

A Diagram Is Worth A Dozen Images

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Abstract. Diagrams are common tools for representing complex concepts, relationships and events, often when it would be difficult to portray the same information with natural images. Understanding natural images has been extensively studied in computer vision, while diagram understanding has received little attention. In this paper, we study the problem of diagram interpretation, the challenging task of identifying the structure of a diagram and the semantics of its constituents and their relationships. We introduce Diagram Parse Graphs (DPG) as our representation to model the structure of diagrams. We define syntactic parsing of diagrams as learning to infer DPGs for diagrams and study semantic interpretation and reasoning of diagrams in the context of diagram question answering. We devise an LSTM-based method for syntactic parsing of diagrams and introduce a DPG-based attention model for diagram question answering. We compile a new dataset of diagrams with exhaustive annotations of constituents and relationships for about 5,000 diagrams and 15,000 questions and answers. Our results show the significance of our models for syntactic parsing and question answering in diagrams using DPGs.

1 Introduction

For thousands of years visual illustrations have been used to depict the lives of people, animals, their environment, and major events. Archaeological discoveries have unearthed cave paintings showing lucid representations of hunting, religious rites, communal dancing, burial, etc. From ancient rock carvings and maps, to modern info-graphics and 3-D visualizations, to diagrams in science textbooks, the set of visual illustrations is very large, diverse and ever growing, constituting a considerable portion of visual data. These illustrations often represent complex concepts, such as events or systems, that are otherwise difficult to portray in a few sentences of text or a natural image (Figure 1).

While understanding natural images has been a major area of research in computer vision, understanding rich visual illustrations has received scant attention. From a computer vision perspective, these illustrations are inherently different from natural images and offer a unique and interesting set of problems.

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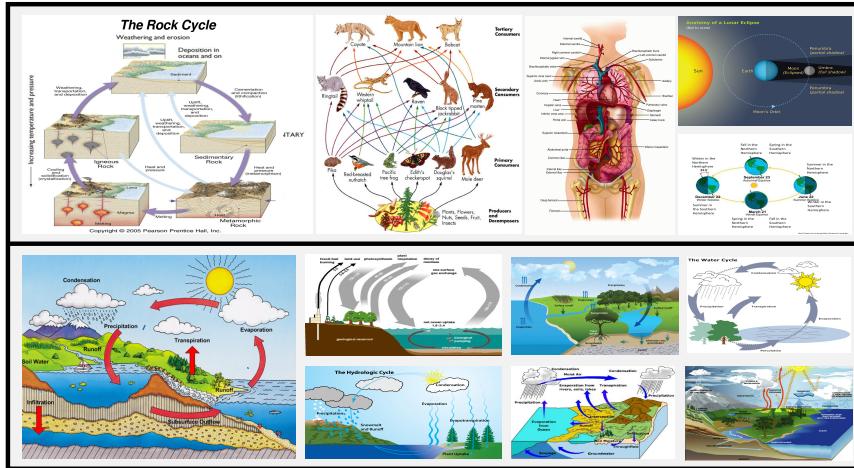


Fig. 1. The space of visual illustrations is very rich and diverse. The top palette shows the inter class variability for diagrams in our new diagram dataset, AI2D. The bottom palette shows the intra-class variation for the Water Cycles category.

Since they are purposefully designed to express information, they typically suppress irrelevant signals such as background clutter, intricate textures and shading nuances. This often makes the detection and recognition of individual elements inherently different than their counterparts, objects, in natural images. On the other hand, visual illustrations may depict complex phenomena and higher-order relations between objects (such as temporal transitions, phase transformations and inter object dependencies) that go well beyond what a single natural image can convey. For instance, one might struggle to find natural images that compactly represent the phenomena seen in some grade school science diagrams, as shown in Figure 1. In this paper, we define the problem of understanding visual illustrations as identifying visual entities and their relations as well as establishing semantic correspondences to real-world concepts.

The characteristics of visual illustrations also afford opportunities for deeper reasoning than provided by natural images. Consider the food web in Figure 1, which represents several relations such as foxes eating rabbits and rabbits eating plants. One can further reason about higher order relations between entities such as the effect on the population of foxes caused by a reduction in the population of plants. Similarly, consider the myriad of phenomena displayed in a single water cycle diagram in Figure 1. Some of these phenomena are shown to occur on the surface of the earth while others occur either above or below the surface. The main components of the cycle (e.g. evaporation) are labeled and the flow of water is displayed using arrows. Reasoning about these objects and their interactions in such rich scenes provides many exciting research challenges.

In this paper, we address the problem of *diagram interpretation* and reasoning in the context of science diagrams, defined as the two tasks of *Syntactic*

parsing and **Semantic interpretation**. *Syntactic parsing* involves detecting and recognizing constituents and their syntactic relationships in a diagram. This is most analogous to the problem of scene parsing in natural images. The wide variety of diagrams as well as large intra-class variation (Figure 1 shows several varied images depicting a water cycle) make this step very challenging. *Semantic interpretation* is the task of mapping constituents and their relationships to semantic entities and events (real-world concepts). For example, an arrow in a food chain diagram typically corresponds to the concept of *consumption*, arrows in water cycles typically refer to *phase changes*, and arrows in a planetary diagram often refers to *rotatory motion*. This is a challenging task given the inherent ambiguities in the mapping functions. Hence we study it in the context of diagram question answering.

We introduce a representation to encode diagram constituents and their relationships in a graph, called diagram parse graphs (DPG) (example DPGs are shown in Figure 6). The problem of syntactic parsing of diagrams is formulated as the task of learning to infer the DPG that best explains a diagram. We introduce a Deep Sequential Diagram Parser Network (DSDP-NET) that learns to sequentially add relationships and their constituents to form DPGs, using Long Short Term Memory (LSTM) networks. The problem of semantically interpreting a diagram and reasoning about the constituents and their relationships is studied in the context of diagram question answering. We present a neural network architecture (called DQA-NET) that learns to attend to useful relations in a DPG given a question about the diagram.

