
MEGAPIXEL IMAGE GENERATION WITH STEP-UNROLLED DE-NOISING AUTOENCODERS

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ABSTRACT

Recent research has pushed sample resolutions higher whilst reducing computational requirements and sampling speeds. One approach is to utilize powerful vector-quantization (VQ) models to reduce computational requirements whilst still producing high quality samples. In this work, we push this further through the use of non-autoregressive (NAR) denoising autoencoders (SUNDAE) and modifications to hierarchical transformers that have found recent success in language modelling. This approach allows for very fast sampling and training (4-6 days) of VQ latents from pre-trained VQ-GAN models. Furthermore, we found the NAR nature of the model made it suitable for complex inpainting with arbitrary masks. Finally, we trained a new VQ-GAN model on a dataset of faces at resolutions exceeding one million pixels, ultimately allowing for megapixel image generation in only two seconds on consumer-grade GPUs.



Figure 1: High-resolution samples produced using our non-autoregressive approach. Each 1024×1024 sample was generated in ≈ 2 seconds on a GTX 1080Ti – including both discrete latent sampling and subsequent decoding. The SUNDAE sampler was trained in 4 days on a single V100 32GB.

1 INTRODUCTION

An ideal deep generative model would satisfy three key requirements: high-quality samples, sample diversity via mode coverage, and computational inexpensive sampling. Arguably, there are other desirable properties such as a meaningful latent space and exact likelihood calculation, however no current generative model can satisfy all three requirements, forming the so-called generative modelling trilemma Xiao et al. (2021).

Models such as generative adversarial networks (GANs) excel at high-quality and fast sampling, but fail to represent the entire data distribution due to not directly optimising for likelihood – using an adversarial loss as a proxy. Variational autoencoders Kingma & Welling (2013) offer excellent mode coverage and fast sampling speeds, but the resulting samples are often blurry even at small resolutions, and have little hope of scaling to greater resolutions like GANs.

Autoregressive models such as PixelSnail Chen et al. (2017), Image Transformer Parmar et al. (2018), and DALLE Parmar et al. (2018) have demonstrated respectable sample quality and mode coverage, even including zero-shot image generation Parmar et al. (2018). However, they are computationally expensive to sample from, requiring many network iterations, making them infeasible for interactive applications. Diffusion and score-based models produce samples that rival or even exceed the quality of GANs whilst still providing good mode coverage, but are still plagued by potentially requiring thousands of network evaluations.

Vector-quantized image modelling [van den Oord et al. \(2017\)](#); [Razavi et al. \(2019\)](#); [Esser et al. \(2021\)](#) alleviates sampling speed issues in autoregressive methods by reducing the spatial dimension at which autoregressive sampling occurs. This results in excellent quality samples whilst improving sampling speeds, but often requires a two-stage approach and still does not match the speed of GANs. Recent work has applied VQ methods to diffusion models [Bond-Taylor et al. \(2021a\)](#) allowing for fast parallel decoding. Other work does not use vector-quantized spaces, but latent spaces nonetheless, to accelerate sampling [Xiao et al. \(2021\)](#); [Vahdat et al. \(2021\)](#).

In this work, we aim to move towards satisfying all three key requirements for an ideal generative model. Like previous work, we use a vector-quantized image model to reduce the spatial dimension of the signal we wish to sample. We then apply new language models to instead model the distribution of discrete latents, ultimately obtaining a powerful prior over the discrete latents. With this and a discrete latent decoder, we obtain the final generative model, allowing sampling of images in a very low number of steps. We go further, and train our own VQ-GAN [Esser et al. \(2021\)](#) at resolutions higher than ever trained before to our knowledge, ultimately allowing for the sampling of 1024×1024 RGB images in only two seconds on a consumer-grade GPU.

Our main contribution are as follows:

- A new approach to generating vector-quantized representations of images, allowing for significantly faster generation than previous auto-regressive and non-autoregressive solutions (≈ 2 seconds).
- Sampling from a uniform prior rather than dedicated masking latents [Bond-Taylor et al. \(2021a\)](#); [Austin et al. \(2021\)](#), allowing for self-correction during sampling and an unbounded number of sampling steps.
- Improvements to hourglass transformer [Nawrot et al. \(2021\)](#) architecture to make it more suited for two-dimensional signals, which we postulate could improve performance when applied directly on pixels also.
- Training of a VQ-GAN [Esser et al. \(2021\)](#) vector-quantization model on higher resolutions than trained on in the original work (1024×1024 RGB images) and, to our knowledge, any other research.

