

Software Engineering Challenges of Deep Learning

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Abstract—Surprisingly promising results have been achieved by deep learning (DL) systems in recent years. Many of these achievements have been reached in academic settings, or by large technology companies with highly skilled research groups and advanced supporting infrastructure. For companies without large research groups or advanced infrastructure, building high-quality production-ready systems with DL components has proven challenging. There is a clear lack of well-functioning tools and best practices for building DL systems. It is the goal of this research to identify what the main challenges are, by applying an interpretive research approach in close collaboration with companies of varying size and type.

A set of seven projects have been selected to describe the potential with this new technology and to identify associated main challenges. A set of 12 main challenges has been identified and categorized into the three areas of development, production, and organizational challenges. Furthermore, a mapping between the challenges and the projects is defined, together with selected motivating descriptions of how and why the challenges apply to specific projects.

Compared to other areas such as software engineering or database technologies, it is clear that DL is still rather immature and in need of further work to facilitate development of high-quality systems. The challenges identified in this paper can be used to guide future research by the software engineering and DL communities. Together, we could enable a large number of companies to start taking advantage of the high potential of the DL technology.

Index Terms—deep learning, machine learning, artificial intelligence, software engineering challenges

I. INTRODUCTION

Deep Learning (DL) has received considerable attention in recent years due to its success in areas such as computer vision tasks (e.g., object recognition [1] and image generation [2]) using convolution neural networks, natural language understanding using recurrent neural networks (RNN) [3] and machine strategic thinking using deep reinforcement learning (DRL) [4]. One of the main differences from traditional machine learning (ML) methods is that DL automatically learns how to represent data using multiple layers of abstraction [5], [6]. In traditional ML, a significant amount of work has to be spent on “feature engineering” to build this representation manually, but this process can now be automated to a higher degree. Having an automated and data-driven method for learning how to represent data improves both the performance of the model and reduces requirements for manual feature engineering work [7], [8].

Given the recent advances in ML, we are also seeing industry starting to increasingly take advantage of these techniques, especially in large technology companies such as Google, Apple, and Facebook. Google applies DL techniques to the massive amounts of data collected in services such as Google Translator, Android’s voice recognition, Google’s Street View, and their Search service [9]. Apple’s virtual personal assistant Siri offers a variety of services such as weather reports, sports news, and generic question-answering by utilizing techniques such as DL [10].

A. Machine Learning and Software Engineering

Machine learning, especially DL, differs partly from traditional software engineering (SE) in that its behavior is heavily dependent on data from the external world. Indeed, it is in these situations where ML becomes useful. A key difference between ML systems and non-ML systems is that data partly replaces code in a ML system, and a learning algorithm is used to automatically identify patterns in the data instead of writing hard coded rules. This suggests that data should be tested just as thoroughly as code, but there is, currently, a lack of best practices for how to do so.

A significant amount of research has been conducted on testing software [11], and also for testing ML performance. However, the intersection of SE and ML has not been so comprehensively studied [12]. It is not only the correctness of the model that needs testing, but also the implementation of a production-ready ML system [13].

B. Big Data and Deep Learning

When DL is combined with the recent growth of big data, opportunities and transformative potentials exist for sectors such as finance, healthcare, manufacturing, and educational services [14]–[18].

Working with big data adds extra requirements to supporting infrastructure. Instead of simply loading all data in memory on a single machine, special infrastructure may be needed such as Apache Spark [19], Apache Flink [20], or Google DataFlow [21]. Big data is often loosely defined by the three Vs: Volume, Variety, and Velocity [22]. It is not only the volume of data that may require big data techniques, but also the variety of different types and formats of data. This is another strength of DL, which can use representation learning to combine different modalities such as images, audio,

text, and tabular data [23], [24]. However, that also presents challenges in how to integrate and transform multiple data sources [25]. Given the large number of different formats for images, video, text, and tabular data, it can be challenging to build a data integration pipeline. Additionally, velocity requirements (i.e. processing time or real-time low latency demands) may also require the use of big data techniques such as streaming processing.

This adds numerous challenges to the task of building a big data DL system. It is not only the process of extraction, transforming and loading (ETL) data but also that novel distributed training algorithms may need to be used. Especially DL techniques are not trivially parallelized and again need special supporting infrastructure [26], [27].