We compile a dataset named AI2 Diagrams (AI2D) of about 5000 grade school science diagrams with over 150000 rich annotations, their ground truth syntactic parses, and more than 15000 corresponding multiple choice questions. Our experimental results show that the proposed DSDP-NET for syntactic parsing outperforms several baseline methods. Moreover, we show that the proposed approach of incorporating diagram relations into question answering outperforms standard visual question answering methods.

Our contributions include: (a) We present two new tasks of diagram interpretation and reasoning, (b) we introduce the DPG representation to encode diagram parses and introduce a model that learns to map diagrams into DPGs, (c) we introduce a model for diagram question answering that learns the attention of questions into DPGs and (d) we present a new dataset to evaluate the above models with baselines¹.

2 Background

Understanding diagrams. The problem of understanding diagrams received a fair amount of interest [41,13,49,29] in the 80’s and 90’s. However, many of these methods used hand written rules, assumed that the visual primitives were manually identified or worked on a specific set of diagrams. More recently,

¹ Dataset and baselines available at http://allenai.org/plato/diagram_understanding

Futrelle et al. [14] proposed methods to analyze finite automata sketches but only worked with vector representations of diagrams. Recently, Seo et al. [36] proposed a method for understanding diagrams in geometry questions that identifies diagram elements by maximizing agreement between textual and visual data. In contrast to these approaches, we propose a unified approach to diagram understanding that builds upon the representational language of graphic representations proposed by Engelhardt [12] and works on a diverse set of diagrams.

The domain of abstract images has also received a considerable amount of interest over the past couple of years [58,54,48,5]. While abstract images significantly reduce the noise introduced by computer vision modules, thus bringing the semantics of the scene into focus, they still depict real world scenes, and hence differ significantly from diagrams which may depict more complex phenomena.

Parsing natural images. Several approaches to building bottom-up and top-down parsers have been proposed to syntactically parse natural images and videos. These include Bayesian approaches [45], And-Or graph structures [55], stochastic context free grammars [26], regular grammars [32], 3D Geometric Phrases [10] and a max margin structured prediction framework based on recursive neural networks [40]. Inspired by these methods, we adopt a graph based representation for diagrams.

Answering questions. The task of question answering is an important area in the NLP community in several sub-domains including machine comprehension (MC) [50,35,16], science questions [20,7], geometry questions [37], algebra word problems [22,19] and open domain QA [52]. Our QA system is inspired from previous works, in particular from text based attention models [42,24] which we extend to diagrams. While MC systems attend on words or sentences from a reading passage, our system attends on the diagram via its parse graph. Analogously, the task of visual question answering (VQA) [4,15,25,34], which is to answer questions about an image has recently received considerable attention from the vision community. Attention models for VQA learn to attend on specific regions in the image, given the question [51,38,56,53,3]. Diagram images are vastly different from real images, and so are the corresponding questions. Hence, QA systems built for real images do not extend well, out of the box, for diagram QA tasks as we show in Section 7.4.

3 The Language of Diagrams

Much of the existing literature on graphic representations [18,9,46] covers only specific types of graphics or specific aspects of their syntactic structure. More recently, Engelhardt [12] proposed a coherent framework integrating various structural, semiotic and classification aspects that can be applied to the complete spectrum of graphic representations. We briefly describe some of his proposed principles below, as they apply to our space of diagrams, but refer the reader to [12] for a more thorough understanding.

A diagram is a composite graphic that consists of a graphic space, a set of constituents, and a set of relationships involving these constituents. A graphic

Intra-Object Label (\mathbb{R}_1): A text box naming the entire object.

Intra-Object Region Label (\mathbb{R}_2): A text box referring to a region within an object.

Intra-Object Linkage (\mathbb{R}_3): A text box referring to a region within an object via an arrow.

Inter-Object Linkage (\mathbb{R}_4): Two objects related to one another via an arrow.

Arrow Head Assignment (\mathbb{R}_5): An arrow head associated to an arrow tail.

Arrow Descriptor (\mathbb{R}_6): A text box describing a process that an arrow refers to.

Image Title (\mathbb{R}_7): The title of the entire image.

Image Section Title (\mathbb{R}_8): Text box that serves as a title for a section of the image.

Image Caption (\mathbb{R}_9): A text box that adds information about the entire image, but does not serve as the image title.

Image Misc (\mathbb{R}_{10}): Decorative elements in the diagram.

Table 1. Different types of relationships in our diagram parse graphs.

space may be a metric space, distorted metric space (e.g. solar system diagram) or a non-meaningful space (e.g. food web). Constituents in a diagram include illustrative elements (e.g. drawings of animals), textual elements, diagrammatic elements (e.g. arrows), informative elements (e.g. legends) and decorative elements. Relationships include spatial relations between constituents and the diagram space, and spatial and attribute-based relations between constituents (e.g. linkage, lineup, color variation, shape). An individual constituent may itself be a composite graphic, rendering this formulation recursive.

Our Representation: Diagram Parse Graph. We build upon Engelhardt’s representation by introducing the concept of *Diagrammatic Objects* in our diagrams, defined as the primary entities being described in the diagram. Examples of objects include animals in the food web, the human body in an anatomy diagram, and the sun in water cycle (Figure 1). The relationships within and between objects include intra-object, inter-object, and constituent-space relationships. We represent a diagram with a *Diagram Parse Graph* (DPG), in which nodes correspond to *constituents* and edges correspond to *relationships* between the constituents. We model four types of constituents: Blobs (Illustrations), Text Boxes, Arrows, and Arrow Heads.² We also model ten classes of relationships summarized in Table 1. Figure 6 shows some DPGs in our dataset.

