Demystifying Networking: Teaching Non-Majors via Analogical Problem-Solving

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ABSTRACT

The goals of a typical Networking course for Computer Science majors include getting students to learn the relevant concepts, delving into details of various protocols, and using Networking utilities. Such focus on low-level details is unlikely to be interesting to non-majors. Also, there is a larger danger of students not understanding the basic concepts due to the perceived complexity in the details and technical jargon. We address both these issues by teaching Networking concepts through solving problems in analogical real-life scenarios. The main idea of our approach is: The instructor poses an analogy problem, students work in groups to devise solutions, followed by a class discussion to map the analogy problem as well as its solution to their corresponding technical details in Networking domain. Thus we emphasize the core concepts of Networking and demystify the specialized technical details. Across three offerings of this course, we have found that: (i) our students' performance on typical Networking questions is comparable or higher than traditionally taught students, (ii) students can solve unseen technical problems, (iii) students' confidence in tackling technical questions is high.

Categories and Subject Descriptors

K.3.2 [Computer Science Education]

General Terms

Design, Human factors

Keywords

Networking, non-majors, analogies, active learning

1. INTRODUCTION

Networking is a course commonly taught to all Computer Science (CS) majors. Often, undergraduate students who choose CS as a minor, or students from other engineering disciplines such as Electrical Engineering, need to take this course. The typical goals of an introductory Networking course for non-majors are to get students to learn the technical aspects of: (i) Concepts such as layering, multiple-access, routing, transport and (ii) Protocols such as Ethernet, OSPF, TCP, SMTP. Sometimes an additional goal is to build familiarity with configuring and using such protocols, either through in-class demonstrations or in laboratory settings.

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However, the focus on such low-level details such as protocols or configuration of networks is unlikely to be relevant or interesting to non-CS majors [8]. There is a larger danger of students not understanding the basic concepts due to the perceived complexity. Students might get mired in the details, thereby losing the view of the underlying conceptual framework. The abundant use of technical jargon may be a deterrent to students being able to apply the concepts. A Networking course need not emphasize minute details or use lots of specialized vocabulary to achieve the primary goals of understanding and applying concepts. At its core, the subject contains a straightforward application of common concepts, such as modularity, abstraction, resource-sharing, addressing, correctness and efficiency. An important objective of a course for non-majors is to get students to apply these concepts in a stepwise manner, in the appropriate situations.

In this paper, we describe a course in Networking, based on solving problems in analogical real-life scenarios. Analogies have been known to promote learning of the properties of unfamiliar concepts as well as develop new abstractions [4]. Students work in groups in the classroom to devise solutions to real-life open design problems. The real-life problem as well as its solution are then mapped to their corresponding technical details in the Networking domain. This process of mapping between the real-life analogy and the technical problem emphasizes the core concepts of Networking and demystifies the specialized technical details, which are the two key goals of our course. We found that the analogical problem-solving method is comparable or better in terms of students' performance on typical Networking questions, when compared with traditional students. Students are able to apply concepts from the analogy domain to solve Networking problems in previously unseen topics. After undergoing the analogical problem-solving course, students' confidence in attempting complex Networking design problems is high.

We begin this paper with the goals of the course and describe how the instructional method addresses the goals (Section 2). We illustrate the process of developing instructional material for the analogies and problems with a detailed example, report how a typical class is structured, and describe the implementation steps of problem-solving with analogies (Section 3). To examine the effectiveness of the instructional method, we analyze students' reasoning via analogies in questions, and investigate student perceptions of the non-traditional learning environment (Section 4). We discuss the benefits and challenges for an instructor in teaching the course, and conclude with guidelines for instructors who potentially want to adopt our technique.

2. COURSE GOALS AND INSTRUCTIONAL METHOD

A course on Networking is a staple in all Computer Science departments, both for majors and non-majors. Typical goals of such courses include exposure to concepts such as ARQ mechanisms, graph algorithms and familiarity with protocol details such as RTS-CTS in WiFi, LSPs in OSPF, TCP variants, and use of Networking utilities such as ifconfig, traceroute, tcpdump. There is wide a range of innovative pedagogies and software tools that have been used in Networking courses to address these goals, for example in [7, 9]. Some courses specifically address 'non-specialists' by the use of hands-on experiences of networking concepts such as packet-tracing and network simulations [10].