C. Technical Debt

Technical debt, a metaphor introduced by Ward Cunningham in 1992, can be used to account for long-term costs incurred by moving quickly in SE. It has been argued that ML systems have a special capacity for incurring technical debt [28]. ML systems not only experience code-level debts but also dependencies related to changes to the external world.

Data dependencies have been found to build similar debt as code dependencies. Few tools currently exist for evaluating and analyzing data dependencies, especially when compared to static analysis of code using compilers and build systems. One example of a data dependency tool is described in [29], where data sources and features can be annotated.

Deep Learning also makes it possible to compose complex models from a set of sub models and potentially reuse pre-trained parameters with so called “transfer learning” techniques. This not only adds additional dependencies on the data, but also on external models that may be trained separately and may also change in configuration over time. External models add additional dependency debt and cost of ownership for ML systems. Dependency debt is noted as one of the key contributors to technical debt in SE [30].

It is not uncommon that the supporting code and infrastructure incur significant technical debt, and care should be taken to properly plan for time needed to develop supporting plumbing code and infrastructure.

A mature system might end up with 95% of the code being plumbing and glue code, which mainly connects different ML libraries and packages together [28]. An ML system is usually dependent on many different pipelines that may also be implemented in different languages, formats, and infrastructure systems. It is not uncommon for pipelines to change, add and remove fields, or become deprecated. Keeping a deployed production-ready ML system up to date with all these changes require a significant amount of work, and requires supporting monitoring and logging systems to be able to detect when these changes occur.

Another common bad practice in ML systems is to have experimental code paths. This is similar to *dead flags* in traditional software [30]. Over time, these accumulated code paths create a growing debt that will be difficult to maintain [28].

An infamous example of experimental code paths was Knight Capital’s system losing \$465 million in 45 minutes, apparently because of unexpected behavior from obsolete experimental code paths [31].

Another technical debt problem of ML systems is configuration management. Configuration of ML systems is frequently not given the same level of quality control as software code, even though it can both have an higher impact on the performance of the model and also be large in size [32]. Configuration changes should be reviewed and possibly even tested in the same way as code changes.

The contribution of this paper is threefold. First, we present and describe seven example ML systems for varying use cases and we identify the potential of ML and specifically DL as a technology. Second, we identify the key SE challenges associated with building DL systems. Finally, we validate the relevance of these SE challenges by providing an overview of the example systems in which we have experienced associated challenges.

II. RESEARCH APPROACH

The findings in this paper are based on seven example ML projects that have been carried out in close collaboration with companies of different sizes and types. The companies range from start-up size to large multinational companies with thousands of employees and many millions of active users. The examples are focused on ML projects of different types where some systems have been in production for more than 10 years, starting from 2005 and onward, and other systems are still in the prototype stage. Experience is collected from people directly employed in associated organizations and working with given case studies, taking a participant observer approach and making use of well-established case study methods [33].

The focus of this study is limited to identifying challenges specifically related to the intersection of SE practices and DL applications. The challenges are based on existing research and validated by empirical studies of selected example projects, and the study adopts an interpretive research approach [34]. Software development is seen as an activity conducted by people in organizations with different values, different expectations, and with different strategies. This type of case study research is appropriate to explore real-life challenges where control over the context is not possible and where there is an interest in accessing people’s experiences related to case studies and associated organizational structures [34].

III. REAL-WORLD ML PROJECTS

A diverse set of real-world ML projects has been selected for this research and are described in this section. The projects have been selected to collectively represent and exemplify different aspects of challenges. A mapping between selected projects and challenges is presented in a later section.

A. Project EST: Real Estate Valuation

Real estate valuation is a cornerstone of financial security for banks. When issuing loans, they need to make sure that

the sales price is reasonably close to the market value and they need to know the total value of their collateral securities. Project EST is a long-running (>10 years) neural network based real estate valuation system used in production by multiple Swedish banks.

The data used by the network consist of historical sales, information about individual properties, demographics, and geography. It was developed by a small team of two data scientists and two backend developers. It initially made use of data from a pre-existing SQL database system and a large collection of legacy data pipeline scripts running on assorted systems.

