GenSLMs: Genome-scale language models reveal SARS-CoV-2 evolutionary dynamics

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ABSTRACT

Our work seeks to transform how new and emergent variants of pandemiccausing viruses, specially SARS-CoV-2, are identified and classified. By adapting large language models (LLMs) for genomic data, we build genome-scale language models (GenSLMs) which can learn the evolutionary landscape of SARS-CoV-2 genomes. By pretraining on over 110 million prokaryotic gene sequences, and then finetuning a SARS-CoV-2 specific model on 1.5 million genomes, we show that GenSLM can accurately and rapidly identify variants of concern. Thus, to our knowledge, GenSLM represents one of the first whole genome scale foundation models which can generalize to other prediction tasks. We demonstrate the scaling of GenSLMs on both GPU-based supercomputers and AI-hardware accelerators, achieving over 1.54 zettaflops in training runs. We present initial scientific insights gleaned from examining GenSLMs in tracking the evolutionary dynamics of SARS-CoV-2, noting that its full potential on large biological data is yet to be realized.

KEYWORDS

SARS-CoV-2, COVID-19, HPC, AI, Large language models, whole genome analyses

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1https://www.gisaid.org

1 OVERVIEW OF THE PROBLEM

Tracking of novel and emergent variants for viruses such as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has been enabled by rapid sequencing and sharing of whole genome sequence data (Otto et al., 2021). As of September 2022, >13 million SARS-CoV-2 genomes have been deposited in the GISAID repository. SARS-CoV-2 represents one of the most deeply sequenced viral genomes and is therefore a rich source of information for understanding various factors that drive its evolution. Despite its slow mutation rate, over the past three years SARS-CoV-2 has evolved several variant strains containing unique mutation patterns, many of which lead to novel viral phenotypes including higher antigenicity, transmissibility, and fitness (Cosar et al., 2022).

This has prompted the US Centers for Disease Control and Prevention (CDC) to identify four SARS-CoV-2 variant categories,
We adapt LLMs developed for understanding human languages to
with the goal of enabling development of robust public health in-
tervention strategies prior to surges in case numbers and better
surveillance of global pandemics and early identification of VOCs.

Total, these factors contribute to significant time expenditure
to recognize and subsequently make informed decisions for public
health intervention strategies (Baker et al., 2021).

Artificial intelligence (AI) and machine learning (ML) approaches
promise to transform real-time pandemic monitoring (Syrowatka
et al., 2021). Instead of reacting after the emergence of variants to
identify VOCs over potentially several weeks (see Sec. 4.1), AI/ML
techniques can leverage deep sequencing data to proactively iden-
tify mutations in viral proteins and characterize evolutionary pat-
terns that can assist in predicting and describing future VOCs (Be-
guir et al., 2022, Hie et al., 2021). However, obtaining high quality,
global-scale genome datasets can be challenging, as diverse se-
quencing technologies can result in variable quality and coverage
of sequenced genomes. Sequence-based feature extraction tech-
niques followed by traditional ML approaches have demonstrated
promise in early identification of VOCs (Beguir et al., 2022, Maher
et al., 2022, Wallace et al., 2022); however, they remain limited to se-
quence signatures of regions of interests in the genome. This unmet
challenge presents an opportunity for effective whole genome-scale
surveillance of global pandemics and early identification of VOCs,
with the goal of enabling development of robust public health in-
tervention strategies prior to surges in case numbers and better
informing vaccine-design strategies on emerging variants.

We posit that by leveraging recent success of large-language
models (LLMs) in natural language processing (NLP) tasks (Wei
et al., 2022), we can develop global-scale, whole genome surveillance
tools. In this paper, we use LLMs to characterize SARS-CoV-2 evolu-
tionary dynamics and reconstruct SARS-CoV-2 variant emergence.
We adapt LLMs developed for understanding human languages to
genomic sequences, called genome-scale language models (GenSLM),
and validate this approach in modeling VOC assignments for SARS-
CoV-2 using historical data. Our contributions include:

- We develop some of the largest biological LMs (models with
2.5 and 25 billion trainable parameters) to date, trained across
a diverse set of >100 million prokaryotic gene sequences.
This represents one of the first foundation models trained on
raw nucleotide sequences to demonstrate substantial im-
provement in predictive performance in identifying VOCs.
We make these models and weights openly available for the
scientific community.

- We design and validate a novel hierarchical transformer-
based model that uses both Generative Pre-trained Trans-
formers (GPT) (on individual gene sequences) and stable
diffusion to capture the correct context and longer-range
interactions in genome-scale datasets. This model enables us
to prospectively model SARS-CoV-2 evolution by leveraging
its generative capabilities.

- We showcase training foundation models on both conven-
tional (GPU-based) systems (Polaris@ALCF and Selene@NVIDIA
and on emerging AI-accelerator hardware (interconnected
Cerebras CS-2 systems), and demonstrate high watermarks
for time-to-solution (model performance described by its per-
plexity or accuracy). In addition, we present scaling bench-
marks, which demonstrate that training GenSLMs can be
intensive - achieving nearly 1.5 zettaflops over the course of
training runs.

Together, these capabilities go beyond state-of-the-art techniques
for global-scale whole genome surveillance of pandemic-causing
viruses and address a critical infrastructure need for the global
public health organizations.

4 CURRENT STATE OF THE ART

Current approaches for tracking viral evolution rely on infectious
disease specialists who examine variations, identify epitopes of
interest (i.e., portions of the virus that elicit immune response),
classify variants, and eventually flag them for further laboratory
testing and analysis (Brouwer et al., 2020, Greaney et al., 2021, Ju
et al., 2020, Zost et al., 2020). This process is widely used for track-
ing viral infections, including seasonal influenza (Doud et al., 2018).
Identifying strains of interest helps prioritize downstream vaccine
development workflows. However, this process is time-consuming
and laborious. While data sharing in the community has enabled
unprecedented progress in developing vaccines for pandemics such
as COVID-19, there still exists an unmet challenge in accelerat-
detection and prediction of viral VOCs via computational and
experimental toolkits.