Our course goals include the typical goals as mentioned above. An additional explicit goal is to get students to engage deeply with the content by (i) drawing connections between Networking topics and real-life analogies, and (ii) retracing the evolutionary steps in the invention of any technology. Specifically, the main learning objectives of our course are:

1. Get students to demonstrate conceptual understanding of Networking protocols.
2. Demystify Networking technologies so that:
    a. Students recognize that design choices for various technologies often stem from commonly known concepts in other real-world applications.
    b. Students recognize that inventing technology is mostly a matter of systematically applying logical thinking towards a goal.

To address the above goals, we emphasize conceptual understanding of the basic ideas underlying various technologies before delving into details of specific technologies. For example, we emphasize understanding of multiple access mechanisms and get students to recognize that GSM is a combination of FDMA and TDMA, before delving into the intricate details of GSM channel structure.

The overview of our instructional method is to use analogical problem-solving through real-life scenarios to develop fundamental concepts. The instructor poses design problems in real-life scenarios which the students solve by working in groups. The instructor then facilitates a class discussion of the solutions to the analogy problem, followed by mapping the analogy problem and solution(s) to the technical domain. Figure 1 shows the overview of the method. The analogy problems have been carefully designed so that the abstract structure of the problem and its solutions, map to corresponding core Networking concepts (see section 3.1 for how these problems were developed). Care is taken to ensure that the mapping does not lead to any ambiguity or misconceptions at the conceptual understanding level [1].

Analogies have been long promoted as a cognitive tool to understand the properties of an unfamiliar idea using a familiar idea and are central to the development of scientific ideas [6]. Analogies are being used in teaching computer science subjects such as programming [3] and algorithms [11]. One role played by analogies in our course is to demonstrate that the subject is a straightforward application of familiar concepts. Further, the power of analogies lies not only in comparing the properties of two domains, but also in the development of new abstraction and mental models [4]. Experts frequently reason through analogies while developing new theories [2]. Analogies have been reported

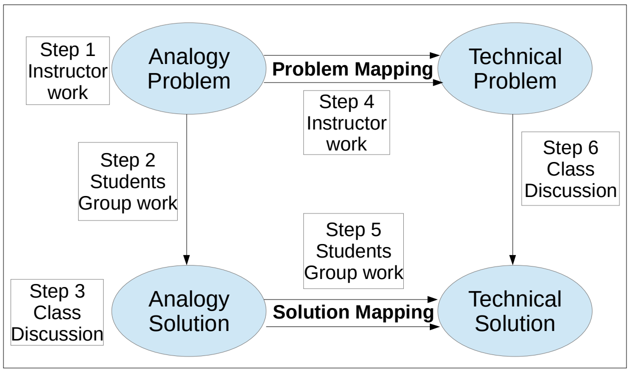

Figure 1. Overview of instructional method

to be an important tool in solving complex problems [5]. It is this power of analogies that we harness in the problem-solving process in our course: students solve complex problems in familiar real-life scenarios, and develop the necessary abstractions, which are then mapped to the Networking domain.

The choice of a familiar real-life scenario especially addresses our second objective of demystifying technology. Studies have shown that success of using analogies for teaching and learning depends on students' understanding of the base domain [4]. In our course, the base domain consists of real-life situations, which have been chosen to maximize students' familiarity. In terms of learning problem-solving skills, students first encounter the problem and attempt its solution in the real-life scenario. Since students learn these new skills in a familiar domain, the initial barrier to begin solving a complex problem is overcome. Finally, real life scenarios increase personalization through connections and relevance, thereby enhancing students' motivation to learn abstract topics. Use of collaborative problem solving further eases the initial barrier and facilitates tackling of complex design problems [12].

3. IMPLEMENTATION DETAILS

3.1 Development of instructional material

Since the basis of the instructional method involves analogies, we first describe how we identified and developed analogies to the relevant Networking concepts. Given the syllabus, we developed instructional material for each topic as follows:

1. Identify the important concepts in that topic. Examine if the basic ideas associated with the concept occur repeatedly, either in Networking or elsewhere.
2. Decide whether an analogy would be useful. We use analogy to (i) emphasize the broad applicability of the concept, or (ii) to overcome the initial barrier of learning the details of a new technology. An example for (i) is: Analogy is useful for teaching multiple access mechanisms since they are similar to resource sharing mechanisms in other areas. An example for (ii) is: Analogy is useful for teaching about the layering, interfaces and protocols. An example where an analogy is not required (by our definition) is: TCP window size.
3. Develop the analogy problem. Consider real-world scenarios or fictitious situations using real-world elements that have an abstract structure similar to the Networking concept. Identify constraints to be imposed on the real-world scenario that can mimic the properties of the network. For example, the CEO

scenario described below (section 3.2, step 1) captures many important concepts in Networking, such as layering, packetization and retransmission.

