLM	588
BD3LM ($L' = 16$)	438
BD3LM ($L' = 8$)	433
BD3LM ($L' = 4$)	420

Future Work

Frequency-Informed Masking

Prioritize masking rare, information-rich tokens (which carry more semantics) rather than common function words, changing *which* tokens are masked, not only *how many*.

Adaptive block size

Adaptively change the block size according to the need for fine-grained detail of each block.

mHC (DeepSeek)

Explore mHC and related recent ideas from the DeepSeek group, and assess how they could be combined with masked/block diffusion to improve the quality–efficiency trade-off.

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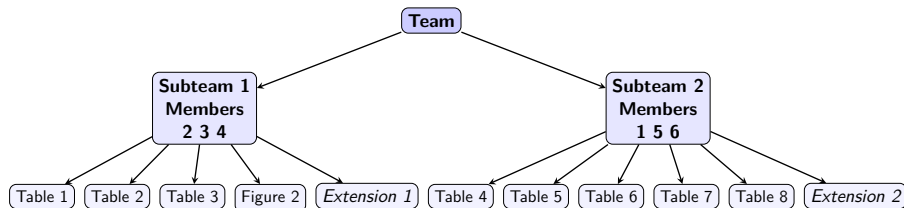
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Team Organization and Structure



Coordination:

- Weekly team meetings
- Subteams internal coordination
- GitHub repo
- Discord server

Phase	Description	Members
1	Paper & codebase study	Everyone
2	Environment & data setup	Georgios M., Petros
3	Initial reproduction	Georgios M., Petros, Ilias
4	Final reproduction	Georgios Nt., Konstantinos, Nikolaos
5	Extension experiments	Everyone
6	Analysis & Writing	Everyone

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- **What challenged us:**

- Limited resources, which constrained training length and the number of ablations we could run.
- The LM1B training pipeline depended on a Hugging Face repository that was temporarily unavailable, causing delays and forcing workarounds.

- **What we could have done better:**

- Align the two subteams on a shared training protocol (same number of training steps and checkpoints) to make results more directly comparable.

Questions?

Paper: Block Diffusion (ICLR 2025)

Code: <https://github.com/kuleshov-group/bd3lms>

Our Repo: <https://github.com/ntua-el21050/bd3lms>

Authors: Arriola, Gokaslan, Chiu, Yang, Qi, Han, Sahoo, Kuleshov