

Learning General Language Processing Agents

Dani Yogatama
dyogatama@gmail.com

DeepMind, London, United Kingdom

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1. Executive Summary

The broad objective of the proposed research is to create a general language processing agent (model) that is capable of performing many language-related tasks (e.g., question answering, translation, summarization) in multiple languages (e.g., English, Chinese, Malay, Tamil) by learning from multimodal data (e.g., text, images, knowledge bases).

Existing machine learning models work well when optimized for a particular task, but they require many in-domain training examples (i.e., input-output pairs that are often costly to collect). In order to do well on multiple tasks, we need a separate model for each task—each of them is trained on specific training examples for the task. As a result, being able to do multiple tasks requires maintaining many specialized models. A key reason for this limitation is the inability of current models to learn abstractions (i.e., concepts and knowledge) that are transferable to tasks outside their training distribution (Yogatama et al., 2019).

The central thesis of this research is that obtaining such an ability requires significant advances in how we acquire, represent, and store abstractions in artificial systems. In particular, we will focus on developments of novel training methods and model architectures toward a general language processing agent.

Our training paradigms will place an emphasis on using multiple data sources (e.g., multilingual text, images, knowledge bases) to facilitate learning grounded task-agnostic concepts. On the architecture side, building on our latest work on semiparametric language models (Yogatama et al., 2021), we will design a new generation of deep learning models that combines a large neural network with a key-value database to effectively store and reuse previously acquired knowledge to adapt to new tasks quickly.

The proposed research is a scientific endeavor to replicate natural intelligence in artificial systems with many immediate applications (e.g., question answering systems, machine translation services). Success in this research will strengthen Singapore’s position as both a scientific leader in artificial intelligence and a pioneer in using computer science to solve real-world problems.

2. Aims and Objectives

Our long-term goal is to build a general language processing agent (i.e., a language model) with human-level linguistic ability. Specific to this proposal, the intended end results are:

- To advance the state-of-the-art on language models that learn from multimodal data (text, images, knowledge bases), as measured by their performance on open-domain question answering (Kwiatkowski et al., 2019), visual question answering (Goyal et al., 2018), and commonsense question answering (Boratto et al., 2020).
- To create a language model that continually gets better as it sees more and more data from new tasks, without having to be retrained on older tasks (contrast this with existing models that always need to be retrained on older tasks to prevent forgetting). We use a broad definition of task, which includes (i) answering factual questions (e.g., Who is the current prime minister of Singapore?), (ii) generating text summaries from many domains (e.g., news articles, social media, scientific text), and (iii) translating across many languages. As a concrete measure of this second objective, our

evaluation goal is to have a language model that achieves comparable performance to current state-of-the-art multitask models on all tasks with significant reduction in training time (since our model will be able to learn new tasks with fewer training examples by transferring concepts and knowledge from previously seen tasks better).

3. Reasons for Wanting to do Research in Singapore

As a researcher, I am passionate about using artificial intelligence (AI) to improve people's lives. Singapore is a multicultural country with world-class universities and industry research laboratories. This creates a unique opportunity to make significant progress on fundamental scientific problems and rapidly transfer these advances to real-world applications.

In particular, I plan to collaborate with research groups at the National University of Singapore (e.g., Professor Min Yen Kan, Professor Wee Sun Lee, Professor Harold Soh, and others). I have had initial discussions with them and they are supportive of my plan to conduct this research at NUS. I believe that this research program will complement existing AI research at NUS and provide a collaboration hub for several research groups working on related topics. Access to top-tier students—which is available at a school such as NUS—is critical to the success of my research. Industry laboratories such as Salesforce Research (whose Asia's branch is headquartered in Singapore), Baidu Research, Google Singapore, and Grab AI are potential commercial partners for future collaborations. I believe that my research will also benefit other technological companies in Singapore that are interested in incorporating automation and AI to their workflows.