Throughout the course, students repeatedly get exposed to real-life problems in which they have to design protocols for the given requirements and constraints. These analogy problems build from simple scenarios to complex ones, mimicking the evolution of the corresponding technologies. The explicit use of analogies and asking students to apply skills required to design systems, addresses our instructional goals 2(a) and 2(b) respectively.

3.2 Classroom learning environment

The treatment of a typical topic involves: introduction and motivation of the problem in the analogy domain, group-problem solving of a question in an analogy domain, analysis of various solutions and then mapping of the analogy problem and solution(s) to the technical domain. This process takes about 90 minutes. An overview of the treatment is given in Figure 1. The details of each step in the treatment are as below.

Process of problem solving using analogies:

STEP 1 (5 minutes): Instructor poses question in analogy domain.

The instructor briefly describes what the question entails and what students are expected to do. One example, which we call the CEO scenario, used as an analogy for Networking layers and TCP/IP actions, is given below:

There are two companies A and B, located in cities about 200 km apart. The CEO of company A wants to send a document, of 100 pages, to the CEO of company B. How can this be done, given the following constraints:

- *There is no email, no fax, no phone, no post office - no form of modern communication whatsoever.*
- *The only means of communication are messenger boys.*
- *The messenger boys are weak. Each can carry only 10 pages at a time!*
- *The messenger boys are fickle. They may decide to quit without notice at any, even while carrying pages!*

STEP 2 (20 minutes): Group problem-solving.

Students work in groups of 4-6 to solve the problem in the analogy domain. The instructor helps students structure their problem-solving process.

STEP 3 (20 minutes): Entire-class discussion.

The instructor facilitates a discussion in which various solutions are analyzed. Each group presents their solution and students critique each others' solution. The class evaluates trade-offs and benefits between different solutions. The instructor guides the discussion by bringing out any missing pieces required for correctness of the various solutions and converges on a 'suitable' solution. For the CEO scenario, the instructor first brings out the need for Secretaries and Dispatch sections at each end, and also the need to specify actions of each entity clearly. Then the instructor discusses the details of the chosen 'suitable' solution. An overview of the solution to the CEO scenario is given in Fig. 2. The problem solving steps are listed below.

- *CEO-A gives data - document (D) and name (CEO-B) to Secretary-A, along with control – send this by tomorrow.*

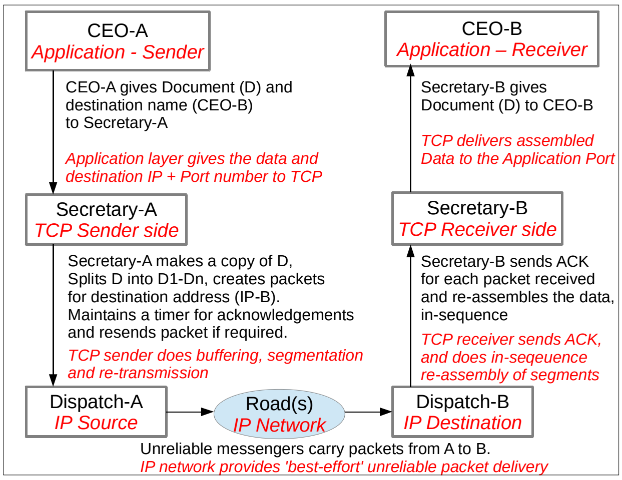

Figure 2: Overview of solution to CEO scenario

- *Secretary-A finds the address for CEO-B, makes a copy of D, creates 10 packets of 10 pages each, and numbers each packet sequentially.*
- *Secretary-A and Secretary-B have an agreed upon protocol for handling packets and sending acknowledgements.*
- *Secretary-A gives each packet to Dispatch-A and waits for acknowledgement from Secretary-B. If the acknowledgement for a packet is not received within a pre-decided time (say due to missing messenger), Secretary-A creates another identical packet (using the copy of D) and re-sends it.*
- *When a messenger arrives at Dispatch-B, Dispatch-B verifies the address and sends the packet to Secretary-B.*
- *Secretary-B sends the acknowledgement for the packet, extracts the 10 pages from the packet and re-assembles the document appropriately. Upon completion, Secretary-B hands over the document to CEO-B.*

STEP 4 (5 minutes): Instructor maps the analogy problem to the technical problem.