B. Project OIL: Predicting Oil and Gas Recovery Potential

When building multi-stage hydraulically fractured horizontal wells in tight gas and oil reservoirs, the main question of importance is how much oil and gas will ultimately be recovered. Many different methods have been proposed and used to obtain an estimate of the Estimated Ultimate Recovery (EUR). Project OIL, started by a US oil and gas exploration company, investigated the use of DL in predicting the EUR based on geological information.

The data consisted of high resolution geological maps combined with a small number of oil/gas wells. These wells have been in production for a sufficiently long period of time to accurately be able to deduce EUR. The project resulted in a decision-support tool that given coordinates in the Eagle Ford Shale could predict the EUR of an average multi-stage hydraulically fractured horizontal well. The development team consisted of two senior data scientists/developers.

C. Project RET: Predicting User Retention

An important metric for any end-user facing company is user retention, e.g. what percentage of users will remain active two weeks after registration. Trying to estimate the percentage of users who will remain active shortly after registration is an important but difficult problem given the small amount of available data per user. Project RET refers to a set of projects built by different teams for this purpose for a media-streaming service. Even though the service may have many millions of active users, being able to predict second-week retention given only few days of data per user is non-trivial.

A number of data sources were used, such as media consumption, client interactions (e.g. mobile application actions), and user demographics. Assuming there are many millions of active users and that data has to be extracted from multiple data sources, this becomes a big data problem with many terabytes to process. Multiple teams are working with this problem, often with a specific functionality of the service in mind. Each team usually consists of 4–10 data scientists and engineers. Predictions are usually tracked on dashboards and can be used to evaluate, for example, randomized tests of product changes.

D. Project WEA: Weather Forecasting

Weather forecasts today rely on physical modelling and are primarily solved using finite element methods. They require

expensive supercomputers, take a long time to perform a single prediction and, for many applications, are rather inaccurate. Project WEA, performed in collaboration with a national meteorological agency, aimed to use DL to do weather forecasts. The ultimate purpose was building better wind turbine generator predictions.

The data, which was large (>1 TB), consisted of satellite images, meteorological observations and topological maps. The data spanned a period of 12 years. Some of it was easily obtainable while other parts required the physical transport of data tapes. The project team consisted of three data scientists, two developers and a number of meteorologists.

E. Project CCF: Credit Card Fraud Detection

For companies in the gaming industry, credit card fraud can be a significant issue due to the possibility of money laundering. If money is deposited using a stolen credit card, it is possible to withdraw “winnings” from another account after losing deliberately or after turning the money round a few times in casino-style games. Preventing or detecting fraudulent deposits early on by combining payment details with activities in the games is crucial.

Project CCF was started with the purpose of building a generalized model for this purpose. Significant time was spent on improving the model efficiency of fraud detection and, in so doing, also reducing levels of blocked, risky payments in a company where the detection was based on hand-crafted rule sets. The data consisted of payment request data (method, amount location, etc.) and customer details (CRM, payment history, activity history). If the payment was approved, subsequent analysis also took into account post-payment activity such as signs of abnormal play. A small dedicated analysis team was responsible for developing the models, and results were handed over to a different department for integration into the payment processing systems.

F. Project BOT: Poker Bot Identification

Online poker grew very quickly in the early 2000s. With a large number of inexperienced players, waging real money there was an opportunity to make substantial winnings for experienced players. However, the stakes were relatively low on the tables favored by inexperienced players so a large number of games had to be played to make a reasonable profit. Therefore, many attempts were made (some successfully) to automate game-playing by writing software, i.e. “poker bots”. For the game sites, it was and is a question of customers’ trust to keep the games free from these bots. Project BOT was initiated to develop methods for detecting automated game-playing, and to be able to quickly lock associated accounts.

The data used was game play activity (i.e. statistics on actions taken given the state of the game as seen from each player’s perspective) together with client technical details such as connection IP, hardware fingerprints, player clicking/timing statistics. The models were developed by a small consultancy team (2–3 people) together with internal experts (1–2 people). Despite promising results, the project was cancelled before

it was finished due to unpredictability of efficiency of the finished product.

