EFFECT OF MODEL AND PRETRAINING SCALE ON CATASTROPHIC FORGETTING IN NEURAL NETWORKS

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ABSTRACT

Catastrophic forgetting presents a challenge in developing deep learning models capable of continual learning, i.e. learning tasks sequentially. Recently, both computer vision and natural-language processing have witnessed great progress through the use of large-scale pretrained models. In this work, we present an empirical study of catastrophic forgetting in this pretraining paradigm. Our experiments indicate that large, pretrained ResNets and Transformers are significantly more resistant to forgetting than randomly-initialized, trained-from-scratch models; this robustness systematically improves with scale of both model and pretraining dataset size. We take initial steps towards characterizing what aspect of model representations allows them to perform continual learning so well, finding that in the pretrained models, distinct class representations grow more orthogonal with scale. Our results suggest that, when possible, scale and a diverse pretraining dataset can be useful ingredients in mitigating catastrophic forgetting.

Continual learning is a current challenge in designing machine learning systems: when trained on multiple tasks in sequence, models tend to suffer performance losses on earlier tasks—this is known as *catastrophic forgetting* (McCloskey & Cohen, 1989). Catastrophic forgetting occurs in many settings, from supervised learning for classification (Zenke et al., 2017) to reinforcement learning for games (Kirkpatrick et al., 2017) and downstream applications such as translation (Bapna & Firat, 2019) or medical diagnoses (Gupta et al., 2021). While many methods have been proposed to help mitigate forgetting, none of these have fully solved the problem; see Kemker et al. (2017) for a review.

Increasing model and dataset size have been key to the success of deep learning (Kolesnikov et al., 2020; BIG-bench collaboration, 2021; Radford et al., 2019; Zhai et al., 2021). A recent trend has been the use of increasingly large models pretrained on diverse datasets, which are subsequently fine-tuned or evaluated without fine-tuning on downstream tasks of interest; see Bommasani et al. (2021) and references therein. A particularly striking realization of this has been large pretrained language models, which show consistent improvement across scales (Kaplan et al., 2020) and can perform well on diverse tasks with no finetuning (Brown et al., 2020). From a continual learning perspective, this behavior is especially dramatic as, without finetuning, any training signal for these tasks appears mixed into a drastically larger pretraining dataset, and thus more than likely appeared many gradient steps before evaluation. This observation in large part inspired our work.

Here, we empirically study continual learning in large pretrained models. Our results suggest that pretrained models are significantly more resistant to catastrophic forgetting than their randomly-initialized counterparts, and that this resistance improves with the scale of both the model and pretraining data. Most of our experiments concern vision—specifically image classification; but we also conduct a preliminary investigation of language models.

Our key observations are as follows:

- Resistance to catastrophic forgetting improves with model and pretraining dataset scale (Figure 1).
- Large, pretrained image-classification models are significantly more resistant to forgetting than models trained from random initialization (Figure 4).
- Both supervised and unsupervised, SimCLR (Chen et al., 2020), pretraining improve forgetting (Figure 7).

- We perform initial experiments aimed at exploring why scale and pretraining reduce catastrophic forgetting, showing that distinct class representations in pretrained models are more orthogonal than in trained-from-scratch models (Figure 8).
- We observe similar phenomena in language models (Figure 9).

1 Related work

Catastrophic forgetting Catastrophic forgetting was identified as a problem for neural networks as early as the late 1980s, as it occurred in the single-hidden-layer networks that were studied at the time (see Delange et al. (2021) for a review). Within the catastrophic forgetting literature, a number of potential solutions to the problem have been devised; some involve replaying previous-task examples during training on later tasks (Rebuffi et al., 2016; Lopez-Paz & Ranzato, 2017; Chaudhry et al., 2018; Shin et al., 2017; Riemer et al., 2018), while others like elastic weight consolidation (Kirkpatrick et al., 2017) limit the extent to which parameters can change once learned (Zenke et al., 2017; Lee et al., 2017; Farajtabar et al., 2019).

Perhaps most similar to our work are proposed mitigation methods which exploit the overparameterization of modern neural networks to perform continual learning of multiple tasks, e.g. by using pruning in Mallya & Lazebnik (2018) or task-specific subnetworks in Wortsman et al. (2020) and recent works studying the impact of pretraining Anonymous (2022) and overparameterization via network width Mirzadeh et al. (2021) on forgetting.

Large-scale models The observation—initially in language models (Kaplan et al., 2020)—that model performance scales predictably with model and dataset size spurred an increased interest in training and deploying increasingly large pretrained models. Large-scale models emerged in natural-language processing with models such as GPT (Radford et al., 2019) and BERT (Devlin et al., 2019), which are pretrained in an unsupervised manner and thus able to make use of the large corpora of natural text available on the internet. More recently, image-classification models have also benefited from pretraining on large datasets (Kolesnikov et al., 2020), both supervised and unsupervised; a key example is the Vision Transformer architecture of Dosovitskiy et al. (2020), which—despite not using the inductive bias provided by convolutions—attains downstream performance comparable to convolutional networks after pretraining on ImageNet-21k (Deng et al., 2009) or JFT-300M (Sun et al., 2017). On many current NLP and computer vision benchmarks, large pretrained models achieve top performance.

All of the experiments in our work follow the pretrain-then-finetune method; recently, another paradigm, side-tuning, was proposed by Zhang et al. (2020), which avoids forgetting altogether by leaving the pretrained model fixed and employing auxiliary networks for downstream tasks.

2 Experimental setup

Tasks: Most of the experiments in this paper are conducted in the standard, task split setting (Kirkpatrick et al., 2017; Zenke et al., 2017). We consider *split CIFAR-10* task sequences – the ten class dataset is split and sequentially trained on two tasks of 5 classes each. We also consider sequential 10 and 50 class splits of CIFAR-100.

We also consider the more recent *input-distribution-shift CIFAR-100* setup (Ramasesh et al., 2021). In this case each task has the same target types made up a fixed subset of the 20 CIFAR-100 superclasses (e.g. aquatic mammals, fish, ...). The sequence of tasks consists of modifying which subclasses are sampled from. For example Task A may have aquatic mammals drawn from beaver and dolphin, while Task B may have otter and whale. This setup allows one to probe forgetting without changing the model head, in a setting where task identity is not known to the model.

For our language model experiments, we consider next token prediction generative tasks and use the IMDb Reviews (Maas et al., 2011) and english Wikipedia (Foundation) datasets.

Vision models: In most of our experiments we use the Vision Transformer (ViT) and ResNet architectures. For the Vision Transformers, we use the ViT-S and ViT-B configurations from Dosovitskiy et al. (2020) and a smaller configuration we call ViT-xS – ranging from 5.7-86.7 million parameters. For ResNets, we use five models: ResNet26, ResNet50, ResNet101, ResNet152, and ResNet200 –

ranging from 14.0-62.6 million parameters; as in Kolesnikov et al. (2020), these models use group normalization (Wu & He, 2018) and weight standarization (Qiao et al., 2019) in place of batch normalization. Details can be found in Tables 1 and 2 in Appendix A.1.2.

Pretraining: Unless otherwise specified, we pretrain our image models in a supervised manner on the ImageNet21k dataset, which contains approximately 14 million images in about 26000 distinct categories using the Adam optimizer (Kingma & Ba, 2017). Further details are in the Appendix.

Finetuning: When fine-tuning on multiple tasks in sequence, we use the SGD optimizer with momentum $\beta = 0.9$. The first task training employs a cosine decay schedule with a linear warmup; later tasks in the sequence are trained with fixed learning rates. For the split-CIFAR-10 task sequences, we use a multi-head setup in which each head is initialized to zeros.

3 Results

3.1 Forgetting improves with model scale

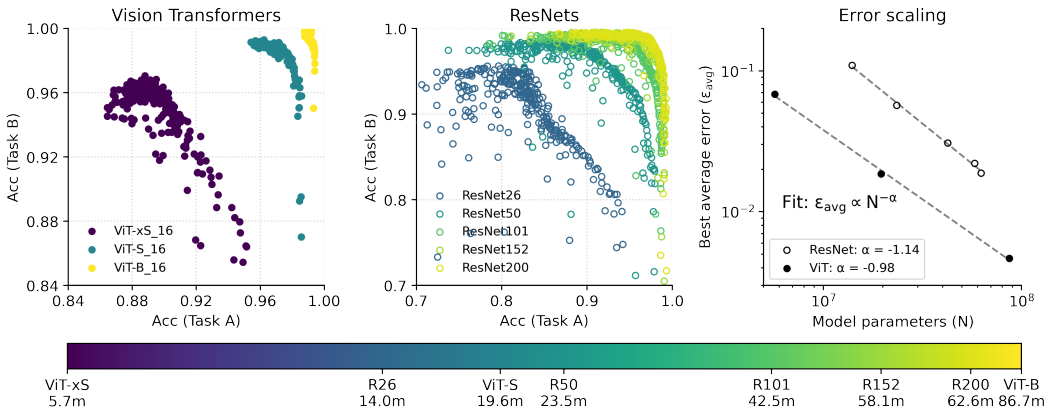

Figure 1: **Forgetting frontier across model scales**. Task A versus Task B performance for both pretrained vision transformers (left) and ResNets (center). Each point represents a different choice of learning rate or finetuning step for Task B. All models were pretrained on ImageNet21k for 90 epochs. (right) the best average Task A/B error improves systematically with model size.

Our main finding is that for both pretrained Vision Transformers and pretrained ResNets, catastrophic forgetting is mitigated to a large extent by scale: that is, larger models suffer less from forgetting. This is shown in Figure 1 for the two-task split CIFAR-10 sequence: Task A {airplane, automobile, bird, cat, deer} $\rightarrow$ Task B {dog, frog, horse, ship, truck}. In order to make a fair comparison, we plot the test accuracies of the model on both tasks at different steps of Task B fine-tuning for a variety of learning rates. This allows us to see, for each model, the maximum performance achievable on the new task for a given performance on the initial task. We call this the forgetting frontier.

Figure 1 shows that the forgetting frontier for both ViT and ResNet models improves significantly with scale. While a 5.7M-parameter ViT-xS model loses about 6.5% in Task A accuracy over the course of learning to perform Task B, an 86.7M-parameter ViT-B model loses less than half a percent. To put this in context, in a previous studies of split-CIFAR-10 task sequences, a ResNet18 model lost close to 40% accuracy with no mitigation methods, 5% when using a replay buffer, and 20% when using elastic weight consolidation (see Figure 1 of Ramasesh et al. (2021) for an example).

It is also important to note that this effect of scale and pretraining on improving forgetting frontiers does not seem to be architecture-dependent. Both vision transformers—based on self-attention—and ResNets—based on convolutions—exhibit improvements in their forgetting frontiers as they grow larger, as long as they are pretrained.

