Goal Representations for Instruction Following: A Semi-Supervised Language Interface to Control

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Abstract: Our goal is for robots to follow natural language instructions like "put the towel next to the microwave." But getting large amounts of labeled data, i.e. data that contains demonstrations of tasks labeled with the language instruction, is prohibitive. In contrast, obtaining policies that respond to image goals is much easier, because any autonomous trial or demonstration can be labeled in hindsight with its final state as the goal. In this work, we contribute a method that taps into joint image- and goal- conditioned policies with language using only a small amount of language data. Prior work has made progress on this using vision-language models or by jointly training language-goal-conditioned policies, but so far neither method has scaled effectively to real-world robot tasks without significant human annotation. Our method achieves robust performance in the real world by learning an embedding from the labeled data that aligns language not to the goal image, but rather to the desired *change* between the start and goal images that the instruction corresponds to. We then train a policy on this embedding: the policy benefits from all the unlabeled data, but the aligned embedding provides an *interface* for language to steer the policy. We show instruction following across a variety of manipulation tasks in different scenes, with generalization to language instructions outside of the labeled data. Videos and code for our approach can be found on our website: https://sites.google.com/view/goal-instructions.

Keywords: Instruction Following, Representation Learning, Manipulation

1 Introduction

Natural language has the potential to be an easy-to-use and powerful form of task specification in robotics. To follow language instructions, a robot must understand human intent, ground its understanding in the current observation of the environment, and solve the task by interacting with the environment. Training robots to do this is challenging, especially given that language-annotated data is limited. Existing approaches require large amounts of expensive human language-annotated demonstrations and are brittle on instructions outside the training data.

Visual goals (i.e., goal images), though less intuitive for humans, provide complementary benefits for task representation in policy learning. Goals benefit from being easy to ground since, as images, they can be directly compared with other states. More importantly, goal tasks provide additional supervision and enable learning from unstructured data through hindsight relabeling [1, 2, 3]. However, compared to commanding robots with instructions, specifying goals is less practical and flexible for real-world applications, where users might prefer to tell the robot what they want rather than having to show it.

Exposing an instruction-following interface for goal-conditioned policies could combine the strengths of both goal- and language- task specification to enable generalist robots that can be easily

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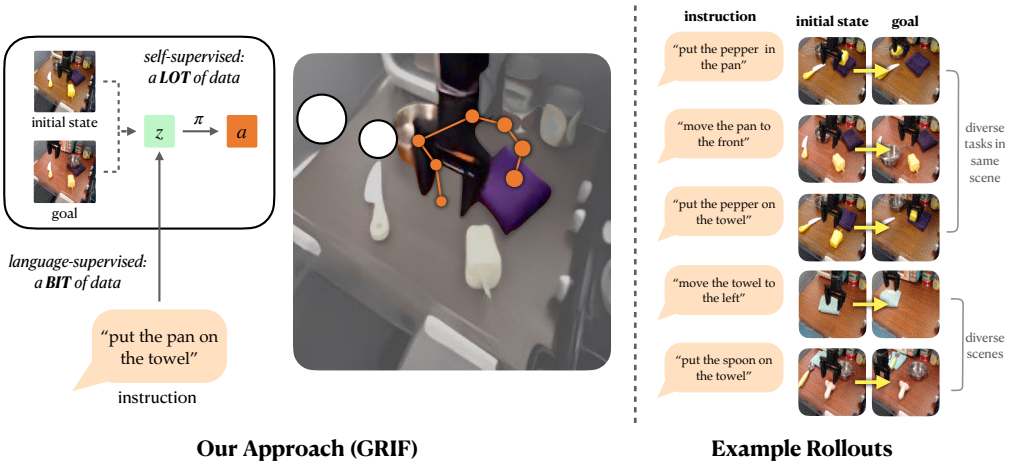

Figure 1: **Left:** Our approach learns representations of instructions that are aligned to transitions from the initial state to the goal. When commanded with instructions, the policy π computes the task representation z from the instruction and predicts the action a to solve the task. Our approach is trained with a small number of labeled demonstrations and large-scale unlabeled demonstrations. **Right:** Our approach can solve diverse tasks and generalize to vast environment variations.

commanded. While goal-conditioned policy learning can help digest unstructured data, non-robot vision-language data sources make it possible to connect language and visual goals for generalization to diverse instructions in the real world.