In general, we find our approach to allow for highly customisable sampling, allowing a user to adjust the trade-off between sample quality, diversity and sampling speed at will.

2 RELATED WORK

This work builds upon much prior research into powerful deep generative models [Bond-Taylor et al. \(2021b\)](#), self-supervised methods, and efficient transformer architectures. We briefly cover relevant prior work into deep generative models in §[2.1-2.3](#) and a recent and highly effective development into a efficient transformer architecture in §[2.4](#).

2.1 AUTOREGRESSIVE GENERATIVE MODELS

One major deep generative model family is autoregressive models, characterised by a training and inference process based on the probabilistic chain rule. During training, they directly aim to maximise the likelihood of the data they are trained on. Prior work using these methods resulted in impressive results in terms of both sample quality and diversity, but are ultimately unwieldy for use in real world applications due to their slow sampling speed.

The slow sampling speed is due to their sequential nature, defined by the chain rule of probability. Given an input $\mathbf{x} = \{x_1, x_2, \dots, x_n\}$, an autoregressive model $p_\theta(\cdot)$ can generates new samples sequentially:

$$p_\theta(\mathbf{x}) = p_\theta(x_1, \dots, x_n) = \prod_{i=1}^n p_\theta(x_i | x_1, \dots, x_{i-1}) \quad (1)$$

meaning that the number of sampling steps is equal to the size of the decomposition of \mathbf{x} , making this slow for large inputs.

For certain tasks, the ordering of the decomposition of \mathbf{x} is obvious, for example on text or speech. For images this is less obvious, however typically a raster scan ordering is used. Certain autoregressive models are order-agnostic, allow for arbitrary ordering to be used during training and inference.

2.2 NON-AUTOREGRESSIVE GENERATIVE MODELS

Non-autoregressive generative models include generative adversarial networks (GANs), score-based (SBMs) and diffusion models, flow-based models, energy-based models (EBMs), and implicit models. Though the number of sampling steps is now independent of the data dimensionality (as we no longer need to use the chain rule) the actual

number of steps varies greatly: from single-step generation in GANs to potentially many thousands in the original diffusion model literature.

Removing the causal constraints also allows for bidirectional context during sampling and flexible inpainting patterns, rather than being limited to left-to-right inpainting in autoregressive models.

2.3 STEP-UNROLLED DENOISING AUTOENCODER

One recent non-autoregressive model is step-unrolled denoising autoencoders (SUNDAE) Savinov et al. (2022) which was evaluated on three language modelling tasks: unconditional text-generation, inpainting of Python code, and machine translation – setting a new state-of-the-art among NAR models for the machine translation task Savinov et al. (2022). It also demonstrates exceptionally fast sampling, producing high quality samples in as few as 10 steps.

SUNDAE is trained using a denoising objective, akin to the BERT Wang & Cho (2019) denoising objective but with multiple denoising steps. Given a uniform prior p_0 over some space $Z = \{1, \dots, v\}^N$ where N is the size of the space and v is the vocabulary size, consider the Markov process $\mathbf{z}_t \sim f_\theta(\cdot | \mathbf{z}_{t-1})$ where f_θ is a neural network parameterised by θ , then $\{\mathbf{z}_t\}_t$ forms a Markov chain. This gives a t -step transition function:

$$p_t(\mathbf{z}_t | \mathbf{z}_0) = \sum_{\mathbf{z}_1, \dots, \mathbf{z}_{t-1} \in Z} \prod_{s=1}^t f_\theta(\mathbf{z}_s | \mathbf{z}_{s-1}) \quad (2)$$

Savinov et al. (2022) and, given a constant number of steps T , our model distribution $p_T(\mathbf{z}_T | \mathbf{z}_0)p_0(\mathbf{z}_0)$ – which is clearly intractable.

Instead, they propose an *unrolled denoising* training method that uses a far lower T than is used for sampling Savinov et al. (2022). To compensate, they unroll the Markov chain to start from corrupted data produced by a *corruption distribution* $\mathbf{z}' \sim q(\cdot | \mathbf{z})$ rather than from the prior p_0 so the model encounters samples more akin to those seen during the full unroll at sample time Savinov et al. (2022). Typically, $T = 2$ during training, as a single step would be similar to the training strategy of BERT Devlin et al. (2019) but would lead to worse performance as seen in earlier work using BERT as a random field language model Wang & Cho (2019).

