Vector Quantized Time Series Generation with a Bidirectional Prior Model

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Abstract

Time series generation (TSG) studies have mainly focused on the use of Generative Adversarial Networks (GANs) combined with recurrent neural network (RNN) variants. However, the fundamental limitations and challenges of training GANs still remain. In addition, the RNN-family typically has difficulties with temporal consistency between distant timesteps. Motivated by the successes in the image generation (IMG) domain, we propose TimeVQVAE, the first work, to our knowledge, that uses vector quantization (VQ) techniques to address the TSG problem. Moreover, the priors of the discrete latent spaces are learned with bidirectional transformer models that can better capture global temporal consistency. We also propose VQ modeling in a time-frequency domain, separated into low-frequency (LF) and high-frequency (HF). This allows us to retain important characteristics of the time series and, in turn, generate new synthetic signals that are of better quality, with sharper changes in modularity, than its competing TSG methods. Our experimental evaluation is conducted on all datasets from the UCR archive, using well-established metrics in the IMG literature, such as Fréchet inception distance and inception scores. Our implementation on GitHub: `https://github.com/ML4ITS/TimeVQVAE`.

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1 INTRODUCTION

Chang et al. (2022) TSG models have been developed to overcome insufficient training data due, for example, to acquisition difficulties or strict privacy constraints (Li et al., 2015; Esteban et al., 2017; Yoon et al., 2019; Ni et al., 2020a; Smith and Smith, 2020; Li et al., 2022; Zha, 2022). Current mainstream TSG methods consist of combining RNNs with the GAN architecture, as done in RCGAN (Esteban et al., 2017), TimeGAN (Yoon et al., 2019), and SigCWGAN (Ni et al., 2020a). However, such methods are unable to effectively produce long sequences, given the limitation of the RNN model in keeping track of temporal dependencies between inputs that are distant in time (Vaswani et al., 2017). This problem is tackled by Li et al. (2022) with TTS-CGAN (Transformer Time-Series Conditional GAN), where the RNN model is replaced by a transformer model (Vaswani et al., 2017). The challenges of training GANs, such as non-convergence, mode collapse, generator-discriminator unbalance, and sensitive hyperparameter selection, however, still remain.

There has been much evidence in the IMG literature that VQ-based models and diffusion models significantly outperform the GAN alternatives (Yu et al., 2022; Gafni et al., 2022; Chang et al., 2022; Saharia et al., 2022; Ramesh et al., 2022). Therefore, a meaningful performance gain is to be expected by extending analogous methodologies in the time series domain. With our proposal, which we call TimeVQVAE, we adopt the two-stage modeling approach appearing in (Van Den Oord et al., 2017). More specifically, VQ-VAE is used for the first stage and MaskGIT (Chang et al., 2022) for the second. Although there are other advanced approaches for the first stage, such as VQ-GAN (Esser et al., 2021) and ViT-VQGAN (Yu et al., 2021), VQ-VAE has been selected as it has shown good performance in several areas, and, to our knowledge, it has never been explored in the TSG domain. The advanced VQ methods could be further investigated in future work. MaskGIT proposes to use a bidirectional trans-

former model for the prior learning unlike VQ-VAE, VQ-GAN, and ViT-VQGAN, where autoregressive models are used. It has experimentally been shown that the bidirectional transformer can capture global consistency better and accelerates the data generation process and achieves better-quality synthetic samples.

In our work, VQ-VAE acts on the time-frequency domain. We, furthermore, propose to separate the VQ modeling into LF and HF, respectively. The time-frequency domain provides richer information, results in better VQ modeling than in the time domain, and it allows disentangling HF components, such as spikes, from LF components, such as trends, more easily. Frequency separation is also motivated by the different predictability and compressibility of LF and HF components, as LF components are more predictable and compressible than HF components by nature. Thus, we let our model generate the LF component first and only subsequently the HF component, which could be viewed as defining the overall shape first and then filling in the details. Frequency separation also allows us to more precisely address several useful downstream tasks, such as anomaly detection for LF and HF components respectively, with explainable restoration (Marimont and Tarroni, 2021). Another related task is time series forecasting using discrete latent vectors, as explored in (Rasul et al., 2022), where an autoregressive model is trained in the discrete latent space, showing competitive forecasting performance. With the proposed LF-HF separation, the VQ forecasting problem can be further eased: LF components can be easily predicted while HF components can be quantified for uncertainty using the likelihood of individual tokens. In our proposed method, TimeVQVAE, we use STFT to transform the time series into the time-frequency domain and split it into LF and HF regions. Then, two sets of encoder, decoder, and vector-quantizer are used to learn the discrete latent spaces for LF and HF, respectively. Next, priors of the LF and HF discrete latent spaces are learned with two bidirectional transformer models. Lastly, we propose to jointly sample sets of LF and HF discrete latent vectors from the learned priors and decode them into time series with the learned decoders.

To evaluate generated samples fairly, robust evaluation metrics and diverse benchmark datasets are necessary. There has, however, been a lack of agreement for which evaluation metrics to use in the TSG literature (Brophy et al., 2021) and most TSG studies have been evaluated only on a small range of datasets (Esteban et al., 2017; Yoon et al., 2019; Ni et al., 2020a; Li et al., 2022; Zha, 2022; Desai et al., 2021). A common visual comparative evaluation of TSG is carried out using PCA and t-SNE on time series (Yoon et al., 2019; Desai et al., 2021; Zha, 2022; Li et al., 2022). But because this cannot be reported as a single value metric, its usability is limited. Also, because each element of time series does not carry semantically-meaningful information but time-step information, the principal axes found by PCA are not effective in capturing the realism of time series. There are other metrics that are occasionally used, such as the discriminative and predictive scores (Yoon et al., 2019; Desai et al., 2021; Zha, 2022), but there is no consensus for those yet, as they lack stability in the sense that the scores can be largely inconsistent for the same methods across different studies (Yoon et al., 2019; Desai et al., 2021; Zha, 2022). The IMG literature has already established standard metrics, such as the inception score (IS) (Salimans et al., 2016), Fréchet inception distance (FID) score (Heusel et al., 2017), and Classification Accuracy Score (CAS) (Ravuri and Vinyals, 2019). Note that CAS is the same as TSTR (Training on Synthetic data and Testing on Real data).

In this work, we propose to use the above-listed metrics – IS and FID in particular – to evaluate TSG models on a wide range of diverse datasets from the UCR archive (Dau et al., 2018) as an evaluation protocol for TSG models. IS and FID score have rarely been used in the TSG literature because there is no pretrained model for time series unlike in the computer vision domain (Paszke et al., 2019). Smith and Smith (2020) was the first to evaluate a TSG model in terms of FID scores over the UCR archive datasets. They trained the Fully Convolutional Network (FCN) model (Wang et al., 2017) on every available UCR dataset and computed FID scores using the pretrained FCN models. Because the FCN model is one of the strongest baselines for time series classification and can effectively capture pattern features of time series (Wang et al., 2017), it is reasonable to use the representations from such a model to compute the FID scores. Unfortunately, though, the pretrained FCN models are not provided by Smith and Smith (2020) on any open-source platform. We thus follow the same protocol as (Smith and Smith, 2020) and contribute by sharing code for the pretrained FCN models on GitHub along with templates for computing the IS and FID scores; available on `https://github.com/danelee2601/supervised-FCN`. It can be easily installed via pip.

Experiments are conducted for unconditional sampling and class-conditional sampling over the entire UCR archive. Our results clearly demonstrate how our proposed method outperforms the current competing TSG models, such as GMMN (Li et al., 2015), RCGAN, TimeGAN, SigCWGAN, and TSGAN, in terms of IS, FID, and CAS.

To summarize, our contributions consist of:

- use of VQ for TSG,
- VQ modeling in the time-frequency domain,
- latent space separation into LF and HF,
- joint sampling from the LF and HF latent spaces,
- guided class-conditional sampling,
- TSG evaluation on the entire UCR archive,

evaluation conducted by reporting IS, FID, and CAS, releasing the pretrained FCN models on the UCR archive.

2 RELATED WORK

2.1 Time Series Generation

GMMN employs maximum mean discrepancy (MMD). MMD is utilized to partially overcome the unstable training problem of GAN. GMMN has a simple objective that can be interpreted as matching all orders of statistics between real samples and synthetic samples. For TSG, GMMN can be combined with an RNN model. The MMD loss can be minimized between the generated time series by the RNN model and the real time series (Ni et al., 2020b).

RCGAN sequentially generates time series using GAN: a latent vector from the noise space is sampled at every temporal step and an RNN model sequentially encodes them generating a synthetic time series.

TimeGAN uses the conventional GAN training combined with a supervised learning approach. It aims to better preserve temporal dynamics of time series with the supervised learning loss.

SigCWGAN addresses the problem of GANs struggling with capturing temporal dependencies by using the signature of a path (Kidger et al., 2019). Ni et al. (2020a) proposes a Signature Wasserstein-1 (Sig) metric that better captures temporal dependencies, and uses it as a discriminator. It provides a universal description of complex data streams without requiring expensive computation like the Wasserstein metric.