To this end, we propose Goal Representations for Instruction Following (GRIF), an approach that jointly trains a language- and a goal- conditioned policy with aligned task representations. We term task representations *aligned* because our objective encourages learning similar representations for language instructions and state transitions that correspond to the same semantic task. GRIF learns this representation structure explicitly through a contrastive task alignment term. Since task representations across language and image goal modalities have similar semantics, this approach allows us to use robot data collected without annotations to improve performance by the agent on image goal tasks when viewed as a goal-conditioned policy, and thus indirectly improve language-conditioned performance in a semi-supervised manner. An overview of GRIF is shown in Figure 1.

We present an approach for learning a language interface for visuomotor control without extensive language labels. With this method, we demonstrate that the semantic knowledge from a pre-trained vision-language model (CLIP [4]) can be used to improved task representations and manipulation even though such models perform poorly at task understanding out-of-the-box. Our experiments show that aligned representations of tasks as scene changes enable improved performance at grounding and following language instructions within diverse real-world scenes.

2 Related Work

Robotic control with language interfaces. Early works in language-conditioned robotic control use hand-designed parse trees or probabilistic graphical models to convert instructions into symbolic states to configure the downstream planners and controllers [5, 6, 7, 8]. To generalize beyond limited human specifications, a growing number of works have trained conditional policies end-to-end to follow natural language instructions [9, 10, 11, 12, 13, 14, 15, 16, 17]. Using the learned language-conditioned policies as the low-level API, these works have paved the way for broad downstream applications [18, 19, 20, 21, 22]. However, most of these methods need high-capacity policy networks on massive labeled demonstration data, which is costly to acquire. As a result, the learned policies often demonstrate limited generalization to unseen scenarios or can only handle limited instructions in real-world scenes.

Vision-language pre-training. Vision-language models (VLMs) enable textual descriptions to be associated with visual scenes [4, 23]. Through contrastive learning over internet-scale data, recent

large-scale VLMs such as CLIP [4] have achieved unprecedented zero-shot and few-shot generalization capability, with a wide range of applications. Despite these advances, apply pre-trained VLMs for robotic control is not straightforward since control requires grounding instructions in motions instead of static images. Through training from scratch or fine-tuning on human trajectories [24, 25], recent approaches learn representations for visuomotor control [26, 27]. These works have only used language labels to supervise the learning of visual representations for control without using the language encoders as an interface to command the policy. Shridhar et al. [28] propose to use pre-trained CLIP [4] to enable sample-efficient policy learning. However, the grounding of instructions in their method is based on predefined pick-and-place motion primitives with known camera parameters. In contrast, our approach learns to align the representations of the instruction and the representation of the transition from the initial state to the goal on labeled robot data. Without any assumptions about the observation or action spaces, the task representations learned by our approach lead to superior success rates in downstream tasks in both seen and unseen settings. Other approaches use VLMs to recover reward signals for reinforcement learning in the environment [29, 30, 31, 32, 3]. In contrast, our approach directly trains language-conditioned policy through imitation learning without the need for online interactions with the environment.