The training objective of SUNDAE is simply the average of all reconstruction losses $L^{(1:T)}(\theta) = \frac{1}{T}(L^{(1)}(\theta) + \dots + L^{(T)}(\theta))$ of the chain after t steps, which is shown to form an upper bound on the actual negative log-likelihood Savinov et al. (2022). Taking more steps T leads to a minor improvement in performance, but considerably slows down training time Savinov et al. (2022) and increases memory usage.

One advantage of this approach is that sampling starts from random tokens, rather than a dedicated “masking” token Bond-Taylor et al. (2021a); Austin et al. (2021). Unmasking approaches means that $T \leq N$ as at minimum, one token is unmasked per step. Additionally, it allows the model to be able to “change its mind” about previously predicted positions during sampling, allowing it to make fine-grained adjustments or fix accumulated errors.

2.4 HOURGLASS TRANSFORMERS

Vanilla transformers incur a hefty memory and time complexity of $O(L^2)$ for each block Vaswani et al. (2017). This is largely due to the multi-head self-attention mechanism, as each input position must attend to every other. Most research into efficient transformers focuses on improving the efficiency of these attention mechanism, such as through sparse attention patterns or approximations of attention.

Recent work however, is now focusing on making the overall architecture more efficient. Funnel-Transformer Dai et al. (2020) progressively downsamples the input sequence and hence reduces the computational cost of the model. The saved FLOPs can then be reassigned to create deeper or wider models and thus outperform vanilla transformers given the same computational budget Dai et al. (2020). However, the final layer does not operate at the same granularity as the input, making it unusable for tasks that require this such as per-token classification or generative tasks. Hourglass transformers Nawrot et al. (2021) include both up- and down-sampling mechanisms, resulting in a computational saving whilst still being general-purpose models.

3 METHODOLOGY

3.1 LATENT DATASET GENERATION

We use the standard two-stage scheme for vector-quantized image modelling van den Oord et al. (2018); Razavi et al. (2019); Esser et al. (2021); Bond-Taylor et al. (2021a) using VQ-GAN Esser et al. (2021) as our feature extractor. Where such models are available, we use pretrained VQ-GANs for our experiments. For higher resolution experiments (for example, FFHQ-1024 Karras et al. (2019)), pretrained models are not available and so training our own VQ-GAN was necessary (see §3.3).

The second stage is to learn a discrete prior model over these latent variables. To enable this, we must first build a latent dataset using our trained VQ-GAN. Formally, given a dataset of images \mathcal{X} , a VQ-GAN encoder E with downsample factor f , and vector-quantization codebook \mathcal{C} with number of codewords v , trained on \mathcal{X} , we define our latent dataset \mathcal{L} as:

$$\mathcal{L} = \{\mathcal{C}(E(\mathbf{x})) \mid \mathbf{x} \in \mathcal{X}\} \quad (3)$$

where $\mathbf{x} \in \mathbb{R}^{3 \times H \times W}$ is a single element of the image dataset and $\mathbf{z} = \mathcal{C}(E(\mathbf{x})) \in \{1, \dots, v\}^{h \times w}$ is the corresponding discrete latent representation. In other words, each $f \times f$ pixels in \mathbf{x} is mapped to a single discrete value from 1 to $|\mathcal{C}|$ (which in turn, corresponds to a vector $\mathbf{e} \in \mathcal{C}$), resulting in a latent representation of shape $\frac{H}{f} \times \frac{W}{f} = h \times w$.

We then use \mathcal{L} to train a discrete prior over the latents. Coupled with the VQ-GAN decoder G , we obtain a powerful generative model.

3.2 2D-AWARE HOURGLASS TRANSFORMER

Inspired by successes in hierarchical transformers for generative language modelling Nawrot et al. (2021), we modify their architecture for use with discrete latent representations of image data. We will later use this architecture as the discrete prior over the VQ-GAN latents.

Hourglass transformers have been seen to efficiently handle long-sequences, outperform existing models using the same computational budget, and meet the same performance as existing models more efficiently by using an explicit hierarchical structure Nawrot et al. (2021). The same benefits should also apply to vector-quantized image modelling.