TTS-CGAN uses a transformer model to overcome the distant temporal dependency problem appearing for the TSG RNN-based GAN models, such as RCGAN, TimeGAN, and SigCWGAN. It also proposes an approach to better induce the class-conditioning information into generated samples. Yet, the fundamental challenges in adopting GANs – that is, non-convergence, mode collapse, unbalance between generator and discriminator, sensitive hyperparameter selection – still exist (Arjovsky and Bottou, 2017; Salimans et al., 2016; Goodfellow, 2016; Goodfellow et al., 2020; Lucic et al., 2018).

TSGAN is built using two WGANs (Arjovsky et al., 2017). The first WGAN generates a synthetic spectrogram from the noise latent vector, and the second WGAN receives the synthetic spectrogram and generates a time series. Therefore, there exist two discriminators. The first discriminator compares the spectrograms while the second discriminator compares the time series. Unlike RCGAN, TimeGAN, and SigCWGAN which use RNN-based generators, TSGAN's generators use convolutional layers.

2.2 Vector Quantization-based Image Generation

VQ-VAE is a type of variational autoencoder that uses vector quantization to obtain a discrete latent representation. There are two main differences between the classical VAE and the VQ-VAE: 1) VQ-VAE maps an input to a discrete latent space rather than a continuous space, and 2) instead of being static, the prior is learned. Because there is no constraint on the prior being Gaussian, as in VAE, VQ-VAE does not suffer from the posterior collapse. Moreover, the discretization allows for sharp and crisp synthetic images. For the sampling process, Van Den Oord et al. (2017) proposes the two-stage modeling approach: The first stage is for learning to project an input to the discrete latent space, that is, the so-called tokenization. To do that, an encoder, decoder, and codebook are trained. The codebook stores K discrete codes (= discrete latent vectors/tokens). The second stage is for learning a prior of the discrete tokens in the discrete latent space. In VQ-VAE, PixelCNN (Van Den Oord et al., 2016) and WaveNet (Oord et al., 2016) are used as prior models for images and audio data, respectively.

MaskGIT proposes a bidirectional transformer model for the prior learning instead of an autoregressive model as in VQ-VAE, VQ-GAN, and ViT-VQGAN. MaskGIT trains the prior model in the masked modeling manner. Chang et al. (2022) shows that using the bidirectional transformer model can accelerate the sampling process by 30-64 times and can achieve better quality and more diversity in the synthetic samples.

VQ-based Text-to-Image Generative Models The current state-of-the-art (SOTA) IMG models include VQ and diffusion models, and not GANs. Among the SOTA VQ-based IMG models there are Parti (Yu et al., 2022), Make-A-Scene (Gafni et al., 2022), and DALLE-E (Ramesh et al., 2021). Their performances are quite competitive to their diffusion-based counterparts, such as Imagen (Saharia et al., 2022), DALL-E-2 (Ramesh et al., 2022), and GLIDE (Nichol et al., 2021). In light of such improvements in the image domain, a performance gain is to be expected also in the time series domain, if adopting one of the above-mentioned methodologies. With such motivation, our work explores the VQ-VAE approach for addressing the TSG problem.

3 METHOD

To produce good quality synthetic samples, optimization in stage 1 (tokenization) and stage 2 (prior learning) needs to be ensured. In the following subsections, our proposals for

stages 1 and 2 are presented.

3.1 Stage 1: Learning Vector Quantization

In stage 1, an encoder, decoder, and codebook are to be optimized by effectively compressing the input into discrete tokens, while minimizing the information loss obtained by comparing the input with the output, given by decoding the selected tokens. In our work, VQ-VAE is used as a basis. VQ-VAE is known to produce sharper reconstructions (Van Den Oord et al., 2017) than AE and VAE (Bank et al., 2020; Pidhorskyi, 2019). However, we have experimentally found that a naive form of VQ-VAE still experiences difficulty with reconstructing time series, especially HF components. We tackle this problem by 1) augmenting the time series into the time-frequency domain, 2) separating the latent space modeling into LF and HF. By doing so, we can compress both LF and HF information of time series into the latent space better.

The overview of our proposal for stage 1 is presented in Fig. 1. The encoder and the decoder are denoted by E and D respectively. STFT and ISTFT stand for Short-time Fourier Transform and Inverse Short-time Fourier Transform, respectively. First, a time series is augmented into the time-frequency domain and separated into two branches where one is zero-padded on the HF region and the other is zero-padded on the LF region. Then, the encoders – E_{LF} and E_{HF} – project the time-frequency domains into the continuous latent space. E_{LF} has a higher downsampling rate than E_{HF}. The higher downsampling rate has a larger receptive field, therefore, enables to capture the overall structure of the data better, which results in globally-consistent synthetic samples (Esser et al., 2021). But such a high downsampling rate fails to retain the HF information in the embedding space (Rombach et al., 2022). To produce globally-consistent synthetic data with fine HF details, we use E_{LF} with a higher downsampling rate and E_{HF} with a lower downsampling rate. The continuous latent space is further transformed into the discrete latent space by the codebook via the argmin process. In the argmin process, each continuous token is compared to every discrete token in the codebook in terms of the Euclidean distance and replaced with the closest discrete token. That is the so-called *quantization*. Then, the decoders project the discrete latent spaces back into the time-frequency domains equipped with the corresponding zero-paddings, which are then mapped to the time domains via ISTFT. At the end, the two branches produce LF and HF components of the time series, respectively $\hat{x}_{LF}$ and $\hat{x}_{HF}$.

The codebook $\mathcal{Z}$ consists of K discrete tokens $\mathcal{Z} = \{z_k\}_{k=1}^{K}$, where each $z_k \in \mathbb{R}^{h \times w}$. The quantization process can be formulated as

$$(z_q)_{ij} = \underset{z_k \in \mathcal{Z}}{\operatorname{argmin}} \|z_{ij} - z_k\|; \tag{1}$$

where z is the activation map after the encoder, and $z_q \in \mathbb{R}^{h \times w}$ for every i, j are its corresponding continuous tokens. The codebook-learning loss is then given by

$$\begin{aligned} L_{\text{codebook}} = {} & \|\text{sg}[E_{LF}(P_{LF}(\text{STFT}(x)))] - z_q^{LF}\|_2^2 \\ & + \|\text{sg}[E_{HF}(P_{HF}(\text{STFT}(x)))] - z_q^{HF}\|_2^2 \\ & + \beta\|E_{LF}(P_{LF}(\text{STFT}(x))) - \text{sg}[z_q^{LF}]\|_2^2 \\ & + \beta\|E_{HF}(P_{HF}(\text{STFT}(x))) - \text{sg}[z_q^{HF}]\|_2^2, \end{aligned} \tag{2}$$

where x denotes the time series, $\text{sg}[\cdot]$ denotes the stop-gradient operation, $P_{[\cdot]}$ denotes the zero-padding operation on either the LF or HF region, $z_q^{[\cdot]}$ denotes the discrete token for either LF or HF, and β is a weighting parameter for the commitment loss terms. The back-propagation through the non-differentiable quantization is achieved simply by copying the gradients from the decoder to the encoder.

The VQ loss also contains the reconstruction loss. In our proposal, the reconstruction tasks are conducted in both the time and time-frequency domains, similar to (Dahlgaard et al., 2022). Thus, the reconstruction loss is given by

$$\begin{aligned} L_{\text{recons}} = {} & \|x_{LF} - \hat{x}_{LF}\|_2^2 + \|x_{HF} - \hat{x}_{HF}\|_2 \\ & + \|u_{LF} - \hat{u}_{LF}\|_2^2 + \|u_{HF} - \hat{u}_{HF}\|_2^2, \end{aligned} \tag{3}$$

where $u_{[\cdot]}$ is equal to $P_{[\cdot]}(\text{STFT}(x))$, $\hat{u}$ is the reconstruction of u, $x_{[\cdot]}$ and $\hat{x}_{[\cdot]}$ are obtained by applying ISTFT to $u_{[\cdot]}$ and $\hat{u}_{[\cdot]}$ respectively.

The total training objective for stage 1 becomes:

$$L_{VQ} = L_{\text{codebook}} + L_{\text{recons}}. \tag{4}$$

3.2 Stage 2: Prior Learning

In stage 2, the encoder, decoder, and codebook are frozen and a model is trained on the pre-trained discrete tokens to learn the prior. Inspired by MaskGIT, a bidirectional transformer is used as the prior model. However, the original form of MaskGIT cannot be applied, as there are two different modalities for the tokens, i.e., LF and HF. Our proposal suggests an approach to overcome this problem.

Prior Model Training An input can now be represented in terms of the codebook-indices of the discrete tokens and is equivalent to a sequence $s \in \{0, 1, \ldots, K-1\}^{h \times w}$, where, recall, h and w denote height and width of z_q. More precisely, each element s_{ij} of such sequence is given by

$$s_{ij} = k, \quad \text{whenever } (z_q)_{ij} = z_k. \tag{5}$$

In the naive MaskGIT, the prior $p(s)$ is modelled by $\prod_M p(s_i|s_M)p(s_M)$, where s_M is the masked sequence. During training, a random subset of s is replaced by a special [MASK] token to produce s_M. In

Figure 1: Overview of our proposed VQ (i.e., tokenization) (stage 1).