Learning language-conditioned tasks by reaching goals. Alternatively, language-conditioned policies can be constructed or learned through goal-conditioned policies [33, 34]. Lynch and Sermanet [35] propose an approach that facilitates language-conditioned imitation learning by sharing the policy network and aligning the representations of the two conditional tasks. Based on the same motivation, we propose an alternative approach which explicitly extends the alignment of VLMs to specify tasks as changes in the scene. By tuning a contrastive alignment objective, our method is able to exploit the knowledge of VLMs [4] pre-trained on broad data. This explicit alignment improves upon past approaching to connecting images and language [36, 37] by explicitly aligning tasks instead merely jointly training on conditional tasks. In Sec. 5, we demonstrate how these design decisions significantly improve the performance of the learned policy and enhance generalization to unseen objects and instructions.

3 Problem Setup

Our objective is to train robots to solve tasks specified by natural language instructions through interactions with the environment. This problem can be formulated as a conditional Markov decision process (MDP) denoted by the tuple $(\mathcal{S}, \mathcal{A}, \rho, P, \mathcal{W}, \gamma)$, with state space $\mathcal{S}$, action space $\mathcal{A}$, initial state probability ρ, transition probability P, an instruction space $\mathcal{W}$, and discount factor γ. Given the instruction $\ell \in \mathcal{W}$, the robot takes action $a_t \in \mathcal{A}$ given the state s_t at each time step t to achieve success. We assume that horizon H is finite and the success condition is determined by the final state s_H and the instruction ℓ.

To solve such tasks, we train a language-conditioned policy $\pi(a|s, \ell)$ on a combination of human demonstrations and autonomously collected trajectories. Since high-quality natural language annotations are expensive and time-consuming to obtain, we assume that only a small portion of the trajectories are labeled with the corresponding instructions. The robot has access to a combination of two datasets—a small-scale labeled dataset $\mathcal{D}_L$ with annotated instructions and a large-scale unlabeled dataset $\mathcal{D}_U$ consists of more diverse play data collected in an open-ended manner. Our goal is to train $\pi(a|s, \ell)$ while taking advantage of both the labeled and unlabeled datasets. We formulate $\pi(a|s, \ell)$ as a stochastic policy that predicts the Gaussian distribution $\mathcal{N}(\mu_a, \Sigma_a)$ where μ_a and Σ_a are the means and standard deviation of the action a.

4 Goal Representations for Instruction Following

We propose Goal Representations for Instruction Following (GRIF) to interface visuomotor policies with natural language instructions in a semi-supervised fashion (Figure. 2). Although the language-conditioned policy cannot be directly trained on the unlabeled dataset $\mathcal{D}_B$, we can facilitate the training through goal-conditioned tasks. Solving both types of tasks requires the policy to under-

stand the human intent, ground it in the current observation, and predict necessary actions. Although the first steps involve understanding task specifications of different modalities (goal images and language), the remaining steps of such processes can be shared between the two settings. To this end, we decouple the language-conditioned policy $\pi(a|s, \ell)$ into a policy network $\pi_\theta(a|s, z)$ and a language-conditioned task encoder $f_\varphi(\ell)$, where $z = f_\varphi(\ell)$ is the representation of the task specified by the instruction ℓ. To solve the goal-conditioned task, we also introduce a goal-conditioned task encoder h_ψ. The policy network π_θ is shared between the language-conditioned and goal-conditioned tasks.

The effectiveness of this paradigm relies on the alignment of task representations. While most existing VLMs align text with static images, we argue that the representation of the goal-conditioned tasks should be computed from the state-goal pair (s_0, g) to support a broad range of instructions. This is because the instruction often focuses on the changing factors from the initial state to the goal rather than directly describing the entire goal image, e.g., "*move the metal pan to the left*". Therefore, the representations of goal-conditioned tasks are computed as $z = h_\psi(s_0, g)$ and we aim to train the encoders such that for (s_0, g, ℓ) sampled from the same trajectory, the distance between $f_\varphi(\ell)$ and $h_\psi(s_0, g)$ should be close and far apart otherwise. We illustrate our high-level approach in Figure 2.

