

# UnDiff

---

## Unsupervised Voice Restoration with Unconditional Diffusion Model

Anastasiia Iashchenko<sup>123\*</sup>, Pavel Andreev<sup>1\*</sup>, Ivan Shchekotov<sup>123\*</sup>, Nicholas Babaev<sup>1</sup>, Dmitry Vetrov<sup>24</sup>

<sup>1</sup>Samsung AI Center, Moscow; <sup>2</sup>HSE University, Moscow; <sup>3</sup>Skolkovo Institute of Science and Technology, Moscow; <sup>4</sup>Artificial Intelligence Research Institute, Moscow; \*equal contribution

Interspeech 2023



# Unsupervised Voice Restoration

Audio restoration tasks are inverse problems with the aim to **Restore the Signal  $\mathbf{x}$  from observations  $\mathbf{y} = A(\mathbf{x})$  that have suffered a Known Type of Degradation  $A$ .**

- e.g., bandwidth extension, declipping, and Mel-spectrogram inversion.

These problems are ill-posed in the sense that several different restorations may be equally plausible. Algorithms are typically constructed for

- A particular type of degradation using domain knowledge, and
- Data-driven generative models have also been recently proposed.

# Unsupervised Voice Restoration

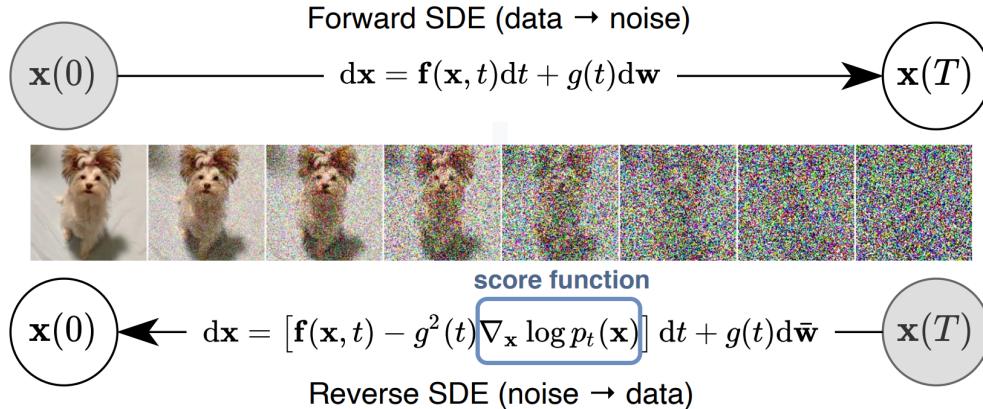
However, A common shortcoming is that an algorithm engineered for one type of degradation is typically **Not Useful for Others**.

To address this issue, this study introduces UnDiff, which uses a differentiable operator  $A$  to guide the **Diffusion Probabilistic Model** to solve various inverse tasks of speech processing.

- Bandwidth extension
- Declipping
- Neural vocoding
- Source separation

UnDiff showcases the latent potential in solving general inverse problems for speech processing under the premise of **Unsupervised Learning**.

# Diffusion Models



---

### Algorithm 3 PC sampling (VP SDE)

---

```
1:  $\mathbf{x}_N \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$ 
2: for  $i = N - 1$  to 0 do
3:    $\mathbf{x}'_i \leftarrow (2 - \sqrt{1 - \beta_{i+1}})\mathbf{x}_{i+1} + \beta_{i+1}\mathbf{s}_{\theta}*(\mathbf{x}_{i+1}, i + 1)$ 
4:    $\mathbf{z} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$ 
5:    $\mathbf{x}_i \leftarrow \mathbf{x}'_i + \sqrt{\beta_{i+1}}\mathbf{z}$  Predictor
6:   for  $j = 1$  to M do
7:      $\mathbf{z} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$ 
8:      $\mathbf{x}_i \leftarrow \mathbf{x}_i + \epsilon_i \mathbf{s}_{\theta}*(\mathbf{x}_i, i) + \sqrt{2\epsilon_i}\mathbf{z}$  Corrector
9: return  $\mathbf{x}_0$ 
```

---

cite: Score-Based Generative Modeling through Stochastic Differential Equations

Connect normal distribution and data distribution through Markov chain or stochastic differential equation (SDE).