G. Project REC: Media Recommendations

The field of recommendation systems has increased in popularity and importance with the uprise of media-streaming services. Having a high-quality recommendation service that does not only understand the users' preference but also specific user contexts can significantly improve the user experience. Traditional techniques such as collaborative filtering work well given that sufficient data exist for both the user and the content. However, it can become problematic when new content is released such as a new movie or song that few users have seen. Being able to quickly recommend new content is important, as users are interested in novel content.

Project REC refers to the work with solving the problem of being able to recommend new content. Using techniques such as deep convolutional networks, it is possible to use e.g. raw media data to learn user preferences for novel content without having any user usage data. Having a hybrid system that makes use of collaborative filtering techniques when sufficient user data exist, and DL for novel content, offers the best of two worlds. This DL project started as a small prototype project, which was later expanded into a full production-ready system by a team of data scientists and a large number of engineers.

IV. SELECTED CHALLENGES

This section presents a list of concisely described challenges in the intersection between ML and SE. They have been grouped into three categories: development, production, and organizational challenges.

A. Development Challenges

There are fundamental differences between developing ML systems compared to traditional SE systems. One of the main differences is that data is used to program the system "automatically" instead of writing the software code manually. The performance of the system is unknown until it has been tested with given data, making it difficult to plan the project in a structured manner.

In addition, the lack of model transparency, inability to understand large and complicated models, and difficulty in debugging using libraries with lazy execution makes it challenging to estimate the effort needed to complete the project.

1) *Experiment Management*: During the development of ML models, a large number of experiments are usually performed to identify the optimal model. Each experiment can differ from other experiments in a number of ways and it is important to ensure reproducible results for these experiments. To have reproducible results, it may be necessary to know the exact version of components such as:

- 1) Hardware (e.g. GPU models primarily)
- 2) Platform (e.g. operating system and installed packages)
- 3) Source code (e.g. model training and pre-processing)
- 4) Configuration (e.g. model configuration and pre-processing settings)

- 5) Training data (e.g. input signals and target values)
- 6) Model state (e.g. versions of trained models).

Version control for ML systems adds a number of challenges compared to traditional software development, especially given the high level of data dependency in ML systems. Different versions of data will yield different results, and the input data are often a conglomerate of data from multiple heterogeneous data sources. It has been argued that one of the most difficult components to keep track of is the data component, and the cost and storing of versioned data can be very high [30].

Furthermore, different versions of the model are created during training of the DL model, each with different parameters and metrics that need to be properly measured and tracked. With the addition of data dependencies and a high degree of configuration parameters, it can be very challenging to properly maintain ML systems in the long run. Also, it is not uncommon to perform hyperparameter tuning of models, potentially by making use of automated meta-optimization methods that generate hundreds of versions of the same data and model but with different configuration parameters [35]. Deep learning can also add the requirement of specific hardware.

2) *Limited Transparency*: Software engineering is based on the principle of reducing complex systems into smaller, simpler blocks. Whenever possible, it is desirable to group blocks into different levels of abstraction that have a similar conceptual meaning. Although DL systems, in principle, do that automatically, it is very difficult to know exactly how it is performed or predict what the abstraction layers will look like once the model has been trained. Furthermore, it is difficult to isolate a specific functional area or obtain a semantic understanding of the model. This can only be performed with approximated methods [36].

The great advances that have been made in fields such as computer vision and speech recognition, have been accomplished by replacing a modular processing pipeline with large neural networks that are trained end-to-end [37]. In essence, transparency is traded for accuracy. This is an unavoidable reality. If the problem was simple enough to be explained in symbolic logic, then there would be no need for complex system to solve it. However, if the problem is complex and the model is inherently irreducible, then an accurate explanation of the model will be as complex as the model itself [38].

3) *Troubleshooting*: A major challenge in developing DL systems is the difficulties in estimating the results before a system has been trained and tested. Furthermore, our poor understanding of the inner workings of complex neural networks makes it difficult to debug them in a traditional way. In a neural network, the structure combines the functional parts and the memory and can also be distributed across multiple machines.

In addition, using libraries such as TensorFlow [39] potentially combined with big data frameworks such as Apache Spark [19] makes it difficult to troubleshoot and debug problems in the code. As they both have a lazy execution graph, where the code is not executed in imperative order, it can

be difficult to troubleshoot bugs using traditional SE tools. Other frameworks such as PyTorch [40], do not have the lazy execution graph problem but have other issues such as lower adoption rate in the AI community.