For the CEO scenario, the corresponding technical problem is "How does reliable communication happen in a client-server application, despite an unreliable IP network?" The instructor highlights the correspondence between the layers of the company 'stack' (CEO-Secretary-Dispatch) and a networking stack (Application-TCP-IP) (Fig.2). The instructor illustrates the technical problem using examples.

STEP 5 (10 minutes): Students map their solution.

Students work in the same groups as before to map their analogy solution to the technical solution.

STEP 6 (30 minutes): Entire-class discussion.

The class discusses the finer details of the technical solution. The instructor emphasizes which common concepts carry over from the analogy to the technical domain, and where, if any, breakdown occurs.

For the CEO scenario, the instructor brings out:

- The notion of layers, protocols and interfaces. The concerns and functions at each layer are different. The interfaces need to be clearly specified for the abstraction to work.

- The similarity between the Secretary's actions and reliable service provided by TCP. The similarity between the messenger boys and best-effort service provided by IP.
- Other topics that have a mapping from the analogy to technical domain. For example: Secretary-A looking up address of CEO-B corresponds to DNS lookup.

In this paper we have presented only one analogy problem, due to want of space. We have developed analogy problems for other concepts such as Multiple Access, Routing, and Roaming. For each concept, the overall treatment (Steps 1-6 above) is done in one class of 90 minutes, followed by delving into detailed technical aspects of relevant technologies in the subsequent 2-3 classes.

3.3 Student characteristics

The students were from Master's level programs across various domains, such as electronics, reliability, mechanical and chemical engineering. Most of them did not have any prior undergraduate course in Networking. Their objective in registering for this course was to get an exposure to communication networks and a working knowledge of various technologies such as TCP/IP, CDMA.

4. EVALUATING EFFECTIVENESS

Our Networking course taught via analogical problem-solving method was offered as a semester-long course three times, once each in 2009 (30 students), 2010 (62 students) and 2011 (28 students). We evaluated if the primary course goals- demonstrate conceptual understanding and demystify technology - have been met by the instructional method. In this section, we report some of these effectiveness studies.

To test conceptual understanding, we show results from exam questions of two kinds: traditional questions testing conceptual understanding in the Networking domain, and analogy-based problems in which students apply concepts from a real-life situation to solve a Networking problem (section 4.1). We analyze data from focus group interviews and classroom observations to determine student perceptions (section 4.2). We report the benefits and challenges to the course instructor from class logs and classroom observations (section 4.3).

4.1 Is analogical problem solving productive to develop conceptual understanding?

We first analyzed how our students perform on typical textbook questions, in which they have to apply Networking concepts to solve a problem. We then studied to what extent our students are able to apply the analogical problem-solving method in attempting problems in a new topic in the Networking domain.

A) Students' performance on traditional Networking questions is comparable to traditionally taught students

Table 1 shows the comparative data of four final exam questions of students from a traditional course without analogical problem solving and our students (analogical problem-solving group). Such questions are common to most standard Networking courses. An example of such a question is: "It has been observed that as the RTS_Threshold in IEEE 802.11 (WiFi). increases from zero, the network throughput initially increases. The network throughput reaches a peak for a certain value of RTS_Threshold and then starts to drop. Explain."

The traditional group consisted of 63 students at the Masters level in the Information Technology department. The analogical problem-solving group consisted of 30 students who took our course in the first course offering in 2009. Students from both groups enter the program via a similar entrance test. Both courses ran in the 1st year of the Masters program and were taught by the same instructor. Hence we consider the groups as equivalent for purposes of comparison.

Table 1. Comparative performance on Networking problems

Final exam question	**Traditional group Mean (SD)** (N=63)	**Analogical problem-solving group Mean (SD)** (N=30)	**Difference significant?**
Problem 1	6.3 (3.6)	5.9 (4.4)	Not significant, $p>0.05$
Problem 2	3.5 (2.8)	5.0 (3.9)	Significant, $p=0.04$
Problem 3	4.7 (2.1)	5.0 (3.9)	Not significant, $p>0.05$
Problem 4	4.9 (3.8)	6.0 (4.4)	Not significant, $p>0.05$

We find that on three out of four questions, there is no significant difference between the mean performance of the two groups of students. In Problem 2, students who learnt via analogical problem-solving had a higher mean score than traditional students, and this difference was found to be significant. This shows that the analogical problem-solving method is comparable or better than traditional methods in terms of students' performance on typical Networking questions, despite the instructor not spending as much class time on typical questions.

