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Leveraging Internet Exchange Points for Improved Internet Cartography

PhD Work Plan

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CONTENTS

1 INTRODUCTION

This document presents a research plan in the context of Internet measurements, to be developed during the PhD, in cooperation with Kimberly Claffy[1] and Bradley Huffaker[2]. It follows an ongoing collaboration with the same group at CAIDA/UCSD, through the PhD student Lucas Muller.

Context. Recently, Autonomous Systems (ASes) are interconnecting at peering infrastructures, such as Internet Exchange Points (IXPs) and colocation facilities (GIOTSAS et al., 2015) to achieve efficient and resilient traffic delivery (YAP et al., 2017; SCHLINKER et al., 2017; MARCOS et al., 2018). These infrastructures simplify interconnection among networks within a region, improving network performance with lower latencies and better routing efficiency (e.g., fewer AS hops for end-to-end paths) (CHATZIS et al., 2013b). The possibility for direct interconnection between ASes allows interdomain traffic to bypass transit providers and flow directly between edge networks, flattening the Internet's hierarchical structure (LABOVITZ et al., 2010).

Relevance of geolocation information. Understanding the developments in the Internet topology is crucial to achieving the goals of network performance and resilience and developing the Internet cartography. Such a task is challenging due to the growing complexity of networking infrastructure and commercial aspects (GIOTSAS et al., 2015). Geolocation inferences about peering interconnection (e.g., multilateral agreements (GIOTSAS et al., 2013)) and topology elements (e.g. router IP addresses (SCHEITLE et al., 2017; HUFFAKER; FOMENKOV; CLAFFY, 2014)) can enhance the understanding of the dynamics of Internet traffic, improve traffic delivery and infrastructure planning (CALDER et al., 2013), and increase responsiveness to outages and attacks (GIOTSAS et al., 2017; MARCOS et al., 2018).

Current limitations. Existing methodologies enable geolocation inferences about peering interconnections and topology elements but fail to provide accurate results in a scalable way. There is a compromise between accuracy, scalability and reproducibility, and neither passive nor active measurement approaches can achieve all at the same time, as follows. Measurement-based geolocation methodologies (active) provide accurate results, but rely on a high number of vantage points (i.e., hosts with known locations) from measurement infrastructures such as Ark (CAIDA..., 2018) or RIPE Atlas (RIPE..., 2018) to geolocate router and hosts targets on the Internet via active probing. They

[1]<http://www.caida.org/~kc/>

[2]<http://www.caida.org/~bhuffake/>

generate a large volume of incoming traffic to the targets, produce a massive amount of collected data and require a significant amount of time for collecting and generating inferences, hampering the scalability. Passive approaches (e.g., geolocation databases), instead, offer information that is readily available for users. However, this information is obtained by combining hostname hints, domain registry information, and other heuristics that can help to obtain geolocation knowledge. Generally, the methodology of these approaches is proprietary, which hinders reproducibility and makes the geolocation conclusions to be unreliable and likely to be inaccurate.

IXPs, in this context, emerge as potential candidates to improve the mapping of the Internet, allowing both active measurements and passive analysis of collected data. These infrastructures play a global role in the Internet topology because carry traffic from a significant fraction of the Internet and generate a large volume of control plane information (CHATZIS et al., 2013a). They are increasingly being deployed all over the world, supporting a growing number of network members and peering interconnections (GIOTSAS et al., 2017). The available data and growing interconnection of ASes in IXPs enable higher visibility and knowledge about the network topology, showing potential in generating geolocation inferences.

Proposal. In this plan, we will investigate the potential of IXPs as powerful vantage points to improve the Internet cartography. We aim to produce a hybrid approach that combines the advantages of both active (i.e., accuracy) and passive (i.e., scalability) solutions while being reproducible. Our method intends to correlate data from active measurements performed from inside of the IXP with analysis of already existing information from control and data planes (e.g., BGP) to produce geolocation knowledge about peering interconnections and network elements.

Our goal is to develop a methodology that is, at the same time, *accurate*, *scalable* and *reproducible*. More specifically, it must be: (i) *accurate* by providing valid, correct and reliable geolocation conclusions; (ii) *scalable* by using few but key vantage points and generating little processing and networking overheads; and (iii) *reproducible* by not relying in complex and ad-hoc solutions and being easily reproducible by researchers and network operators. We plan to deploy and validate our methodology using the Brazilian IX ecosystem, to which we have access.

