MirrorCoT: Lightweight Multimodal Interleaved Chain-of-Thought

Anonymous ACL submission

Abstract

Recent advances in multimodal interleaved Chain-of-Thought(CoT) (Li et al., 2025) have exhibited great potential in boosting the reasoning performance of Multimodal Large Language Models (MLLMs). However, existing work rarely examines *how* and *when* visual information should be injected during multimodal reasoning. In this work, we systematically study **MirrorCoT**, a lightweight multimodal interleaved CoT with **query-triggered visual injection** mechanism. We conduct comprehensive comparisons against state-of-the-art baselines (e.g., VoCoT, VQD) on LLaVA-1.5 and InternVL-3 across seven benchmarks, including MMStar and HallusionBench. Our key finding is that a simple structural modification, which **forces the model to explicitly emit a sub-question that triggers a visual information injection**, consistently outperforms dense visual token insertion. This modification not only boosts task accuracy (e.g., delivering a 5.1% improvement on LLaVA-1.5) but also cuts the number of visual tokens required by 91.1%. Further analysis reveals that the gains stem from **Dynamic Inquiry** (deciding *when* to look) and **Targeted Feature Extraction** (deciding *what* to retrieve), which also mitigates hallucination in long-context generation.

1 Introduction

Chain-of-Thought (CoT) prompting has unlocked substantial reasoning gains in large language models (LLMs) by encouraging explicit intermediate steps (Kojima et al., 2022; Wei et al., 2022; Yao et al., 2023). This success naturally spurred the exploration of multimodal CoT, aiming to extend step-by-step reasoning to vision-language settings (Zhang et al., 2023b, 2024b; Xu et al., 2024; Xiang et al., 2024). However, long-horizon multimodal generation exposes a mechanistic flaw: a widening gap between *producing* a fluent rationale and *grounding* it in visual reality. Empirical studies

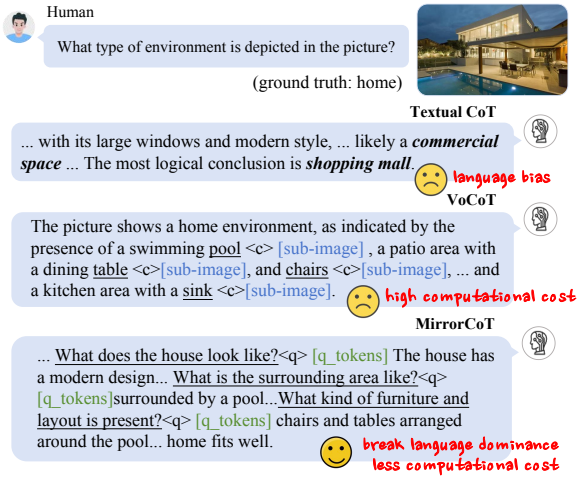

Figure 1: Comparison of multimodal reasoning paradigms. **Textual CoT** (Wei et al., 2022) solely relies on language priors, often leading to hallucinations. **Visual CoT** (e.g., VoCoT (Li et al., 2025)) inserts raw image tokens [sub-image], causing high computational redundancy. In contrast, our **MirrorCoT** actively generates sub-questions to extract query-specific visual features into learnable tokens [q_tokens].

reveal that MLLMs often suffer from "textual inertia": as the reasoning trace grows, the model becomes increasingly conditioned on its own generated text, causing attention to drift away from the image and leading to hallucinations that are logically plausible but visually ungrounded (Huang et al., 2024; Leng et al., 2024; Kang et al., 2025). This suggests that the effective influence of visual evidence systematically decays as auto-regressive decoding progresses.

A common belief is that grounding can be sustained by injecting more visual information into the reasoning stream. Recent systems thus attempt to strengthen the "vision pathway" via strategies such as delegating decomposition to external LLMs (Zheng et al., 2023; Surís et al., 2023) or reallocating inference-time attention from text to image (Liu et al., 2024a). More recently, VoCoT (Li et al.,

2025) proposed interleaving dense, object-centric image tokens directly into the output sequence. While effective, such approaches introduce substantial redundancy. As illustrated in Figure 1, VoCoT mechanically inserts raw image patches [sub-image] whenever an object is mentioned, flooding the context with visual tokens that may not be relevant to the *current* reasoning sub-goal. This passive injection increases compute overhead without ensuring attention to verification-critical features.

A motivating finding: Informativeness outweighs quantity in visual tokens. We posit that the core challenge of long-horizon CoT is not insufficient visual grounding capability, but the lack of a mechanism for extracting task-relevant compact features. We prompt the model to raise sub-questions to inquire about visual evidence that supports the reasoning. Our observations indicate that performance gains are still achievable even when the volume of injected visual tokens is drastically reduced, provided that these tokens are *contextually tailored* to the current reasoning step. This points to a first-principles diagnosis: effective grounding requires a *minimal-yet-efficient* visual evidence insertion mechanism that interrupts text dominance and amplifies visual influence exactly when needed.

MirrorCoT: target visual evidence acquisition under a token budget. Motivated by this view, we propose **MirrorCoT**, a paradigm that casts multimodal reasoning as *target visual evidence acquisition*. Instead of passively receiving a stream of visual tokens, the model learns to (i) explicitly emit a sub-question when textual priors are insufficient, and (ii) actively retrieve only the visual content needed to verify that step. Concretely, MirrorCoT interleaves reasoning with a lightweight vision operator. Conditioned on a generated query (e.g., `<IMAGE_QUERY>...`), this operator extracts *query-specific* features into a small set of learnable tokens [q_tokens], injecting them back into the stream (see Figure 1). This design establishes a bidirectional loop: (1) **Vision-to-Language Alignment**: Visual tokens are distilled strictly for the current sub-goal (e.g., checking the specific attributes of a "couch" rather than just seeing generic furniture features), filtering out irrelevant noise. (2) **Language-to-Vision Alignment**: The active injection of these evidence tokens breaks the language-dominant inertia, forcing the model to re-anchor its reasoning to the image without the cost of re-encoding full visual features.

Our main contributions are summarized as follows:

- We conceptualize multimodal CoT grounding as an **effective visual evidence acquisition** problem and refine the visual information injection manner in multimodal interleaved Chain-of-Thought.
- We propose **MirrorCoT**, a framework that employs a dynamic, query-triggered visual evidence operator to inject *step-specific* visual tokens, significantly reducing redundancy compared to dense insertion baselines while improving interpretability.
- We develop an automated data construction pipeline to distill strong teacher reasoning into MirrorCoT-style traces. Experiments show consistent improvements, boosting LLaVA-1.5 by **5.1%** on average across seven benchmarks and InternVL-3 by a 7.1% gain on the complex M^3CoT benchmark.

2 Related Works

Multimodal Chain-of-Thought. The huge success of CoT in textual modality inspires a lot of works to explore the potential of multimodal CoT in cross-modal scenarios.(Besta et al., 2024; Zhang et al., 2023a; Sprague et al., 2025) Visual Programming (VisProg)(Gupta and Kembhavi, 2023; Surís et al., 2023) makes use of the in-context learning ability of LLMs to generate stepwise solutions in the form of Python-like modular programs, and each line of the program invokes one of the VLMs or Python functions. Since LLMs are prone to generating programs that seem to match the questions but are irrelevant to the image content without "seeing" the images, the performance of VisProg is dependent on the quality of the programs. With the advancement of MLLMs and the emergence of various multimodal reasoning datasets, researchers attempt to guide the MLLMs to think step by step (Azzolini et al., 2025; Jaech et al., 2024). QVQ(Wang et al., 2024c), Kimi k-1.5(Team et al.) adopts long-CoT and exhibits powerful reasoning abilities in challenging math problems and Contest-Level Tasks. The generated CoT is expressed in text. VoCoT extends the modality of CoT by introducing coordinates and visual tokens of objects into the text tokens. However, this introduces an unnecessary computational burden when performing complex reasoning tasks.