4.1 Early warning systems for tracking viral
evolution

Several early warning systems for tracking COVID-19 have been
developed; however, they utilize case counts, internet search pa-
rameters, and other allied data focused on monitoring case counts
in a local geographic area (Ramchandani et al., 2020). The Bacte-
rial and Viral Bioinformatics Resource Center (BV-BRC)3 provides
the SARS-CoV-2 Emerging Variant Tracking and Early Warning
System, which enables users to browse current and past variant
lineages and track their prevalence by isolation date, geographic
location, and other metadata fields. A heuristic is used to compute
month-over-month growth rates and highlight rapidly growing
variants that may cause future infection surges. Mutations from
each variant are mapped to known epitope sites and regions of the
genome known to be involved in antibody escape to enable further
assessment of mutation impact. Recently, Hie et al. (Hie et al., 2021)
used protein language models (PLMs) and adapted concepts from
NLP to model escape variants across three different viruses, includ-
ing SARS-CoV-2. In each virus, they identified a certain protein (e.g.,
SARS-CoV-2 Spike/ S protein) and modeled its evolutionary history
using transformers to describe differences between ordinary vari-
ants and VOCs. Similarly, Beguir et al. (Beguir et al., 2022) leveraged

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3https://www.bv-brc.org

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4.2 Large language models (LLMs)

The introduction of transformers - beginning with Bidirectional Encoder Representations from Transformers (BERT) (Devlin et al., 2018) and subsequent LLMs such as generative pre-trained transformers (GPT) (Radford et al., 2018) - has revolutionized natural language understanding. These models have been used to generate text, speech (Gulati et al., 2020), and images (Han et al., 2022). They have also been employed to understand the language of nucleic acids (DNA/RNA) and proteins. Protein language models (PLMs), using amino acid alphabets, are the most heavily investigated biological LLMs (Elnaqar et al., 2022, Rives et al., 2021), with demonstrated success in many downstream tasks (e.g., protein function prediction (Unsal et al., 2022) and engineering (Ferruz et al., 2022)). Nucleotide LLMs, using DNA/RNA alphabets, are still understudied (Avese et al., 2021). Compared to the rich alphabet and short length of information-dense protein sequences that traditional attention models from NLP can successfully learn, nucleotide LLMs rely on much simpler alphabets and extremely long-range signal (e.g., across open reading frames or co-evolutionary patterns) and require significant domain adaptation to yield good results. When applied on the scale of entire genomes, GenSLMs also operate on much larger sequence lengths than are traditionally seen in NLP applications - the max sequence length for SARS CoV2 tasks was 10,240 tokens in comparison to the standard 1,024 or 2,048. Further, viral genomes often undergo frameshift mutations leading to differential translation, introducing ambiguity not present at the protein scale. Our work addresses these challenges by leveraging a hierarchical LLM: a generalized pre-trained transformer (GPT) to capture shorter/local (codon-level) interactions, and a diffusion-based model to capture longer-range interactions to describe the biological complexity of viral evolution (Sec. 5.2).

4.3 Workflow infrastructure

Scientific applications for HPC are increasingly written as a composition of many interconnected components. Application components may have different hardware or software requirements, run durations and execution frequencies, or dependencies with other components. Workflow systems such as Swift, Parsl, Balsam and RADICAL Cybertools support the design of applications as directed graphs of tasks and manage their execution on available resources.

There is significant diversity in workflow implementation; e.g., Swift/T expresses workflows in bespoke programming languages that are compiled into an MPI program (Wozniak et al., 2013). Parsl, in contrast, is built on Python’s native concurrency library and dynamically constructs a task graph as a Python program is interpreted (Babuji et al., 2019). Balsam (Salim et al., 2019) and RADICAL CyberTools (Balasubramanian et al., 2019) rely on a central task database from which the launcher, running on compute resources, pulls and executes tasks. A centralized database enables state persistence across runs, and task dependencies can be defined as a DAG. Most workflow systems support interfacing with HPC job schedulers or cloud providers to acquire resources and transmit files between remote resources - key features our use case requires.

Dynamic workflows, where new tasks are continually added in response to new results, are emerging as an extension of workflow managers. Many dynamic workflow systems, such as DeepHyper (Balaparakash et al., 2018) and RocketSled (Dunn et al., 2019), are purpose-built to solve optimization problems. LibEnsemble (Hudson et al., 2022) provides a more general interface where users decouple a dynamic ensemble into a "generator", which spawns new tasks based on results from a "simulator". Toolkits such as Ray (Moritz et al., 2018) and Colmena (Ward et al., 2021) provide more flexible approaches where a number of "agents" can cooperatively coordinate tasks. These libraries handle where and how tasks are executed and provide useful abstractions so users can focus on component/task logic (i.e., what and when).

5 INNOVATIONS REALIZED

Given the limitations of current approaches in identifying VoCs, there is a need to develop an integrated system that can automatically 'learn' features within the SARS-CoV-2 genome that distinguish VoCs, while also being able to generate new sequences that characterize emerging variants of the virus. We posit that by leveraging existing sequencing data on the virus, we can train LLMs that can model the SARS-CoV-2 evolutionary trajectory. Training LLMs on SARS-CoV-2 genome datasets is non-trivial: (1) one needs to address the limitations of training LLMs with genomic sequence; and (2) one needs to overcome infrastructural challenges to enable LLM training on formidable sequence lengths in a reasonable time.

5.1 Data collection and description

SARS-CoV-2 genome dataset: The Bacterial and Viral Bioinformatics Resource Center (BV-BRC) web resource provides integrated data and analysis tools for bacterial and viral pathogens to support infectious disease research. BV-BRC hosts >600,000 bacterial genomes and 8.7 million viral genome sequences, including 6.4 million SARS-CoV-2 genomes. All SARS-CoV-2 genome sequences were acquired from NCBI’s GenBank and SRA databases and uniformly annotated using VIGOR4 (Wang et al., 2012) to provide accurate and consistent annotation of ORFs and mature peptides across all SARS-CoV-2 genomes. Automated and manual curation provided accurate and uniform metadata across all genomes, including host name, geographic location, and collection date.