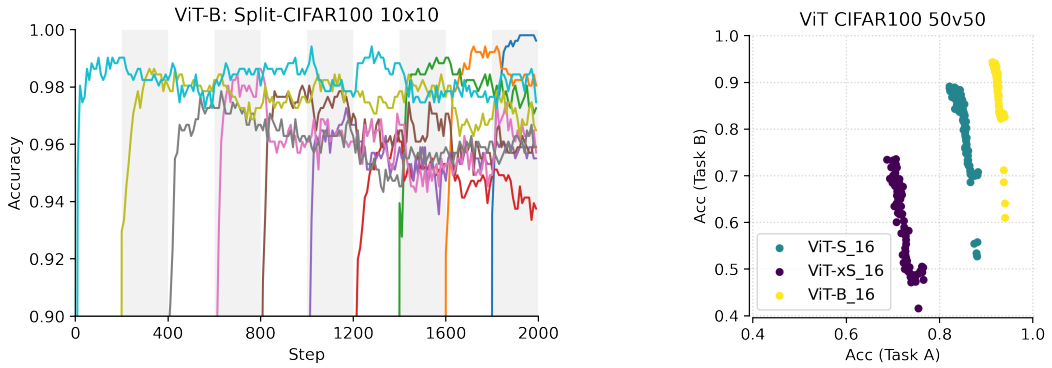

Figure 2: **Split CIFAR-100 tasks**. (left) Sequential training of a pretrained ViT-B model on a 10-task sequence, where each task consists of classifying between 10 categories in the CIFAR-100 dataset. In this continual learning setup, the model is able to learn all 10 tasks without much forgetting: on average, the model loses 1.8% accuracy on each task; at most, the model loses 2.9%. (right) Forgetting frontiers for vision transformers on a 2-task, 50-class split CIFAR-100, showing the same increase with scale as on the split-CIFAR-10 version.

We see this improvement in forgetting performance beyond the simple two-task split-CIFAR-10 scenario. Across a 10-task sequence of 10-class split-CIFAR-100 tasks (Figure 2 left), sequential 50-class splits of CIFAR-100 (Figure 2 right), and the CIFAR-100 single-head input-distribution-shift task (Figure 3), large-scale pretrained models exhibit resistance to forgetting, and continual learning ability appears to improve systematically with scale.

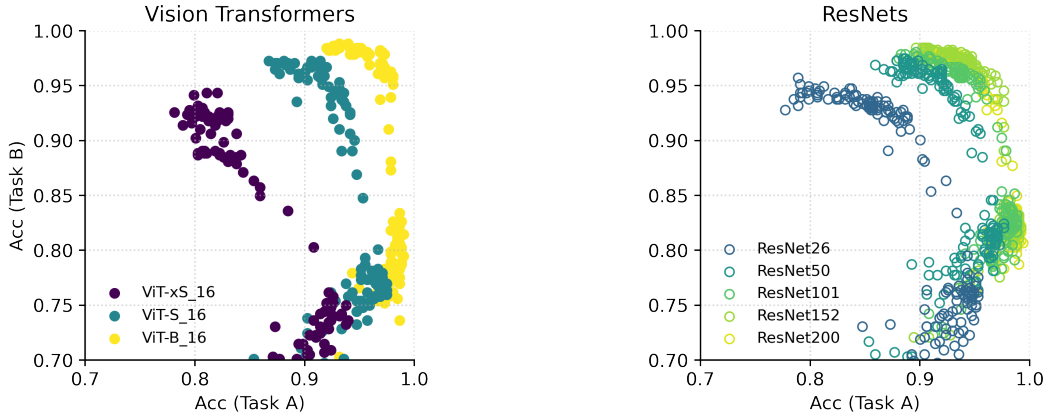

Figure 3: **Single-head models on CIFAR-100 distribution shift task**. As with the multi-head setup, the forgetting in Vision Transformers (left) and ResNets (right) is largely mitigated by pretraining and scale. The full task details are given in Appendix A.1.3

3.2 Forgetting in pretrained models vs. models trained from scratch

In the previous section, we saw that the amount of catastrophic forgetting in models pretrained on large datasets decreased with increasing model size, to the point that the largest models (ViT-B, with 86.7M parameters and ResNet200 with 62.6M parameters) suffer very little performance loss from second-task training. In this section, we investigate whether this improvement in forgetting is simply a consequence of the improvement in performance on Task A. That is, do pretraining and scale have benefits with respect to forgetting beyond simply improving the fine-tuned performance on downstream tasks?

To check this, we compare the performance and amount of forgetting in pretrained ResNet models to models trained from scratch. We handicap the pretrained ResNets so that their maximum accuracy on on Task A matches that of the corresponding trained-from-scratch ResNet; this is done simply by

reducing the number of steps for which we fine-tune. Figure 4 shows the results of this experiment, with additional results and details in Appendix B.1. While the trained-from-scratch ResNets achieve the same performance as their pretrained counterparts on Task A, their Task A performance degrades significantly more than the pretrained ResNets when trained on Task B; pretrained ResNets forget less, and this improves with model scale.

This result suggests that pretraining and model scale confer benefits upon models which go beyond simply improving performance. From Figure 4 it is also clear (see also Figure 12 in the appendix, which plots the same data in a different way) that pretraining is required to see the benefits of scale. Simply scaling up the model size in trained-from-scratch ResNets does not yield clear improvements in their forgetting performance.

We focused in this section exclusively on ResNets (rather than Vision Transformers) because obtaining decent performance on image classification tasks with Vision Transformers seems to require pretraining. In our experiments, for example, a trained-from-scratch ViT-S model was unable to achieve better than 75% test accuracy on five-class CIFAR-10, while the same model, pretrained, achieved better than 98% accuracy.

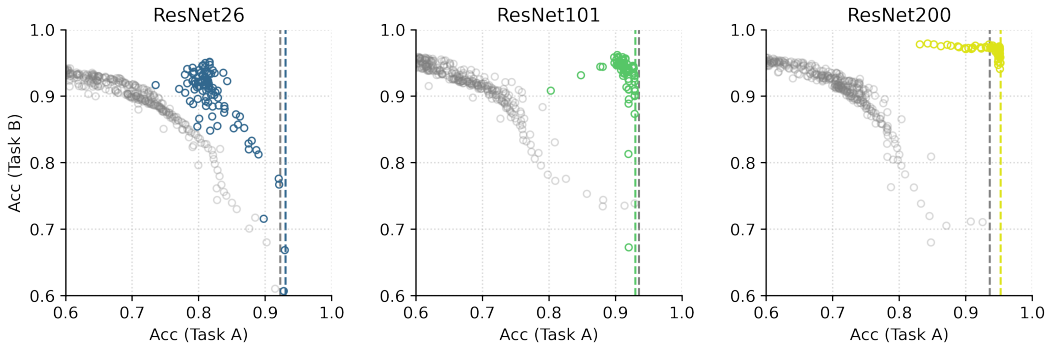

Figure 4: **Pretrained versus trained-from-scratch models**. ResNet models trained from scratch (gray) exhibit inferior forgetting performance than pretrained models (colored), even for the pretrained models shown here, which were handicapped during fine-tuning, in order to match Task A performance. Futhermore, the trained-from-scratch models are unable to take advantage of model scale – the forgetting frontier is largely independent of model size (see also Figure 12 in the Appendices). Dashed vertical lines show the maximum accuracy on Task A.

3.3 Dependence on pretraining time, pretraining dataset size, and finetuning time

Having seen in the previous sections that pretraining on large datasets improves models' resilience to catastrophic forgetting, in this section we explore the dependence of this phenomenon on the duration of pretraining, the size of the pretraining dataset, and the number of steps for which we finetune on Task A.

First, we study the influence of pretraining time on downstream forgetting. This is motivated by previous studies (e.g. Hernandez et al. (2021)) showing that downstream performance does not always monotonically improve with pretraining time and performance. By contrast, in the case of forgetting we find (see Figure 5 for ViT-S results) that as the pretraining process continues, both downstream performance and the forgetting frontier improve. This was the case for all models (ViTs and ResNets) and downstream task sequences (CIFAR-10, CIFAR-100, etc.) we studied. We found no evidence of forgetting frontiers getting worse with increased pretraining.

Along similar lines, we show the influence of pretraining data scale on downstream forgetting in Figure 6, pretraining a model on varying fractions of ImageNet21k. While the full dataset contains over 14 million images, we find that training on even one-sixteenth of the dataset (roughly the size of the standard ImageNet ILSVRC 2012 dataset) yields a model which only loses about 3% performance in forgetting on split-CIFAR-10. This suggests that one does not need to pretrain models on unreasonably large datasets in order to reap benefits for continual learning.

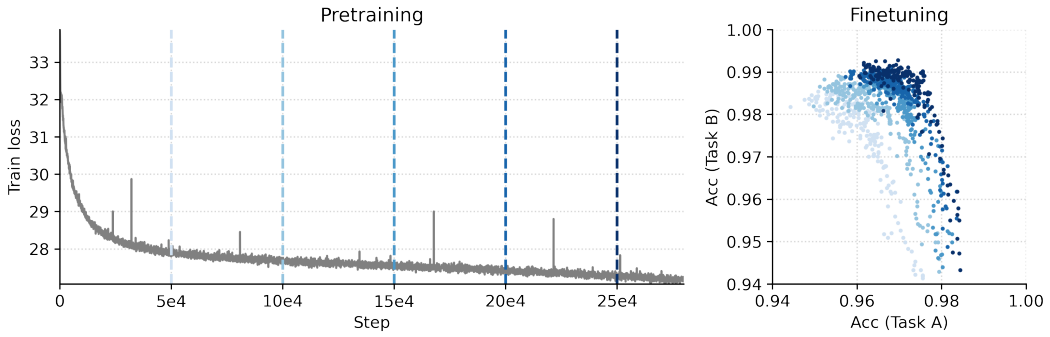

Figure 5: **Varying pretraining time**. We take pretrained checkpoints at 50k, 100k, 150k, 200k, and 250k steps (shown in colored ticks at the left) for a ViT-S model pretrained on ImageNet21k. (right) The forgetting frontiers improve with increased pretraining time.

Finally, we study the forgetting frontier of pretrained models as we vary the amount of first-task fine-tuning (number of training steps). This is partly inspired by a recent study (Andreassen et al., 2021) of robustness in pretrained models, which found that during fine-tuning, pretrained models evolved some robustness to distribution shift which vanished at the end of fine-tuning. Figure 6 shows forgetting frontiers for pretrained ViT-B and ResNet101 models, fine-tuned for a number of steps between 100 and 5000. The results in the figure suggest that in our setting, increasing the fine-tuning steps to maximize performance on Task A does not appear to cause increased forgetting. On the contrary, even training for about ten times more steps than it takes to achieve saturating performance does not impact forgetting.

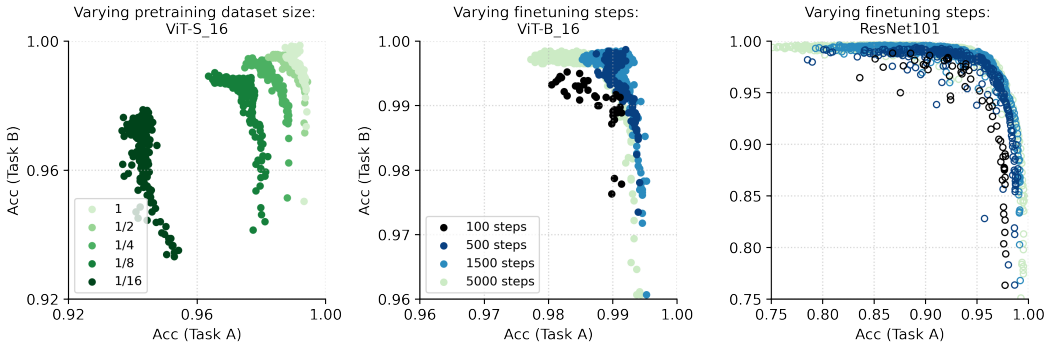

Figure 6: **Varying dataset size and finetuning time**. (left) The forgetting frontier for a vision transformer (ViT-S16) finetuned on a two-task CIFAR-10 sequence, pretrained on varying fractions of the ImageNet21k dataset shows improvement with pretraining dataset size. (center, right): The forgetting frontiers for models pretrained on ImageNet21k, with varying amounts of fine-tuning – Task A performance saturates around 500 steps; even training for ten times as many steps does not affect the forgetting frontier.