Even if it was possible to step through the source code and set break points, manual evaluation is, in practice, often impossible as it would involve the inspection of millions of parameters. Compared to traditional SE, a small bug in the source code may not be detected at neither compile- nor runtime. During training, the only information that the developer or data scientist may have is a global error estimate. As large neural networks sometimes take days or even weeks to train, there is no way of guaranteeing that a certain performance level will ever be reached. Hence, the effort required to build them can become very large [25].

4) *Resource Limitations*: Working with data that require distributed system adds another magnitude of complexity compared to single machine solutions. It is not only the volume of the data that may require a distributed solution, but also computational needs for extracting and transforming data, training and evaluating the model, and/or serving the model in production. For DL systems, it can also be limited GPU memory that requires special techniques to split the model across multiple GPUs.

Working with distributed systems, both for data processing such as Apache Spark [19] and DL training such as Distributed TensorFlow or TensorFlowOnSpark [27], [39], adds complexity in a number of dimensions. It not only requires additional knowledge and time to operate them, but also additional management and cost of associated hardware and software.

5) *Testing*: ML systems require testing of software used for building data pipelines, training models, and serving in production. Given the high data dependency of ML systems, data also need to be tested. However, currently only a few data-testing tools exist compared to software testing. A frequent pattern seen when testing data is to make use of a small sample of the full dataset. It is challenging to provide a sample that includes all the edge cases that may exist in the full dataset. Also, as the external world is dynamic and changes over time, new edge cases will continue to appear later in time.

In addition, the non-deterministic nature of many training algorithms makes testing of models even more challenging. Another challenge can be that data processing and model serving in production mode can differ in implementation compared to training or testing mode, causing a training-serving skew in model performance [41]. Having the proper tests in place then becomes crucial.

B. Production Challenges

Particularly for DL, it is important to take advantage of the latest hardware. This yields a significant challenge to maintain frequent updates to state-of-the-art software and managing associated dependencies. To accurately detect problems introduced by changing behaviour in dependencies, including data sources that have been modified, requires careful and clever monitoring.

More interestingly, since ML systems are often used directly by end-users, the model might cause a change in the reality it tries to understand. Hence, it may introduce a hidden feedback loop between the production and training data used by the model.

1) *Dependency Management*: Traditional SE typically builds on the assumption that hardware is at best a non-issue and at worst a static entity that has to be taken into consideration. DL systems are primarily trained on GPUs as they provide a 40-100x speedup over classic CPUs. For the past 5 years, the performance has significantly improved and new GPUs are released 1–2 times per year.

As each step increases the performance significantly (beyond Moore’s Law) [42] and hardware performance directly translates to reduced training time (or better results for equivalent training time) there is a great incentive for the software to tightly follow the hardware development.

The DL software platforms are continuously updated on a weekly and sometimes daily basis and the updates typically result in noticeable improvements. This works well for academic research and for developing proofs of concept but can cause considerable issues for production-ready systems. Unlike other ML methods, DL often scales directly with model size and data amount. As training times can be very long (typically a few days up to several weeks) there is a very strong motivation to maximize performance by using the latest software and hardware.

Changing the hardware and software may not only cause issues with being able to maintain reproducible results, they may also incur significant engineering costs with keeping software and hardware up to date.

2) *Monitoring and Logging*: Building a toy example ML system or even an offline research prototype is easy compared to the amount of work required to build a production-ready ML system [12]. In real-world ML applications beyond toy examples, it can become difficult to cover all the edge cases that may occur once a model has been deployed in production. It is also common that people fail to recognize the effort needed to maintain a deployed ML system over time [28].

An ML system may be retrained frequently and thus change behavior autonomously. As the behavior of the external world changes, the behavior of the ML system can suddenly change without any human action in “control” of the system. In this situation, unit testing and integration tests are valuable but not sufficient to validate the performance of the system. Old thresholds that may have been manually assigned may no longer be valid given drifts in the data from the external world.

Live monitoring of the system performance can help, but choosing what metrics to monitor can be challenging.