Furthermore, I am also enthusiastic about increasing ethnic, gender, and cultural diversity in AI. I believe that progress in AI should benefit everyone in the world. At 670 million people, Southeast Asians constitute nearly 10% of the world's population, but we remain extremely underrepresented in artificial intelligence. Data from ICML 2018, a premier machine learning conference, suggests that fewer than 0.5% of ICML attendees are from Southeast Asian institutions (all of them are from Singapore). I am eager to train next-generation machine learning researchers and engineers in Southeast Asia. I have taken concrete steps toward this goal. For example, I am a co-founder of the Southeast Asia Machine Learning School (SeaMLS), which is an annual five-day event held in Southeast Asia where participants (students, industry practitioners) attended lectures given by world-renowned experts. Beyond Singapore, I also have strong connections with many universities and technological companies in the region (e.g., Indonesia, Vietnam) that support SeaMLS. My goal is to build a regional machine learning community in Southeast Asia that could actively contribute to the global AI ecosystem.

I believe that conducting my research program in Singapore will strengthen Singapore's position as the AI center of Southeast Asia and accelerate the creation of a thriving regional collaboration network.

4. Background and Significance

4.1 Background

Advances in deep learning have considerably improved the performance of language models on many tasks. These models are first pretrained on a large corpus in an

unsupervised fashion (without any labeled training data). The models are then used for various downstream tasks by retraining (i.e., fine tuning) on supervised (labeled) training examples (input-output pairs) for the task of interest. The pretraining stage (i.e., representation learning) has been shown to significantly reduce the number of supervised training examples that are needed to adapt a model to perform a downstream task (Peters et al., 2018; Devlin et al., 2019; Yang et al., 2019). Since it only relies on unlabeled data, we can leverage the vast amount of text that is available on the web.

There are three limitations of state-of-the-art language models that we plan to address. First, fine tuning still requires a large number of supervised training examples, which are often expensive to annotate. Second, the resulting downstream model only works well on a single task it is fine-tuned on. Performing well on many tasks requires maintaining multiple variants of the models, fine-tuned separately for each task. Recent work attempts to design a single model to perform many language generation tasks (McCann et al., 2018; Lewis et al., 2019; Raffel et al., 2020; Brown et al., 2020). However, the performance of such a model is still below its task-specific counterparts. Third, existing model architectures—which are mostly based on transformer (Vaswani et al., 2017)—are limited in their ability to process long context (e.g., processing long articles). Many variants of memory-augmented neural networks have been developed to try to address this problem (Grave et al., 2017; Dai et al., 2019; Kitaev et al., 2020; Khandelwal et al., 2020, *inter alia*). However, each of them has its own drawbacks and the best method to incorporate long-term information into a language model is still an open research question.

Our approach to overcome these limitations is through innovations in model architectures and training paradigms. In particular, we seek (i) to use advances in multilingual (Conneau and Lample, 2019; Huang et al., 2019; Cao et al., 2020) and multimodal learning (Lu et al., 2019; Tan and Bansal, 2019; Chen et al., 2020; Li et al., 2020) to learn abstractions that are transferable across many tasks and (ii) to combine neural networks with key-value databases to better remember long-term information. We provide more detailed descriptions in Section 5.2.

This research builds on an ongoing research program that I lead at DeepMind. I joined DeepMind in March 2016 and I have been leading a team to work on general language models since the summer of 2018. My PhD work (2010–2015) on efficient (sparse) language models greatly influences my thinking on this subject.

At DeepMind, my current group consists of two research scientists, one research engineer, and one research intern. My past and present group members include PhD graduates from Carnegie Mellon University, University of Oxford, University of Cambridge, and PhD interns from the University of Washington, Carnegie Mellon University, University of Oxford, and University of the Basque Country. I regularly publish at top-tier venues in machine learning and natural language processing. Over the last few years, my group has published many conference papers and journal articles on general language models (Yogatama et al., 2017; Yogatama et al., 2018; Kong et al., 2019; de Masson d’Autume et al., 2019; Kong et al., 2020; Artetxe et al., 2020; Peng et al., 2021; Yogatama et al., 2021). We also have a track record of releasing open-source resources. For example, we released a new multilingual question answering dataset (XQuAD; <https://github.com/deepmind/xquad>) last year.