In addition, we have analyzed students' performance on more than 20 test questions over the three years our course was offered. We find that students' are indeed successful in solving such questions. Even though students spend significant class time discussing real life scenarios, they are able to abstract the underlying technical principles and successfully apply them to the relevant Networking topics.

B) Students are able to apply concepts from real life domain to new unseen topic in Networking domain

In each course offering, there were 2-3 problems in various exams in which students had to first solve a problem in the analogy domain (from a real-life scenario or a fictitious scenario in a day-to-day context), then had to map its solution to a problem in a *previously unseen* Networking topic. An example is shown below:

> *Analogy problem:* Consider 3 mountains in a straight line, A-B-C. There is a watch-tower on top of each mountain, each having a security guard. The only mode of communication between the guards is by shouting! The distances between A-B-C are such that A-B are within shouting and hearing range of each other. Similarly, B-C are within range. However, A-C are not within range of each other. Now, the guards want to talk to each other, every once in a while. For example, A and C may want to talk to B, while B wants to talk to C, and so on. Design a protocol to be

used in the above scenario, such that A-B-C may communicate meaningfully with each other.

Technical problem: Consider computers connected using wireless links instead of Ethernet cables. WiFi is a popular Ethernet-like protocol for such wireless LANs. WiFi also uses CSMA (Carrier Sense Multiple Access) in a manner similar to Ethernet. but instead of Collision Detection (CD), it uses Collision Avoidance (CA). Suppose you are asked to design such a CSMA/CA protocol. What would be the main steps of your protocol?

Our goal was to investigate if students can productively use analogy based reasoning to solve new problems. We show results on the above pair of problems, which were given to students in a mid-term exam during the first offering. Table 2 shows students' performance (N=29) on the analogical problem, and its corresponding technical Networking problem. It is important to note that students were not explicitly taught the Networking topic when they encountered this problem. We coded the solutions to both problems into three categories: A) Broad solution and details correct, B) Broad solution and a few details missing and C) Solution reported does not solve the problem.

Table 2. Students' performance on analogy and Networking problems

	Analogy problem (number of students)	**Networking problem (number of students)**	**Mapping done? (number of students)**
A: Broad solution and details correct	13	11	11
B: Broad solution correct but a few details missing	13	12	7
C: Solution does not answer the question	3	6	0

We found that 79% students (23 out of 29 from categories A and B in Table 2) were able to solve the Networking problem either with all details correct or at least to the level where the broad solution and some details were correct. Out of students who got the broad solution and details of the Networking problem correct (A), 100% students were found to have explicitly used mapping between the analogy problem and the technical problem to arrive at their solution. Out of students who got only the broad solution of the Networking problem correct but missed some details (B), 7 out of 12 (58%) and students had explicitly used mapping between the analogy problem and the technical problem. However, the students who did not solve the Networking problem correctly did not use mapping at all.

These results show that i) students are able to productively abstract the relevant concepts from the analogy to solve a previously unseen technical problem and ii) students who are successful in solving technical problem use mapping from the analogy. Secondly, from the instructor's point of view, this result shows that using analogies instead of directly teaching in the technical domain is a feasible technique. Thirdly, the fact that students are able to solve a problem in a hitherto unknown technical topic by first solving the analogical real-life problem shows that our goal of using analogies - to demystify technology has been achieved.

4.2 How do students perceive the course environment?

We explore how students react to the non-traditional learning environment in this course, and their perceptions about their learning in this course. To study student perceptions, we conducted focus group interview of 16 students at the end of the course in the first offering. The interview lasted for 45 minutes and was conducted by an external observer (2nd author of this paper). Data were audio-recorded and transcribed. We also show course evaluation data from each of the three offerings

From the focus group interview, we found that students' confidence in tackling technical problems is high, by having been exposed to the analogical problem solving method. Several comments in the focus group interview related to the usefulness of analogies in problem-solving.

> *"When I was solving a technical problem [in an exam], I only had to worry about a few minute technical details. The rest – the broad solution – was very clear because of the analogy."*

> *"We keep going back to the analogy while solving the technical problem."*

> *"Learning with analogies was a completely new way of thinking, this is thinking out of the box. … We are made to think about the actual problem underlying the scenario. Concept becomes easier to learn."*

The overall percentages of the end of semester course evaluation were 89.6, 84.2 and 87.8, for the three offerings respectively. These are comparable to the top course scores in our institution.