4.1 Explicit Alignment through Contrastive Learning

We propose explicitly aligning the representations of goal-conditioned and language-conditioned tasks through contrastive learning [36]. Compared to implicitly aligning the task presentations through joint training of the two conditional policies, contrastive alignment requires that all relevant information for selecting actions be included in the shared task representation. This improves the transfer between the action prediction tasks for both goal and language modalities by preventing the policy from relying on features only present in one task modality in selecting actions. Using an InfoNCE objective [37], we aim to train the two encoders f_φ and h_ψ to project instructions ℓ and transitions (s_0, g) according to their task semantics. More concretely, for (s_0, g) and ℓ that correspond to the same task, we would like their embeddings $z_\ell = f_\varphi(\ell)$ and $z_g = h_\psi(s_0, g)$ to be close in the latent space, while z_ℓ and z_g corresponding to different tasks to be far apart.

To compute the InfoNCE objective, we first define the metric $\mathcal{C}(s, g, \ell) = \cos(f(\ell), h(s, g))$ with the cosine similarity $\cos(\cdot, \cdot)$. We sample positive data $s^+, g^+, \ell^+ \sim \mathcal{D}_L$ by selecting the start state, end state, and language annotation of a random trajectory. We sample negative examples $s^-, g^- \sim \mathcal{D}_L$ by selecting the start state and end state of a random trajectory, and sample $\ell^- \sim \mathcal{D}_L$ by selecting the language annotation of another random trajectory. For each positive tuple, we sample k negative examples and denote them as $\{s_i^-, g_i^-\}_{i=1}^k$ and $\{\ell_i^-\}_{j=1}^k$. Then the InfoNCE $\mathcal{L}_{\text{task}}$ can be defined with the two terms $\mathcal{L}_{\text{lang}\to\text{goal}}$ and $\mathcal{L}_{\text{goal}\to\text{lang}}$:

$$
\begin{aligned}
\mathcal{L}_{\text{lang}\to\text{goal}} &= -\log \frac{\exp(\mathcal{C}(s^+, g^+, \ell^+)/\tau)}{\exp(\mathcal{C}(s^+, g^+, \ell^+)/\tau) + \sum_{i=1}^k \exp\big(\mathcal{C}(s_i^-, g_i^-, \ell^+)/\tau\big)} \\
\mathcal{L}_{\text{goal}\to\text{lang}} &= -\log \frac{\exp(\mathcal{C}(s^+, g^+, \ell^+)/\tau)}{\exp(\mathcal{C}(s^+, g^+, \ell^+)/\tau) + \sum_{j=1}^k \exp\big(\mathcal{C}(s^+, g^+, \ell_j^-)/\tau\big)} \\
\mathcal{L}_{\text{task}} &= \mathcal{L}_{\text{lang}\to\text{goal}} + \mathcal{L}_{\text{goal}\to\text{lang}}
\end{aligned} \tag{1}
$$

where τ is a temperature hyperparameter. $\mathcal{L}_{\text{lang}\to\text{goal}}$ and $\mathcal{L}_{\text{goal}\to\text{lang}}$ represent the log classification accuracy of our alignment in predicting goals from language and language from goals respectively.

4.2 Weight Initialization with Vision-Language Models

To enable robots to handle tasks involving objects and instructions beyond what is contained in the limited labeled dataset, we aim to incorporate prior knowledge from broader sources to encoders f_φ and h_ψ. For this purpose, we investigate practical ways to incorporate Vision-Language Models (VLMs) [4] pre-trained on massive paired images and texts into our encoders. Pre-trained VLMs demonstrate effective zero-shot and few-shot generalization capability for vision-language tasks [4, 38]. However, they are originally designed for aligning a single static image with its caption without