To build GenSLMs for detecting and predicting SARS-CoV-2 variants of interest, we used >1.5 million high-quality BV-BRC SARS-CoV-2 complete genome sequences. We filtered out any genome sequences with < 29,000 bp and >1% ambiguous bases. However, we note here that the data collected might not have sufficient diversity - meaning that any model trained on the SARS-CoV-2 dataset may end up overfitting to the data, with little opportunity to generalize. Hence, we took a foundation model based approach that allowed us to first build a more general model using a much larger collection of diverse genomic data, namely gene-level data from prokaryotes.
We also utilized a dataset collected by the Houston Methodist Hospital System - one of the largest single-institution collections of SARS-CoV-2 genome sequences in the United States. We started here with 70,000 SARS-CoV-2 patient samples collected from May 15, 2020 to January 14, 2022 and sequenced on Illumina instruments. To ensure high quality, we first masked the leading and trailing 100 nucleotides for each sequence, as well as 56 positions in the spike protein-encoding region that had low depth due to poor primer binding. Sequences with >256 ambiguous characters were discarded, leaving 16,545 total sequences. This subset was used for building phylogenetic analyses at genome scale (see Sec. 5.3).

**BV-BRC dataset.** To allow for better generalization and avoid overfitting of the models to the SARS-CoV-2 data, we used >110 million unique prokaryotic gene sequences from BV-BRC. The BV-BRC database provides cross-genera protein families, PGfams, which allow collection of homologous gene or protein sequences across taxa that perform the same biological function (Davis et al., 2016). We queried BV-BRC to find 10,206 unique PGfams, each with >30,000 unique members. For each PGfam, we collected high-quality non-redundant gene and protein sequences after filtering out any sequences that were more than one standard deviation from the PGfam’s mean length. The Genome-Scale Language Models (GenSLMs) models trained on this data are referred to as foundation models.

### 5.2 Large language models

Large-language model (LLM) training required both algorithmic and performance-level innovations. For algorithmic innovations, we describe two key limitations of current LLMs. For performance innovations in achieving optimal time-to-solution (training time to achieve some accuracy or perplexity), we leverage an interconnected cluster of four Cerebras CS-2 AI-accelerators and scale to large GPU-based supercomputers to train our LLMs.

#### 5.2.1 Genome-scale Language Models (GenSLMs)

We introduce GenSLMs as a means to go beyond current PLMs to describe evolutionary dynamics of SARS-CoV-2. Instead of focusing on specific proteins, GenSLMs leverage genome-scale data to model individual mutations at nucleotide scale, thus implicitly accounting for protein-level mutations at codon level. Fig. 1 shows that GenSLMs take nucleotide sequences of SARS-CoV-2 genomes as input and builds LLMs that learn a semantic embedding of individual codons, which can then be translated to the 29 individual protein sequences that are encoded by the virus.

However, there are two fundamental challenges when training GenSLMs directly from SARS-CoV-2 genome sequences: (1) The entire genome consists of ~30,000 nucleotides (which translates to ~10,000 codons/aa). LLM training on long sequences can be challenging because attention mechanisms largely focus on shorter/local segments of the genome rather than global patterns. (2) The overall sequence similarity in SARS-CoV-2 genomes is quite high (~99%), with only a small (yet significant) number of changes that yield distinct phenotypes. Thus, there is a need to address diversity in the sequences such that the trained model can generalize. In addition, it is necessary to account for drifts in viral genomes.

To overcome these challenges, GenSLM implicitly recognizes intrinsic hierarchy (based on the central dogma) of individual protein production via DNA transcription and mRNA translation. We trained on gene-level data from BV-BRC (see Sec. 5.1) to mimic this process with GenSLMs. Although mapping between codons and amino acids is degenerate (multiple codons may encode the same amino acid) (Shin et al., 2015), we posited that with sufficient diversity in the dataset, GenSLMs could exploit intrinsic organization of gene-level data to learn biologically-meaningful latent representations. The training process follows a procedure similar to the one outlined in (Zhang et al., 2022). We refer to the models trained on the BV-BRC dataset as GenSLM foundation models.

While the benefits of pre-training LLMs on natural text are well known (Turc et al., 2019), obtaining the optimal number of transformer layers and training on such a diverse set of gene data were challenging. We therefore trained GenSLM foundation models on a wide set of parameter scales ranging from 25 million to 25 billion, with maximum sequence length of 2,048 tokens on the BV-BRC dataset. Additionally, to evaluate performance on downstream tasks, we fine-tuned the foundation model GenSLMs using a maximum sequence length of 10,240 tokens for the 25M and 250M model sizes on the SARS-CoV-2 datasets (see Table 1). We note that for the larger model sizes (2.5B and 25B), training on the 10,240 length SARS-CoV-2 data was infeasible on GPU-clusters due to out-of-memory errors during attention computation.

The entire repertoire of results from the GenSLM foundation models is beyond the scope of this paper. However, as an empirical demonstration of the power of GenSLMs trained on the SARS-CoV-2 genomes, the learned latent space projected onto a low-dimensional manifold as determined by t-Stochastic Neighborhood
GenSLMs reveal SARS-CoV-2 evolutionary dynamics

Figure 2: GenSLMs learned latent space describes biologically meaningful properties for SARS-CoV-2 genomes. (A) The embeddings from GenSLMs are visualized with t-stochastic neighborhood embedding (t-SNE) and each gene sequence is represented as a dot in the 2D plot. We paint each sequence by its variant ID – although we have more than 515 PANGO (Rambaut et al., 2020) lineages represented in the data, we only show those with WHO designated labels. (B) The latent space can also be painted with the MAFFT-determined alignment score (Yamada et al., 2016) with respect to an Omicron genome; clustering in the distance measures is clearly visible. Visualizing the sequence log-likelihood (blue bar) and the cross-protein attention (orange lines) from (C) Delta and (D) Omicron SARS-CoV-2 strains highlights how different the co-evolutionary patterns are in these lineages. It is interesting to note that while the Spike protein from Delta strain shows coupling to nsp3, nsp5, and other proteins, these couplings are not observed in the Omicron strain.