# Diffusion Models

Estimate noise  $\varepsilon$

$$\begin{aligned} & \mathbb{E}_{\mathbf{x} \sim p_{data}, \varepsilon \sim \mathcal{N}(\mathbf{0}, \mathbf{I})} \left( \lambda(t) \|\mathbf{s}_\theta(\mathbf{x}_t, t) - \nabla_{\mathbf{x}_t} \log p_t(\mathbf{x}_t)\|_2^2 \right) \\ &= \underbrace{\mathbb{E}_{\mathbf{x} \sim p_{data}, \varepsilon \sim \mathcal{N}(\mathbf{0}, \mathbf{I})} \left( \lambda(t) \|\mathbf{s}_\theta(\mathbf{x}_t, t) - \frac{\varepsilon}{\sqrt{1 - \bar{\alpha}(t)}}\|_2^2 \right)}_{\text{in VP-SDE, } \mathbf{x}_t = \sqrt{\bar{\alpha}(t)}\mathbf{x} + \sqrt{1 - \bar{\alpha}(t)}\varepsilon} \end{aligned}$$

# Inverse Problems with Diffusion Models

$$p(x|y) = \frac{p(y|x)p(x)}{p(y)}$$
$$\Rightarrow \nabla_{x_t} \log p(x_t|y) = \nabla_{x_t} \log p(y|x_t) + \underbrace{\nabla_{x_t} \log p(x_t)}_{\text{Unconditional Diffusion Models}}$$

# Inverse Problems with Diffusion Models

$$\begin{aligned} p(\mathbf{x}|\mathbf{y}) &= \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{y})} \\ \Rightarrow \nabla_{\mathbf{x}_t} \log p(\mathbf{x}_t|\mathbf{y}) &= \underbrace{\nabla_{\mathbf{x}_t} \log p(\mathbf{y}|\mathbf{x}_t)} + \nabla_{\mathbf{x}_t} \log p(\mathbf{x}_t) \\ \approx \nabla_{\mathbf{x}_t} \log p(\mathbf{y}|\hat{\mathbf{x}}_0) &= \frac{1}{\sqrt{\bar{\alpha}(t)}} (\mathbf{x}_t - (1 - \bar{\alpha}(t)) \mathbf{s}_\theta(\mathbf{x}_t)) \\ &= -\xi(t) \nabla_{x_t} \|\mathbf{y} - A(\hat{\mathbf{x}}_0)\| \end{aligned}$$

$A(\mathbf{x})$  is a differentiable degradation operator.

# Speech Inverse Tasks: Bandwidth Extension

Frequency bandwidth extension (also known as audio super-resolution) can be viewed as a realistic restoration of waveform's high frequencies.

