RECOVERY-ON-THE-LINE: LINEAR TRENDS IN POST-QUANTIZATION PERFORMANCE RECOVERY

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ABSTRACT

Many state-of-the-art large language models exceed tens of billions of parameters. To compress these models, several prior works have proposed *quantizing* the weights and activations of these models, using techniques like GPTQ and QuIP. An important reference for quantized language models is their ability to *recover* performance metrics such as accuracy after quantization; that is, the quantized language models should be as accurate as the original base models. It remains, however, unclear, *which* evaluations are most needed to assess *recovery*. If, for instance, recovery across all tasks is strongly linear (i.e. recovery on task A is a linear function of recovery on task B), then there should exist a dense subset of (independent) evaluations that are most necessary. In this paper, we examine the trends in recovery across pairs of tasks and metrics. Drawing from prior works which have shown that in-distribution and out-of-distribution accuracy often exhibit a strong linear relationship, we show that this relationship holds for recovery of accuracy as well.

1 INTRODUCTION

Post-training quantization (PTQ) has emerged as a popular method to improve the memory footprint and scalability of large language models (LLMs) while maintaining performance (Frantar et al., 2022; Chee et al., 2024; Huang et al., 2024). Typically, performance is measured by evaluating both the base and quantized LLM on a suite of benchmark tasks and assessing the quantized model's ability to *recover* baseline performance metrics (Kurtic et al., 2024; Hong et al., 2024). These evaluations ideally cover a large array of tasks and metrics, such as multiple choice accuracy, calibration error, and safety of generations (Xu et al., 2024).

Running such extensive evaluations, however, is time-consuming and expensive. For instance, running MosaicML's EvalGauntlet on both the LLama-3.1-8B base and it's 4-bit quantized version requires several GPU hours.

Prior work in classification settings has shown that performance (e.g. accuracy) across tasks is often linearly correlated, even between in-distribution (ID) and out-of-distribution (OOD) tasks, a phenomenon known as *accuracy-on-the-line* (Miller et al., 2021; Santurkar et al., 2020; Sanyal et al., 2024; Cohen-Wang et al., 2024; Mania & Sra, 2020). Several works have extended this empirical observation to other metrics as well, including pairwise agreement (Baek et al., 2022; Saxena et al., 2024; Kim et al., 2024), pairwise disagreement Deng et al. (2022), and model invariance and generalization Lee et al. (2023). Others have noted that ID and OOD performance don't always correlate linearly, for instance when comparing model performance across subpopulations (Liang et al., 2023).

We investigate whether such a relationship exists for *recovery* of performance in quantized language models. There are two key reasons to study this relationship:

1. **Understanding evaluations**: The relationship in the recovery of performance, both across tasks (e.g. question-answering, multiple choice, etc.) and metrics (accuracy, calibration, etc.) is poorly understood. Investigating these relationships provides a basis for generating new tasks and metrics which current evaluations fail to cover.
2. **Evaluation efficiency**: For generative models, one can always generate new evaluations, but these evaluations may be redundant. Analyzing the quantization recovery relationship across tasks can find a core subset of tasks that "covers" all key evaluations. For instance, if recovery on one task exactly predicts recovery on all other tasks (e.g. linear relationship), then one evaluation is sufficient to measure recovery.

We empirically show with evaluations across 24 tasks that several state-of-the-art LLMs exhibit strong correlation in recoveries across benchmark datasets and metrics, showing that (a) accuracy recovery generally follows a strongly linear relationship across all tasks and quantization levels, and (b) this relationship seems to break down when evaluating non-accuracy metrics.

2 ANALYSIS

We compress four widely-used, open-source LLMs—`Llama-3.1-8B-Instruct`, `Qwen2.5-7B-Instruct`, `Falcon-3-7B-Instruct`, and `Mistral-7b-instruct-v0.3` using the GPTQ framework (Frantar et al., 2022) at four distinct bitwidth configurations: `W8A8`, `W4A16`, `W3A16`, and `W2A16`. Here, `WxAy` refers to `x`-bit weight and `y`-bit activation quantization respectively. We follow standard hyperparameter settings for GPTQ and quantize each model separately at each bitwidth setting.