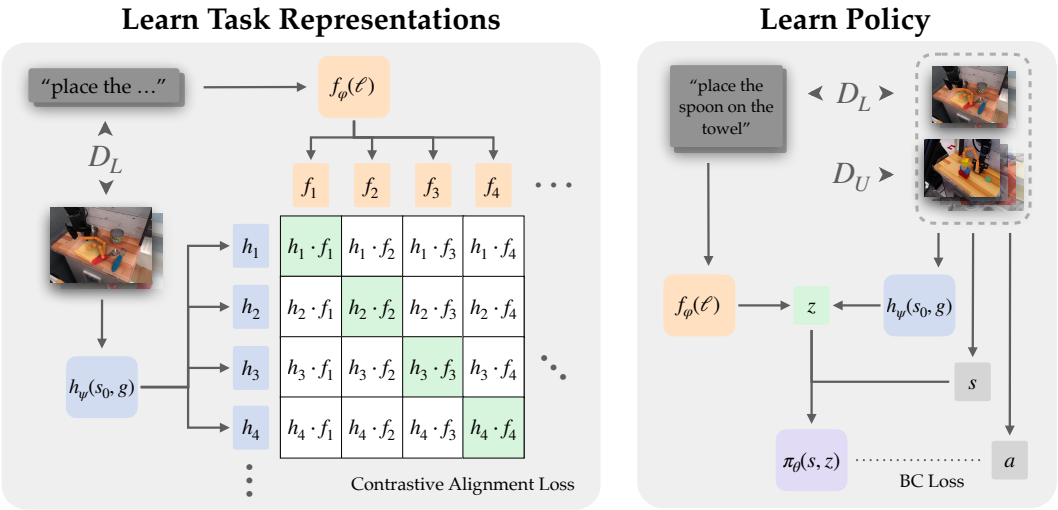

Figure 2: **Left:** We explicitly align representations between goal-conditioned and language-conditioned tasks on the labeled dataset $\mathcal{D}_L$ through contrastive learning. **Right:** Given the pre-trained task representations, we train a policy on both labeled and unlabeled datasets.

the ability to understand environment dynamics or motions required in many instruction-following tasks. It is not clear how to encode the change between two images while still taking full advantage of the prior knowledge in pre-trained VLMs.

To address this issue, we devise a mechanism to accommodate and fine-tune the CLIP [4] model for aligning the transition (s_0, g) with the instruction ℓ. Details on how we modify the pre-trained CLIP to accommodate encoding changes are presented in Appendix C.2. In practice, we find this mechanism significantly improves the generalization capability of the learned policy $\pi_\theta(a|s, g)$.

4.3 Policy Learning with Aligned Representations

We train the policy jointly on the two datasets $\mathcal{D}_L$ and $\mathcal{D}_U$ with the aligned task representations. By sampling (ℓ, s_t, a_t) from $\mathcal{D}_L$, we train the policy network $\pi_\theta(a|z)$ to solve language-conditioned tasks with $z = f_\varphi(\ell)$. And by sampling (s_0, g, s_t, a_t) from $\mathcal{D}_L \cup \mathcal{D}_U$, π_θ is trained to reach goals with $z = h_\psi(s_0, g)$. We train the policy through behavioral cloning by maximizing the likelihood of the sampled action a_t.

We investigate two ways to train the policy given the encoders f_φ and h_ψ. The straightforward way is to jointly train the policy network π_ϕ and the two encoders end-to-end. This process adapts the encoders with the policy network to encourage them to incorporate information that facilitates downstream robotic control, but can also backfire if the policy learns to rely on visual-only features that are absent in the language conditioned setting. Alternatively, we can freeze the pre-trained weights of the two encoders and only train the shared policy network π_ϕ on the two datasets. In Sec. 5, we evaluate and discuss the performances of both options.

5 Experiments

Our work started with the premise of tapping into large, goal-conditioned datasets. To build a language interface for goal-conditioned policy learning, we proposed to learn explicitly aligned task representations, and to align instructions to state changes rather than static goals. Lastly, we advocated for the use of pre-trained VLMs to incorporate larger sources of vision-language knowledge. Therefore, we aim to test the following hypotheses in our experiments:

H1: Unlabeled trajectories will benefit the language-conditioned policy.