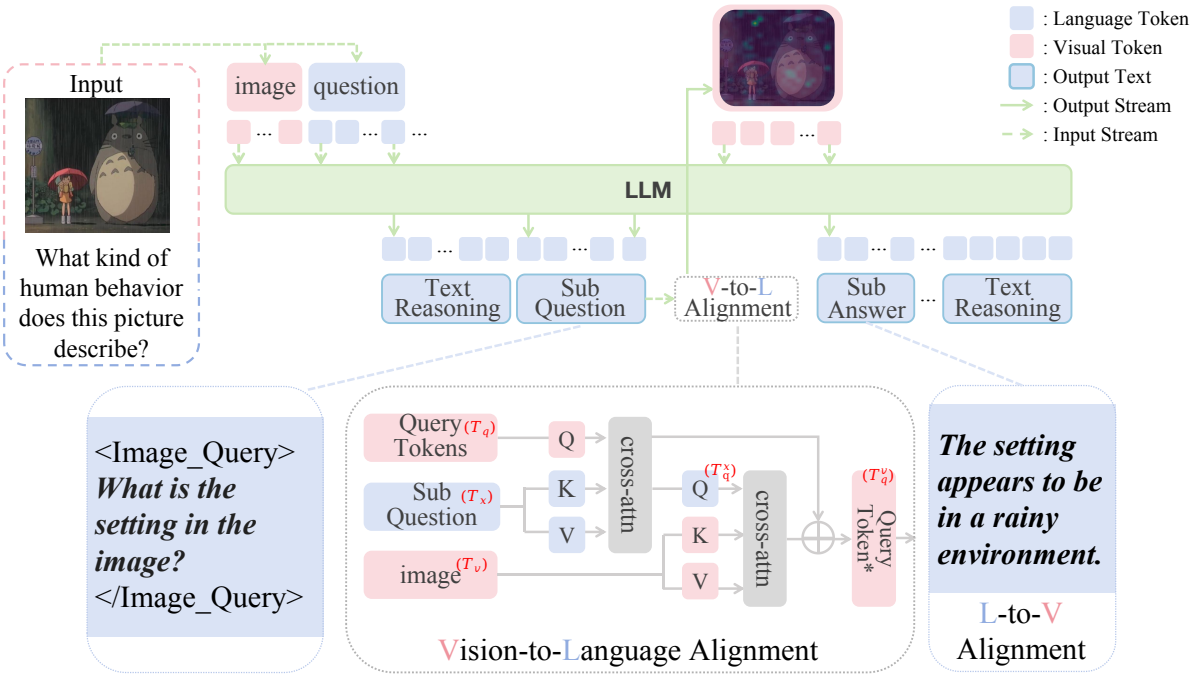

Figure 2: Pipeline of MirrorCoT. Given an image and a question, e.g., "What kind of human behavior does this picture describe", the MLLM begins standard next-token prediction to perform stepwise reasoning. During reasoning, the model is trained to explicitly emit sub-questions like "What is the girl doing" when visual information is required. A cross-attention module processes the image and current sub-question to extract question-relevant visual features into learnable query tokens. These tokens are inserted after the sub-question in the text sequence. Then, the text generation continued with this visually augmented context.

Vision Language Alignment in MLLMs. Hallucination refers to cases where the generated text contradicts or is not grounded in the input image. To address the hallucination caused by data bias, some researchers devise strict data-evaluation strategies (Yu et al., 2024a; Liu et al., 2023; Wang et al., 2024b) and spend a large amount of manpower on annotation data. Another cause of hallucination is the over-reliance on text and decreased attention to image context. (Huang et al., 2024; Liu et al., 2024a) intervene in the model's inference process and adjust the attention weights assigned to the image tokens. Although those methods are training-free, the effectiveness of those methods depends on the original ability of the MLLMs. Apart from processing during generation, post-processing (Zhou et al., 2024; Yin et al., 2024; Lee et al., 2024) is proposed to detect the hallucination and modify the generated text. (Yin et al., 2024) trains an external verification model to inspect and validate objects mentioned in the generated text, and uses the verification results to guide the model to revise or regenerate responses. While these approaches can effectively improve factual consistency, they significantly increase computational overhead, which limits their practicality in real-time applications.

3 Methodology

When engaging in complex multimodal reasoning, humans typically decompose the task into a series of logically interconnected subtasks. As reasoning progresses, attention dynamically shifts across modalities to retrieve task-relevant information. Our proposed method aims to simulate this cognitive process to establish a more robust and interpretable chain-of-thought (CoT) paradigm. We name this approach **MirrorCoT**, as the two modalities mutually align with each other, like dual reflections in a mirror, ensuring coherent and step-aligned reasoning.

Preliminaries. We first recall some background on MLLMs in this section. Given an image I and an instruction T, the MLLMs processes multimodal inputs through three core components: (1) A vision encoder VE_ψ (e.g., CLIP-ViT(Radford et al., 2021)) extracts patch embeddings $E_v = \text{VE}_\psi(I) \in \mathbb{R}^{N_v \times d_v}$ from input image I; (2) A projector (typically an MLP) Proj_ϕ aligns visual features to the semantic space of LLM via $\hat{E}_v = \text{Proj}_\phi(E_v) \in \mathbb{R}^{N_v \times d_{\text{text}}}$; (3) An LLM (e.g., Vicuna(Chiang et al., 2023)) LLM_θ jointly attends to projected visual tokens $\hat{Z}_v$ and text tokens T through cross-modal

attention, generating coherent text outputs. This pipeline (Eq. 1) enables multimodal reasoning by unifying visual and linguistic representations in a shared latent space.

$$\text{Output} = \text{LLM}_\theta\left(\text{Proj}_\phi\left(\text{VE}_\psi(I)\right) \parallel T\right) \quad (1)$$

Multimodal Interleaved CoT. Different from textual CoT, MirrorCoT introduces the visual modality to simulate cross-modal interactions during reasoning. MirrorCoT uses the following interleaved format:"{text reasoning} <IMAGE_QUERY> {Visual Query} </IMAGE_QUERY> {query tokens} {text reasoning}..." We prompt the model to raise sub-questions(Visual Query) if visual evidence is needed and enclose each question with <IMAGE_QUERY> and </IMAGE_QUERY>. Once the </IMAGE_QUERY> token is detected, the query tokens carrying question-related image features will be inserted immediately after the </IMAGE_QUERY> tag. The process of text reasoning, question generation, and query token insertion can be iterated multiple times, allowing the model to perform multi-step reasoning while continuously incorporating visual information.

Vision-to-Language Alignment. Previous research in multimodal reasoning primarily focuses on improving the quality of pure text-based Chain-of-Thought (CoT), while some attempts have been made to incorporate image tokens that cover the mentioned objects. However, these approaches still lack advanced mechanisms for more fine-grained visual feature selection. To address this limitation, we propose leveraging query tokens (Li et al., 2023) to dynamically extract text-aligned visual features, which are then strategically inserted into the textual CoT sequence. Unlike heuristically selecting visual tokens (e.g., object crops), our method operates at a finer granularity, enabling more effective image feature selection. We build a cross-attention module to select image features. The activated cross-attention module identifies the question within the <IMAGE_QUERY> tags and subsequently extracts question-related image features into query tokens. The architecture of the module is followed (Tong et al., 2025) and is shown in Figure 2. Firstly, given query tokens T_q, image tokens T_v, and text tokens T_x. We first interact T_q and T_x via cross-attention:

$$\mathbf{T}_q^x = \text{CrossAttention}(\mathbf{T}_q, \mathbf{T}_x, \mathbf{T}_x) \quad (2)$$

Here, $\mathbf{T}_q^x \in \mathbb{R}^{n \times d}$ are the derived text queries. Then, we can use $\mathbf{T}_q^x$ to query visual information from the visual tokens $\mathbf{T}_v$, defined by

$$\mathbf{T}_q^v = \text{CrossAttention}(\mathbf{T}_q^x, \mathbf{T}_v, \mathbf{T}_v) \quad (3)$$

The query tokens output from the module of vision-to-language alignment will be appended to the sub-question. Both cross-attention operations share the same formulation as Eq. 4 but operate on different inputs:

$$\mathbf{CrossAttention}(\mathbf{Q}, \mathbf{K}, \mathbf{V}) = \mathbf{Softmax}\left(\frac{(\mathbf{Q}\mathbf{W}_q)(\mathbf{K}\mathbf{W}_k)^\top}{\sqrt{d_k}}\right) \cdot \mathbf{V}\mathbf{W}_v. \quad (4)$$

where $\mathbf{W}_q, \mathbf{W}_k, \mathbf{W}_v$ are the projection weight matrices, with d_k denoting their dimension.