2D-Aware Downsampling – The original formulation of hourglass transformers Nawrot et al. (2021) introduced both upsampling and downsampling layers, allowing the use of hierarchical transformers in tasks that have output sequence length equal to the input sequence length. However, applying their proposed resampling strategies directly on the vector-quantized image may not be the best strategy. Resampling is applied to flattened token sequence, meaning that the corresponding two-dimensional vector-quantized image is actually resampled more in one axis compared to the other. In their work they did not address this, except for experiments on ImageNet32 Russakovsky et al. (2015) where they resampled with a rate of $k = 3$, corresponding to three colour channels.

In our formulation, we instead reshape the flattened sequence back into a two-dimensional form and then apply resampling equally in the last two axes. With a resampling rate of k we apply \sqrt{k} in each axis. We found this to significantly improve the performance of the discrete prior model, and suspect a similar approach could improve performance if applied to pixels directly, which we leave for future work.

Rotary Positional Embeddings Su et al. (2021) are a good default choice for injecting positional information into transformer models, requiring no additional parameters. Additionally, they can be easily extended to the multi-dimensional case Biderman et al. (2021) which we do here. Though transformers are clearly capable of learning that elements far apart in a flattened sequence may be close in a multi-dimensional final output, we find that explicitly extending positional embeddings to the multi-dimensional case to provide a modest boost in performance.

Removal of Causal Constraints – In the original autoregressive formulation of hourglass transformers, great care was taken to avoid information leaking during resampling, and hence making the model non-causal Nawrot et al. (2021). We use a non-autoregressive method which is therefore not causal. Hence, in our approach we do not make any special considerations to avoid information leaking into the future.

3.3 TRAINING A MEGAPIXEL VQ-GAN

Training at higher resolutions usually means greater computational requirements and sampling speeds. With an autoregressive model, the sampling speed can be especially immense, even with an auxiliary vector-quantized image

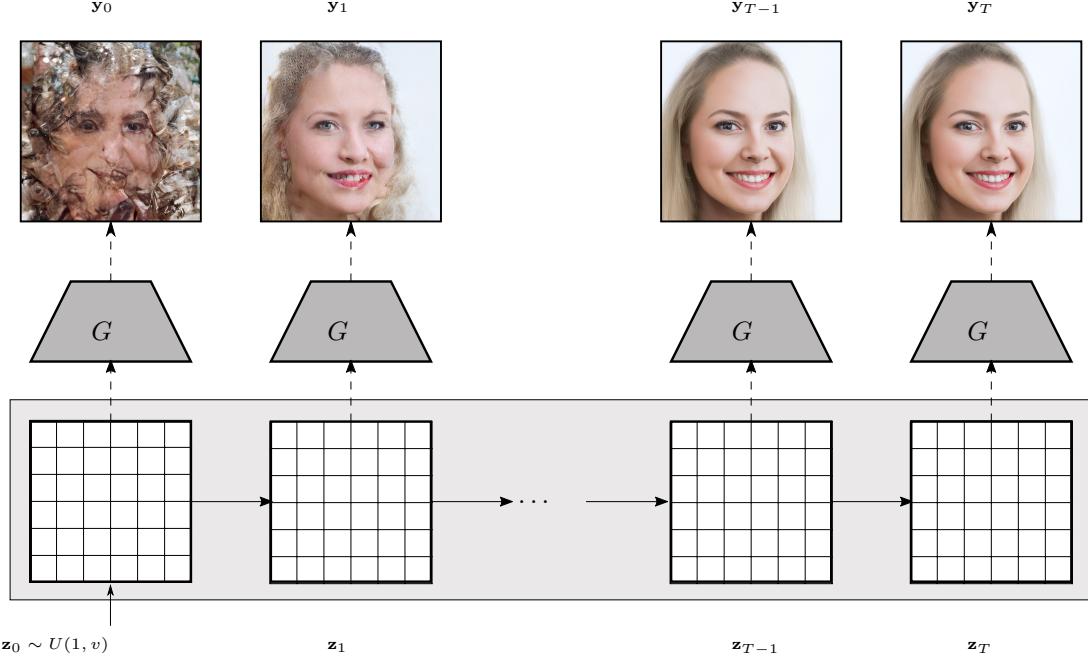


Figure 2: The sampling process. SUNDAE gradually denoises from \mathbf{z}_0 to the final sample \mathbf{z}_T . At each step, it is possible to decode with G to produce a final image.

model [Esser et al. \(2021\)](#). With a non-autoregressive model however, one question to explore is whether sampling at very high resolutions becomes feasible.