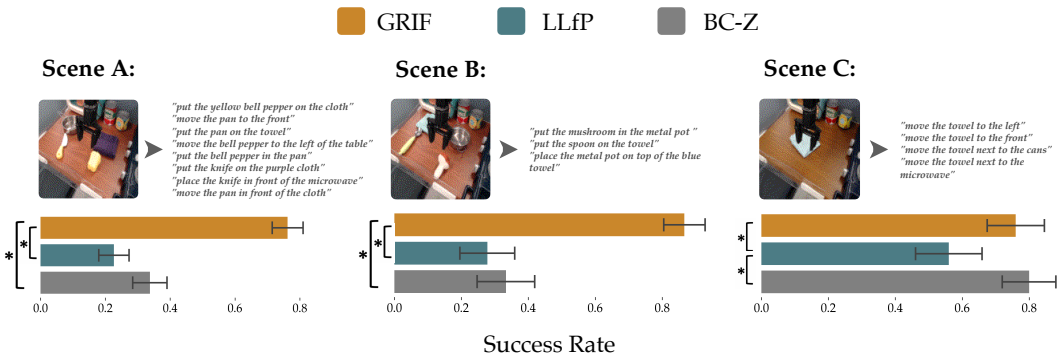

Figure 3: Comparison of success rates ±SE between the top three methods across all trials within the three scenes. Two other baselines LCBC and R3M (not shown) achieved 0.0 success in all evaluation tasks although they do succeed on tasks that are heavily covered in the training data. Statistical significance is starred. The initial observation and instructions of each scene are shown.

H2: Explicitly aligning task representations improves upon the implicit alignment from LangLfP-style joint training [35].

H3: The prior knowledge in pre-trained VLMs can improve learned task representations.

H4: Aligning *transitions* with language enable better use of VLMs compared to conventional image-language contrastive methods [32, 39].

Our experiments are conducted in an table-top manipulation domain. For training, we use a labeled dataset $\mathcal{D}_L$ containing 7k trajectories and an unlabeled $\mathcal{D}_U$ containing 47k trajectories. The evaluation scenes and instructions are shown in Figure 3. Additional details about the environment, the dataset, and the breakdown of results are described in the Appendix.

5.1 Comparative Results

We compare the proposed GRIF with four baseline methods on a set of 15 tasks from all 3 scenes and report the aggregated results in Figure 3. The per-task success rates can be found in Appendix E. **LCBC** [9] uses a behavioral cloning objective to train a policy conditioned on language analogously prior methods on instruction-conditioned imitation learning. This approach only uses the $\mathcal{D}_L$ data. **LLfP** [35] jointly trains a goal conditioned and language conditioned policy on partially labeled data, but does not learn aligned task representations. **R3M** [27] provides pre-trained state representations for robot manipulation that are predictive of language-conditioned rewards. We use this approach as a baseline by jointly training goal- and language-conditioned policies while using R3M state encodings as goal representations (i.e., $h_\psi(s_0, g) = \text{R3M}(g)$). **BC-Z** [10] jointly trains language- and video-conditioned policies and uses an additional cosine similarity term to align video and language embeddings. This approach does not transfer directly into our goal-conditioned setting, but we create a baseline that adapts this design to our setting, by jointly training goal- and language-conditioned policies while aligning task representations with a cosine distance loss. The architecture choices are standardized across all methods for fair comparisons. Unless stated otherwise, all baselines use a ResNet-18 as the goal encoder $h_\psi(s_0, g)$. In our preliminary experiments, this architecture was found to give good performance when used to train goal-conditioned policies in our setting. For the language encoder $f_\varphi(\ell)$, all baselines use a pre-trained and frozen MUSE model [40], as is standard in previous work [35, 10].