Expected contributions. We believe that leveraging IXPs as scalable vantage points will provide greater visibility and understanding about the geolocation of peering interconnections and network elements. The proposed work expects to generate the following benefits: (i) improvement on the mapping methodologies of peering interconnections and topology elements; (ii) discovery of gaps in existing physical and measurements (BGP) infrastructures; (iii) identification of how connectivity between ASes varies in developing areas (e.g., Latin America) and across different regions of the world, and (iv) enhancement on knowledge about topology redundancy. We expect that our methodology will improve our understanding about Internet topology, and allow better resilience and recovery methods to mitigate disruption events.

Outline of the proposal. Chapter 2 provides background and terminology. Chapter 3 presents the state-of-the-art and the main related work. In Chapter 4, we present the proposal work. In Chapter 5, we show the expected methodology, set of steps and schedule. Chapter 6 provides the expected results and main contributions. Finally, in Chapter 7, we present the expected coursework of the PhD course.

2 PEERING INFRASTRUCTURES

Peering infrastructures are comprised of both Internet exchange points (IXP) and colocation facilities. The largests ones are responsible for exchanging more than 4 Tbps, on average, of traffic per day (DE-CIX. . . , 2018), support 600+ network members (IX. . . , 2018b), and are available in more than 500 different locations all over the world (AMS-IX. . . , 2018b).

2.1 Internet Exchange Points

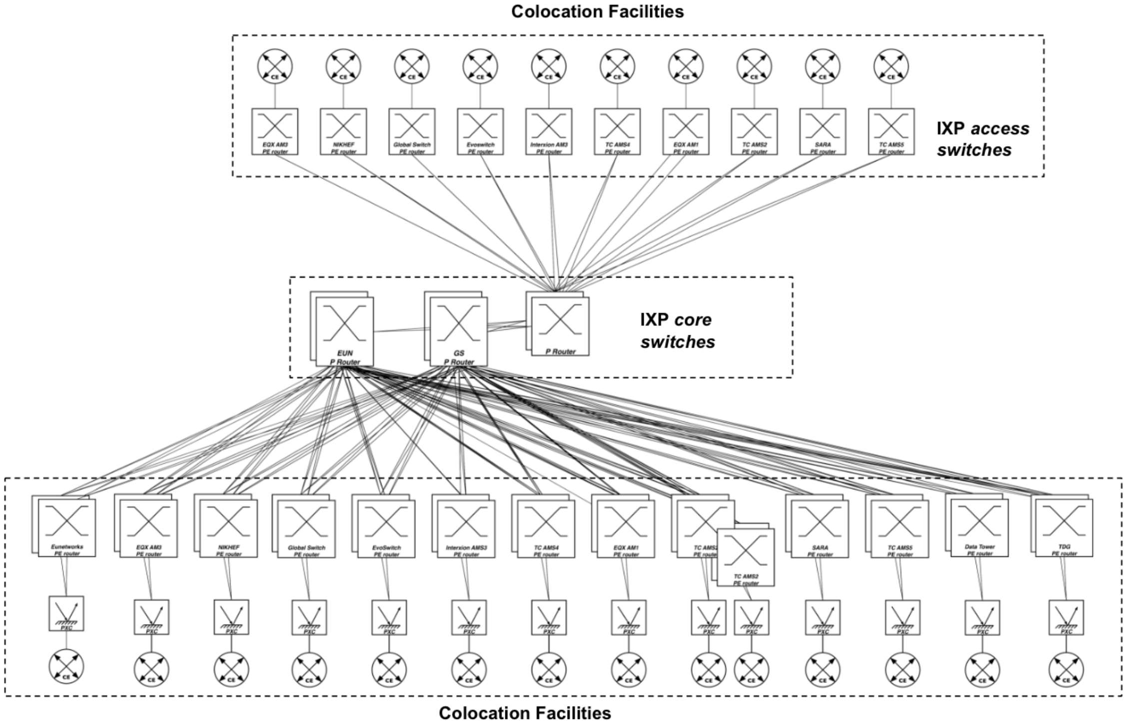
Internet Exchange Points are physical network infrastructures where a set of autonomous systems can interconnect their networks to exchange traffic. Figure 2.1 shows the architecture of AMS-IX, one of the largest IXPs in the world. IXPs provide a shared switching fabric where participating networks can interconnect their routers. The switch fabric carries the traffic resulting from public and private peering of all interconnected ASes. Each IXP has one or more *core switches* in the shared fabric for redundancy. They also associate with several Colocation Facilities and install *access switches* to reach city-level interconnection with other networks (GIOTSAS et al., 2015).