Figure 2: Overview of the prior model training (stage 2). The dark green block represents the [MASK] token.

our proposal, we model the prior by $p(s^{LF}, s^{HF})$ $\prod_M p(s^{HF} | s^{LF}, s^{HF}_M) p(s^{LF} | s^{LF}_M) p(s^{LF}_M) p(s^{HF}_M)$. The overview of the prior model training is presented in Fig. 2, where $\hat{s}$ denotes the predicted s. Two bidirectional transformers are used: one for s^{LF} and the other for s^{HF}; $p(s^{LF} | s^{LF}_M)$ is modelled by the LF bidirectional transformer and $p(s^{HF} | s^{LF}, s^{HF}_M)$ is modelled by the HF bidirectional transformer.

The training objective is to minimize the negative log-likelihood of the masked tokens, that is,

$$L_{mask} = E_s[\log p_{\theta}(s^{LF} | s^{LF}_M) + \log p_{\phi}(s^{HF} | s^{LF}, s^{HF}_M)], \quad (6)$$

where θ and ϕ represent the parameters of the LF and HF bidirectional transformers, respectively.

Iterative Decoding In theory, the prior model can predict all the [MASK] tokens and generate a synthetic sample in a single step. However, challenges are encountered if one proceeds this way. Thus, Chang et al. (2022) proposed to predict the [MASK] tokens in iterative multiple steps, i.e., iterative decoding. The overview of MaskGIT's iterative decoding is presented in Fig. 3. The decoding process goes from $t = 0$ to T. To generate a synthetic sample, we start from a sequence that entirely consists of the [MASK] token indices, which we denote by $s^{(0)}_M$. We then make predictions for all the [MASK] tokens $p(\hat{s}^{(t)}_{ij} | s^{(t)}_M)$, for $t > 0$ and any i, j. A number of $\hat{s}_{ij}$ with the largest probabilities are selected to form $s^{(t+1)}_M$. This number is determined by a mask scheduling function. Additionally, Chang et al. (2022) used temperature annealing to encourage sample diversity. We use the cosine mask scheduling function and the temperature annealing following (Chang et al., 2022).

However, because we have two types of s, that is, s^{LF} and s^{HF}, the decoding iteration requires two passes. The overview of the proposed double-pass iterative decoding is presented in Fig. 4, motivated by Jukebox's ancestral sampling (Dhariwal et al., 2020). In the first pass, $\hat{s}^{LF}(T)$ is decoded starting from $s^{LF}_M(0)$. In the second pass, $\hat{s}^{HF}(T)$ is decoded starting from $s^{HF}_M(0)$, using the conditional probability dependent on $\hat{s}^{LF}(T)$ computed in the first pass. The second pass mimics the training objective $p_{\phi}(s^{HF} | s^{LF}, s^{HF}_M)$ by $p_{\phi}(\hat{s}^{HF}(t) | \hat{s}^{LF}(T), \hat{s}^{HF}_M(t))$ by assuming $s^{LF} \approx \hat{s}^{LF}(T)$ and $s^{HF}_M \approx \hat{s}^{HF}_M(t)$. To better ensure the assumption, the stochastic sampling (Lee et al., 2022) is used to stochastically sample $\hat{s}^{LF}$ and $\hat{s}^{HF}$ during training. It can reduce the discrepancy between predictions in training and inference. With the stochastic sampling, z_q is sampled as $z_q \sim (k | z_{ij} \propto z_k k)$ where $\sim$ denotes the softmax distribution.

To generate synthetic time series, $\hat{s}^{LF}(T)$ and $\hat{s}^{HF}(T)$ are

Figure 3: Overview of MaskGIT's iterative decoding. The TopK operation is equivalent to `torch.topk` from PyTorch (Paszke et al., 2019). TopK returns indices of the ℓ largest elements of a given input.

[1] Full derivation is available in Appendix A.

Figure 4: Overview of the proposed iterative decoding. It is designed to maximize $p(\hat{s}^{LF}|\cdot)$ and $p(\hat{s}^{HF}|\cdot)$. TF-LF and TF-HF denote the LF and HF bidirectional transformers, respectively.

Figure 5: Example of the proposed iterative decoding process. Each column shows decoded time series of $\hat{s}^{LF}(t)$ and $\hat{s}^{HF}(t)$. The dataset of interest is Wafer.

mapped back to their corresponding discrete tokens z_q^{LF} and z_q^{HF}. Afterwards, the discrete tokens are decoded to $\hat{x}_{LF}$ and $\hat{x}_{HF}$, respectively. The complete synthetic time series is obtained by $\hat{x} = \hat{x}_{LF} + \hat{x}_{HF}$. An illustrative example of the proposed iterative decoding is presented in Fig. 5.

Learning to Sample both Unconditionally and Class-Conditionally We train our model such that it can generate synthetic time series both unconditionally and class-conditionally. It is achieved by appending a class token index c to s similar to how a class token is appended in the Vision Transformer model (Dosovitskiy et al., 2020). Then c is stochastically sampled by $c \in \{\emptyset, c_0, c_1, \ldots\}$ where $\emptyset$ indicates no-class (for unconditional sampling) and c_i indicates a certain class (for class-conditional sampling). This approach is adopted from the classifier-free guidance technique (Ho and Salimans, 2022). The probability of sampling $\emptyset$ is given by p_{uncond}, so the probability of sampling one of the c_i is given by $1 - p_{\text{uncond}}$. Following (Ho and Salimans, 2022), p_{uncond} is set to 0.2. Gafni et al. (2022) proposes guided sampling for a VQ-based text-to-image model. We slightly modify it and propose guided class-conditional sampling $p_g(\hat{s}|\hat{s}_M; c_i) = p(\hat{s}|\hat{s}_M; \emptyset) + \gamma_g (p(\hat{s}|\hat{s}_M; c_i) - p(\hat{s}|\hat{s}_M; \emptyset))$ where γ_g is the guidance scale and the subscript g denotes the guided class-conditional sampling. When γ_g is larger than 1, class-conditional sampling complies with class information better.

4 EXPERIMENTS[2]

4.1 Evaluation Metrics

There are mainly three metrics used in the experiments: IS, FID score, and CAS. IS measures the quality of synthetic samples by using the entropy of the distribution of labels predicted by a pretrained model – i.e., Inception v3 (Szegedy et al., 2015) for IMG and FCN for TSG in this work – and evenness of the predictions across all labels. IS ranges from 1 to the number of classes. Better quality corresponds to higher IS. Unlike IS, FID score measures the quality by comparing distributions of generated samples and real samples. Its lowest score is 0 and it has no upper boundary. Better quality corresponds to lower FID. CAS is used to assess the quality of class-conditionally generated samples. It involves first training a classifier on synthetic samples – i.e., ResNet-50 (He et al., 2016) for IMG and FCN for TSG in this work – and then testing on real data, measuring the resulting accuracy.

4.2 Experimental Setup

All datasets from the UCR archive are used in the experiments. Each dataset is normalized such that it has zero mean and unit variance, following (Franceschi et al., 2019). For our encoder and decoder, those from VQ-VAE are adopted. Our implementation for VQ uses the library from (Wang et al., 2022). The implementation of the prior models, i.e., bidirectional transformers, is taken from (Wang, 2022). Further details on the parameter choices and implementation are available in Appendix C.

[2] Full results are available in Appendix E.

4.3 Unconditional Time Series Generation

GMMN, RCGAN, TimeGAN, SigCWGAN, and TimeVQVAE are compared for the unconditional sampling experiment in terms of FID and IS in Fig. 6. No code is available for TTS-CGAN at the time of writing, thus, it has not been included in the comparative study. The implementations of the competing models are taken from (Ni et al., 2020b). Among them, RCGAN and TimeGAN are the two most compared methods in the TSG literature. The model sizes are adjusted to be comparable to each other. Although TSGAN reports the FID scores on the UCR datasets, the reported FID scores are far off the normal range of the FID scores, that is, the scores are too high. Thus, due to the concern of a potential miscalculation, TSGAN's reported FID scores are not used here. Fig. 6 shows that TimeVQVAE considerably outperforms its competing methods. Fig. 7 presents visualization of generated samples by the different methods. It is noticeable that the competing methods suffer from the limitation of RNN, that is, RNN typically has difficulties with temporal consistency between two distant timesteps. TimeVQVAE does not have the problem because all time steps are globally attended by the transformer's self-attention mechanism.

Figure 6: Critical difference diagram of the unconditional sampling performances in terms of FID and IS. The FID scores are multiplied by a factor of -1 in order to rank them in ascending order. Therefore, a higher rank indicates a lower FID score overall. For IS, a higher rank indicates a higher IS overall.

4.4 Class-conditional Time Series Generation

Smith and Smith (2020) reports CAS of WGAN and TSGAN on 70 subset datasets of the UCR archive. In Fig. 8, WGAN, TSGAN, and TimeVQVAE are compared for the class-conditional sampling in terms of CAS$_g$, in this experiment, is set to 1. It indicates the synthetic sample distributions generated by TimeVQVAE is closer to the real distribution than WGAN and TSGAN. There is another advantage of TimeVQVAE. Smith and Smith (2020) implements the class-conditional sampling by training the same model$N$ times on$N$ different subsets of a dataset according to$N$ different classes. TimeVQVAE, on the other hand, is trained for unconditional and class-conditional sampling at the same time.

Figure 8: Critical difference diagram of the class-conditional performances in terms of CAS. A higher rank indicates higher CAS overall.