4.3 What are the instructor's perceptions of teaching with analogies and problem solving?

In this section, we discuss the benefits and challenges to an instructor in teaching Networking using analogical problem-solving. We have three data sources: i) The instructor (1st author of this paper) maintained detailed logs of each class. ii) In addition, the other author of this paper attended all classes as an external observer in the first offering and maintained notes and audio-recordings of classroom observations. About 20% of the classes were also video-recorded. (iii) Interview of the course instructor to determine why his motivation to use analogical problem-solving to teach Networking, and his experiences.

<u>Benefits:</u>

1) The instructor found that not only was the course goal of conceptual understanding met but also that students reasoned at greater depth. The instructor observed that (i) a higher number of students were able to keep up with the technical discussion (in all topics) and (ii) some students were able to come up with scenarios and explanations that indicate depth. For example, on the topic of placement of buffers in routers, some students came up with the idea of parallel iterated matching, which was beyond the syllabus.

2) The instructor found that students could systematically 'invent' current technologies by starting with simple ideas and following the logical steps in the evolution of the technology. The instructor led students through the historical discovery process of many technologies and posed the same question that researchers posed

decades ago. Students were able to replicate the evolution process: they asked questions at the points where problems existed in the historical process and arrived at similar answers. For example, on the topic of packet scheduling, students came up with weighted round-robin for variable packet size, by progressing systematically from first-in-first-out scheduling for fixed packet size.

3) The instructor found that the analogical problem-solving method led to increased efficiency. For example, class logs showed that the instructor had prepared for a 90 minute class on two topics (buffers and scheduling), but due to students leading the discussion, the topics were covered in 60 minutes, whereas a traditional treatment would need 120 minutes. While this was not an explicit course goal, we report this finding as an important side-effect of the instructional method.

Challenges:

1) Almost every student is able to come up with a solution in the analogy domain. When the similarities with the technical domain are pointed out, some of them feel that they understand the technical topic and gloss over the details. In reality, they have only got a start to understanding the technical topic and the details are as important to understand why/how a solution actually works.

2) Caution is needed to ensure that the analogy is not extended to its breakdown point, which could lead to student misconceptions.

3) Some students get overwhelmed with the multiple possibilities while solving the analogy problem, and do not proceed. They find it hard to eliminate possibilities required to converge on one fully working and correct solution, even if it is not optimal.

4) Students who are already somewhat familiar with the technical topic may attempt to reverse map their incomplete understanding.

5. CONCLUSION

Analogies are routinely used by experts to understand new ideas by a process of productive abstraction [2]. In our course, the analogical problem-solving technique helps students focus on the core concepts necessary to solve the problem without getting distracted by the details. It is important to note that in our technique, it is the students who collaboratively devise the solutions to the analogy problems, and thereby construct their own knowledge of new concepts. This technique is more powerful than merely telling students the similarity between two domains, since it is rooted in the principles of active engagement and collaborative learning.

The primary intention of the instructor to use analogical problem solving as a teaching technique was to demystify the technical details that are ubiquitous in Networking courses. For this goal, analogies play the role of engaging students, and helping them see real life connections. Our studies showed that even novice students (to CS topics) are not daunted by the technical details. In fact, they are more likely to begin solving the problem if it is presented in the analogy domain. This technique gets students to overcome the initial barrier of attempting a new problem and thus erases the perceived difficulty. Their confidence in attempting further complex technical problems is increased. Students get over the perception that only a specialist can design network protocols.

For an instructor interested in using the analogical problem-solving technique to teach Networking, we have the following recommendations:

- Choose the problems in the analogy domain carefully. Use analogy problems that map well to the technical problem. Make sure that the analogy problem is in a scenario culturally familiar to the students. (The authors would be happy to provide interested readers with their problems).
- During the problem-solving step, use the analogy to draw students' attention to the core concepts. Help students differentiate between the essential points and the non-essential details.
- Do not be discouraged if no immediate productive discussion seems to happen during group discussion or if some students do not seem to participate. We found that it often took 10-12 minutes of 'floundering' (or silence) before students began to solve the problem. Since the problem is in a familiar domain, students will eventually come up with *a* solution.
- Let each student-group describe their solution during the class-wide discussion. This builds ownership to the problem. They get more involved with topic, as they want to see their analogy solution ideas appear in the technical domain. They also question - why is my analogy solution not exactly suitable – which helps all students become familiar with the nature of technological problem-solving.

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