4 Syntactic Diagram Parsing

Syntactic diagram parsing is the problem of learning to map diagrams into DPGs. Specifically, the goal is to detect and recognize constituents and their syntactic relationships in a diagram and find the DPG that best explains the diagram. We first generate proposals for nodes in the DPG using object detectors built for each constituent category (Section 7.1). We also generate proposals for edges in the DPG by combining proposal nodes using relationship classifiers (Section 7.2).

² Separating arrow heads from arrow tails enables us to represent arrows with a single head, multiple heads or without heads in a uniform way.

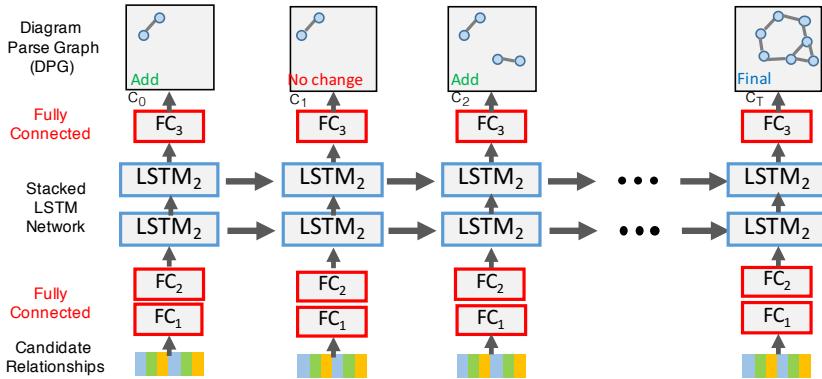


Fig. 2. An overview of the DSDP-NET solution to inferring DPGs from diagrams. The LSTM based network exploits global constraints such as overlap, coverage, and layout to select a subset of relations amongst thousands of candidates to construct a DPG.

Given sets of noisy node and edge proposals, our method then selects a subset of these to form a DPG by exploiting several local and global cues.

The constituent and relationship proposal generators result in several hundred constituent proposals and several thousand relationship proposals per diagram. These large sets of proposals, the relatively smaller number of true nodes and edges in the truth DPG and the rich nature of the structure of our DPGs, makes the search space for possible parse graphs incredibly large. We observe that forming a DPG amounts to choosing a subset of relationships among the proposals. Therefore, we propose a sequential formulation to this task that adds a relationship and its constituents at every step, exploiting local cues as well as long range global contextual cues using a memory-based model.

Model. We introduce a Deep Sequential Diagram Parser (DSDP-NET). Figure 2 depicts an unrolled illustration of DSDP-NET. Central to this is a stacked Long Short Term Memory (LSTM) recurrent neural network [17] with fully connected layers used prior to, and after the LSTM. Proposal relationships are then sequentially fed into the network, one at every time step, and the network predicts if this relationship (and its constituents) should be added to the DPG or not. Each relationship in our large candidate set is represented by a feature vector, capturing the spatial layout of its constituents in image space and their detection scores (more details in Section 7.3).

Training. LSTM networks typically require large amounts of training data. We provide training data to the DSDP-NET in the form of relationship sequences sampled from training diagrams. For each training diagram, we sample relationship sequences using sampling without replacement from thousands of relationship candidates, utilizing the relationship proposal scores as sampling weights.

For each sampled sequence, we sequentially label the relationship at every time step by comparing the generated DPG to the groundtruth DPG.³

The DsDP-NET is able to model dependencies between nodes and edges selected at different time steps in the sequence. It chooses relationships with large proposal scores but also learns to reject relationships that may lead to a high level of spatial redundancy or an incorrect structure in the layout. It also works well with a variable number of candidate relationships per diagram. Finally, it learns to stop adding relationships once the entire image space has been covered by the nodes and edges already present in the graph.

Test. At test time, relationships in the candidate set are sorted by their proposal scores and presented to the network. Selected relationships are then sequentially added to form the final DPG.

5 Semantic Interpretation

DPGs represent the syntactic relationships between constituents of a diagram. They, however, do not encode the semantics of constituents and relationships. For example, the corresponding DPG in Figure 4 indicates that `tree` and `mule deer` are related via an Inter-Object Linkage relationship, but it does not represent that the arrow corresponds to *consuming*. Constituents and relationships with a similar visual representation may have different semantic meanings in different diagrams. For example, the Inter-Object Linkage relationship can be interpreted as *consuming* in food webs and as *evaporation* in water cycles. Moreover, diagrams typically depict complex phenomena and reasoning about these phenomena goes beyond the tasks of matching and interpretation. For example, answering the question in Figure 4 requires parsing the relationship between `trees` and `deer`, grounding the linkage to the act of *consuming* and reasoning about the effects of consumption on the populations of flora and fauna.

In order to evaluate the task of reasoning about the semantics of diagrams, we study semantic interpretation of diagrams in the context of diagram question answering. This is inspired by evaluation paradigms in school education systems and the recent progress in visual and textual question answering. Studying semantic interpretation of diagrams in the context of question answering also provides a well-defined problem definition, evaluation criteria, and metrics.

Diagram Question Answering. A diagram question consists of a diagram d in raster graphics, a question sentence q , and multiple choices $\{c_1 \dots c_4\}$. The goal of question answering is to select a single correct choice c_k given d and q (example questions in Figure 7.)

We design a neural network architecture (called DQA-NET) to answer diagrammatic questions. The main intuition of the network is to encode the DPG into a set of facts and learn an attention model to find the closest fact to the

³ A relationship labeled with a positive label in one sampled sequence may be labeled with a negative label in another sequence due to the presence of overlapping constituents and relationships in our candidate sets.

