Hey AI, Can You Solve Complex Tasks by Talking to Agents?

Anonymous ACL submission

Abstract
Training giant models from scratch for each complex task is resource- and data-inefficient. To help develop models that can leverage existing systems, we propose a new challenge: Learning to solve complex tasks by communicating with existing agents (or models) in natural language. We design a synthetic benchmark, COMMAQA, with three complex reasoning tasks (explicit, implicit, numeric) designed to be solved by communicating with existing QA agents. For instance, using text and table QA agents to answer questions such as "Who had the longest javelin throw from USA?". We show that black-box models struggle to learn this task from scratch (accuracy under 50%) even with access to each agent’s knowledge and gold facts supervision. In contrast, models that learn to communicate with agents outperform black-box models, reaching scores of 100% when given gold decomposition supervision. Importantly, the target end-task is designed to be too difficult for current models to learn based only on end-task supervision. The goal is instead to build models that learn to solve the target task by decomposing it into sub-tasks solvable by these agents, and interacting with these agents in natural language to do so.

1 Introduction
A common research avenue pursued these days is to train monolithic language models with billions of parameters to solve every language understanding and reasoning challenge. In contrast, humans often tackle complex tasks by breaking them down into simpler sub-tasks, and solving these by interacting with other people or automated agents whose skill-sets we are familiar with. This approach allows us to learn to solve new complex tasks quickly and effectively, by building upon what’s already known. Can AI systems learn to do the same?

To facilitate research in this direction, we propose a new reasoning challenge and a benchmark called COMMAQA where, in addition to the usual end-task supervision, one has access to a set of pre-defined AI agents with examples of their natural language inputs. Importantly, the target end-task is designed to be too difficult for current models to learn based only on end-task supervision. The goal is instead to build models that learn to solve the target task by decomposing it into sub-tasks solvable by these agents, and interacting with these agents in natural language to do so.

As a motivating example, consider the interaction depicted in Figure 1 where a system is asked to buy a book series with a certain property. The system breaks this goal down, using agent-1 (here Google Assistant) to identify the referenced book series as well as the list of books in that series, and then using agent-2 (here Amazon Alexa) to make the purchase. While both of these agents interact with the system in natural language, they have different and complementary skill sets, rely on privately held knowledge sources, and have been built at an enormous cost. At the same time, neither agent by itself can accomplish the original goal.

Figures 1: Motivating example for a setup where a system is expected to learn to accomplish goals by interacting with agents via a natural language interface.

1 Our benchmark will be released upon publication.
2 but not necessarily mutually exclusive skills
An alternative to building such a system that interacts with existing agents is to teach all requisite sub-tasks and skills to a large black-box system, say via multi-task learning (Khashabi et al., 2020; Gupta et al., 2021). This, however, not only wastes time and resources, but is often also infeasible. For example, agents such as Google Assistant and OpenAI GPT-3 use private knowledge resources and are computationally expensive to train even once. It would thus be nearly impossible to build a single system with the capabilities of both of these agents.

We note that agents need not be sophisticated AI assistants. An agent may simply be a previously developed question-answering (QA) model, a math module, a function of textual input, an image captioning system—anything the community already knows how to build. The goal is to learn to leverage existing agents for more complex tasks.

To enable the development of general systems for this task, we identify the minimal inputs that must be assumed for the task to be learnable—training data for the complex task, existing agents that together can solve the complex task, and examples of valid questions that can be asked of these agents (capturing the agents’ capabilities). We build a new synthetic benchmark dataset called COMMAQA (Communicating with agents for QA), containing three complex multi-hop QA tasks (involving Explicit, Implicit, and Numeric reasoning) and four input QA agents that can solve these tasks.

COMMAQA is not yet another multi-hop reading comprehension dataset. It is designed to facilitate the development of a new family of techniques that teach systems to communicate with a wide variety of agents to solve different types of complex tasks.

We demonstrate that black-box models struggle on COMMAQA even when provided with auxiliary data, such as domain-relevant agent knowledge. On the other hand, a model that leverages the agents (Khot et al., 2021) can achieve very high accuracy but relies on auxiliary supervision (decomposition annotations). While it is possible to identify valid decompositions using just the end-task labels, the search space is extremely large and naive approaches, as we show, help only with one of the datasets. COMMAQA thus serves as a new challenge for the NLP community.

**Contributions:** We (1) propose a new challenge of learning to solve complex tasks by communicating with agents; (2) develop a synthetic multi-hop QA dataset COMMAQA with three reasoning types; (3) provide auxiliary training data and a compositional generalization test set; (4) demonstrate the challenging nature of COMMAQA for black-box models; and (5) show the promise of compositional models that learn to communicate with agents.

### 2 Related Work

**Semantic Parsing** typically focuses on mapping language problems to executable symbolic representation based on a pre-defined grammar (Krishnamurthy et al., 2017; Chen et al., 2020). Similar ideas are also found in the area of program synthesis (Gulwani, 2011; Desai et al., 2016). These goals, like ours, seek to simplify complex problems into simpler executable forms, without relying on explicit intermediate annotation (Clarke et al., 2010; Berant et al., 2013). We, however, diverge from this line by seeking agent communication in free-form language, not bound to any pre-specified set of operations or domain specific languages.