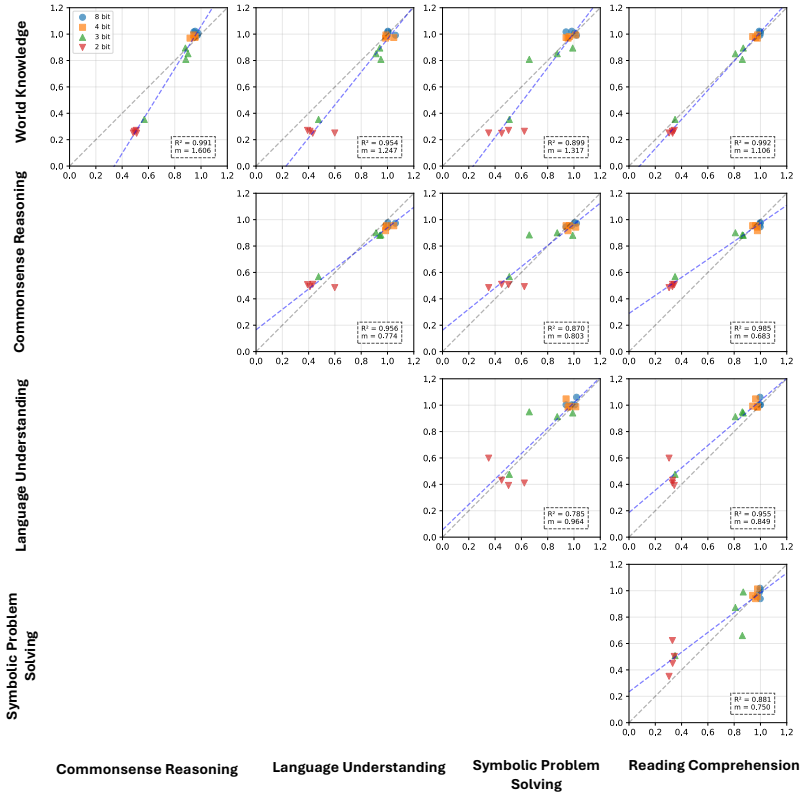

Figure 1: Across all categories of tasks in EvalGauntlet, we see strong linear trends in recovery.

We evaluate model performance recovery, which we define as the ratio of the quantized model's metric performance to that of its dense (uncompressed) counterpart. Formally, recovery for **Accuracy** is defined as:

$$\text{RecoveryAccuracy} = \frac{\text{Accuracy}_{\text{Quantized}}}{\text{Accuracy}_{\text{Dense}}} \tag{1}$$

We evaluate the models across the following task categories using 24 tasks:

- **World Knowledge**: ARC Easy (3-shot), ARC Challenge (3-shot), MMLU (5-shot), TriviaQA (3-shot)
- **Commonsense Reasoning**: COPA (0-shot), Social IQA (3-shot), Commonsense QA (0-shot), PIQA (0-shot), OpenBookQA (10-shot), Bigbench Strange Stories Multiple Choice (0-shot), Bigbench StrategyQA Multiple Choice (0-shot)
- **Language Understanding**: Lambada Openai (0-shot), Hellaswag (0-shot), Winograd (3-shot), Winogrande (5-shot)
- **Symbolic Problem Solving**: Bigbench Elementary Math QA Multiple Choice (1-shot), Bigbench Operators Generate Until (3-shot), GSM8K (0-shot), Agieval LSAT AR (5-shot)
- **Reading Comprehension**: Boolq (0-shot), Coqa (0-shot), Agieval LSAT RC (5-shot), Agieval LSAT LR (5-shot), Agieval SAT EN (5-shot)

To quantify the linear trends in estimating recoveries, we use the coefficient of determination (R^2) which specifically answers, "What fraction of the variation in one variable can be explained by a linear relationship with the other variable?".

For calibration error, we evaluate it on four open-sourced multiple choice datasets available on HuggingFace: OpenbookQA (Mihaylov et al., 2018), CosmosQA (Huang et al., 2019), MMLU (Hendrycks et al., 2020), and MMLU-Pro (Wang et al., 2024) using three models from the Llama-3 suite (Dubey et al., 2024). Recovery for calibration, measured by Expected Calibration Error (ECE), is inversely calculated (since lower values of ECE are preferable):

$$\text{RecoveryECE} = \frac{\text{ECE}_{\text{Dense}}}{\text{ECE}_{\text{Quantized}}} \tag{2}$$

2.1 Results

Recovery of Accuracy We show that recovery of accuracy across various benchmark tasks is highly correlated, with a strong linear fit in most cases. We analyze recovery on every pair of 24 tasks drawn from EvalGauntlet, resulting in 276 total pairwise comparisons.

On average, tasks in this evaluation set were highly correlated in accuracy recovery (mean pairwise $R^2 = 0.84$, median $R^2 = 0.92$). We evaluate the slope (of the line of best fit) and correlation (measured by R^2) for each pair of tasks in EvalGauntlet, similar to the plots shown in Figure 1 (except disaggregated to not be just within categories). The overall distribution of pairwise correlations across tasks, shown in Figure 2, suggests that most pairs of tasks are strongly correlated, with a small subset that are independent of other evaluations. This independent subset includes symbolic problem solving tasks (e.g, mathematical reasoning tasks) (Zhong et al., 2023).