Historically, IXPs can be considered as the successors of Network Access Points (NAPs), which were responsible for the smooth transition from the monolithic government network to the modern Internet (CHATZIS et al., 2013b). Since 1995, the four existing NAPs have been replaced by more than 850 IXPs in 200+ cities around the world, interconnecting 50k+ networks (INTERNET. . . , 2018; GIOTSAS et al., 2015).

Large IXPs (e.g., DE-CIX Frankfurt) exchanges, on average, 4 Tbps of traffic per day (DE-CIX. . . , 2018), amounts of data similar to Tier 1 Internet Service Provider (ISPs). Chatzis et al. (CHATZIS et al., 2013a) report that one European IXPs can observe traffic from a large portion of the Internet, including 42K+ routed ASes, almost all 450K+ routed prefixes and around a quarter billion IP addresses from all around the globe.

Richter et al. (RICHTER et al., 2014) point a growth of 10-20% annually in the membership rates of ASes connecting in IXPs and of 50-100% per year in traffic rates. The largest IXP in terms of members (IX.br) has over 3000 connected members (IX. . . , 2018b). Kotronis et al. (KOTRONIS et al., 2015) show that about 40% of IP prefixes advertised on the Internet can be reached directly from around 5 IXPs. Besides, despite the focus to deploy peering infrastructures in Europe and USA (CHATZIS et al.,

Figure 2.1: AMS-IX Platform Layer 1. Adapted from (AMS-IX. . . , 2018a)



2013b; CHATZIS et al., 2015), studies reveal that developing regions as Latin America, and Africa are recently increasing the adoption of IXPs to enhance network performance (BRITO et al., 2016; FANOU; VALERA; DHAMDHERE, 2017).

2.2 Colocations Facilities

Colocation facilities (Colos) are physical locations which provide essential infrastructures like power, space, cooling, physical security, and storage to their associated ASes. More specifically, it is a place where operators of multiple networks place their networking equipment for interconnection (INTERCONNECTION. . . , 2014). The deployed facilities lower the infrastructure costs and drive small and medium providers to house their equipment (storage, server, routers) in the Colos (KOTRONIS et al., 2017).

The Colos platform connects the member's network to various IXPs, transit networks, cloud/content providers and other ASes in multiple locations worldwide. In large metropolitan areas, a colocation facility operator may install various facilities in the same city, interconnected, to allow access from ASes present at one facility to networks at another facility in the same region (GIOTSAS et al., 2015). Large carrier-neutral companies such as Equinix (EQUINIX. . . , 2018) and Telehouse (TELEHOUSE. . . , 2018) are the leading operators of colocation facilities all over the world.

3 RELATED WORK

We now present the state-of-the-art on the main topics related to the proposed work. In Section 3.1 and Section 3.2, we present the efforts to improve the accuracy of mapping peering interconnections and topology elements to physical locations, respectively. The work mentioned in these sections presents valuable and solid geolocation and infrastructure inferences. However, they either do not scale, relying on a large number of active measurements or have limited scope, providing rich inferences for just a subset of topology elements. The drawbacks reveal vast potential and opportunity to improve the generation of geolocation knowledge.

3.1 Mapping of peering interconnections and infrastructures

Measuring and mapping the Internet at AS-level is valuable to understand the underlying structure of the topology. However, mapping at this level considerably abstracts rich information about connectivity between networks at the Internet. Accurate knowledge of interconnection geolocation helps network troubleshooting, outage detection, and attack diagnosis. Recent efforts attempt to infer peering matrices (i.e., who peers with whom at which IXP) and map interconnections to physical locations where they occur.

Augustin et al. (AUGUSTIN; KRISHNAMURTHY; WILLINGER, 2009) proposes a method to infer peering interconnections established at IXPs, identify IXP-specific peering matrices and better understand the IXP substrate of the Internet's AS-level ecosystem. The mechanism detected 278 IXPs and discovered the existence of about 44K IXP-related peering links. However, the method is costly both in time and number of active measurements.