3) *Unintended Feedback Loops*: A ML system is, by definition, always open-ended as it is driven by external data. No matter how carefully the model is designed and tested, its final performance will always be heavily dependent on the external data [28].

Furthermore, especially in models deployed in a big data context (as ML systems often are), there is a risk of creating

an unintended feedback loop where real-world systems adapt to the model rather than the other way around. Imagine having a widely used real estate price prediction system. When such a system becomes sufficiently popular, the predictions can easily become a self-fulfilling prophecy. As known from control theory, apart from controlled special cases, positive feedback loops are inherently unstable [43].

4) *Glue Code and Supporting Systems*: An unfortunate property of ML systems, and especially DL systems, is that only a small part of the system deals with the model. In a production-ready system, only 5% of the code may deal with the model and the rest is “glue code” that interacts with supporting systems and glues libraries and systems together [28].

Using cloud services can greatly improve development time and decrease maintenance needs. However, keeping the glue code up to date, and keeping up with external changes in cloud services, can introduce unexpected challenges in production-ready systems.

C. Organizational Challenges

To put an ML model into production usually requires collaboration between many different teams with different ideas, priorities, and cultural values. This not only introduces organizational challenges from a cultural point of view, but also in being able to properly estimate the amount of effort needed by the different types of teams.

1) *Effort Estimation*: The reductionist modular SE design of a non-ML project makes it considerably easier to estimate the time and resources required to complete it. In a ML project, the goal might also be well defined but it is unclear to what extent a learned model will achieve that goal, and an unknown number of iterations will be needed before the results reach acceptable levels. This is in the nature of any research project. It is also difficult to decrease scope and run the project in a time-based setting, with a predefined delivery date, since it is hard to determine when, if at all, acceptable performance will be achieved.

An added complication is the lack of transparency inherent in many ML models, especially in DL with powerful but complex and poorly understood models [38]. Since, in many cases, there is no easy way to understand how a model works, it is also very difficult to understand how it should be modified to reach better results.

2) *Privacy and Data Safety*: A lack of understanding of the internal workings of a large neural network can have serious implications for privacy and data safety. The knowledge in a neural network is stored in a distributed manner across the weights of the network. Although we know that specialization occurs in specific regions of the neural network, its exact mechanism is poorly understood. Thus, it is very difficult for designers to control where and how information is stored. It is also not uncommon for companies to have terms of service agreements with their end-users that prevents them from using raw data as direct input to a ML model, and instead have to make use of anonymized and/or aggregated statistics of the user data [41]. This can not only reduce the performance on

the model, but can also make tasks such as data exploration and troubleshooting problems more difficult. New regulations such as the European General Data Protection Regulation [44] go to great lengths to keep the data safe and to protect privacy concerns. However, while keeping data safe is important, it also adds a significant challenges in how to develop and manage ML systems.

Although the information in a model is obscured and there is no trivial way of transforming it back to humanly readable information, it is not impossible to do so. There has been some work on preserving the safety and privacy of data, e.g. differential privacy [45], k-anonymity [46], and encrypted networks that make use of homomorphic encryption to keep sensitive data safe [47].

However, more work is needed to preserve the privacy and safety of sensitive datasets while still being able to efficiently perform data exploration, develop models, and troubleshoot problems.

3) *Cultural Differences*: Building a production-ready ML system usually involves a collaboration between people with different roles. A data scientist might be “pragmatic” about their code as long as it achieves the desired results in a controlled environment, whereas members of the engineering teams care much more about maintainability and stability. Transforming an initial prototype into a production-ready system that also interacts with existing backend and frontend systems usually requires a significantly larger effort. This normally includes collaboration with, for example, backend engineers, UX designers, and product owners.

It is not uncommon that the culture, skills, and interest areas differs between these people. For example, data scientists may be lacking in SE skills and understanding of good engineering practices. UX designers, who have a good understanding of how to optimize the user experience, may also have a different culture and ways of working that can introduce challenges in working together to develop a production-ready ML system [41].