3.4 Forgetting in models with unsupervised pretraining

In previous sections, the models we studied were pretrained in a supervised manner on ImageNet21k. Part of the conceptual motivation for this work came from the properties of language models trained in an unsupervised fashion. Furthermore, recently, unsupervised pretraining methods have yielded vision models which achieve good downstream performance; among these are SimCLR (Chen et al., 2020), MoCo (He et al., 2020), DINO (Caron et al., 2021), and BYOL (Grill et al., 2020). Given the increased prevalence of such unsupervised pretraining methods, we investigate in this section whether unsupervised pretraining, combined with scale, provides resistance to forgetting similarly to supervised pretraining. We take publicly-available ResNet models which were pretrained using SimCLR on the ImageNet ILSVRC-2012 dataset (Russakovsky et al., 2015), and finetune them on the two-task split CIFAR-10 sequence. The resulting forgetting frontiers,

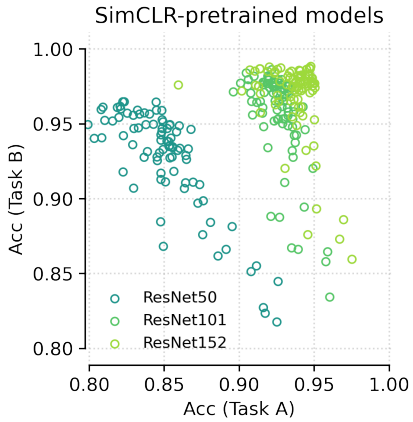

Figure 7: **Unsupervised pretraining**. ResNets pretrained using unsupervised SimCLR on ImageNet1k exhibit a similar trend to that observed in the supervised setting of forgetting robustness improving with model scale.

shown in Figure 7, show that as in supervised pretraining, SimCLR pretraining yields models which are resilient to forgetting, especially as scale is increased. We leave a thorough exploration of the continual-learning properties of other unsupervised pretraining methods for future work.

3.5 Representation overlap and forgetting

In this section we take steps toward understanding why large pretrained models seem to be resistant to forgetting. Following the work of Ramasesh et al. (2021), we measure the similarity between a models representation of Task A and Task B data.

In detail, if we denote the P model features (penultimate layer activations) on an input, x, by $f(x) \in \mathbb{R}^P$, Ramasesh et al. (2021) propose measuring the similarity of $f_A := \{f(x) : x \in \text{Task A}\} \in \mathbb{R}^{|\text{Task A}| \times P}$ and $f_B := \{f(x) : x \in \text{Task B}\} \in \mathbb{R}^{|\text{Task B}| \times P}$ using the *trace overlap*,

$$S_{AB} = \frac{\mathrm{Tr}(\Theta_{\mathrm{AB}}\Theta_{\mathrm{AB}}^{\mathrm{T}})}{\sqrt{\left(\mathrm{Tr}(\Theta_{\mathrm{AA}}\Theta_{\mathrm{AA}}^{\mathrm{T}})\mathrm{Tr}(\Theta_{\mathrm{BB}}\Theta_{\mathrm{BB}}^{\mathrm{T}})\right)}}\,. \tag{1}$$

Here $\Theta_{AB} = f_A f_B^T$ is the matrix of inner-products between Task A and Task B features.

Ramasesh et al. (2021) show empirically that forgetting is maximal for intermediate values of S_{AB}, and derive this property analytically in a simplified model. In particular Ramasesh et al. (2021) propose that a minimal trace overlap (corresponding to orthogonality of representations of different tasks) will lead to minimal forgetting. Inspired by this, we measure representation overlaps in models finetuned on split CIFAR-10, taking representations at the end of Task A training.

We consider the 10x10 matrix, S, formed by taking the indices A and B to run over the different classes in CIFAR-10. The numerator in the above expression can be thought of as an empirical (batch) estimate of the inner product between feature vectors for random draws from classes A and B; trace overlaps close to zero indicate that representations are nearly orthogonal.

Using the above definition, we return to the original split-CIFAR-10 setting of §3.1 and §3.2. For each of the models used in those experiments (see Tables 1 and 2), we compute the representation overlap matrix. We focus on two comparisons: (i) how does the representation overlap matrix differ between pretrained and trained-from-scratch ResNets? and (ii) how does the orthogonality of representations vary as we scale the model size, for both ResNets and Vision Transformers?

Pretrained vs. trained-from-scratch representations: We show representative trace overlap matrices for both pretrained and trained-from-scratch ResNet101 models in Figure 8(left and center) (see Figure 13 for additional models). Each element of this matrix corresponds to the representation overlap between two batches, each drawn entirely from a single class. The representation overlap between disjoint classes (off-diagonal class overlap matrix elements) is much smaller for

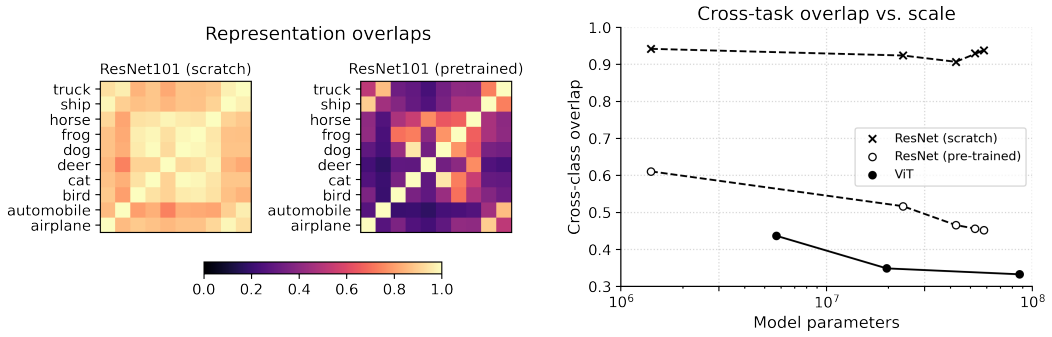

Figure 8: **Trace overlap of CIFAR-10 class representations**. (left) The cross-class representation overlap matrices (Equation 1) are significantly lower for a pretrained ResNet101 than for one trained from scratch. (right) For both Vision Transformers and ResNets, the cross-class overlap decreases as the model size increases. These representation overlaps are computed *after* training the model on the initial CIFAR-10 subtask. See Appendices for additional models and measurements.

the pretrained ResNets than those trained from scratch. Averaging cross-class overlaps over class pairs from different tasks quantifies this difference: for trained-from-scratch ResNet101, the average overlap is 0.907, while for the pretrained model this value is only 0.466. For all sizes of ResNet, the pretrained models exhibit representations which have much smaller overlap than their trained-from-scratch counterparts.

Representation overlap across scales—Figure 8(right) shows the average cross-task overlap for both ResNets and Vision Transformers plotted against model size (number of parameters). For pretrained Vision Transformers and ResNets, this overlap decreases with model size, while for trained-from-scratch ResNets, there is not a clear decreasing trend. Interestingly, Vision Transformers appear to form more orthogonal representations than ResNets do, a fact which can also be seen in the overlap matrices presented in supplementary Figure 14, and perhaps explains their improved forgetting performance.

These observations suggest that pretrained models store representations of different classes with much less overlap than trained-from-scratch models, and that this orthogonality increases with scale. As this mirrors the the observed trend in forgetting in these models, it is suggestive that the increased orthogonality of representations is a partial explanation for the forgetting resilience seen in large pretrained models.

4 Forgetting in Language Models

Transfer learning from unsupervised pretraining is commonplace in Natural Language Processing. It has become standard to pretrain models on data crawled from the internet and then finetune on smaller, downstream tasks (Devlin et al., 2019; Radford et al., 2019; Raffel et al., 2020; Brown et al., 2020). This bears similarities with both the unsupervised pretraining and the experiments in Figure 3 where a single head was used to train on different distributions (subclasses). Indeed, as mentioned above, part of the conceptual motivation for this work came from the observation that large language models with diverse pretraining perform well on tasks with no finetuning – ostensibly retaining information for many gradient steps. In this subsection and in the Supplement, we include some preliminary empirical results probing catastrophic forgetting directly in large language models.

We consider decoder only transformer models pretrained on data scraped from the web, including C4 (Raffel et al., 2020). These models range in size from 57 million to 8.6 billion non-embedding parameters and were originally trained as part of the BIG-bench collaboration (2021). In Figure 9, we consider sequentially finetuning the models on Task A: IMDb Reviews for 1.5k steps followed by Task B: english Wikipedia for 10k steps. The longer finetuning time for Task B is intended to highlight forgetting, as these models are relatively robust.

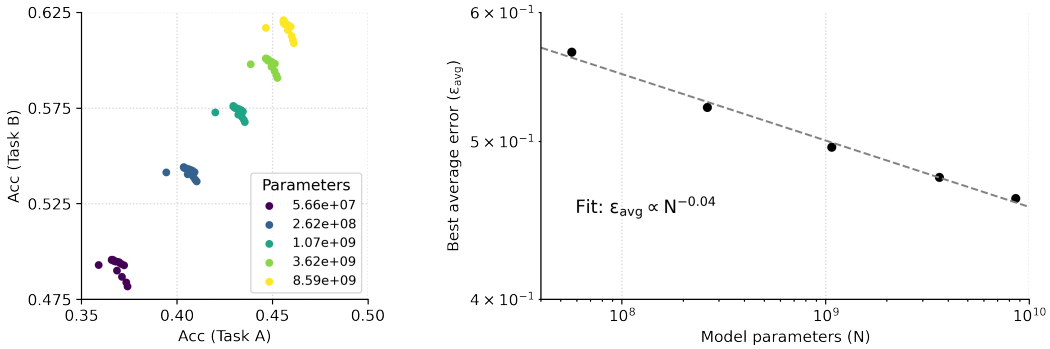

Figure 9: **Forgetting in sequential language-modeling**. Token accuracy for decoder-only transformer models show systematic improvement in joint Task A, Task B performance across scales.

We find that, as in the case of pretrained vision models, the best joint Task A, Task B performance improves with scale.

5 Discussion

The central observation we have reported in this paper is that scaling up models pretrained on large datasets is effective at mitigating catastrophic forgetting in the settings studied. While it was known that large pretrained models can achieve impressive performances in downstream tasks, our experiments show that pretraining and scale can confer benefits beyond simply the achievable downstream loss or accuracy values.

A natural question is what relationship between pretraining and finetuning tasks is required to confer benefit. In the vision setting, we considered ImageNet pretraining followed by CIFAR classification, so both pretraining and finetuning distributions consisted of natural images (albeit with different resolutions and collection techniques). In the language setting, finetining and pretraining tasks both consisted of English language modeling. It would be interesting to explore to what degree distributional overlap of pretraining and finetuning data underlies the improved resistence to forgetting.