Language-to-Vision Alignment. As described in the above paragraph, once the cross-attention module is triggered, it can integrate relevant visual features into the query tokens, which are subsequently inserted into the output text sequence. Then the model continues to perform next-token prediction. The following generated textual tokens are based on both textual and visual context. Let T_x^i denote the text token, T_v^i denote the image token, and T_q^i denote the query token. The LLM generates the next token by jointly attending to previous text tokens and the sequence of query tokens, ensuring that each step of reasoning is tightly anchored to the visual input. The predicted text tokens follow the formulation in Eq.5:

$$\hat{T_x^i} \sim \mathcal{LLM}_\theta(T_x^i \mid T_v, T_x^0, \hat{T_x^1}, \hat{T_q^1}, \cdots, \hat{T_x^{i-1}}, \hat{T_q^i}) \quad (5)$$

This is consistent with the existing training paradigm of causal language modeling (Radford et al., 2019). Therefore, we can employ the standard auto-regressive loss to optimize in the same fashion.

Training Strategy. Our training involves two stages: 1) **Pre-training Stage.** We observe that random initialization of the cross-attention module and query tokens increases fine-tuning difficulty. Thus, pre-training for these components is essential. The objective of pre-training is to enable the cross-attention module to extract question-relevant image features. For this stage, we collect single-step solvable image-question-answer pairs as training data. The query tokens are appended to the input questions and output sub-questions. 2) **CoT Fine-tuning Stage.** Following pre-training, the second stage fine-tunes the model to align with

the MirrorCoT reasoning paradigm. The learnable query tokens are appended not only to the original question but also to each sub-question in the output. The embeddings at these query token positions are then replaced with the outputs of the cross-attention module, which processes the input image, question, and the corresponding answer at every step. For this stage, we train with our constructed dataset in the format of MirrorCoT.

4 Experiment

4.1 Experiments Setup

Training Data. We construct our training dataset based on LVIS-INSTRUCT4V (Wang et al., 2023) and LLaVA-CoT-100k (Xu et al., 2024). In the first training phase, only query tokens are learnable to learn to extract image features relevant to individual sub-questions, using single-step question-answer pairs sampled from LVIS-INSTRUCT4V and the multi-step reasoning chains during the subsequent CoT fine-tuning stage. For the CoT fine-tuning stage, we sample image-question pairs from the LLaVA-CoT-100k dataset and employ the QwenVL-2.5-72B (Bai et al., 2025; Wang et al., 2024c) model to generate MirrorCoT reasoning chains, explicitly prompting sub-question generation when visual evidence is required.

Benchmarks and Models. To evaluate the effectiveness of MirrorCoT, we conduct comprehensive experiments by integrating it with LLaVA-1.5-7B across six datasets spanning multimodal reasoning (MMStar (Chen et al., 2024a), MMBench (Liu et al., 2024b), MM-Vet (Yu et al., 2024b), ScienceQA (Lu et al., 2022)) and hallucination tasks (HallusionBench (Guan et al., 2024), HaloQuest (Wang et al., 2024d)). We also evaluate our method on the highly challenging M^{3}CoT (Chen et al., 2024b) dataset, which demands an average of 10.9 reasoning steps per question. To demonstrate the superiority of our MirrorCoT, we compare it with state-of-the-art multimodal reasoning methods, i.e., VAR(adjust attention assignment when inference) (Kang et al., 2025), VoCoT (Li et al., 2025) (interleave raw sub-image tokens with textual tokens), and textual CoT, including classic CoT (Wei et al., 2022) and VQD (Zhang et al., 2024a)(decompose the complex question into simple sub-questions), under a fair comparison.

Implementation Details. All experiments are conducted on NVIDIA A100 GPUs. Our training involves two stages, i.e., the Pre-training and CoT Fine-tuning stages with our constructed data. For the implementation of the comparison methods, we directly reproduce the results of these SOTA methods by using their official open-source code with default hyperparameters. Please refer to Section A.1 in Appendix for more implementation details about our training data and experimental settings.

4.2 Experimental Results and Analyses

MirrorCoT strengthens the textual CoT. As shown in Table 1, *our MirrorCoT consistently outperforms the direct answer baseline (Direct) on all the benchmarks* while offering enhanced interpretability. Furthermore, we evaluate MirrorCoT against the textual CoT fine-tuning(CoT) methods to assess its effectiveness. Given the same amount of data for fine-tuning LLaVA-1.5, *MirrorCoT achieves comparable or superior performance over four reasoning tasks over CoT.* Moreover, MirrorCoT exhibits reduced hallucination compared to textual CoT on the two hallucination benchmarks. MirrorCoT also surpasses CoT on M^{3}CoT by 1.1% as shown in Table 2. (The results in the Theory split exhibit significant discrepancy due to its minimal size, i.e., 11 questions.) Since our MirrorCoT introduces sub-questions, we further contrast MirrorCoT with VQD (Zhang et al., 2024a). (See Section A.5 in Appendix for detailed case studies comparing MirrorCoT with VQD.) As evidenced in Table 1, MirrorCoT outperforms VQD by 2.7% on MMStar, 1.8% on MMBench, and 2.0% on HallusionBench with fewer parameters. These findings indicate that MirrorCoT not only preserves the strengths of traditional CoT but also demonstrates significant improvements in both reasoning accuracy and anti-hallucination capabilities of MLLMs.

MirrorCoT surpasses multimodal interleaved CoT. As demonstrated in Table 1, *our MirrorCoT outperforms VoCoT across 5 benchmarks* except MMStar. We speculate that this is because VoCoT is optimized specifically for handling object-centric tasks, which make up a large proportion (62.4%) of MMStar. Furthermore, we compare the average visual tokens introduced by VoCoT and MirrorCoT. The results (see Section A.4 in Appendix) indicate that MirrorCoT achieves comparable performance while requiring 91.1% fewer visual tokens (23.9 per question) than VoCoT (268.7 per question). Meanwhile, MirrorCoT also exhibits better task versatility in non-object-centric tasks. This validates the superiority of our MirrorCoT, thanks to the proposed dynamic visual token insertion strategy.

Table 1: Benchmark results on general vision-language task. Performance is evaluated across two categories of datasets: general cross-modal benchmarks (MMStar, MMBench, MM-VET, ScienceQA) and hallucination-specific benchmarks (HallusionBench, HaloQuest). The experiments marked with ‡ are conducted using the maximum amount of data available.