Giotsas et al. (GIOTSAS et al., 2015) propose an algorithm to infer the physical interconnection facility where an interconnection occurs among all possible candidates. The methodology provides accurate results but is unable to scale to large scenarios involving several colocation facilities, IXPs and ASes, given a large amount of active probing resources needed. The initial process of mapping networks and IXPs to facilities, required by the methodology, is manual and time-consuming to be developed/updated. Additionally, the methodology has a significant limitation because of the complexity to reproduce results and to apply it to other contexts.

3.2 Mapping of topology elements

Mapping network elements accurately to physical locations is a crucial task. Precise knowledge of router geolocation helps to detect BGP threats, estimate the geographic presence of ASes, and customize content delivery. It is possible to geolocate IP addresses through public or commercial databases, delay-based or DNS-based methods.

Geolocation databases. Gharaibeh et al. (GHARAIBEH et al., 2017) compare router geolocation coverage and reliability in four popular geolocation databases. The authors show that despite having a high coverage at country-level, databases are not accurate in geolocating routers at neither country- nor city-level, even if they agree significantly among each other. Poese et al. (POESE et al., 2011) evaluates five IP geolocation databases. The results show that the vast majority of entries in the databases are biased to few popular countries. For example, a single country (e.g., United States) concentrates more than 45% of the entries in these databases. Besides, the entries do not reflect official IP allocations and BGP routing tables.

Delay-based. Topology-based Geolocation (TBG) (KATZ-BASSETT et al., 2006) converts Internet route measurements from landmarks to target into constraints to geolocate the target and all of the routers along the path. The drawback is that the methodology is very sensitive to measurement errors, such as inflated latencies. GeoPing (PADMANABHAN; SUBRAMANIAN, 2001) uses active delay measurements and needs landmarks with known geographic locations to geolocate a target host. It combines measurements to estimate the coordinates of a host. However, the geolocation of a target can only be accurately predicted if there is a landmark near the target host.

DNS-based. The work of Huffaker et al. (HUFFAKER; FOMENKOV; CLAFFY, 2014) and Scheitle et al. (SCHEITLE et al., 2017) propose methods to geolocate routers based on geography-related strings in hostnames and validate the results with active measurements from different decentralized probes. Despite showing accurate results, the scope of both proposals is restricted since only a small subset of routers have apparent geographic hints in their DNS names. For example, (HUFFAKER; FOMENKOV; CLAFFY, 2014) mention that only 3.6M of nearly 19M nodes ($\sim$19%) in their dataset have apparent geographic hints in their DNS names.

4 PROPOSED WORK

Recent studies reveal the opportunity to improve the generation of geolocation knowledge. IXPs, in this context, shows potential for the emergence of new solutions involving Internet mapping, due to their central roles in topology enable higher visibility and knowledge about the network.

This PhD work plan seeks to investigate techniques to explore Internet Exchange Points as powerful vantage points to improve the Internet cartography and generate geolocation inferences of peering interconnections and topology elements. We aim to produce a hybrid approach that combines the advantages of both active (i.e., accuracy) and passive (i.e., scalability) solutions while being reproducible. First, we plan to gather already collected information on control and data planes (e.g., BGP) of a single IXP to obtain a preliminary geolocation knowledge about the Internet topology. Next, we intend to perform active measurements campaigns from inside of the IXP and correlate with passive data analysis to increase the accuracy of the generated inferences. Finally, we aim to scale our methodology on several IXPs to obtain comprehensive and accurate geolocation inferences. We will contact network operators and use additional available public and private data sources (e.g., flow samples) to validate our results.

Our goal is to develop a methodology that achieves *accuracy*, *scalability* and *reproducibility* at the same time. Designing a solution with these three purposes will generate a reproducible technique able to provide reliable and correct geolocation conclusions while using few key vantage points and generating little processing and networking overheads. We intend to produce a methodology that can be used by academia and industry for the development of new research and by network operators to apply to practical situations. We plan to deploy and validate our methodology using the Brazilian IX ecosystem, to which we have access.