To further investigate these correlations and how they change with quantization levels, we aggregate our suite of 24 tasks into five categories – **commonsense reasoning**, **language understanding**, **symbolic problem solving**, **world knowledge**, and **reading comprehension** – using the categories defined in EvalGauntlet. As shown in Figure 1, most pairs of categories exhibit a strong linear relationship in their recovery of accuracy, with smaller (2-bit) models having significantly poorer recovery than larger ones, which often have recovery close to 1. We again observe that symbolic problem solving tasks, which include various mathematical and analytical reasoning questions, are least correlated in recovery to other tasks. In particular, the least correlated task in our evaluation suite is AGIEvalLSAT Arithmetic Reasoning (mean $R^2 = 0.018$) and most correlated is HellaSwag (mean $R^2 = 0.905$).

Moreover, the slope of the category-to-category linear fit is always bounded between 0.5 and 2 after aggregation [1].

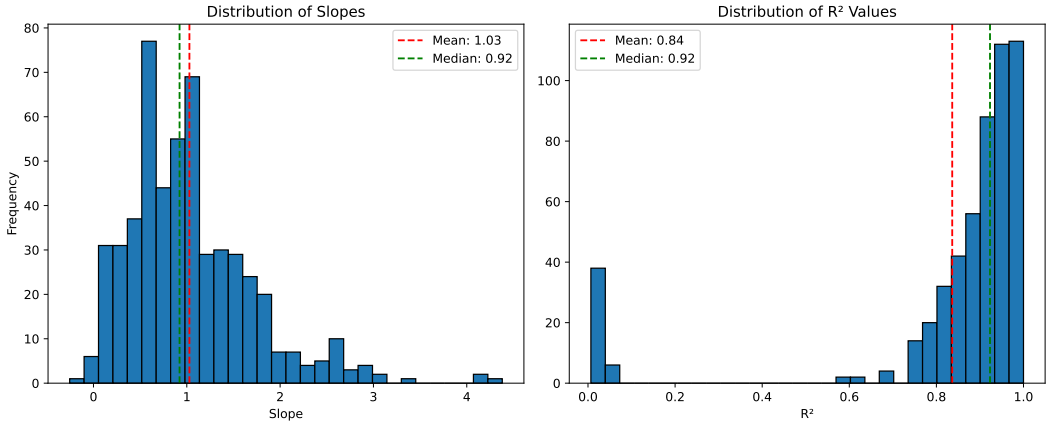

Figure 2: Slope and R^2 distribution of the best-fit line of the pairwise task-recovery plots evaluated across all 24 tasks. Majority of the tasks have high coefficient of determination, indicating the linear trend of performance recovery.

Recovery of Additional Metrics The strong linear trend in recovery of accuracy fails to hold for other metrics, such as calibration and entropy. The 5 shows the trends in calibration recovery across relevant benchmark datasets.

In particular, we observe that base models are often (very) *overconfident* and that quantizing mildly *corrects* this overconfidence. For instance, as shown in Figure 3 with Llama-3.1-8B-Instruct, the token-level entropy increases post-quantization, which in turn corrects overconfidence in the base model. Here, we quantify the model's uncertainty at each token by computing the entropy of its predicted probability distribution.

3 Discussion and Future Work

Here we showed preliminary evidence that performance recovery post-quantization follows a strongly linear trend, especially in the recovery of accuracy. In the future, we hope to extend these results to find a *robust subset* of evaluations that "covers" all evaluations needed to assess recovery. This includes both extending to new tasks and, more importantly, new metrics, such as perplexity

[1]The original accuracy-on-the-line papers use *probit scaling* before estimating their linear fits, to account for the fact that accuracies are bounded in $[0, 1]$. Given that recovery can be > 1, we do not use this rescaling. We additionally tried logit-scaling our plots, which maintained the linear relationship (see Appendix A.5.