To answer this question, we train a larger variant of VQGAN with $v = 8192$ operating on 1024×1024 RGB images. To our knowledge, this is the highest resolution VQGAN has been applied to [Esser et al. \(2021\)](#). Once trained, can generate a latent datasets as before, the only difference being an increased sequence length – greater than was ever tested in the original work [Savinov et al. \(2022\)](#).

3.4 NON-AUTOREGRESSIVE GENERATOR TRAINING

We train a SUNDAE model on the flattened extracted VQ latents $\mathbf{z} = \{\mathbf{z}_1, \dots, \mathbf{z}_N\}$ where $N = h \cdot w$. The function f_θ is implemented using our 2D-aware hourglass transformer. Though the default $T = 2$ performed well, we found $T = 3$ to result in more diverse results during unconditional generation.

3.5 GENERATING HIGH-RESOLUTION IMAGES

During sampling, we simply sample sequentially $\mathbf{z}_t \sim f_\theta(\mathbf{z}_t | \mathbf{z}_{t-1})$ for a constant number of steps T , beginning randomly from \mathbf{z}_0 [Savinov et al. \(2022\)](#). The original work proposed a number of improved strategies for sampling in smaller number of steps, including low-temperature sampling and updating a random subset of tokens [Savinov et al. \(2022\)](#), rather than all simultaneously.

Sampling, however, with a lower temperature can reduce the diversity of the resulting samples. To alleviate this, we instead anneal the temperature down from a high value (≈ 1.0) down to a lower value towards the end of the sampling process. We found this retained the fast sampling whilst also improving diversity.

In certain latent sampling configurations, updating only a random subset of tokens does improve performance. However, we found that for low step scenarios ($T < 20$) that all tokens must be able to be updated in order to produce meaningful samples before the maximum number of steps is reached. Hence in these cases, we do not follow this strategy.



Figure 3: An example of inpainting on a 1024×1024 image using our model.

Additionally, if an individual sample does not change between step $t - 1$ and t , we freeze it, preventing any further change. If all samples are frozen, sampling may terminate early, further improving sampling speed with little cost to sample quality. This is significant when performing large-batch sampling.

Once sampling has terminated, the sampled latent code \mathbf{z}_T can be given to the VQGAN decoder G to produce a final sample \mathbf{y} .

3.6 ARBITRARY PATTERN INPAINTING

As noted in the original work Savinov et al. (2022) and other non-autoregressive solutions Bond-Taylor et al. (2021a) one clear advantage of non-autoregressive models is that they are not limited to causal inpainting. In general, they support arbitrary inpainting masks and can draw on context in both the past and the future, enabling them to perform inpainting tasks not possible with autoregressive sampling.

Given a sampled image $\mathbf{y} \in \mathbb{R}^{H \times W \times 3}$ we can mask a proportion of it using a pixel-level binary mask $m_p \in \{0, 1\}^{H \times W}$. By taking $f \times f$ regions of m_p and applying a logical and in them, we can obtain a latent level mask $m_{vq} \in \{0, 1\}^{h \times w}$. We then sample as normal from the latents, allowing the model full context, but only update regions that were masked according to m_{vq} . Like with sampling, we then use G to decode the sampled latent code, producing the output \mathbf{y} .

4 EVALUATION

4.1 UNCONDITIONAL IMAGE GENERATION

foobar

4.2 ARBITRARY IMAGE INPAINTING

foobar

5 CONCLUSION

In this work, we proposed using denoising autoencoders for the non-autoregressive prediction of VQ latents. This enables fast sampling times and flexible inpainting. In addition, we made changes to the hourglass transformer architecture to make it more suited for two-dimensional signals. Additionally, we demonstrate the scalability of our

approach by training a VQ-GAN at extremely high resolutions and training our model on the resulting latent dataset. Ultimately, this allows for the sampling of high quality and diverse 1024×1024 images in mere seconds. Further work is required to improve sampling time further – closing the gap with single-step methods like GANs – and to improve the reconstruction quality of VQ-GAN when operating at high downsampling factors. Additionally, we note that the adversarial component of the VQ-GAN image model may still lead to issues such as mode collapse, which can only be resolved with research into more powerful VQ representation models that do not rely on an adversarial component.