**Multi-hop QA** focuses on reasoning with multiple facts. Despite the development of many datasets (Khashabi et al., 2018; Yang et al., 2018; Khot et al., 2020; Geva et al., 2021) and models (Min et al., 2019b; Pan et al., 2021), existing benchmarks often contain single-hop shortcuts (Min et al., 2019a), resulting in brittle models (Gardner et al., 2020) and little progress towards true multi-hop reasoning (Trivedi et al., 2020). Additionally these datasets often contain sub-problems not solvable by existing models, further disincentivising the development of compositional models (Khot et al., 2021).

**Question Decomposition** is used to solve multi-hop QA but the resulting models (Talmor and Berant, 2018; Min et al., 2019b; Perez et al., 2020; Khot et al., 2021) are often dataset-specific, rely on decomposition annotations, and limited to one or two QA agents. To address these limitations, our proposed challenge covers three dataset types and four agents. Additionally, models are expected to learn to decompose the task by interacting with the agents, rather than relying on human annotations.

**Synthetic Reasoning Challenges** have recently been proposed (Lake and Baroni, 2018; Sinha et al., 2019; Clark et al., 2020) to help systematically identify the weaknesses of existing models and inspire modeling innovation (Liu et al., 2021). Our new tasks are unique and focus on simulating complex agent interaction to motivate the development of decomposition-based modeling approaches.
3 Challenge Task Definition

We formalize the new challenge task of learning to talk with agents to solve complex tasks. To ensure generality of solutions, we identify minimal inputs for the task to be well-defined and learnable.

First, we must define $f_i$, the agents or models that solve simpler sub-tasks. 3 Minimally, we need to define the space of valid inputs $L_i$ for each agent $f_i$, i.e., how can they be invoked. For a system to identify the appropriate agent for each sub-task, we also need to define the capabilities of each agent.

Since these agents are often defined for natural language tasks, the space of inputs captures the capabilities of these agents too. For instance, “Buy the book “Harry Potter and the Sorcerer’s Stone”” captures the Alexa agent’s capability of buying books. Instead of complex formal specifications of the agent’s capabilities, we use natural language inputs as a rich and convenient representation.

Next, we need a target task $T$ that can be solved via a composition of the capabilities of $\{f_i\}$. Finally, to pose this as a machine learning problem, we need training data $D = \{(x_k, y_k)\}_{k=1}^N$ for $T$. Since collecting annotations for complex tasks can be difficult, $D$ is expected to be relatively small. Models must therefore use the available agents, instead of learning the complex task from scratch.

Given these pre-requisites, we can define the challenge task as follows:

**Challenge**: Learn a model to solve a complex task $T$, given only:
- Training dataset $D = \{(x_k, y_k)\}_{k=1}^N$ for $T$;
- Agents $\{f_1, \ldots, f_m\}$ that can help solve $T$;
- Examples from the space $L_i$ of valid inputs for each agent $f_i$ that captures its capabilities.

One example of this challenge is answering multi-hop questions given two agents: an open-domain TextQA agent $f_1$ and an open-domain TableQA agent $f_2$. Agent $f_1$ can use large textual corpora to answer questions such as “Who directed Kill Bill?” . Agent $f_2$ can use tables (e.g., Filmmography tables) to answer questions such as “List the movies directed by Quentin Tarantino”. Finally, the training data $T$ for the complex task would contain examples such as (“What movies has the director of Kill Bill appeared in?” , “Reservoir Dogs”, …]).

### Auxiliary Information.

Apart from the above minimal pre-requisites, in some cases we may be able to obtain additional training supervision, or additional data about the internals of the agents. We emphasize that such auxiliary information may not always be available (e.g., when using a proprietary agents such as Alexa). A general-purpose system should thus ideally learn to solve this challenge without relying on it. However, it’s acceptable for initial methods to use some auxiliary signals as stepping stones toward more general systems.

We consider two kinds of such information—auxiliary supervision for the complex task’s training examples $(x_k, y_k) \in D$, and auxiliary data about the agents $\{f_i\}$ themselves (not tied to $D$).

For auxiliary supervision, we consider having access to annotated decomposition $D_k$ of a complex task training input $x_k$ into valid inputs for various agents. We also consider annotated gold facts $F_k$ that could be used to answer $x_k$.

For auxiliary data, we consider having access to the training data used to build the agents, or the underlying knowledge base $K_i$ used by them (and possibly even a question-specific relevant subset $K_{ik}$). In the example above, $K_i$ would be equivalent to the entire text and table corpora used by the agents, and $K_{ik}$ could be the texts and tables relevant to the movie domain. Such information can be used to train a stronger black-box model on the end-task, e.g., fine-tuning on the agent’s training data first or using the gold facts to identify relevant context. These approaches that circumvent the agents are not the target of our dataset, but we nevertheless evaluate them to highlight their limits.

In summary, we have the following potential auxiliary information as stepping stones:

#### Auxiliary Supervision for $(x_k, y_k) \in D$:
- Gold Decomposition $D_k$ for $x_k$
- Gold Knowledge $F_k$ for $x_k$

#### Auxiliary Data for agents $\{f_i\}$:
- Training data $D_{f_i} = \{(u_{ij}, v_{ij})\}_{j=1}^M$ for agent $f_i$, where $u_{ij} \in L_i$ and $v_{ij} = f_i(u_{ij})$
- Complete knowledge resource $K_i$ used by $f_i$, or a manageable subset $K_{ik} \subset K_i$ containing $F_k$

4 Dataset: COMMAQA Benchmark

We next propose a new benchmark dataset COMMAQA that enables the development of models that can learn to communicate with existing agents. Specifically, we provide a collection of three syn-

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1As mentioned earlier, we use agents to refer interchangeably to models, assistants, or functions that take free-text as input and produce free-text as output.