Embedding (t-SNE) meaningfully distinguishes the SARS-CoV-2 variants as shown in Fig. 2. This observation is significant because this GenSLM-25M model was specifically trained only on the first year of the SARS-CoV-2 data (consisting of ~ 85,000 SARS-CoV-2 genome sequences) – meaning that the model did not have the opportunity to see any of the other strains. Thus, the ability of GenSLM to generalize and distinguish among SARS-CoV-2 variants implies that the learning process is robust and the underlying features can generalize to downstream tasks. We also note that as the model parameters increase, the perplexity of the model also increases.

We note however that these training runs frequently take >1 week on dedicated GPU resources (such as Polaris@ALCF). To enable training of the larger models on the full sequence length (10,240 tokens), we leveraged AI-hardware accelerators such as Cerebras CS-2, both in a stand-alone mode and as an inter-connected cluster, and obtained GenSLMS that converge in less than a day (Sec. 5.2.4).

5.2.2 Reward-guided beam search for generative modeling. A subsequent use of the GenSLM models is in its ability to generate new SARS-CoV-2 sequences, with the eventual goal of predicting yet unseen VOCs. One challenge with such sequence-based generation strategies is sampling sequences with particular properties. Given a conditional sequence model \( p_\theta \) with weights, \( \theta \), the most likely sequence is \( p_\theta(x) = \prod_{t=1}^{T} p_\theta(x_t|x_{0}, \ldots, x_{t-1}, c) \) where \( c \) is the context from the previous inference. However, computing this directly is generally intractable as it is \( O(4^T) \), where \( T \) is the maximum sequence length with a vocabulary of size 64. Heuristics like greedy sampling are commonly used, where a sequence is generated iteratively, with the next token, \( x_t \) maximizing \( p_\theta(x_t|x_0, \ldots, x_{t-1}, c) \) with complexity \( O(T) \).

Beam search is standard practice, combining a search strategy with a heuristic where \( k \) is the number of beams explored with complexity \( O(kT) \). First, \( k \) samples are drawn with highest probability or sampled from a multinomial distribution and added to the set of possible hits \( \Lambda_{\text{beam}} \). Let \( X_t^{i} \) be the set of beams of length \( i \). Then, for time step \( t \), select \( k \) tokens \( x_t \) from the set of all tokens, which score highest (or sampled from multinomial distribution) via \( p_\theta(x_t|x_0, \ldots, x_{t-1}, c) \). The highest scoring beams from \( \Lambda_{\text{beam}} \) are selected via \( \frac{1}{k^T} \sum_{t=1}^{T} \log p_\theta(x_t|x_0, \ldots, x_{t-1}, c) \) is output where \( L \) is the length of a sequence and \( \sigma \) is a length penalty.

Given an episodic reward function \( R(x) = \sum_{t=1}^{L} r_t(x_t) \), we modify the scoring function for beam search with

\[
\mu \sum_{t=1}^{L} \log p_\theta(x_t|x_0, \ldots, x_{t-1}, c) + (1 - \mu)R(x)
\]

where \( 0 < \mu < 1 \) is a hyperparameter. Since the reward function is episodic, at each step of beam search, the highest scoring beams are chosen with

\[
\mu p_\theta(x_t|X^{i}_{\text{beams}}) + (1 - \mu)r_t(x_t).
\]

This scoring modification effectively alters the likelihood of tokens to be sampled based on maximizing the reward function. In order to sample sequences which are similar to a fixed sequence \( y \), we utilize \( r_t(x_t) \) equal to the global alignment score between \( y_t \) and \( x_t \) (Needleman and Wunsch, 1970). This scoring bias modification effectively implements a property scoring function into beam search without altering the complexity of beam search sampling. In the case of non-episodic reward functions, rewards can only be computed at the final time step in eq. 1.

5.2.3 Diffusion-based hierarchical modeling. Token-level autoregressive modeling has difficulty in generating coherent long sequences due to its underlying challenge in capturing long-range dependencies (Papalampidi et al., 2022, Sun et al., 2021, 2022). We developed a new hierarchical-modeling method based on a latent-space diffusion model that operates on the ‘sentence’ level. For each genome sequence, we uniformly truncated every 512 codons by a special separator symbol; these 512 codons are considered a ‘sentence’.

Our diffusion-based hierarchical modeling method consists of three parts: (1) Learning high-level representations: We trained a new encoder to embed sentences into a latent space with a contrastive loss such that learned features better capture high-level dynamics. Our contrastive loss is similar to the masked language

\footnote{We set 512 codons to be a sentence such that the average number of sentences per sequence (around 20) matches the number of open reading frames and non-coding regions (around 17).}
representations, we predict missing sentences in the middle by conditioning on
Vincent, 2011), we used denoising score matching as the training
objective; we gradually apply noise to desired target representations
and the diffusion model learns to denoise at each step.

Given encoder output of each genome, i.e., a sequence of sentence
randomly sampled sentences as negatives (distractors).

For these models we were also able to train on the 10,240
sequence length for the full genome.

Table 1: Description of GenSLMs foundation model archi-
tectures. #H – number of attention heads; #L – number of
layers; \(d_{\text{model}}\) – embedding size; LR – learning rate (if range
is specified, decayed by factor of 10 each update); B – global
batch size in number sequences per step; P – total number
of trainable parameters; MSL – maximum sequence length.
† For these models we were also able to train on the 10,240
sequence length for the full genome.

Figure 3: Illustration of diffusion-based hierarchical mod-
ing. To predict a codon (such as TAA), we use both the
previous codons within the context window (we use size 3
for illustration) and the high-level representations z.