DeepMind is a world leader in artificial intelligence research. I strongly believe that my experience leading a team at such a place provides a solid foundation to lead a similar research program in Singapore.

4.2 Significance

The ability to continuously learn and generalize to new tasks quickly is a hallmark of general intelligence. Humans are able to accumulate task-agnostic knowledge from multiple modalities to facilitate faster learning of new skills. The goal of the proposed research—which is to build an artificial agent with human-level linguistic ability—is a scientific endeavor to better understand natural intelligence and replicate it in artificial systems with many immediate applications. For example, real-world systems that will benefit from my research include multilingual question answering systems and machine translation services. As many public services move to autonomous systems, the ability to provide information in multiple languages (e.g., the four official languages of Singapore) becomes more and more important.

There are two hypotheses that drive this research program. First, learning a language model from multiple modalities allows the discovery of abstract concepts, which will help the model to adapt to new tasks more efficiently. In contrast to existing approaches that either focuses on text-only models or take a rudimentary approach to combine multimodal data (i.e., by input concatenation), we will focus on innovative architectures and training paradigms (Section 5.2). Success in this research will produce language models that can be easily adapted to any downstream task with very few supervised training examples, allowing widespread deployments for many services.

Second, limitations of existing approaches (Section 4.1) are inherently caused by the way we train our models as parametric neural networks. In other words, all of the learned knowledge is encoded in the parameters of a large neural network, making it difficult to interpret and sensitive to changes in environments (i.e., distributions from which examples come from). We take a unique semiparametric approach, where we aim to combine a large neural network—which is responsible for processing an input to produce an output—with a key-value database responsible for storing long-term knowledge. We consider such a modular design to be a necessary architectural bias and a more viable alternative to training an ever-larger neural network. Success in this research will result in more efficient (i.e., a smaller number of parameters is needed to achieve comparable performance, which translates to reduction in training and prediction time), more interpretable, and overall better language models.

Furthermore, this research will train students and postdoctoral researchers who will continue to benefit Singapore as they will become experts in artificial intelligence, which is shaping up to be one of the most important technologies of the next few decades.

5. Research Design and Methods

5.1 Research Design

This project involves myself as the principal investigator, three PhD student researchers, and one postdoctoral researcher at a given time. The proposal would support the three

graduate student researchers for five years, one postdoctoral researcher in Years 2 and 3, and another postdoctoral researcher in Years 4 and 5. In particular:

- Student 1 will focus on learning from multimodal data.
- Student 2 will focus on learning multilingual language models.
- Student 3 will focus on model architectures for memory networks.
- Postdoctoral Researcher 1 (Years 2 and 3) will create a prototype for a multilingual multimodal model. Their responsibilities will include co-advising Students 1 and 2 to ensure that the progress made can be consolidated to a single model.
- Postdoctoral Researcher 2 (Years 4 and 5) will create a prototype of our general language processing agents. They will have the option to co-advise two students above (Students 1 or 2; Students 3).

We estimate 40% of the grant to be allocated to compensate researchers in the project. Throughout the duration of the project, there will be regular weekly group meetings to discuss overall progress and brainstorm ideas as a group, as well as individual weekly meetings between each researcher and myself.

The funds from the research grant will also be used to buy equipment necessary to carry out this research. The main requirement is a compute cluster that is equipped with latest-generation graphical processing units. NVIDIA DGX A100 is the most suitable infrastructure for training large scale deep learning models. The cost to obtain it is approximately 199,000 USD. We plan to obtain two DGX A100 at Year 1 to make sure that exploratory research can be performed side by side with training more mature large-scale models. We expect this resource to still be useful beyond the duration of the grant. In addition to the two DGX A100s, we also plan to use on-demand cloud services such as Google Compute Engine (GCE) and Amazon Web Services (AWS) when there is a periodical increase in our compute demands (e.g., near conference deadlines). Overall, I estimate 40% of the grant to be allocated for equipment purchase (including personal workstations for our researchers) and monthly or hourly rental (i.e., GCE and AWS).