2Existing datasets lack this requirement, making it impossible to focus only on the agent communication aspect.
thet datasets where each question is answerable by talking to simple QA agents. Note that we are not proposing a new class of questions but a new dataset for the proposed challenge task.

We choose QA as the underlying task and use QA agents for this challenge because the question-answer format can capture a broad range of tasks (Gardner et al., 2019) while also naturally surfacing the capability of each agent. For instance, the question “What are the key frames in v?” describes a capability of the invoked agent (namely, identifying key frames), in addition to the specific inputs. We next describe our framework for building COMMAQA, which we believe can be extended to other complex tasks, e.g., video summarization.

4.1 Agent Definition

To define the $i$-th agent, we build a knowledge base that captures its internal knowledge resource $\mathcal{K}_i$. We use natural language question templates to define the set of questions that this agent can answer over this internal knowledge. For example, given a KB with relations such as “directed(x, y)”, the agent would answer questions based on the template: “Who directed the movie __?”

Knowledge Base, $\mathcal{K}_i$. To build the knowledge base, we define a KB schema as a set of binary relations between entity types, e.g., director(movie, person). We build a list of entity names that belong to each entity type. To avoid potential conflicts with the LM’s pre-training knowledge, all entity names are generated non-existent words.\(^5\)

Rather than building a static and very large KB, we sample a possible world independently for each question, by sub-sampling entities for each entity type and then randomly assigning the KB relations between these entities. This prevents memorization of facts across the train and test splits, which in the past has led to over-estimation of QA model performance (Lewis et al., 2021). This also encourages models to learn proper multi-hop reasoning using the agents, rather than memorizing answers.

Examples of Valid Inputs. To define the space of valid inputs for each agent $f_i$, we define a set of question templates that can be answered by it over $\mathcal{K}_{ik}$ (e.g., Who directed __?). We construct questions corresponding to a relation in both directions, e.g., “Who all directed ___?” and “For which movies was ___ a director?”. To emulate redundancy in natural language, we specify multiple phrasings for the same question. We use these templates to generate examples of valid inputs in $\mathcal{L}_i$ by grounding them with entities of the appropriate entity type (e.g., Who directed Kill Bill?).

To ensure generalization to a broad set of tasks, we do not limit the questions to only single span answers. Depending on the question, the agent can produce answers as a single string (span, boolean or a number), a list of strings (e.g., “Which movies did Spielberg direct?”), or a map (e.g., “What are the states and their capitals in USA?”).

Implementation. To answer the question, agents convert questions into queries against the internal knowledge (based on the templates) which we implement as a symbolic function (written in Python), instead of a model. While a language model might be able to generalize to out-of-distribution variations in language, its behavior can be often unpredictable. By implementing the agents as pattern-based functions, we ensure that the resulting systems would stay within the language constraints of each agent and generalize to restricted language models. Additionally, this enables faster develop-

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\(^5\)https://www.thisworddoesnotexist.com/

<table>
<thead>
<tr>
<th>Operator</th>
<th>Pseudo-code</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>select</td>
<td>return $f(q(a))$</td>
<td>$#1=[23, 35]$ q=&quot;Which is largest value in $#1$? $f=\text{mathqa}$ $\rightarrow 35$</td>
</tr>
<tr>
<td>project</td>
<td>return $[(x, f(q(x)))$ for $x$ in $a$]</td>
<td>$#1=[\text{Jordan, Johnson}]$ q=&quot;What were the lengths of throw by $#1$? $f=\text{textqa}$ $\rightarrow {(\text{Jordan}, [23, 34]), (\text{Johnson}, [45, 56])}$</td>
</tr>
<tr>
<td>projectValues</td>
<td>return $[(k, f(q(v)))$ for $(k, v)$ in $a$]</td>
<td>$#1=[\text{Jordan, [23, 34]}, (\text{Johnson, [45, 56]}]$ q=&quot;Which is largest value in $#1$? $f=\text{mathqa}$ $\rightarrow {(\text{Johnson, 56})}$</td>
</tr>
<tr>
<td>filter</td>
<td>return $[x$ for $x$ in $a$ if $f(q(x))]$</td>
<td>$#1=[23, 34, 56]$ q=&quot;Is #1 greater than 50?&quot; $f=\text{mathqa}$ $\rightarrow 56$</td>
</tr>
<tr>
<td>filterValues</td>
<td>return $[(k, v)$ for $(k, v)$ in $a$ if $f(q(v))]$</td>
<td>$#1=[\text{Jordan, [23, 34]}, (\text{Johnson, 56}]$ q=&quot;Is #1 greater than 50?&quot; $f=\text{mathqa}$ $\rightarrow {(\text{Johnson, 56})}$</td>
</tr>
</tbody>
</table>
ment of approaches without spending resources on running a large-scale LM for each agent.