Our work suggests natural follow-up investigations to further understand continual learning in large pretrained models. First, while we have taken initial steps towards identifying the reason for the resistance to catastrophic forgetting we observed – noting that increased orthogonality of representations is a plausible mechanism – we have not performed extensive experiments showing that this is causally linked to the forgetting behavior. Second, we explored unsupervised pretraining only via the SimCLR method; confirming that our results hold in other label-free methods such as DINO, BYOL, MoCo, and others would also be a valuable study.

Another natural direction for future work is understanding what underlies the systematic improvement with model scale (e.g. Figures 1 and 9 right). The rate at which performance improves with model size in Figure 1, with power-law exponent close to -1, is reminiscent of the *variance limited* behavior discussed in Bahri et al. (2021). Namely when the number of parameters is much larger than the training dataset size (as is the case for split-CIFAR fintetuning) performance is predicted to scale as N^{-1}. This behavior is noticeably not seen in Figure 9 for language modeling – this is reminiscent of the disparate scaling behaviors observed in Sharma & Kaplan (2020) between language modeling and classification tasks. More generally, understanding what underlies and predicting the rate of improvement to forgetting with model size is an important direction for future research.

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A EXPERIMENTAL DETAILS

A.1 VISION

A.1.1 SUPERVISED PRETRAINING

Here we detail the settings used to in supervised pretraining, resulting in the models used in the experiments of sections 3.1, 3.2, 3.3, and 3.4. We pretrain seven models: (ViT-B, ViT-S, ViT-xS, R26x1, R50x1, R101x1, R152x1, R200x1) on ImageNet21k for 90 epochs. Pretraining is done using the Adam optimizer ($\beta_1 = 0.9$ and $\beta_2 = 0.999$); for all models, we use a batch size of 4096. Our learning-rate schedule includes a warmup of 10k steps to a maximum learning rate $\eta = 10^{-3}$, followed by a linear decay to 10^{-5}. For the Vision Transformer models, we use a weight decay penalty of 0.03 and a dropout rate of 0.1; for ResNet models, we do not use weight decay or dropout. These settings are largely identical to those found in Dosovitskiy et al. (2020).

A note on ImageNet21k: We use the version of ImageNet21k available in TensorFlow Datasets 4.0.1 and apply minimal preprocessing, simply converting the labels to one-hot vectors and cropping the image to be 224x224 pixels in size. During training, this crop is an Inception-style random crop, while during evaluation it is a deterministic central crop; during training we additionally augment the data by performing random horizontal flips and apply label smoothing, with values 0.9999 and 0.0001. Importantly, ImageNet21k is class-imbalanced and heavy-tailed, with the uneven distribution of label occurrences shown in Figure 10. We do not balance the dataset.

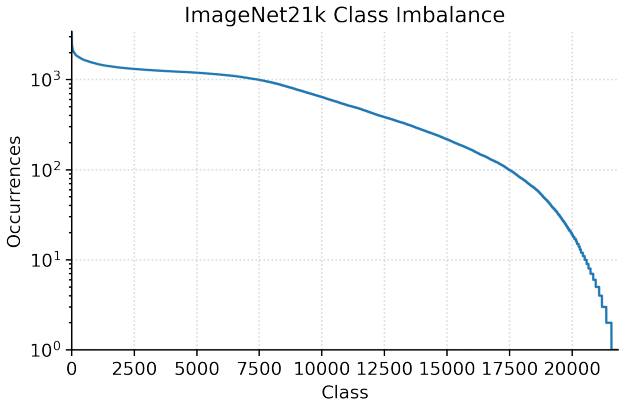

Figure 10: **ImageNet21k is highly class-imbalanced**. While roughly 7500 classes of the ImageNet21k dataset feature over 1000 examples, there are over 3000 classes with less than 100 examples. As mentioned in the main text, in this work we do not class-balance ImageNet21k before pretraining.

A.1.2 VISION TRANSFORMER MODEL DETAILS

For full description of the Vision Transformer architecture, see the original paper by Dosovitskiy et al. (2020). Abbreviated details are given here. We process 2D images of height H, width W, and C channels, $\mathbf{x} \in \mathbb{R}^{H \times W \times C}$ by first reshaping them into a 1D sequence of flattened patches–in this work, we exclusively use patch size 16. Each patch is mapped (via a learned linear transformation) to an embedding vector of dimension D (for our models, $D_{xS} = 256$, $D_S = 516$, and $D_B = 768$, as in Table 1). As both our pretraining and finetuning is supervised, we prepend a (learnable) '[class]' token embedding to this sequence of patches, add a learnable 1D position embedding, and pass the sequence through the Transformer encoder. The Transformer encoder alternates between multi-headed self-attention layers and MLP (plus residual connection) layers, with layernorm applied before both the attention and MLP layers.

For classification, we use a classification head which acts on only the transformed '[class]' token representation. During pretraining, this classification head is an single-hidden-layer MLP, as in the original Vision Transformer work; during finetuning, the classification head is a linear layer (in the

split-CIFAR-10 setting, we use a multi-head setup with a different classification layer for each task in the sequence). We initialize all classification layers with zeros.

Table 1: Configurations of ViT models

Model	Layers	Width	Dim.	Heads	Params
ViT-xS	4	256	256	4	5.7M
ViT-S	6	516	516	6	19.6M
ViT-B	12	768	768	12	86.7M

Table 2: Configurations of ResNet models

Model	Resblocks	Params
R26	[2, 2, 2, 2]	14.0M
R50	[3, 4, 6, 3]	23.5M
R101	[3, 4, 23, 3]	42.5M
R152	[3, 8, 36, 3]	58.1M
R200	[3, 24,36,3]	62.6M

A.1.3 CIFAR-100 Distribution Shift Task

Here we provide more information about the CIFAR-100 distribution-shift task, which was introduced in Ramasesh et al. (2021) and forms the basis of our experiments in section A.1.3 of the main text. The idea behind this task is to mimic a way in which catastrophic forgetting might occur in practice, in image-classification settings where the class labels remain constant but the distribution of the images changes. A key features of this type of setting is that the identity of the task is not known to the model at inference time, so task-specific components (such as multiple readout layers) are not allowed. For example, in a medical setting, one might seek to classify images as displaying signs of a disease or not, and the system might be trained sequentially on images taken at various hospitals. While the CIFAR-100 dataset features images divided into 100 distinct classes, these classes are grouped into 20 *superclasses*. The CIFAR-100 distribution shift task sequence involves classifying an image by its superclass; individual tasks in the sequence draw images from a single subclass for each superclass. As a concrete example, in the experiments in the main text we use the five superclasses *aquatic mammals*, *fruits and vegetables*, *household electrical devices*, *trees*, and *vehicles-1*[1]. For the first task in the sequence, Task A, we uses the classes dolphin (for aquatic mammals), apple (for fruits and vegetables), lamp (for household electrical devices), maple tree (for trees), and bicycle (for vehicles-1). For the second task, Task B, we use the classes whale (for aquatic mammals), orange (for fruits and vegetables), television (for household electrical devices), willow (for trees), and motorcycle (for vehicles-2).

A.2 Finetuning experimental details

In this section we provide details on the finetuning procedures for the experiments in the main text. All finetuning was done using stochastic gradient descent with momentum ($\beta = 0.9$), clipping gradients at unity; batch size is fixed at 512. In the first task, we used a schedule with a 5-step linear ramp to a maximum learning rate followed by a cosine decay to zero over the full first-task training. In the second task, we used constant learning rates.

Section 3.1, Figure 1: Finetuning both the Vision Transformers and ResNets was done for 500 steps. For Vision Transformers, the first-task training used a warm-up from $\eta = 0.01$ to $\eta = 0.05$. For each model we perform four different runs, with second-task (constant) learning rates 0.001, 0.003, 0.007, and 0.01. For ResNets, the task-A learning rate warm-up was from $\eta = 0.002$ to $\eta = 0.01$. The (constant) second-task learning rates we used were 0.008, 0.004, 0.002, 0.001, 0.0003, and 0.0001.

Section 3.1, Figure 2: In the 10-task split-CIFAR100 sequence (left), each task was trained for 200 steps; the initial task used a learning-rate schedule with a 5-step warmup from $\eta = 0.01$ to $\eta = 0.05$ followed by a cosine decay to 0 over the 200 steps, while all subsequent steps used constant $\eta = 0.005$. In the 2-task 50-class split-CIFAR100 sequence (right), the settings are identical to those of the Vision Transformer training in Figure 1.

Section 3.1, Figure 3: For ResNets, we used a first-task warmup from $\eta = 0.001$ to $\eta = 0.005$, and trained each task for 300 steps. Constant second-task learning rates were 0.001, 0.0003, and

[1]The CIFAR-100 dataset features two vehicle superclasses, denoted *vehicles-1* and *vehicles-2*

	Head Only	Full finetuning		Head Only	Full Finetuning
ViT-xS_16	0.7676	0.9527	ResNet26	0.8767	0.9474
ViT-S_16	0.7906	0.9857	ResNet50	0.9030	0.9805
ViT-B_16	0.9490	0.9937	ResNet101	0.9371	0.9896
			ResNet152	0.9362	0.9913
			ResNet200	0.9557	0.9933

Table 3: Accuracies achieved by training a linear classifier on the task A split of CIFAR10 (used in the main text), freezing the features of the pretrained models after training on ImageNet21k.

0.0001. For Vision Transformers, we trained each task for 200 steps, using a first-task warmup from $\eta = 0.01$ to $\eta = 0.05$. Constant second-task learning rates were 0.01, 0.003, and 0.001.

Section 3.2, Figure 4: The pretrained models in this figure were the same as those in Figure 1. For the trained-from-scratch models, we used a linear warm-up from $\eta = 0.006$ to $\eta = 0.03$, and trained each task for 15,000 steps. Constant second-task learning rates were 0.001, 0.0003, and 0.0001. Note that training here is much longer than for the pretrained models.

Section 3.3, Figure 5: Vision Transformer training settings are identical to those of Figure 1.

Section 3.3, Figure 6: In the left panel, Vision Transformer training settings are identical to those of Figure 1. In the right two panels, settings are also identical to those of Figure 1, with the exception of the number of finetuning steps, as indicated in the figure legend.

Section 3.4, Figure 7: We finetune for 300 steps on each task, with a maximum learning rate of $\eta = 0.0002$ (we omit the linear warm-up for these models, but keep the cosine decay). Constant second-task learning rates are $\eta = 0.0002$, $\eta = 0.0001$, $\eta = 0.00004$, and $\eta = 0.00002$.

A.3 Language

Models are decoder-only transformers which were pretrained using Adafactor and learning rate 1.0, context length 1024 and batch size 256. We finetuned with batch size of 8 and set a constant learning rate equal to the learning rate at the end of pretraining rescaled by the relative batch size, $8/256$.

B Additional results

B.1 Comparing pretrained and trained-from-scratch ResNets

In the main text, we showed forgetting frontiers on the split-CIFAR-10 task sequence for selected ResNet models: ResNet26, ResNet101, and ResNet200. Here, we show the forgetting frontiers for all ResNets (11), and we also plot the data in a slightly different way (12) to make it apparent that while the forgetting frontiers of the pretrained ResNet models clearly improve with model size, the forgetting frontiers of trained-from-scratch ResNet models do not.