The observation operator is a lowpass filter

$$\mathbf{y} = A(\mathbf{x}) = \text{LPF}(\mathbf{x})$$

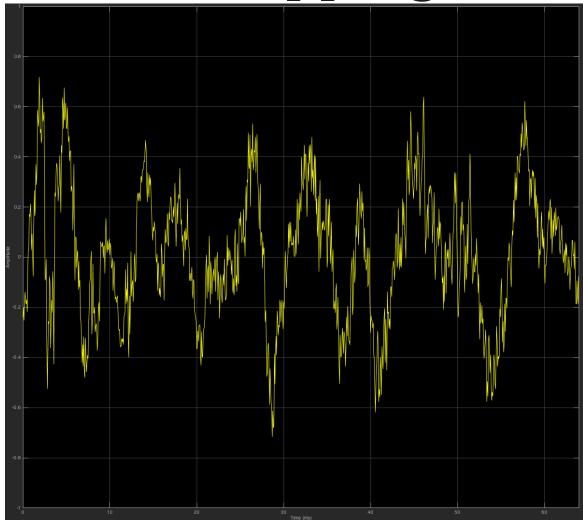
And apply data consistency steps, where the observed low frequencies are replaced with the denoised estimate following  $\bar{\mathbf{x}}_0 = \mathbf{y} + \hat{\mathbf{x}}_0 - \text{LPF}(\hat{\mathbf{x}}_0)$ .

We can rewrite  $\mathbf{s}_\theta$  using  $\bar{\mathbf{x}}_0$

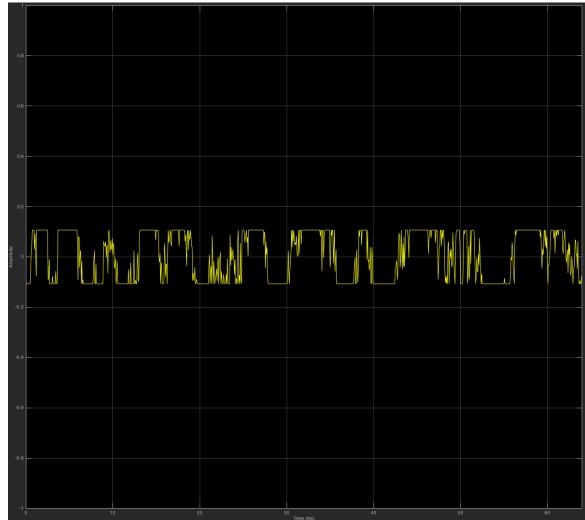
$$\Rightarrow \bar{\mathbf{s}}_\theta = \frac{1}{1 - \bar{\alpha}(t)} (x_t - \sqrt{\bar{\alpha}(t)} \bar{x}_0)$$

# Speech Inverse Tasks: Declipping

What is clipping?



$$\begin{aligned} A(\mathbf{x}) &= \mathbf{clip}(\mathbf{x}) \\ &= \frac{1}{2}(|\mathbf{x} + c| - |\mathbf{x} - c|) \end{aligned}$$



cite: [Audio Declipping](#)

# Speech Inverse Tasks: Neural Vocoder

The majority of modern speech synthesis systems decompose this task into two stages.

1. Low-resolution intermediate representations (e.g., linguistic features, mel-spectrograms) are predicted from text data.
2. Transform intermediate representations to raw waveform by **Neural Vocoder**.

$$\text{Vocoder: } \mathcal{L} = \|\mathbf{x} - \text{Vocoder}(A(\mathbf{x}))\|_2^2$$

## Issue of Supervised Vocoder

Vocoders based on different intermediate representations **CANNOT be Used Universally**.

# Speech Inverse Tasks: Neural Vocoder

The majority of modern speech synthesis systems decompose this task into two stages.

1. Low-resolution intermediate representations (e.g., linguistic features, mel-spectrograms) are predicted from text data.
2. Transform intermediate representations to raw waveform by **Neural Vocoder**.

## Degradation Operator of Vocoder Task

$$A(\mathbf{x}) = \text{Mel}(\mathbf{x})$$

# Speech Inverse Tasks: Source Separation

The goal of single-channel speech separation is to extract individual speech signals from a mixed audio signal, in which multiple INDEPENDENT speakers are talking simultaneously.

$$p(x^{(1)}, x^{(2)}|y) = p(x^{(1)}|y)p(x^{(2)}|y) = \frac{p(y|x^{(1)}, x^{(2)})p(x^{(1)})p(x^{(2)})}{p(y)}$$
$$\nabla_{x_t^{(1)}} \log p(x_t^{(1)}|y) = \nabla_{x_t^{(1)}} \log p(y|x_t^{(1)}, x_t^{(2)}) + \nabla_{x_t^{(1)}} \log p(x_t^{(1)})$$