4.5 Ablation Study

Naive VQ-VAE vs TimeVQVAE Our proposed VQ modeling adds several novelties on top of VQ-VAE. Two cases are experimented: 1) naive VQ-VAE for stage 1 with the MaskGIT's approach for stage 2, 2) TimeVQVAE. The naive VQ-VAE simply takes time series instead of images. Fig. 9 shows the considerable performance advantage of TimeVQVAE over its naive form.

VQ in Time and Time-frequency Domains The VQ modeling can be done in the time domain – the naive VQ-VAE for stage 1 – or in the time-frequency domain as proposed. Fig. 10 shows that the VQ modeling in the time-frequency domain is more beneficial. To sorely compare the domain difference, the LF-HF separation is not used for the latter case and both cases have the same downsampling rate.

Separation of LF and HF Latent Spaces The LF and HF latent spaces are separately learned in TimeVQVAE. Fig. 11 shows the positive effects of the LF-HF separation.

Guided Class-conditional Sampling Fig. 12 shows that the higher $_g$ results in the clearer class-boundaries of the generated samples.

Perceptual Loss In VQ-GAN, the GAN and perceptual losses are additionally used from VQ-VAE. Those losses help generate perceptually-pleasing images. We experiment with the perceptual loss function proposed by Dosovitskiy and Brox (2016)$_k C(x) \quad C(x)k_2^2$ where$C$ denotes a pretrained model for feature extraction and$x$ and$x$ are real and reconstructed samples, respectively. In our experiments, the pretrained FCN model is used as$C$. The effects of the perceptual loss are presented in Fig. 13. A minor yet positive performance gain is achieved, similarly to the IMG studies (Johnson et al., 2016).

5 LIMITATIONS

Because TimeVQVAE incorporates the Fourier Transform, it has difficulties with digital signal-like time series such as the Earthquakes and Computers datasets from the UCR archive. This problem, perhaps, could be overcome by employing the Wavelet Transform. It has the advantage

Figure 7: Visual inspection of generated samples by the different methods. Each row presents each of the following UCR datasets: MixedShapesSmallTrain, InsectWingbeatSound, Yoga, EOGHorizontalSignal, and ECG5000.

Figure 9: Performance comparison between the naive VQ-VAE and TimeVQVAE.

Figure 10: Performance comparison between VQ modeling in the time domain and the time-frequency domain.

of better locality in the time and frequency domains than STFT. Also, MaskGIT has some drawbacks (Lezama et al., 2022). Its token selection is made independently for each token and is based on predicted con dence by the generator, which can be prone to a modeling error. Moreover, the selected tokens are not correctable in a later iteration. Resolving the above-mentioned limitations could lead to better TSG.

Figure 11: Ablation study results with respect to the LF-HF separation. w/ Sep and w/o Sep denote with and without the LF-HF separation, respectively.

Figure 12: 2-dimensional t-SNE mapping of the pretrained FCN's representations of real samples (train) and generated samples (gen). The used dataset is StarLightCurves. The different colors denote different classes.

Figure 13: Ablation study results with respect to the perceptual loss (PerceptLoss).

6 CONCLUSION

Motivated by the successes in the IMG literature, we propose TimeVQVAE for TSG by leveraging VQ-VAE. Our experiments show that TimeVQVAE outperforms its competing methods in both unconditional and class-conditional sampling, plus it can be trained for both tasks at the same time, which greatly increases efficiency. Moreover, positive performance gains are shown by adopting VQ modeling in the time-frequency domain, carrying out LF-HF latent space separation, and including the guided class-conditional sampling and the perceptual loss.

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A FULL DERIVATION OF THE JOINT PROBABILITY OF s^{LF} AND s^{HF}

$$
\begin{aligned}
& p(s^{LF}, s^{HF}) \\
&= \sum_{M} p(s^{LF}, s^{HF}, s_M^{LF}, s_M^{HF}) \\
&= \sum_{M} p(s^{HF} | s^{LF}, s_M^{LF}, s_M^{HF}) p(s^{LF}, s_M^{LF}, s_M^{HF}) \\
&= \sum_{M} p(s^{HF} | s^{LF}, s_M^{LF}, s_M^{HF}) p(s^{LF} | s_M^{LF}, s_M^{HF}) p(s_M^{LF}, s_M^{HF}) \\
&= \sum_{M} p(s^{HF} | s^{LF}, s_M^{HF}) p(s^{LF} | s_M^{LF}, s_M^{HF}) p(s_M^{LF}, s_M^{HF})
\end{aligned}
\tag{7}
$$

Recall that by HF and LF we mean *high frequency* and *low frequency*, respectively. In the above equation, $p(s^{HF} | s^{LF}, s_M^{LF}, s_M^{HF})$ is replaced by $p(s^{HF} | s^{LF}, s_M^{HF})$ because s_M^{LF} is a subset of s^{LF} and information of the masked tokens is provided by s_M^{HF}. The equation can be further simplified with the following independence assumptions – $p(s^{LF} | s_M^{HF}) = p(s^{LF})$ and $p(s_M^{LF}, s_M^{HF}) = p(s_M^{LF}) p(s_M^{HF})$. The second and third terms of the last equation in Eq. (7) are simplified with the assumptions. We show the simplification of the second term and third term in order. Then, we finally show the simplified equation of Eq. (7).

The second term is simplified as:

$$
\begin{aligned}
& p(s^{LF} | s_M^{LF}, s_M^{HF}) \\
&= \frac{p(s_M^{LF}, s_M^{HF} | s^{LF}) p(s^{LF})}{p(s_M^{LF}, s_M^{HF})} \\
&= \frac{p(s_M^{LF} | s^{LF}) p(s_M^{HF} | s^{LF}) p(s^{LF})}{p(s_M^{LF}) p(s_M^{HF})} \\
&= \frac{p(s_M^{LF} | s^{LF}) \frac{p(s^{LF} | s_M^{HF}) p(s_M^{HF})}{p(s^{LF})} p(s^{LF})}{p(s_M^{LF}) p(s_M^{HF})} \\
&= \frac{p(s_M^{LF} | s^{LF}) \frac{p(s^{LF}) p(s_M^{HF})}{p(s^{LF})} p(s^{LF})}{p(s_M^{LF}) p(s_M^{HF})} \\
&= \frac{p(s_M^{LF} | s^{LF}) p(s_M^{HF}) p(s^{LF})}{p(s_M^{LF}) p(s_M^{HF})} \\
&= \frac{p(s_M^{LF} | s^{LF}) p(s^{LF})}{p(s_M^{LF})} \\
&= p(s^{LF} | s_M^{LF})
\end{aligned}
\tag{8}
$$

The third term is simplified as:

$$
p(s_M^{LF}, s_M^{HF}) = p(s_M^{LF}) p(s_M^{HF}) \tag{9}
$$

Finally, Eq. (7) is simplified to:

$$
p(s^{LF}, s^{HF}) = \sum_{M} p(s^{HF} | s^{LF}, s_M^{HF}) p(s^{LF} | s_M^{LF}) p(s_M^{LF}) p(s_M^{HF}) \tag{10}
$$

B PRETRAINING SETUP FOR THE SUPERVISED FCN MODEL

The FCN model consists of a few convolutional blocks with the global average pooling (GAP), linear, and softmax layers followed. The source code for the FCN model is from (Tseng, 2021). Its representation (feature) vector for computing FID is extracted right after the GAP layer. AdamW (Loshchilov and Hutter, 2017) is used for an optimizer with batch size: 256, initial learning rate (LR): 1e-3, LR scheduler: cosine scheduler, weight decay: 1e-5, max epoch: 1,000. Our open-source code for the pretrained FCN model is available at https://github.com/danelee2601/supervised-FCN .

C IMPLEMENTATION DETAILS

C.1 Datasets

For the unconditional and class-conditional sampling experiments, 128 datasets, all the datasets, from the UCR archive are used, on which IS, FID, and CAS are reported. CAS reported by Smith (2020) is available only for 70 datasets out of 128. The missing scores are left blank in our result table below.

C.2 Evaluation Metrics: IS, FID, and CAS

To compute IS and FID, the same number of synthetic samples is unconditionally generated as that of a test set unless the test set has less than 256 samples. For datasets with less than 256 test samples, 256 synthetic samples are generated to better ensure the distribution of $p_{;}(s^{LF}; s^{HF})$, which results in more consistent IS and FID score.

To compute CAS, the same number of synthetic samples per class is generated as that of a training set. If the training set has less than 1,000 samples, 1,000 samples are generated according to the class distribution of the training set to ensure the distribution of $p_{;}(s^{LF}; s^{HF}|c)$ and to prevent the over tting problem in the FCN model's training. c denotes the class token index. For instance, if a training set has 50 and 150 samples for class 1 and class 2, then 5 times the number of samples of each class are generated – that is, 250 for class 1 and 750 for class 2 – so that a total number of generated samples becomes 1,000. An average of 5 CAS from 5 runs is reported.