B.2 Head-only training

One way to probe the quality of representations generated by the pre-trained models are to train a simple linear classifier on the initial five-class split of CIFARR10, freezing the representations after pre-training (on ImageNet21k). As shown in Table 3, even with freezing the model weights, a linear classifier can achieve high accuracy on the downstream tasks.

B.3 Representation overlap matrices for all ResNet and ViT models

In the main text, we described the computation of the classwise representation overlap matrices for our models at the end of Task A training, showing an example of such a matrix for both a pretrained and a trained-from-scratch ResNet101 model. In Figure 13, we show representation overlap matrices for all of the ResNet models, which bears out our statement in the main text that pretrained ResNet representations were much closer to orthogonal than their trained-from-scratch counterparts. In Figure 14, we show representation overlap matrices for the (pretrained) Vision Transformer models.

As with the pretrained ResNet models, the cross-class representation overlaps become closer to orthogonal as we increase the model size.

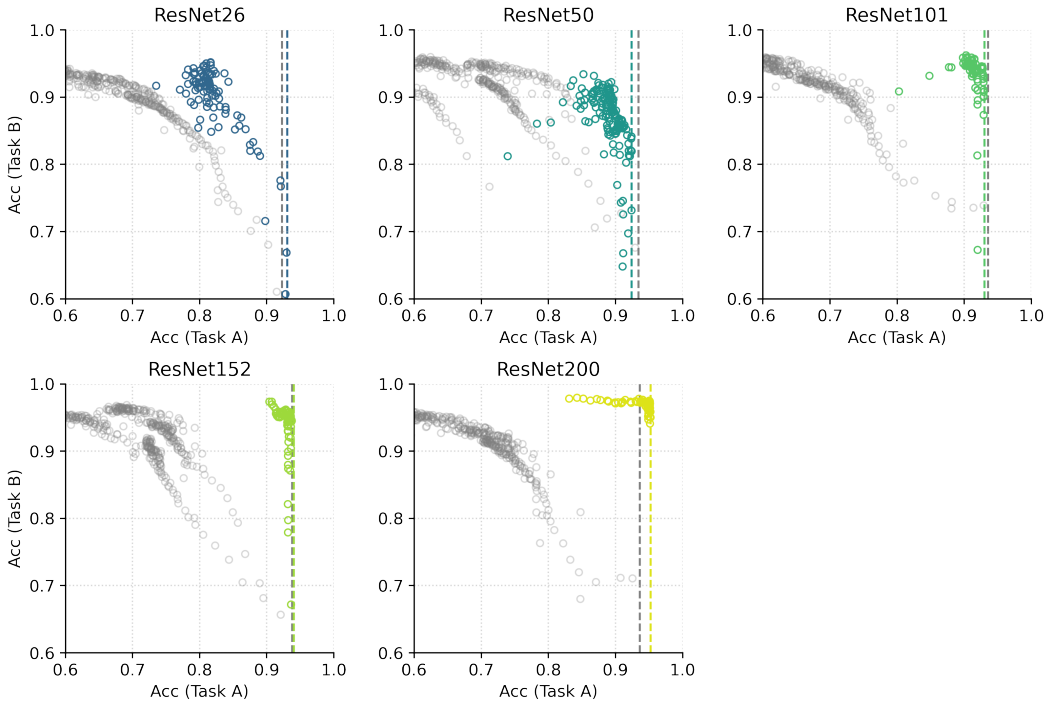

Figure 11: Forgetting frontier for ResNets trained from scratch, vs. pretrained ResNets (on ImageNet21k). The pretrained ResNets were handicapped during fine-tuning, in order to match the Task A performance of the from-scratch model. This figure is identical to Figure 4 in the main text, with the addition of the ResNet50 and ResNet152 models.

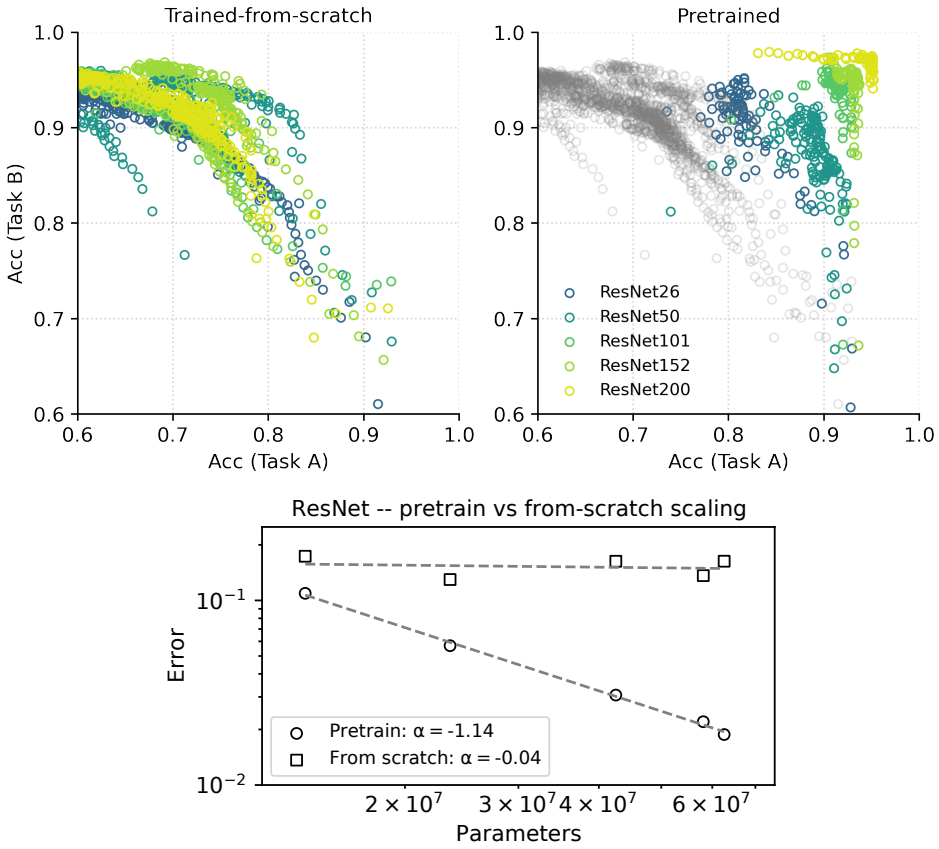

Figure 12: Forgetting frontier for ResNets trained from scratch, vs. pretrained ResNets (on ImageNet21k). The pretrained ResNets were handicapped during fine-tuning, in order to match the Task A performance of the from-scratch model. The data plotted here is the same as that plotted in Figure 4 in the main text; here, the intention is to make clear that the performance of the trained-from-scratch models do not exhibit any apparent benefit with scale, while the pretrained models do.

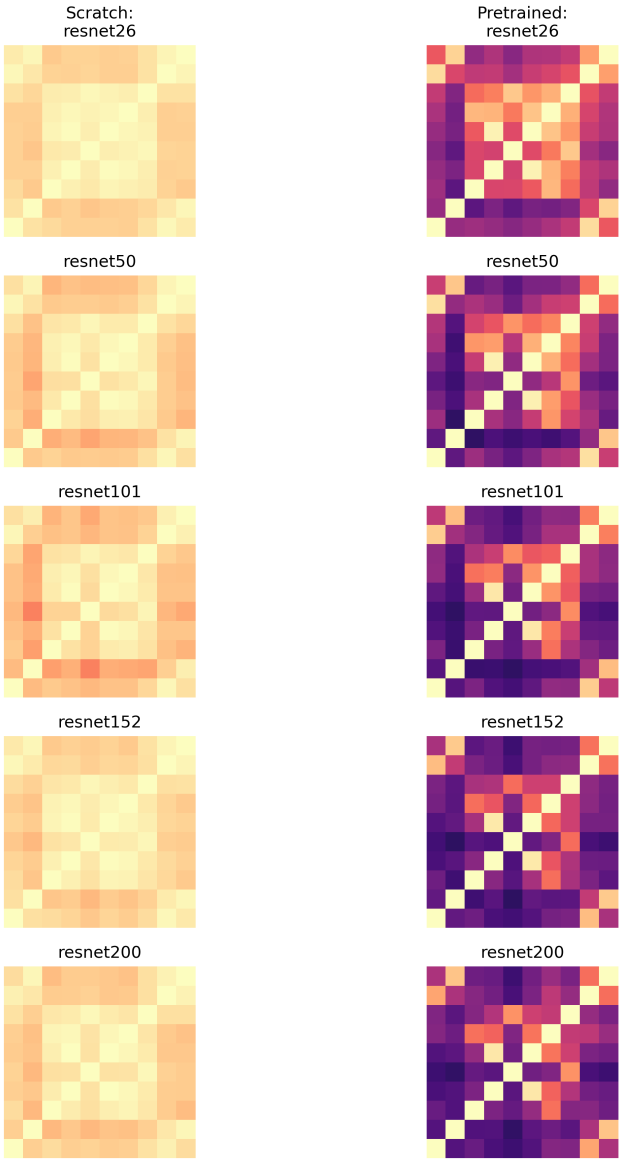

Figure 13: Classwise representation matrices for ResNet models, taken after the end of training on the first task (Task A) of a two-task split CIFAR-10 sequence. Classes are ordered alphabetically, left to right and down to up, i.e. the order is *airplane*, *automobile*, *bird*, *cat*, *deer*, *dog*, *frog*, *horse*, *ship*, *truck*.

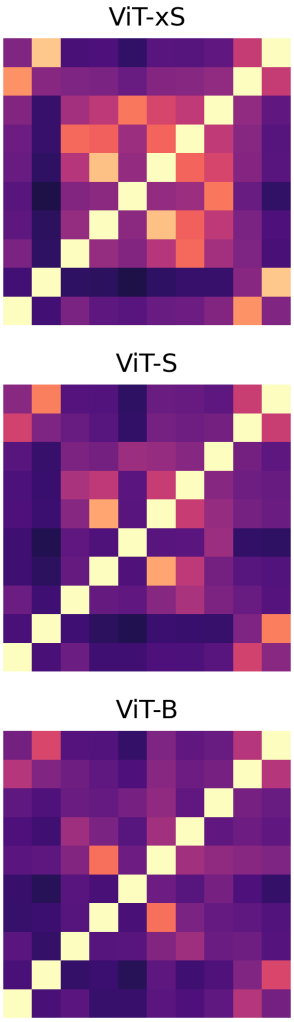

Figure 14: Classwise representation matrices for Vision Transformer models, taken after the end of training on the first task (Task A) of a two-task split CIFAR-10 sequence. Classes are ordered alphabetically, left to right and down to up, i.e. the order is *airplane*, *automobile*, *bird*, *cat*, *deer*, *dog*, *frog*, *horse*, *ship*, *truck*.