We find that language-conditioned policies must make use of unlabeled trajectories to achieve non-zero success rates in support of **H1**. LCBC does not use unlabeled data and fails to complete any tasks. R3M jointly trains goal- and language-conditioned policies, but it also fails all tasks. This is likely due to its goal encodings being frozen and unable to be implicitly aligned to language during joint training. Methods that use implicit or explicit alignment (GRIF, LLfP, BC-Z), are able to exploit unlabeled goal data to follow instructions to varying degrees of success. The comparison

between our method and prior work suggests that the combined effect of using pre-trained CLIP to align transitions with language significantly improves language-conditioned capabilities. Our model outperforms all baselines on 8 out of 15 tasks, achieving high success rates on several tasks where the baselines almost completely fail (*"place the knife in front of the microwave", "move the pan in front of the cloth", "put the knife on the purple cloth"*). Where baselines failed, we often observed *grounding* failures. The robot reached for incorrect objects, placed them in incorrect locations, or was easily distracted by nearby objects into performing a different task.

5.2 Ablation Study

We run a series of ablative methods to analyze the performance of GRIF and test the hypotheses **H2**, **H3**, and **H4** respectively. **No Align** ablates the effect of explicit alignment by removing the contrastive objective. We also unfreeze the task encoders so that they are implicitly aligned via joint training of the language- and goal-conditioned policies. **No CLIP** ablates the effect of using pretrained CLIP by replacing the image and text encoders with a ResNet-18 and pre-trained MUSE language encoder. In **No Start**, the image task representaions only depend on goals as $h_\psi(g)$, instead of depending on transitions as $h_\psi(s_0, g)$. This is the conventional way to connect goals and language with CLIP that is often used in previous work [39, 32]. **GRIF** (Joint) trains the task alignment and policy losses jointly, taking gradients through the image encoder and freezing the language encoder. This is the end-to-end approach discussed in Section 4.3. We refer to our full approach without joint training as **GRIF** (Frozen) in the remainder of this section.

As shown in Figure 4, explicit alignment, pretrained CLIP, and transition-based task representations jointly play critical roles in achieving high success rates. Notably, the conventional approach of aligning static goals and instructions with CLIP (**No Start**) fails almost completely in our setting. This is in support of **H4** and confirms our intuition about the need to encode the transitions instead of static images. Regarding **H2** and **H3**, we observe that removing either alignment or CLIP results in a large drop in performance. We also observed that **No Align** outperforms its counterpart *LLfP* by using the pre-trained CLIP model (after the modification in Sec. 4.2) in the task encoder. We hypothesize that this is because CLIP has already been explicitly aligned during pre-training, and some of its knowledge is retained during joint training with the policy. Lastly, whether or not to freeze the task encoders during policy training does not appear to have a significant effect on our model's overall performance. This is probably because the contrastive learning phase already learns representations that can represent the semantic task, and there is less to gain from further implicit alignment during joint training.

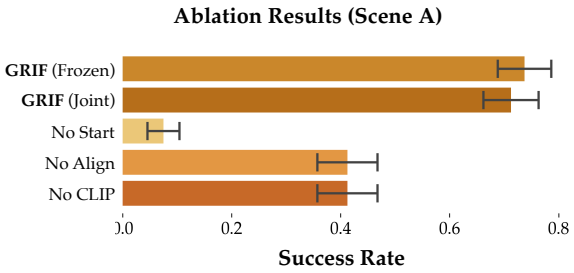

Figure 4: Success rates of ablations with one standard error.

5.3 Analysis on the Learned Task Representations

For additional analysis, we wish to evaluate our model's task grounding capabilities independently of the control layer and compare it with ablations. More specifically, we want to evaluate how well our model can connect new language instructions to correct goals in a scene. This is important to downstream policy success: if the model is able to project the language to a representation $f_\varphi(l)$ that is close to that of the correct (but unprovided) goal $h_\psi(s_0, g)$, then the policy will likely be able to execute the task since it has been trained on a lot of goal-conditioned data.

