

Deep Learning for Audio

Lecture 6

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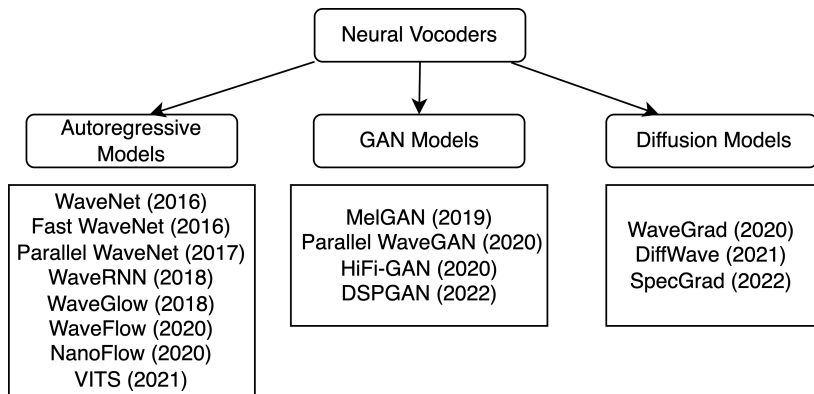
Outline

1. Neural Vocoder
2. WaveNet
3. Parallel WaveGAN
4. DiffWave

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Neural Vocoders



Neural Vocoders

Model type	Model	MOS on LJ Speech
Autoregressive	WaveNet	3.68
	WaveRNN	3.96
GAN	MelGAN	3.73
	Parallel WaveGAN	3.99
Diffusion	WaveGrad	3.85
	DiffWave	4.07
	Griffin-Lim	3.68
	Ground Truth	4.10

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WaveNet

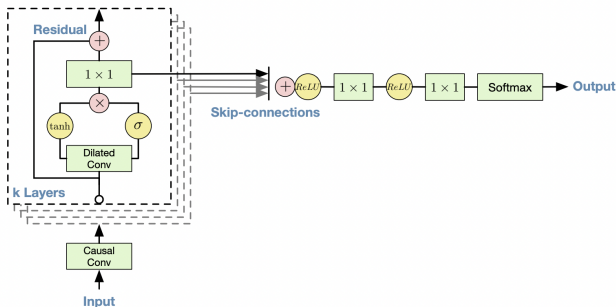


Figure: WaveNet architecture: uses **causal** dilated convolutions

- ▶ The joint probability of a waveform $x = \{x_1, \dots, x_T\}$:
$$p(\mathbf{x}) = \prod_{t=1}^T p(x_t \mid x_{1:t-1})$$
- ▶ Each conditional $p(x_t \mid x_{1:t-1})$ models the distribution for the timestamp t