(2) Modeling high-level dynamics with a diffusion model:
Given encoder output of each genome, i.e., a sequence of sentence
embeddings, we train a diffusion model to learn their distribution.
The diffusion model parameterizes the distribution of high-level
representations by applying a sequence of denoising operations on
top of Gaussian noise. Similar to previous work (Ho et al., 2020,
Vincent, 2011), we used denoising score matching as the training
objective; we gradually apply noise to desired target representations
and the diffusion model learns to denoise at each step.

(3) Fine-tuning LMs with high-level planning: Similar to
Time Control LM (Wang et al., 2022), we fine-tuned GenSLMs as the
decoder to generate the genome sequence conditioned on high-
level representations learned in step (1), which we term the ‘high-
level plan’. The decoder predicted the current codon token using
previous codon tokens within the context window size and the

Figure 4: Diffusion-based hierarchical modeling of SARS-
CoV-2 genomes results in generation of sequences that cap-
tures the correct context of various open reading frames
(ORFs). (A) Comparison of statistics measured on generated
sequences and on real data for the ORFs. Diffusion-based
hierarchical LM has a global high-level plan whereas the
baseline can only take into account the previous 1023 codons.
(B) Generated sequences (light blue) from the model overlaid
on the phylogenetic tree demonstrate that these sequences
are also closer to the various observed strains.

We conducted experiments by training a baseline LM and a
diffusion-based hierarchical LM on the 1.5M BV-BRC-SARS-CoV-
2 dataset mentioned in Section 5.1. The goal of this experiment
was to primarily assess if the diffusion model can ‘stitch’ together
the context of the genes together at the genome-scale (much like
how words are ordered in a sentence). The baseline LM is the hi-
erarchical LM without high-level guidance - essentially, a normal
transformer language model. We initialized both the baseline LM
and the hierarchical LM decoders from the 2.5B foundation model
trained on individual genes from BV-BRC (Davis et al., 2016). We
used a context window size of 1,024. The sentence encoder is ini-
tialized from the 25M foundation model. The diffusion denoising
model is a transformer with the same architecture as BERT (Kenton
and Toutanova, 2019). We used 10 nodes from Polaris@ALCF for
training, with a total of 40 A100 GPUs. We used an Adam optimizer
with a learning rate of 1e-4, a batch size of 2, and trained for 13k
updates. Training took approximately 6 hours. At generation time,
we used a sliding window-based approach: we first generate 1,023
codons from a start-of-sequence symbol, then move the window 512
codons to the right, generate the next 512 codons, and repeat this
process until either end-of-sequence is generated or a maximum of
15k codons have been generated.
To evaluate if the generated samples capture high-level dynamics, we compared the distribution of the number of 5’-3’ ORFs on real data and on 1,000 samples from the model. The results are plotted in Fig. 4A, and we observed that the diffusion-based hierarchical model does better in this regard, possibly due to the high-level plan, whereas the baseline can only account for the previous 1,023 codons. We also plotted the phylogenetic tree (see Sec. 5.3) of the generated sequences from the diffusion-based hierarchical model against real data in Fig. 4B. The plot exhibits that the generated sequences cover the different lineages including all the variants. Note that sequences with >120 mutations (1.4% of all generated sequences) were excluded; this demonstrates that the model can generate sequences that are relatively higher quality than just the transformer-based model.

5.2.4 Training with full viral genome sequences on Cerebras Wafer-Scale Cluster. Training LLMs on whole SARS-CoV-2 genomes with dense attention is extremely challenging using traditional approaches and hardware. With codon-based encoding, the model needs to handle sequences of 10,240 tokens. This results in high memory and computational demand, severe limitations to batch sizes to fit on a single device, and thus a need to develop and orchestrate complicated hybrid parallelism approaches to get reasonable performance with clusters of traditional devices. We overcome these challenges with the Cerebras Wafer-Scale Cluster (Hall et al., 2021), where it offers significant speed improvements over LLMs trained on very long sequences.

5.3 Phylogenetic analyses of whole genomes

As described in Sec. 5.1, we used a set of 16,545 sequences from the Houston Methodist Hospital System that were filtered for high-quality in order to analyze GenSLM outputs. We selected a diverse subset by embedding these sequences, tessellating the embedding space using Gaussian mixture models, and then sampling each tessellation using a beta distribution, resulting in a set of 1,000 sequences maximizing coverage of the embedding space.

The 1,000 sequence subset was aligned to the NC_045512 reference genome. The alignment was used to generate a phylogenetic tree. This tree was then used to label variant sites. The analysis was repeated using a similar approach, but with a different alignment method.

5.4 Integrated visualization

When visualizing long-distance genomic relationships, a linear layout created edges crossing over entities and affected readability. We therefore used a circular arrangement to visualize relationships between entities and positions. The visualization is flexible and supports a rich set of layers to encode various data properties. The outermost layer shows open reading frames (ORFs) along the SARS-CoV-2 genome, while the next layer displays protein-coding locations. These interactive layers allow users to select an ORF or protein for closer examination. All other layers (except the innermost) display different properties of codons in the gene sequence. The layers encode codon properties and are presented with custom visualizations based on the property type; e.g., Fig. 2C and 2D, where probabilities of codons are encoded using a radial bar chart (intensity of the color represents the probability). The innermost layer visualizes the GenSLM attention relationships between codons. To reduce visual clutter, we employed hierarchical edge bundling techniques. It is important to note that the visualization is integral to the platform developed where model training runs and the downstream prediction tasks are part of the same job.

5.5 Workflow infrastructure

As illustrated in Fig. 5, we implemented and scaled the reward-guided beam search procedure from Section 5.2.2 leveraging a workflow to couple two applications; (1) a GenSLM sequence generator, and (2) a Bayesian optimizer to tune the reward mixing
Figure 5: Conceptual overview of our workflow. A “Thinker” orchestrates data flow between two applications, namely the sequence generator and the Bayesian optimization to drive the generated sequences towards a target property using reward-guided beam search, where $\mu$ represents the mixing constant used balance the reward function against the log likelihood of generating the next token.