First, we aim to enhance geolocation inferences in developing regions such as Latin America, which show rich, but weakly examined, peering infrastructures (IX..., 2018a; BRITO et al., 2016). Next, we aim to extend our methodology to other worldwide available IXPs and develop a better understanding of the geolocation characteristics of these infrastructures in the Internet Topology.

Research Questions. In this work, we aim to answer the following research questions:

- Can IXPs be used as vantage points to generate geolocation inferences about peering interconnections and Internet topology?

- How can we obtain accurate geolocation of infrastructure elements from inside the IXP?
- Is it possible to correlate active measurement data with collected information on control and data planes (e.g., BGP) to improve the Internet cartography?
- Which and how many IXPs are necessary to have a precise view of the Internet?
- What are the implications of using this approach concerning computational cost, network traffic, and privacy?
- How is it possible to measure in a scalable and automatized way?

Risks and limitations. The proposed research presents risks on data and IXP access. More specifically, data from the IXP is usually confidential and may not be available to the general public. Besides, IXPs tend to restrict access to their network. We will not face these risks because of already collected data and ongoing collaborations with the Brazilian IXP from another PhD study. Besides, our methodology can present potential limitations. We could face inaccurate results when using few IXPs given that their visibility, individually, may not perfect and our technique may not be applied in regions (e.g., US) where IXPs tend to be more restrictive.

5 METHODOLOGY

We now present the methodology, schedule, and collaboration of the proposed work. First, we outline the incremental steps needed to develop the research described in this plan (Section 5.1). Next, in Section 5.2, we detail a proposed schedule for the entire PhD period, composed of actions and their expected duration. Finally, we conclude describing the collaboration with one of the leading research groups in the topic of the PhD plan (Section 5.3).

5.1 Steps

1. **Geolocation inferences from passive analysis**: in the first step, we plan to perform a passive analysis using already collected data from a few IXPs in the Brazilian system. First, we will design a technique capable of generating geolocation inferences about peering interconnections and network elements using existing control plane data (e.g., BGP). Next, we will obtain and prepare the data to serve as input for the proposed solution. Finally, we will perform an evaluation and validate our results. We expect to submit a paper using the generated results.
2. **Geolocation inferences from hybrid approach**: in this phase, we will extend our first methodology by performing active measurements campaigns from inside the IXPs without incurring network overheads. We will remain using few IXPs in the Brazilian system. We pretend to correlate the data obtained from the active measurements with the information from the previous passive approach to increase the accuracy of the resulting geolocation inferences. We will perform an evaluation of the technique and validation of the results of the extended methodology. We expect that the obtained results will generate a publication.
3. **Extension to larger scenarios**: in the third and last point, we plan to scale and apply our technique using active measurements and passive data analysis to a more significant number of IXPs. We will address potential limitations of the approaches from previous steps and apply optimizations to increase both accuracy and scalability of our methodology. The deployment in more IXPs will improve our visibility of the network topology and allow more rich geolocation inferences. We plan to evaluate the methodology and validate all of our results. We believe that the final

technique will present rich results, generating a new publication.

5.2 Proposed schedule

1. In-depth state-of-the-art study and monitoring about themes related with thesis;
2. Qualification Exam;
3. Examination of proficiency in English;
4. Modeling of the first technique based on passive analysis;
5. Access and processing of existing data;
6. Evaluation of the first proposed technique;
7. Validation of the results obtained by the first methodology;
8. Writing and submission of first conference/journal article
9. Modeling of the second technique based on hybrid approach;
10. Period reserved for doctorate sandwich;
11. Conduction of active measurements and processing of data;
12. Thesis Proposal Defense;
13. Evaluation of the second proposed technique;
14. Validation of the results obtained by the second methodology;
15. Writing and submission of second conference/journal article
16. Examination of proficiency in a foreign language;
17. Extension of the previously developed techniques;
18. Conduction of active measurements in more IXPs and processing of data;
19. Evaluation of the extended methodology proposed technique;
20. Validation of the results obtained by the extended methodology;
21. Writing and submission of a third conference/journal article
22. Thesis writing;
23. Thesis defense;
24. Participation in conferences and symposia related to the theme of the thesis;

Table 5.1: Schedule of activities during the PhD period

Activities	2019/1	2019/2	2020/1	2020/2	2021/1	2021/2	2022/1	2022/2
1	■	■	■	■	■	■	■	■
2	■							
3	■							
4	■							
5	■							
6		■						
7		■						
8			■					
9			■	■				
10				■	■			
11				■				
12				■				
13					■			
14					■			
15					■			
16					■			
17						■		
18						■		
19							■	
20							■	
21							■	
22						■	■	
23								■
24	■	■	■	■	■	■	■	■

5.3 Collaboration

The proposed PhD is joint work with the University of California San Diego (UCSD) in cooperation with Kimberly Claffy[1] and Bradley Huffaker[2]. The collaboration aims to expand the existing relationship between both universities and presents the opportunity for a sandwich doctorate. The second year of PhD is expected to be located at CAIDA/UCSD. The funding for the away period is yet to be determined.