### 4.2 Complex Task Definition

Given the space of valid input questions for each agent, we construct training examples for the complex task using templated theories. These theories consist of a complex question template and a composition rule expressed as a sequence of questions asked to appropriate agents. For example, "What movies have the directors from $1$ directed?" $\#1 = \text{[select]} \text{[textqa]}$ "Who is from the country $1$?" $\#2 = \text{[tableqa]}$ "Which movies has $\#1$ directed?"

**Composition Operators.** While this simple theory would work for single span answers, these agents often return list or map answers. Even within this simple example, there can be multiple directors from a given country and this list cannot be directly fed to the textqa model, i.e., "Which movies has [...] directed?". This problem gets even more challenging with complex structures. E.g., maintaining a map structure while operating on the values of the map (see 3rd row in Table 1).

To handle the different answer structures, we define a special set of compositional operators in Table 1. These operators take agent $f_i$, a structured answer $a_i$, and a query with a placeholder as inputs, and execute a set of queries (as defined by the pseudo-code in Table 1) against $f_i$. These operators are inspired by QDMR (Wolfson et al., 2020), but modified to be actually executable. E.g., the "project" operator in QDMR: "return directors of #1?" does not specify how to execute this query whereas our operation (project) [textqa] "Who are the directors of #1?" specifies how to use the TextQA model and #1 to generate a map.

We also define a set of agent-independent data structure transformations in Table 2, e.g., convert a map into a list of its keys. Since longer chains of reasoning are prone to more errors (Fried et al., 2015; Khashabi et al., 2019), we don’t model these simple transformations as additional reasoning steps. Instead, we concatenate compositional operators with transformations to create about 20 new, combined operators such that transformations can be applied after an operation in a single step, e.g., project_Values operation performs the project operation followed by the Values transformation.

<table>
<thead>
<tr>
<th>Transf.</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLAT</td>
<td>Flatten list of lists into a single list</td>
</tr>
<tr>
<td>UNIQUE</td>
<td>Return the unique items from a list</td>
</tr>
<tr>
<td>KEYS</td>
<td>Return the list of keys from a map</td>
</tr>
<tr>
<td>VALUES</td>
<td>Return the list of values from a map</td>
</tr>
</tbody>
</table>

Table 2: Simple transformations that modify the output data structure. These transformations can be chained together with an operation, e.g., PROJECT_VALUES.

**Building Examples.** Given a KB schema, question templates for each agent, and theories, we can now build examples for the complex task (Fig. 2). We first sample a possible world based on the KB schema. We assign each relation to one of the agents based on which agents are likely to answer such questions, i.e., only this agent would answer questions about this relation. This captures multimodality of knowledge, e.g., movie awards might be described in text or a table, but a person’s birth date is likely described in text. When a relation can be captured by knowledge in multiple modalities, it is assigned to one of them per KB. This emulates the challenging setting where a model must interact with multiple agents to find the answer.  

As a stepping stone towards solving the full challenge and to evaluate the limits of current baselines given oracle supervision, we provide auxiliary information as mentioned in Sec. 3. Specifically, we provide the gold decomposition $D_k$ for each example $x_k$ using the same language as the theories (see Fig. 3). We verbalize each relation to create the underlying knowledge resource $K_{ik}$ used by the agent $f_i$ (e.g., relation director(M, P) is converted into "M was a movie directed by P" or "movie: M; director: P" depending on the agent assigned to this relation). While our KB and resulting facts are intentionally simple to show the limitations of black-box models, such verbalization may not always be possible with larger KBs. For each training example, we collect the facts used by each agent in the decomposition and treat these as gold facts $F_k$.

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6With real questions and agents, models may be able to avoid this by just memorizing the agents.

7has a non-empty answer and up to five answer spans
4.3 COMMAQA Dataset

We use the above framework to build three datasets capturing three challenges in multi-hop reasoning.

**COMMAQA-E: Explicit Decomposition.** This dataset consists of multi-hop questions from the movie domain where the reasoning needed to answer the question is **Explicitly described in the question itself** (Yang et al., 2018; Ho et al., 2020; Trivedi et al., 2021). For example, "What awards have the movies directed by Spielberg won?". We use a TextQA and TableQA agent where certain relations can be either be expressed in text or table (more details in App. Fig. 5).

**COMMAQA-I: Implicit Decomposition.** This dataset consists of multi-hop questions where the reasoning needed is **Implicit** (Khot et al., 2020; Geva et al., 2021), for example, "Did Aristotle use a laptop?". Inspired by such questions in StrategyQA (Geva et al., 2021), we create this dataset using three agents (TextQA, KBQA and MathQA) with just two question styles: (1) "What objects has \( \_ \_ \) likely used?" and (2) "What objects has \( \_ \_ \) helped make?". However, each question has three possible strategies depending on the context (see App. Fig. 6 for more details). This is a deliberate choice as similar sounding questions can have very different strategies in a real-world setting, e.g., "Did Steve Jobs help develop an Iphone?" vs. "Did Edison help develop the television?".

**COMMAQA-N: Numeric Decomposition.** This dataset consists of **Numeric** (also referred to as discrete) reasoning questions (Dua et al., 2019; Amini et al., 2019) requiring some mathematical operation, in addition to standard reasoning. For example, "Who threw javelins longer than 5 yards?". We create this dataset in the sports domain with TextQA, TableQA and MathQA agents (more details in App. Fig. 7).