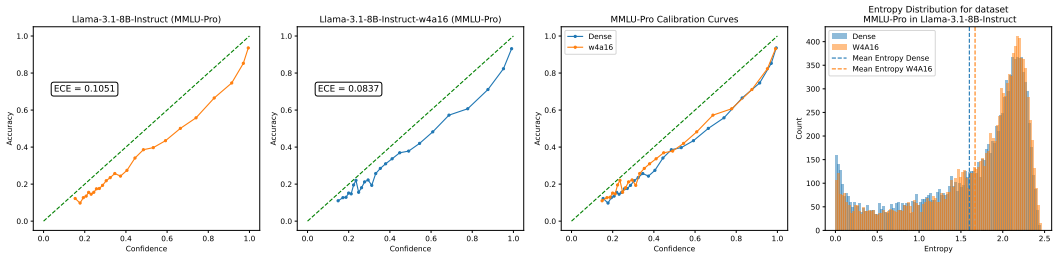

Figure 3: Quantizing models often *improves* calibration error. The base model tends to be overconfident at all confidence levels (left), which is partially mitigated after quantizing to 4 bits (middle). This is evident in the entropy distribution among the multiple choice options, where we see that the quantized model has greater entropy (right).

and the proportion of answers which flip after quantization, some of which may be poorly correlated with accuracy (Dutta et al., 2024). A second direction of future work is to analyze the bit-level trends in recovery, i.e. analyzing the scaling of recovery against quantization-level across our dense subset. Finally, a further direction is to explore the *interpretability* of compression and it's relationship with recovery by analyzing the activations of these compressed models, gaining insights into how quantization affects their internal representations.

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A APPENDIX

A.1 HIGH CORRELATION BETWEEN TASKS OF SAME CATEGORIES

In Figure 4, we show heatmaps illustrating correlation of quantization recovery for tasks *within* each of the five evaluation categories (e.g., World Knowledge, Language Understanding). We observe that tasks within a single category exhibit consistently high correlations, mirroring the strong *cross-category* correlations described in the main text.

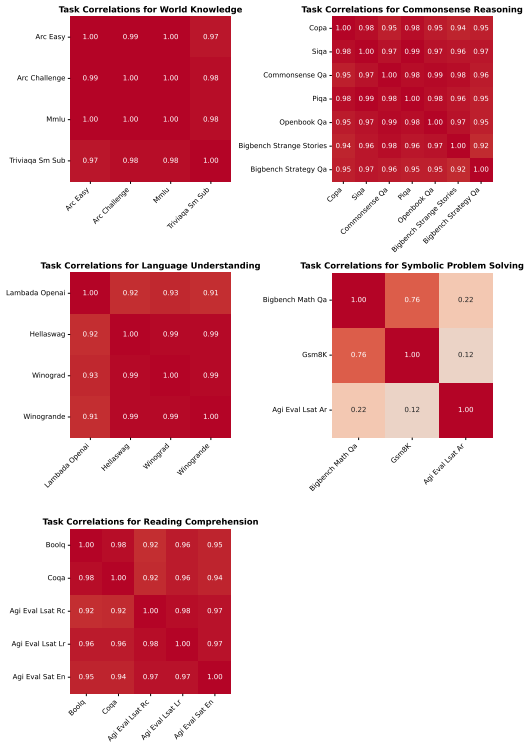

Figure 4: Correlation heatmaps by category, demonstrating that tasks within the same category exhibit high accuracy recovery correlations. Only in Symbolic Problem Solving do the tasks show notably weaker correlations compared to the other categories.

A.2 CALIBRATION RECOVERY IS NOT FULLY CORRELATED WITH ACCURACY RECOVERY

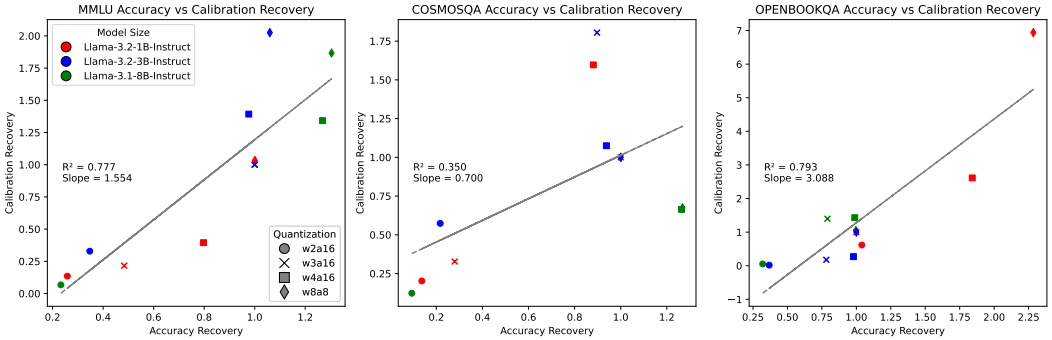

Figure 5: The linear trends we observe in recovery of accuracy across tasks do not hold across metrics, for instance between accuracy and calibration on the same task.