[1] <http://www.caida.org/~kc/>
[2] <http://www.caida.org/~bhuffake/>

6 EXPECTED RESULTS

We now present the expected results of the Ph.D. First, we describe the main contributions of the proposed work in Section 6.1. Finally, in Section 6.2, we present some of the leading journals (Table 6.1) in which the results obtained during the doctorate can be published and some of the main conferences related to the research areas involved in this plan (Table 6.2).

6.1 Main Contributions of the Thesis

The following contributions are expected in each of the previously mentioned steps with the development of the proposed work:

1. **Geolocation inferences from passive analysis**: in this step, we expect to find if Internet Exchange Points can be used as powerful scalable vantage points to map and generate geolocation inferences, their strengths and limitations. Besides, the passive analysis can discover gaps in existing physical and measurements (e.g., BGP) infrastructures
2. **Geolocation inferences from hybrid approach**: we believe that correlating active measurements with passive analysis of data can improve the generation of geolocation knowledge. It can help the identification of connectivity between ASes varies in developing areas (e.g., Latin America) and across different parts of the world. Besides, a precise mapping of peering interconnections and topology elements can improve the efficiency of traffic delivery for ASes and enhance knowledge about topology redundancy.
3. **Extension to larger scenarios**: we expect to provide a methodology accurate, scalable and reproducible to improve the mapping of peering interconnections and topology elements by exploiting the characteristics of the Internet Exchange Points, introducing new datasets and validations. We hope that using several IXPs can improve the Internet cartography.

It is also expected that during the development of this work there will be the participation of master and scientific initiation students, performing work related to the doctoral thesis proposed in this plan. The participation in the training of these student's knowledge is then considered as one of the possible contributions.

6.2 Publications

The development of PhD activities will generate results which will be used as a basis for the writing of 2-3 articles for journals and congresses. Table 6.1 presents some of the main journals in which the results obtained during the doctorate can be published, while Table 6.2 presents some of the leading conferences of the research areas involved in this plan.

Table 6.1: Journals related to PhD

Journal	**Impact Factor**	**Qualis**
Communications of the ACM	4.027	A1
IEEE/ACM Transactions on Networking	3.376	A1
ACM CCR	2.008	B1
Elsevier Computer Networks	2.516	A1

Table 6.2: Conferences related to PhD

Conference	**Acceptance Rate**	**H-index**	**Qualis 2016**
ACM Internet Measurements (IMC) Conference	24.7%	75	A1
Network Traffic Measurement and Analysis Conference (TMA)	39.2%	–	–
Passive and Active Network Measurement Conference (PAM)	40.8%	–	A2
ACM Special Interest Group on Data Communication (SIGCOMM) Conference	18%	67	A1
ACM International Conference on emerging Networking EXperiments and Technologies(CoNEXT)	17.2%	35	A1
USENIX Symposium on Networked Systems Design and Implementation (NSDI)	15.4%	62	A1
USENIX Security Symposium	19.1%	70	–

7 COURSEWORK

We now present the expected coursework to be taken in PhD course. Table 7.1 shows the courses and the number of credits that will be taken during the PhD. All courses sums a total of 20 credits, agreeing with the minimum required for the doctorate degree.

Table 7.1: Courses to be taken in PhD

Code	**Period**	**Period**	**Credits**
CMP410	Teaching Practice I	2019/1	1
CMP600	Qualification Exam	2019/1	2
CMP230	Computer System Security	2019/1	4
CMP411	Teaching Practice II	2019/2	1
CMP267	Novel Internet Architectures and Paradigms	2019/2	4
CMP223	Computer System Performance Analysis	2019/2	4
CMP182	Computer Network	2020/1	4

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