V. PROJECT CHALLENGE MAPPINGS

Given selected projects and identified challenges, a mapping between the two is provided in Table I. The top row of the table lists the three letter acronyms for respective project, e.g. EST refers to “Project EST: Real Estate Valuation”. An “X” means that the project has clearly experienced the specific challenge. A “-” (dash) means that the challenge is not applicable for the specific project, e.g. because the project was never deployed. To further motivate and explain the mappings, see respective motivating text below. Due to the limited space in this paper, we are unable to describe every mapping in the table, but motivating highlights for how projects are related to challenges are provided.

A. Experiment Management

In the Real Estate Valuation (EST) project, a large number of experiments were conducted, and the code behind pre-processing, training, and evaluation of the models were

TABLE I
CHALLENGES FACED IN SELECTED PROJECTS

Category	Challenge	EST	OIL	RET	WEA	CCF	BOT	REC
Dev	Experiment Management	X	X	X	X		X	X
	Limited Transparency	X	X		X	X		X
	Troubleshooting	X		X	X			X
	Resource Limitations	X		X	X			X
	Testing	X	X	X	X	X	X	X
Prod	Dependency Management	X		X	X	X		X
	Monitoring and Logging			X	-	-	-	
	Unintended Feedback Loops	X						X
	Glue Code and Supporting Systems	X		X	X			X
Org	Effort Estimation	X		X		X	X	X
	Privacy and Safety	X		X		X	X	
	Cultural Differences	X	X	X		X	X	

“X”: the project has clearly experienced associated challenge
“-”: the challenge is not applicable to the associated project

continuously improved. During one code refactoring in this project, a data shuffle flag was accidentally switched from false to true. This caused a significant decrease of the model performance. Several days of work were lost in identifying and resolving this shuffle problem. This illustrates one of the challenges with understanding differences between experiments, merely understanding potential code modifications between experiments is hard, especially whether or not they influenced the model performance. Being able to efficiently compare software, platform environment, configurations, and potential changes in the data is a difficult but important challenge.

B. Limited Transparency

In the OIL project, a number of very expensive engineering decisions had to be made based on the results. Since the system was not perfect and the data could be noisy, the engineers responsible for the exploration wanted to know why the neural network made a certain decision. Given that it is virtually a black box model, no direct simple explanation could be made. Sensitivity analysis was used to estimate the impact of the various geological parameters, but this could not take into account when data were locally of poor quality. Subsequently, the engineers were highly reluctant to risk drilling a bore hole (cost >\$ 1M) without additional corroboration.

C. Troubleshooting

One of the principle components of the weather prediction system (WEA) was an autoencoder that compressed weather data. Early in the testing, the resolution of the reconstructed output was of very poor quality. There was no immediately obvious explanation and several hundreds of experiments with different neural network models was done over a period of two weeks.

Because of the lack of easy to use debugging tools for deep neural networks, it took a long time to identify the cause of the error. It turned out to be a pooling (subsampling) operation that was too aggressive, leading to a loss of resolution before the data were actually encoded.

D. Resource Limitations

There can be many reasons for the need of special techniques to handle resource limitations such as a lack of memory (CPU or GPU), long training time, or low-latency serving needs. One common reason is the need for distributed data processing, to pre-process and prepare the data before training the model. For example, the media recommendations service has both a collaborative filtering part and a DL part. The DL part learns how to recommend novel media that has only been seen a few times by a user, and it needs to process raw media data. This involves processing data at petabyte scale, and also training a rather computationally expensive convolutional neural network.

These resource demands are extensive, involving many days’ processing on hundreds of machines. This is an example of having both a big data processing challenge and distributed DL training problem.

E. Effort Estimation

The difficulties in estimating sufficient time and resources were clearly experienced during the development of Project BOT. The business owners grew increasingly impatient and decided to cancel it even though it had proceeded quite well according to the ML team.

Until a working model is designed, it is very hard to claim that anything of value has been accomplished to the client. Thus, being unable to set a final delivery date may lead to projects being shut down despite promising intermediate results.

F. Privacy and Safety

An example of how efforts to ensure the privacy can cause challenges can be seen in the User Retention project. As part of the terms of service agreement with the users of the service, personal data needs to be anonymized and encrypted. This includes any information that might be used to reverse-engineer the identify of the user, e.g. gender, age, and city.

Even though this information would be useful to have and could improve the performance of the model, it is encrypted

and can be difficult to make use of when training models and building the system.