C.3 TimeVQVAE

STFT, ISTFT, and Convolutional Kernel and Stride Sizes STFT and ISTFT are implemented with `torch.stft` and `torch.istft`, respectively. Their main parameter `n_fft`, size of Fourier transform – can be any arbitrary integer, but we set it to 8 and we use default parameters for the rest. The frequency is separated into LF and HF by assigning the bottom rows (with the lowest) to LF and the rest to HF. `n_fft` of 8 indicates that the frequency axis has a range of [1, 2, 3, 4, 5] and the length of the temporal dimension becomes half as long as a given time series because `hop_length` is set as `n_fft/4` by default. This setting is chosen due to different temporal lengths of datasets, causing dif culties with selecting the convolutional kernel and stride sizes for downsampling. The encoder has several downsampling layers to compress an input into the latent space. The downsampling rate is determined by the kernel and stride sizes, typically downsampling by 2 with `f kernel_size=4, stride=2, padding=1` at each downsampling layer. But a choice of the sizes is dif cult because the temporal and frequency axes have different lengths across the different datasets. Therefore, we let the downsampling layers downsample along the temporal axis only, not the frequency axis. Then, the downsampling layer becomes `Conv2d` with `f kernel_size=(3,4), stride=(1,2), padding=(1,1)`. We have experimentally found that smaller `n_fft` such as 4 or 8 leads to better performance. That is associated with compression amount of input data. The higher `n_fft` leads to the wider frequency axis and shorter temporal axis, and the compression amount becomes smaller because the downsampling is only applied along the temporal axis. The global consistency of generated samples is typically poorer with the smaller compression amount (i.e., a lower downsampling rate).

Encoder and Decoder The same encoder and decoder architectures from the VQ-VAE paper are used and their implementations are from (nadavbh12 et al., 2021). The encoder consists of downsampling convolutional blocks (Conv2d – BatchNorm2d – LeakyReLU), followed by residual blocks (LeakyReLU – Conv2d – BatchNorm2d – LeakyReLU – Conv2d). The downsampling convolutional layers are implemented by `Conv2d(kernel_size=(3,4), stride=(1,2), padding=(1,1))` – Note that the downsampling is to be conducted along the temporal axis only. The residual convolutional layers are implemented by `Conv2d(kernel_size=(3,3), stride=(1,1), padding=(1,1))`. The decoder similarly has residual blocks, followed by upsampling convolutional blocks. The upsampling convolutional layers are implemented by `ConvTranspose2d(kernel_size=(3,4), stride=(1,2), padding=(1,1))`. The downsampling rate is determined as 2^D. We set such that z has width of around 8 and 32 for the LF and HF encoders and decoders, respectively. We refer to the width as the downsampled width. Note that the downsampled width cannot exactly be the speci ed value unless input length can be expressed as 2^D. We set the downsampling rate such that the width of z can be as close as to the speci ed downsampled width. If a dataset has temporal length shorter than the downsampled width, the downsampling rate is set to 1, i.e., no downsampling. Different sizes of the encoder and decoder are speci ed in Table 1. Large size is not considered due to our computational limitation. The Basesized encoder and decoder are used for the unconditional and class-conditional sampling experiments.

Table 1: Different sizes of the encoder and decoder.

Sizes of the encoder & decoder	Small	Base
Hidden dimension size	32	64
Number of residual blocks	2	4

Trick for Length Match Between x and $\hat{x}$ When length of x does not follow 2^n or is an odd number such as 89, length mismatch between x and $\hat{x}$ occurs. The problem can be easily resolved with the following trick: Adding one additional upsampling layer, followed by linear interpolation in the decoder. `torch.nn.functional.interpolate(.., size=length(x), mode='linear')` is used for the interpolation in our implementation. If the interpolation is only used without the additional upsampling layer, it leads to loss of high-frequency information in $\hat{x}$.

VQ Our implementation for VQ-VAE is from (Wang et al., 2022). The codebook size K is set to 32 and the code dimension size is the same as the hidden dimension size of the encoder and decoder for both LF and HF. Because the datasets from the UCR archive are less complex and much smaller than an image benchmark dataset such as ImagNet (Deng et al., 2009), the small-sized codebook was found to be sufficient. For the codebook-learning loss, we use both the commitment loss and the exponential moving average alternative, following (Wang et al., 2022). We use β of 0.25 and the exponential moving average decay rate of 0.8. The codebook embeddings learned in stage 1 are used to initialize the codebook embeddings in stage 2 to benefit the prior learning. This can be especially helpful when a training set is very small such as Fungi. The dataset, Fungi, has only 18 training samples.

Prior Learning The number of iterations T, is set to 10, following (Chang et al., 2022). Our implementation for MaskGIT is adopted from (dome272, 2022) and implementation for the prior model, bidirectional transformers, is from (Wang, 2022). Different sizes of the prior model are specified in Table 2. Base size is used for the unconditional and class-conditional sampling experiments. To better stabilize the transformer model, we use Root Mean Square Layer Normalization proposed by Zhang and Sennrich (2019).

Table 2: Different sizes of the prior model – bidirectional transformer. Its sizes are referred from (Hassani et al., 2021). The feed-forward (FF) ratio denotes a ratio of hidden dimension size to input dimension size. Note that the FF layer augments its input into a larger dimension and back into its original dimension.

Size of the transformer	Small	Base
Hidden dimension size	64	256
Number of layers	2	4
Number of heads	2	2
Feed-forward ratio	1	1

Optimizer The AdamW optimizer is used with the batch size for stage 1: 128, batch size for stage 2: 256, initial LR: 1e-3, LR scheduler: cosine scheduler, weight decay: 1e-5. Maximum epochs are for stage 1: 2,000, stage 2: 10,000 for the TimeVQVAE model in the unconditional and class-conditional sampling experiments.

C.4 GMMN, RCGAN, TimeGAN, and SigCWGAN

The implementations of GMMN, RCGAN, TimeGAN, and SigCWGAN from (Ni et al., 2020b) are used for the unconditional sampling experiments. For the above-mentioned methods, AR-FNN (Auto-Regressive Feed-forward Neural Network) proposed by Ni et al. (2020a) is used for a generator and discriminator. To be comparable with TimeVQVAE in terms of a number of trainable parameters, the AR-FNN model is set to have 18 hidden layers and hidden dimension size of 32. The exact number of trainable parameters varies depending on datasets due to different lengths. The AR-FNN generator requires values at the previous p timesteps to predict the next p timesteps. p is determined as 10% of input length. The longer p compromises the integrity of data generation and the shorter makes the autoregressive model difficult to generate reasonable samples. p is set to 1 for GMMN, RCGAN, and TimeGAN and 3 for SigCWGAN. p does not have to be any larger because data is autoregressively generated at each timestep. The Adam optimizer (Kingma and Ba, 2014) is used for both generator and discriminator with batch size: 256, initial LR: 2e-4, max epochs: 10,000.

C.5 Training the FCN Model for CAS

To compute CAS, the FCN model is trained on a set of synthetic samples. To train the FCN model, the AdamW optimizer is used with batch size: 256, initial LR: 1e-3, LR scheduler: cosine scheduler, weight decay: 1e-5, max epochs: 1,000. Basically, the same setting as the supervised FCN model is used.

D EXPERIMENT DETAILS FOR THE ABLATION STUDIES

The experiments for the ablation studies are conducted in a smaller scale due to a large number of experimental cases. The datasets with training set size equal or smaller than 1,000 are used – Yet, it still sums to 120 datasets; enough to capture the overall ranking. The optimizer settings are the same as in the prior section except that the maximum epochs used for stage 1: 1,000, stage 2: 5,000 are used. For the prior model, the Small-sized bidirectional model is used for all the ablation studies.

D.1 Model Details

There are 4 ablation studies with quantitative experiments. The model details for each ablation study are stated in the following paragraphs. Unless specified differently, the model parameters are the same as in the prior section.

Naive VQ-VAE vs TimeVQVAE The Small-sized encoder and decoder are used for TimeVQVAE. TimeVQVAE has two sets of the encoder and decoder, but the naive VQ-VAE has one set of them. To be better comparable, size of the naive VQ-VAE's encoder and decoder is set by hidden dimension size: 32, number of residual blocks: 4, and K is set to 64. The downsampled width of the naive VQ-VAE is to be around 8. For the naive VQ-VAE, 2-dimensional convolutional layers are replaced with the 1-dimensional convolutional layers as it takes 1-dimensional time series as an input instead of 2-dimensional time-frequency data.

VQ in Time and Time-frequency Domains The encoder and decoder with hidden dimension size: 32, number of residual blocks: 4 are used for both cases. Both, also, use the downsampled width of 8 and K of 64. The case VQ in Time domain is identical to the naive VQ-VAE.

Separation of LF and HF Latent Spaces The case without the LF-HF separation uses the encoder and decoder size of hidden dimension size: 32, number of residual blocks: 4, K of 64, and the downsampled width of around 8. The case without the separation is identical to the case VQ in Time-frequency domain above. The case with the separation is identical to TimeVQVAE.

Perceptual Loss TimeVQVAE with the Small-sized encoder and decoder is used.

E FULL RESULTS

The number of training parameters of TimeVQVAE in Tables 3-5 varies between 0.8 M and 1.6 M for stage 1 (i.e., encoder, codebook, and decoder) depending on the downsampled width, and the number varies between 2.3 M and 2.4 M for stage 2 (i.e., bidirectional transformer). The results for FID, IS, and CAS in Tables 3-5 are reported with mean and standard deviation of the scores over 3 runs.

Table 3: Full results of the unconditional sampling experiments with FID. The FID score larger than 1,000 is marked as nan because such a large FID score already indicates that the synthetic sample quality is significantly poor.