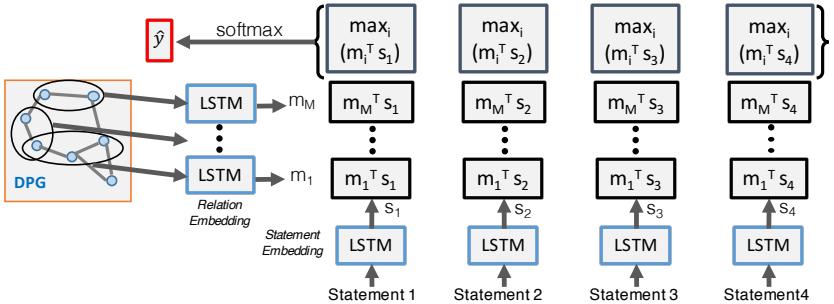


Fig. 3. An overview of the DQA-NET solution to diagram question answering. The network encodes the DPG into a set of facts, learns to attend on the most relevant fact, given a question and then answers the question.

question. For example, Figure 7 shows facts that DQA-NET has selected to answer questions. More formally, DQA-NET consists of the following components: (a) a question embedding module that takes the question q and a choice $c_k, k \in \{1 \dots 4\}$ to build a statement s_k and uses an LSTM to learn a d -dimensional embedding of the statement $s_k \in \mathbb{R}^d$; (b) a diagram embedding module that takes the DPG, extracts M relations $m_i, i \in \{1 \dots M\}$ from DPG, and uses an LSTM to learn a d -dimensional embedding of diagram relations $m_i \in \mathbb{R}^d$; (c) an attention module that learns to attend to the relevant diagram relations by selecting the best statement choice that has a high similarity with the relevant diagram relations. For every statement s_k , our model computes a probability distribution over statement choices by feeding the best similarity scores between statements and diagram relations through a softmax layer.

$$\gamma_k = \max_i s_k^T \cdot m_i, \quad \hat{y} = \text{softmax}_k(\gamma_k) = \frac{\exp(\gamma_k)}{\sum_{k'} \exp(\gamma_{k'})}$$

We use cross entropy loss to train our model: $L(\theta) = H(y, \hat{y}) = -\sum_k y_k \log \hat{y}_k$. More details about the parameters can be found in Section 7.4.

6 Dataset

We build a new dataset (named AI2 Diagrams (AI2D)), to evaluate the task of diagram interpretation. AI2D is comprised of about 5000 diagrams representing topics from grade school science, each annotated with constituent segmentations and their relationships. In total, AI2D contains more than 118K constituents and 53K relationships. The dataset is also comprised of more than 15000 multiple choice questions associated to the diagrams. We divide the AI2D dataset into a train set with about 4000 images and a blind test set with about 1000 images and report our numbers on this blind test set.

The images are collected by scraping Google Image Search with seed terms derived from the chapter titles in Grade 1-6 science textbooks. Each image is

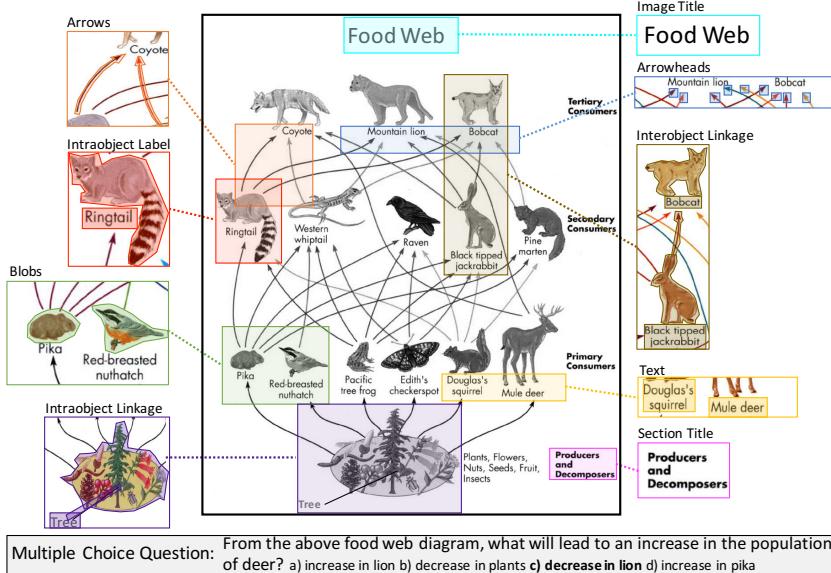


Fig. 4. An image from the AI2D dataset showing some of its rich annotations.

annotated using Amazon Mechanical Turk (AMT). Annotating each image with rich annotations such as ours, is a rather complicated task and must be broken down into several phases to maximize the level of agreement between turkers. Also, these phases need to be carried out sequentially to avoid conflicts in the annotations. The phases involve (1) annotating low-level constituents, (2) categorizing text boxes into one of four categories: relationship with the canvas, relationship with a diagrammatic element, intra-object and inter-object relationship, (3) categorizing arrows into one of three categories: intra-object, inter-object relationship or neither, (4) labelling intra-object linkage and inter-object linkage relationships. For this step, we display arrows to turkers and have them choose the origin and destination constituents in the diagram, (5) labelling intra-object label, intra-object region label and arrow descriptor relationships. For this purpose, we display text boxes to turkers and have them choose the constituents related to it, and finally (6) multiple choice questions with answers, representing grade school science questions are then obtained for each image. Figure 4 shows some of the rich annotations obtained for an image in the dataset.