Task A	Task B	Task C	Task D	Task E
Apple	Bowl	Chair	Dolphin	Lamp
Aquarium Fish	Boy	Chimpanzee	Elephant	Lawnmower
Baby	Bridge	Clock	Flatfish	Leopard
Bear	Bus	Cloud	Forest	Lion
Beaver	Butterfly	Cockroach	Fox	Lizard
Bed	Camel	Couch	Girl	Lobster
Bee	Can	Crab	Hamster	Man
Beetle	Castle	Crocodile	House	Maple tree
Bicycle	Caterpillar	Cup	Kangaroo	Motorcycle
Bottle	Cattle	Dinosaur	Keyboard	Mountain

Task F	Task G	Task H	Task I	Task J
Mouse	Plain	Rose	Squirrel	Train
Mushroom	Plate	Sea	Streetcar	Trout
Oak tree	Poppy	Seal	Sunflower	Tulip
Orange	Porcupine	Shark	Sweet pepper	Turtle
Orchid	Possum	Shrew	Table	Wardrobe
Otter	Rabbit	Skunk	Tank	Whale
Palm tree	Raccoon	Skyscraper	Telephone	Willow tree
Pear	Ray	Snail	Television	Wolf
Pickup truck	Road	Snake	Tiger	Woman
Pine tree	Rocket	Spider	Tractor	Worm

Table 4: 10-subtask split of CIFAR100 used in our experiments.

B.4 More language results

For completeness, Figure 15 displays the token accuracy on task A as a function of the number of steps.

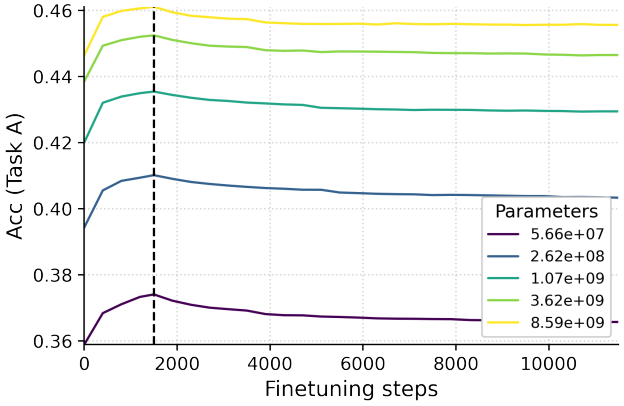

Figure 15: **Forgetting in sequential language-modeling**. Token accuracy as a function of steps for the different models.

B.5 Extension past the two-task setting

In this section, we extend our results on vision past the two-task setting which was the primary focus of the main text. Specifically, we use a 10-class, 10-subtask split of the CIFAR100 dataset to study how forgetting in this scenario varies as a function of model and dataset scale. The specific split we use is shown in Table 4. As in the main text, we study the performance of Vision Transformer and ResNet models.

We find that:

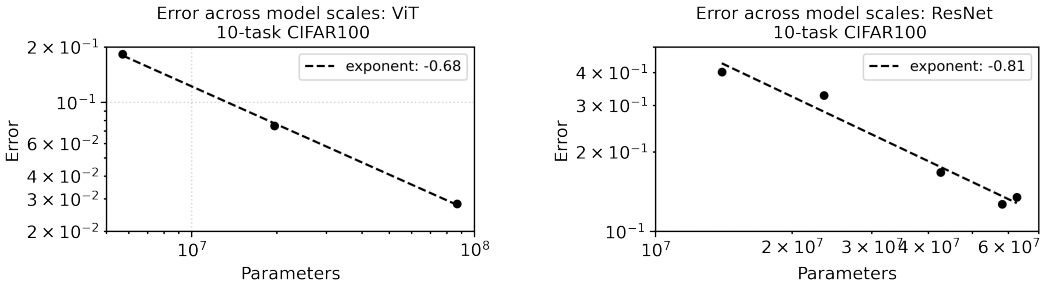

Figure 16: **Model scaling on 10-subtask split-CIFAR100**. (left) Scaling of best average error with parameter count for vision transformer models. (right) Scaling of best average error with parameter count for ResNet models.

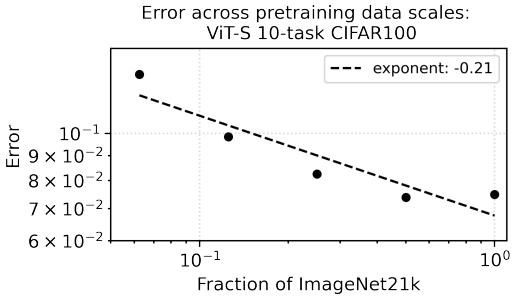

Figure 17: **Data scaling on 10-subtask split-CIFAR100**. Scaling of best average error with pre-training dataset size (measured in a fraction of the full ImageNet21k dataset) for the ViT-S_16 model.

- As in the two-task setting, both the forgetting frontiers and the best average accuracy improve with model scale as a power-law in the number of model parameters.
- When we scale the size of the pre-training dataset, we also observe an improvement with scale, though with some saturation around the full ImageNet21k dataset..

Model scaling: Model-scaling plots showing the best average accuracy as a function of model parameters are show in Figure 16. As in the two-task split CIFAR10 sequence, these scaling plots are one way to show that the continual-learning performance of both architectures improves with scale. The power-law exponents are different in this 10-task setting than they are for the two-task setting, but interestingly all are close to unity.

Another way to see the improvement in continual-learning ability with model scale is to plot forgetting frontiers, which we do in Figures 18 and 19. In this setting with more than two tasks, plotting a single forgetting frontier is not possible, but we plot two-task frontiers for all pairs of subtasks (with 10 subtasks, there are $10 \times 9/2 = 45$ pairs). These frontiers are constructed in exactly the same way as the two-task frontiers, showing the test accuracies for each subtask throughout the entirety of the 10-task training. As the figures show, forgetting frontiers of larger models dominate the forgetting frontiers of smaller models of the same architecture. This complements the previous scaling-plot as a demonstration of improving continual-learning with scale, though the behavior here is not as clean as it was in the two-task setting.

Data scaling: A data-scaling plot showing the best average accuracy for a ViT-S model as a function of pretraining dataset size is shown in Figure 17. Forgetting frontiers are shown in Figure 20.

C Learning rate and step

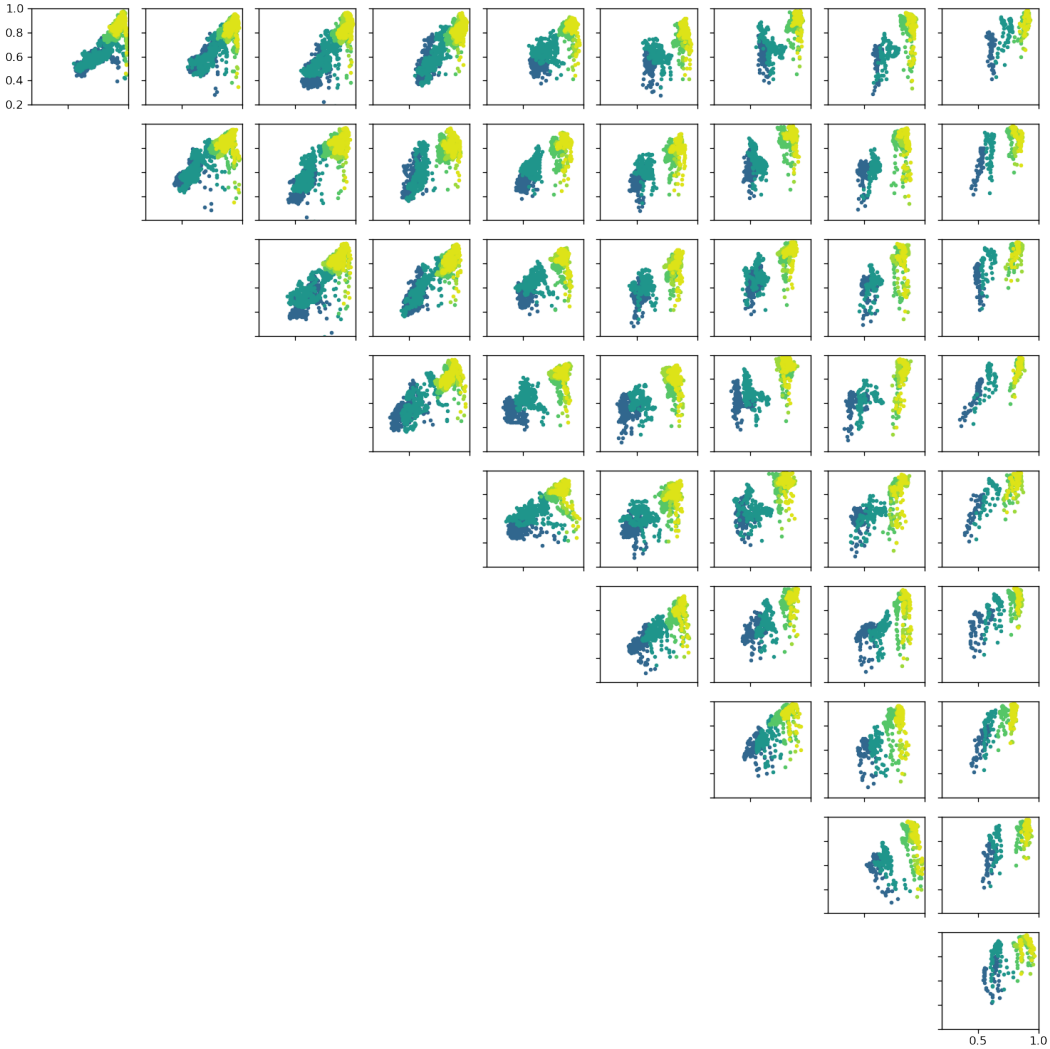

Figure 18: **Forgetting frontiers for 10-task Split CIFAR100, Resnet**. Colors are the same as in Figure 1 of the main text. All images in each row share the same task for the x-axis, i.e. the x-axis of the top row represents task A, x-axis of the second-from-the-top row represents task B, etc. All images in each column share the same task for y-axis, i.e. the y-axis of the leftmost column represents task B, the y-axis of the second-to-leftmost column represents task C, etc.