The remaining 20% of the grant will be used for travel costs for presenting the work and as a backup for other miscellaneous expenses (e.g., paying crowd annotators to create a new dataset if a new dataset is needed to evaluate our models).

5.2 Research Methods

A perfect generative language model—in theory—should be able to do any language-related task (e.g., by formulating the task as a question and querying the language model to generate answers). Our research will focus on improving language models in several directions. We divide this section into three parts, each outlining a concrete innovation to drive this research forward.

5.2.1 Multimodal Learning

This research builds on our work on representation learning and semiparametric language models (Kong et al., 2020; Yogatama et al., 2021). In this new direction, we aim to make advances in language processing agents that learn from multimodal data. We plan to use two sources of multimodal data: image databases and knowledge bases.

Existing multimodal (vision and language) models rely on paired image-text datasets (e.g., image captioning datasets) to pretrain on. This limits the availability of pretrained

datasets to restricted domains where such paired data is available. We will design a model that can learn from any unaligned pair of corpus (e.g., Wikipedia articles) and image database (e.g., ImageNet). For a given sequence of text from a Wikipedia article, the model will retrieve a relevant set of images from the database. This retrieval mechanism needs to be trained, since otherwise the model does not know which images are relevant. We will rely on existing image captioning and visual question answering datasets to pretrain the retrieval. It will then be further updated during the language model training, where given a set of retrieved images and a text sequence, the model is trained to predict the next word by attending to textual context and retrieved images. Finally, a gating function will be used to combine visual and textual information. Our approach is different from existing approaches that concatenate visual and textual information (no gating function) and are trained on paired image-text datasets (no retrieval mechanism).

In addition to vision and language models, we will apply the same framework to train a language model that retrieves relevant information from a knowledge base (e.g., Google Knowledge Graph). Initially, this will be done independently of the vision and text model above, by replacing the image database where we retrieve relevant signals from by a structured knowledge base.

We plan to evaluate our multimodal representation learning work on benchmark question-answering datasets, including open-domain question answering (e.g., Natural Questions; Kwiatkowski et al., 2019), common-sense question answering (e.g., ProtoQA; Boratko et al., 2020), and visual question answering (e.g., VQA; Goyal et al., 2017).

5.2.2 Multilingual Learning

This research builds on our work on learning multilingual representations (Artetxe et al., 2020). Our goal is to learn multilingual models that work well across many languages.

Existing multilingual models work much better for high resource languages (e.g., English) compared to low resource languages. In high resource languages, there are many corpora that cover many possible distributions (i.e., different domains such as news text, social media text, scientific text, and others). Since existing models are trained with Empirical Risk Minimization (i.e., minimizing the error of examples sampled from a training distribution), it naturally results in models that perform better on high resource languages. However, this can create a problem when the models are used in practice. A fair multilingual model should perform equally well on any of the languages, instead of overfitting to one language and neglecting the rest.

In order to learn a better model, we will rely on Distributionally Robust Optimization (DRO). DRO is an optimization framework that is used to train a machine learning model on a collection of distributions. In DRO, the objective function that we minimize intuitively upweights examples that come from distributions which incur high losses (errors) and downweights examples from distributions with low losses, resulting in a model that performs uniformly well across all distributions in the collection. Success in this project could lead to a widespread adoption of DRO as a training framework in the multilingual community.

Our multilingual language models will be evaluated based on their generation capability (as measured by perplexity) on benchmark multilingual corpora—e.g., multilingual C4 (Xue et al., 2020). If necessary, we also plan to create other multilingual corpora as a part of this project. For example, we can target a more representative set of

languages for Singapore by creating a new multilingual corpus that consists of articles in English, Chinese, Malay, and Tamil.

5.2.3 Memory Networks

Machine learning models often fail when the data distribution shifts—a phenomenon known as catastrophic forgetting (McCloskey and Cohen, 1989; Ratcliff, 1990). In language models, this problem manifests in several ways, such as the inability to work with long documents (more than a few thousand words) and performance degradation on old tasks over time when a model continues learning on new tasks.