To calculate recovery of calibration, we use the following equation:

$$\text{Recovery}_{\text{ECE}} = \frac{\text{ECE}_{\text{base}}}{\text{ECE}_{\text{quantized}}}$$

We flip the equation relative to the accuracy recovery since a lower calibration error is better.

A.3 TASKS IN MOSAICEVAL GAUNTLET V0.3

Category	Task	N-shot
Common sense reasoning tasks	copa	0
	social_iqa	3
	commonsense_qa	0
	piqa	0
	openbookqa	10
	bigbench_strange_stories_multiple_choice	0
	bigbench_strategyqa_multiple_choice	0
Reading comprehension tasks	boolq	0
	coqa	0
	agieval_lsat_rc	5
	agieval_lsat_lr	5
	agieval_sat_en	5
Symbolic problem solving tasks	bigbench_elementary_math_qa_multiple_choice	1
	bigbench_operators_generate_until	3
	gsm8k	0
	agieval_lsat_ar	5
World knowledge tasks	arc_easy	3
	arc_challenge	3
	mmlu	5
	triviaqa	3
Language understanding tasks	lambada_openai	0
	hellaswag	0
	wsc273	3
	winogrande	5

Table 1: Categories, tasks, and their respective N-shot values in EvalGauntlet.

A.4 ACCURACY RECOVERY TREND BETWEEN TASKS IN DIFFERENT CATEGORIES

Figures 6-10 shows pairwise comparisons of quantization recovery across tasks within and across the five major categories in our evaluation suite. Overall, we observe near-linear correlations in many of these task pairs (e.g., reading comprehension tasks), while more diverse tasks (e.g., symbolic problem solving) exhibit weaker correlations. These findings indicate that some tasks can serve as strong proxies for others when assessing performance recovery, but not all categories share equally strong relationships.