7 Experiments

We describe methods used to generate constituent and relationship proposals with evaluations⁴. We also evaluate our introduced model DSDP-NET for syntac-

⁴ Constituent CNN models and DSDP-NET built using Keras [11], DQA-NET built using TensorFlow [1] and Random Forest models built using Scikit-learn [30].

tic parsing of diagrams that forms DPGs with comparisons to several baselines. Finally, we evaluate the proposed diagram question answering model DQA-NET and compare with standard visual question answering approaches.

7.1 Generating Constituent Proposals

Diagram Canvas: A diagram consists of multiple constituents overlaid onto a canvas, which may be uniformly colored, textured or have a blended image. We classify every pixel in the diagram into canvas vs constituent. We build non-parametric kernel density estimates (KDE) in RGB, texture and entropy spaces to generate features for a Random Forest (RF) classifier with 100 trees to obtain an Average Precision (AP) of 0.9142.

Detecting blobs: Blobs exhibit a large degree of variability in their size, shape and appearance in diagrams, making them challenging to model. We combine segments at multiple levels of a segmentation hierarchy, obtained using Multiscale Combinatorial Grouping (MCG) [6] with segments produced using the canvas probability map to produce a set of candidates. Features capturing the location, size, central and Hu moments, etc. are provided to an RF classifier with 100 trees. *Baselines.* We evaluated several object proposal approaches including Edge Boxes [57], Objectness [2] and Selective Search [47]. Since these are designed to work on natural images, they do not provide good results on diagrams. We compare the RF approach to Edge Boxes, the most suitable of these methods, since it uses edge maps to propose objects and relies less on colors and gradients observed in natural images. **Results.** Our approach produces a significantly higher AP of 0.7829 compared to 0.02 (Figure 5(a)).

Detecting arrow tails: Arrow tails are challenging to model since they are easily confused with other line segments present in the diagram and do not always have a corresponding arrow head to provide context. We generate proposal segments using a three pronged approach. We obtain candidates using the boundary detection method in [21], Hough transforms and by detecting parallel curved edge segments in a canny edge map; and recursively merge proximal segments that exhibit a low residual when fit to a 2nd degree polynomial. We then train a 2 class Convolutional Neural Network (CNN) resembling VGG-16[39], with a fourth channel appended to the standard 3 channel RGB input. This fourth channel specifies the location of the arrow tail candidate smoothed with a Gaussian kernel of width 5. All filters except the ones for the fourth input channel at layer 1 are initialized from a publicly available VGG-16 model. The remaining filters are initialized with random values drawn from a Gaussian distribution. We use a batch size of 32 and a starting learning rate (LR) of 0.001. **Results.** Figure 5(b) shows the PR curve for our model with an AP of 0.6748. We tend to miss arrows that overlap significantly with more than three other arrows in the image as well as very thick arrows that are confused for blobs.

Detecting arrow heads: Arrow head proposals are obtained by a scanning window approach over 6 scales and 16 orientations. RGB pixels in each window undergo PCA followed by a 250 tree RF classifier. We then train a binary class CNN resembling the standard architecture of AlexNet [23] and initialize using a

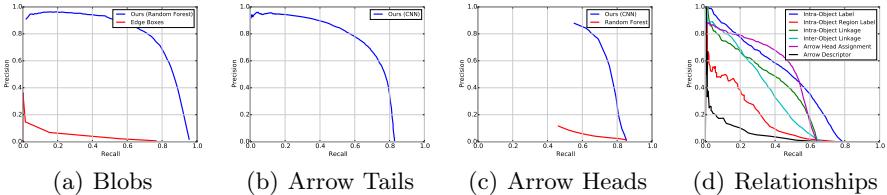


Fig. 5. Precision Recall curves for constituent and relationship proposal generators.

publicly available model. We use a batch size of 128 and a starting LR of 0.001.

Results. Figure 5(c) shows the PR curves for our CNN model as well as the first pass RF model. We miss arrow heads which are extremely small and some which are present in poor quality images.

Detecting text: We use Microsoft Project Oxford’s Optical Character Recognition (OCR) service [27] to localize and recognize text. To improve the performance on single characters, we train a single character localizer using a CNN having the same architecture as AlexNet[23]. We use three training resources: (1) Chars74K (a character recognition dataset for natural images [8]), (2) a character dataset obtained from vector PDFs of scientific publications and (3) a set of synthetic renderings of single characters. The localized bounding boxes are then recognized using Tesseract [43]. **Results.** Using Tesseract end-to-end provides poor text localization results for diagrams with a 0.2 precision and a 0.46 recall. Our method improves the precision to 0.89 and recall to 0.75. Our false negatives comprise of vertically oriented and curved text, cursive fonts and unmerged multi-line blocks.

7.2 Generating Relationship Proposals

Relationship categories are presented in Table 1. Categories \mathbb{R}_1 through \mathbb{R}_6 relate two or more constituents with one another. We compute features capturing the spatial layout of the constituents with respect to one another as well as the diagram space and combine them with constituent detection probabilities. A 100 trees RF classifier is trained for each category. At test time, we generate proposal relationships from the large combinatorial set of candidate constituents using a proximity based pruning scheme. Categories \mathbb{R}_7 through \mathbb{R}_{10} relate a single constituent with the entire image. We model each category using a non parametric Kernel Density Estimate (KDE) in X,Y space. **Results.** Figure 5(d) shows the PR curves for the relationships built using the RF classifier. The AP for several of relationships is low, owing to the inherent ambiguity in classifying relationships using local spatial decisions.