**Dataset Statistics.** The final dataset\(^8\) consists of the three QA sub-datasets described above (see Appendix for statistics in Table 7 in the App.). We have 10K total examples in each dataset with 80%/10%/10% train/dev/test split. To prevent models from guessing answer spans, we introduce more distractors by sampling a large number of facts for COMMAQA-E and COMMAQA-I. This results in a larger number of facts in the KB (~170) and larger length of the KB in these two datasets (~2500 tokens). Since COMMAQA-N can have derived answers from numeric reasoning and has larger numbers (avg #steps 4.7 vs. 2.7 in COMMAQA-E), we do not need a large number of distractor facts (80 facts/KB).

**Metrics.** The answer \( y_k \) to each question \( x_k \) in COMMAQA is an unordered list of single-word entities.\(^9\) By the design of the dataset, a model that performs the desired reasoning should be able to output \( y_k \) correctly, barring entity permutation. Hence, we use **exact match accuracy** as the metric.\(^{10}\) (see Appendix for a softer metric, F1 score)

5 Experiments

We next evaluate state-of-the-art models on COMMAQA, with and without auxiliary information.

5.1 Models

**Models with Access to Agent Knowledge:** Given access to the facts associated with each (train or test) question \( x_k \), i.e., each agent’s domain-relevant knowledge \( K_{ik} \), the facts can be concatenated to create a context and frame the challenge as a reading comprehension (RC) task.\(^{11}\) We train two stan-
What awards have movies written by people born in 1905 won? (select) [text] Who were born in the year 1905? A: ["Gigafuna"] (project_values_flat_unique) [table] What movies has #1 written? A: ["Pneumodendron", "Pipesia", "Riten"] (project_values_flat_unique) [table] Which awards were given to #2? A: ["Pludge", "Dessication", "Pianogram"]

What objects has Calcid helped to make? (select) [text] Calcid is the founder of which companies? A: ["Dufferate"] (project_values_flat_unique) [text] #1 produces which materials? A: ["comander"] (project_values_flat_unique) [text] Which objects use #2 as a material? A: ["chickenpot", "yaki"]

Who threw discuses shorter than 51.8? (select) [text] Who threw discus? A: ["Lobsteroid", "Karfman", "Terbaryan", ...] (project) [text] What were the lengths of the discus throws by #1? A: ["Lobsteroid", [65.6, 46.0]], ["Karfman", ...] (filterValues_keys) [math_special] What is the smallest value among #2? A: ["Lobsteroid", 46.0], ["Karfman", 51.8], ...]

Figure 3: Sample Decomposition Annotations for example questions in COMMAQA. We denote the composition operators using the format (operation) [agent] "question".

dard black-box models, T5-L (Raffel et al., 2020) and UnifiedQA-L (Khashabi et al., 2020),\textsuperscript{12} to generate answers\textsuperscript{13} given the question and context.

Models with Fact Supervision: If, in addition to access to the underlying knowledge $K_{ik}$, we also have the auxiliary supervision for the gold facts $F_k$, we can use this annotation to train a model to first retrieve a small subset of relevant facts from $K_{ik}$ (see App. D.1 for details). Since the context is shorter, we also train a T5-3B model\textsuperscript{14} on this task.

Models with Decomposition Supervision: Given decomposition supervision, we can develop a model that actually solves the task of communicating with the agents. Specifically, we use the Text Modular Network (TMN) framework (Khot et al., 2021) that trains a NextGen model that communicates with the agents. This model is trained to produce the next question (including operation and agent) in a decomposition chain, given the questions and answers so far, which is then executed against the agent to produce the answer for the current step. Additionally this framework samples multiple questions at each step of the chain to search\textsuperscript{15} for the most likely chain of reasoning. We refer to this model as TMN-S when we use this search and TMN-G when we greedily select the most likely question at each step.

Models with No Supervision: Finally, we develop a baseline approach that directly targets the challenge task without relying on any auxiliary information. To this end, we generate the training data for NextGen via distant supervision. Specifically, we perform a brute-force search where we

COMMAQA without invoking agents, which deviates from the purpose of our benchmark dataset. Nevertheless, we conduct experiments in this setting for completeness.

\textsuperscript{12}We use T5 models as they can handle longer contexts.

\textsuperscript{13}We alphabetically sort answers for a deterministic order.

\textsuperscript{14}T5-11B performed worse than or same as the 3B model.

\textsuperscript{15}Score is the sum log likelihood of the generated questions.

\textsuperscript{16}$o$ is set based on the length of the rules in each dataset, i.e., $o = 3$ for COMMAQA-E, $o = 4$ for I, $o = 7$ for N.

\textsuperscript{17}We also found random generally performed worse.
We also design compositional generalization test sets COMMAQA-E\textsuperscript{CG} and COMMAQA-N\textsuperscript{CG}. Specifically we create questions using novel composition of queries that have been seen during training but never together in this form. For instance, we create a new question "What awards have the directors of the ___ winning movies received?", given that the model was trained on questions such as "What awards have the actors of the ___ winning movies received?", "What movies have the directors from ___ directed?", and "What movies have people from the country ___ acted in?".

As shown in Table 4, all models exhibit a drop in accuracy relative to their score in Table 3, but the compositional model trained on gold decomposition still outperforms black-box models. Our error analysis of TMN\textsuperscript{-S} on COMMAQA-E identified this key issue: While TMN\textsuperscript{-S} learns to generalize, it generates questions outside the space of valid agent inputs (e.g., "Who are the directors in the movie ___?" vs. "Which movies has ___ directed?").