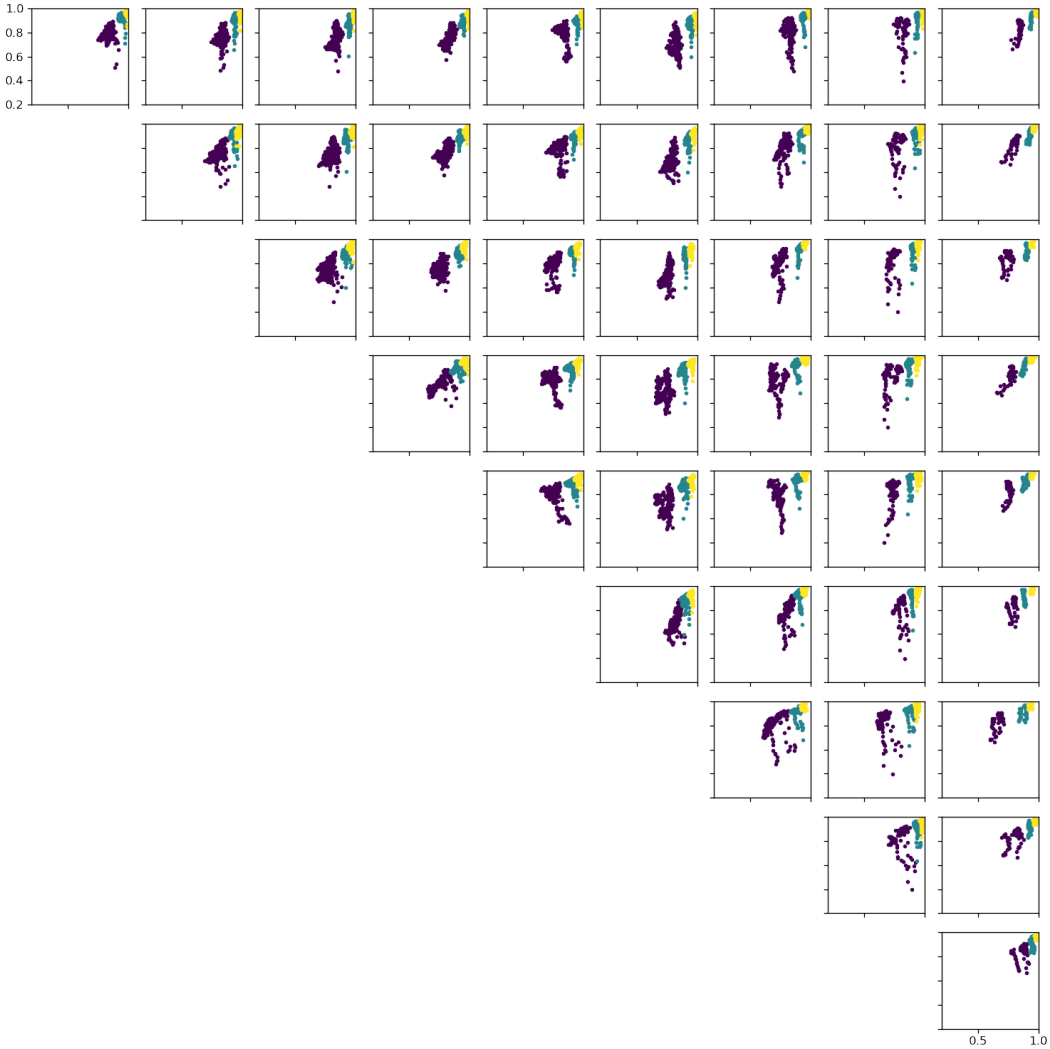

Figure 19: **Forgetting frontiers for 10-task Split CIFAR100, Vision Transformer**. Colors are the same as in Figure 1 of the main text. All images in each row share the same task for the x-axis, i.e. the x-axis of the top row represents task A, x-axis of the second-from-the-top row represents task B, etc. All images in each column share the same task for y-axis, i.e. the y-axis of the leftmost column represents task B, the y-axis of the second-to-leftmost column represents task C, etc.

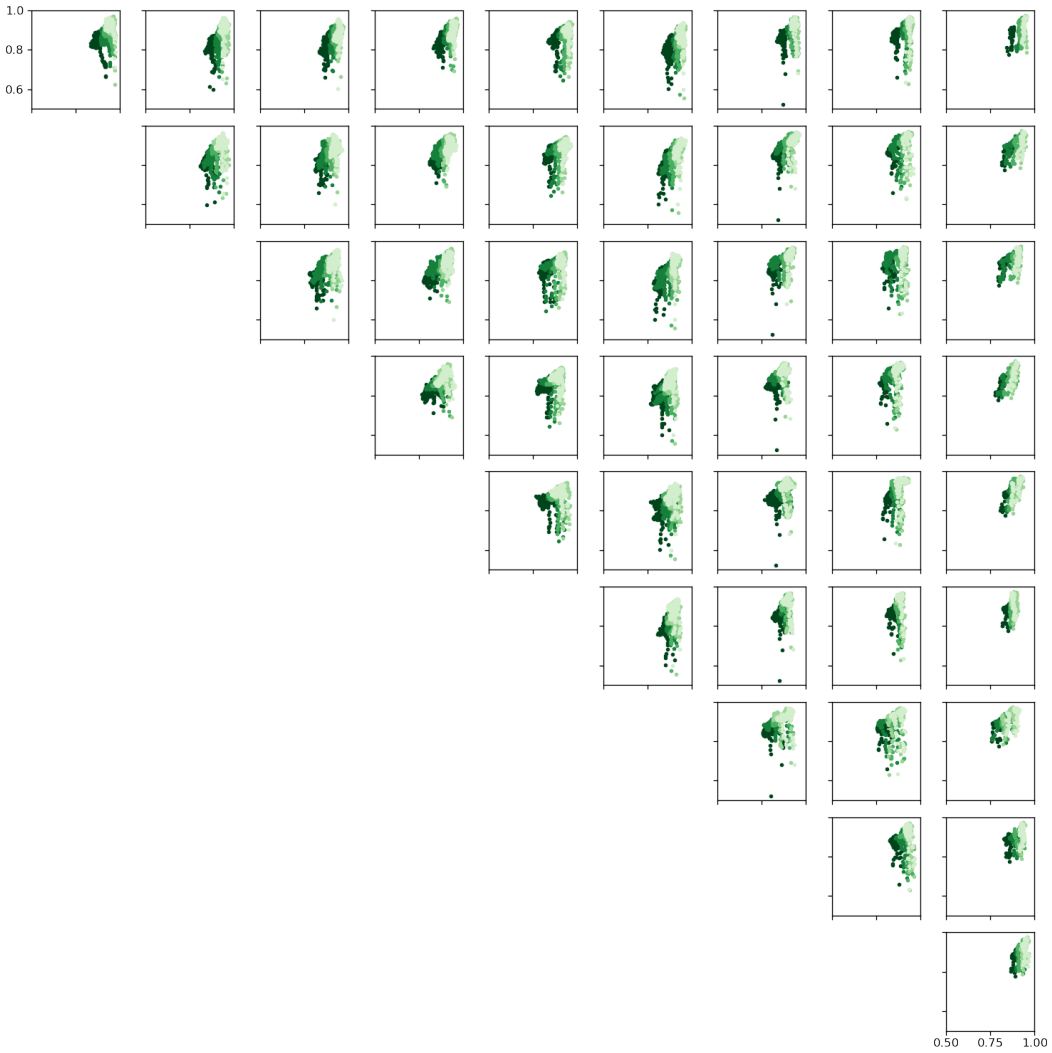

Figure 20: **Forgetting frontiers for 10-task Split CIFAR100 versus data scale**. These frontiers are plotted for a ViT-S_16 model. Colors are the same as in Figure 6(left) of the main text. All images in each row share the same task for the x-axis, i.e. the x-axis of the top row represents task A, x-axis of the second-from-the-top row represents task B, etc. All images in each column share the same task for y-axis, i.e. the y-axis of the leftmost column represents task B, the y-axis of the second-to-leftmost column represents task C, etc.

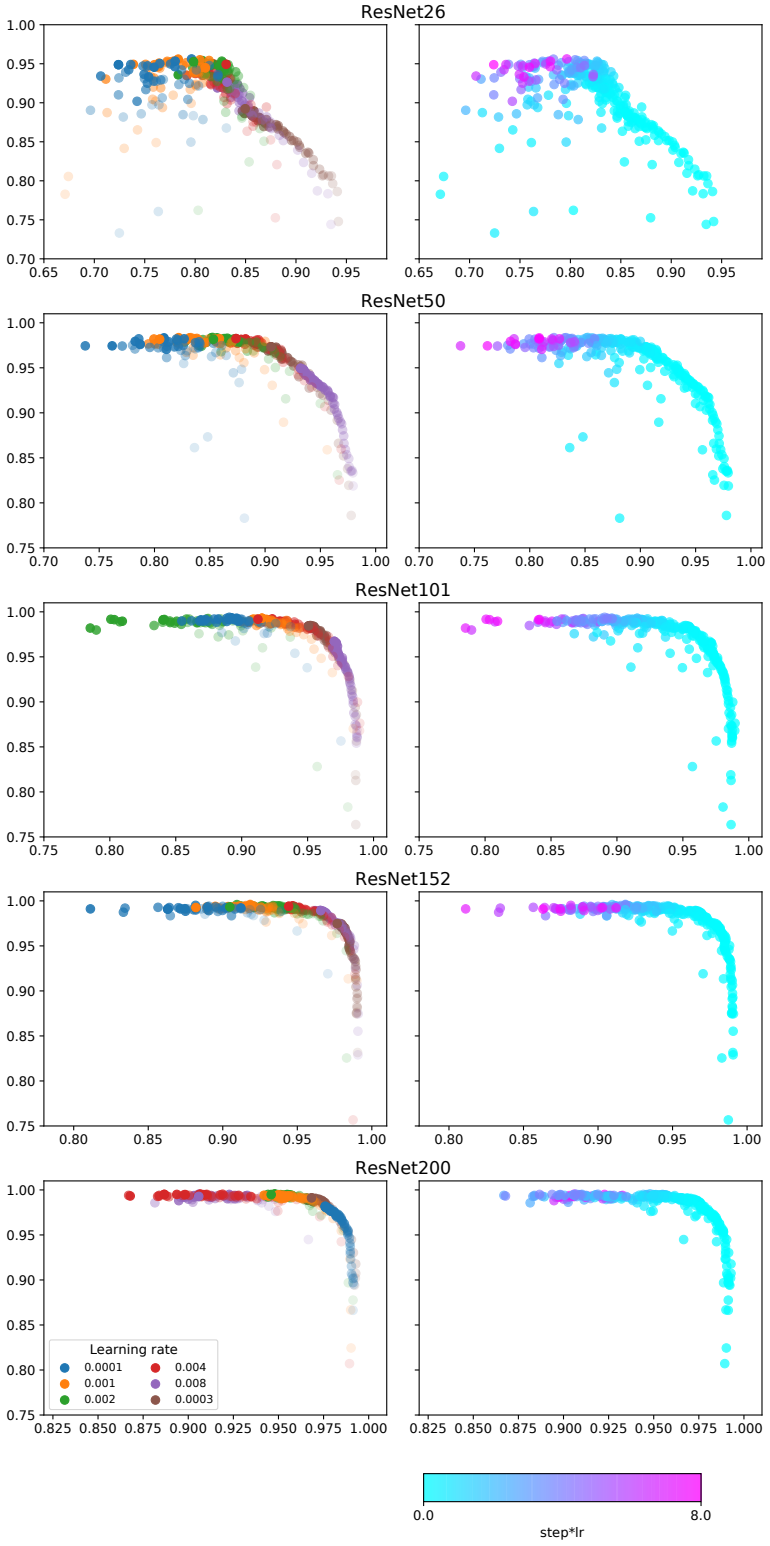

Figure 21: **Step and learning rate along forgetting frontier for ResNets**. We plot the forgetting frontier of Figure 1. The left column is colored by learning rate with transparency set by step (darker) is later during task 2 training. The right column is colored by step times learning rate.