Model	Param	MMStar	MMB	MMVet	SQA	HalluBench	Haloq
Random	-	24.9	25.3	-	25.2	47.3	19.1
Closed-source LVLMs							
GPT-4V(Yang et al., 2023)	-	**46.1**	**69.6**	**67.7**	**81.4**	**65.3**	-
GeminiPro-Vision(Team et al., 2023)	-	42.6	68.1	63.1	80.6	36.9	-
Open-source LVLMs							
VAR(Kang et al., 2025)	7B	29.9	65.4	29.5	64.3	27.8	23.8
VoCoT(Li et al., 2025)	7B	36.2	68.1	29.0	62.8	48.2	18.0
VQD(Zhang et al., 2024a)	13B	33.4	68.0	27.8	**70.8**	48.4	20.6
LLaVA-1.5	7B	31.9	64.3	29.0	64.7	47.4	20.3
+CoT	7B	34.7	70.8	22.2	63.2	28.9	20.1
+MirrorCoT	7B	**37.3**	68.7	23.5	65.3	29.4	23.1
+CoT‡	7B	33.7	**72.6**	29.5	64.2	**50.5**	25.4
+MirrorCoT‡	7B	35.9	69.8	**29.5**	**65.8**	50.4	**33.2**
InternVL-3	2B	**54.1**	80.1	52.8	88.3	45.4	60.0
+CoT	2B	46.8	63.5	47.0	76.1	53.4	64.2
+MirrorCoT	2B	46.2	**81.4**	**50.3**	**88.7**	**50.0**	**66.7**

Table 2: Results on M^3CoT. The baseline methods encompass direct answer and CoT fine-tuning.

Model	Param	Science			Commonsense			Mathematics			Total
		Lang	Natural	Social	Physical	Social	Temporal	Algebra	Geometry	Theory	
Random	-	32.7	30.6	26.7	33.0	22.2	20.3	35.7	27.5	23.8	28.6
VAR(Kang et al., 2025)	7B	73.2	73.3	18.3	41.4	23.5	15.0	15.4	19.4	9.1	28.6
VoCoT(Li et al., 2025)	7B	26.4	36.3	25.2	41.4	31.0	45.0	35.4	25.0	27.3	32.1
VQD(Zhang et al., 2024a)	13B	48.3	29.2	26.6	63.4	64.7	36.7	32.3	22.2	27.3	35.3
LLaVA-1.5	7B	43.7	29.7	17.6	75.6	68.9	16.7	18.4	16.7	18.1	31.4
+CoT	7B	40.2	34.3	27.2	80.5	62.1	36.7	26.2	22.2	72.7	37.1(+5.7)
+MirrorCoT	7B	34.5	34.3	27.9	68.3	62.1	48.3	53.8	22.2	63.6	**38.2**(+6.8)
InternVL-3	2B	11.8	30.7	23.3	43.9	55.2	30.0	18.5	5.5	36.4	29.8
+CoT	2B	25.3	33.5	29.6	41.5	47.4	25.0	26.2	19.4	27.3	30.8(+1.0)
+MirrorCoT	2B	31.0	42.7	22.6	75.6	60.3	56.7	18.5	22.2	27.3	**37.9**(+7.1)

MirrorCoT mitigates performance degradation of CoT fine-tuning. For InternVL3-2B, direct-answer accuracy on datasets like MMStar and MMBench is already near the ceiling. The standard textual CoT fine-tuning hurt performance on these high-baseline sets; as reported in (Wang et al., 2025), the drop is caused by the distribution shift inherent to SFT-teacher forcing. In contrast, MirrorCoT substantially alleviates this issue and even surpasses the direct-answer baseline on MMBench (81.4 vs. 80.1) while largely preserving performance on MMVet and SQA. We attribute this improvement to the recurrent injection of visual query tokens during reasoning: even if the model drifts slightly in the auto-regressive phase, the injected query tokens recurrently re-align the attention distribution with the evidence present in the image, mitigating error accumulation. Moreover, on low-baseline datasets such as M^3CoT and HaloQuest, MirrorCoT delivers larger improvements than purely textual CoT.

5 Ablation Studies

Ablation on CoT formats. As depicted in Figure 2, our MirrorCoT has two key components: sub-questions and learnable query tokens. We ablate the two key components of our method to analyze their contributions. Adding sub-questions alone improves the CoT baseline on MMStar and MM-Vet, while further incorporating learnable query tokens brings an additional gain of +1.0% (from 47.7% to 48.7%) on average, showing the combination of sub-question and query token is necessary.

Effects of training strategy. As delineated in Section 4.1, our proposed framework adopts a two-phase training paradigm: the pretraining stage(Stage 1) followed by the CoT fine-tuning stage(Stage 2). To evaluate the contribution of each training stage, we conduct ablation experiments based on LLaVA-1.5-7B with the maximum amount of data. The baseline model without training achieves 47.5% task accuracy on average. When introducing only the CoT fine-tuning stage, it

Table 3: Ablation on components of MirrorCoT. Sub-questions activate the language-to-vision alignment, and query tokens serve as the carrier of visual information in vision-to-language alignment.

Model	Sub Question (L → V)	Query Tokens (V → L)	MMStar	MMB	MMVet	ScienceQA	Average
Direct			31.9	64.3	29.0	64.7	47.5
MirrorCoT	✓		35.1	68.4	**25.2**	61.9	47.7
MirrorCoT	✓	✓	**37.3**	**68.7**	23.5	**65.3**	**48.7**

demonstrates a 1.3% improvement in average task performance compared to the baseline, but shows a 2.6% reduction compared to the model trained with both stages.

Effects of training data volume and number of query tokens. We ablate the impact of training data scaling and query token length based on the LLaVA-1.5-7B backbone. As the amount of training data increases, the performance of LLaVA-1.5-MirrorCoT on the four datasets shows an overall upward trend. While MirrorCoT exhibits a performance decline before improving at low data volumes(6k,30k). We speculate that training with limited data amplifies data bias-induced hallucinations, which manifest most prominently on hallucination benchmarks.

Regarding the query token capacity, increasing the token count from 6 to 18 generally enhances model performance due to richer visual representations. For instance, scaling tokens from 9 to 18 improves MMBench accuracy from 69.8% to 70.6%. However, this performance gain exhibits diminishing marginal returns as the token length continues to scale, suggesting a trade-off between capacity and efficiency.

Effects of the quality of sub-questions. To investigate how the quality of sub-questions influences model performance, we conduct an experiment by employing three prompt variants with distinct preferences for sub-question types to fine-tune LLaVA-1.5 via our MirrorCoT. Concretely, these three levels of prompt variants, listed as follows, can significantly influence the generated sub-questions with different levels of requirements: 1) Fine-grained Level: , which restricts reasoning and enforces explicit, highly specific sub-questions (e.g., "What is the color of the strips?"). 2) Default Level: Currently used by our MirrorCoT. 3) Coarse-grained Level, which encourages global, abstract, and high-level reasoning questions. (e.g., "What visible elements suggest an artistic activity?")

The results in Table 5 demonstrate that these three prompt variants achieve comparable performance. Most notably, the Default Level averagedly delivers the best performance on three of four benchmarks. This suggests that excessive prompt engineering may not always yield superior results, and less constrained prompts might be superior by allowing for more natural model reasoning.

6 Discussions

6.1 Visualization of MirrorCoT workflow

We visualize the bidirectional loop of MirrorCoT in Figure 4, allowing us to explore the effectiveness of its active visual evidence extraction mechanism.

Vision-to-Language Alignment. As the model progressively generates each reasoning step, it simultaneously raises sub-questions (e.g., "What item is the man carrying?") to inquire about visual evidence. Our cross-modal attention mechanism simultaneously captures the subject and its surroundings. These visual features are embedded into subsequent tokens (e.g., <Query 2 Token> in Fig. 4), leading to precise visual findings (e.g., "carrying a suitcase"). From an information entropy perspective, this alignment increases effective information, reducing uncertainty and narrowing the search space for reasoning.

Language-to-Vision Alignment. By interleaving query tokens within the textual CoT, MirrorCoT forces the reasoning process to dynamically ground on discriminative visual features (e.g., backrest structures) rather than relying on language priors. As shown in Fig. 8, while standard textual CoT suffers from hallucinated descriptions (e.g., misidentifying a sofa as a table), MirrorCoT redistributes attention toward the visual modality, effectively disrupting language dominance.

6.2 Computation Efficiency Analysis

Compared to text-only Large Language Models, incorporating visual modalities inevitably introduces additional inference latency due to cross-modal interactions and expanded sequence lengths. Rather than inserting raw image patches, MirrorCoT introduces an "Active Query-Triggered Extraction" mechanism that radically compresses the visual context. As demonstrated in Table 6, our method

Table 4: Ablation on training stages. The experiment is conducted with the maximum amount of data.