Dataset names	GMMN	RCGAN	TimeGAN	SigCWGAN	TimeVQVAE.mean	TimeVQVAE.std
ACSF1	74.3	98.3	81.3	nan	27.1	0.8
Adiac	98.2	54.3	45.1	nan	7.8	0.9
AllGestureWiimoteX	180.7	nan	nan	nan	3.8	0.7
AllGestureWiimoteY	23.5	nan	nan	660.4	3.0	0.5
AllGestureWiimoteZ	nan	2.8	7.9	278.9	1.8	0.2
ArrowHead	8.1	15.5	22.2	nan	2.0	0.3

Beef	215.2	36	18.3	nan	1.8	0.2
BeetleFly	246.4	348.5	nan	nan	2.1	1.2
BirdChicken	9.9	8.5	7.6	735.5	0.3	0.1
BME	77.6	179.6	140.1	nan	23.9	5.7
Car	101.5	579.5	186.1	nan	2.6	0.4
CBF	147.1	483.9	5.5	24.4	2.3	0.4
Chinatown	27.3	70.4	59.9	25.8	5.5	0.9
ChlorineConcentration	41.6	7.4	7.1	132.4	1.1	0.1
CinCECGTorso	nan	172.3	57	nan	7.7	1.5
Coffee	16.2	18.1	nan	nan	0.3	0.2
Computers	29.1	nan	nan	19.8	3.5	0.4
CricketX	115.8	404.8	23	26.9	3.0	0.5
CricketY	33	nan	nan	17.6	3.0	0.4
CricketZ	60.1	105.3	14.4	19.8	4.0	0.3
Crop	80.7	14.9	18.7	35.3	3.9	0.7
DiatomSizeReduction	138.6	232.9	88.7	nan	12.8	1.4
DistalPhalanxOutlineAgeGroup	13.9	9	110.6	nan	6.3	1.0
DistalPhalanxOutlineCorrect	9.2	12	16	50.4	1.8	0.3
DistalPhalanxTW	16.8	19.2	21.3	nan	13.2	1.5
DodgerLoopDay	56.8	429.9	30.1	14.4	1.9	0.2
DodgerLoopGame	44.8	nan	21.6	63.4	5.9	0.9
DodgerLoopWeekend	9.6	273.2	16.1	14.7	6.2	1.1
Earthquakes	nan	nan	nan	5.4	1.6	0.5
ECG200	3	2.8	2.7	20.6	1.9	0.3
ECG5000	26.6	4.5	35.2	55.9	0.7	0.0
ECGFiveDays	15	22.3	7.1	523.2	0.6	0.2
ElectricDevices	37.1	151.9	79.9	105.5	6.8	1.1
EOGHorizontalSignal	287.8	47.3	95.5	nan	3.5	0.6
EOGVerticalSignal	238.1	457.7	100.6	nan	6.8	1.2
EthanolLevel	19.4	15.7	18	nan	0.2	0.2
FaceAll	42.4	10.3	nan	33	4.4	0.0
FaceFour	18.6	65	56.5	26.5	3.6	1.3
FacesUCR	39.7	7.3	20.6	39.7	3.2	0.4
FiftyWords	nan	27.7	81.7	821.9	9.7	1.5
Fish	nan	36.3	47.4	nan	11.5	0.1
FordA	3.6	178	nan	nan	3.0	0.4
FordB	nan	45.6	nan	nan	1.4	0.6
FreezerRegularTrain	56	41.6	27.6	176.9	7.3	1.3
FreezerSmallTrain	49.3	32	42.7	109.6	9.5	0.7
Fungi	48.4	86	82.9	nan	2.1	0.5
GestureMidAirD1	nan	nan	nan	nan	9.9	5.1
GestureMidAirD2	nan	nan	306.8	nan	3.8	0.5
GestureMidAirD3	214.7	nan	nan	nan	46.4	19.1
GesturePebbleZ1	163.4	29.5	10.6	26.2	3.0	2.3
GesturePebbleZ2	16.7	350.8	22.3	49.9	3.7	1.1
GunPoint	16	8.8	3.5	nan	0.8	0.4
GunPointAgeSpan	314.7	19.7	267.3	nan	1.1	0.5
GunPointMaleVersusFemale	nan	44.6	237.5	215.4	0.6	0.3
GunPointOldVersusYoung	14.1	nan	13.2	nan	0.3	0.1
Ham	nan	43.5	27.4	427	0.6	0.2
HandOutlines	9.4	3.7	1.3	nan	0.1	0.0

Haptics	nan	nan	nan	nan	2.5	0.2
Herring	35	3.9	75.8	nan	0.5	0.1
HouseTwenty	26.6	nan	38	100.3	4.8	2.7
InlineSkate	96	143.3	119.5	nan	13.3	5.0
InsectEPGRegularTrain	7.3	28.5	0.9	0.3	2.5	1.0
InsectEPGSmallTrain	121.2	113.5	125.9	80.8	3.6	3.3
InsectWingbeatSound	14.5	6.2	132.3	nan	9.9	0.7
ItalyPowerDemand	5.7	57.5	5.8	4.6	1.6	0.4
LargeKitchenAppliances	8.3	47.3	31.8	281	0.9	0.3
Lightning2	19.5	8.6	71.7	162.3	1.2	0.4
Lightning7	79.2	78.6	27	92.1	1.1	0.2
Mallat	nan	11.4	nan	nan	1.1	0.2
Meat	134.7	18.2	nan	nan	7.7	3.8
MedicalImages	20.9	24	nan	55.3	3.5	0.4
MelbournePedestrian	66.6	35.5	62.5	90.1	2.4	0.9
MiddlePhalanxOutlineAgeGroup	18.7	12.6	13.8	590.2	20.0	1.6
MiddlePhalanxOutlineCorrect	7.2	21.2	162.3	535.4	1.2	0.4
MiddlePhalanxTW	62.2	27.4	19.8	nan	3.3	0.5
MixedShapesRegularTrain	379	412.2	nan	nan	34.1	6.5
MixedShapesSmallTrain	20.6	13.3	262.1	nan	7.6	1.8
MoteStrain	5.6	5.9	4	13.9	1.5	0.3
NonInvasiveFetalECGThorax1	438.5	nan	nan	nan	16.0	2.8
NonInvasiveFetalECGThorax2	126.8	117.9	150	nan	30.6	13.9
OliveOil	9.8	9.5	9.9	nan	1.7	0.1
OSULeaf	nan	nan	nan	nan	13.2	0.9
PhalangesOutlinesCorrect	1.9	3	2.3	73.4	0.7	0.1
Phoneme	nan	nan	nan	nan	12.1	0.4
PickupGestureWiimoteZ	275.6	380.9	nan	116	2.1	0.2
PigAirwayPressure	111.2	188.5	642.6	274.4	38.1	11.9
PigArtPressure	291.4	nan	nan	80.3	72.4	13.3
PigCVP	107.6	nan	nan	343.3	57.7	9.7
PLAID	797.4	nan	335.9	nan	552.8	474.5
Plane	39.2	38.9	36.2	nan	6.6	0.5
PowerCons	18.3	15	16.5	30	1.0	0.4
ProximalPhalanxOutlineAgeGroup	73.2	93.9	22.1	nan	0.4	0.2
ProximalPhalanxOutlineCorrect	3.7	1.7	13.8	nan	0.4	0.2
ProximalPhalanxTW	60.8	24.2	16.2	nan	2.8	0.4
RefrigerationDevices	nan	nan	nan	9.2	16.2	3.6
Rock	nan	nan	nan	23.5	6.0	3.1
ScreenType	32.7	nan	30.9	28.4	6.3	0.8
SemgHandGenderCh2	14.4	nan	nan	69.9	4.6	0.2
SemgHandMovementCh2	164.6	71.8	199.1	59.4	14.1	0.3
SemgHandSubjectCh2	37	nan	nan	108.1	29.6	2.3
ShakeGestureWiimoteZ	nan	42.5	22.4	116.7	2.4	0.7
ShapeletSim	8.4	2.6	nan	0.8	9.0	2.5
ShapesAll	nan	nan	nan	nan	14.4	2.2
SmallKitchenAppliances	19	nan	20.8	233.1	4.7	0.4
SmoothSubspace	nan	7.7	14.1	8.2	0.6	0.1
SonyAIBORobotSurface1	31.7	nan	14.3	81.7	8.8	1.8
SonyAIBORobotSurface2	22.6	21.2	14.5	10.7	1.4	0.3
StarLightCurves	27.6	42.9	6.7	nan	0.7	0.1

Strawberry	70.6	20.8	333.9	nan	0.4	0.1
SwedishLeaf	46.3	16.5	24.7	151.5	7.9	0.4
Symbols	33.8	29.9	57.2	407.6	5.6	1.6
SyntheticControl	14.7	12.6	14	17.4	3.7	0.9
ToeSegmentation1	19.2	502.3	nan	7	4.1	0.6
ToeSegmentation2	3.5	2.8	154.7	89	6.2	0.3
Trace	93	90.8	21.7	187.4	5.7	0.7
TwoLeadECG	10.4	12.2	8.7	49.5	0.2	0.1
TwoPatterns	15.4	31.8	29.6	51.3	2.2	0.6
UMD	454.1	11.4	15.5	501.3	1.2	0.4
UWaveGestureLibraryAll	737.2	nan	nan	586.1	4.5	0.2
UWaveGestureLibraryX	31.5	nan	nan	nan	6.8	0.3
UWaveGestureLibraryY	nan	22	nan	nan	7.0	0.0
UWaveGestureLibraryZ	9.6	24.3	nan	nan	27.7	2.5
Wafer	26.8	nan	23.6	164	1.5	0.3
Wine	nan	nan	nan	nan	0.4	0.1
WordSynonyms	34.4	11.3	42.3	nan	2.9	0.1
Worms	nan	nan	nan	nan	8.0	0.5
WormsTwoClass	nan	nan	nan	nan	8.0	1.5
Yoga	nan	nan	nan	nan	2.3	0.2

Table 4: Full results of the unconditional sampling experiments with IS.