Specifically, note that  $y$  depends only the sum of  $x_1$  and  $x_2$ ,

$$\Rightarrow y = x^{(1)} + x^{(2)} = \frac{1}{\sqrt{\bar{\alpha}(t)}}(x_t^{(1)} + x_t^{(2)}) + \sqrt{\frac{2(1-\bar{\alpha}(t))}{\bar{\alpha}(t)}}\varepsilon$$

$$\Rightarrow p(y|x_t^{(1)}, x_t^{(2)}) = p(y|x_t^{(1)} + x_t^{(2)}) = \mathcal{N}(y; \frac{1}{\sqrt{\bar{\alpha}(t)}}(x_t^{(1)} + x_t^{(2)}), \frac{2(1-\bar{\alpha}(t))}{\bar{\alpha}(t)})$$

## Speech Inverse Tasks: Source Separation

$$p(y|x_t^{(1)}, x_t^{(2)}) = p(y|x_t^{(1)} + x_t^{(2)}) = \mathcal{N}(y; \frac{1}{\sqrt{\bar{\alpha}(t)}}(x_t^{(1)} + x_t^{(2)}), \frac{2(1-\bar{\alpha}(t))}{\bar{\alpha}(t)})$$

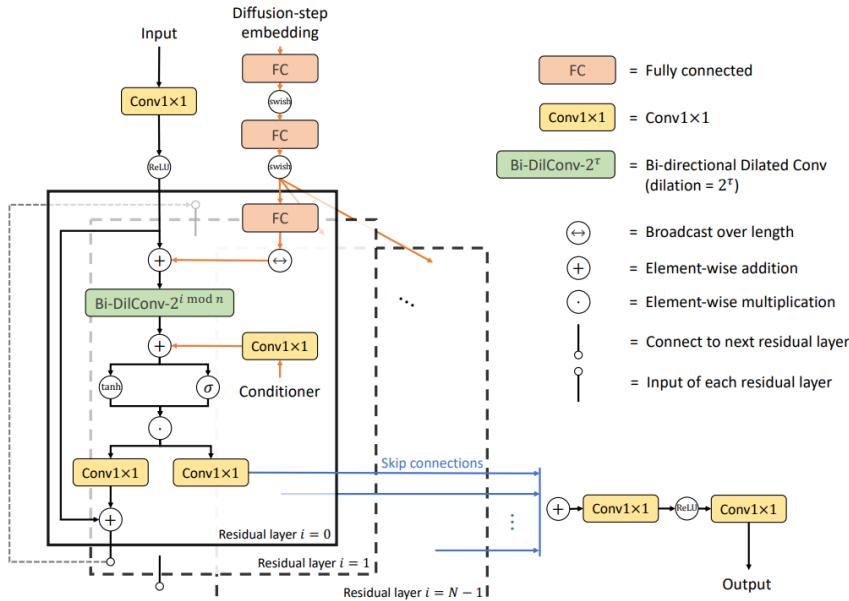
$$\log p(y|x_t^{(1)}, x_t^{(2)}) = -\frac{1}{2} \frac{\bar{\alpha}(t)(y - \frac{1}{\sqrt{\bar{\alpha}(t)}}(x_t^{(1)} + x_t^{(2)}))^2}{2(1-\bar{\alpha}(t))} + C$$

$$\Rightarrow \nabla_{x_t^{(1)}} \log p(y|x_t^{(1)}, x_t^{(2)}) = \frac{\sqrt{\bar{\alpha}(t)}(y - \frac{1}{\sqrt{\bar{\alpha}(t)}}(x_t^{(1)} + x_t^{(2)}))}{2(1 - \bar{\alpha}(t))}$$

$\nabla_{x_t^{(1)}} \log p(y|x_t^{(1)}, x_t^{(2)})$  and  $\nabla_{x_t^{(2)}} \log p(y|x_t^{(1)}, x_t^{(2)})$  can be derived without the need to compute the gradient of  $\|\mathbf{y} - A(\mathbf{x}_t)\|_2^2$ .