Model	Stage1	Stage2	MMStar	MMB	MMVet	ScienceQA	Average
Direct			31.9	64.3	29.0	64.7	47.5
MirrorCoT		✓	35.7	68.2	29.0	62.1	48.8
MirrorCoT	✓	✓	**35.9**	**69.8**	**29.5**	**65.8**	**50.3**

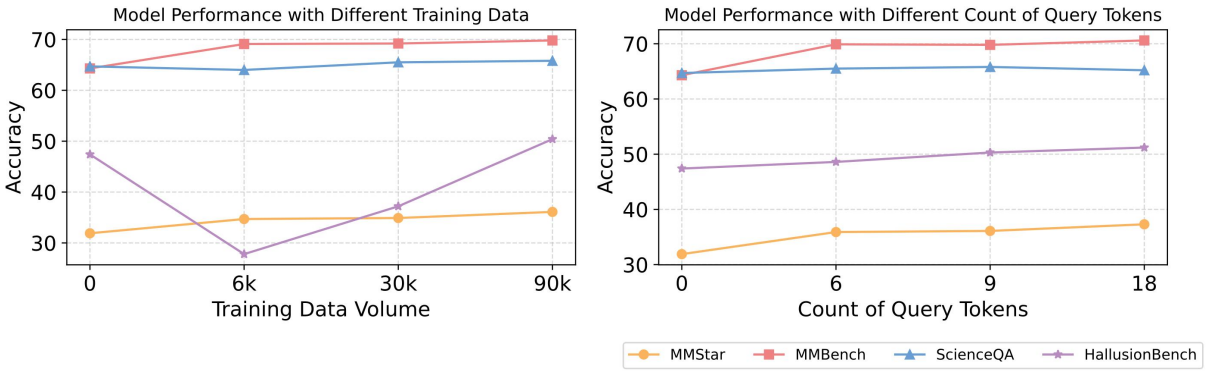

Figure 3: Ablations on the volume of training data and the count of query tokens.

Table 5: The evaluation results on the MMStar, MMBench, MMVet, and SQA benchmarks.

Prompt Variant	MMStar	MMB	MMVet	SQA	Avg.
Fine-grained	34.7	68.9	23.9	65.1	48.2
Default	37.3	68.7	23.5	65.3	**48.7**
Coarse-grained	35.6	63.2	22.0	64.8	46.4

Table 6: Comparison of visual token consumption.

Method	Visual Tokens per Query
VoCoT	~268.7
MirrorCoT (Ours)	**~23.9 (91% ↓)**

slashes the visual tokens per query from ~268.7 to ~23.9, achieving a **91% reduction**. Although the cross-attention mechanism brings a modest throughput penalty (from 54 to 23 tokens/s), this generation speed remains well above the average human reading pace.

7 Conclusion

This paper focused on the core challenge in MLLMs when performing long-term multimodal interleaved CoT generation: effective visual information extraction. We propose MirrorCoT, a lightweight multimodal CoT with query-triggered injection: (1) a vision operator to extract text-relevant visual features instead of raw image patches for vision-to-language grounding, and (2) a token-level conditioning mechanism that dynamically integrates these query tokens into decoder inputs during text generation, ensuring language-to-vision alignment by forcing explicit reference to visual context. This design alleviates the excessive visual-token overhead inherent in prior multimodal interleaved approaches.

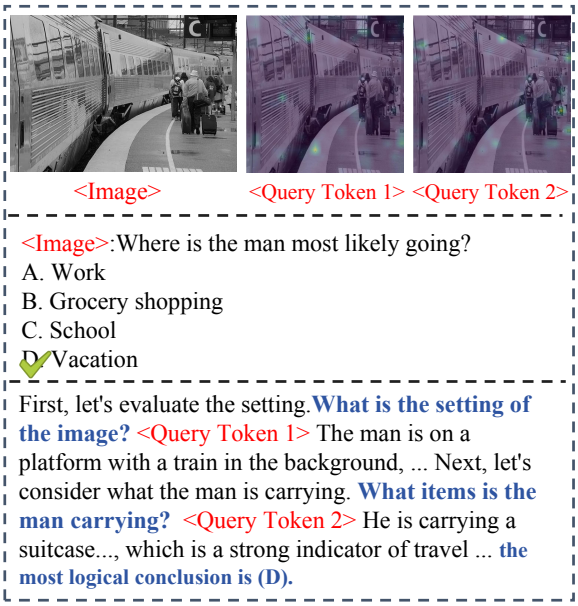

Figure 4: Visualization of the attention weights of the last cross-attention layer formulated by Eq.3. The attention maps highlight the regions of interest corresponding to the specific questions posed.

Limitations

Compared to pure textual CoT, the additional latency of MirrorCoT stems from essential cross-modal interactions. Bridging this remaining speed gap via more efficient modality fusion remains a promising direction for future work.

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A Technical Appendices and Supplementary Material

A.1 More Implementation Details

Training Settings. Our training involves two stages, i.e., the Pre-training and CoT Fine-tuning stages. The objective of pre-training is to enable the cross-attention module to extract question-relevant image features. Following pre-training, the second stage fine-tunes the model to align with the MirrorCoT reasoning paradigm. All experiments are conducted on NVIDIA A100 GPUs. For LLaVA-1.5-7B, we pre-trained the model for 5 epochs (batch size 8, learning rate 2×10^{-5}), followed by 1 CoT fine-tuning epoch (batch size 10, learning rate 2×10^{-5}). The pre-training requires 6 hours, and the CoT fine-tuning requires 16 hours with the maximum amount of data(90k). For InternVL-3-2B, we adjust the hyperparameters to 3 pre-training epochs (batch size 8, learning rate 4×10^{-5}) and 4 fine-tuning epochs (batch size 10, learning rate 4×10^{-6}). The pre-training requires 7 hours, and the CoT fine-tuning requires 9 hours. In the first stage, only the parameters of the cross-attention module and query tokens are updated. In the second stage, besides query tokens and the cross-attention module, the last 6 layers of the LLaVA-1.5 language backbone and the last 4 layers of the InternVL-3-2B language backbone are unfrozen.

Training data construction. We construct our training dataset based on LVIS-INSTRUCT4V (Wang et al., 2023) and LLaVA-CoT-100k (Xu et al., 2024). For the pre-training stage, we curate a dataset consisting of 12,000 question-answer pairs sampled from LVIS-INSTRUCT4V, and 8,000 question-answer pairs extracted from the multi-step reasoning chains in the CoT fine-tuning stage. For the CoT fine-tuning stage, we sample 95,000 image-question pairs from LLaVA-CoT-100K and use QwenVL-2.5-72B (Bai et al., 2025) to generate the reasoning chains in the MirrorCoT paradigm automatically. This transformation introduces explicitly dynamic sub-question generation when visual evidence is required and structured reasoning steps that alternate between visual verification and logical inference. The examples of our data are demonstrated in Figure 5.

A.2 More Hyperparameter Analysis

We further conduct hyperparameter sensitivity experiments on LLaVA-1.5-7B with 30k training samples. Specifically, we study the effects of learning rate and the number of trainable LLM layers. We observe that excessively large learning rates(e.g., 2×10^{-4}) leads to unstable optimization (28.1 on MMStar), while overly small learning rates(e.g., 2×10^{-6}) result in insufficient adaptation(32.3 vs. 37.3). A moderate learning rate achieves the best trade-off between preserving pre-trained knowledge and adapting to the target task. We also study different numbers of trainable LLM layers. Increasing trainable layers improves task adaptation but may introduce more severe catastrophic forgetting on certain benchmarks. We conjecture that aggressively updating deeper language layers disrupts the original visual-language alignment of the pre-trained model, especially under limited-scale fine-tuning data. Overall, the method demonstrates relatively stable performance within a reasonable hyperparameter range.