## 6 Closing Remarks

We motivated a new challenge task of solving complex task by communicating with existing AI agents. Developing approaches for this challenge, we argue, can result in more generalizable and efficient models. Towards this goal, we introduced a new benchmark dataset COMMAQA which involves multi-hop questions with three multi-hop reasoning challenges, all solvable by composing four QA agents. Experiments with state-of-art language models indicated that they struggle to solve COMMAQA, even when provided with agents' internal knowledge. In contrast, a model that is able to learn to communicate with the agents, albeit using annotated decompositions, is able to solve this task. These results point to the need for and the potential of such approaches, but without reliance on auxiliary annotations, to solve complex tasks.

COMMAQA is only one instantiation of our overall framework. One can extend it in many ways, such as using LMs to enrich lexical diversity, emulating the behavior of imperfect real-world agents that even attempt to answer out-of-scope questions, and diversifying to other reasoning types such as Boolean questions where using distant supervision is even harder (Dasigi et al., 2019).

### Table 3: Accuracy of models trained and tested separately on the 3 datasets. Last column reports average accuracy across the datasets (weighed equally).

<table>
<thead>
<tr>
<th>Model</th>
<th>Aux. Info</th>
<th>E</th>
<th>I</th>
<th>N</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>T5-L</td>
<td>{K_ik}</td>
<td>0.9</td>
<td>10.2</td>
<td>35.4</td>
<td>15.5</td>
</tr>
<tr>
<td>UQA-L</td>
<td>{K_ik}</td>
<td>1.0</td>
<td>10.2</td>
<td>39.0</td>
<td>16.7</td>
</tr>
<tr>
<td>T5-L</td>
<td>_x, {K_ik}</td>
<td>42.2</td>
<td>49.4</td>
<td>44.7</td>
<td>45.4</td>
</tr>
<tr>
<td>UQA-L</td>
<td>_x, {K_ik}</td>
<td>40.1</td>
<td>49.7</td>
<td>43.4</td>
<td>44.4</td>
</tr>
<tr>
<td>T5-3B</td>
<td>_x, {K_ik}</td>
<td>42.3</td>
<td>49.9</td>
<td>43.4</td>
<td>46.2</td>
</tr>
<tr>
<td>TMN-G</td>
<td>_k</td>
<td>75.4</td>
<td>36.0</td>
<td>100.0</td>
<td>70.5</td>
</tr>
<tr>
<td>TMN-S</td>
<td>_k</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>TMN-S</td>
<td>_k (l=5)</td>
<td>0.0</td>
<td>0.0*</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>TMN-S</td>
<td>_k (l=10)</td>
<td>17.0</td>
<td>0.0*</td>
<td>0.0</td>
<td>5.7</td>
</tr>
</tbody>
</table>

### Table 4: Lower accuracy on compositional generalization test sets. TMN-S with decomposition supervision still outperforms other models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Aux. Info</th>
<th>COMMAQA-E\textsuperscript{CG}</th>
<th>COMMAQA-N\textsuperscript{CG}</th>
</tr>
</thead>
<tbody>
<tr>
<td>T5-L</td>
<td>_x, {K_ik}</td>
<td>37.0</td>
<td>2.0</td>
</tr>
<tr>
<td>T5-3B</td>
<td>_x, {K_ik}</td>
<td>39.2</td>
<td>23.8</td>
</tr>
<tr>
<td>TMN-S</td>
<td>_k</td>
<td>79.4</td>
<td>97.6</td>
</tr>
<tr>
<td>TMN-S</td>
<td>_k (l=10)</td>
<td>16.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>
References


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A Multiple Answers in a Question

If a question refers to multiple answers, e.g. "Is #3 a part of #2?", the operator execution is unclear. To handle such cases, the operator must specify the answer to operate over as a parameter. E.g. \( \text{filter(#3)) [mathqa]} \) "Is #3 a part of #2?" would filter the answers in #3 whereas \( \text{filter(#2)) [mathqa]} \) "Is #3 a part of #2?" would filter the answers in #2.

B Search Approach

We describe the approach used to build the training data \( \hat{D} \) using the simple search technique in more detail. To generate the space of possible decompositions, for each question, we first select \( f \) operations from the list of valid operations in Table 5. We only consider these operations as these are the only operators needed for COMMAQA. Note that even with this restricted set of operators, models struggle on COMMAQA-I and COMMAQA-N. Additionally, we only consider the select operation for the first step. For all subsequent steps, we only consider replacements of \( \_\_ \) with a previous answer index.

To select the questions, we first simplify the space of inputs by converting the questions into Fill-In-The-Blank (FITB) questions by removing the named entities. E.g "Who was born in 1991?" is changed to "Who was born in \( \_\_ \)?". This is also a necessary step as the operators need questions with placeholders to handle structured answers. At every step, we expand this pool of questions by replacing the blanks with entities in the complex question and any answer index from the previous steps (e.g. #1, #2 in the third step of a decomposition). To avoid wasteful sampling, we use lexical overlap between questions in this expanded question pool and the input question to identify the top \( g \) most relevant questions. The agent associated with each question is tracked throughout this process.

In the end, we consider the cross product between the \( f \) operations and \( g \) questions to produce \( l = f \times g \) total questions at each steps. These \( l \) questions are then executed using the appropriate agent and only the successful questions (i.e. answered by the agent) are considered for the next step. This is the key reason why the search space is much smaller than \( l^o \) for \( o \) reasoning steps.