Hyperparameter $\mu$ to bias the generator towards a target property. On startup, an ensemble of GenSLM generators are submitted to perform an initial grid search over the $\mu \in (0, 1)$ parameter space, providing sequences to update a Gaussian process surrogate model. This, in turn, suggests new $\mu$ values throughout the duration of the workflow. Parameters are chosen by random sampling of $n$ points, and are scored by their negative expected improvement (the optimization is a minimization). Each generation task uses a single A100 GPU on Polaris to run an instance of the a 25M parameter (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC-ND 4.0 International license. $\mu$ values throughout the duration of the workflow. Parameters are chosen by random sampling of $n$ points, and are scored by their negative expected improvement (the optimization is a minimization). Each generation task uses a single A100 GPU on Polaris to run an instance of the a 25M parameter GenSLM model, whereas the optimizer task uses the CPUs on a single compute node.

We extend the Colmena workflow toolkit providing an Application abstraction for each of the tasks (components) in the workflow. The Application provides a few additional features: (1) inter-process communication when tasks are externally executable programs, and (2) warm-able functions to avoid duplicate initialization. The Application abstraction enables us to isolate the many generator tasks from the Bayesian optimizer such that a single Thinker, executed on the login node, orchestrates communication and task submission to drive the property optimization. Leveraging Colmena allows us to concisely implement a multithreaded Thinker where one thread is responsible for handling outputs from the sequence generators and immediately submitting a new generation request to maximize utilization of the workers. This thread then handles any potential task failures by checking the return status and allows the workflow to be robust to application-level failures due to uncaught exceptions and hardware failures. The successful results are placed onto a queue where another thread reads and batches the results, ($\mu$, sequence) pairs, for submission to the Bayesian optimizer application. To further improve utilization of the workflow, we augment the Thinker with a inference-only copy of the surrogate model which is periodically transferred via pickling from the Bayesian optimizer application.

### HOW PERFORMANCE WAS MEASURED

We evaluate performance of GenSLM models on a diverse set of systems. We first explore the performance on two leadership class GPU-bases supercomputing systems: 1) Polaris supercomputer at the Argonne Leadership Computing Facility (Polaris@ALCF), and 2) Selene supercomputer at NVIDIA (Selene@NVIDIA). Next, we evaluate the performance on the Cerebras CS-2 wafer-scale cluster.

In the June 2022 Top-500 list (Top500, 2022), Polaris is ranked at #14 with a peak of 44 PFLOPS and Selene is at #8 with a 63.4 PFLOPS peak. Table 2 compares the two systems used for evaluation. The Polaris system is an HPE Apollo Gen10+ system with 560 nodes interconnected with Mellanox HDR fabric. Each node consists of an 8-socket AMD “Milan” processor with 32 cores, 64 GB memory, and 8 NVIDIA A100 GPUs - each with 40GB memory. Each node has two Slingshot-10 endpoints at 12.5 GB/s for the interconnect network. Selene is based on the NVIDIA DGX SuperPOD platform and consists of 560 nodes interconnected with Mellanox HDR fabric. Each node consists of two 8-core “Rome” processors, each with 64 cores and 2TB system memory. Each node has eight NVIDIA A100 GPUs, each with 80GB memory. Each node has eight Mellanox ConnectX-6 HDR endpoints at 20 GB/s each for the interconnect network. Each A100 NVIDIA GPU is capable of achieving a peak of 19.5 TFLOPS in FP32, 156 TFLOPS in TF32, and 312 TFLOPS in FP16 and BF16.

GenSLM was written with the PyTorch Lightning API (Pytorch, 2022), using transformer models from the Hugging Face repository (huggingface, 2022). PyTorch Lightning allows the use of several distributed training strategies to scale model training on
clusters and supercomputers. This includes DistributedDataParallel and DeepSpeed (Rasley et al., 2020). We focused our efforts on DeepSpeed, as its employment of various ZeRO strategies for optimization reduces the overall memory utilization in model training, particularly for large parameter models (Rajbhandari et al., 2020). Briefly, ZeRO strategies partition memory for training models - including the optimizer, gradient, and model states - to use aggregate memory across all GPUs. This enables training larger models on GPU-based systems and trades overall memory capacity for additional re-computation and communication. In particular, ZeRO-1 partitions optimizers across GPUs, ZeRO-2 partitions both the optimizers and gradients across all GPUs, and ZeRO-3 partitions the parameters, in addition to Zero-2 optimizations, across all GPUs. Additionally, ZeRO-3 can scale model sizes by leveraging CPU memory and any node-local storage to offload optimizer states, gradients, parameters, and optionally activations to CPU. We used PyTorch 1.12.0 and used NVIDIA NCCL 2.10.3 as the backend for DeepSpeed. We used an environment with Docker containers for the runs on Selene, and a bare-metal build using Conda on Polaris.

To measure compute performance of GenSLM model training, we use the DeepSpeed flops profiler (Deepspeed, 2022). The DeepSpeed flops profiler provides the flops and latency of the forward and backward passes and latency of the weight updates, and thus the compute performance of the GenSLM models. For scaling studies, we measure the entire end-to-end time including I/O as well as model training at scale. We measure achieved throughput in samples per second as the number of GPUs scales on the system. To reason with performance for an in-depth analysis, we use the NVIDIA Nsight tool (Bradley, 2012).

Cerebras Wafer-Scale Cluster: We also evaluated training performance on full viral genomic sequences on a Cerebras Wafer-Scale Cluster with four CS-2s (Hall et al., 2021). The Cerebras Wafer-Scale Cluster uses a weight streaming execution mode where weights are stored off-chip on MemoryX, a memory extension. Weights are streamed onto each CS-2 node using a broadcast/reduce fabric called SwarmX. Each CS-2 node is powered by the Wafer-Scale Engine, with 850,000 compute cores, 40 GB of on-chip memory, and 20 petabytes/s of memory bandwidth. After the computations, gradients are streamed back to MemoryX where weights are updated.