Method	LR	Layers	MMStar	MMVet
MirrorCoT	2e-5	4	33.2	23.3
	2e-5	8	32.5	26.5
	2e-4	6	28.1	-
	2e-6	6	32.3	23.1
Ours (selected)	2e-5	6	37.3	23.5

Table 7: Hyperparameter sensitivity study on learning rate and number of last unfrozen LLM layers. "Ours" denotes the selected configuration used in main experiments.

A.3 Benchmarks and Evaluation

We conduct extensive evaluations on seven benchmarks, which can be categorized into two distinct classes. The first class comprises cross-modal reasoning datasets, designed to assess the models' abilities to integrate and reason across different modalities. Benchmarks requiring LLM-based evaluation use Qwen-Plus (Yang et al., 2024) as the judge model.

MMStar MMStar (Chen et al., 2024c) is an elite vision-indispensable multimodal benchmark comprising 1,500 challenge samples meticulously selected by humans. The samples are chosen to ensure visual dependency, minimal data leakage, and the need for advanced multimodal capabilities for solutions.

MMBench MMBench (Liu et al., 2024b) is a comprehensive benchmark designed to evaluate the multimodal understanding capability of large vision-language models.

MM-Vet MM-Vet (Yu et al., 2024b) assesses the

Pre-training Stage

Source: LVIS-INSTRUCT4V

Question: **<Fig1>**What is the position of the man relative to the plants?
Answer: The man is in the foreground, and the plants are behind him, separated by a glass partition.

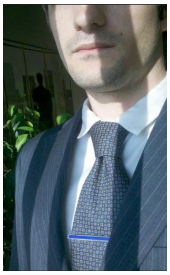
Source: Sub-questions extracted from MirrorCoT reasoning chains

Question: **<Fig2>**What letters are visible on the train?
Answer: The letters "OBB" are clearly visible on the side of the train.

CoT Finetuning Stage

Source: LLaVA-CoT-100k

Question: **<Fig2>**What letter appears twice in a row on the train?
A. g B. d C. w D. b
Answer: <SUMMARY> The core objective of the question is to identify which letter appears twice in a row on the train from the given options: A. g, B. d, C. w, D. b. </SUMMARY>
<CAPTION> The image shows a train at a station platform during nighttime. The train is red and has the letters "OBB" prominently displayed on its side. The platform is well-lit, and there are some people in the background near the entrance of the station. </CAPTION>
<REASONING> To answer this question, we need to carefully examine the letters visible on the train.<IMAGE_QUERY> What letters are visible on the train? </IMAGE_QUERY> The letters "OBB" are clearly visible on the side of the train.<IMAGE_QUERY> Are any of these letters repeated consecutively? </IMAGE_QUERY> Yes, the letter "B" appears twice in a row in the sequence "OBB".By comparing the visible letters with the given options, we can determine that the letter "B" matches option D.</REASONING>
<CONCLUSION> D. b </CONCLUSION>



<Fig1>

<Fig2>

Figure 5: Examples of our training data in the two training stages.

performance of models in six fundamental vision-language skills: numeracy, recognition, knowledge, spatial awareness, language creation, and optical character recognition (OCR).

M^{3}CoT M^{3}CoT (Chen et al., 2024b) aims to advance multi-domain, multi-step, and multi-modal reasoning by integrating visual and textual modalities. The dataset requires models to perform complex, multi-step reasoning. On average, each question involves 10.9 steps to reach a conclusion, significantly higher than other benchmarks like ScienceQA (which averages 2.5 steps).

ScienceQA ScienceQA (Lu et al., 2022) is a benchmark focused on evaluating models' ability to answer science-related questions using both visual and textual information. The second class encompasses hallucination question-answering datasets that evaluate the models' performance in addressing hallucination-related issues.

HallusionBench HallusionBench (Guan et al., 2024) is an advanced diagnostic suite designed to evaluate the visual illusions and knowledge hallucinations of large vision-language models. Given the cross-modal nature of our research, we evaluate model performance on its image split.

HaloQuest HaloQuest (Wang et al., 2024d) is a novel Visual Question Answering (VQA) dataset focusing on multimodal hallucinations in vision-language models (VLMs). It combines real images and synthetic images, with questions and answers designed to trigger and evaluate hallucinations.

A.4 Comparison with VoCoT

To better illustrate the advantage of MirrorCoT over VoCoT, we perform a quantitative comparison between MirrorCoT and VoCoT.

Task Versatility. While VoCoT specializes in object-centric tasks to enhance visual grounding, we propose MirrorCoT as a more versatile framework for general multimodal reasoning. To systematically evaluate this advantage, we categorize each dataset into object-centric and non-object-centric subsets through LLM-assisted annotation. As depicted in Figure 6(a), MirrorCoT surpasses VoCoT over the non-object-centric split of MMBench, MM-Vet, ScienceQA, and M^{3}CoT.

Less Computational Cost. VoCoT inserts raw image tokens whenever object references are detected in the text, regardless of their relevance to the reasoning task. As demonstrated in Section 6, this leads to excessive insertion of non-critical visual tokens. We quantify this inefficiency by measuring the average number of visual tokens per sample. Meanwhile, we compare the per-sample average visual tokens required between MirrorCoT and VoCoT across three multimodal benchmarks: MMStar, MMBench, and MM-Vet. The results demonstrate that MirrorCoT achieves comparable performance while requiring 91.1% (23.9) fewer visual tokens than VoCoT (268.7).

Table 8: Benchmarks and Evaluation strategy.

	MMStar	MMBench	MM-Vet	ScienceQA	M^3CoT	HallusionBench	Haloquest
Split	-	dev	test	test	dev	image	val
Metric	Acc	Acc	Score	Acc	Acc	Acc	Acc
LLM-Eval			✓				✓

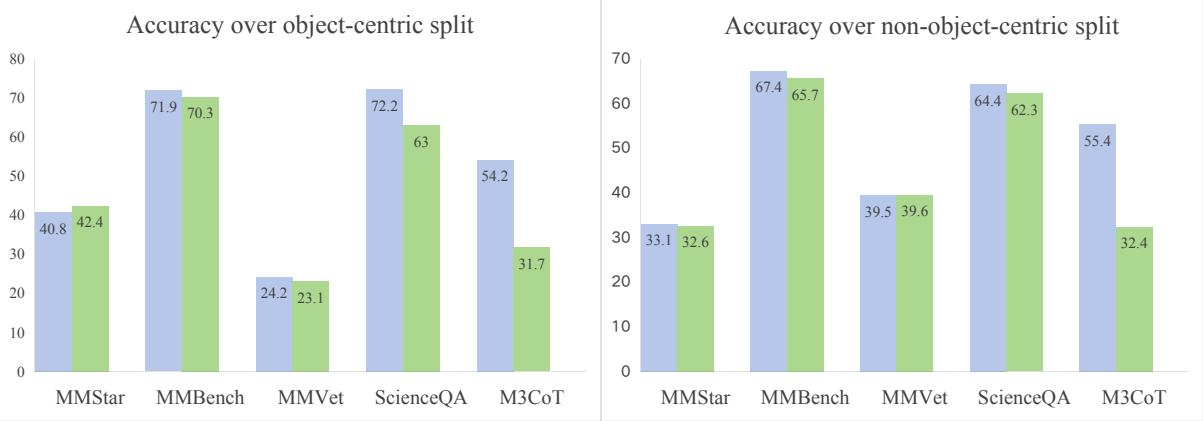


Figure 6: The results of MirrorCoT and VoCoT on benchmarks that are divided into object-centric and non-object-centric splits.