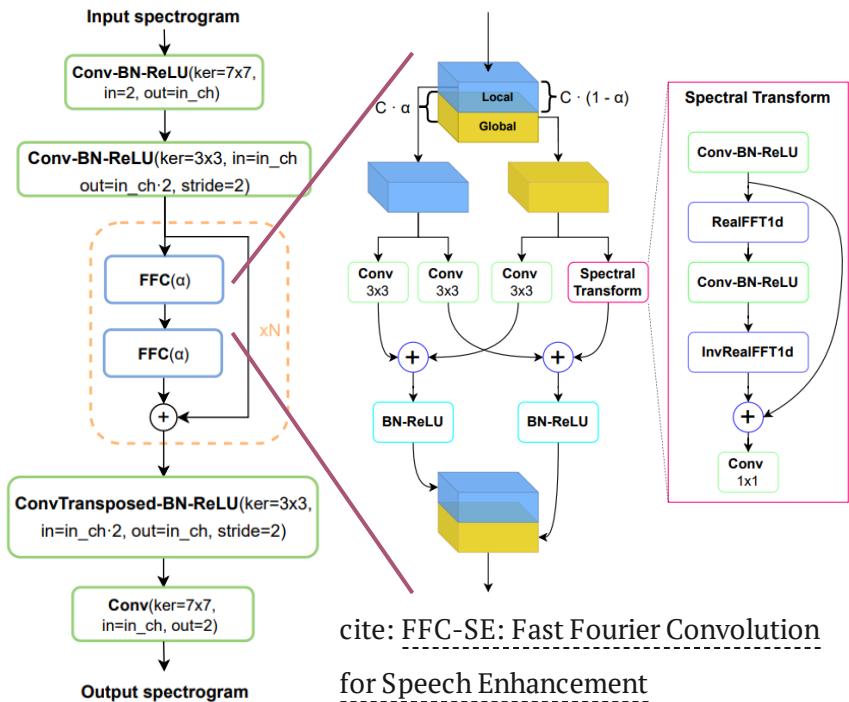
# Architecture of Diffusion Model

## Diffwave



cite: DiffWave: A Versatile Diffusion Model for Audio Synthesis

## FFC-AE



cite: FFC-SE: Fast Fourier Convolution for Speech Enhancement

# Experiments

Table 2: Results of bandwidth extension (BWE) on VCTK.

Model	Supervised	WV-MOS	LSD	MOS
Ground Truth	-	4.17	0	$4.09 \pm 0.09$
<b>BWE 2kHz → 8kHz</b>				
HiFi++ [15]	✓	<b>4.05</b>	1.09	<b>3.93 ± 0.10</b>
Voicefixer [31]	✓	3.67	1.08	$3.64 \pm 0.10$
TFiLM [32]	✓	2.83	1.01	$2.71 \pm 0.10$
UnDiff (Diffwave)	✗	3.48	<b>0.96</b>	$3.59 \pm 0.11$
UnDiff (FFC-AE)	✗	3.59	1.13	$3.50 \pm 0.11$
Input	-	2.52	1.06	$2.42 \pm 0.09$
<b>BWE 4kHz → 8kHz</b>				
HiFi++ [15]	✓	<b>4.22</b>	1.07	<b>4.04 ± 0.10</b>
Voicefixer [31]	✓	3.95	0.98	$3.92 \pm 0.10$
TFiLM [32]	✓	3.46	0.83	$3.43 \pm 0.10$
UnDiff (Diffwave)	✗	4.00	<b>0.76</b>	$3.74 \pm 0.11$
UnDiff (FFC-AE)	✗	3.88	0.96	$3.72 \pm 0.10$
Input	-	3.34	0.85	$3.39 \pm 0.10$

Table 3: Results of declipping (input SNR = 3 db) on VCTK.