Causal Convolution

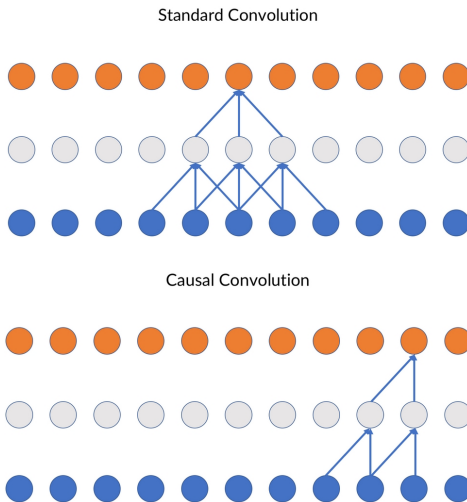


Figure: Standard vs causal convolutions. Causal makes convs autoregressive

Dilated Convolution

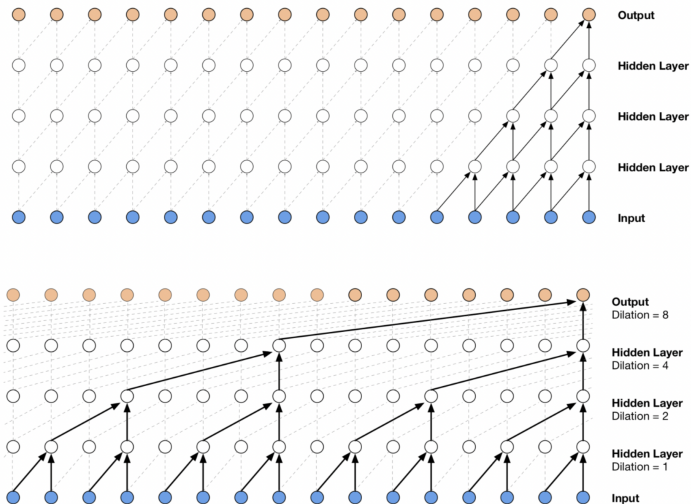
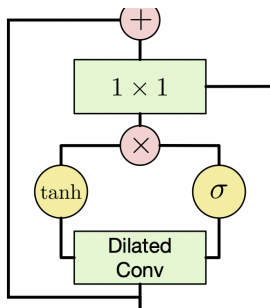


Figure: Non-dilated vs dilated causal convolutions. Dilated convs increase receptive fields

Conditional gated units

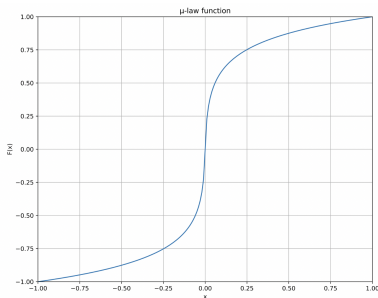


Gated activation unit as used in the gated PixelCNN + condition \mathbf{y}

$$\mathbf{z} = \tanh(W_{f,k} * \mathbf{x} + V_{f,k} * \mathbf{y}) \odot \sigma(W_{g,k} * \mathbf{x} + V_{g,k} * \mathbf{y}).$$

$*$ – convolution, \odot – element-wise multiplication, $\sigma(\cdot)$ – sigmoid function, f and g – filter and gate, respectively, W – learnable convolution filter, V – learnable linear projection

Mu Law Encoding



- ▶ Raw audio \sim 16-bit integer values \Rightarrow softmax layer need to output 65,536 probabilities per timestep
- ▶ Solution: apply a μ -law transformation to the data, and then quantize it to 256 possible values:

$$f(x_t) = \text{sign}(x_t) \frac{\ln(1 + \mu |x_t|)}{\ln(1 + \mu)}, \quad -1 < x_t < 1, \mu = 255$$

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Parallel WaveGAN

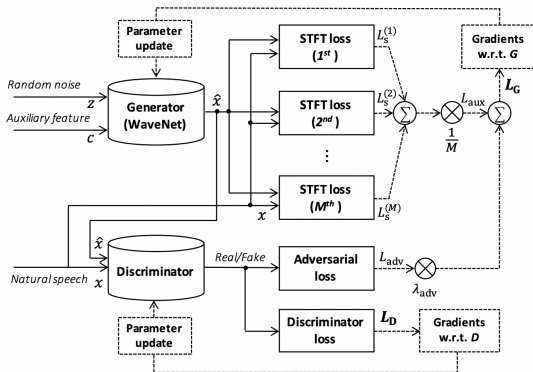
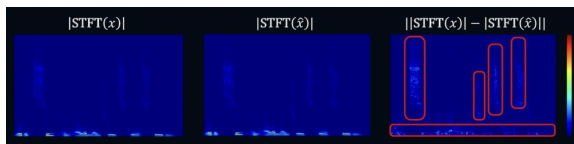


Figure: Parallel WaveGAN

Yamamoto et al., *Parallel Wavegan: A Fast Waveform Generation Model Based on Generative Adversarial Networks with Multi-Resolution Spectrogram*, IEEE ICASSP, 2020