REFERENCES

- Jacob Austin, Daniel D. Johnson, Jonathan Ho, Daniel Tarlow, and Rianne van den Berg. Structured denoising diffusion models in discrete state-spaces, 2021. [2](#), [3](#)
- Stella Biderman, Sid Black, Charles Foster, Leo Gao, Eric Hallahan, Horace He, Ben Wang, and Phil Wang. Rotary embeddings: A relative revolution. [blog.eleuther.ai/](#), 2021. [Online; accessed]. [4](#)
- Sam Bond-Taylor, Peter Hessey, Hiroshi Sasaki, Toby P. Breckon, and Chris G. Willcocks. Unleashing transformers: Parallel token prediction with discrete absorbing diffusion for fast high-resolution image generation from vector-quantized codes, 2021a. [2](#), [3](#), [4](#), [6](#)
- Sam Bond-Taylor, Adam Leach, Yang Long, and Chris G. Willcocks. Deep generative modelling: A comparative review of vaes, gans, normalizing flows, energy-based and autoregressive models. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, pp. 1–1, 2021b. ISSN 1939-3539. doi: 10.1109/tpami.2021.3116668. URL <http://dx.doi.org/10.1109/TPAMI.2021.3116668>. [2](#)
- Xi Chen, Nikhil Mishra, Mostafa Rohaninejad, and Pieter Abbeel. Pixelsnail: An improved autoregressive generative model, 2017. [1](#)
- Zihang Dai, Guokun Lai, Yiming Yang, and Quoc V. Le. Funnel-transformer: Filtering out sequential redundancy for efficient language processing, 2020. [3](#)
- Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. Bert: Pre-training of deep bidirectional transformers for language understanding, 2019. [3](#)
- Patrick Esser, Robin Rombach, and Björn Ommer. Taming transformers for high-resolution image synthesis, 2021. [2](#), [4](#), [5](#)
- Tero Karras, Samuli Laine, and Timo Aila. A style-based generator architecture for generative adversarial networks, 2019. [4](#)
- Diederik P Kingma and Max Welling. Auto-encoding variational bayes, 2013. [1](#)
- Piotr Nawrot, Szymon Tworkowski, Michał Tyrołski, Łukasz Kaiser, Yuhuai Wu, Christian Szegedy, and Henryk Michalewski. Hierarchical transformers are more efficient language models, 2021. [2](#), [3](#), [4](#)
- Niki Parmar, Ashish Vaswani, Jakob Uszkoreit, Łukasz Kaiser, Noam Shazeer, Alexander Ku, and Dustin Tran. Image transformer, 2018. [1](#)
- Ali Razavi, Aaron van den Oord, and Oriol Vinyals. Generating diverse high-fidelity images with vq-vae-2, 2019. [2](#), [4](#)
- Olga Russakovsky, Jia Deng, Hao Su, Jonathan Krause, Sanjeev Satheesh, Sean Ma, Zhiheng Huang, Andrej Karpathy, Aditya Khosla, Michael Bernstein, Alexander C. Berg, and Li Fei-Fei. Imagenet large scale visual recognition challenge, 2015. [4](#)
- Nikolay Savinov, Junyoung Chung, Mikolaj Binkowski, Erich Elsen, and Aaron van den Oord. Step-unrolled denoising autoencoders for text generation, 2022. [3](#), [5](#), [6](#)
- Jianlin Su, Yu Lu, Shengfeng Pan, Bo Wen, and Yunfeng Liu. Roformer: Enhanced transformer with rotary position embedding, 2021. [4](#)
- Arash Vahdat, Karsten Kreis, and Jan Kautz. Score-based generative modeling in latent space, 2021. [2](#)
- Aaron van den Oord, Oriol Vinyals, and Koray Kavukcuoglu. Neural discrete representation learning, 2017. [2](#)
- Aaron van den Oord, Oriol Vinyals, and Koray Kavukcuoglu. Neural discrete representation learning, 2018. [4](#)
- Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N. Gomez, Łukasz Kaiser, and Illia Polosukhin. Attention is all you need, 2017. [3](#)
- Alex Wang and Kyunghyun Cho. Bert has a mouth, and it must speak: Bert as a markov random field language model, 2019. [3](#)
- Zhisheng Xiao, Karsten Kreis, and Arash Vahdat. Tackling the generative learning trilemma with denoising diffusion gans, 2021. [1](#), [2](#)