7.3 Syntactic Parsing: DPG Inference

Our model DSDP-Net: The introduced DSDP-NET (depicted in Figure 2) consists of a 2 layer stacked LSTM with each layer having a hidden state of

Method	GREEDY SEARCH	A* SEARCH	DSDP-NET
JIG Score	28.96	41.02	51.45

Method	Q + I (VQA)	Q	Q + I (VQA)	Q + OCR	Q + I + OCR	DQA-NET
Train Set	VQA	AI2D	AI2D	AI2D	AI2D	AI2D
Accuracy	29.06	33.02	32.90	34.21	34.02	38.47

Table 2. Results: (top) Syntactic parsing (bottom) QA (Q:question, I:image)

dimensionality 512. The LSTM is preceded by two fully connected layers with an output dimensionality of 64 and a Rectified Linear Unit (ReLU) [28] activation function each. The LSTM is proceeded by a fully connected layer with a softmax activation function. This network is trained using RMSProp [44] to optimize the cross-entropy loss function. The initial learning rate is set to 0.0002.

Each candidate relationship is represented as a 92 dimensional feature vector that includes features for each constituent in the relationship (normalized x,y coordinates, detection score, overlap ratio with higher scoring candidates and the presence of this constituent in relationships presented to the network at prior time-steps) and features describing the relationship itself (relationship score and the presence of tuples of candidates in relationships presented to the network at previous time steps). We sample 100 relationship sequences per training image to generate roughly 400000 training samples. At test time, relationships are presented to the network in sorted order, based on their detection scores.

Baselines: GREEDY SEARCH: The first baseline is a greedy algorithm whereby nodes and edges are greedily added to the DPG using their proposal scores. It uses an *exit* model as a stopping condition. The exit model is trained to score DPGs based on their distance to the desired completed DPG. To train the exit model, we use features capturing the quality, coverage, redundancy and structure of the nodes and edges in the DPGs and use 100 tree RF models.

A* SEARCH: The second baseline is an A* search, which starts from an empty DPG and sequentially adds nodes and edges according to a cost. We improve upon the greedy algorithm by training a RF model that utilizes local and contextual cues to rank available constituents and relationships. The cost function for each step is a linear combination of the RF score and the distance of the resultant DPG to the desired complete DPG. We use the same exit model as before to approximate the distance from the goal.

DIRECT REGRESSION: We also trained a CNN to directly regress the DPG, akin to YOLO [33]. This generated no meaningful results on our dataset.

Evaluation. To evaluate these methods, we compute the Jaccard Index between the sets of nodes and edges in our proposed DPG and the ground truth DPG. We refer to this metric by the Jaccard Index for Graphs (JIG) score. The Jaccard Index, which measures similarity between finite sample sets, is defined as the size of the intersection divided by the size of the union of the sample sets.

Results. Table 2(*top*) shows the mean JIG scores, computed over the test set for each method. The DSDP-NET method outperforms both the GREEDY SEARCH

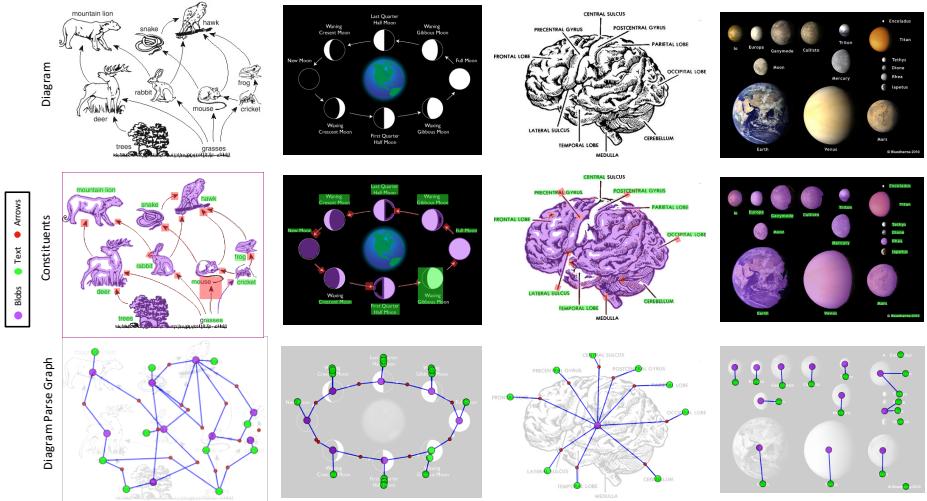


Fig. 6. Inferred DPGs using DSDP-NET. The first row shows the diagram, the second row shows the constituent segmentations and the third row shows the inferred DPGs.

and A* SEARCH by a considerable margin. This shows the importance of our sequential formulation to use LSTMs for adding relationships to form DPGs. Figure 6 shows qualitative examples of inferred DPGs using DSDP-NET.

7.4 Diagram Question Answering

Our model DQA-Net: DQA-Net uses GloVe [31] model pre-trained on 6B tokens (Wikipedia 2014) to map each word to a 300D vector. The LSTM units have 1 layer, 50 hidden units, and forget bias of 2.5. We place a 50-by-300 FC layer between the word vectors and the LSTM units. The LSTM variables in all sentence embeddings (relation and statement) are shared. The loss function is optimized with stochastic gradient descent with batch size of 100. Learning rate starts at 0.01 and decays by 0.5 every 25 epochs, for 100 epochs in total.

Baselines. We use the best model (LSTM Q+I) from [4] as the baseline. Similar to the DQA-Net setup, a question-answer pair is translated to a statement and then passed through an LSTM into a 50D vector. The diagram is passed through a pre-trained VGG-16 model [39] followed by an FC layer into a 50D vector. We then compute the dot product between the statement and image vectors, followed by a softmax layer. We use cross entropy loss and the same optimization techniques as in DQA-Net. We also perform an ablation study using similar models but with just the question text (Q), question+image (Q+I) (VQA) and question + image + outputs of an OCR system (Q+I+OCR).