We used data-parallelism in the Cerebras Wafer-Scale Cluster through the appliance workflow, where no code changes or additional libraries were required to use either one or multiple CS-2 systems. GenSLM 123M and 1.3B were trained using the Cerebras reference implementation for GPT-2 model. This implementation is based on the TensorFlow estimator and is instrumented to collect accuracy, perplexity and throughput measurements. We worked with a Python virtual environment that included Cerebras software version 1.6. All training was done using mixed precision.

7 PERFORMANCE RESULTS

We evaluated performance of scaling GenSLM training on the Selene and Polaris systems. We used two target sequence lengths (2,048 and 10,240) in our scaling studies. Fig. 6 depicts performance, in terms of overall throughput measured in samples/sec, as we scaled with the number of GPUs on both systems. In our runs, we used one rank per GPU with ZeRO-3 optimizations. As we scaled the number of GPUs, we kept the batch size per GPU constant and scaled the global batch size appropriately. We modified the learning rate parameter to account for scaling the number of ranks. On Selene, for sequence length 2048, we employed twice the batch size of that on Polaris for the 25M, 250M, and 2B models, as the A100 GPUs on Selene have twice the memory capacity of those on Polaris. The performance obtained is the average of the throughput obtained over multiple iterations.

We observed that as model size increases from 25M to 25B, the total achievable throughput, in terms of samples/sec, decreases. This is expected as increasing the model size increases the computational, memory and communication requirements. In case of the 25M, 250M, and 2.5B models, we observe nearly a 2X improvement in throughput on Selene in comparison to Polaris, as a double batch size is employed. In terms of efficiency, for smaller models, such as 25M, we observed a drop in scaling efficiency as we scaled beyond 256 GPUs. Two key attributes contributing to this include the fact that for smaller model sizes that run with ZeRO-3, the ratio of data movement to computational flops is much higher that we are unable to completely overlap these. We see better performance efficiency for larger models as they have higher utilization of computation and are able to better overlap communication with computation. Some inefficiencies here are also due to the performance of collectives and we investigate this further next. In case of the 25B model, we are able to fit just a single batch on the GPU and observe a 50% improvement in the throughput achieved on Selene over Polaris. We attribute this to the increased interconnect performance we have on Selene together with the larger memory capacity. We observe a super-linear speedup for the 25B case on both systems as we scale to 1024 GPUs in comparison to the performance at 8 GPUs. This is attributed to the increased memory and data movement overheads at smaller GPU scales.

To gain detailed insights on the runs, we performed a profiling study on the 25M parameter model on both Polaris and Selene systems using the NVIDIA Nsight tool (NVIDIA, 2022). To account for the difference in the number of GPUs in a single node on both systems, we performed profiling runs with the 32 GPUs on 8 nodes on Polaris and 4 on Selene separately. It was observed that there was no significant delay between the steps/iterations - data loading and I/O was not a bottleneck. Given that the Selene DGX node has 80 GB memory compared with 40GB on the Polaris node, it allowed doubling the batch size for the 25M parameter model, thereby achieving higher throughput than Polaris.

In addition, we performed a study comparing the scaling behavior of the distributed training framework implementations for PyTorch DistributedDataParallel (DDP) and with DeepSpeed with ZeRO Stage 2 and 3 on Selene. With DDP, we were constrained to smaller model sizes as it currently does not employ any memory optimization, unlike DeepSpeed. As seen from Fig. 6(B), DDP-based runs exhibit linear behavior, while the performance of DeepSpeed runs saturated beyond 256 GPUs for the stage 2 optimizer and 512 GPUs for the stage 3 optimizations. For the 25M case, at 512 GPUs, DDP achieves 99% scaling efficiency with a 10% improvement over ZeRO Stage-3 and a 2X improvement over ZeRO Stage-2. This could be attributed to the fact that DDP implements AllReduce collective communication while DeepSpeed implements AllGather collective communication operations. The performance of the NCCL backend.
Table 3: Compute Performance of the production runs by varying the model size for a sequence length of 2,048. This includes the I/O, computations needed for forward pass, backward pass and weight updates, and communication.

<table>
<thead>
<tr>
<th>Model</th>
<th>TFlips per step</th>
<th>Time per step (sec)</th>
<th>TFlips per GPU</th>
<th>GPUs in a science run</th>
<th>Number of Steps</th>
<th>% Scaling (ZettaFlops)</th>
<th>Overall ZeTaflops</th>
</tr>
</thead>
<tbody>
<tr>
<td>25M</td>
<td>13.2</td>
<td>8.9</td>
<td>14.7</td>
<td>512</td>
<td>1550</td>
<td>46.3</td>
<td>0.01</td>
</tr>
<tr>
<td>250M</td>
<td>58.7</td>
<td>3.4</td>
<td>17.3</td>
<td>512</td>
<td>1800</td>
<td>85.9</td>
<td>0.05</td>
</tr>
<tr>
<td>2.5B</td>
<td>135.4</td>
<td>4.5</td>
<td>30.3</td>
<td>256</td>
<td>2250</td>
<td>75.2</td>
<td>0.06</td>
</tr>
<tr>
<td>25B</td>
<td>654.9</td>
<td>14.9</td>
<td>43.7</td>
<td>1024</td>
<td>1800</td>
<td>117.8</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Table 4: Final loss and perplexity values achieved by the GenSLM Foundation (F) (2,048 tokens) and SARS-CoV-2 (S) (10,240 tokens) models. Reported values for S models are trained on the first year of SARS-CoV-2 genomes. Perplexity is computed by taking the exponential of the loss and can be interpreted as the number of guesses needed for the model to correctly fill a masked token.