This research builds on our effort on learning memory-augmented language models (Yogatama et al., 2018; de Masson d’Autume et al., 2019; Nematzadeh et al., 2020; Peng et al., 2021; Yogatama et al., 2021), where we have shown the benefit of augmenting a language model with a long-term memory in the form of a key-value database.

While the long-term memory database mitigates catastrophic forgetting, key limitations still exist. In particular, the size of the database in current models grows linearly with the amount of experience (i.e., the number of seen examples). We will explore novel techniques to selectively store past examples, discard unused examples, and dynamically merge similar examples into a single database entry (i.e., learning what to remember and forget). Previous work has argued that some examples are “easy” for a neural network to predict correctly, and it spends most of its training time to learn “hard” examples (Toneva et al., 2019). They also show that a significant number of examples can be omitted from the training set without much degradation in performance. We will use insights from this work to better structure our long-term memory database. In addition, we will continue innovating on the architecture side, particularly on how to combine information retrieved from the long-term memory component with the current input.

Our goal is to demonstrate comparable performance of a constant-size memory network to a linear-growth memory network on existing tasks where long-term memory has been shown to be beneficial such as book language modeling (Rae et al., 2020) and continual question answering (de Masson d’Autume et al., 2019). We will continue taking inspirations from neuroscience and cognitive science to make progress in this area.

6. Milestones and Deliverables

6.1 Milestones

Year 1

- **Multimodal learning.** Initial work on retrieval-augmented vision and language model, focusing on learning retrieval of relevant images for a given sequence of English text.
- **Multilingual learning.** Initial work on DRO for multilingual models using up to ten languages to show that DRO is a feasible framework for training multilingual models.
- **Memory networks.** Set up the necessary infrastructure to combine large neural networks with a key-value database, including a replication of our work on adaptive semiparametric language models (Yogatama et al., 2021) as open-source software.

Year 2

- **Multimodal learning.** Integration of the retrieval model developed in Year 1 to a representation learning model. Evaluation on question answering datasets. Given a positive outcome, submit a paper to a top-tier conference.
- **Multilingual learning.** Scaling up DRO training to a hundred languages. Given a positive outcome, submit a paper to a top-tier conference.
- **Memory networks.** Using the infrastructure set up in Year 1, focus on research on constant-size memory architectures.

Year 3

- **Multimodal learning.** Research on incorporating structured knowledge bases to our representation learning model. The focus is on ensuring that relevant information from the knowledge bases can be retrieved for a given sequence of text.
- **Multilingual multimodal learning.** Initial work on incorporating visual information to ground multilingual models to language-independent concepts.
- **Memory networks.** Continue research on architectures, focusing on combining long-term memory with current inputs. Evaluation on language modeling and question answering. Given a positive outcome, submit a paper to a top-tier conference.

Year 4

- **Multimodal learning.** Continue research on incorporating knowledge bases to a representation learning model. The focus in the second year of this project is on designing architectures to make the best use of the retrieved information from the knowledge bases. Given a positive outcome, submit a paper to a top-tier conference.
- **General language processing agents.** Initial work on a language model that combines images, knowledge bases, and multilingual textual information. The focus is on setting up the infrastructure to incorporate progress made during the duration of the project into a single model.

Year 5

- **General language processing agents.** The culmination of our work in Years 1, 2, 3, and 4. Research on general language processing agents, open source the resulting models, and submit a journal article about the work.

6.2 Deliverables

The primary product of this research program will be new publications appearing in Years 2, 3, 4, and 5 satisfying Objectives 1 and 2 in Section 2. We target top-tier journals and conferences in natural language processing and machine learning such as Journal of Machine Learning Research, Transactions of the Association for Computational Linguistics, Conference on Neural Information Processing Systems, Conference of the Association for Computational Linguistics, and other similar venues. When appropriate, we will release our code and model parameters as open-source software.

I regularly give high-profile invited talks about my group's work. The last three talks are at New York University (November 2020), University of Cambridge (November 2020), and ICML 2020 Retrospective Workshop (July 2020). I expect this to continue and intend to frequently communicate results from this research to the wider scientific community.

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