Our task representations are trained with a contrastive objective, which offers a convenient way to evaluate the alignment between language and goals. On an dataset of labeled held-out trajectories,

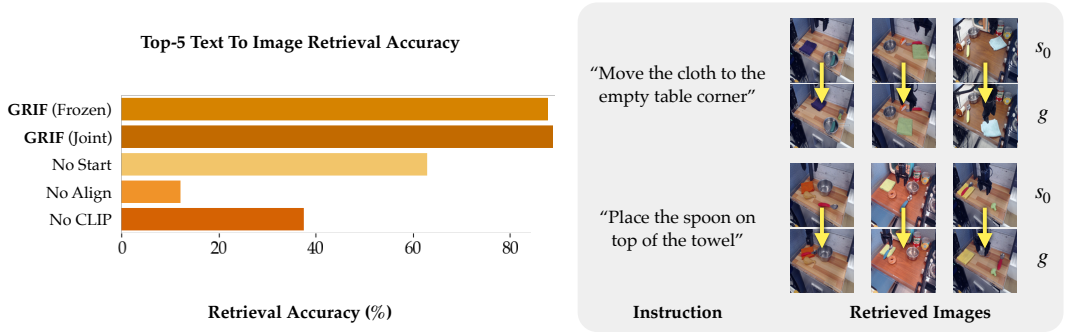

Figure 5: Left: Comparison of the top-5 text to image retrieval accuracy of representations learned by different ablations. Right: Examples of retrieved image pairs given instructions.

we compute the similarities between all pairs of visual task representations $h_\psi(s_0, g)$ and langauge task representations $f_\varphi(\ell)$. For each language instruction, we retrieve the top k most similar (s_0, g) transitions and compute the accuracy that the correct transition is retrieved. We compute this metric in fixed batches of 256 examples and average over the validation set to report a text-to-image retrieval accuracy. We compute this metric for representations from each of our ablations and report the results in Figure 5. Our task representations show significanly better generalization compared to using a conventional image-language alignment (**No Start**), despite it being CLIP's original pre-training objective. The alignment accuracy is also more than 50% higher than when using non-VLM encoders (**No CLIP**), suggesting potentially large gains in grounding capability through using VLMs.

6 Discussion, Limitations, and Future Work

Our approach to aligning image goals and language instructions enables a robot to utilize large amounts of unlabeled trajectory data to learn goal-conditioned policies, while providing a "language interface" to these policies via aligned language-goal representations. In contrast to prior language-image alignment methods, our representations align *changes* in state to language, which we show leads to significantly better performance than more commonly used CLIP-style image-language alignment objectives. Our experiments demonstrate that our approach can effectively leverage unlabeled robotic trajectories, with large improvements in performance over methods that only use the language-annotated data, and outperforms a number of baselines and prior methods.

Limitations and future work. While our results demonstrate the effectiveness of our method for leveraging unlabeled data via goal-conditioned training, our method has a number of limitations that could be addressed in future. First, while our method uses unlabeled robot data for learning goal-conditioned policies, we do not evaluate the sensitivity of the approach to the particular data distribution used for training. Ideally, robots could collect large unlabeled datasets autonomously, but our experiments directly use the Bridge Dataset [41], which consists of demonstration data. Second, our method might not be well suited for tasks where instructions say more about *how* to do the task rather than *what* to do (e.g., "*pour the water slowly*") – such qualitative instructions might require other types of alignment losses that more effectively consider the intermediate steps of task execution. An exciting direction for future work would be to extend our alignment loss to utilize non-robotic vision-language data, such as videos, to learn rich semantics from Internet-scale data. Such an approach could then leverage two otherwise unconnected sources of training data, both of which are in principle very large, to enable broadly generalizable and powerful robotic policies that can follow user instructions.

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