<table>
<thead>
<tr>
<th>Metric</th>
<th>25M F</th>
<th>250M F</th>
<th>2.5B F</th>
<th>25B F</th>
<th>25M S</th>
<th>250M S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss</td>
<td>0.57</td>
<td>0.46</td>
<td>0.30</td>
<td>0.70</td>
<td>0.015</td>
<td>0.011</td>
</tr>
<tr>
<td>Perplexity</td>
<td>1.78</td>
<td>1.59</td>
<td>1.34</td>
<td>2.01</td>
<td>1.02</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 5: Cerebras Wafer-Scale Cluster throughput training GenSLMs on a sequence length of 10,240 tokens.

<table>
<thead>
<tr>
<th>Model size</th>
<th>Samples/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>123M</td>
<td>11.1</td>
</tr>
<tr>
<td>1.3B</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Figure 6: (A) Scaling results on Polaris and Selene systems for MSL=2048; (B) Scaling behavior of DDP vs. DeepSpeed runs on Selene (C) Scaling results on Polaris and Selene systems for MSL=10240;
Table 6: Metrics of GenSLMs pretrained from scratch on a sequence length of 10240 using Cerebras Wafer-Scale Cluster.

<table>
<thead>
<tr>
<th></th>
<th>GenSLM 123M</th>
<th>GenSLM 1.3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training steps</td>
<td>5,000</td>
<td>4,500</td>
</tr>
<tr>
<td>Training samples</td>
<td>165,000</td>
<td>49,500</td>
</tr>
<tr>
<td>Time to train (h)</td>
<td>4.1</td>
<td>15.6</td>
</tr>
<tr>
<td>Validation accuracy</td>
<td>0.9615</td>
<td>0.9622</td>
</tr>
<tr>
<td>Validation perplexity</td>
<td>0.9625</td>
<td>0.9947</td>
</tr>
</tbody>
</table>

Figure 7: Workflow utilization measured by the number of active workers (applications actively serving requests) as a function of workflow runtime measured on 224 nodes of Polaris (896 A100 GPUs). The warm-apple application design realizes 97% utilization, enabling 1.9X more sequences to be generated compared to a cold start baseline.

>96% and perplexity <1.03 using one CS-2 and with four CS-2s. Validation measurements were taken from checkpoints every 500 steps. For GenSLMs of the same size, fewer training steps were required to achieve comparable validation results when the global batch size was increased in a four-CS-2 Wafer-Scale Cluster with data parallelism. Reduced number of training steps plus linear weak scaling led to a reduction of at least a third of the training time when using four CS-2s versus one. All GenSLM training with full genomes on CS-2s converged within 12 hours. GenSLM-1.3B requires fewer training samples than the smaller GenSLM-123M to achieve comparable validation metrics, following the sample efficiency observation in neural language model scaling laws (Kaplan et al., 2020). We note that further hyperparameter tuning is required to 1) optimize the throughput on the Wafer-Scale Cluster, 2) draw firmer conclusions on the impact of model size on model quality.

Workload Performance: We measured utilization of the sequence generation workflow on 224 nodes of Polaris by counting the number of workers actively serving a request as a function of runtime. As shown in Fig. 7, we achieve 97.0% utilization over the 5.5 hour duration of the workflow. Persisting the GenSLMs in GPU memory between requests generated 3.85 sequences per second, whereas without model caching we estimate the workflow would have only generated 1.98 sequences per second by extrapolating the mean cold start time across the number of workers. This achieves 1.9X faster time to solution for generating synthetic sequences with notable properties, allowing for rapid analysis at time scales not previously feasible.

8 IMPLICATIONS

In this paper, we presented GenSLMs, one of the first LLMs trained on nucleotide sequences, particularly at the genome scale, and demonstrated its performance in modeling evolutionary dynamics of SARS-CoV-2. Our approach overcomes key challenges related to training LLMs for biological data, specifically with respect to longer sequence lengths and building biologically meaningful latent spaces which can then be used for a variety of downstream prediction tasks. GenSLM is a foundation model for biological sequence data and opens up avenues for building hierarchical AI models for several biological applications, including protein annotation workflows, metagenome reconstruction, protein engineering, and biological pathway design. We scaled the training of GenSLM for sequence length up to 10240 tokens and 25B parameters on GPU-based supercomputers. We scaled to 4,096 GPUs and utilized 1.5 Zettaflops for science runs. We identified scaling avenues to be pursued in order to tackle larger models and sequence lengths needs for science. We demonstrated the efficacy of the Cerebras Wafer-Scale Cluster, an AI accelerator, to scale the training of GenSLM with high user-productivity and achieved linear scaling for 10,240 tokens and models up to 1.3B.

We also note that the information contained within nucleotide sequences represents a much richer vocabulary compared to PLMs alone. Thus, the learned representation lets us capture a much larger repertoire of biological properties that are perhaps diminished while using PLMs, and enables a more faithful generation process that captures the intrinsic organization of the SARS-CoV-2 sequences. Further, the attention mechanism also reveals co-evolutionary patterns at the whole-genome scale that requires future investigation to fully understand how these long-range interactions may influence our ability to inform epitope modeling, immune escape, antibody design, and even vaccine design strategies. We however note that there is a need to rigorously compare PLMs with GenSLM-like approaches. It remains to be seen if the GenSLM model does possess richer representative power and if so how it can be further used. Note that we have also not been able to address the aspects of noise and bias in the data — similar to natural language models where the models demonstrated extreme bias, there needs to be rigorous analyses of GenSLMs generative capabilities. We welcome the community to drive the development of suitable test harnesses for rigorously evaluating GenSLM-like models.

A straightforward extension to our work would include the integration of GenSLMs with protein structure prediction workflows such as AlphaFold (Jumper et al., 2021)/OpenFold to model both immune escape and fitness, which determine the ability of the virus to adapt to its host (human) (Beguir et al., 2022). We will also explore the use of molecular docking surrogates and faster protein folding models (Lin et al., 2022). Further, incorporating experimental data into our workflow from antibody binding assays and other quantitative metrics can also guide the training regimes for these models such that the generative process can be constrained to focus on potential future VOCs.

http://openfold.io
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