Results. Table 2 (*bottom*) reports the accuracy of different methods on the test set. DQA-Net outperforms VQA, both when it is trained on the VQA dataset as well as the AI2Ddataset. This shows that the DPG more effectively encodes

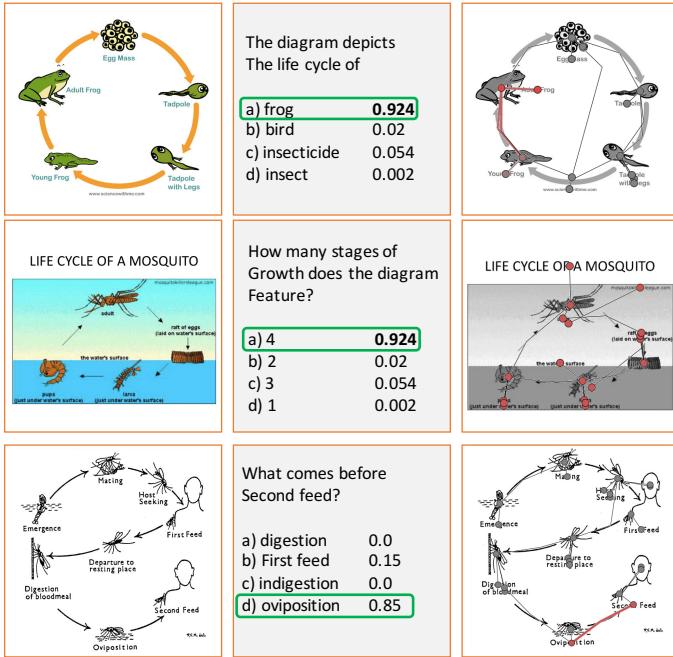


Fig. 7. Sample question answering results using DQA-NET. The second column shows the answer chosen and the third column shows the nodes and edges in the DPG that DQA-NET decided to attend to (indicated by red highlights).

high-level semantics of the diagrams, which are required to answer AI2D questions. Figure 7 shows examples of correctly answered questions by DQA-NET.

8 Conclusion

We introduced the task of diagram interpretation and reasoning. We proposed DSDP-NET to parse diagrams and create DPGs that encode the syntactical information depicted in the diagram. We introduced DQA-NET that learns to answer diagram questions by attending to diagram relations encoded with DPGs. Our experimental results show improvements of DSDP-NET in parsing diagrams compared to strong baselines. We also show that DQA-NET outperforms standard VQA techniques in diagram question answering. Diagram interpretation and reasoning raises new research questions that goes beyond natural image understanding. We release AI2D and our baselines to facilitate further research in diagram understanding and reasoning. Future work involves incorporating diagrammatic and commonsense knowledge in DQA.

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References

1. Abadi, M., et al.: TensorFlow: Large-scale machine learning on heterogeneous systems (2015)
2. Alexe, B., Deselaers, T., Ferrari, V.: Measuring the objectness of image windows. *IEEE Transactions on Pattern Analysis and Machine Intelligence* (2012)
3. Andreas, J., Rohrbach, M., Darrell, T., Klein, D.: Learning to compose neural networks for question answering. In: NAACL (2016)
4. Antol, S., Agrawal, A., Lu, J., Mitchell, M., Batra, D., Lawrence Zitnick, C., Parikh, D.: Vqa: Visual question answering. In: ICCV (2015)
5. Antol, S., Zitnick, C.L., Parikh, D.: Zero-shot learning via visual abstraction. In: ECCV (2014)
6. Arbelaez, P.A., Pont-Tuset, J., Barron, J.T., Marques, F., Malik, J.: Multiscale combinatorial grouping. In: CVPR (2014)
7. Berant, J., Srikumar, V., Chen, P.C., Linden, A.V., Harding, B., Huang, B., Clark, P., Manning, C.D.: Modeling biological processes for reading comprehension. In: Proceedings of EMNLP (2014)
8. de Campos, T.E., Babu, B.R., Varma, M.: Character recognition in natural images. In: International Conference on Computer Vision Theory and Applications (2009)
9. Card, S.K., Mackinlay, J.D., Shneiderman, B.: Readings in information visualization: using vision to think. Morgan Kaufmann (1999)
10. Choi, W., Chao, Y.W., Pantofaru, C., Savarese, S.: Understanding indoor scenes using 3d geometric phrases. In: CVPR (2013)
11. Chollet, F.: Keras. <https://github.com/fchollet/keras> (2015)
12. von Engelhardt, J.: The language of graphics: A framework for the analysis of syntax and meaning in maps, charts and diagrams. Yuri Engelhardt (2002)
13. Ferguson, R.W., Forbus, K.D.: Telling juxtapositions: Using repetition and alignable difference in diagram understanding. *Advances in Analogy Research* (1998)
14. Futrelle, R.P., Shao, M., Cieslik, C., Grimes, A.E.: Extraction, layout analysis and classification of diagrams in pdf documents. In: ICDAR (2003)
15. Gao, H., Mao, J., Zhou, J., Huang, Z., Wang, L., Xu, W.: Are you talking to a machine? dataset and methods for multilingual image question answering. In: NIPS (2015)
16. Hermann, K.M., Kočiský, T., Grefenstette, E., Espeholt, L., Kay, W., Suleyman, M., Blunsom, P.: Teaching machines to read and comprehend. In: NIPS (2015)
17. Hochreiter, S., Schmidhuber, J.: Long short-term memory. *Neural Computation* (1997)
18. Horn, R.: Visual language: Global communication for the 21st century. Century. Brainbridge Island, WA, MacroVU (1998)
19. Hosseini, M.J., Hajishirzi, H., Etzioni, O., Kushman, N.: Learning to solve arithmetic word problems with verb categorization. In: EMNLP (2014)
20. Khashabi, D., Khot, T., Sabharwal, A., Clark, P., Etzioni, O., Roth, D.: Question answering via integer programming over semi-structured knowledge. In: IJCAI (2016)
21. Kokkinos, I.: Highly accurate boundary detection and grouping. In: CVPR (2010)
22. Koncel-Kedziorski, R., Hajishirzi, H., Sabharwal, A., Etzioni, O., Damon Ang, S.: Parsing algebraic word problems into equations. *Transactions of the Association for Computational Linguistics* (2015)