Dataset names	GMMN	RCGAN	TimeGAN	SigCWGAN	TimeVQVAE.mean	TimeVQVAE.std
ACSF1	1.4	1.9	1.5	2	3.3	0.1
Adiac	1.1	1.4	1.6	1.6	6.2	0.3
AllGestureWiimoteX	3.6	3.2	4.3	1.5	2.5	0.2
AllGestureWiimoteY	3.4	3.2	3.1	1.7	3.0	0.1
AllGestureWiimoteZ	2.6	2.3	2.3	1	2.6	0.0
ArrowHead	1.9	1.1	1.1	1	2.5	0.1
Beef	1.2	1.4	1.5	1	2.7	0.2
BeetleFly	1	1.1	1	1	1.7	0.2
BirdChicken	1	1.1	1.1	1	1.8	0.0
BME	1	1.2	1.2	1.1	2.1	0.2
Car	1.7	1	1	1	2.3	0.1
CBF	1	1.1	1.5	1.1	2.7	0.0
Chinatown	1.8	1	1.3	1.6	2.0	0.0
ChlorineConcentration	1.2	2	1.9	1	1.6	0.1
CinCECGTorso	1.5	1.3	1.6	1	1.8	0.2
Coffee	1.1	1	1	1	1.9	0.0
Computers	1.2	1.8	1.4	1.2	1.6	0.1
CricketX	1.8	2	2.3	1.8	3.3	0.3
CricketY	2.3	3	3.6	2	3.6	0.1
CricketZ	3	1.9	2.5	1.9	3.3	0.1
Crop	5.7	7.7	7.8	7.5	17.0	0.1
DiatomSizeReduction	1	1.2	1.3	1	2.8	0.0
DistalPhalanxOutlineAgeGroup	1.5	1.6	1.3	1	1.9	0.1
DistalPhalanxOutlineCorrect	1.2	1.4	1.7	1.8	1.5	0.0

DistalPhalanxTW	1.9	1.9	1.7	2.1	2.5	0.2
DodgerLoopDay	1	1.2	1.2	1.3	2.6	0.2
DodgerLoopGame	1	1.2	1	1.1	1.9	0.0
DodgerLoopWeekend	1.2	1	1.6	1.1	1.9	0.0
Earthquakes	1.2	1	1	1.1	1.1	0.0
ECG200	1.4	1.5	1.4	1.5	1.5	0.0
ECG5000	1.7	1.7	1.6	1.6	2.0	0.0
ECGFiveDays	1.1	1	1.2	1.7	1.7	0.1
ElectricDevices	2.9	3.8	4.4	2.8	4.7	0.1
EOGHorizontalSignal	1.3	2.5	1.3	2	4.7	0.2
EOGVerticalSignal	1.5	1.7	1.7	1.2	3.2	0.1
EthanolLevel	1	1.1	1	2	1.3	0.1
FaceAll	2	2.2	3	1.8	5.3	0.2
FaceFour	1.2	1.3	1.1	1.2	2.7	0.2
FacesUCR	1	1.9	2.1	1.5	3.3	0.3
FiftyWords	2.7	1.9	1.3	1.8	4.6	0.2
Fish	1	1.2	1.2	1	3.1	0.0
FordA	1.5	1.3	1	1	1.5	0.0
FordB	1	1.7	1	1	1.4	0.1
FreezerRegularTrain	1	1	1	1.6	1.4	0.1
FreezerSmallTrain	1.8	2	1.9	1.2	1.9	0.0
Fungi	1	1.1	1.3	1	7.3	0.8
GestureMidAirD1	2.1	2.5	2.6	1.4	3.4	0.5
GestureMidAirD2	1.1	1.1	1.5	1	4.6	0.2
GestureMidAirD3	3.3	2.9	1.7	2.6	2.0	0.1
GesturePebbleZ1	1.2	1.1	2	1.4	2.9	0.5
GesturePebbleZ2	1.3	1.7	1.9	1	2.8	0.2
GunPoint	1.4	1.3	1.6	1	1.9	0.0
GunPointAgeSpan	1.5	1.1	1	1	1.7	0.1
GunPointMaleVersusFemale	1	1.1	1	1	1.9	0.0
GunPointOldVersusYoung	1.7	1.3	1.9	1.3	1.9	0.0
Ham	1.1	1.5	1.4	1.3	1.6	0.1
HandOutlines	1.2	1	1.4	1	1.2	0.0
Haptics	1.9	1	1	1	1.9	0.0
Herring	1	1	1.1	1	1.3	0.0
HouseTwenty	1	1.2	1	1	1.6	0.0
InlineSkate	1.7	1.2	1.7	1	1.5	0.0
InsectEPGRegularTrain	2.5	2.2	2.8	2.8	2.5	0.2
InsectEPGSmallTrain	1	1	1	1	2.4	0.2
InsectWingbeatSound	2.3	1.8	1.1	1.5	2.9	0.1
ItalyPowerDemand	1.6	1.2	1.6	1.6	2.0	0.0
LargeKitchenAppliances	1.4	1.5	1.4	1.8	2.3	0.0
Lightning2	1.2	1.2	1.5	1	1.6	0.0
Lightning7	1	1.1	1.6	1.4	3.4	0.2
Mallat	1	1.1	1	1	4.6	0.5
Meat	1.1	1.2	1.4	1	1.2	0.2
MedicalImages	2.4	1.2	1.4	2.4	2.6	0.2
MelbournePedestrian	4.2	4.8	3.8	4.7	8.9	0.1
MiddlePhalanxOutlineAgeGroup	1.6	1.6	1.7	1.1	2.0	0.1
MiddlePhalanxOutlineCorrect	1.4	1.7	1.1	1.1	1.6	0.1
MiddlePhalanxTW	2.2	2	2.3	2.4	2.8	0.1

MixedShapesRegularTrain	2.2	1.9	2.3	1.2	1.3	0.1
MixedShapesSmallTrain	1.3	2.2	1.5	1	2.2	0.2
MoteStrain	1.8	1.5	1.4	1.2	1.9	0.0
NonInvasiveFetalECGThorax1	2.3	1.4	2.9	1	7.6	0.7
NonInvasiveFetalECGThorax2	2	1.2	2.6	1.6	7.0	1.8
OliveOil	1.2	1	1	1	1.0	0.0
OSULeaf	2.1	1.6	1	1.1	1.4	0.0
PhalangesOutlinesCorrect	1.3	1.5	1.5	1	1.4	0.0
Phoneme	3.7	3.7	3	2	2.8	0.1
PickupGestureWiimoteZ	1.3	1.5	1.2	1	4.7	0.3
PigAirwayPressure	2.5	1.2	1	1.2	3.8	0.7
PigArtPressure	3.6	2.9	2.1	1.2	2.1	0.2
PigCVP	3	1.6	1.6	1.1	3.0	0.4
PLAID	1.9	2.8	2.2	1.3	1.4	0.1
Plane	1.2	1.6	1.3	1	5.2	0.1
PowerCons	1.2	1.1	1.1	1.5	1.7	0.0
ProximalPhalanxOutlineAgeGroup	1	1.7	1.9	1.9	2.4	0.1
ProximalPhalanxOutlineCorrect	1.4	1.6	1.4	1.2	1.6	0.1
ProximalPhalanxTW	1.5	2.2	1.8	1.1	2.7	0.1
RefrigerationDevices	1.3	1.2	2	1.3	1.6	0.2
Rock	1	1	1	1	2.5	0.2
ScreenType	1.4	1.2	1.2	1.3	2.2	0.0
SemgHandGenderCh2	1	1.3	1	1	1.4	0.0
SemgHandMovementCh2	2.2	1.8	1.4	1.1	1.9	0.1
SemgHandSubjectCh2	2	3.6	3.1	1.1	2.0	0.1
ShakeGestureWiimoteZ	1.9	2.5	2.4	1.3	5.3	0.2
ShapeletSim	1.1	1.1	1.2	1.1	1.8	0.1
ShapesAll	1.4	3.2	2.7	1.3	5.9	0.1
SmallKitchenAppliances	1.3	1.4	1.2	1.6	1.6	0.0
SmoothSubspace	1	1.9	1.9	1.8	2.6	0.0
SonyAIBORobotSurface1	1.1	1.1	1.3	1	1.7	0.1
SonyAIBORobotSurface2	1.3	1.2	1.5	1.5	1.9	0.0
StarLightCurves	1.8	1.8	1.6	1.1	2.3	0.1
Strawberry	1.3	1	1	1	1.8	0.0
SwedishLeaf	1.6	2.5	2	1.6	7.2	0.1
Symbols	1.3	1.1	2.2	1.3	4.0	0.2
SyntheticControl	2.4	2.3	2.4	2.1	4.4	0.2
ToeSegmentation1	1	1.4	1.7	1.3	1.7	0.1
ToeSegmentation2	1.2	1.2	1.6	1	1.8	0.0
Trace	1.1	1	1.5	1	3.0	0.1
TwoLeadECG	1.3	1.3	1.4	1.2	1.9	0.0
TwoPatterns	1.6	1.7	1.6	1.6	2.8	0.1
UMD	1	1.8	1	1.3	2.5	0.0
UWaveGestureLibraryAll	2.4	2.1	3.2	1.9	3.2	0.1
UWaveGestureLibraryX	2.3	2.2	1	2.2	3.9	0.0
UWaveGestureLibraryY	3.2	1.8	1	1.8	3.3	0.1
UWaveGestureLibraryZ	2.6	2.9	2.2	1.1	3.0	0.1
Wafer	1.2	nan	1.1	1.6	1.3	0.0
Wine	1.1	1.8	1.1	1	1.7	0.1
WordSynonyms	1.3	1.6	1.4	1.4	1.9	0.0
Worms	1.2	1.5	1.1	1.1	2.0	0.1