Table 6 presents the overall statistics of the search approach.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>NumQs/Step</th>
<th>Models calls</th>
<th>Num +ve chains</th>
<th>Num qs w/ +ve chains</th>
<th>Dev Acc</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMMAQA-E</td>
<td>5</td>
<td>70001</td>
<td>246</td>
<td>242</td>
<td>0</td>
</tr>
<tr>
<td>COMMAQA-E</td>
<td>10</td>
<td>110006</td>
<td>456</td>
<td>421</td>
<td>17</td>
</tr>
<tr>
<td>COMMAQA-E</td>
<td>15</td>
<td>541816</td>
<td>1325</td>
<td>870</td>
<td>32.8</td>
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<tr>
<td>COMMAQA-E</td>
<td>20</td>
<td>683108</td>
<td>2505</td>
<td>1669</td>
<td>98.9</td>
</tr>
<tr>
<td>COMMAQA-I</td>
<td>5</td>
<td>81325</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COMMAQA-I</td>
<td>10</td>
<td>123202</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COMMAQA-I</td>
<td>15</td>
<td>1149762</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COMMAQA-I</td>
<td>20</td>
<td>1529736</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COMMAQA-N</td>
<td>5</td>
<td>94481</td>
<td>40</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>COMMAQA-N</td>
<td>10</td>
<td>391176</td>
<td>46</td>
<td>27</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5: Set of operations considered in the search approach.\( \_\_ \) can be replaced by any of the answer indices from the previous steps to create a new operation.

Figure 4: With an order of magnitude increase in search space, we can achieve close to 100% accuracy on COMMAQA-E. However COMMAQA-I and COMMAQA-N need smarter search strategies to generate useful training supervision.
C Search Cost vs Accuracy

One could always exhaustively search for all possible decompositions to reproduce the gold decompositions for all the questions. But this would be computationally highly expensive as each call to the agent would often invoke a large-scale LM or a complex AI assistant. To characterize the computational cost of these approaches, we extend the search parameter to include \( l = 15 \) and \( l = 20 \) (capped at 5M agent calls) and compute the accuracy of the TMN-S model trained on the resulting dataset (shown in Fig. 4). We can achieve close to 100% accuracy on COMMAQA-E when the search is sufficiently exhaustive (about 700K model calls) mainly due to the shorter rules and the lexical signal. COMMAQA-I and COMMAQA-N, on the other hand, even with an order of magnitude increase in the number of agent calls, don’t observe any increase in the model accuracy.

D Black Box Models

We train the T5 models on each of the three datasets to generate the answer given the question and facts. We format the input sequence as \(<\text{concatenated facts}> Q: \text{<question}> A:.\) Since many of the answers can be multiple spans, we sort\(^\text{18}\) and concatenate them into a single string with ‘+’ as the separator. As noted in Table 7, the verbalized facts can result in a context over 2K tokens long. We trained T5-Large models on A100 80G GPUs and RTX8000s to train on such a long context. Transformers designed for longer documents (Beltagy et al., 2020; Zaheer et al., 2020) would be able to handle such contexts more efficiently but generally under-perform due to sparse attention. Hence we don’t evaluate them here.

For all T5-based models, model tuning was standardly performed using a random hyper-parameter search in the style of Devlin et al. (2019) using the public huggingface implementation (Wolf et al., 2020); model selection was done based on the highest EM accuracy on the development sets. We specifically experimented with learning rates in the range of \((1e^{-3} - 5e^{-5})\) using both Adam and Adagrad optimizers and generally found the settings comparable to the original T5 pre-training parameters (Raffel et al., 2020) to be optimal (Adafactor, lr=\(0.001\), 10 epochs, 0-1000 warmup steps, gradient accumulation was used extensively in place of batching to fit long sequences into GPU memory). The optimal T5-3B models and T5-L for full context on COMMAQA-E were trained with lr=\(5e^{-5}\). All other models were trained with a lr of \(1e^{-3}\). We will release the complete list of optimal hyper-parameters along with the code.

D.1 Models with Fact Supervision

To select the relevant facts, we train a RoBERTa-Large (Liu et al., 2019) model on the gold facts and select the top-scoring facts to produce a shorter context that fits in 512 tokens. The RoBERTa model was training using the AllenNLP library (Gardner et al., 2017) with the standard parameters used for RoBERTa – learning rate of 2e-5, triangular LR scheduler with 10% warmup steps, gradient accumulation was used extensively in place of batching to fit long sequences into GPU memory). The optimal T5-3B models and T5-L for full context on COMMAQA-E were trained with lr=\(5e^{-5}\). All other models were trained with a lr of 1e-3. We will release the complete list of optimal hyper-parameters along with the code.

\(^{18}\)To ensure a deterministic order, we sort the answers in alphabetical order.
rameter search, so kept these parameters constant. The model was trained to score each fact independently on the train set and the best model was selected based on the accuracy on the dev set. The model was then evaluated on the facts from the train, dev and test set to produce the shorter context for all three sets. The facts were sorted based on the model’s scores and the top-scoring facts were added to the context till the number of tokens did not exceed 512 tokens (white-space splitting).