23. Krizhevsky, A., Sutskever, I., Hinton, G.E.: Imagenet classification with deep convolutional neural networks. In: NIPS (2012)
24. Kumar, A., Irsoy, O., Ondruska, P., Iyyer, M., Bradbury, J., Gulrajani, I., Zhong, V., Paulus, R., Socher, R.: Ask me anything: Dynamic memory networks for natural language processing. In: ICML (2016)
25. Malinowski, M., Fritz, M.: A multi-world approach to question answering about real-world scenes based on uncertain input. In: NIPS (2014)
26. Martinovic, A., Gool, L.J.V.: Bayesian grammar learning for inverse procedural modeling. In: CVPR (2013)
27. Microsoft: Project oxford. <https://www.projectoxford.ai/>
28. Nair, V., Hinton, G.E.: Rectified linear units improve restricted boltzmann machines. In: ICML (2010)
29. O’Gorman, L., Kasturi, R.: Document Image Analysis. IEEE Computer Society Executive Briefings (1997)
30. Pedregosa, F., et al.: Scikit-learn: Machine learning in Python. Journal of Machine Learning Research (2011)
31. Pennington, J., Socher, R., Manning, C.D.: Glove: Global vectors for word representation. In: EMNLP (2014)
32. Pirsiavash, H., Ramanan, D.: Parsing videos of actions with segmental grammars. In: CVPR (2014)
33. Redmon, J., Divvala, S.K., Girshick, R.B., Farhadi, A.: You only look once: Unified, real-time object detection. In: CVPR (2016)
34. Ren, M., Kiros, R., Zemel, R.: Exploring models and data for image question answering. In: NIPS (2015)
35. Richardson, M., Burges, C.J.C., Renshaw, E.: Mctest: A challenge dataset for the open-domain machine comprehension of text. In: EMNLP (2013)
36. Seo, M.J., Hajishirzi, H., Farhadi, A., Etzioni, O.: Diagram understanding in geometry questions. In: AAAI (2014)
37. Seo, M.J., Hajishirzi, H., Farhadi, A., Etzioni, O., Malcolm, C.: Solving geometry problems: Combining text and diagram interpretation. In: EMNLP (2015)
38. Shih, K.J., Singh, S., Hoiem, D.: Where to look: Focus regions for visual question answering. In: CVPR (2016)
39. Simonyan, K., Zisserman, A.: Very deep convolutional networks for large-scale image recognition. arXiv preprint arXiv:1409.1556 (2014)
40. Socher, R., Lin, C.C.Y., Ng, A.Y., Manning, C.D.: Parsing natural scenes and natural language with recursive neural networks. In: ICML (2011)
41. Srihari, R.K.: Computational models for integrating linguistic and visual information: A survey. Artificial Intelligence Review (1994)
42. Sukhbaatar, S., Szlam, A., Weston, J., Fergus, R.: End-to-end memory networks. In: NIPS (2015)
43. Tesseract: Open source ocr engine. <https://github.com/tesseract-ocr/tesseract>
44. Tieleman, T., Hinton, G.E.: Lecture 6.5-rmsprop: Divide the gradient by a running average of its recent magnitude. COURSERA: Neural Networks for ML (2012)
45. Tu, Z., Chen, X., Yuille, A.L., Zhu, S.C.: Image parsing: Unifying segmentation, detection, and recognition. In: CLOR (2003)
46. Twyman, M.: A schema for the study of graphic language (tutorial paper). Processing of visible language (1979)
47. Uijlings, J.R.R., van de Sande, K.E.A., Gevers, T., Smeulders, A.W.M.: Selective search for object recognition. International Journal of Computer Vision (2013)

48. Vedantam, R., Lin, X., Batra, T., Zitnick, C.L., Parikh, D.: Learning common sense through visual abstraction. In: ICCV (2015)
49. Watanabe, Y., Nagao, M.: Diagram understanding using integration of layout information and textual information. In: ACL (1998)
50. Weston, J., Bordes, A., Chopra, S., Mikolov, T.: Towards ai-complete question answering: A set of prerequisite toy tasks. In: ICLR (2016)
51. Xu, H., Saenko, K.: Ask, attend and answer: Exploring question-guided spatial attention for visual question answering. arXiv preprint arXiv:1511.05234 (2015)
52. Yang, Y., Yih, W., Meek, C.: WikiQA: A challenge dataset for open-domain question answering. In: EMNLP (2015)
53. Yang, Z., He, X., Gao, J., Deng, L., Smola, A.: Stacked attention networks for image question answering. In: CVPR (2016)
54. Zhang, P., Goyal, Y., Summers-Stay, D., Batra, D., Parikh, D.: Yin and yang: Balancing and answering binary visual questions. arXiv preprint arXiv:1511.05099 (2015)
55. Zhu, S.C., Mumford, D.: A stochastic grammar of images. Foundations and Trends in Computer Graphics and Vision (2006)
56. Zhu, Y., Groth, O., Bernstein, M.S., Fei-Fei, L.: Visual7w: Grounded question answering in images. In: CVPR (2016)
57. Zitnick, C.L., Dollár, P.: Edge boxes: Locating object proposals from edges. In: ECCV (2014)
58. Zitnick, C.L., Parikh, D.: Bringing semantics into focus using visual abstraction. In: CVPR (2013)