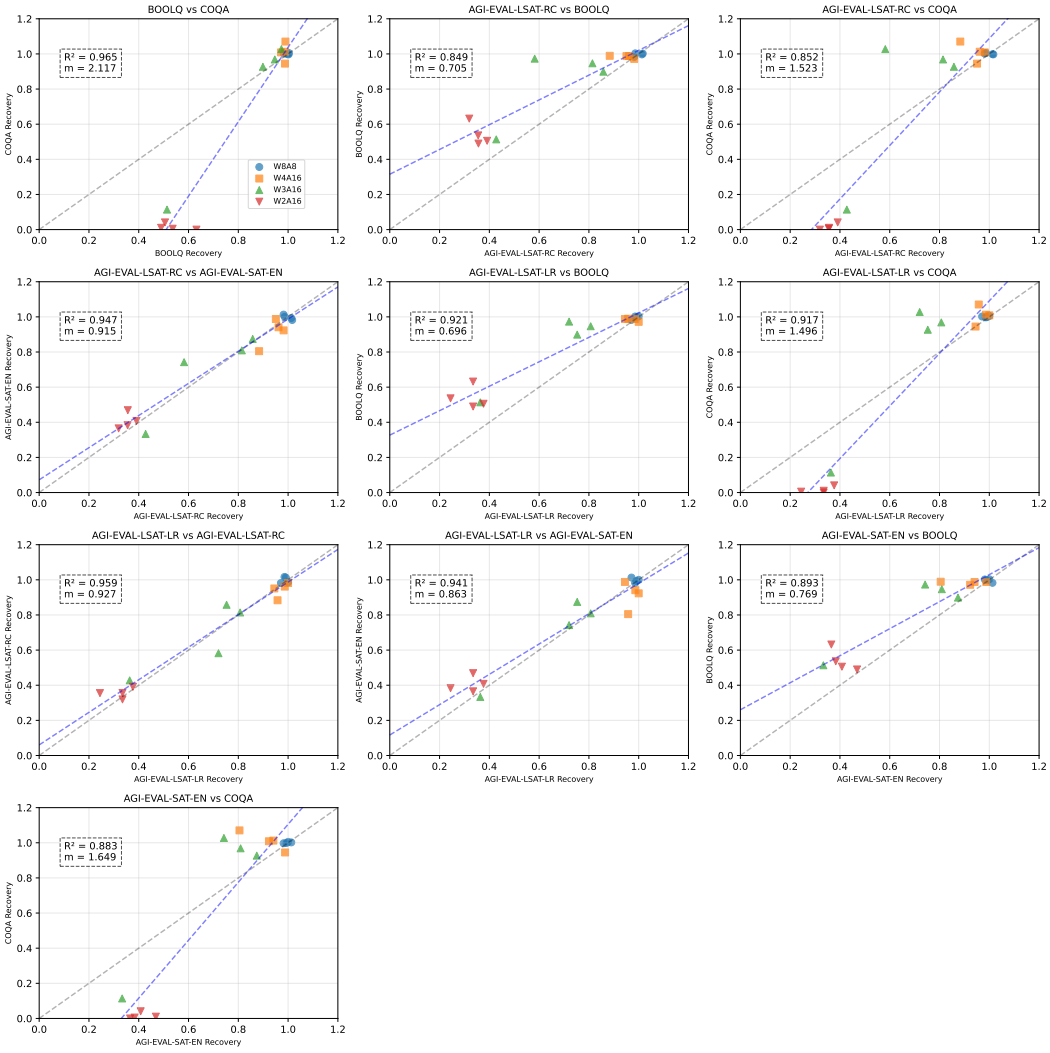

Figure 6: Accuracy recovery in reading comprehension tasks.

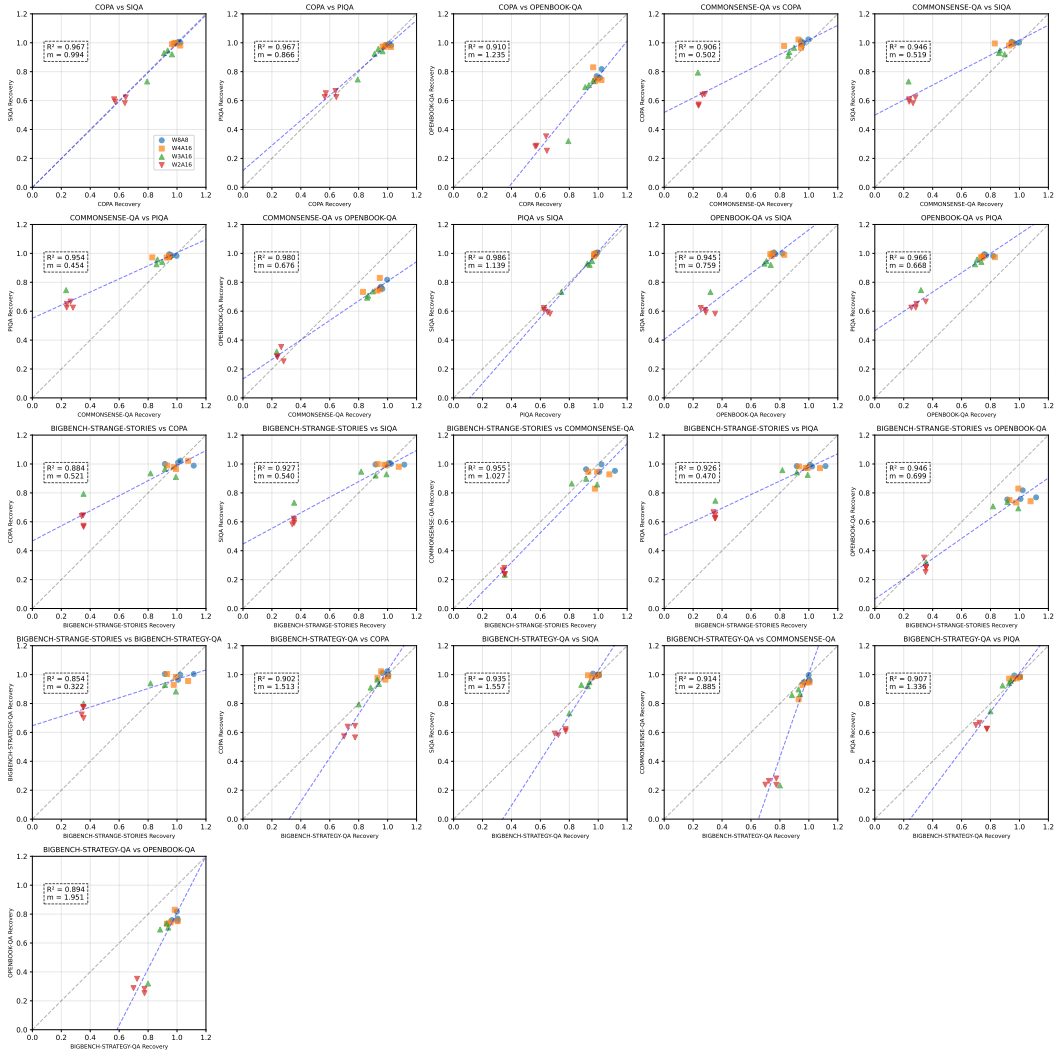

Figure 7: Accuracy recovery in commonsense reasoning tasks.