STFT Loss



$$\mathcal{L}_s(G) = \mathbb{E}_{\mathbf{z} \sim p(\mathbf{z}), \mathbf{x} \sim p_{data}} [\mathcal{L}_{sc}(\mathbf{x}, \hat{\mathbf{x}}) + \mathcal{L}_{mag}(\mathbf{x}, \hat{\mathbf{x}})]$$

$$\mathcal{L}_{sc}(\mathbf{x}, \hat{\mathbf{x}}) = \frac{|||STFT(\mathbf{x})| - |STFT^T(\hat{\mathbf{x}})|||}{|||STFT(\mathbf{x})|||_F}$$

$$\mathcal{L}_{mag}(\mathbf{x}, \hat{\mathbf{x}}) = \frac{1}{N} \|\log |STFT(\mathbf{x})| - \log |STFT(\hat{\mathbf{x}})|\|_1$$

$$\mathcal{L}_{aux}(G) = \frac{1}{M} \sum_{m=1}^M \mathcal{L}_s^{(m)}(G), M - \text{number of STFT losses}$$

Takaki et al., *STFT Spectral Loss for Training a Neural Speech Waveform Model*,
IEEE ICASSP, 2019

GAN Loss

- ▶ Discriminator Loss:

$$\mathcal{L}_D(G, D) = \mathbb{E}_{\mathbf{x} \sim p_{\text{data}}} [(1 - D(\mathbf{x}))^2] + \mathbb{E}_{\mathbf{z} \sim N(0, I)} [D(G(\mathbf{z}))^2]$$

- ▶ Generator Loss

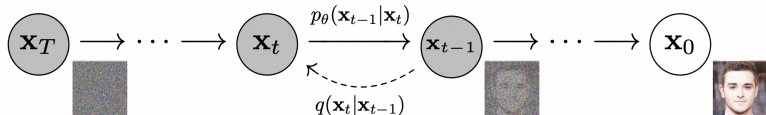
$$L_{\text{adv}}(G, D) = \mathbb{E}_{\mathbf{z} \sim N(0, I)} [(1 - D(G(\mathbf{z})))^2]$$

$$L_G(G, D) = L_{\text{aux}}(G) + \lambda_{\text{adv}} L_{\text{adv}}(G, D)$$

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Diffusion models idea



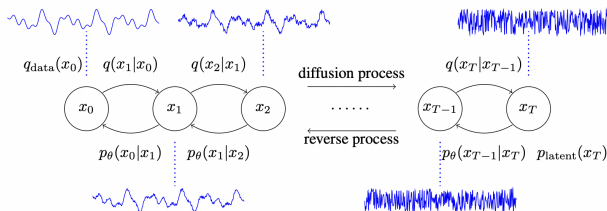
- **Diffusion probabilistic model:** parameterized Markov chain from data x_0 to the latent variable x_T

$$q(x_1, \dots, x_T | x_0) = \prod_{t=1}^T q(x_t | x_{t-1})$$

- **Reverse process:** Markov chain from x_T to x_0 parameterized by θ :

$$p_{\text{latent}}(x_T) = \mathcal{N}(0, I), \quad p_{\theta}(x_0, \dots, x_{T-1} | x_T) = \prod_{t=1}^T p_{\theta}(x_{t-1} | x_t)$$

DiffWave



- **Sampling:** reverse process $x_T \sim \mathcal{N}(0, I)$, $x_{t-1} \sim p_\theta(x_{t-1}|x_t)$ for $t = T, T-1, \dots, 1$. x_0 – sampled data.
- **Training:** $p_\theta(x_0) = \int p_\theta(x_0, \dots, x_{T-1}|x_T) \cdot p_{\text{latent}}(x_T) \mathbf{d}x_{1:T}$ (likelihood) is intractable to calculate \Rightarrow model trained by maximizing its variational lower bound (ELBO):

$$\begin{aligned} \mathbb{E}_{q_{\text{data}}(x_0)} \log p_\theta(x_0) &\geq \\ &\geq \mathbb{E}_{q(x_0, \dots, x_T)} \log \frac{p_\theta(x_0, \dots, x_{T-1}|x_T) \cdot p_{\text{latent}}(x_T)}{q(x_1, \dots, x_T|x_0)} := \text{ELBO} \end{aligned}$$

DiffWave: advantages

- ▶ **Non-autoregressive**: much faster than WaveNet
- ▶ **Compact model**: smaller footprint than flow-based models
- ▶ No auxiliary losses in training (e.g., spectrogram-based losses): **no mode collapse** like in GANs/VAEs