Model	Supervised	WV-MOS	SI-SNR	MOS
Ground Truth	-	3.91	-	$3.84 \pm 0.11$
A-SPADE [33]	✗	2.63	8.48	$2.67 \pm 0.11$
S-SPADE [34]	✗	2.69	8.50	$2.55 \pm 0.11$
Voicefixer [31]	✓	2.79	-22.58	$2.98 \pm 0.12$
Undiff (Diffwave)	✗	<b>3.62</b>	<b>10.57</b>	<b>3.59 ± 0.12</b>
Undiff (FFC-AE)	✗	3.01	7.35	$3.06 \pm 0.12$
Input	-	2.30	3.82	$2.19 \pm 0.09$

Table 4: Results of neural vocoding (LJ speech dataset).

Model	Supervised	WV-MOS	MOS
Ground Truth	-	4.32	$4.26 \pm 0.07$
HiFi-GAN (V1) [18]	✓	<b>4.36</b>	<b>4.23 ± 0.07</b>
Diffwave [10]	✓	4.19	$4.15 \pm 0.07$
Griffin-Lim [35]	✗	3.30	$3.46 \pm 0.08$
Undiff (Diffwave)	✗	3.99	$3.79 \pm 0.08$
Undiff (FFC-AE)	✗	4.08	$4.12 \pm 0.07$

# Experiments: Source Separation

Table 5: *Results of source separation (VCTK dataset).*

Model	Supervised	SI-SNR	STOI
Mixture (input)	-	-0.04	0.69
Undiff (Diffwave)	✗	5.73	0.79
Undiff (FFC-AE)	✗	3.39	0.76
Conv-TasNet [36]	✓	<b>15.94</b>	<b>0.95</b>

Although Undiff is able to correctly separate voices in local regions, it mixes different voices within one sample.

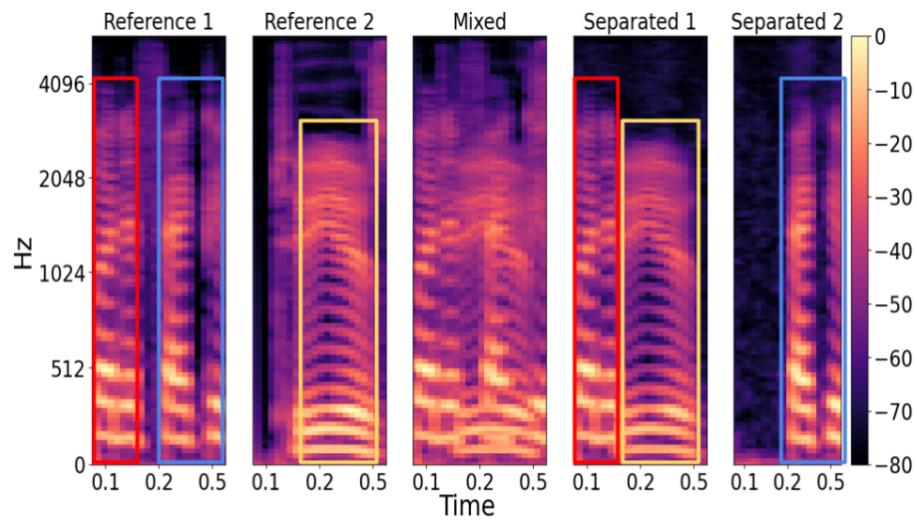


Figure 1: *Failure case of source separation with Undiff model.*

# Conclusions

- The results highlight the potential of the **Unconditional Diffusion Models** to serve as general voice restoration tools.
- Enabling models to produce globally coherent voices during source separation could be An interesting directions for future work.