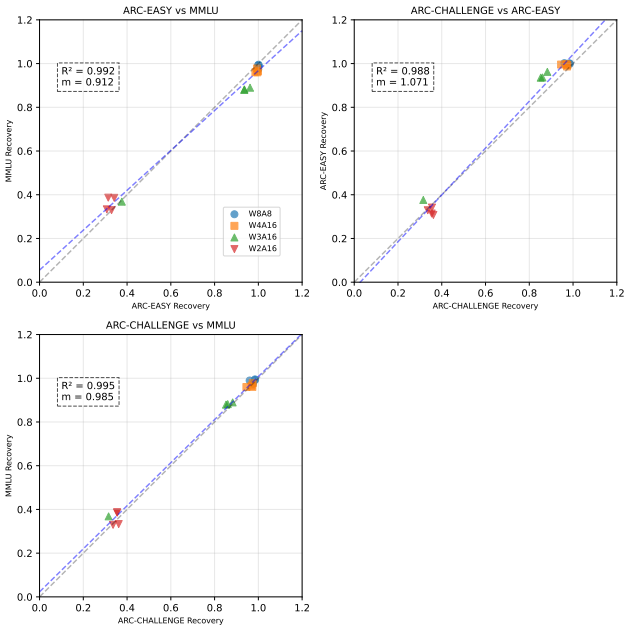

Figure 8: Accuracy recovery in world knowledge tasks.

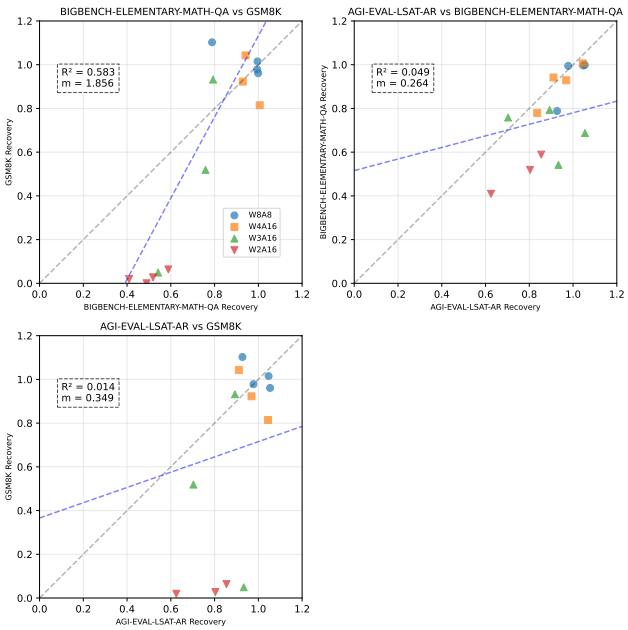

Figure 9: Accuracy recovery in symbolic problem solving tasks.

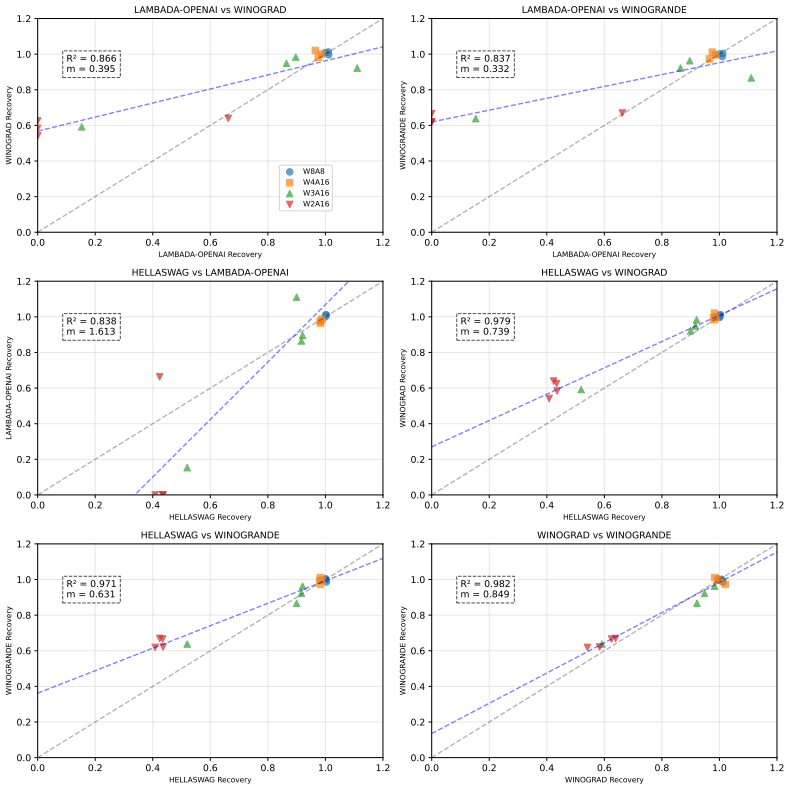

Figure 10: Accuracy recovery in language understanding tasks.