G. Cultural Differences and Logging

As mentioned in the description of the challenge IV-C3, there are many examples of how people with different skills and cultures need to interact. One example of cultural differences and difficulties interacting between data scientists and product owners was experienced in the User Retention project. One purpose for this project was to be able to predict second-week user retention, which partly can be used to evaluate user experience in randomized tests (A/B tests).

A product owner has many responsibilities, including being able to push changes to production in time. As it may take time to, for instance, implement sufficient logging and to analyze the results, a product owner may be unwilling to spend sufficient time implementing necessary logging. Without proper logging in place, there will not be sufficient data to make accurate retention predictions. This can result in discussions between data scientists and product owners, that may not only have different goals, but also different mindsets in how decisions should be made.

VI. RELATED WORK

A number of dimensions have been explored to understand the challenges in ML systems. Aspects and risk factors of hidden technical debt for ML systems were explored in [28], including risk factors such as boundary erosion, entanglement, hidden feedback loops, undeclared consumers, data dependencies, configuration issues, and changes in the external world.

Traditional SE practices have shown the value of clear abstraction boundaries using, for example, encapsulation and modular design. However, ML systems with complex models can erode these boundaries, partly due to the dependency to the external world. ML systems also tend to entangle signals and parameters with each other. The CACE principle states that Changing Anything Changes Everything. A model is not only sensitive to changes in data from the external world, but also, for example, hyperparameters for the model such as number of layers, learning rate, and regularization parameters.

With the addition of transfer learning where complex models are composed of sub models, this can lead to “correction cascades” where a small improvement in a dependency may lead to a decrease in performance of the consuming system.

The problem of having undeclared consumers of ML systems, where consumers silently use the output of the system, is similar to what is referred to as “visibility debt” in traditional SE [30]. This tight undeclared coupling of systems can lead to use in ways that are intended and poorly understood. Additionally, these undeclared consumers can introduce hidden feedback loops between the systems.

A scoring system for production-readiness of ML systems was proposed in [12]. Scoring 0 points means it is more of a research prototype rather than a production-ready system. Scoring 12+ points means there are exceptional levels of automated testing and monitoring. They focus on the ML

specific tests needed for a production-ready system such as tests for: 1) features and data, 2) model development, 3) infrastructure, and 4) monitoring.

ML applications are highly data-driven, and another field that is also highly data-driven is the database field. Wang et. al review challenges and opportunities with combining the fields of DL and databases [48], [49]. As the database community has rich experience working with system optimization, the DL community could benefit from taking advantage of database techniques to accelerate training speed. In particular, the fields of distributed computing and memory management are central to both the database and DL community [26], [39], [50].

Another field closely related to ML and DL is that of big data. Chen et. al review challenges and perspectives in the intersection of these two fields [25]. The area of big data offers opportunities but also adds significant engineering challenges.

VII. CONCLUSIONS

As we have seen in recent years, companies such as Google, Microsoft, and Facebook are transforming their companies to make AI, and specifically DL, become a natural component of their products across the line [51], [52]. However, there are many challenges with building production-ready systems with DL components, especially if the company does not have a large research group and a highly developed supporting infrastructure.

The main goal of this research is to identify and outline main SE challenges with building systems with DL components. Seven projects were described to exemplify the potential for making use of the ML and specifically the DL technology. For these projects, the main problematic areas and challenges with building these systems were identified. To clarify these problematic areas in more detail, a set of 12 challenges were identified and described in the areas of: development, production, and organizational challenges. The main focus of this paper is not to provide solutions, but rather to outline problem areas and, in that way, help guide future research. In addition, the outlined challenges also provide guidance on potential problem areas for companies interested in building high-quality DL systems.

One clear conclusion of this work is that, although the DL technology has achieved very promising results, there is still a significant need for further research into and development in how to easily and efficiently build high-quality production-ready DL systems. Traditional SE has high-quality tools and practices for reviewing, writing test, and debugging code. However, they are rarely sufficient for building production-ready systems containing DL components. If the SE community, together with the DL community, could make an effort in finding solutions to these challenges, the power of the DL technology could not only be made available to researchers and large technology companies, but also to the vast majority of companies around the world.

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