WormsTwoClass	1.2	1.8	1.5	1.5	1.0	0.0
Yoga	1.5	1.1	1	1	1.4	0.0

Table 5: Full results of the class-conditional sampling experiments with CAS.

Dataset names	WGAN (Smith, 2020)	TSGAN (Smith, 2020)	TimeVQVAE.mean	TimeVQVAE.std
ACSF1			72.7	3.2
Adiac			77.2	2.5
AllGestureWiimoteX			55.6	1.6
AllGestureWiimoteY			67.3	1.0
AllGestureWiimoteZ			62.2	2.3
ArrowHead	61.7	85.7	81.7	4.0
BME	80	82.7	75.3	1.2
Beef	20	60	72.2	8.4
BeetleFly	55	90	91.7	5.8
BirdChicken	90	75	83.3	7.6
CBF	70.9	87.3	96.5	0.4
Car	65	70	83.9	13.6
Chinatown			97.8	0.7
ChlorineConcentration	56.5	54.5	70.5	0.8
CinCECGTorso	40.6	49.1	75.5	5.5
Coffee	100	100	100.0	0.0
Computers	50.8	65.2	67.1	3.2
CricketX			70.3	3.0
CricketY			71.7	2.6
CricketZ			71.7	1.6
Crop			67.6	0.7
DiatomSizeReduction	73.5	79.7	92.3	2.3
DistalPhalanxOutlineAgeGroup	73.4	70.5	73.9	5.1
DistalPhalanxOutlineCorrect	68.8	64.9	78.7	1.3
DistalPhalanxTW			69.3	2.5
DodgerLoopDay			47.5	4.5
DodgerLoopGame			69.1	3.0
DodgerLoopWeekend			97.1	0.7
ECG200	82	82	89.0	1.0
ECG5000	78.2	86	93.3	0.2
ECGFiveDays	92.6	98.8	96.3	2.6
EOGHorizontalSignal			58.6	1.5
EOGVerticalSignal			47.3	0.8
Earthquakes	69.1	74.8	73.4	0.7
ElectricDevices			63.5	0.2
EthanolLevel	24.8	30.2	43.7	6.3
FaceAll			83.2	0.8
FaceFour	65.2	84.2	92.4	3.3
FacesUCR			93.2	0.4
FiftyWords			62.8	0.6
Fish			92.2	0.3
FordA	80	89.2	87.2	3.7

FordB	62.2	61.4	68.7	8.9
FreezerRegularTrain	50	50.1	93.9	5.2
FreezerSmallTrain	50.7	76	77.4	1.9
Fungi			98.6	0.3
GestureMidAirD1			67.2	2.5
GestureMidAirD2			54.4	0.9
GestureMidAirD3			26.7	2.4
GesturePebbleZ1			82.6	2.5
GesturePebbleZ2			78.5	2.2
GunPoint	100	100	99.1	1.0
GunPointAgeSpan	41.3	44.1	98.5	0.3
GunPointMaleVersusFemale	52.5	52.5	99.9	0.1
GunPointOldVersusYoung	11.4	52.4	100.0	0.0
Ham	68.6	68.6	70.2	2.7
HandOutlines	64.1	65.7	75.7	9.8
Haptics	20.8	31.5	44.7	1.9
Herring	46.9	65.6	59.4	0.0
HouseTwenty	58	42.1	88.0	5.7
InlineSkate			28.7	4.2
InsectEPGRegularTrain	64.3	64.3	100.0	0.0
InsectEPGSmallTrain	16.9	35.7	100.0	0.0
InsectWingbeatSound			38.0	1.9
ItalyPowerDemand			95.3	1.2
LargeKitchenAppliances	59.5	74.9	84.1	1.0
Lightning2	70.5	72.2	74.3	7.4
Lightning7			69.4	3.2
Mallat			96.4	0.6
Meat	88.3	46.7	68.9	17.7
MedicalImages			73.2	2.6
MelbournePedestrian			94.2	0.3
MiddlePhalanxOutlineAgeGroup	40.9	50	54.8	2.5
MiddlePhalanxOutlineCorrect	73.5	75.3	78.5	3.3
MiddlePhalanxTW			49.6	3.1
MixedShapesRegularTrain			79.2	4.3
MixedShapesSmallTrain	55.5	82.6	82.7	6.8
MoteStrain	87.9	87.3	90.1	0.6
NonInvasiveFetalECGThorax1			72.6	5.8
NonInvasiveFetalECGThorax2			75.4	7.9
OSULeaf			83.5	1.1
OliveOil	40	40	31.1	15.4
PLAID			35.8	2.2
PhalangesOutlinesCorrect	73.9	76.9	79.0	1.0
Phoneme			28.0	1.0
PickupGestureWiimoteZ			75.3	3.1
PigAirwayPressure			39.1	10.9
PigArtPressure			97.0	1.0
PigCVP			27.7	6.5
Plane			100.0	0.0
PowerCons	51.1	52.2	89.4	0.6
ProximalPhalanxOutlineAgeGroup	87.3	85.9	81.5	2.2
ProximalPhalanxOutlineCorrect	84.5	88.3	88.8	4.3

ProximalPhalanxTW			75.6	2.0
RefrigerationDevices	33.1	42.4	40.4	1.4
Rock	20	36	58.0	6.9
ScreenType	52	56.8	54.3	3.5
SemgHandGenderCh2	65.2	65.2	60.5	9.6
SemgHandMovementCh2			31.5	2.6
SemgHandSubjectCh2	26	29.3	28.8	3.7
ShakeGestureWiimoteZ			92.0	3.5
ShapeletSim	50	50	82.8	14.5
ShapesAll			74.5	2.7
SmallKitchenAppliances	56.5	64	72.4	5.9
SmoothSubspace	66.7	68	96.2	2.7
SonyAIBORobotSurface1	89.5	92.8	98.1	0.6
SonyAIBORobotSurface2	92.2	84.7	97.2	0.6
StarLightCurves	48.7	81.4	95.6	1.1
Strawberry	83.2	93.2	95.7	0.8
SwedishLeaf			95.0	0.3
Symbols			96.8	0.7
SyntheticControl			97.2	0.8
ToeSegmentation1	88.6	93.4	92.0	1.8
ToeSegmentation2	80.8	91.5	86.9	2.3
Trace	97	100	97.7	2.5
TwoLeadECG	99.5	99.8	97.6	1.3
TwoPatterns	76.7	86.8	86.5	0.5
UMD	97.2	97.9	99.3	0.0
UWaveGestureLibraryAll			59.4	3.3
UWaveGestureLibraryX			63.7	0.6
UWaveGestureLibraryY			56.1	1.4
UWaveGestureLibraryZ			60.8	4.3
Wafer	91.5	79.2	99.4	0.1
Wine	55.6	61.1	61.7	8.4
WordSynonyms			52.4	1.8
Worms	44.2	59.7	41.1	0.7
WormsTwoClass	71.4	76.6	63.2	2.0
Yoga	53.6	84.5	74.1	1.8

E.1 Quantitative Result Summaries of the Ablation Studies

The ablation study results in the main paper are presented by critical diagrams. Here we present those results more in detail. Figs. 14-17 present bar graphs where the x-axis represents dataset names and y-axis represents a metric such as FID or IS. For FID, the lower score denotes better performance. For IS, the higher score denotes better performance.

F ADDITIONAL ABLATION STUDY

F.1 The Independence Assumptions

We simplify Eq. (7) with the following independence assumptions $p(s^{LF}|s_M^{HF}) = p(s^{LF})$ and $p(s_M^{LF}, s_M^{HF}) = p(s_M^{LF})p(s_M^{HF})$. Such simplification greatly reduces complexity of the proposed iterative decoding process, which would look like Fig. 18, if not assuming independence in Eq. (7). Without the independence assumptions, the sampling of s_M^{LF} is tangled with that of s_M^{HF}, therefore, the downsampling rate of the LF and HF encoders must be the same. The performance