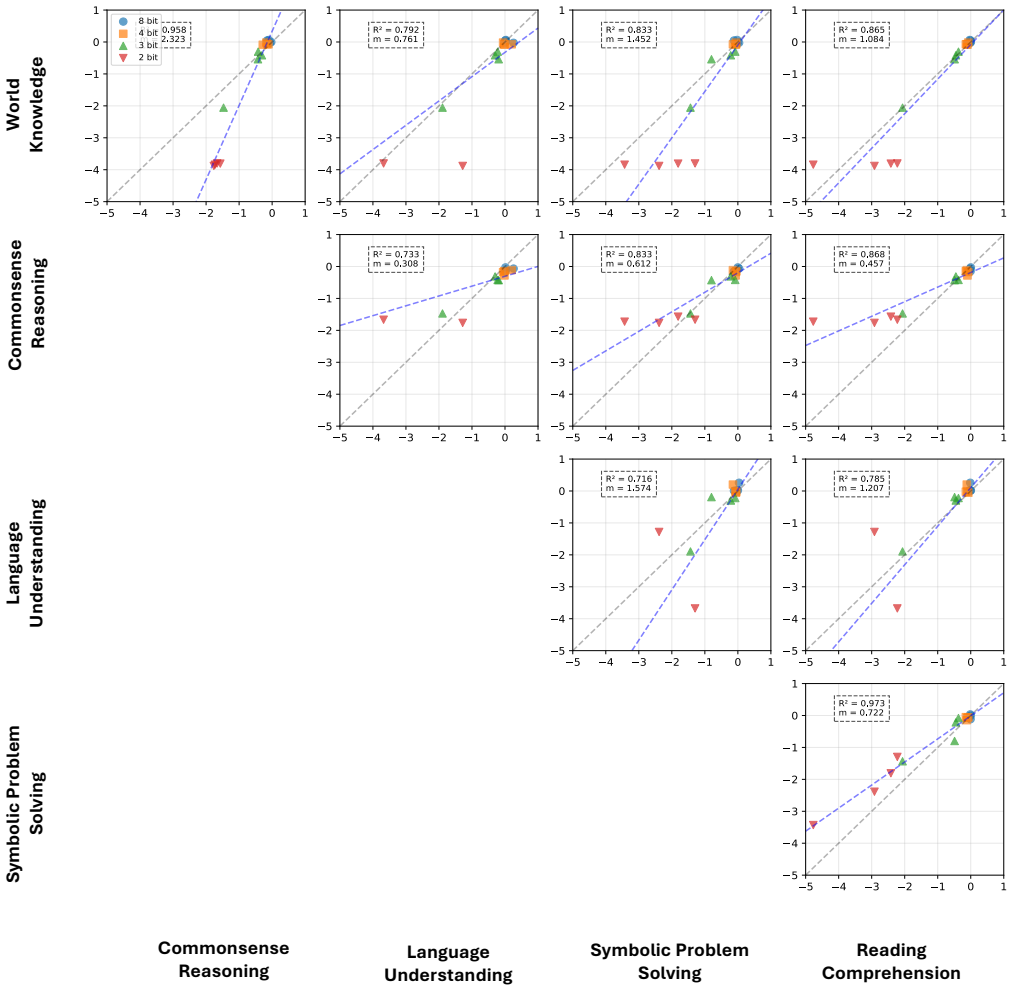

Figure 11: Logit-scaling recovery metrics preserves most linear trends.

A.5 Logit-scaling preserves linear trends in recovery

The original accuracy-on-the-line works applied *probit scaling* to the raw accuracies before fitting a best fit line, as accuracies range in $[0, 1]$. Probit scaling rescales the raw accuracies using the inverse Gaussian CDF, i.e. $\text{Acc}_{\text{rescaled}_} = \Phi^{-1}(\text{Acc}_{\text{original}})$, which stabilizes the linear fits. Probit scaling is not applicable to our setting, as recovery can exceed 1 if the quantized model is more accurate than the base model. Instead, we apply *logit scaling* to our recoveries, where we defined

$$\text{Acc}_{\text{logit-scaled}} = \text{logit}(\text{Acc}_{\text{quantized}}) - \text{logit}(\text{Acc}_{\text{base}})$$

This does not substantially improve the linear fits, and we leave it as future work to find the best rescaling in which the linear trends stabilize.