E TMN

To train the NextGen model for TMNs, we use the same parameters as the prior work (Khot et al., 2021). We train a T5-Large model as the NextGen model using a batch size of 64, 1r of 5e-6, 5 epochs and warmup of 1000 steps in all our experiments. We used the public huggingface implementation (Wolf et al., 2020) to train this model. During inference, we use a beam size of 10 and select 5 questions at each step. We use nucleus sampling with p=0.95 and k=10. For greedy search, we use the same parameters but select one question at each step. We use the sum log likelihood of each generated question as the score of the reasoning chain. All the code will be released on publication for reproducibility.

Figure 5: Example KB, space of valid inputs and theory used to construct COMMAQA-E
When studying kinneticket, saltcoat would be used. Stretchwork is often used by people working as bartery. Carpoon device was developed based on the vout technology. Triclops studied chasmogon in college. Rawpack was first invented in the year 1943. Gambilla was invented in 2005. Kapod studied duriel in college. Noosecutter is commonly used in the field of blaubrudin. Chaudelaire died in 1980. Chickenshaw was invented in 1940. Gambill was born in 1937. Stoptite was produced by the Coathanger company. Chickenspaw material is needed to make stretchwork. Terbaryan was developed by the Coathanger company.

**Valid Inputs for Agents**

- What occupation do people who study scampot work in?
- What would be the field of study for someone working as a matularch?
- What devices are types of teeplemole?
- What is the device Pomorpha a type of?
- What is Fludgel a type of?

**Complex Questions (and Theory)**

- QC: What objects has Loisy likely used?
  - What is Loisy’s field of study? A: “cougarism”, “nightslash”
  - project flat unique <text> Which objects are used by a #? A: “cannolium”, “microallocation”, “tenderstiltskin”, “monovacuum”

- QC: What occupation has Triclops helped to make?
  - project flat unique <text> Triclops is the founder of which companies? A: “Mechanicsism”
  - project flat unique <text> # which devices has #1 developed? A: “Terbaryan”

- QC: What objects has Stoptite helped to make?
  - project flat unique <text> Which technologies has Stoptite developed? A: “thralline”
  - project flat unique <text> # technology is used in which devices? A: “Cabaretillonite”

- QC: What objects has Kapod helped to make?
  - project flat unique <text> Which companies has Kapod founded? A: “Superglitch”
  - project flat unique <text> Which field have people working as #1 graduated from? A: “kernwood”, “kinneticket”

- QC: What objects has Minimiseries likely used?
  - project flat unique <text> # what Minimiseries work as? A: “infiling”, “glodome”
  - project flat unique <text> Which objects are used in the study of #2? A: “pistarnmen”, “pleifork”, “enablingness”

- QC: What objects has Duriel likely used?
  - project flat unique <text> Which invented objects are mentioned? A: “[legault”, “stoptite”, “stridery”, “hydrallium”, ... “waxbox”]

**Figure 6: Example KB, space of valid inputs and theory used to construct COMMAQA-I**
**Complex Questions (and Theory)**

**QC: Who threw javelins longer than 89.6?**

- Which country does Matrix play for?
- Who are the discus throwers from Premoy?
- Which country is Entine from?
- Who are the discus throwers from Waxsear?
- Which country does Thym play for?
- Which country is Queness from?

**QC: What were the lengths of the javelin throws by Predigime?**

- Who was a discus thrower for 55.0?
- Who threw the discus for 67.6?
- Who threw the javelin for 67.2?
- Who was a javelin thrower for 93.0?
- Who was a discus thrower for 60.0?
- Who threw the javelin for 67.21?
- Who performed discus throws?

**QC: How many discus throws were shorter than 48.0?**

- What lengths were #1's discus throws?
- What lengths were #1's javelin throws?

**QC: Who threw discus throws shorter than 48.0?**

- What lengths were #1's discus throws?
- What lengths were #1's javelin throws?

**QC: Who threw javelin throws longer than 89.6?**

- Who performed javelin throws?
- Who were the javelin throwers from Pistarmen?
- Which country is Queness from?
- Which country does Entine from?
- Which country does Thym play for?
- Which country is Besprit from?

**QC: What was the gap between the longest and shortest discus throws by Honeywax?**

- Who threw discus?
- Who performed discus throws?
- Who threw the discus for 67.6?
- Who threw the discus for 55.0?
- Who was a discus thrower for 55.0?
- Who threw the javelin for 67.2?
- Who was a javelin thrower for 93.0?
- Who performed discus throws?

**QC: Who were the discus throwers from Waxsear?**

- Which country does Thym play for?
- Which country is Entine from?
- Who were the javelin throwers from Pistarmen?
- Who performed discus throws?

**QC: What was the gap between the longest and shortest javelin throws by athletes from Misapportionment?**

- Which country does Thym play for?
- Which country is Entine from?
- Who performed discus throws?
- Who threw the discus for 67.6?
- Who was a discus thrower for 55.0?
- Who threw the javelin for 67.2?
- Who was a javelin thrower for 93.0?
- Who was a discus thrower for 60.0?
- Who threw the javelin for 67.21?
- Who performed discus throws?

**QC: What are the discus throwers from Waxsear?**

- Who threw the discus for 67.6?
- Who was a discus thrower for 55.0?
- Who threw the javelin for 67.2?
- Who was a javelin thrower for 93.0?
- Who was a discus thrower for 60.0?
- Who threw the javelin for 67.21?
- Who performed discus throws?