A.5 Case Study

Comparison with VQD. We further contrast MirrorCoT with VQD(Zhang et al., 2024a) (Visual Question Decomposition), a representative approach that decomposes main questions into sub-questions and draws the conclusion based on those sub-questions and corresponding answers. Instead of proposing all sub-questions at first, MirrorCoT introduces them progressively as the reasoning unfolds. For example, as illustrated in Figure 9, VQD decomposes "What can be inferred about the location shown in the image?" into a sub-question ("Are the animals in the picture already fenced in?"). The information gleaned from the sub-question is insufficient to address the original query. However, MirrorCoT progressively asks "What types of animals are visible, and how are they being treated", "Are there any signs of structured activity or infrastructure?". Each sub-question builds on the insights gained from the previous ones, creating a chain of reasoning that progressively collects visual evidence and drives the model toward a more accurate final answer. More cases please refer to Figure 9 and Figure 10.

Comparison with Textual CoT and VoCoT. To highlight the comparative advantages of MirrorCoT over conventional CoT and VoCoT(Li et al., 2025), Figure 11 and Figure 12 present representative case studies. For example, in the second case of Figure 11, MirrorCoT accurately identifies the distance between Pair 1 and Pair 2, whereas both CoT and VoCoT produce erroneous measurements, demonstrating the superior modality alignment capability of MirrorCoT.

Table 9: Results on AMBER generative task.

Method	CHAIR↓	Cover↑	Hal↓	Cog
VAR	8.3	52.5	38.8	4.3
VQD	6.6	42.4	18.8	1.2
Direct	7.5	51.7	35.1	4.2
CoT	7.5	51.7	34.7	4.2
MirrorCoT	**5.0**	**53.6**	**29.6**	2.7

A.6 Hallucination Alleviation

Contradictions between the image input and the textual output are called hallucinations. The experimental results in Section 3.2 of the main text demonstrate that our MirrorCoT is also effective in alleviating the hallucination of MLLMs. Since our paper aims to improve reasoning ability through the promotion of modality alignment, we did not extensively address the capability of our method to mitigate hallucination in the main text. In the supplementary material, we demonstrate more experimental results of our MirrorCoT on the hallucination benchmark.

Benchmark and Baselines. AMBER(Wang et al., 2024a) is an LLM-free multi-dimensional benchmark designed for evaluating multi-modal hallucinations in large language models (LLMs). It

Your Task: Classify the given question into object-centric or non-object-centric based on the definitions and examples below.
Definitions:
Object-Centric Questions:
Explicitly refer to specific objects/entities (e.g., "car", "person", "book").
Focus on physical attributes (color, shape, position), counts, or spatial relationships (e.g., "left of", "holding").
Examples: "What color is the vase on the table?", "How many dogs are in the image?", "Is the laptop open or closed?"
Non-Object-Centric Questions:
Concern abstract concepts, scene-level understanding, or subjective interpretation.
May involve emotions, intentions, temporal dynamics, or non-visual context.
Examples: "Why is this scene unusual?", "Describe the mood of the photograph.", "What might happen next in this situation?"
If it is object-centric, please answer with "1". Otherwise, answer with "0".
question: {question}
your response:

Figure 7: Prompt for dividing datasets into object-centric and non-object-centric splits.

is capable of assessing both generative and discriminative tasks. We evaluate MirrorCoT and CoT fine-tuning methods on the generative task of AMBER. AMBER introduces several metrics to evaluate hallucinations in the generative task: **CHAIR**(Rohrbach et al., 2019) measures the frequency of hallucinatory objects appearing in the responses. **Cover** measures the extent to which the response covers the image description. **Hal** represents the proportion of responses with hallucinations. **Cog** assesses whether the hallucinations in MLLMs are similar to those in human cognition.

Qualitative Results. As presented in Table 9, MirrorCoT demonstrates significant advantages over textual CoT(VQD(Zhang et al., 2024a) and CoT fine-tuning) and VAR(Kang et al., 2025)(identify and reallocate excess attention weights from visual trap tokens to more informative visual tokens within an image) across all four evaluation metrics in the AMBER generative task. Notably, our method achieves the lowest CHAIR (5.0) and Hal (29.6) scores among all methods. The superior performance is further evidenced by MirrorCoT attaining the highest Cover score (53.6), indicating that the responses of MirrorCoT are not only more accurate but also more detailed. These quantitative improvements demonstrate MirrorCoT's effectiveness in producing more reliable and semantically comprehensive outputs while mitigating hallucination risks.

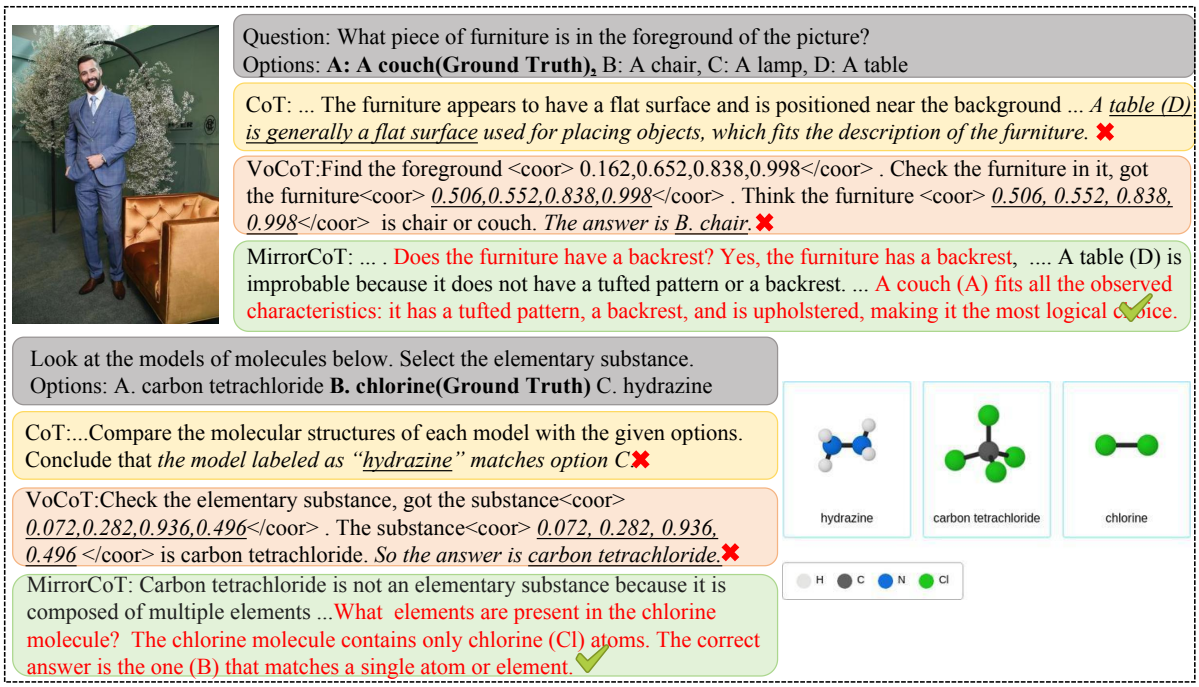


Figure 8: Case study. Comparison of CoT, VoCoT, and our MirrorCoT.