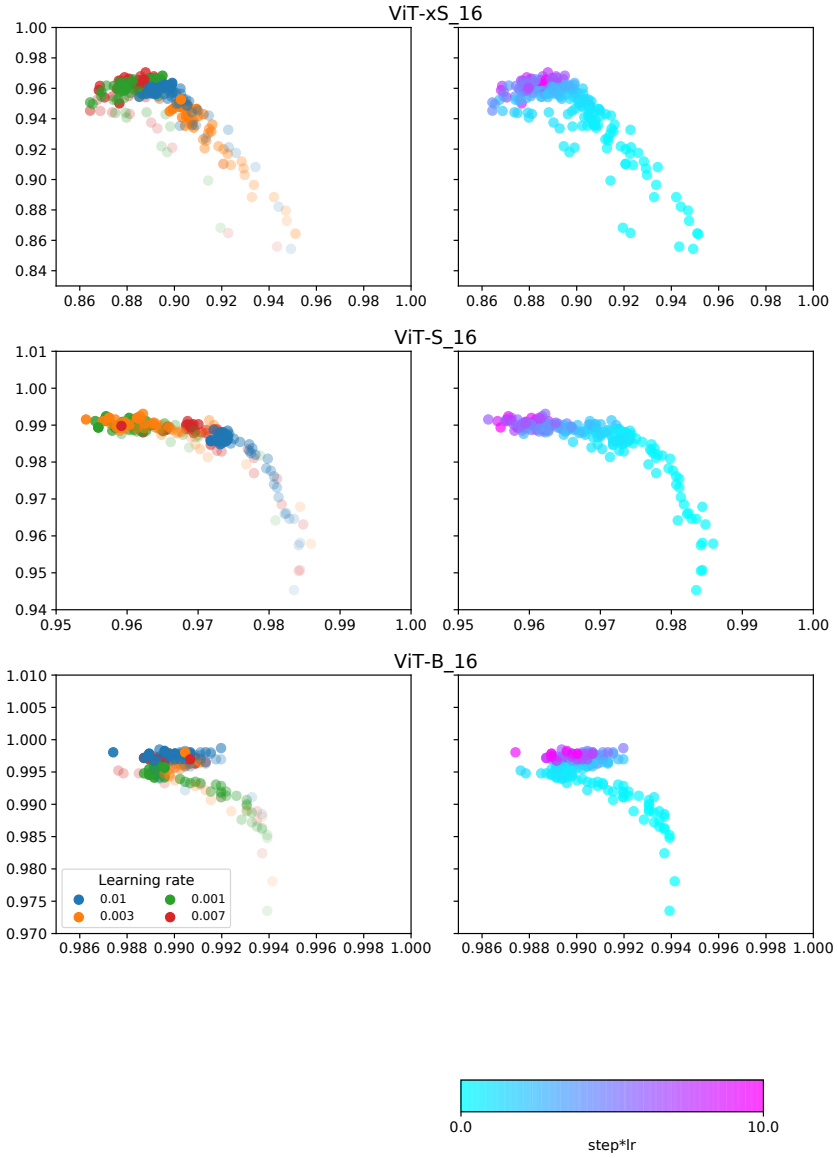

Figure 22: **Step and learning rate along forgetting frontier for ViT models**. We plot the forgetting frontier of Figure 1. The left column is colored by learning rate with transparency set by step (darker) is later during task 2 training. The right column is colored by step times learning rate.

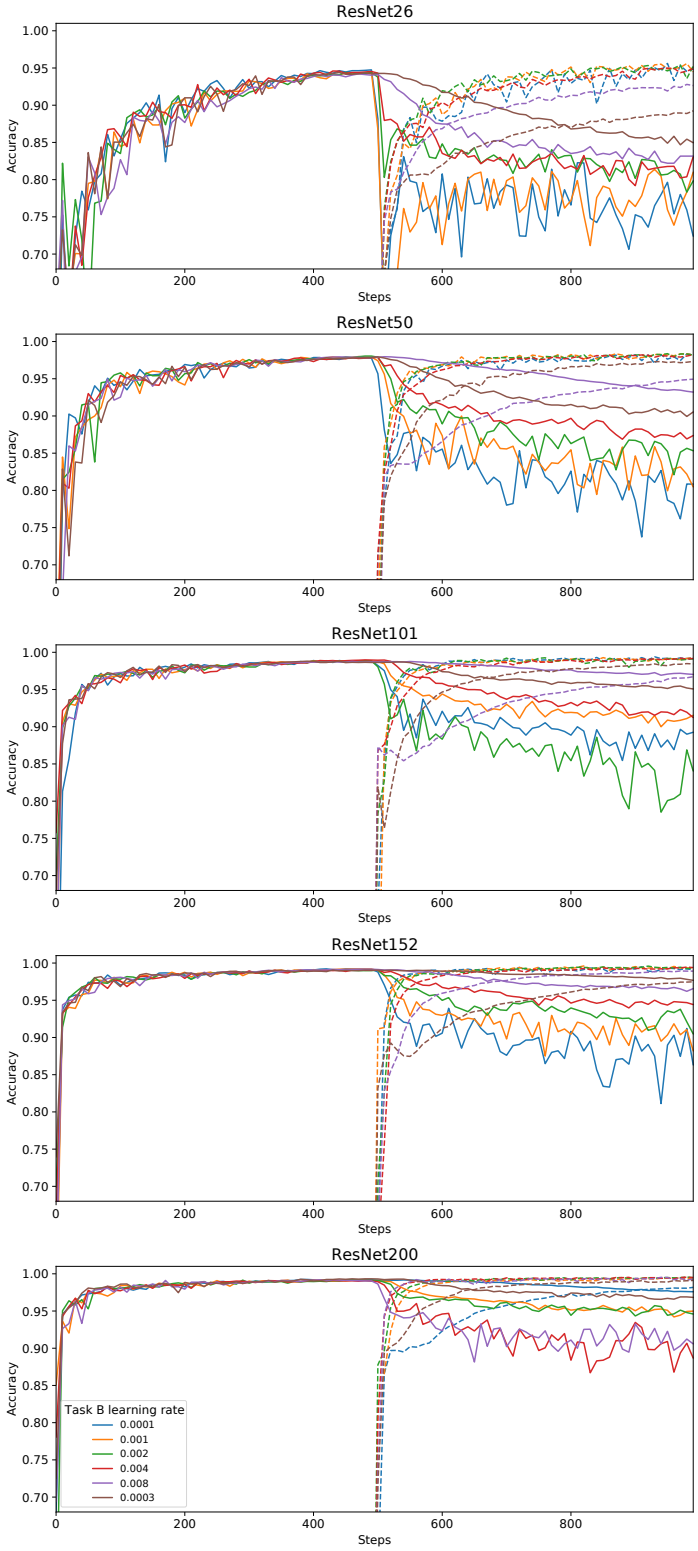

Figure 23: **ResNet Learning curves**. Learning curves for the ResNet models of Figure 1. The solid/dashed lines are Task A/B accuracy.

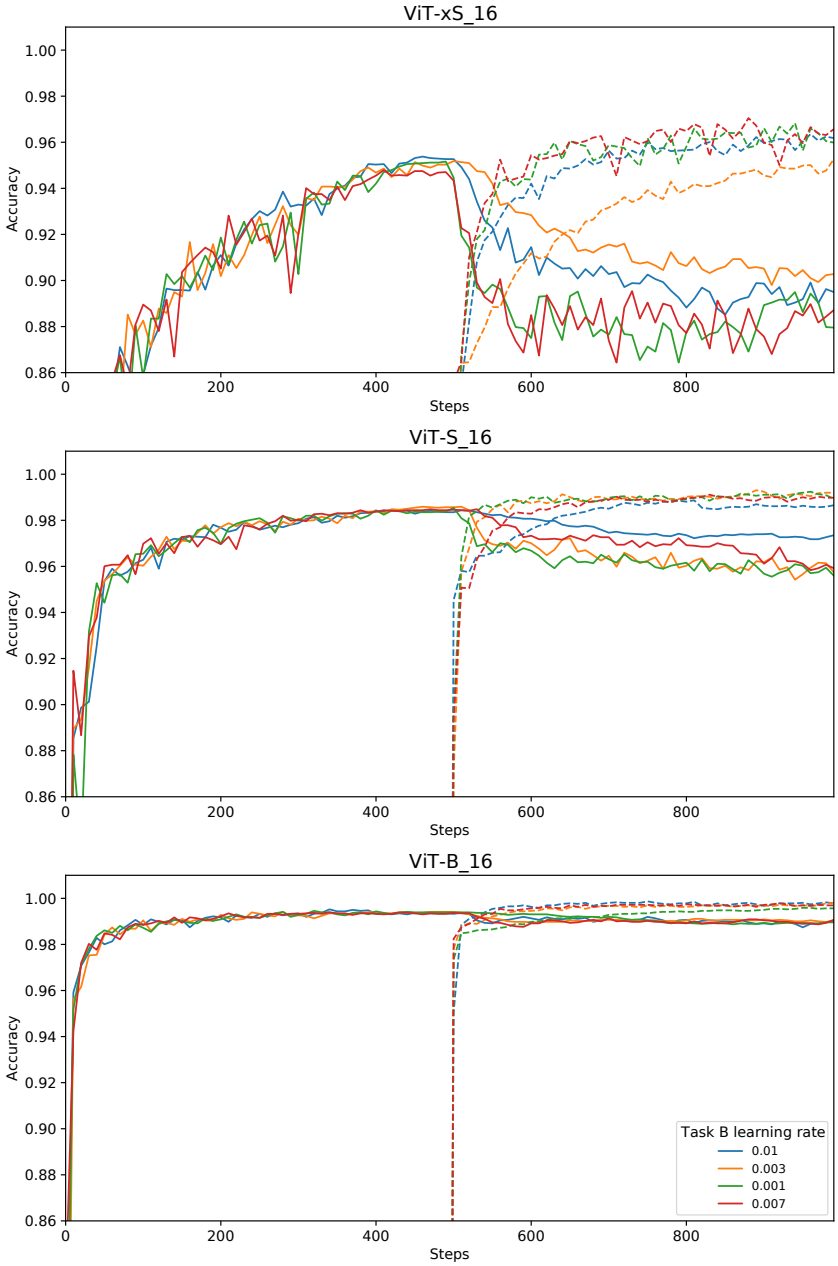

Figure 24: **ViT Learning curves**. Learning curves for the ViT models of Figure 1. The solid/dashed lines are Task A/B accuracy.

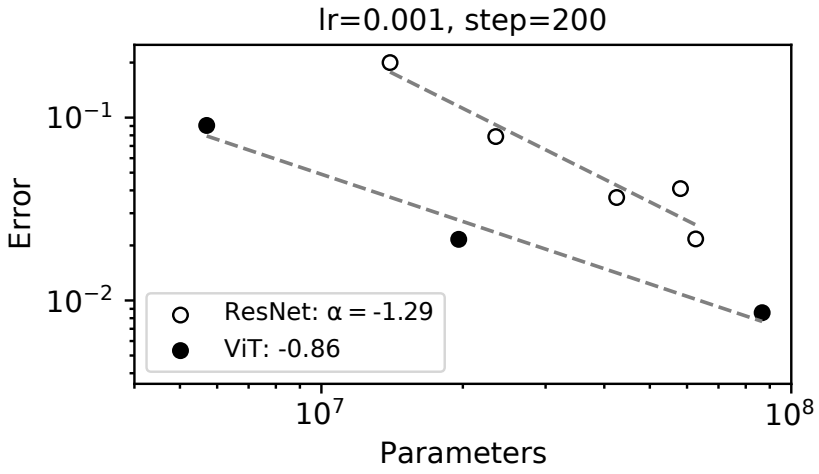

Figure 25: **Average error scaling at fixed learning rate and step**. We plot the average Task A Task B error for the setup in Figure 1 for a fixed learning rate of 0.001 and 200 Task B training steps for both ViTs and ResNets.