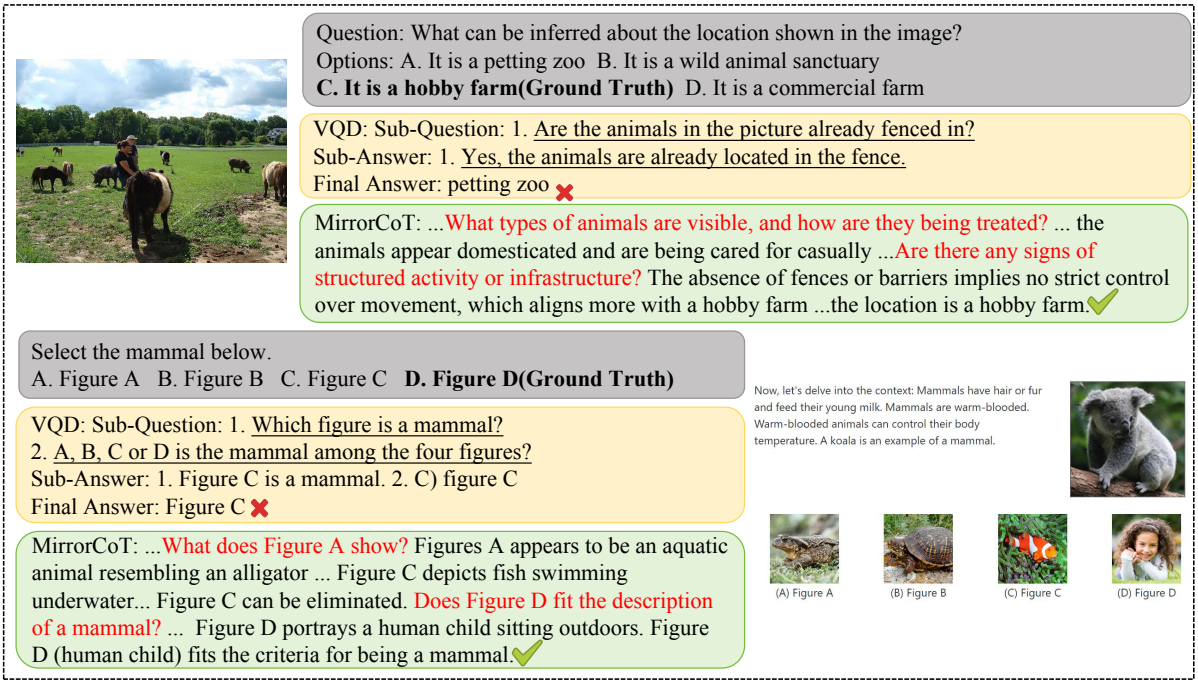
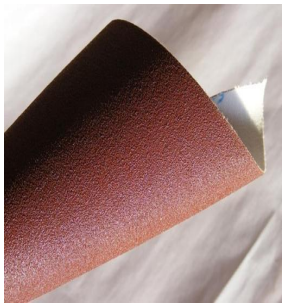


Figure 9: Comparison of our MirrorCoT and VQD.

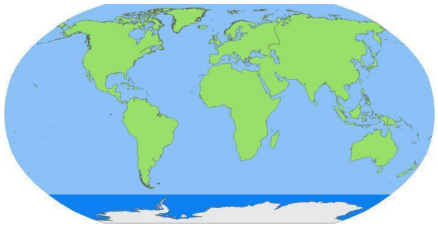


Question: What's the function of the demonstrated object?
A. Measure the temperature **B. burnish(Ground Truth)** C. Brushing D. Cut the grass

VQD: Sub-Question: 1. Does the bumpy surface of the object suggest that it is designed for brushing? 2. Does the object's shape and its function of cutting grass indicate its purpose?
Sub-Answer: Yes, ... *2. Yes, the object is quite like a lawn mower.*
Final Answer: D) cut the grass ✗

MirrorCoT: ...What is the shape and texture of the object? The object has a curved shape and a textured surface, which suggests it might be used for brushing or polishing. ... the most logical conclusion is that the object is used for Burnish (B). ✓

Question: Which ocean is highlighted?
Options: **A: the Southern Ocean(Ground Truth)** B: the Pacific Ocean
C: the Arctic Ocean D: the Indian Ocean



VQD: Sub-Question: 1. Does the map show the outline of the continents and the shape of the oceans? 2. Which ocean has its shape and the outlines of the continents that border it clearly visible?
Sub-Answer: 1. Yes, the map shows the outline of the continents and the shape of the oceans clearly. 2. *The Pacific Ocean*
Final Answer: B: the Pacific Ocean ✗

MirrorCoT: ...What is the size and shape of the highlighted ocean? The ocean appears to be relatively large and has a distinctive shape that aligns with the Southern Ocean ... the Southern Ocean as the correct answer. ✓

Figure 10: Comparison of our MirrorCoT and VQD.

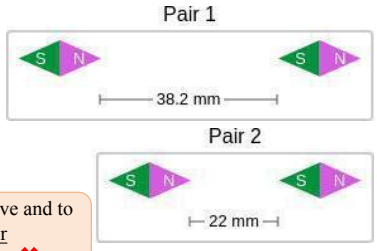
Question: What bird species are shown in the image?
Options: A: White pelicans, B: White storks, C: Black swans, **D: Snowy egrets(Ground Truth)**

CoT: The birds in the image have long necks and are white, which are characteristics typical of storks. These features are not associated with pelicans, swans, or egrets. ... the conclusion is B. ✗

VoCoT: The image shows two white pelicans ✗ <coor> 0.578,0.372,0.638,0.500</coor> and <coor> 0.678, 0.372, 0.742,0.480</coor> perched on a nest <coor> 0.480,0.444,0.814,0.592</coor>.

MirrorCoT: ... What are the notable physical features of the birds in the image? the birds have long necks and are standing on a nest made of twigs. ... What does the background of the image look like? The background is a clear blue sky with scattered clouds... Snowy egrets are small wading birds with long necks... . the most logical conclusion is that the bird species shown in the image is the Snowy egret (D). ✓

Question: Think about the magnetic force between the magnets in each pair. Which of the following statements is true?
Options: **A: The magnitude of the magnetic force is greater in Pair 2.(Ground Truth)**
B: The magnitude of the magnetic force is greater in Pair 1. C. ... D. ...



CoT:...In Pair 1, the magnets are 4.2 mm apart, while in Pair 2, they are 28 mm apart. Since the distance in Pair 1 is smaller than in Pair 2, the magnitude of the magnetic force is greater in Pair 1. . ✗

VoCoT: In Pair 1, the magnets...one <coor> 0.440,0.453,0.500,0.520</coor> being slightly above and to the right of the other <coor> 0.020,0.453,0.100,0.533</coor> . ... the magnets in Pair 1 are closer together and more aligned, which would naturally lead to a stronger magnetic force between them. ✗

MirrorCoT: First, let's recall the relationship between magnetic force and distance. ... What is the distance between the poles of Pair 1 and Pair 2? Pair 1 has a distance of 38.2 mm between the poles, while Pair 2 has a distance of 22 mm. Pair 2, with its smaller distance, will have a greater magnetic force compared to Pair 1... the most logical conclusion is that the magnitude of the magnetic force is greater in Pair 2. ✓

Figure 11: Comparison of our MirrorCoT, CoT, and VoCoT.

Question: How many fish are swimming next to the cat?
Ground Truth: There are no fish in this image.

CoT: ... First, observe the entire image for any fish-like creatures. ... Count the fish by visually estimating... There are *3 fish swimming* next to the cat. ✖

VoCoT:The image shows a cat <coor> 0.252,0.170,0.702,0.834</coor> swimming in water, and *there are also two fish <coor> 0.350,0.002,0.678,0.132</coor> and<coor> 0.350,0.002,0.678,0.132</coor>* swimming next to it. *So, the answer is two*. ✖

MirrorCoT: ... What is the main subject of the image? The main subject of the image is a cat, ...What is the environment like in the image? ... suggesting an underwater setting. Are there any visible fish in the image? No, there are no visible fish in the image. ... So, there are no fish swimming next to the cat. ✔

Question: How many large wheels are on the water's edge?
Ground Truth: two

CoT:...The large circular objects on the water's edge are clearly visible and resemble wheels. ... The count of *three wheels* matches the typical number of wheels found on a roundabout. ✖

VoCoT:Find the water <coor> 0.383,0.469,0.999,0.590</coor> . Check the edge of it, got the edge<coor> 0.591,0.536,0.999,0.642</coor> . Check the large wheel on it, got the wheel<coor> 0.829,0.556,0.866,0.604</coor> . So *the answer is 1*. ✖

MirrorCoT: To determine the number of large wheels on the water's edge, let's start by examining the area around the water feature. Are there any large wheels visible on the water's edge? Yes, there are two large wheels visible on the water's edge. ✔

Figure 12: Comparison of our MirrorCoT, CoT, and VoCoT.